Environmental *Change* Institute

Exploring Digitalisation's Footprint

Yee Van Fan

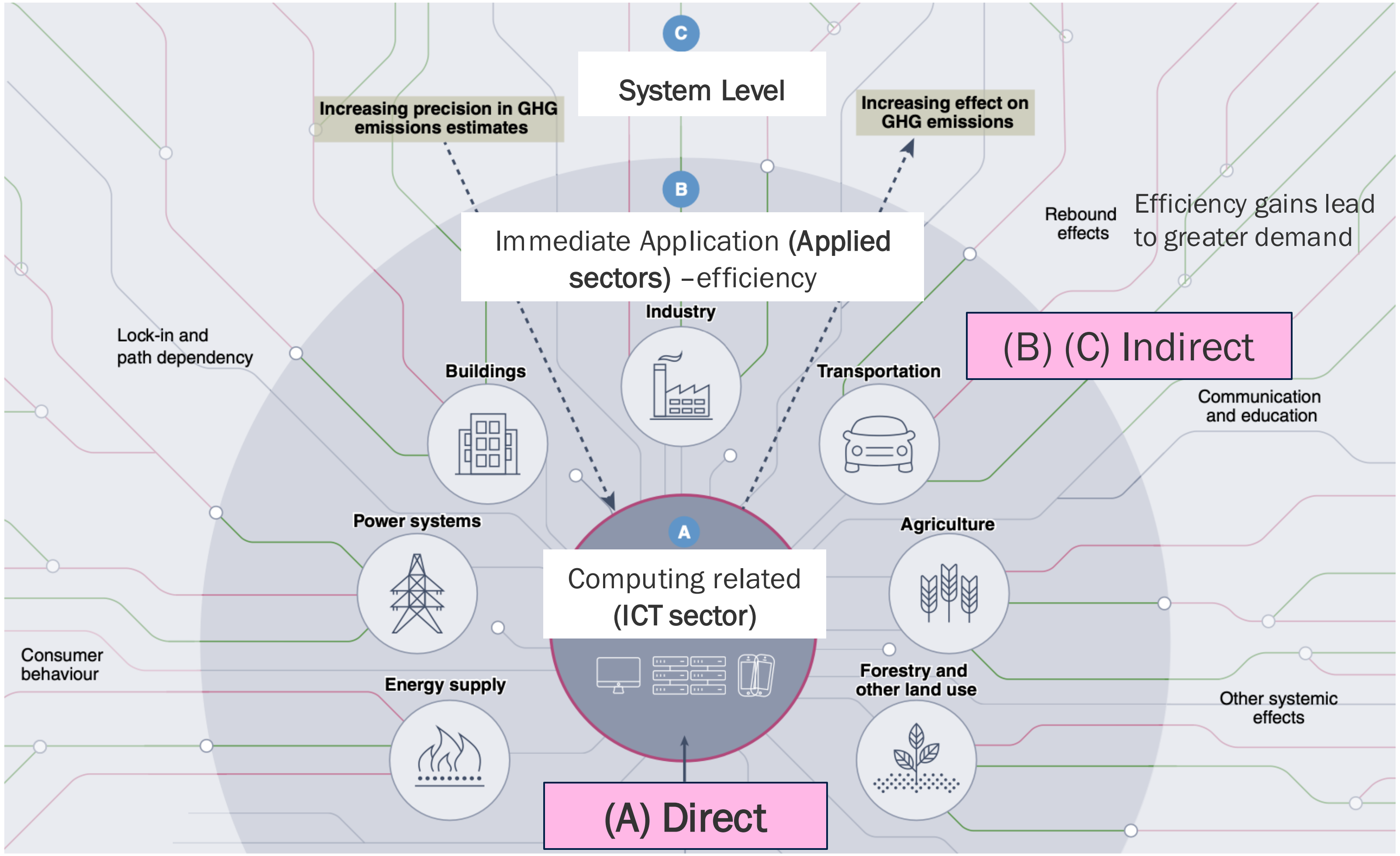
Digitalisation: AI is today's wave

	Digitise	Connect	Compute/Act
Concept	represent work / information in bits	link people + systems in real time	use data to decide and take action
Examples	mainframes, PCs, office software, databases/storage	internet, web, email, browsers, social platform, smartphone, cloud	robotics or automation, AI: machine learning, deep learning, LLMs, agentic systems
Milestones	~1951: 1st computer commercially available ~1981: laptop computer introduced	~1971: 1st email sent ~1989: www is invented ~1991: dial up internet ~2003: Skype is launched ~2007-2010: IPhone & IPad launched	~2012: Google tests self driving cars ~2023: OpenAI release ChatGPT

Each waves built on the previous one, expanding what digitalisation can do.....

Source (Milestones): Stratability Global

Direct Footprint: A Key Part of Understanding the Total Impact



- **Data Centre** (backbone of digital ecosystem, growing faster, opportunities for intervention)
- Network Infrastructure
- Devices

Kaack et al. (2022). "Aligning artificial intelligence with climate change mitigation." Nature Climate Change. doi.org/10.1038/s41558-022-01377-7

Now: ~10,000–12,000 Data Centres Worldwide

- ~ 1200 are **hyperscale** facilities
- Account for 44 % of data centre capacity

https://www.datacentermap.com/datacenters/
https://www.datacenterknowledge.com/hyperscalers/hyperscalers-will-command-60-of-global-data-center-capacity-by-2030-report?utm_source=chatgpt.com

World’s Densest Data Centre Hub (Northern Virginia)

