Analyzing the Total Cost of Ownership of Carbon in Data Centers

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Introduction

- ❖ **Context: Data centers are major contributors to global carbon emissions due to high energy consumption and embodied carbon.**
  - ➢ Estimated to be ~1-1.3% of the world's electricity consumption. [1]
  - ➢ Expected growth: 240–340 TWh → 290–600 TWh by 2030. [2]
  - ➢ Conservative Estimate: ~2× growth within 6 years.
- ❖ **Environmental Impact:**
  - ➢ Responsible for ~1% of energy-related GHG emissions. [1]
  - ➢ Comparable to the emissions of the aviation industry.
- ❖ **Rising Scrutiny:**
  - ➢ Increasing demand for digital services raises questions about sustainability.
  - ➢ Need to address both operational and embodied carbon to mitigate environmental impact.

Agenda

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- Background
- *CarbonStream*
- Evaluation
- Conclusion
- Future Work

Problem Statement and Goals

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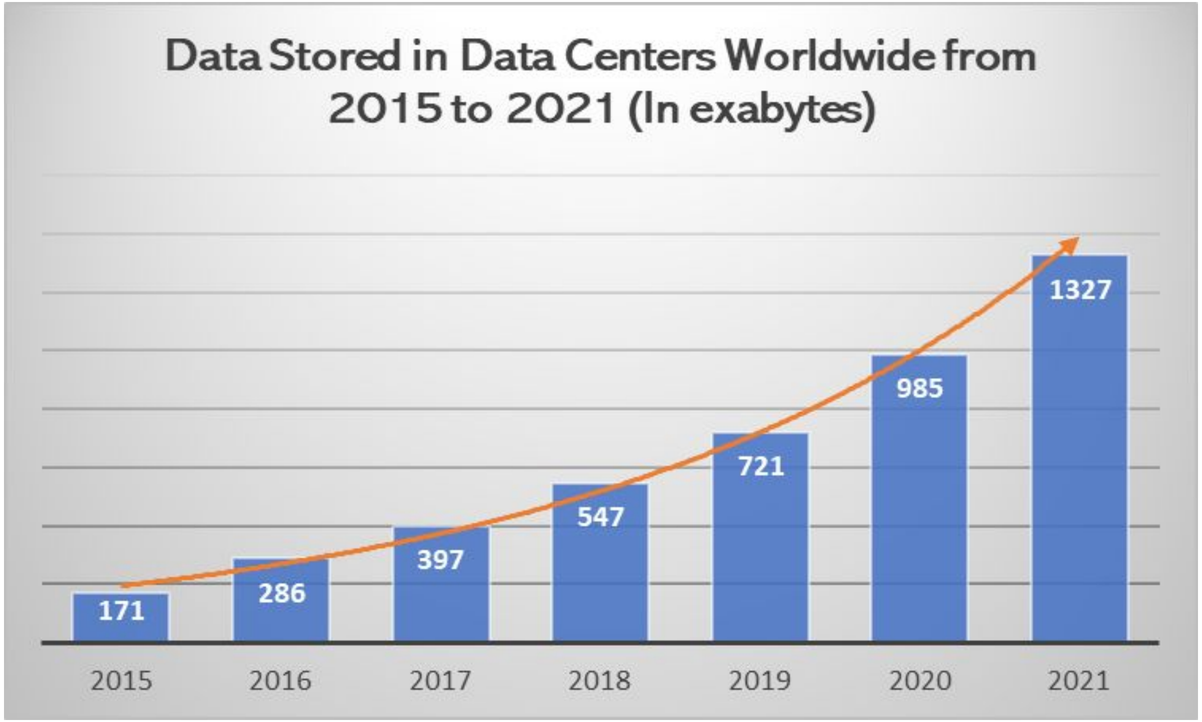
- Problem Statement: Storage media contribute significantly to the embodied carbon in data centers, especially for storage-heavy workloads.
- Research Goal: Compare the Total Cost of Ownership (TCO) of carbon across SSDs, HDDs, tape, and glass-based storage, exploring if glass-based storage can reduce total carbon impact.

Background

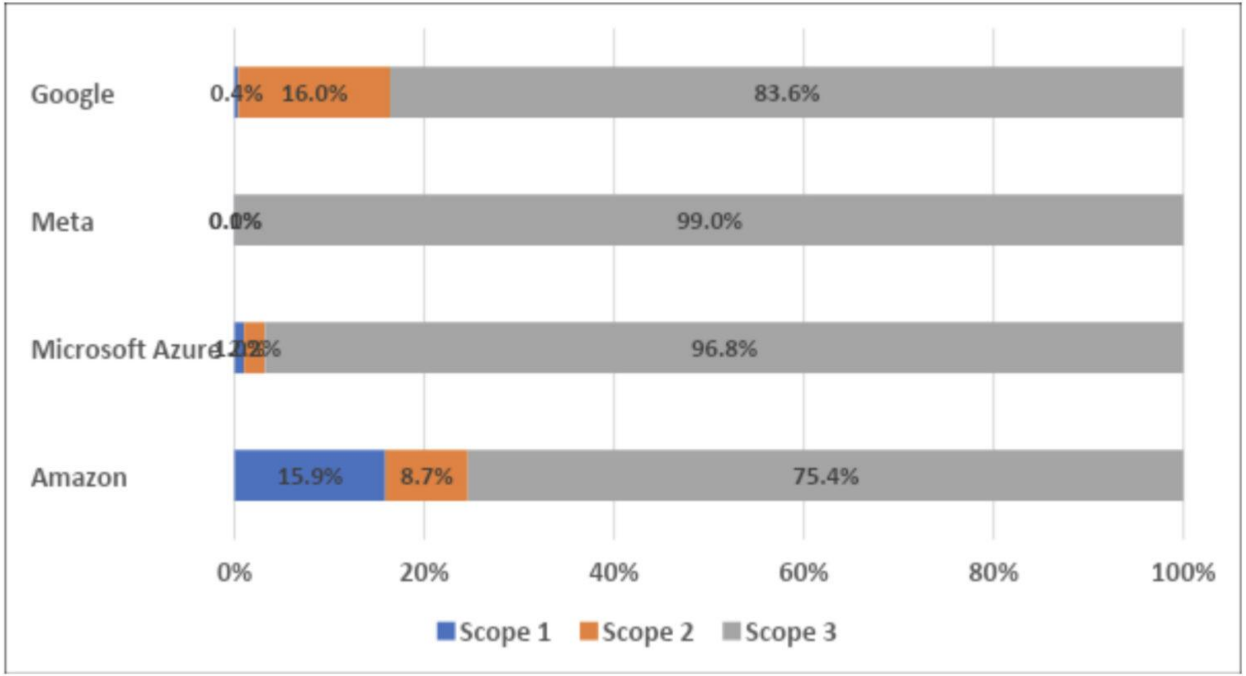
- **Data Centers and Carbon Emissions:**
  - Significant contributors to global greenhouse gas (GHG) emissions.
  - Demand for digital services continues to grow, amplifying energy use and carbon footprint.
- **Greenhouse Gas (GHG) Emissions:**
  - Scope 1: Direct emissions from owned or controlled sources.
  - Scope 2: Indirect emissions from purchased electricity.
  - Scope 3: Indirect emissions from the value chain, including embodied carbon in infrastructure.
- **Total Cost of Ownership (TCO) of Carbon = Operational Carbon (Scope 2) + Embodied Carbon (Scope 3)**
- **Environmental Impact: Rising scrutiny on data center sustainability due to energy consumption and carbon footprint.**
- **Focus Shift: Emphasis traditionally focused on Scope 2 emissions, but Scope 3 is increasingly recognized for its impact.**

