



The environmental Impact of Decentralized Storage: A comparative analysis

Research on the environmental impact of different data storage methodologies and evaluation of associated carbon emissions.

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Summary

The exponential growth of the global datasphere represents a significant challenge to environmental sustainability. Data storage and distribution increasingly contribute to the global carbon footprint.

The analysis of the environmental impact of data storage must consider not only the operational energy consumption of storage devices but also the carbon footprint resulting from their production and transportation. Research shows that these factors often outweigh the impact of the devices' operation. A critical issue arises from the widespread underutilization of storage drives—most operate well below their maximum capacity while consuming nearly the same energy as a fully utilized drive.

The research highlights three key areas for reducing the carbon footprint:

1. Maximizing the lifespan and utilization of existing drives
2. Optimizing data redundancy
 - To ensure durability
 - To guarantee geographic distribution and performance
3. Efficient balancing between HDD and SSD storage

Certiblok offers an enterprise-grade S3-compatible cloud storage solution that leverages the unused capacity of independently managed drives on a global scale. This document analyzes the carbon costs of centralized cloud storage, examines Certiblok's differentiated approach, and presents a model for estimating potential CO₂ savings.

Analyses indicate a potential carbon emissions reduction of 66-83% per TB of data over a three-year period, equivalent to over 200 kg CO₂/TB.

The Challenge of Data Growth

According to IDC projections, 64.2 zettabytes of data were generated or replicated in 2020. Forecasts indicate a compound annual growth rate (CAGR) of 23% between 2020 and 2025, leading to over 180 zettabytes of data created and replicated by 2025¹.

Durability (%)			
Copies	0.5% annual failure rate	1.0% annual failure rate	2.5% annual failure rate
1	99.501247919268200	99.004983374916800	97.530991202833200
2	99.995033208665900	99.980264677289000	99.879089572574900
3	99.999944379031300	99.999560004506000	99.993352635849300
4	99.999999343911600	99.999898669042200	99.999615316607400
5	99.99999992029700	99.999999750204800	99.999977080897800
6	99.9999999901300	99.99999993844600	99.999998608598100
7	99.9999999998700	99.999999999846300	99.999999914411300
8	99.9999999999900	99.99999999996100	99.99999994683800
9	99.99999999999900	99.99999999999900	99.99999999967300

Figure 1: Analysis of file durability based on the number of copies and expected failure rates².

Data replication represents a significant multiplying factor for the required storage capacity. To ensure data durability, organizations typically maintain multiple copies through various methodologies:

- Protection against hardware failures
- Backups for recovery from human errors
- Geographic redundancy for disaster recovery
- Regional distribution to optimize access

Most hyperscalers store a minimum of three copies of data. The 3-2-1 backup rule (maintaining 3 copies of data, on 2 different types of media, with at least 1 off-site copy) is a commonly cited practice³.

If a company needs to store 3 copies of a given dataset, the data has an expansion factor of 3. One functional TB of data ends up requiring 3 TB of capacity, distributed across 3 different drives, along with the associated economic and carbon costs of those drives.

¹ Worldwide IDC Global DataSphere Forecast 2022-2026

² http://www.suaybarslan.com.tr/Reliability_Systems_14.pdf

³ [US Chamber 3-2-1 Backup Rule](#)

To achieve reasonable durability guarantees, most companies rely on replication. The majority of cloud storage providers replicate data three times within a single region to ensure sufficient durability. However, if the data needs to be stored across multiple regions for disaster recovery or distribution purposes, that number is multiplied by the number of regions.

Key Factors in Data Storage

Factor #1: Energy Demand of Data Centers

Global data centers consume approximately 416 terawatt-hours of energy annually⁴, with some estimates reaching up to 770 terawatt-hours⁵.