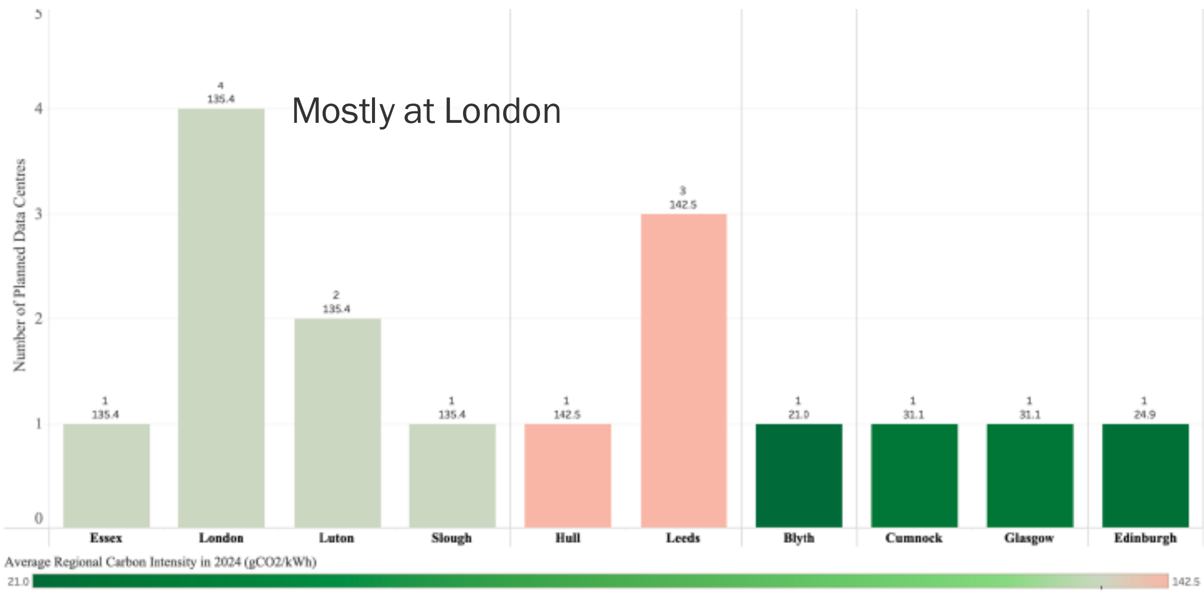
- 397 Data Centre
- 252 Operational
- 145 Developing
- Worldwide: 2.2 trillion will be spent on data centres

Growing fast….

https://www.datacentermap.com/content/nova/
https://www.bbc.co.uk/news/articles/ckg2ldpl9leo

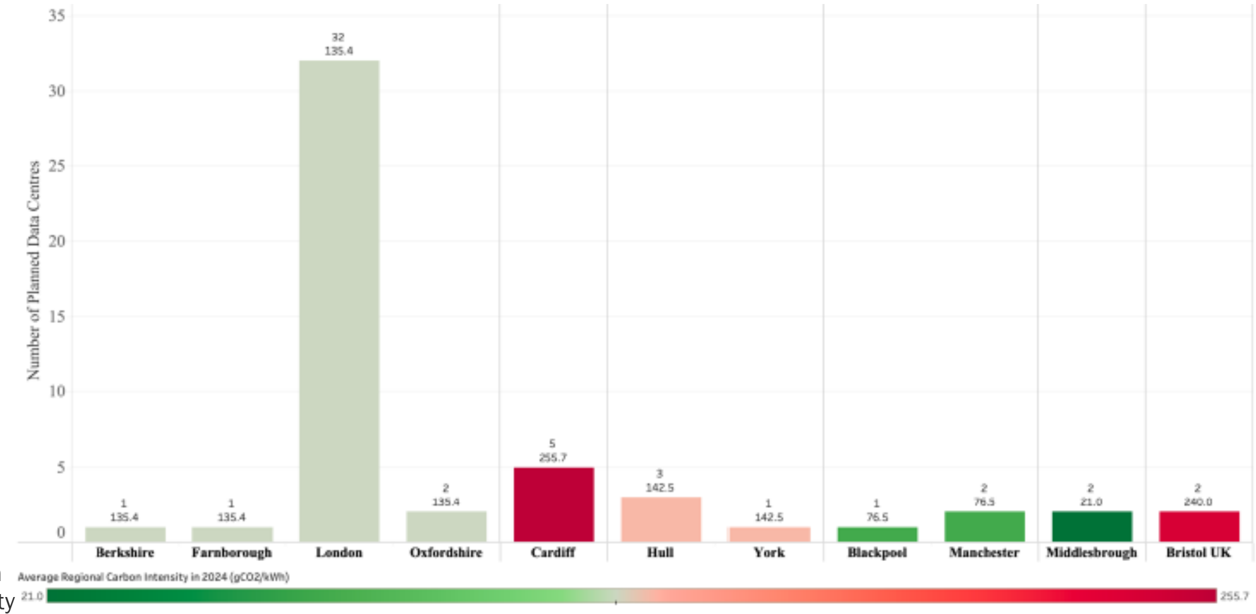
UK: Estimated that Another 78-100 Data Centres Will Be Built (Accelerating)

Planned Hyperscale/Campus Data Centres



Carbon intensity

Planned Colo/Enterprise Data Centres



- Power constraints rather than carbon intensity drive shift towards ‘Tier 2’ markets
- Far down the list of priorities for sitting decisions
- Decisions concerning carbon intensity are primarily framed at the country level, not sub-national

Is the environmental factor considered in siting decisions?