Global Data Center Storage Capacity



Source: Statista [3]

Carbon Emissions of Cloud Providers



Sources: Schneider Electric 2023 derived from the sustainability reporting of listed organisations. [4]

Embodied Carbon in Data Centers

- Definition: Embodied carbon includes greenhouse gas emissions from the full lifecycle of a product.
- Impact: Storage media are a major source of embodied carbon, particularly in high-demand data centers.
- Storage is not negligible.
- Servers dominate $.

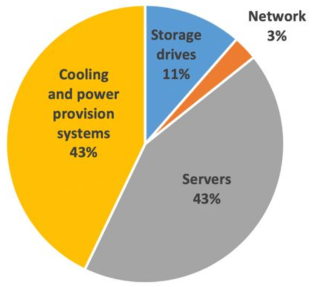
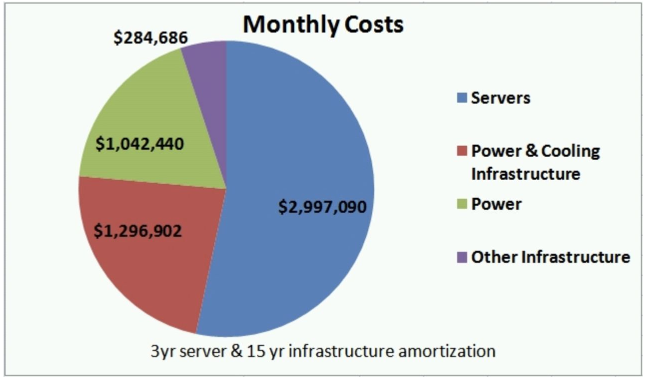


Figure 1. Fraction of U.S. data center electricity use in 2014, by end use. Source: Shehabi 2016.



Cost of Power in Large-Scale Data Centers [5]

Storage Technologies Compared

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Storage Type	Cost	Performance	Key Characteristics
DRAM	Very expensive	Extremely high speed, low latency	Extremely fast, volatile memory
SSD	Expensive	High speed, low latency	High speed, non-volatile storage
HDD	Cheap	Moderate speed, high latency	High capacity, slower than SSDs
Tape	Cheap	Very low speed, very high latency	Ideal for backups, low operational cost
Glass	?	Very low speed, very high latency	Low carbon cost, highly durable

Previous Research

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- **Operational Focus (Scope 2): Most prior studies in the last 30 years aimed at reducing operational carbon through:**
  - Dynamic voltage and frequency scaling. [6]
  - Renewable energy adoption. [7]
  - Workload balancing. [8]
- **Emerging Interest in Embodied Carbon (Scope 3):**
  - *Carbon Explorer* [9] and *Chasing Carbon* [10] frameworks highlight embodied carbon as critical for holistic carbon assessment.

Rationale for This Study

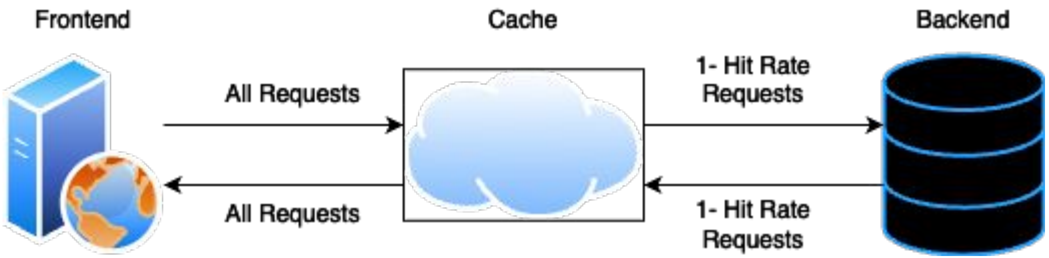
- **Need for Comprehensive Carbon Analysis:**
  - Embodied carbon in data centers is significant yet under-addressed.
  - Lifespan of storage devices directly impacts replacement carbon costs.
- **Focus on Lifespan:**
  - Longer lifespans reduce total replacements, lowering TCO of carbon.
  - Trade-offs exist between durability, performance, and carbon footprint.
- **Contribution:**
  - Provides a comparative carbon analysis of SSDs, HDDs, tape, and glass-based storage, with a focus on device lifespan impacts on sustainability.

CarbonStream

- ❖ Purpose: Custom simulation model to estimate TCO of carbon in data centers.
- ❖ System Architecture: Three-tiered setup (frontend, cache, backend).
- ❖ Metrics: Includes embodied, operational, and replacement carbon costs.
- ❖ Inputs: System configuration and workload parameters
- ❖ Outputs: Graph of calculated costs and optimal storage system setup

System Architecture

- **Components:**
  - Frontend Tier: Processes requests. (DRAM/SSD)
  - Cache Tier: Holds frequently accessed data. (DRAM/SSD)
  - Backend Tier: Primary data storage (SSDs, HDDs, tape, glass).



SLO Parameters

- **Service-Level Objective (SLO): Measurable target that defines the level of service a customer can expect to receive.**
- **Key Metrics:**
  - Latency Requirement: Max end-to-end time for data requests.
  - Throughput Requirement: Data requests per second.

