

NTN DAYS 2026 · CONSTELLATION DYNAMICS, EMULATION AND ORBITAL COMPUTING

Ungrounded Computing in Low-Earth Orbit

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A lifecycle audit in three acts

with Robin Ohs, Gregory F. Stock, Andreas Schmidt, Holger Hermanns (Saarland University)

Inria · INSA Lyon · CITI · Cnam Paris, 14 October 2026



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1,000,000 satellites.
What could possibly go wrong?

Computing has left the planet

Starcloud-1

1 sat · 1 H100 · flown Nov 2025

Blue Origin Sunrise

51,600 sats · Mar 2026

Starlink
 $\approx 10^4$ sats

SpaceX FCC filing
 $\leq 10^6$ sats · Jan 2026

six orders of magnitude

Starcloud-1: LLM trained and served in orbit

Google Suncatcher: TPU clusters

The case on file is sustainability: terrestrial AI is short of **energy**, **water** and **land**; orbit offers sunlight, vacuum and room.

Starcloud (Nov 2025) · SpaceX FCC application (Jan 2026) · Blue Origin Project Sunrise (Mar 2026) · Google Project Suncatcher (2025)



The pitch, and the bill

The promise

×4

sunlight: 1,361 vs 340 W/m²

>99%

time in sun, dawn–dusk orbit

0 L

cooling water

0 m²

land, no grid queue

Data centers: 415 TWh in 2024 (1.5% of world electricity), more than double by 2030 (IEA).

Ohs et al., *Dirty Bits in Low-Earth Orbit*, ACM SIGENERGY EIR 2025 [HAL](#) · Ohs et al., *Dark Clouds Rising in LEO*, ACM LEO-NET 2026 [HAL](#) · Fraire et al., *Ungrounded Computing in LEO*, IEEE Computer (under review)

LAUNCH,
RE-ENTRY
& SPARES
SOLD
SEPARATELY

The pitch, and the bill

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×4

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Data centers: 415 TWh in 2024 (1.5% of world electricity), more than double by 2030 (IEA).

The bill: lifecycle carbon per delivered GPU-hour

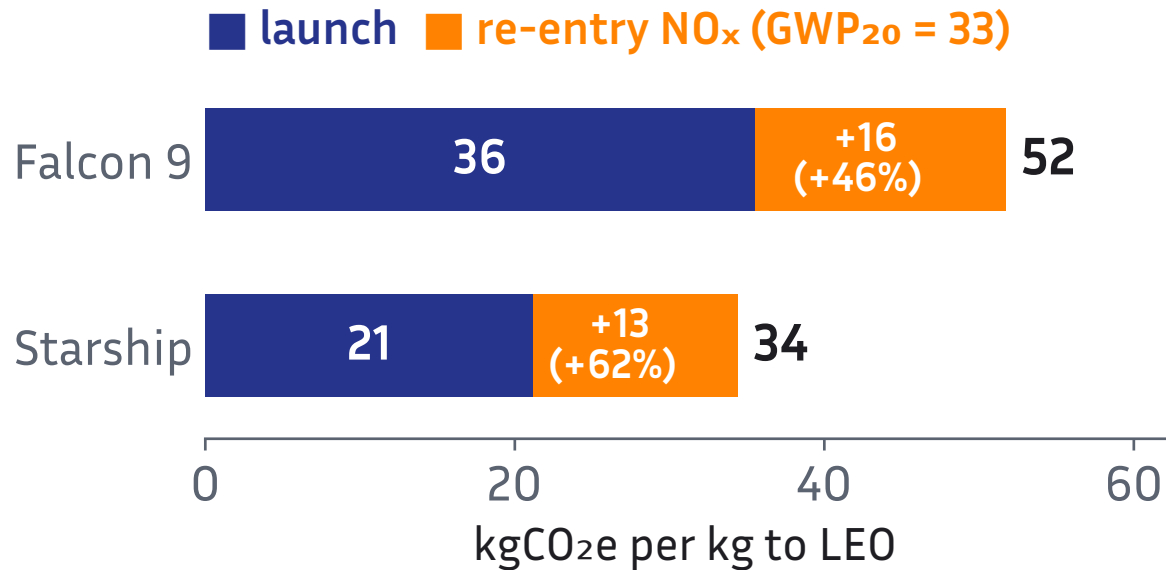
$$I = \frac{C_{\text{emb}} + C_{\text{op}}}{U} \quad C_{\text{emb}} = \sum_k m_k (e_k + I_{\text{L\&R}})$$

m_k launched mass of compute, solar, battery, radiator · e_k production carbon per kg · $I_{\text{L\&R}}$ launch + re-entry per kg · U GPU-hours actually delivered