Data Centres are Massive

Main Systems

- ❖IT equipment: server, network, storage,
- ❖Power Infrastructure
- ❖Cooling and air conditioning
- ❖Racks and containment

Small

- 5000-20,000 sq.ft
- 500-200 servers
- 1-5MW

Large or hyperscale

- 100,000 sq.ft to **several million sq.ft**
- Thousands of servers
- 20 to over **100MW** → enough to supply ~80,000 UK homes

World's Largest (≈ 150 MW)

= 10,763,910 sq.ft (≈ 1,000,000 m²)

Buckingham Palace x13

Heathrow T5 x3

https://www.datacenterknowledge.com/energy-power-supply/data-center-power-fueling-the-digital-revolution
https://datacentremagazine.com/top10/top-10-biggest-data-centres

The Loudest Headline: Environmental Concern

Efficiency

Productivity

Convenience

Ethics/Inequality

Environmental Concern

Security

Local (Direct) Near Term

- Data-centres in Ireland could account for 32% of all **electricity** demand by 2026
- U.S. data centres co… million gallons of **water** per day
- Each 100-word AI prompt is estimated to use roughly one bottle of **water**

already beginning to experience

Global (Direct) **Mid-Long Term**

- Global data centres expected to consume more **electricity** than Japan by 2030 (implication on **emissions**)
- **Embodied carbon** can comprise up to 50-90 % or more of total lifecycle **emissions. (+ material security, e-waste issue)**

Source: IEA (2025), ERM (2025), EESI (2025)

Modelling Energy and Material Futures for Data Centres (Mid-Long Term)

What we are doing

- Exploring/projecting ranges of possible **futures**
- Assessing pathways are compatible with climate targets

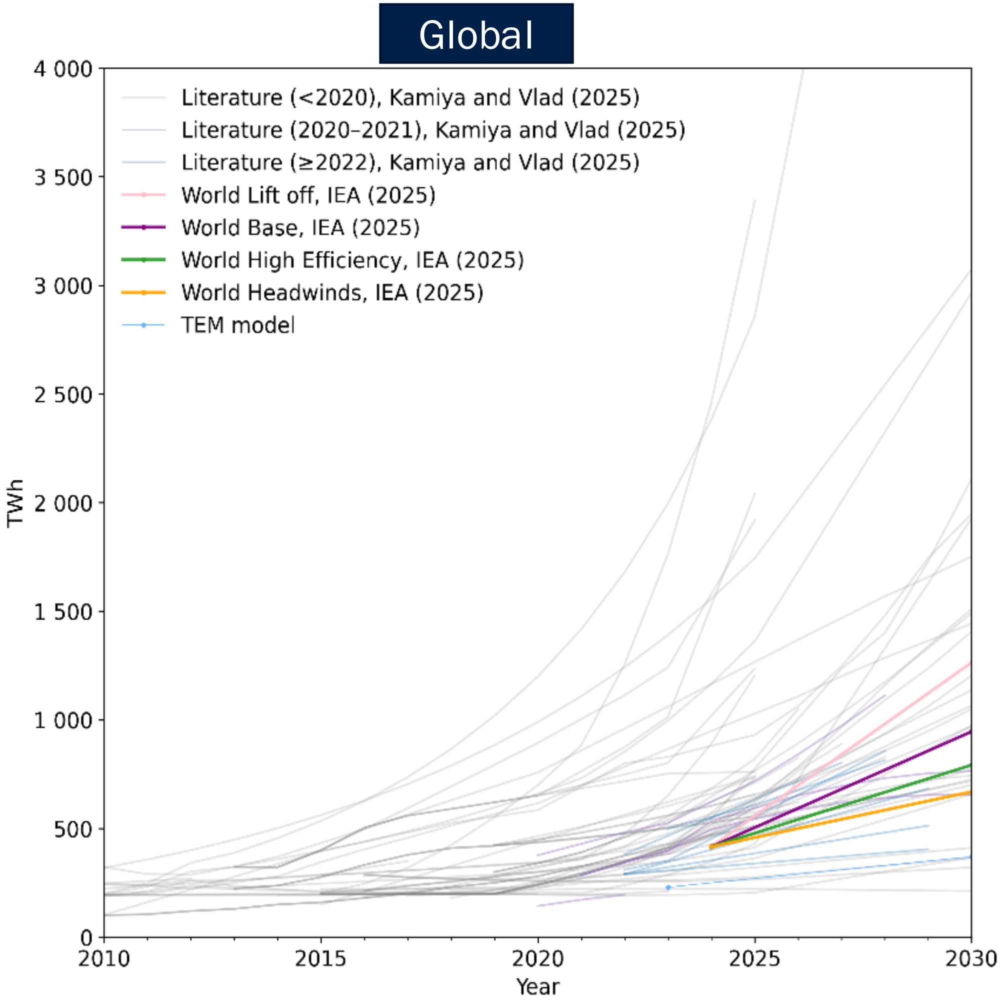
Why we do it

- Despite its enabling potential (across sectors), sustainable **steering** requires understanding digitalisation's **own footprint**
- Exploring **net** climate consequences needs a credible direct baseline first

Will Data Centres Put the Paris Climate Targets Out of Reach?

Will Data Centres Increase Our Dependence on Certain Countries for Critical Raw Materials?

Many projections — Big Spread and Most Stop in 2030



- Newer base years may align with higher forecasts due to technological breakthroughs
- It also depends heavily on scenario assumptions and framing.
- Most projections avoid going beyond 2030 (Why it Matters?)
- We need consistent and longer-term projections to inform climate-mitigation strategies

The Challenge of a Longer Term Projection: Up to 2050

- **High uncertainty** due to rapid evolution

- **Overestimation** of linear extrapolation (hype is large and the growth rate short term is explosive)

Past estimates of ICT energy use were often alarmistic and **later proven too high**

- Late 1990s to early 2000s: “Dig more coal, PCs are coming” - could soon consume half of all U.S. electricity.

- Late 2010s: “Tsunami of data could consume one fifth of global electricity by 2025”