Calculation of Carbon Costs

- **Types of Costs:**
  - Embodied Carbon Cost: Full lifecycle emissions.
    - Embodied Carbon Cost = ∑(# of Devices × Carbon Intensity per Unit)
  - Operational Carbon Cost: Emissions during use.
    - Active Operation Cost = ∑(# of Servers × Active Power Consumption × Carbon Intensity of Energy × Operational Time × Active Time %)
    - Idle Operation Cost = ∑(# of Servers × Idle Power Consumption × Carbon Intensity of Energy × Operational Time × Idle Time %)
  - Replacement Carbon Cost: Emissions from hardware replacements.
    - Replacement Carbon Cost = ∑(# of Replacements × Embodied Carbon Cost per Device)

Calculation of Average Latency

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- **Includes: Latency from frontend, cache, backend, and network delays.**
- **Formula:**
  - Average Latency = Frontend Latency + Cache Hit Rate × Cache Latency + (1 − Cache Hit Rate) × (Cache Latency + Backend Latency) + Network Latency + Processing Latency

Calculation of Peak Throughput

- **Minimum throughput capacity of frontend, cache, and backend tiers.**
- **Formula:**
  - Peak Throughput = min(Frontend Total Throughput, Cache Total Throughput, Backend Total Throughput)

Calculation of the Number of Servers Needed

- **Objective: Ensure system can meet throughput demands.**
- **Formula:**
  - Number of Servers = ⌈ Desired Throughput / Throughput per Server ⌉
- **Considerations:**
  - Balances required server capacity with carbon costs per server.

Calculation of the Cache Hit Rate

- **Definition: Likelihood that data requests are served from the cache instead of backend storage.**
- **Formula: Cache Hit Rate = Total Cache Size / Total Data Size**
  - Where: Total Cache Size = Number of Cache Servers x Cache Server Size
- **Impact on Performance: Higher cache hit rate lowers backend load, reducing latency and operational carbon costs.**

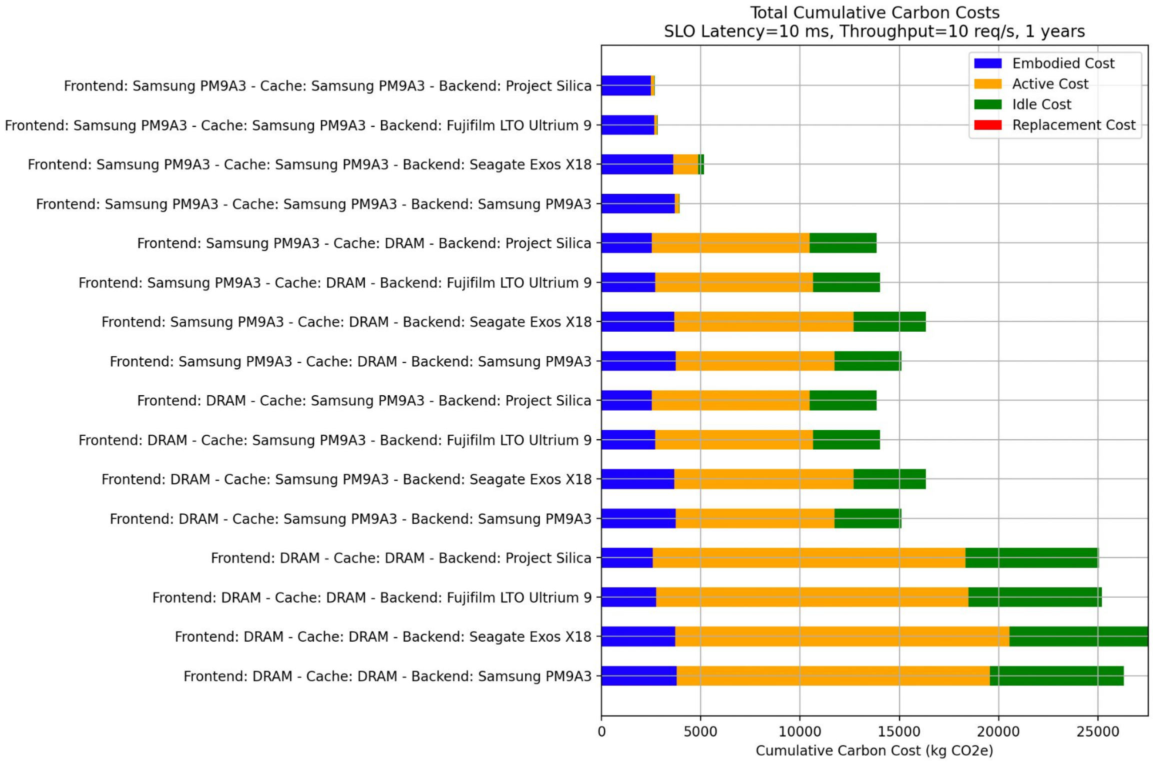
Evaluation - Model Implementation

- Implemented in Python.
- Simulation set to run over a predefined period.
  - 10 years by default.
- Tracks the energy consumption, device replacements, latency, throughput, and overall carbon footprint.
- System is assumed to store a set amount of data.
  - 10 Billion GB (10 EB) by default.