ESpaS: open lifecycle estimator

DepTax: dependability–sustainability framework

Act I · The carbon of getting there

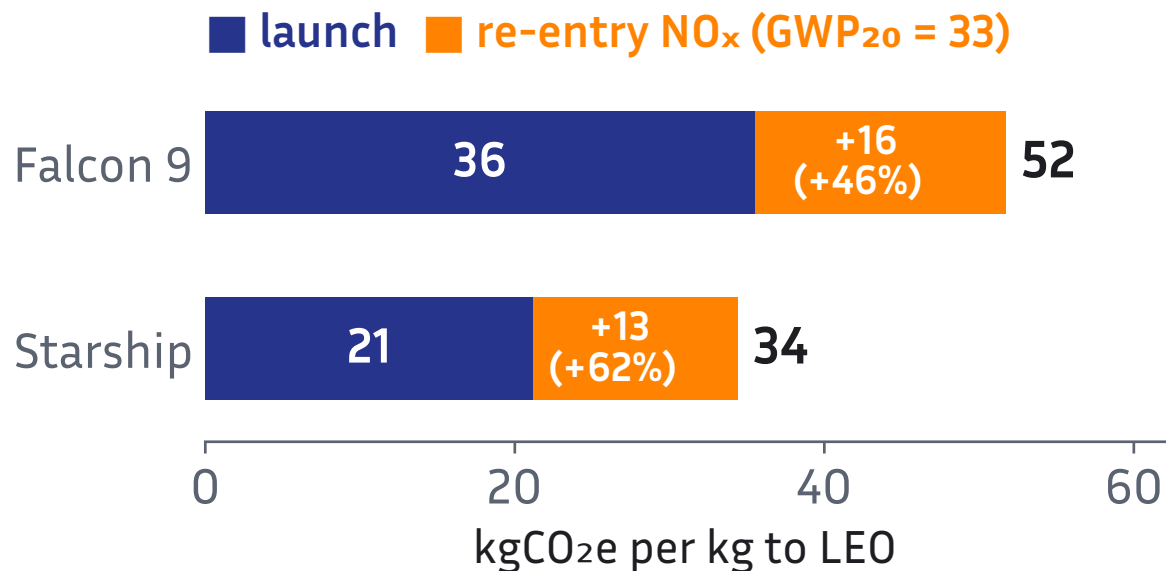


$$\text{re-entry: } 0.4 \frac{\text{kg NO}_x}{\text{kg}} \times \underbrace{33}_{\text{GWP}_{20}} \approx 13 \frac{\text{kgCO}_2\text{e}}{\text{kg}}$$