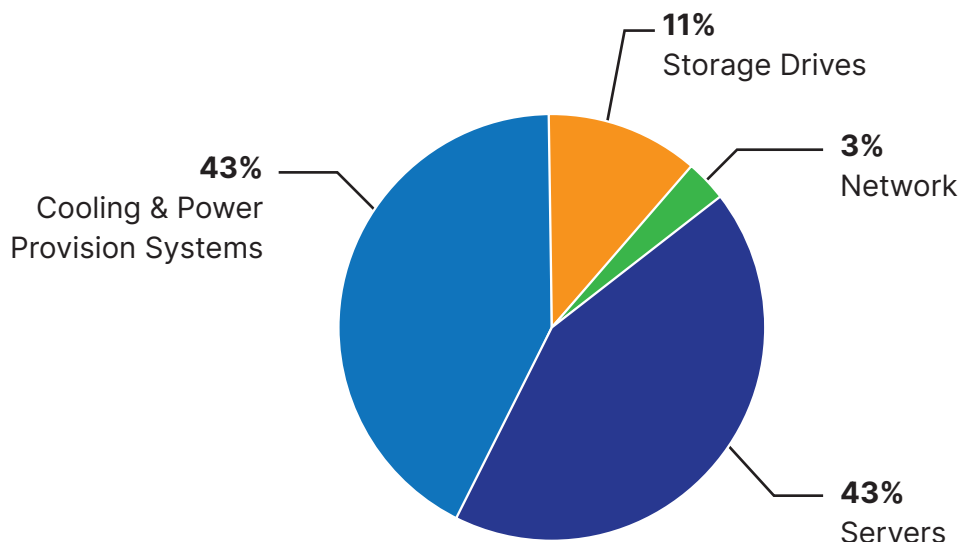


Figure 2: Breakdown of energy consumption in U.S. data centers by usage category

11% of the total energy consumption is directly attributable to powering drives. A significant portion of the energy used for cooling, power supply, processing, and networking is also related to data management and storage.⁶

Major cloud providers can boast superior carbon efficiency due to:

- Economies of scale in data center overhead
- Strategic positioning near clean energy sources
- Resource utilization optimization

⁴ [C&C Tech Group - Understanding Data Center Energy Consumption](#)

⁵ [IEA Data Centers and Data Transmission Networks Report](#)

⁶ [Shehabi et. al. \(2016\). United States Data Center Energy Usage Report](#)

Two additional environmental considerations involve:

1. The refrigerants used for cooling, often composed of harmful chemicals
2. Backup batteries, whose lifecycle has significant environmental impacts

Factor #2: Impact of Drive Production

The environmental footprint of storage is not only derived from operational energy consumption but also from the production, transportation, and disposal of devices.

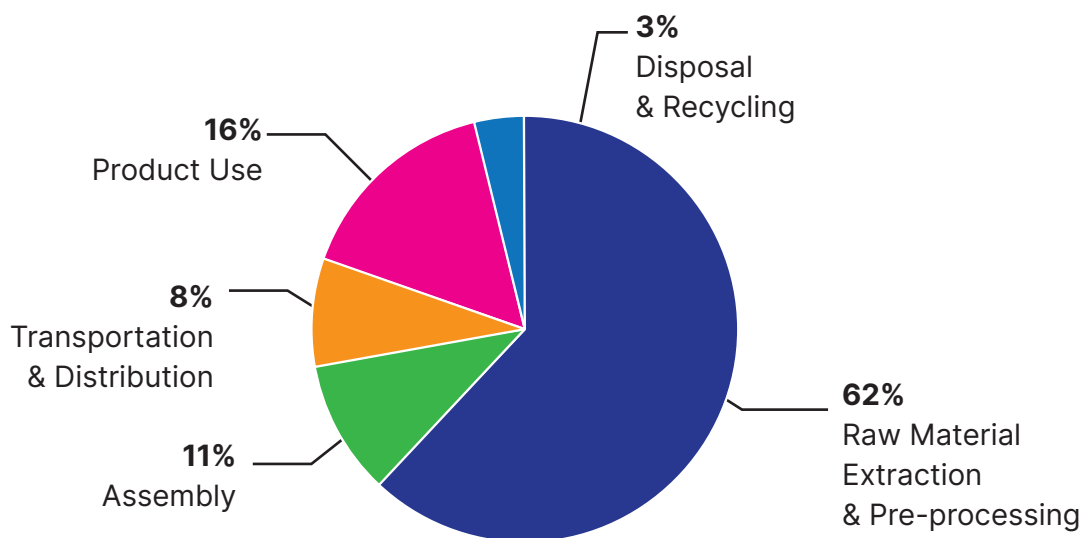


Figure 3: Distribution of environmental impact across the lifecycle stages of a 1TB drive.⁷

