

Unmasking the Environmental Impact of Advanced Connectivity

Executive Summary

Digital connectivity is often treated as weightless and clean, yet the physical infrastructure delivering gigabits of data per second carries a substantial environmental footprint. This briefing synthesises recent [Life Cycle Assessment \(LCA\)](#) data across satellite, fixed fibre, and mobile cellular networks. It identifies four structural realities:

1. **Satellites:** Launch exhaust is not the main climate culprit; hardware manufacturing and user dishes generate 78% of emissions.
2. **Fibre Broadband:** Earth-moving civil works and trenching drive 46% of a fibre network's lifecycle carbon footprint in clean-grid regions.
3. **The Measurement Paradox:** Changing the carbon metric (per gigabyte delivered vs. per square kilometre covered) completely flips whether fibre or satellite appears greener.
4. **Mobile Networks:** Energy efficiency gains cannot outpace exponential data growth; meeting Net Zero requires structural "digital sufficiency".

1. Introduction: The Invisible Cost of Seamless Connectivity

Modern digital culture encourages a convenient illusion: that sending terabytes of data through the cloud is weightless and clean. As consumers stream 4K video, use ultra-low-latency satellite broadband, and connect to high-speed 5G mobile networks, digital connectivity is casually viewed as a green, post-industrial utility.

Yet behind this invisible screen lies a resource-intensive global physical infrastructure. Delivering high-speed data across cities and rural communities requires physical equipment with complex, counter-intuitive carbon footprints. Worldwide, the Information and Communications Technology (ICT) sector consumes approximately 4% of global electricity and produces roughly 1.4% of total greenhouse gas emissions (around 780 Mt CO₂e per year). Telecommunication network infrastructure alone accounts for roughly a quarter of that footprint.^{[1](#)}

This reality creates a major challenge for global telecommunications strategy. On one side, governments enforce ambitious digital expansion mandates, pushing to roll out 5G across all populated regions and eliminate rural broadband divides. On the other side, major network

operators have committed to stringent Net Zero targets under Science Based Targets initiative (SBTi) frameworks.²

For example, BT Group aims for Net Zero operations by 2031 and across its full value chain by 2041, while Virgin Media O2 targets full value-chain decarbonisation by 2040. Achieving these goals requires slashing absolute emissions across Scopes 1, 2, and 3 by up to 90%.³ Reconciling bandwidth growth with absolute decarbonisation means challenging longstanding assumptions about how networks operate.

By synthesising comprehensive Life Cycle Assessment (LCA) data across satellite, fibre, and mobile networks, we uncover four structural realities that redefine how digital sustainability and circular economy principles must be applied.

2. Satellite Internet's Carbon Mystery (It's Not the Rocket Launch)

Public debate on Low Earth Orbit (LEO) satellite mega-constellations; such as Starlink or OneWeb, tends to focus almost entirely on rocket launches. News reports regularly highlight rocket soot, stratospheric propellant combustion, and black carbon injected into the upper atmosphere.

However, full-scope Life Cycle Assessment (LCA) modelling compliant with international ISO standards reveals that rocket launches represent only a secondary share of a constellation's climate impact.⁴ When analysing a model constellation of 8,000 LEO satellites emitting approximately 546 kilotonnes of CO₂ equivalent (kt CO₂e) each year, the carbon footprint breaks down by hardware lifecycle stage rather than exhaust plumes:

- **Satellite Manufacturing (Space Segment):** 40%
- **User Terminals (Dish and Modem Kits):** 38%
- **Launch Activities (Rocket Construction and Fuel Burn):** 17%
- **Ground Stations (Gateways and Tracking Facilities):** 5%

Key Finding: Direct launch activities; combining rocket manufacturing and fuel burn, account for only 17% of total annual constellation emissions.⁵ The real climate burden lies in hardware production: manufacturing the satellites and the millions of subscriber dish kits together generates 78% of all emissions.