Falcon 9 also burns its 4-t upper stage → 16

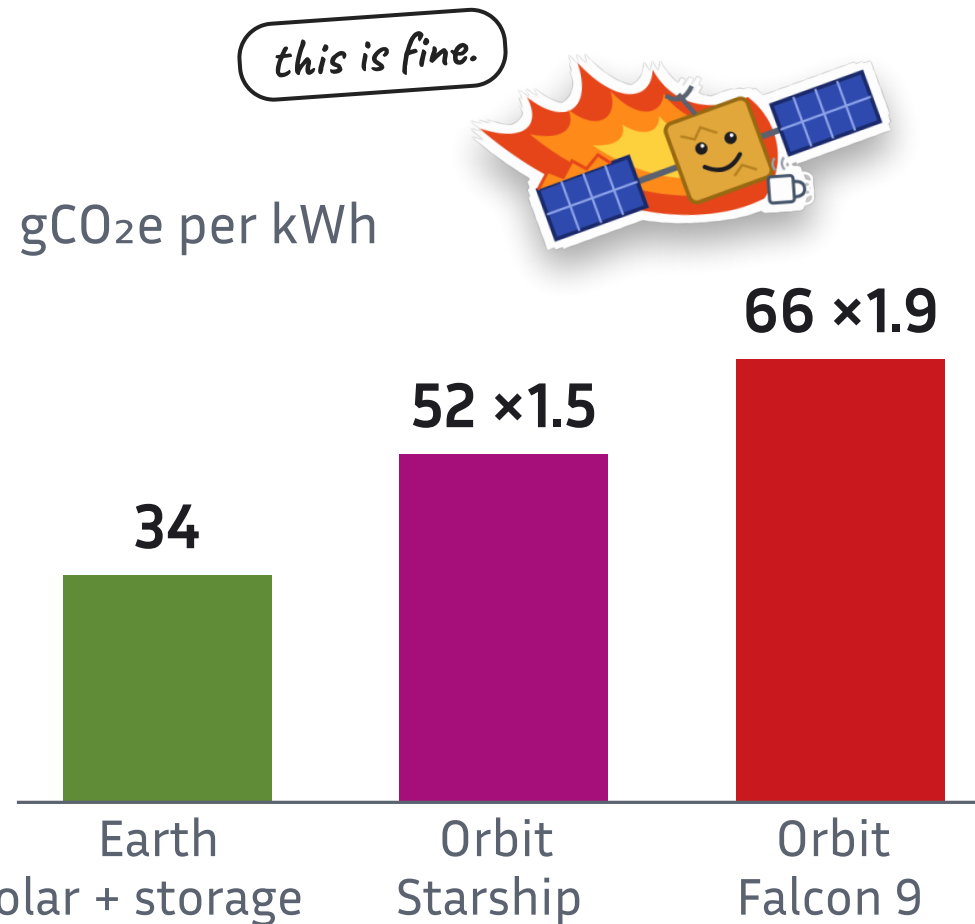
Burned on a cycle: FCC disposal within 5 years after the mission ends. Graveyard parking skips the NO_x and pays in **orbital footprint** instead.

Act I · The carbon of getting there



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Falcon 9 also burns its 4-t upper stage → 16



"Energy is free in space": eclipses need batteries, and batteries are launched mass with embodied carbon.

Burned on a cycle: FCC disposal within 5 years after the mission ends. Graveyard parking skips the NO_x and pays in **orbital footprint** instead.

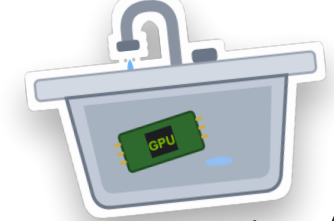
Act II · The mass of staying alive



■ radiator 50% ■ battery 28%
■ solar 17% ■ computer 5%

1 kW node · 61 kg launched · ■ = 1%

Radiator calibrated on the ISS early thermal system (42 m² for 14 kW). Ohs et al., *Dark Clouds Rising*, LEO-NET 2026 [HAL](#) · sensitivity: DepTax repository