A lifecycle analysis of a 1TB Seagate Momentus drive reveals that only 16% of its climate impact comes from operational energy consumption. Most of the impact originates from:

- Material extraction and pre-processing (62%)
- Assembly (11%)
- Transportation and distribution (8%)

The production process⁸ begins with the extraction of rare earth elements, primarily in China, continues with the production of magnets in Japan, the assembly of actuators in Malaysia, and the final assembly in Thailand. Illegal rare earth extraction, estimated at 30% of the total, causes particularly severe damage to the environment and public health.

Each year, nearly 1 billion HDDs reach the end of their lifecycle, with most being simply destroyed and minimal material recovery⁹.

⁷ [Seagate life cycle analysis of the Momentus drive and impact on climate change](#)

⁸ [Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives](#)

⁹ [Mostafa Sabbaghi, et al, The Global Flow of Hard Disk Drives: Quantifying the Concept of Value](#)

Studies show that reusing drives provides the greatest environmental benefit, saving approximately 5 kg of CO₂ for every six months of extended life¹⁰.

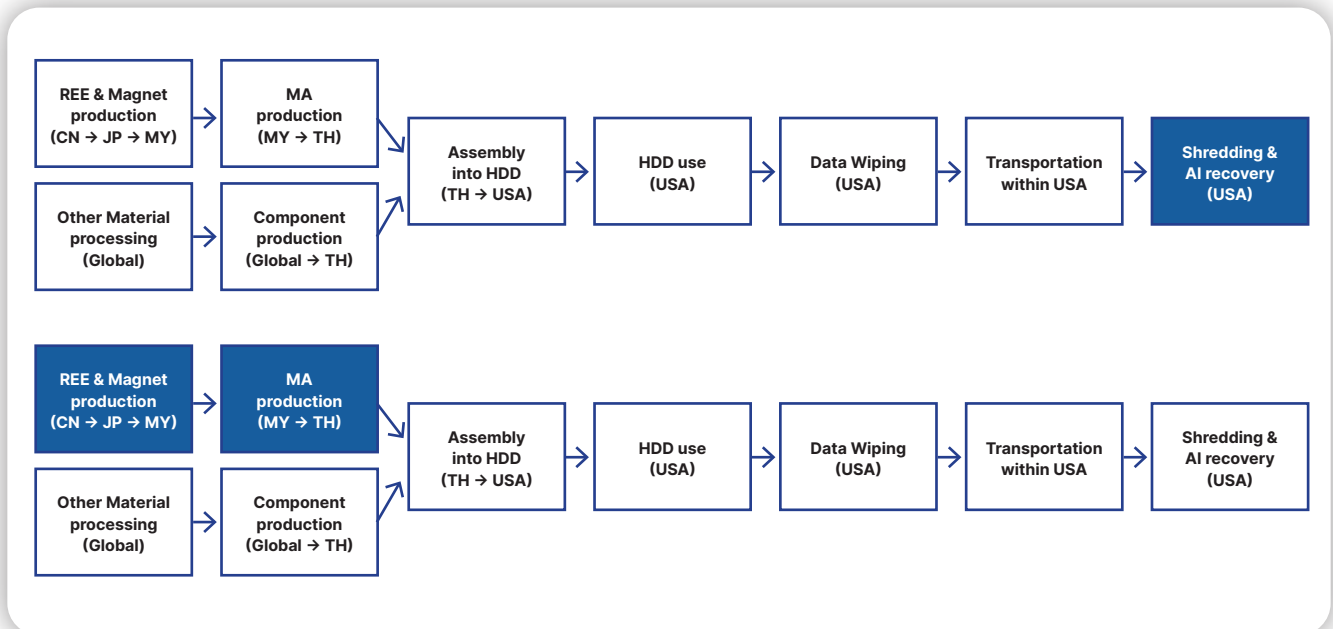


Figure 4: Representation of the typical lifecycle of a hard drive¹¹.