Annual Emissions per Subscriber

When measured per subscriber, an 8,000-satellite LEO constellation generates an annual carbon footprint of roughly 137 kg CO₂e per year. This is markedly higher than older Geostationary Orbit (GEO) satellites and terrestrial fibre networks:⁶

Network Architecture	Annual Emissions per Subscriber	Primary Drivers
LEO Mega-Constellation	137.0 kg CO₂e/year	Satellite build & launch (60%), User kits (40%)
GEO Satellite System	39.0 kg CO₂e/year	User equipment dominates (73%), Space segment (27%)
Terrestrial Fibre (France)	23.4 kg CO₂e/year	Infrastructure allocation across dense user base

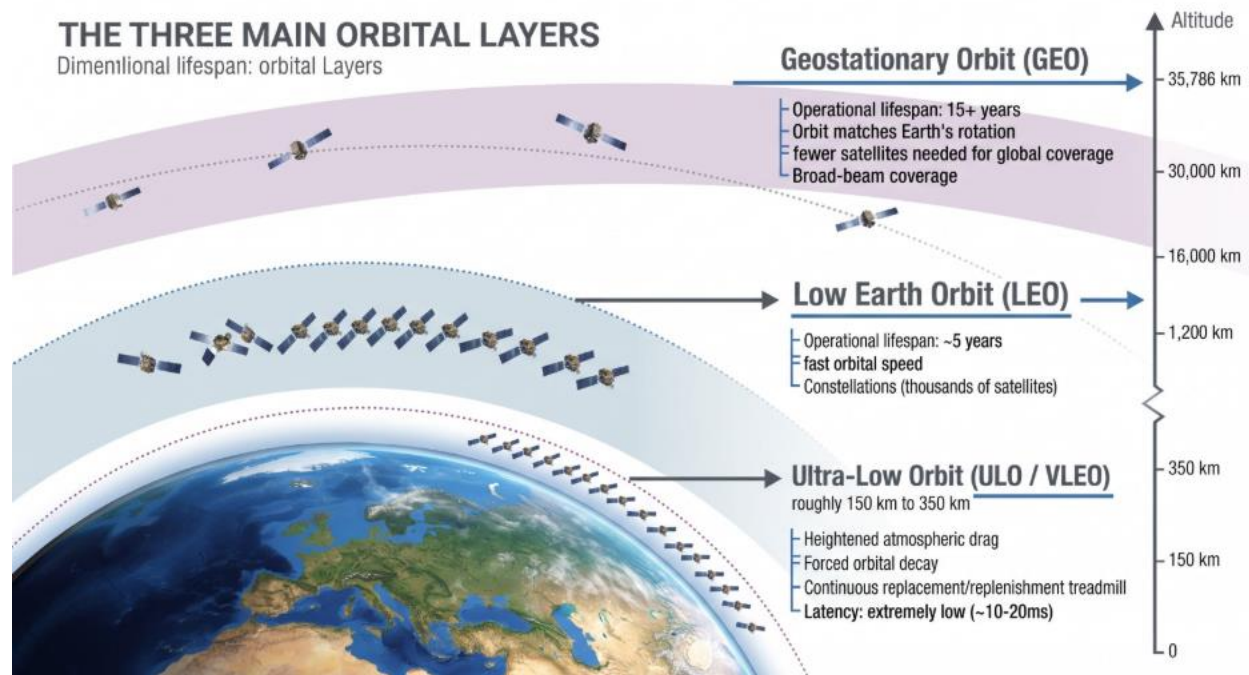
Why LEO and GEO Footprints Differ

The contrast between LEO and GEO networks comes down to orbital physics and hardware turnover:

- **GEO satellites** orbit at 35,786 km. A small fleet of long-lasting satellites (with 15-year lifespans) provides broad, continuous coverage. Because spacecraft last so long, user equipment creates the majority (73%) of the footprint.
- **LEO satellites** orbit between 500 km and 1,200 km, where residual atmospheric drag degrades their orbits. This limits their working lifespan to around 5 years. Operators must run a constant manufacturing and launch replenishment treadmill to keep service alive.
- **The Shift to Ultra-Low Orbit:** Industry plans to shift satellites into ultra-low orbits (~350 km) to reduce latency will worsen this problem. Atmospheric drag at 350 km cuts satellite life well below 5 years. This accelerates replacement schedules and significantly increases embodied carbon.