let that (heat) sink in

Act II · The mass of staying alive

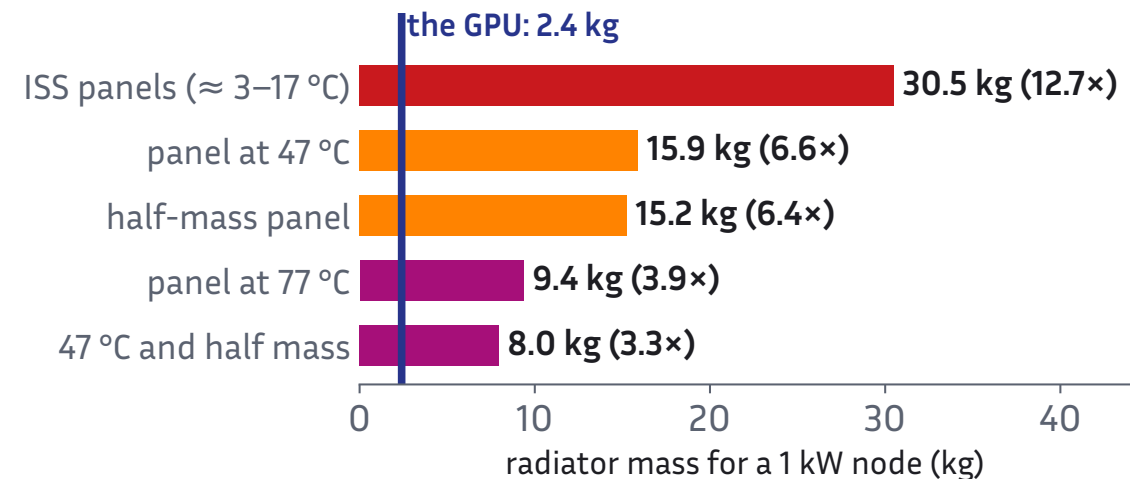


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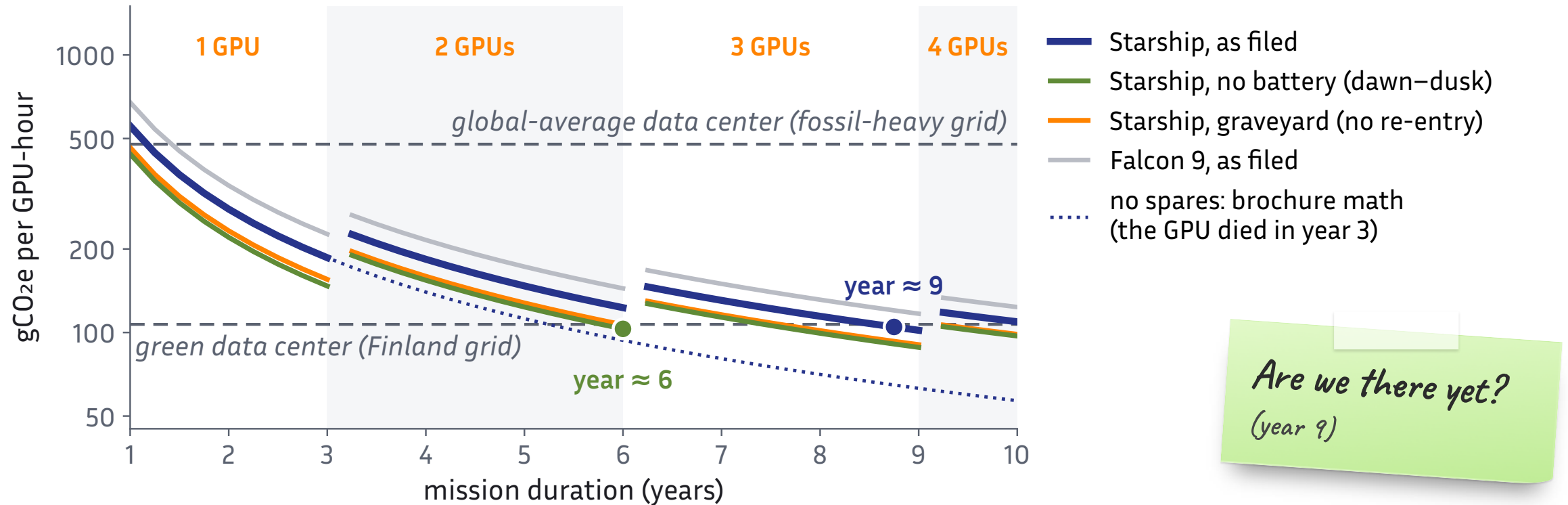
$$P_{\text{rej}} = \varepsilon \sigma A (T_r^4 - T_{\text{sink}}^4), \quad T_r \leq T_{\text{chip}} \approx 80^\circ \text{C}$$

P_{rej} heat to shed (every watt the node draws) · ε panel emissivity · σ Stefan–Boltzmann constant · A radiator area · T_r panel temperature · T_{sink} what the panel sees: cold space, warm Earth · T_{chip} hottest the silicon may run