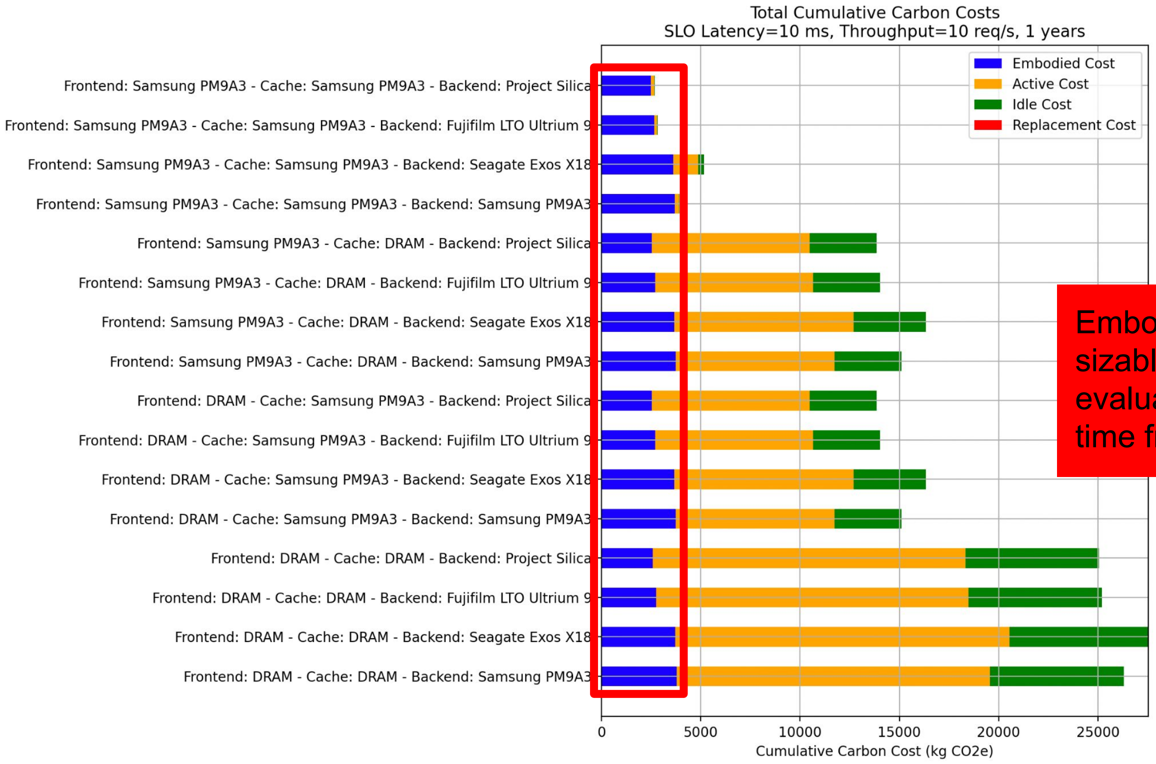
Evaluation - System Hardware

	DRAM	SSD	HDD	Tape	Glass
Device Name	N/A	Samsung PM9A3	Seagate Exos X18	Fujifilm LTO Ultrium 9	Project Silica
Capacity	4 TB	3.84 TB	18 TB	18 TB	7 TB
Latency	10 ns	0.08 ms	4.16 ms	10000 ms	2000 ms
Throughput	20 GB/s	5 GB/s	270 MB/s	400 MB/s	210 MB/s
Embodied Cost	0.31 kg CO2e/GB	0.16 kg CO2e/GB	0.0017 kg CO2e/GB	0.00042 kg CO2e/GB	0.0001 kg CO2e/GB
Power Consumption	2.5 KW	12 W (A), 3.5 W (I)	9.5 W (A), 5.3 W (I)	0.26 W (A), 0 W (I)	0.13 W (A), 0 W (I)
Lifespan	10 years	5 years	5 years	30 years	100 years