Even for hard drives in constant use, their production represents a significant component of their climate impact. Tannu and Nair, in a report on the embodied carbon in SSDs, used Life Cycle Assessment (LCA) data from manufacturers of 26 units of various sizes to estimate that producing 1 TB of HDD capacity generates a carbon footprint of approximately 20 kg. Powering that capacity over a five-year lifespan adds another 76 kg of carbon¹². However, even the 20 kg figure might underestimate the significant cost, both in terms of carbon and other environmental impacts, of hard drive production.

Referring to the research by Jin et al., the global warming impact of disk production is just one of the environmental damages. The authors frame their study in terms of savings from drive reuse compared to other forms of recycling (e.g., recycling actuators or magnets).

Leakage in E-waste Recovery Systems.

¹⁰ [Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives](#)

¹¹ [Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives](#)

¹² [The Dirty Secret of SSDs: Embodied Carbon, Swamit Tannu University of Wisconsin-Madison and Prashant J Nair University of British Columbia.](#)

Impact category	Unit	HDD reuse	MA reuse	M2M	Hydro	Pyro	ER
Ozone depletion	kg CFC-11 eq	3.7E-07	2.7E-07	1.1E-07	-4.2E-08	3.2E-07	-1.7E-08
Global Warming	kg CO ₂ eq	5.5	1.9	0.7	-0.30	0.02	0.01
Smog	kg CO ₃ eq	3.9E-01	1.7E-01	7.9E-02	8.5E-03	9.2E-02	2.4E-02
Acidification	kg SO ₂ eq	4.6E-02	5.5E-02	3.1E-02	9.4E-03	3.4E-02	1.4E-02
Eutrophication	kg N eq	1.2E-02	2.2E-02	1.2E-02	6.7E-03	4.3E-02	7.7E-03
Carcinogenics	CTUh	3.1E-07	1.8E-07	3.4E-08	-4.0E-08	3.5E-07	2.4E-08
Non carcinogenics	CTUh	1.4E-06	4.5E-07	1.6E-07	6.9E-07	9.7E-06	7.6E-07
Respiratory effects	kg PM2.5 eq	5.2E-03	5.2E-03	2.7E-03	-3.6E-05	2.7E-03	5.0E-04
Ecotoxicity	CTUe	3.2E+01	1.0E+01	2.3E+00	1.4E+01	2.1E+02	1.7E+01
Fossil fuel depletion	MJ surplus	5.9E+00	2.4E+00	8.9E-01	-3.7E-05	6.0E-01	1.0E-01

Figure 5: Comparison of environmental benefits among different end-of-life management strategies¹³.

The savings in the first column of Figure 5 represent the benefits of extending a disk's lifespan by 6 months, accounting for roughly 10% of the production cost over its entire lifecycle. In their model, HDD production not only contributes 55 kg of CO₂ emissions but also causes significant additional environmental harm, including smog, eutrophication, carcinogens, and ecotoxicity during the manufacturing process.

Analysis Assumptions

Statistics from NRDC and IBM indicate that servers operate on average at 12-18% capacity¹⁴, highlighting a vast reserve of already-produced but underutilized storage capacity. It is important to note that a drive consumes nearly the same amount of energy whether it operates at 20% or 80% capacity.

Optimizing the utilization of existing capacity thus represents a significant opportunity to reduce the overall carbon footprint of data storage and distribution.

A Sustainable Approach to Data Storage

As emphasized by Vinod Khosla during a presentation at Stanford, for green technology to succeed, it must first be economically advantageous¹⁵. The goal is to achieve both economic and environmental benefits while ensuring the essential characteristics in the data world: durability, availability, performance, security, and privacy.

¹³ [Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives](#)

¹⁴ [Are Your Data Centers Keeping You From Sustainability?, IBM](#)

¹⁵ [Stanford Business: Vinod Khosla - Green Tech Must Make Economic Sense](#)

The Innovation of Decentralized Storage

Certiblok provides enterprise-grade S3-compatible cloud object storage by leveraging the unused capacity of independently managed drives worldwide. Operators of distributed storage nodes are compensated for the capacity and bandwidth they contribute to the network.