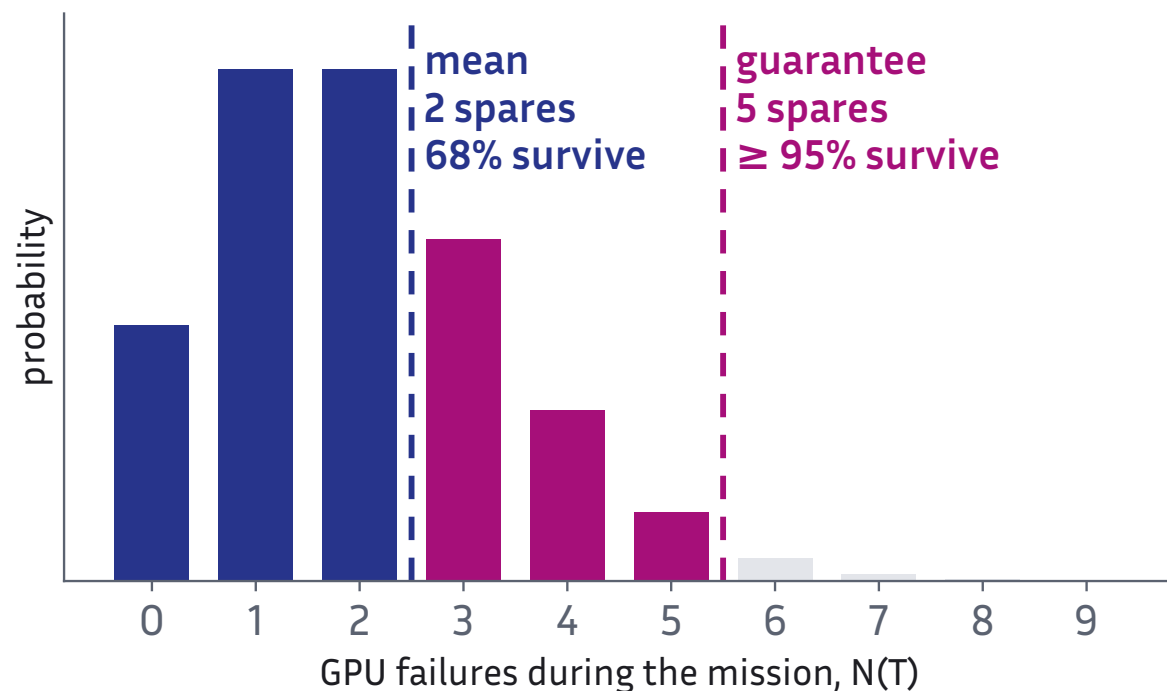
PUE (power usage effectiveness) = facility power ÷ IT power. ≈ 1 in orbit, and blind: the cost moved into embodied mass.

Act II · When does a 1 kW node break even?



Carbon per GPU-hour, launch + production, re-entry NO_x at GWP₂₀ = 33. Terrestrial anchors, H100 at 700 W plus chip embodied carbon: 477 (global mix, PUE 1.54) and 107 (Finland, PUE 1.2) gCO₂e per GPU-hour, as in *Dark Clouds Rising* [HAL](#). GPU life: working assumption, consistent with public dose tests (CAVU Aerospace, 2026). Radiator: ISS calibration. DepTax / ESpaS.

Act III · The price of never repairing



$$P_{\text{surv}}(T) = \Pr [N(T) \leq r] \geq 1 - \varepsilon \Rightarrow r^* \gg \mathbb{E}[N(T)]$$

T mission length · $N(T)$ GPU failures by T , $\text{Poisson}(\lambda T)$ · λ radiation hazard, 0.1–1 per year · r cold spares on board · $1-\varepsilon$ survival target · r^* spares the target demands, well above the mean $\mathbb{E}[N(T)]$ · shown: $\lambda T = 2$