Simulation 1: Latency = 10 ms, Throughput = 10 req/s, 1 Year

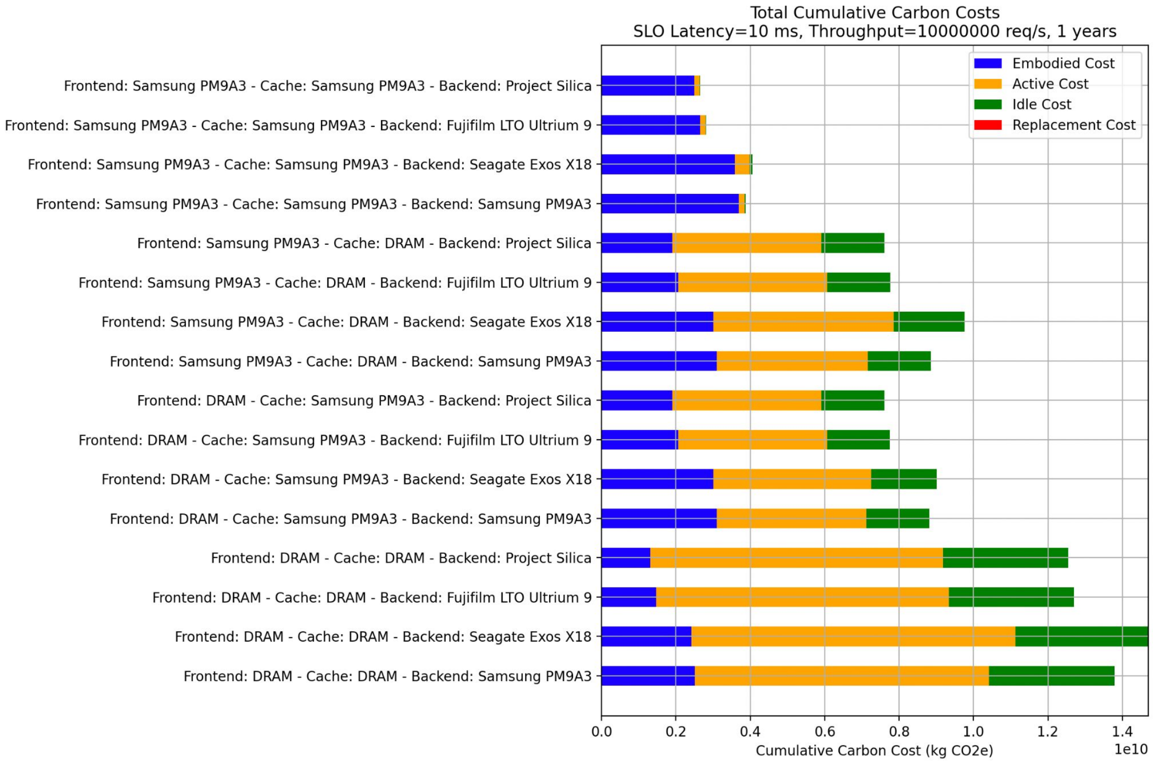


Simulation 1: Latency = 10 ms, Throughput = 10 req/s, 1 Year

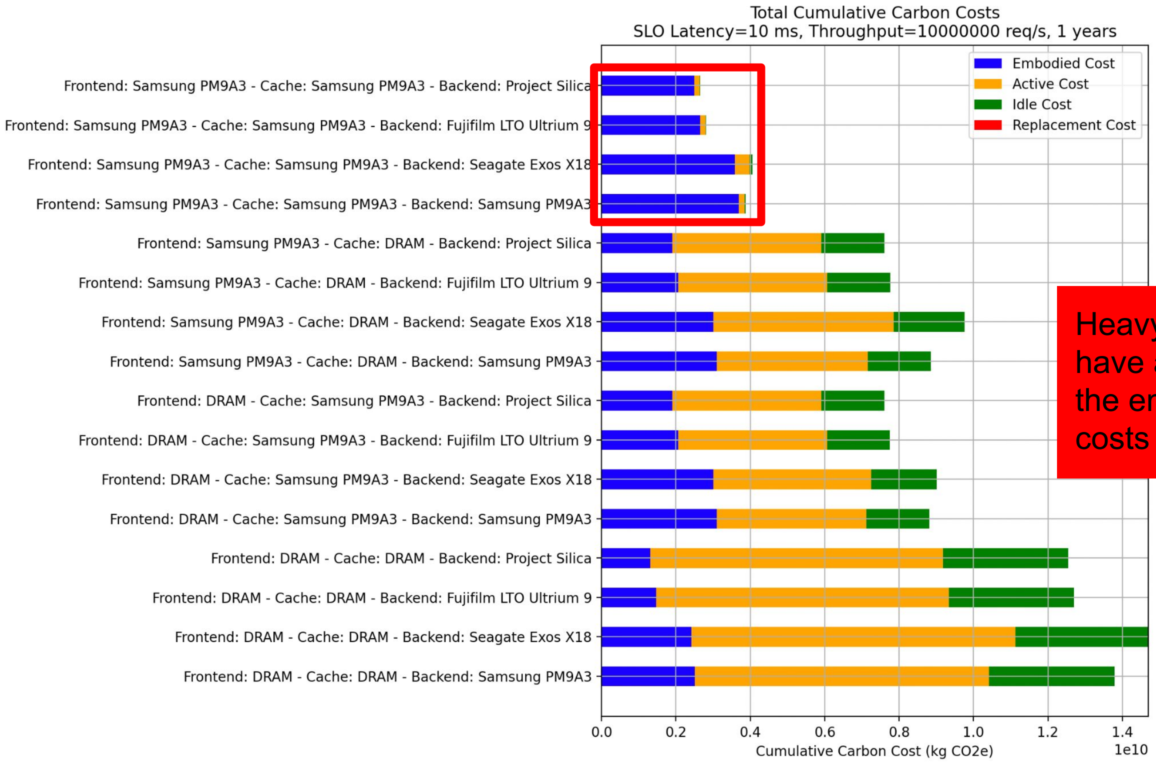


Embodied carbon is a sizable cost when evaluating over shorter time frames.

Simulation 2: Latency = 10 ms, Throughput = 10000000 req/s, 1 Year

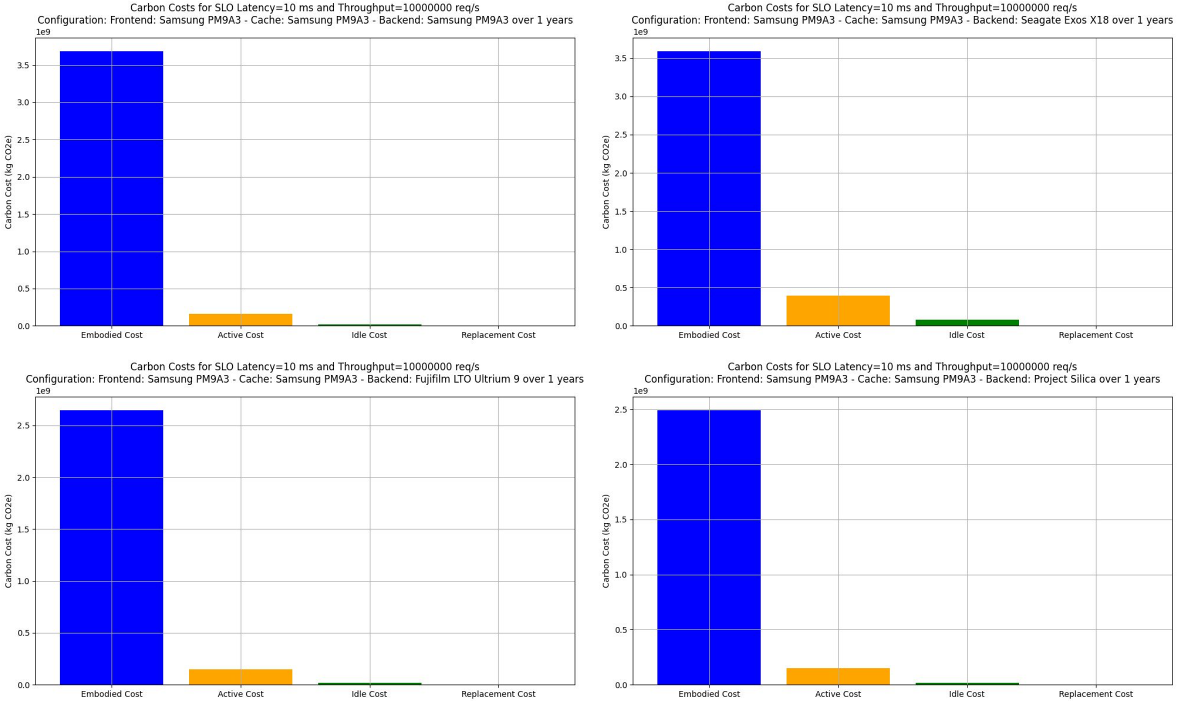


Simulation 2: Latency = 10 ms, Throughput = 10000000 req/s, 1 Year

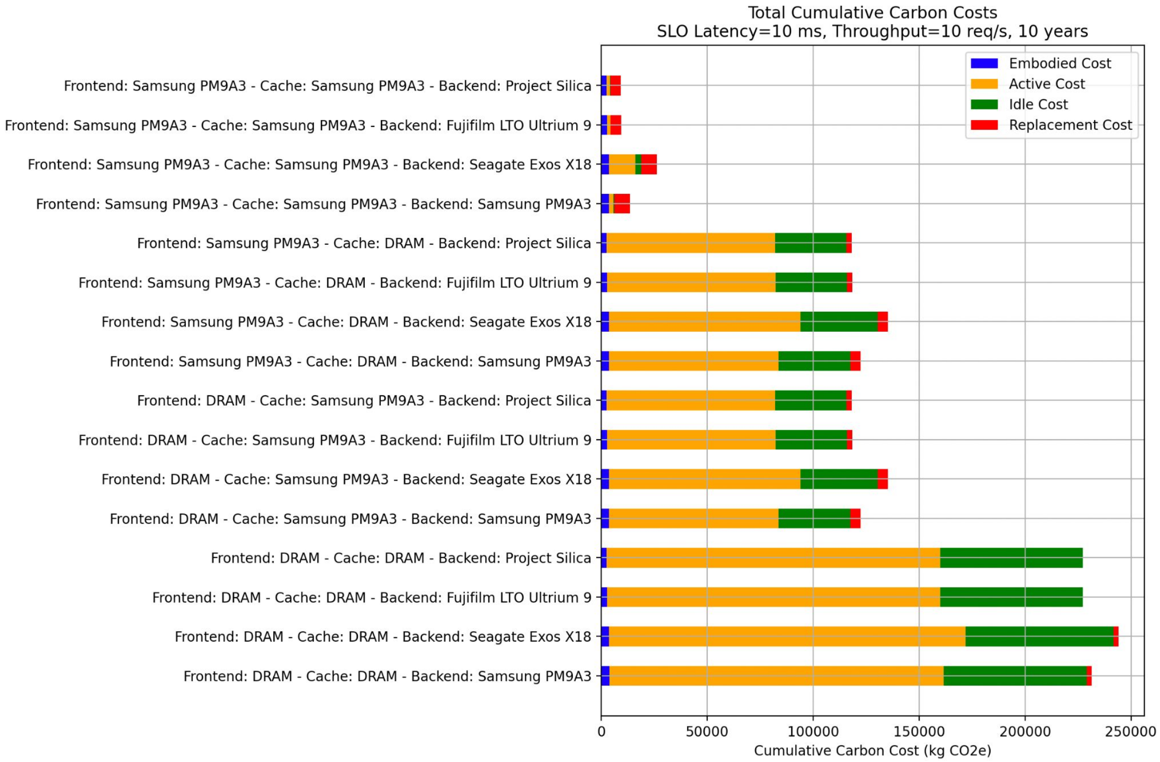


Heavy workloads can have a sizeable impact on the embodied carbon total costs of data centers.