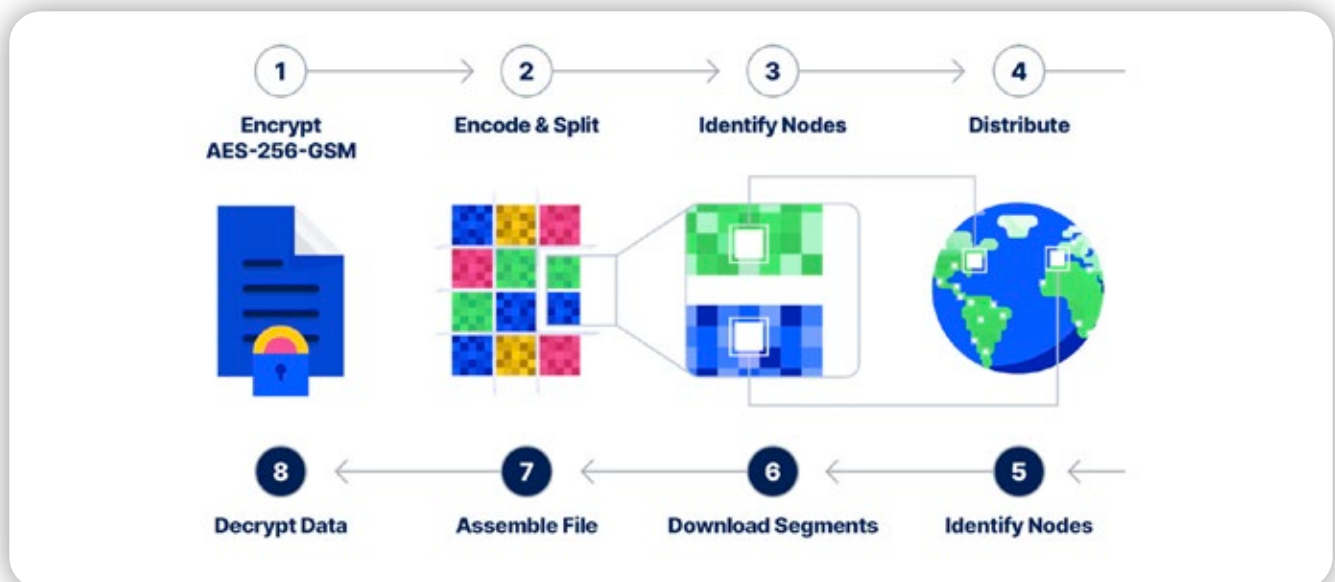


Figure 6: Architecture of the Certiblok decentralized storage system

The system implements:

1. Encryption with AES-256
2. Erasure coding and segmentation
3. Intelligent node identification
4. Geographic distribution
5. Optimized retrieval
6. Efficient reassembly
7. Secure decryption

Large files are:

- Segmented into 64 MB encrypted units
- Divided into 80 fragments with erasure coding
- Distributed across different drives globally
- Reconstructable with only 29 fragments

This approach ensures:

- 11 9's durability¹⁶
- Superior global performance
- Advanced security
- More efficient use of existing storage capacity

5 Emission Reduction Strategies

1. Optimization of Existing Capacity

Surveys show that:

- 21% of capacity comes from already operational drives
- Minimal incremental carbon impact
- Marginal operational costs
- Efficient utilization of existing resources

2. Lifecycle Extension

The technology enables:

- Surpassing traditional limits of 3-5 years
- Safely using out-of-warranty drives
- Managing failures through erasure coding
- Achieving high durability with distributed redundancy

3. Reduction of Replication

Advantages over traditional systems:

- Expansion factor of 2.7x instead of 3x or more
- Built-in multi-region protection
- Resilience against catastrophic events
- Increased storage efficiency

¹⁶ “11 nines durability” (or “eleven nines durability”) refers to a data retention probability of 99.999999999%. Practically, this means there is only a one-in-100-billion chance of losing a data object. This level of durability is often highlighted by cloud storage services like Amazon S3 to indicate the extreme reliability of their data storage systems. To put it into perspective: the probability is so high that it's more likely to win the lottery multiple times in a row than to lose a data object in a system with this durability.