*Have you tried turning it off and on again?
(from 550 km away)*

+77–86%

lifecycle carbon to **guarantee** survival, over the carbon-optimal redundancy

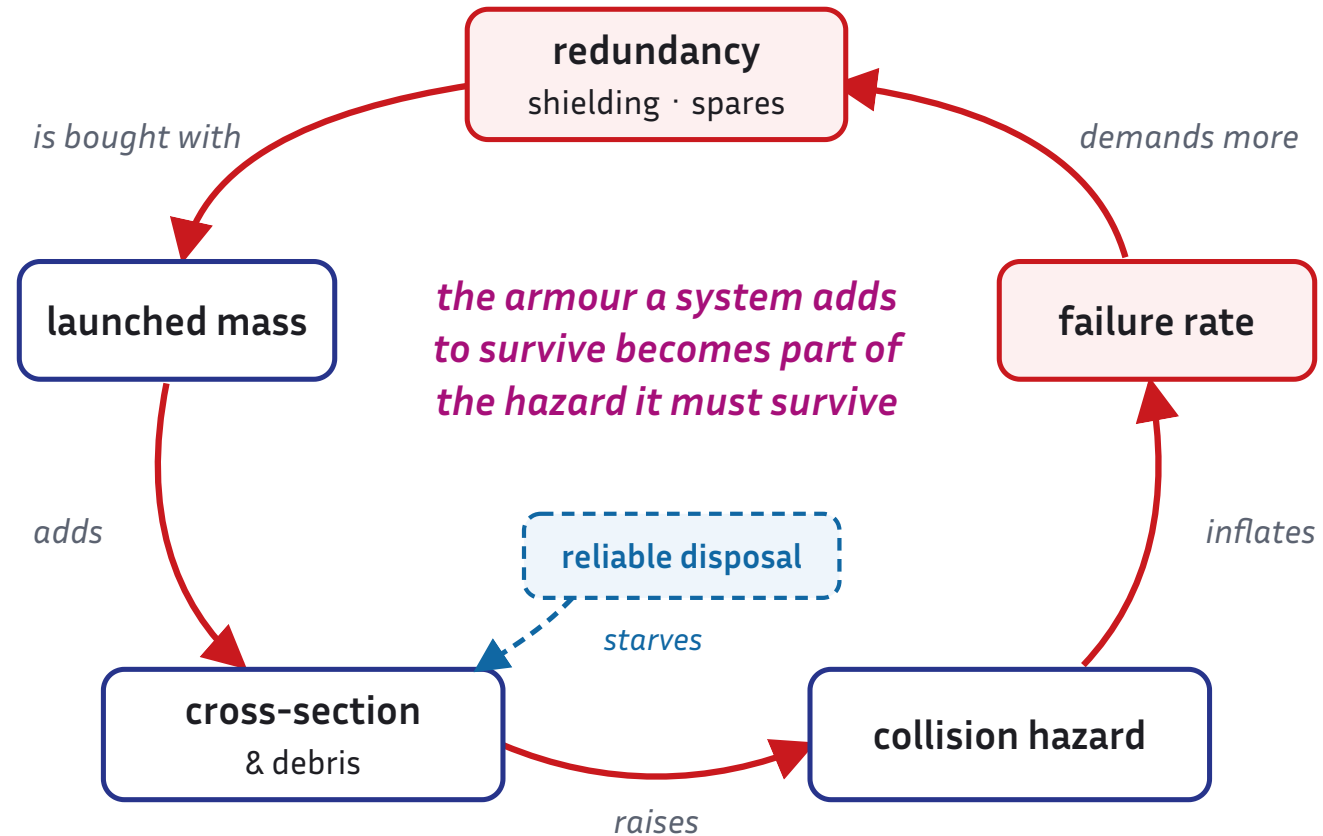
+31%

carbon for the first cold spare, which usually pays for itself per **delivered** GPU-hour