The Rural Exception: In ultra-remote, low-density rural areas without existing infrastructure, satellite systems become environmentally competitive on a per-user basis. Running physical cables into remote terrain requires extensive digging for very few households, making shared satellites a carbon-efficient choice for remote connections.

Figure 1. The Three Main Orbital Layers



3. The Dirtiest Part of Fibre Broadband is Literally the Dirt

Fixed optical fibre is widely seen as the gold standard for green digital infrastructure. However, a landmark 2024 Life Cycle Assessment of a fixed network in Sweden (analysing 100,000 km of fibre cables, 19,200 hardware units, and 2,100 node facilities) challenges common assumptions.⁷

In countries with clean electricity grids; such as Sweden (21 g CO₂e/kWh) or France (19.6 g CO₂e/kWh), operational electricity during data transmission accounts for only 11% of annual greenhouse gas emissions.⁸ Instead, 81% of the lifecycle climate impact is locked in upfront as embodied carbon (raw materials, production, and civil works). End-of-life processing accounts for the remaining 7%, mainly from battery and cooling refrigerant disposal.

The single largest source of emissions is not data routing or glass fibre manufacturing. It is civil engineering: excavation and trenching account for 46% of total network emissions, creating an overall network intensity of 37 kg CO₂e per cable-kilometre each year.

Fibre Network Emissions Breakdown

Lifecycle Phase / Asset Group	Share of Footprint	Primary Drivers & Dynamics
Cable Installation / Civil Works	46%	Diesel diggers, asphalt cutting, urban trenching
Equipment Manufacturing	17%	Telecom chassis, switches, routers (short 10-year lifespan)
Cable Manufacturing	15%	High core-count glass drawing, protective polymer jackets
Operational Electricity (Use Phase)	11%	Active node power draw under clean grid mix (21 g CO ₂ e/kWh)
End-of-Life Processing	7%	Refrigerant leaks (5%), battery and generator recycling
Node Frame Manufacturing	3%	Structural housings, outdoor cabinets, physical frames

Because heavy excavation machinery dominates emissions, the civil installation technique chosen by network engineers determines the environmental cost of rollout:

Carbon Intensity by Cable Installation Method

Installation Method	Carbon Intensity (t CO ₂ e / cable-km)
Traditional Urban Excavation	83.7
Traditional Greenfield Trenching	3.6
Microtrenching (Urban)	2.6
Microtrenching (Greenfield)	2.2
Greenfield Ploughing / Milling	1.6

Sensitivity modelling shows that civil engineering decisions determine network sustainability:

- A ±20% change in duct lifetime, cable density, or traditional excavation kilometres changes the total network carbon footprint by ±18%.
- In contrast, varying active hardware power draw or grid electricity carbon intensity by ±20% shifts the total network footprint by only ±1%.

Planetary Boundaries and Sustainability Thresholds

When evaluated through [Absolute Environmental Sustainability Assessment \(AESA\)](#) frameworks; which assess industrial systems against Earth's planetary boundaries, current fibre deployment practices exceed safe carrying capacities across three major impact categories:⁹

- **Mineral & Metal Resource Use:** Exceeds boundary by **11.45×** (Sustainability Ratio: 11.45)
- **Particulate Matter Formation:** Exceeds boundary by **2.60×** (Sustainability Ratio: 2.60)

- **Climate Change (Global Warming):** Exceeds boundary by **1.80×** (Sustainability Ratio: 1.80)
- **Acidification:** Within boundary (0.90)
- **Ionising Radiation:** Within boundary (0.20)

(Note: Any ratio above 1.0 indicates that environmental carrying capacity has been breached.)