Could misdirecting long term investment and policy

Managing the Challenge: Bounded Futures under SSPs

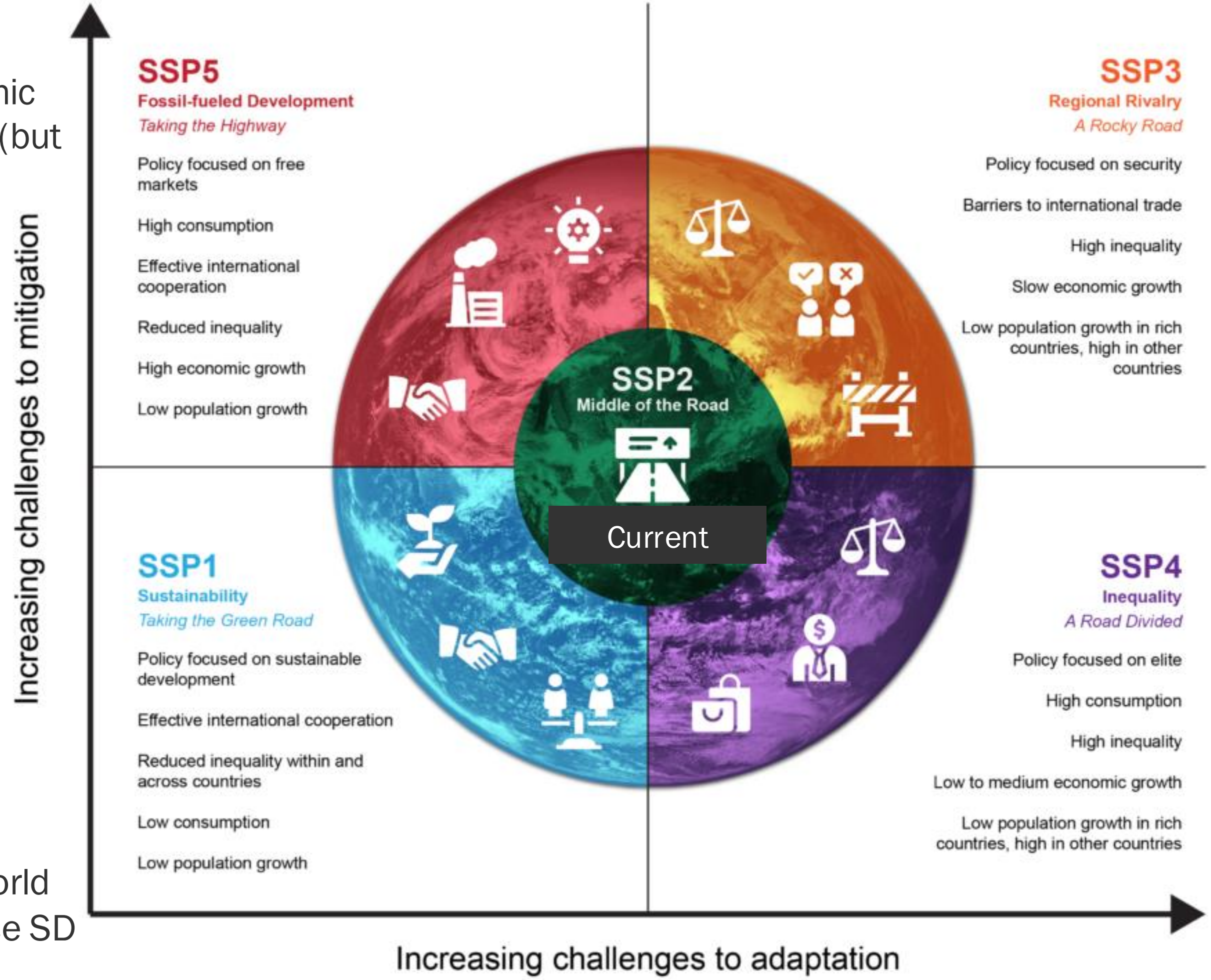
- **Uncertainty:** Scenario envelope - Use Shared Socioeconomic Pathways (SSPs) as the scenario backbone. (Not to choose one number, but to see which futures meet net-zero and what gets us there)

- **Overestimation of extrapolation:** IEA bottom-up projections for the near term, and then bound 2030–2050 growth using empirically observed (and derived) elasticities in two historical phase.

Our Scenarios: SSPs Framework “Different Future World”

Rapid economic growth (but fossil based)

Fragmented World (patterns seen in some recent political movements)