≈ 3×

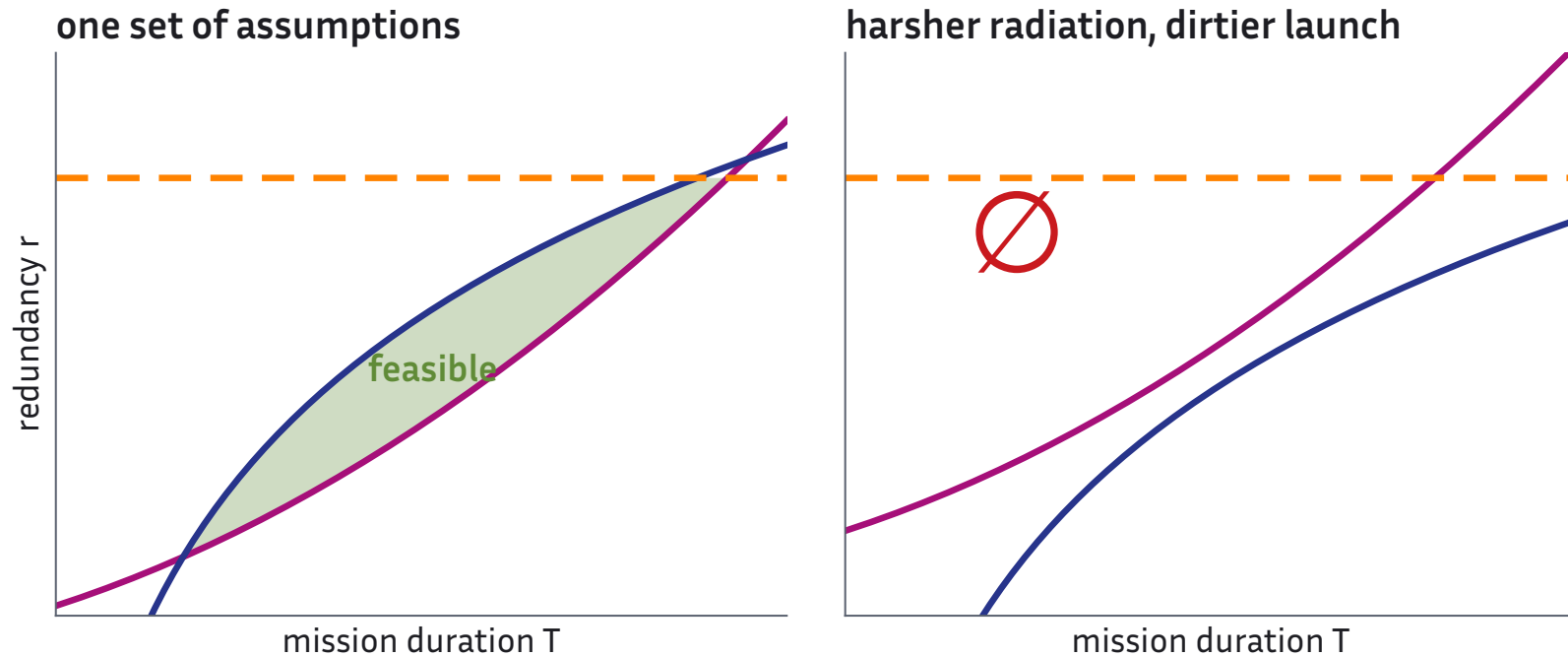
greener: spares on board vs. launch-on-failure

Act III · The loop that closes on itself



The fleet writes its own hazard: a consistent design is a fixed point, one that survives the environment it helps create.

Sustainability is a region, and it can be empty



— survives the mission (above)

— greener than the ground (below)

— within footprint cap (below)

$$\mathcal{F} = \{ x : P_{\text{surv}}(T; x) \geq 1 - \varepsilon \wedge I(x) \leq I_{\text{terr}} \wedge \Phi(x) \leq \Phi_{\text{max}} \}, \quad x = (\text{orbit}, T, r, \text{disposal}, \text{application})$$

Schematic. The region is computed with ESpaS + DepTax for one node; mapping it at fleet scale is open.