To achieve absolute environmental sustainability in clean-grid regions, fixed fibre networks must meet two operational targets:

1. **Subscriber Density:** Service an average density of at least **13 active users per cable-kilometre**.
2. **Carbon Threshold:** Limit total annual emissions strictly below **21 kg CO₂e per cable-kilometre per year** (a 43% reduction from the current baseline of 37 kg CO₂e/cable-km/year).

4. The "Functional Unit Paradox" (How You Measure Carbon Flips the Winner)

Deciding whether satellite or terrestrial fibre is the greener connectivity option depends entirely on how emissions are normalised. Changing the mathematical denominator; known in LCA as the "functional unit", completely reverses which technology wins.

- **Metric A: Emissions per Gigabyte Delivered (kg CO₂e / GB):**

Under a data-volume metric, **terrestrial fibre is the clear winner**. Optical fibre carries terabits of data per second across 30 to 40-year lifespans. Amortising high construction carbon across massive data volumes serving dense populations reduces the emissions per gigabyte to near zero. Satellites carry much lower cumulative data volumes over their lifespans, resulting in a higher carbon footprint per gigabyte.

- **Metric B: Emissions per Square Kilometre Covered (kg CO₂e / km²):**

Under a geographic coverage metric, **satellite constellations are the clear winner**. A single satellite constellation covers hundreds of millions of square kilometres across oceans, mountains, and rural zones. Providing equivalent physical coverage with terrestrial fibre would require millions of kilometres of underground trenching (at 83.7 t CO₂e/km for urban excavation and 3.6 t CO₂e/km for greenfield trenching).

Because reported performance can swing by more than an order of magnitude depending on metric selection, non-standardised reporting creates serious risks of corporate greenwashing. To address this, regulators are introducing standardised life cycle frameworks:

- The European Commission is advancing its **Product Environmental Footprint Category Rules (PEFCR)** for space activities.[10](#)

- The proposed **European Space Act** seeks to mandate transparent, multi-criteria life cycle accounting across both orbital space and ground networks.[11](#)

5. Why "Energy Efficiency" Won't Save Us: The Case for Digital Sufficiency

In mobile cellular networks, the Radio Access Network (RAN); comprising base station masts, antennas, transceivers, and baseband processors, is the primary energy hot spot. It accounts for roughly 80% of total mobile network power consumption.

The mobile industry has historically pursued technical energy efficiency, measured under [3GPP standards](#) as data transferred per unit of energy (bits per joule). However, bottom-up life cycle modelling of national mobile networks shows that technical efficiency alone cannot deliver Net Zero.[12](#)

Applying three explicit decarbonisation levers to a national mobile network (using baseline data of 372 Mt CO₂e) demonstrates the limits of technical optimisation:[13](#)

- **Lever 1: Extending Equipment Lifespan:** Keeping active hardware (baseband and radio units) in service for 10–12 years instead of 5–7 years reduces manufacturing carbon, yielding a **19% overall reduction** (down to 301 Mt CO₂e).
- **Lever 2: Slashing Operational Energy:** Cutting base station power consumption by a factor of 4 (using advanced sleep modes, smart antenna power scaling, and dynamic carrier shutdown) yields a **42% overall reduction** (down to 216 Mt CO₂e).[14](#)
- **Lever 3: Combined Application:** Applying both levers simultaneously achieves a **61% total reduction** (down to 145 Mt CO₂e).

National RAN Decarbonisation Pathways vs Net Zero Target

Strategy Scenario	Emissions Level	Reduction Achieved	Gap to Net Zero Target
Baseline (Reference Scenario)	372 Mt CO ₂ e	0%	Baseline
Lever 1: Hardware Lifespan (+5 years)	301 Mt CO ₂ e	-19%	264 Mt CO ₂ e gap
Lever 2: Energy Reduction (Factor of 4)	216 Mt CO ₂ e	-42%	179 Mt CO ₂ e gap
Combined Levers (1 + 2)	145 Mt CO ₂ e	-61%	108 Mt CO ₂ e gap
Operator Net Zero Target (-90%)	37 Mt CO₂e	-90%	Target Met

While a 61% reduction is significant, it leaves a substantial gap: operators must achieve a 90% absolute cut to meet Science Based Targets initiative (SBTi) criteria.