Certiblok does not rely on 3-2-1 replication to achieve durability and distribution but instead uses Reed Solomon¹⁷ erasure coding. Certiblok can achieve over 11 nines of durability with an effective expansion factor of $80/29 = 2.7$. This includes multi-region protection against risks affecting data centers or even entire geographical areas, such as fires, floods, power outages, and civil unrest.

4. Optimization of Geographic Distribution

The decentralized architecture offers unique advantages:

- Automatic global distribution of fragments
- Downloads from the 29 fastest nodes out of 80 available
- Localized performance without additional replication
- Optimized access for each geographic area

For example, a user in Italy will access a different set of nodes compared to a user in New York, ensuring excellent performance without the need for dedicated regional copies, without increasing the expansion factor, and reducing both economic costs and carbon emissions.

5. Intelligent HDD-SSD Balancing

Many use cases require the utilization of both HDDs and SSDs. For example, a typical video distribution use case involves the entire content library being implemented on HDD-based origin servers, with replicas distributed across various geographic locations. Closer to the edge, particularly “hot” content is stored in SSD-based caches or Content Delivery Networks (CDNs). However, the overall carbon lifecycle costs of SSDs are nearly double those of HDDs¹⁸. Consequently, significant economic and carbon savings can be achieved by enabling efficient storage distribution between HDDs and Solid State Drives (SSDs).

The solution adopted by Certiblok significantly reduces the need for multiple HDD-based origin servers, thanks to the presence of a globally distributed and globally performant storage layer. Moreover, the speed of the Certiblok system allows a significant share of the library’s content to be served performantly directly from the origin itself, rather than relying on SSD-based caching. While SSD-based caching is still often desirable for the most popular content, the amount of SSD-based storage can be significantly reduced, leading to both carbon and economic savings.

¹⁷ [Reed-Solomon erasure coding definition](#)

¹⁸ [The Dirty Secret of SSDs: Embodied Carbon, Swamit Tannu University of Wisconsin-Madison and Prashant J Nair University of British Columbia.](#)

Calculation Methodology

Carbon Savings Estimation Model

The comparison of carbon impact between rare earth extraction and powering a drive involves many good-faith estimates. As with most other carbon savings calculations, it is not possible to measure the savings precisely, but we believe our calculations provide a conservative and robust estimate of the savings achieved through the use of Certiblok. The numbers in the model represent good-faith estimates that can be used to assess the CO₂ savings specifically derived from using Certiblok's network and, more broadly, from similar efforts to make better use of hard drives¹⁹.

Carbon Impact of Different Storage Methods

	Traditional Methods		Certiblok Methods			
	Hyperscaler	Corporate DC	Certiblok Standard*	Certiblok Reused*	Certiblok New Nodes	Certiblok Blended
Annual cost per TB at 100% utilization (kg CO ₂)	20.9	20.9	2.3	18.0	21.3	16.6
Utilization (%)	75%	40%	85%	85%	85%	90%
Energy Mix Factor (%)			74.5%	74.5%	74.5%	0.7%
Effective Carbon Cost/TB-Year (kg CO ₂ /TB)	36.2	67.9	2.0	15.8	18.7	14.6

Certiblok Network Weighting

% of the Certiblok Network			0.21%	0.208%	0.582%	100%
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Client-Specific Factors

Data TB (TB)	1.0	1.0	1.0	1.0	1.0	1.0
Retention Years (Years)	3.0	3.0	3.0	3.0	3.0	3.0
Replication for Durability (expanded data/source data)	3.0	4.0	2.7	2.7	2.7	2.7
Multi-Region Factor (# of regions)	2.0	2.0	1.0	1.0	1.0	1.0
Total at Full Capacity (kg CO ₂)	326	679	15	121	144	112