THE OPEN PROBLEM

We lack the science to map where orbital computing is dependable and sustainable



juanfraire.space

papers · open models (ESpaS, DepTax) · slides

Tomorrow 16:00, Cnam: **AI for Space, Space for AI**

*No satellites were
harmed in the making of
this talk.*

Inria

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Dirty Bits in Low-Earth Orbit: The Carbon Footprint of Launching Computers

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Abstract

Low-Earth Orbit (LEO) satellites are increasingly proposed for communication and in-orbit computing, achieving low-latency global services. However, their sustainability remains largely unexamined. This paper investigates the carbon footprint of computing in space, focusing on lifecycle emissions from launch over orbital operation to re-entry. We present ESpaS, a lightweight tool for estimating carbon intensities across CPU usage, memory, and networking in orbital vs. terrestrial settings. Three worked examples compare (i) launch technologies (state-of-the-art rocket vs. potential next generation), (ii) operational emissions of data center workloads in orbit and on the ground and, (iii) in-orbit aggregation with raw data transmission. Results show that, even under optimistic assumptions, in-orbit systems incur significantly higher carbon costs—primarily due to embodied emissions from launch and re-entry. Our findings advocate for carbon-aware design principles and regulatory oversight in developing sustainable digital infrastructure in orbit.

The risk is not only technical but systemic. As highlighted by Muriga et al. [31], the current trajectory of LEO development is consolidating power in the hands of a few dominant players. These vertically integrated actors—often controlling orbital infrastructure and end-user services—pose risks to openness, interoperability and fair access. In response, some have advocated for decentralized models of satellite operation and ownership [34]; yet, sized approaches may inadvertently accelerate the deployment of redundant or poorly coordinated constellations. A key concern is the escalating accumulation of space debris [13, 36], but mounting warnings also point to radio astronomy interference [1] and environmental toll of satellite manufacturing [28] as critical sustainability threats. Without cohesive governance and shared technical principles, LEO networks face a growing tension between scalability and sustainability.

While governance, orbital congestion, and electromagnetic interference are well-recognized challenges in the discourse on constellations, a critical dimension remains conspicuously unexplored: the carbon footprint of orbital infrastructure. Recent work by Ogutu et al. [33] shows that LEO satellite broadband

HotCarbon '25

Dark Clouds Rising in Low-Earth Orbit: On Environmental Limits to Massive Orbital AI

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Abstract

In 2026, we saw rising numbers of proposals for orbital data centers to facilitate AI, e.g., by SpaceX (up to one million satellites), Blue Origin, and Google—yet none include rigorous lifecycle sustainability analysis. We present ESpaS-ODC, a lifecycle carbon model that accounts for the three subsystems physically unavoidable at GPU-class power densities but absent from prior work: a thermal radiator sized from ISS data, solar-array degradation and eclipse margin, and cold-standby spares for no-repair access. Applying the model to an edge data center in a 510 km orbit reveals that the service-overhead-scaled radiator weighs about eleven times the GPU it serves and that modeled power and thermal infrastructure dominate launched component mass—not compute. Using and manufacturing carbon, model-boundary parity with a global-average terrestrial DC occurs within the first two mission years in our parameter sweep. With respect to a renewables-powered green-energy DC (Finland grid intensity: 68 gCO₂/e/kWh, PUE: 1.2),

ACM Reference Format:

Robin Ohs, Gregory F. Stock, Andreas Schmidt, Juan A. Fraire, Jörg Ott, and Holger Hermanns. 2026. Dark Clouds Rising in Low-Earth Orbit: On Environmental Limits to Massive Orbital AI. In *4th Workshop on LEO Networking and Communication (LEO-NET '26)*, August 17–21, 2026, Denver, CO, USA. ACM, New York, NY, USA, 6 pages. <https://doi.org/10.1145/3789240.3827598>

1 Introduction

The natural resource demands of terrestrial Artificial Intelligence (AI) infrastructure are accelerating [7], prompting serious proposals to move computing into orbit. In 2026 alone, SpaceX filed for a constellation of up to one million Low-Earth Orbit (LEO) satellites targeting large-scale AI inference [11]. Blue Origin announced Project Sunrise with up to 51,600 sun-synchronous satellites [13, 24], and Google revealed Project Suncatcher, adapting Trillium-generation Tensor Processing Units (TPUs) for on-orbit deployment [1, 19]. Starcloud-1 moved from proposal [12] to head-to-head competition with 2025: a 60 kg satellite

LEO-NET '26

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Inria