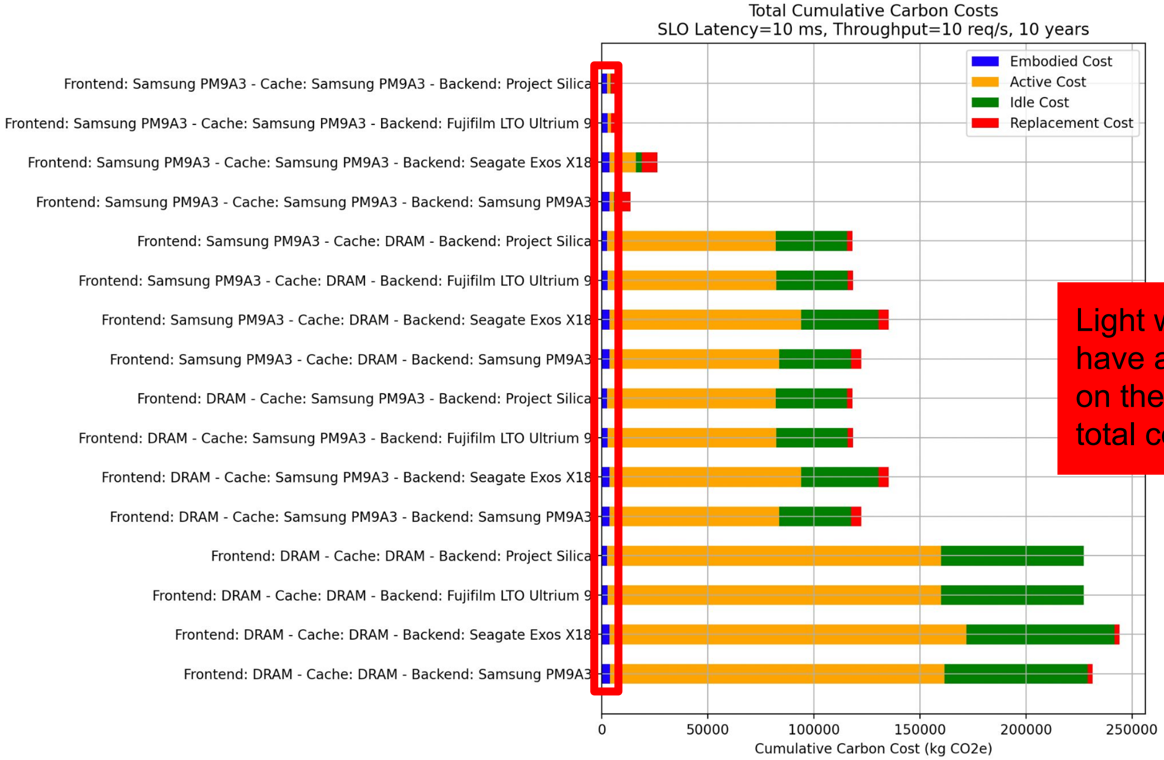
Simulation 2 Backend Configuration Comparison