Carbon Savings

Carbon Savings from Certiblok Std vs. Alternative (kg CO ₂)	311	664				
Carbon Savings from Certiblok Blended vs. Alternative (kg CO ₂)	214	567				
Carbon Savings from Certiblok Std vs. Alternative (%)	95.3%	97.7%				
Carbon Savings from Certiblok Blended vs. Alternative (%)	65.6%	83.5%				

* Certiblok Standard: drives already provided and powered
 * Certiblok Reused: Old drives brought back online

Figure 7: Framework for Quantifying the Carbon Output of Data Storage

¹⁹ Estimates on data center and storage usage vary widely. Some sources include: [C&C Technology Group](#), [Natural Resources Defense Council \(NRDC\)](#) and [IBM](#). To keep our calculations conservative, we used the higher range of estimates for usage, which makes the comparative results for Certiblok less favorable than they might otherwise be.

Results

Carbon Savings Estimation Model

Using the assumptions outlined in Appendix A, the model suggests that using Certiblok in its pure form to store 1 TB of data for 3 years generates 15 kg of CO₂. Storing this data with a hyperscaler generates 326 kg of CO₂, while using an enterprise data center generates 679 kg of CO₂.

This means that using Certiblok for data storage results in a reduction of 311 kg of CO₂ per TB compared to hyperscaler storage and a reduction of 664 kg of CO₂ compared to an enterprise data center. This represents a reduction of 95% and 98%, respectively.

To put this into perspective, a car produces approximately 0.24 kg/km of emissions²⁰. Therefore, for a single TB of effective storage, emissions equivalent to those produced by 1,300–2,800 km of car travel can be eliminated.

Of course, these are only good-faith estimates, but they highlight the potential of this model. If even a fraction of the ZBs of data expected to be produced in the near future and the ZBs of capacity in drives already deployed and powered worldwide could be migrated to Certiblok, the environmental impact would be significant.

SUMMARY TABLE				
Carbon Impact of Various Storage Methods				
	Traditional Methods		Certiblok Methods	
	Hyperscaler	Corporate DC	Certiblok Standard*	Certiblok Blended
Total at Full Capacity (kg CO ₂)	326	679	15	112
Carbon Savings from Certiblok Std vs. Alternative (kg CO ₂)	311	664	-	-
Carbon Savings from Certiblok Blended vs. Alternative (kg CO ₂)	214	567	-	-
Carbon Savings from Certiblok Std vs. Alternative (%)	95%	98%	-	-
Carbon Savings from Certiblok Blended vs. Alternative (%)	66%	83%	-	-

Figure 8: Summary of Model Results for Carbon Emission Impact in Data Storage

²⁰ [Carbon Dioxide, Part 2: Walk, Drive a Car, or Ride a Bike? | GLOBE Scientists' Blog.](#)

Appendix A: Parameters and Assumptions

Operational Carbon Impact

The estimates are based on:

- 20 kg CO₂/TB for production (LCA analysis on 24 HDDs)
- 36.8 kWh/year/TB for energy consumption
- Conversion factor of 0.7 kg CO₂/kWh
- Annual operational impact of 15.9 kg CO₂

Marginal impact of writing:

- Write energy: 0.005 watt-hours/GB
- CO₂ conversion: 0.7 kg/kWh
- Impact per TB: 3.5 kg CO₂

Infrastructure Overhead

Calculation of coordination services impact:

- Monthly CO₂ footprint: 3600 kg
- Annualized: 43200 kg
- Current network storage: 18933 TB
- Overhead per TB/year: 0.19 kg CO₂

Device Lifespan

- Cloud providers: 4 years
- Enterprise data centers: 4 years
- Decentralized network: 6 years

Utilization Factors

- Enterprise data centers: 40%
- Cloud providers: 75%
- Decentralized network: 85%

Appendix B: Considerations for Refining the Model

1. Impact of Reads

The current model does not include:

- Carbon generated by read operations
- Impact of data transmission
- Variations for different access patterns
- Differences between storage platforms

2. SSD Optimization

Key considerations:

- SSDs require 4x more carbon for production
- Lower operational costs compared to HDDs
- Potential cache reduction through distributed architecture
- Balancing performance and sustainability