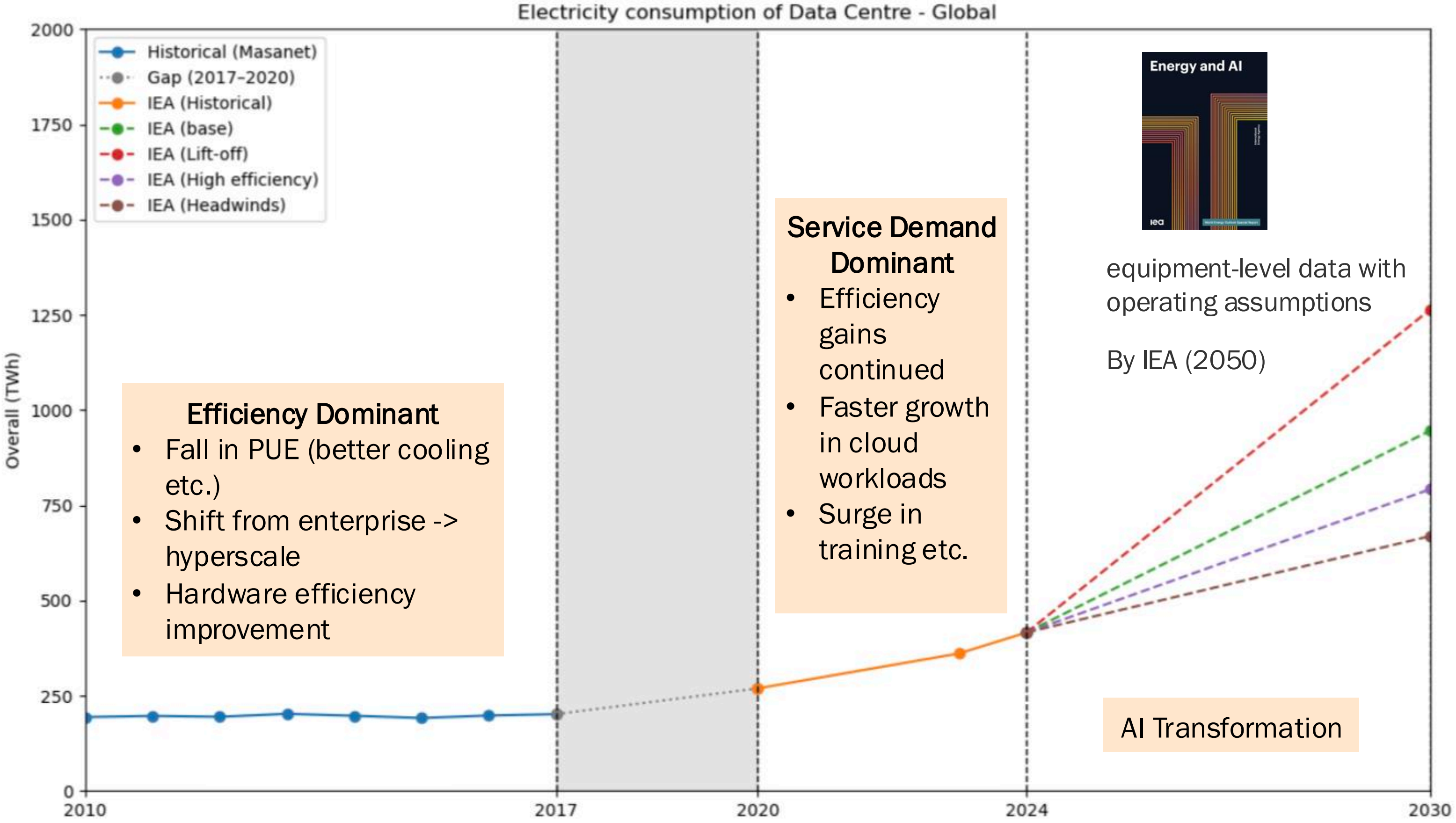
SDG World Prioritise SD

Strong inequality between elites and the rest

- 5 different plausible socioeconomic futures
- Internationally recognised “future worlds” used by IPCC and the climate modelling community
- Credibility + comparability + consistency (same underlying structure)

Figure: https://climatedata.ca/resource/understanding-shared-socio-economic-pathways-ssps/

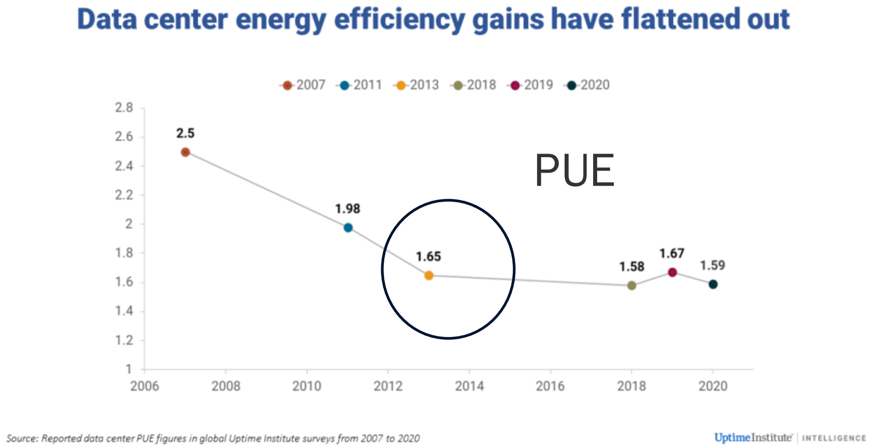
Using Distinct Historical Growth Phases to Define Extrapolation **Bounds**