The Rebound Paradox and Grid Dynamics

Why doesn't efficiency close the gap?

1. **The Jevons Paradox (Rebound Effect):** Efficiency gains measure relative data transport (bits/joule), not absolute energy use. If network efficiency doubles but consumer data demand quadruples, total energy consumption still doubles.
2. **The Embodied Carbon Penalty:** In clean-grid countries, manufacturing hardware generates more carbon than running it. Prematurely replacing older equipment with newer, "ultra-efficient" gear generates an immediate spike in manufacturing carbon that years of energy savings cannot repay.

Moving from Shallow to Deep Leverage Points

Applying systems thinking (such as [Donella Meadows' framework on leverage points](#)) shows that fine-tuning technical hardware parameters represents a "shallow" intervention. True decarbonisation requires "deep" systemic change through Digital Sufficiency (or Digital Sobriety).¹⁵

As formulated by Santarius et al. (2023), digital sufficiency operates across four practical pillars:

- **Hardware Sufficiency:** Extend the lifespan of masts, servers, and consumer handsets. Mandate modular repairability, component reuse, and avoid rushing into premature network generation rollouts (such as unneeded 6G upgrades).¹⁶
- **Software Sufficiency:** Develop lean, unbloated software protocols that reduce processor workloads, cut baseband energy use, and halt software-induced hardware obsolescence.
- **User Sufficiency:** Encourage sustainable data consumption by design—such as defaulting video streaming to standard definition over mobile networks, stopping autoplay videos, and pruning redundant cloud backups.
- **Economic Sufficiency:** Reshape telecom business models to decouple corporate revenue from continuous data volume inflation and constant handset upgrades.¹⁷

6. Conclusion: Rethinking the Infrastructure of Tomorrow

Achieving a sustainable and circular digital future requires leaving behind the myth that digital connectivity has no physical impact. Rigorous life cycle assessments show that the primary drivers of telecommunications emissions are deeply material:

- The rapid manufacturing turnover of short-lived LEO satellites;
- Heavy civil excavation and trenching for fixed fibre networks; and
- The embodied manufacturing carbon locked within mobile network hardware.

While renewable grid energy and hardware efficiency are essential, they cannot achieve Net Zero alone. Addressing the environmental footprint of digital connectivity demands a systemic pivot:

- **Infrastructure Sharing:** Prioritise shared civil engineering, public conduit sharing, and co-located mobile base stations.
- **Low-Impact Civil Works:** Maximise existing ducts and deploy microtrenching or mole ploughing instead of open road excavation.
- **Hardware Longevity:** Extend operating lifecycles to 10–12 years through modular upgrades and circular remanufacturing.[18](#)
- **Digital Sufficiency:** Align regulatory policy and digital network planning with Earth's physical carrying capacity.[19](#)

As digital connectivity expands, policymakers, network operators, and technology leaders face a fundamental question: **How do we engineer a digital ecosystem that balances societal demand for connectivity with the planetary boundaries of our finite Earth?**

The DICE Network+

The [DICE Network+](#) is a three-year UKRI EPSRC funded programme that seeks to leverage the power of the digital revolution to drive a circular economy across sectors and value chains. Led by the University of Exeter, our expert academic team comprises eleven investigators from nine UK universities. We are creating an inclusive, connected community harnessing interdisciplinary collaboration and research to guide industry partners, government bodies and policy makers towards a digitally enabled sustainable and circular economy.

Our work is focused on two key challenge areas:

- **EMBED:** Embedding sustainability and circularity within the design and development of digital and communication technologies.
- **ENABLE:** Realising the potential of the digital revolution to enable a circular economy across sectors.

By adopting a network of networks approach, harnessing interdisciplinary collaboration, research, and technological innovation, our network is a beacon for change, inspiring and guiding industries, policymakers, and communities towards a digitally enabled sustainable and circular economy.

We welcome engagement from policymakers, industry & academic partners DICE-Network@exeter.ac.uk

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For and behalf of the [DICE Network+](#)

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