3. Energy Mix

Variable factors:

- Different energy sources by region
- Greater relative production impact in areas with clean energy
- Seasonal variations in carbon footprint
- Possible geographic optimization

4. Drive Types

Significant differences between:

- Enterprise vs consumer drives
- Capacity and lifecycle
- Operating modes
- Energy efficiency

5. Cooling Considerations

Critical aspects:

- Higher energy consumption in data centers
- Correlation with drive usage
- Amplified impact on carbon savings
- Efficiency of cooling systems

6. Alternative Configurations

Potential optimizations:

- Private or restricted networks
- Improved encoding ratios
- Reduced expansion factor
- Optimized performance

Appendix C: Bibliography

1. Worldwide IDC Global DataSphere Forecast 2022-2026
2. http://www.suaybarslan.com.tr/Reliability_Systems_14.pdf
3. US Chamber 3-2-1 Backup Rule
[C&C Tech Group - Understanding Data Center Energy Consumption](#)
4. IEA Data Centers and Data Transmission Networks Report
5. Shehabi et. al. (2016). United States Data Center Energy Usage Report
6. [Seagate life cycle analysis of the Momentum drive and impact on climate change](#)
7. Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives
8. Mostafa Sabbaghi, et al, The Global Flow of Hard Disk Drives: Quantifying the Concept of Value
9. Leakage in E-waste Recovery Systems. Mostafa Sabbaghi, et al, The Global Flow of Hard Disk Drives: Quantifying the Concept of Value
10. Leakage in E-waste Recovery Systems.
11. Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives
12. Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives
13. The Dirty Secret of SSDs: Embodied Carbon, Swamit Tannu University of Wisconsin-Madison and Prashant J Nair University of British Columbia.
14. Hongyue Jin, et al, Life cycle assessment of emerging technologies on value recovery from hard disk drives
15. [Are Your Data Centers Keeping You From Sustainability?, IBM](#)
16. Stanford Business: Vinod Khosla - Green Tech Must Make Economic Sense
17. "11 nines durability" (or "eleven nines durability") refers to a data preservation probability of 99.999999999%. Practically speaking, this means there is only a one in 100 billion chance that a data object will be lost. This level of durability is often advertised by cloud storage services like Amazon S3 to highlight the extreme reliability of their data storage systems. To put it into context: this probability is so high that it is more likely to win the lottery several times in a row than to lose a data object in a system with this level of durability.
18. Reed-Solomon erasure coding definition
19. The Dirty Secret of SSDs: Embodied Carbon, Swamit Tannu University of Wisconsin-Madison and Prashant J Nair University of British Columbia.
20. Estimates on data center and storage utilization vary widely. Some sources include C&C Technology Group, the Natural Resources Defense Council (NRDC), and IBM. To keep our calculations conservative, we used the highest range of utilization estimates, which makes the comparative results for Certiblok less favorable than they might otherwise be.
21. [Carbon Dioxide, Part 2: Walk, Drive a Car, or Ride a Bike? | GLOBE Scientists' Blog.](#)

CO₂ Savings Calculation Formula

For 1 TB of data over a three-year period:

$$\text{CO}_2 \text{ Savings} = (\text{EMC} - \text{EMD}) * C * T$$

Where:

EMC = Centralized Cloud Emissions

326 kg CO₂/TB (cloud provider)

679 kg CO₂/TB (corporate data centers)

EMD = Decentralized Cloud Emissions

112 kg CO₂/TB

C = Capacity in TB

T = Time in years / 3

Conversion for MB:

$$\text{CO}_2 \text{ Savings per MB} = (\text{EMC} - \text{EMD}) * (1 / 1,048,576) * T$$

Practical example for 1 MB annually:

$$\text{Savings} = (326 - 112) * (1 / 1,048,576) * (1 / 3)$$

$$= 0.000068 \text{ kg CO}_2 \text{ per MB}$$

$$\approx 0.068 \text{ grams of CO}_2 \text{ saved per MB}$$

Variables influencing the results:

1. Regional energy mix
2. Infrastructure efficiency
3. Storage technologies used
4. Usage patterns
5. Storage duration

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