Simulation 3: Latency = 10 ms, Throughput = 10 req/s, 10 Years

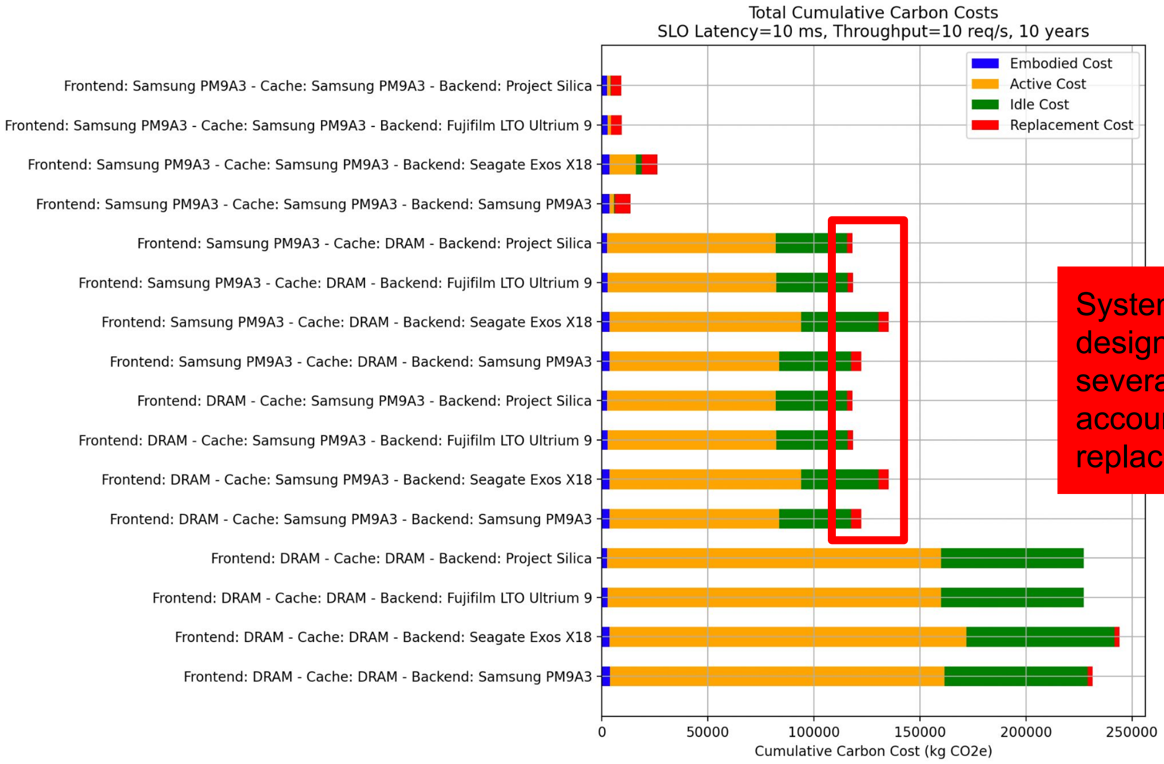


Simulation 3: Latency = 10 ms, Throughput = 10 req/s, 10 Years



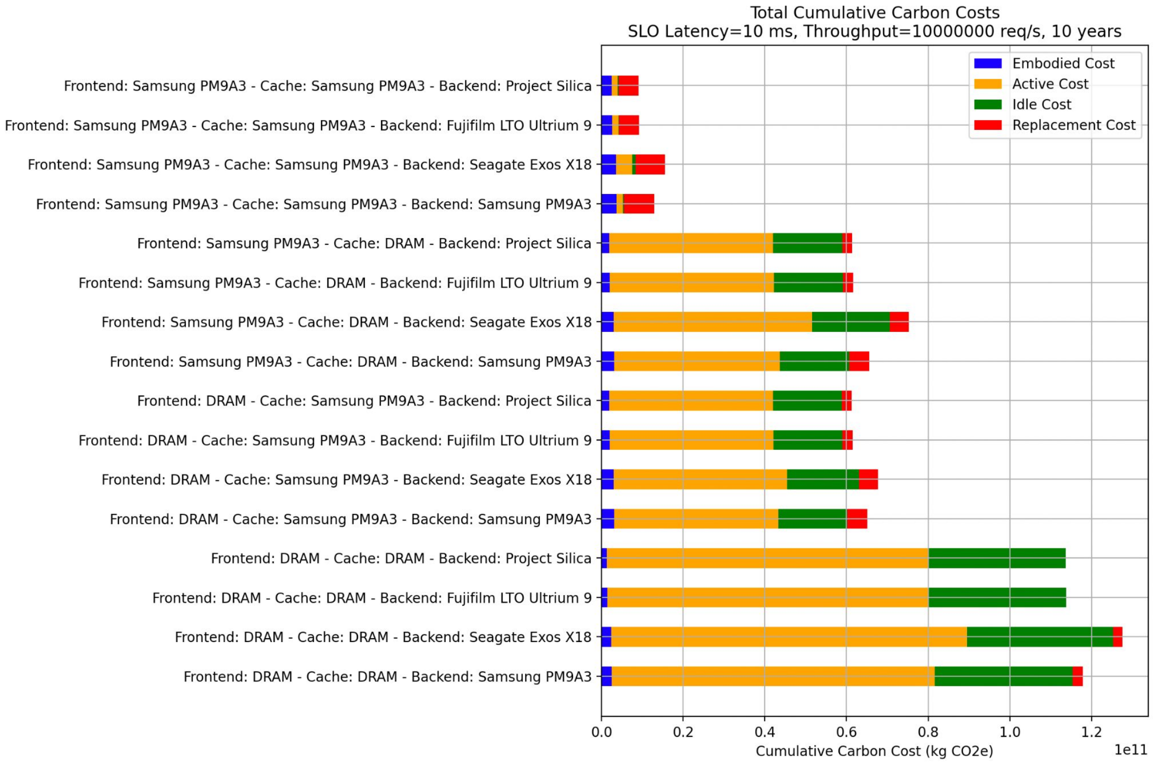
Light workloads often have a negligible impact on the embodied carbon total costs of data centers.

Simulation 3: Latency = 10 ms, Throughput = 10 req/s, 10 Years

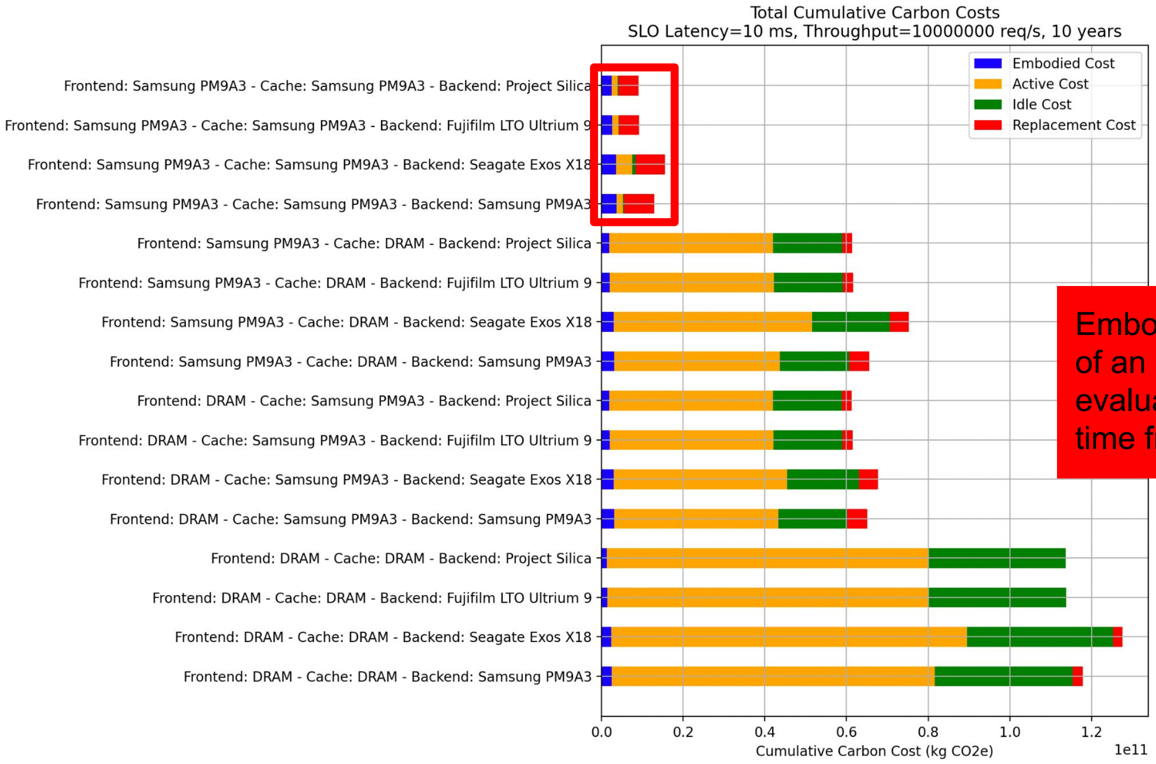


Systems that are designed to last for several years must account for device replacements.