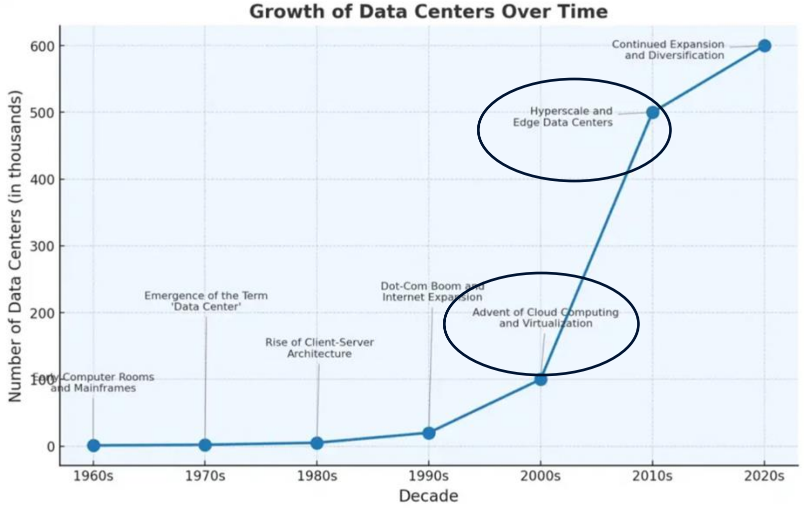


Energy and AI

equipment-level data with operating assumptions

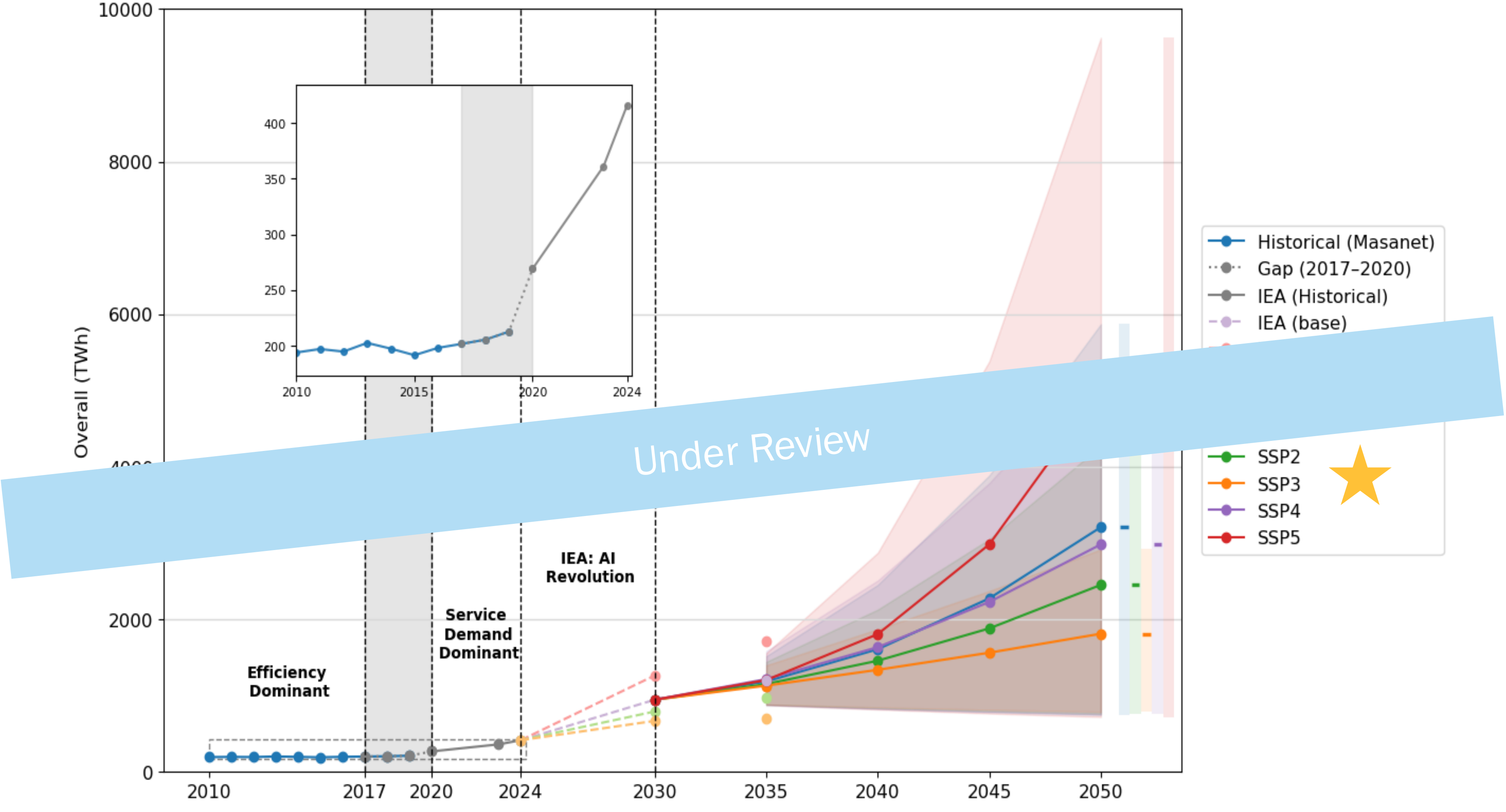
By IEA (2050)





Masanet (2020); IEA (2025); https://www.datacate.net/data-centers-a-timeline-of-growth-and-expansion/

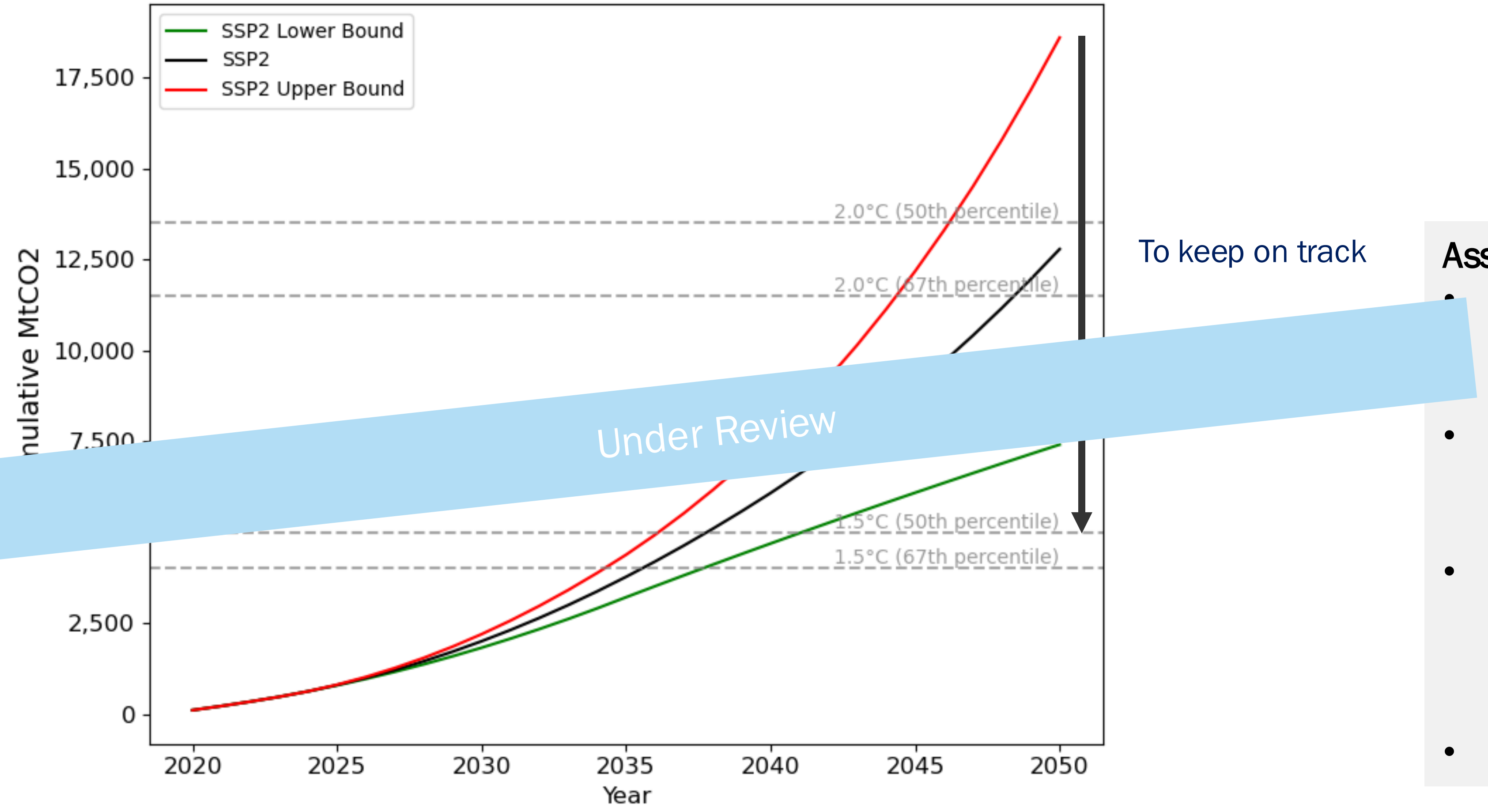
Our SSP2 Run Suggests Global Electricity Demand Could Reach ~2 500 TWh by 2050