Simulation 4: Latency = 10 ms, Throughput = 10000000 req/s, 10 Years

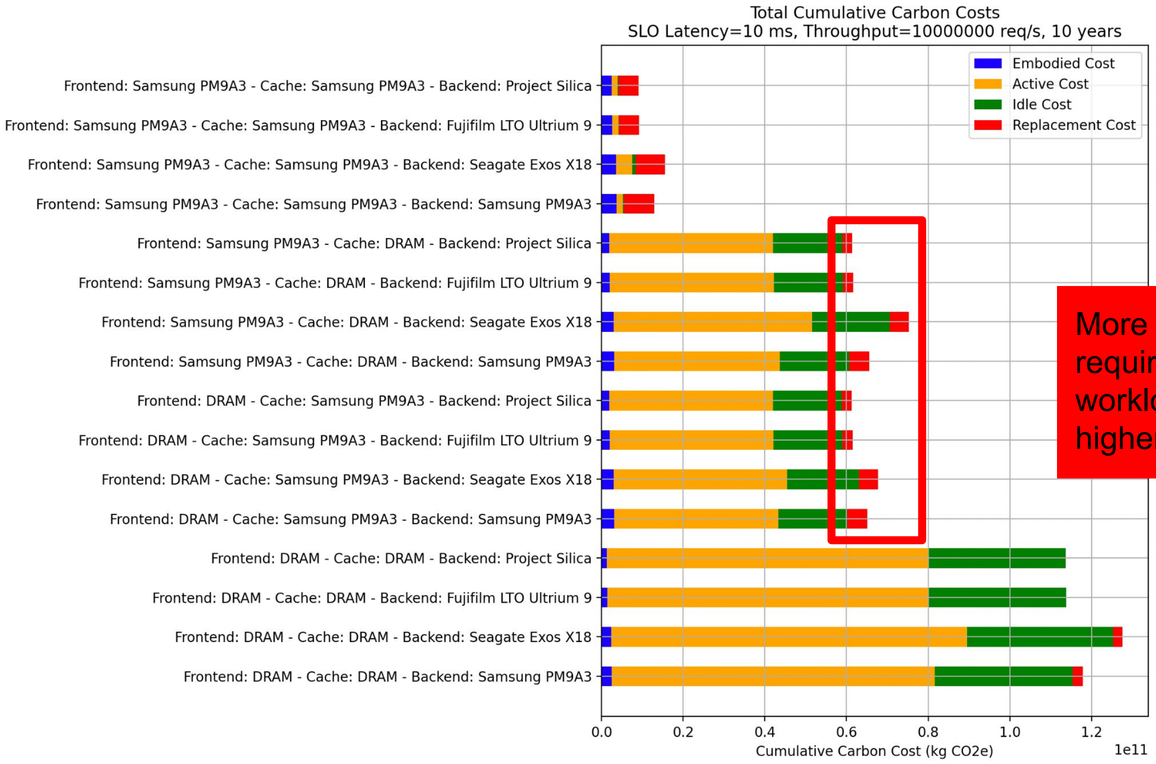


Simulation 4: Latency = 10 ms, Throughput = 10000000 req/s, 10 Years



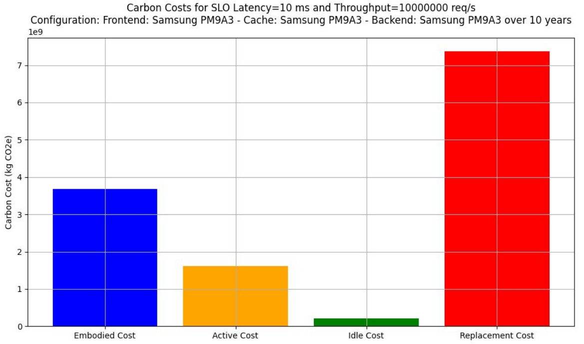
Embodied carbon has less of an impact when evaluating over longer time frames.

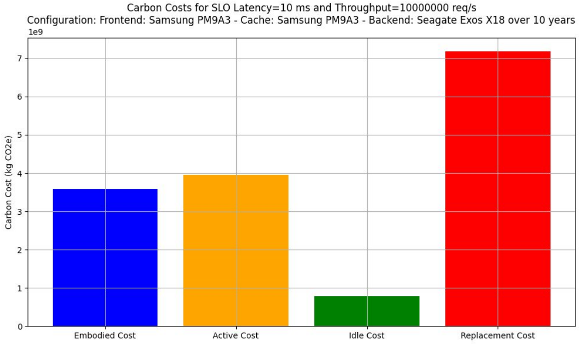
Simulation 4: Latency = 10 ms, Throughput = 10000000 req/s, 10 Years

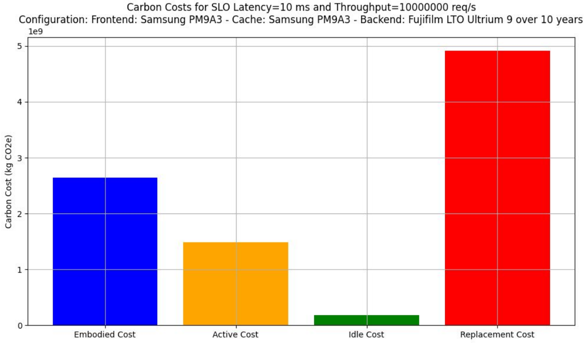


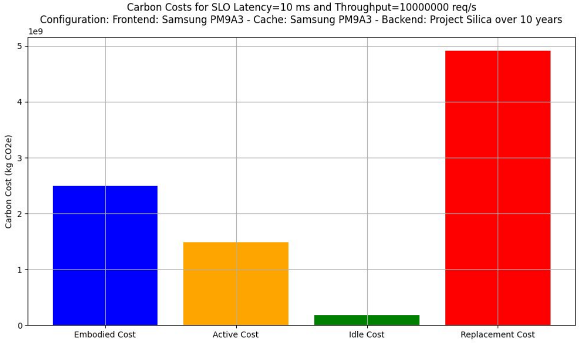
More storage devices are required to support heavy workloads, which leads to higher replacement costs.

Simulation 4 Backend Configuration Comparison









Impact of Frontend and Cache Configurations

- **DRAM**
  - Provides the highest performance and the lowest latency.
  - Higher embodied and operational carbon costs.
- **SSDs**
  - Slower performance.
  - Lower environmental costs.
- Takeaway: Use DRAM when performance is critical and SSDs when carbon cost is a concern.

Total Carbon Cost Analysis

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- ❖ DRAM: Highest performance but highest embodied carbon; impact lessens over time.
- ❖ SSDs: High performance with lower carbon cost than DRAM; effective for long-term use.
- ❖ HDDs: Lower embodied carbon than SSDs but highest total carbon usage overall.
- ❖ Tape Storage: Low carbon cost, ideal for infrequent archival storage.
- ❖ Glass-Based Storage: Emerging, durable, and environmentally promising, especially with SSDs in hybrid systems.
- ❖ Conclusion: Balancing performance and carbon impact is critical; tape and glass storage excel in sustainability for long-term use.

Conclusion

- Glass-based storage stands out as a viable, low-carbon solution for storing archival data in data centers.
- Tape also presents a strong option for archival storage.
- SSDs, while fast, come with high embodied costs.
- Key Insight: Informed storage choices and cache configurations can significantly impact sustainability.

Future Work

- ❖ Data compression integration.
- ❖ Variable data access patterns.
- ❖ Redundancy management strategies.
- ❖ Carbon intensity fluctuations.
- ❖ Durability testing for glass storage.
- ❖ Workload influence on storage configurations.

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Thank You

Questions?