- 1,800 and 5,000 TWh by 2050
- 2024-2030: CAGR = 15 % per year
- 2024-2050: CAGR =7 % per year (slower growth rate)

Will data centres put the Paris climate targets out of reach?

Yes, Data Centres Could Possibly Push the Paris targets Beyond Reach If Trends Continue

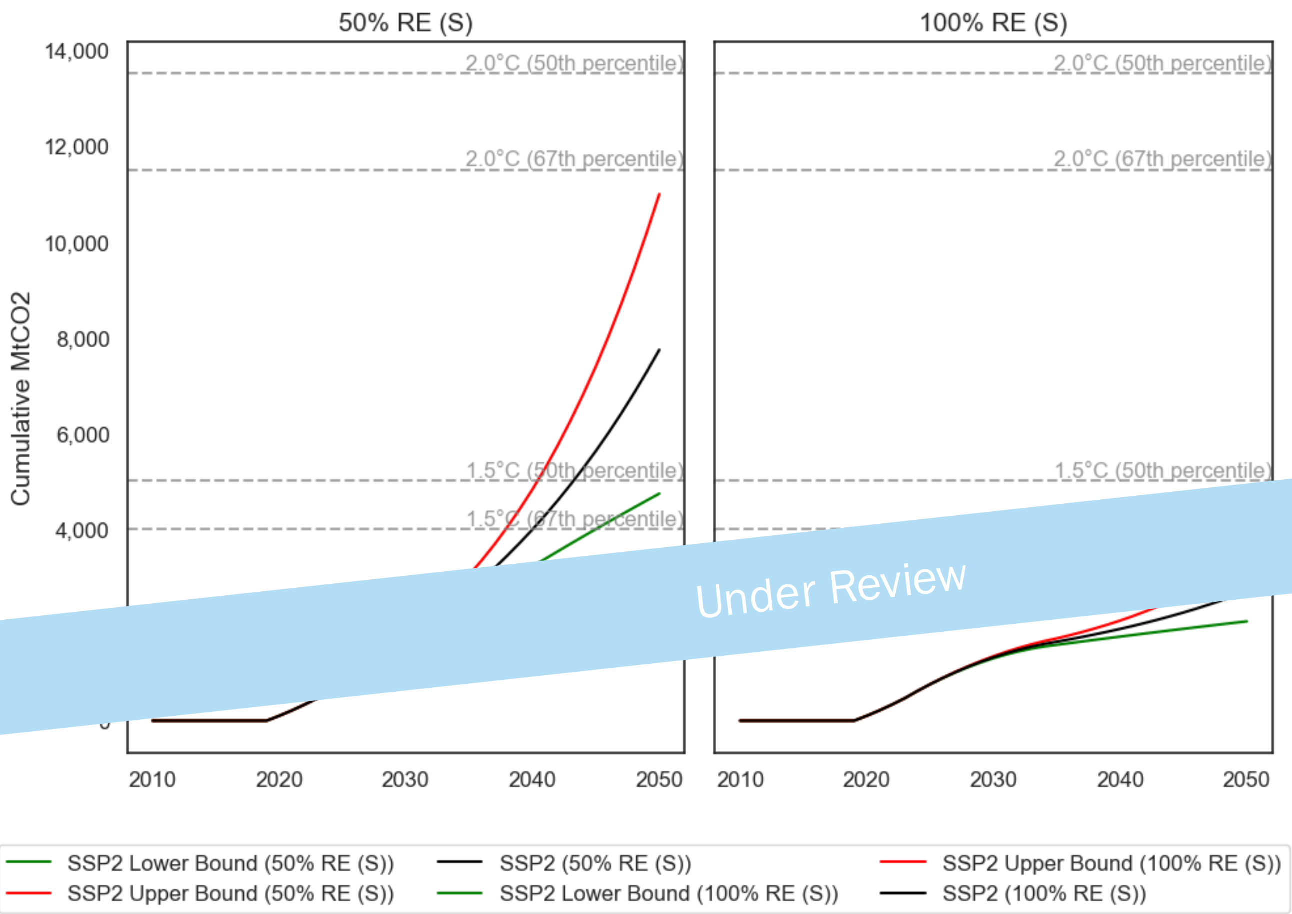


Assumptions:

- Other sectors are assumed to stay within 99% of the emissions budget.
- Data centres are allocated 1% of the total emissions budget
- Indirect emissions from digitalisation are attributed to the respective sectors.
- SSP2 carbon intensity (grid mix) = BaU

On-going research. Please do not cite

Renewable Energy to Reduce Data Centre Emissions



Under Review

- Sustainability commitments and procurement strategies: potentially a “Lower” carbon intensity than the average grid mix
- The target: 100% (Short-term reality: rising fossil-based supply to meet rapid demand)
- e.g. 24/7 carbon free energy matching, Neutral Data Centre Pact (100 % by
- The GHG emission consequences of data centre is important but manageable

To remain compatible with 1.5 °C climate targets, we estimate that the average weighted carbon intensity of electricity must fall below ~100 gCO_2/kWh from 2030.

Modelling the Material Futures: Beyond Operational Demand and Emissions

Critical Raw Material, Rare Earth: Major Geopolitical Topic (Push for Diversification)

China's critical mineral curbs shake AI data center suppliers

China's grip on minerals threatens AI boom in **US**

US and **Ukraine** sign minerals deal set to reduce China's rare earths dominance

How the US overtook China as **Africa**'s biggest foreign investor

Trump Signs Rare Earths Deal With **Australia**

Putin orders road map for **Russian** rare earths extraction

EU targets **Africa's** mineral wealth and green energy in new partnership

Malaysia's rare earths ambition: **Lynas** expands operations

Vietnam emerges as key rare earth source as Korea reduces reliance on China

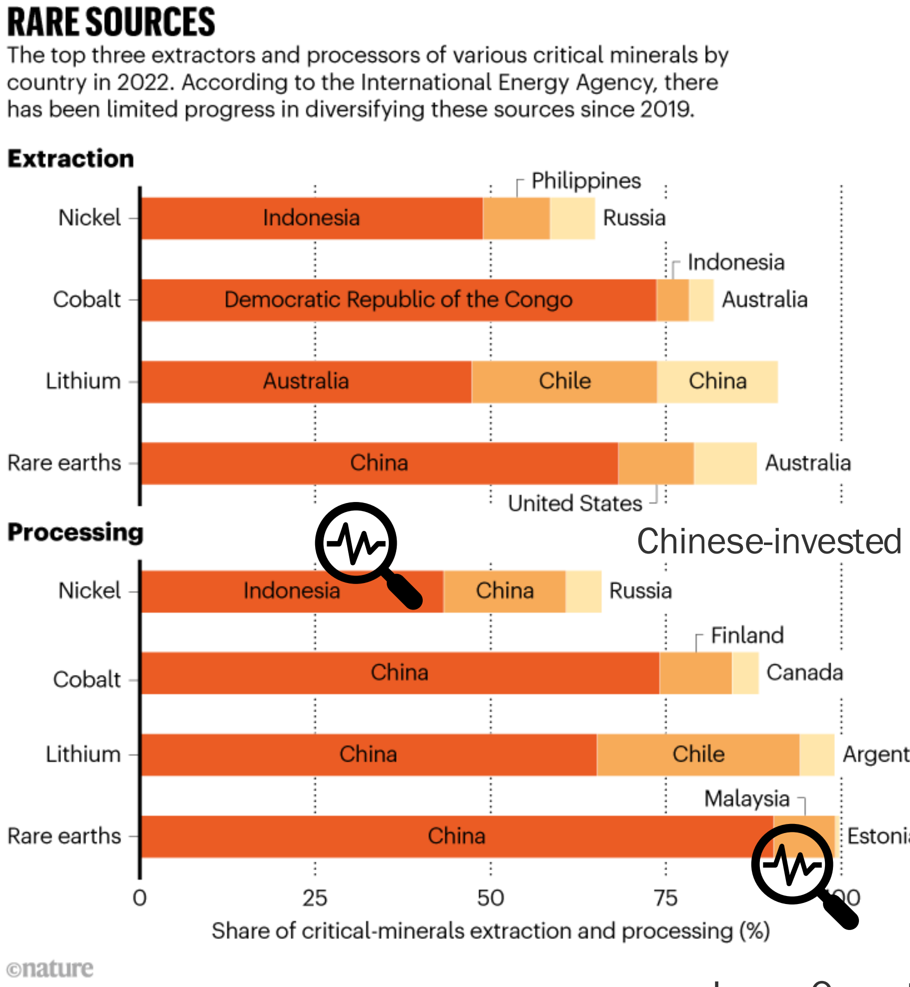
The story behind the scramble for **Greenland'**s rare earths

UK closes in on critical minerals deal with Greenland

Limited Progress in Diversifying: Top 3 Extractors & Processors

Concentrated in a few countries

Even more concentrated (China dominates this stage)



Chinese-invested firms

Lynas Operation

Countries with mineral resources, or with processing capacity, are becoming part of this global race

https://www.nature.com/articles/d41586-023-02330-0

Rare Earth

- Chemical family
- 17 metallic elements
- Abundant in crust but rarely concentrated
- Light vs Heavy REEs
- Heavy REEs is rarer, harder to separate and often more critical for advanced technologies

All rare earths are "critical," but many critical materials are not rare earths

Critical Raw Material

- Policy category (economic importance and supply risk)
- In EU: Dynamic list (every 3 years) (e.g. copper and nickel are added to the list as strategic raw material)
- 34 CRMs in 2023 list

To respond to these risks, Critical Raw Materials Act (EU):

- Extracting 10% of the EU's CRM needs (annual).
- Processing 40%.
- Recycling 25%.
- Limiting dependency on a single third-country supplier to 65%.

EC (2023) "study on the critical raw materials for the EU"

Rock-to-Metal Ratios and Energy Intensity

Ore mined and waste rock removed to produce a refined unit of a mineral commodity

- Aluminium = 7:1
- Iron= 9:1
- Copper = 513:1
- Lithium = 1634:1
- Rare Earth
  - Cerium = 23:1
  - Dysprosium = 17,000:1
- Gold = 1,500,000:1

not just about having the material in the ground

Primary energy required to produce a usable mineral concentrate (data: early 2010s)

- Aluminium = 31 GJ/t
- Iron = 0.7 GJ/t
- Copper = 53 GJ/t
- **Lithium = 12.5 GJ/t**
- Rare earth element = 40 GJ/t
- Gold = 135,496 GJ/t
- Platinum group metal = 175,000 GJ/t

around →

1200 L petrol
(25 full tank)

Electricity for 4 years
(2700kWh/y)

Note: Rare earth use in small quantities (g), and for material: overall footprint depends on lifetime unlike operational

Rock to metal ratio: Nassar et al. (2022) and (2023); GER: Aramendia et al. (2023)

What Is Inside a Data Centre? — Key Materials

Al Cu Fe Ni Zn

Ag Au Pd Pt Ru Sn Pb

Replaced by Li

Many more materials

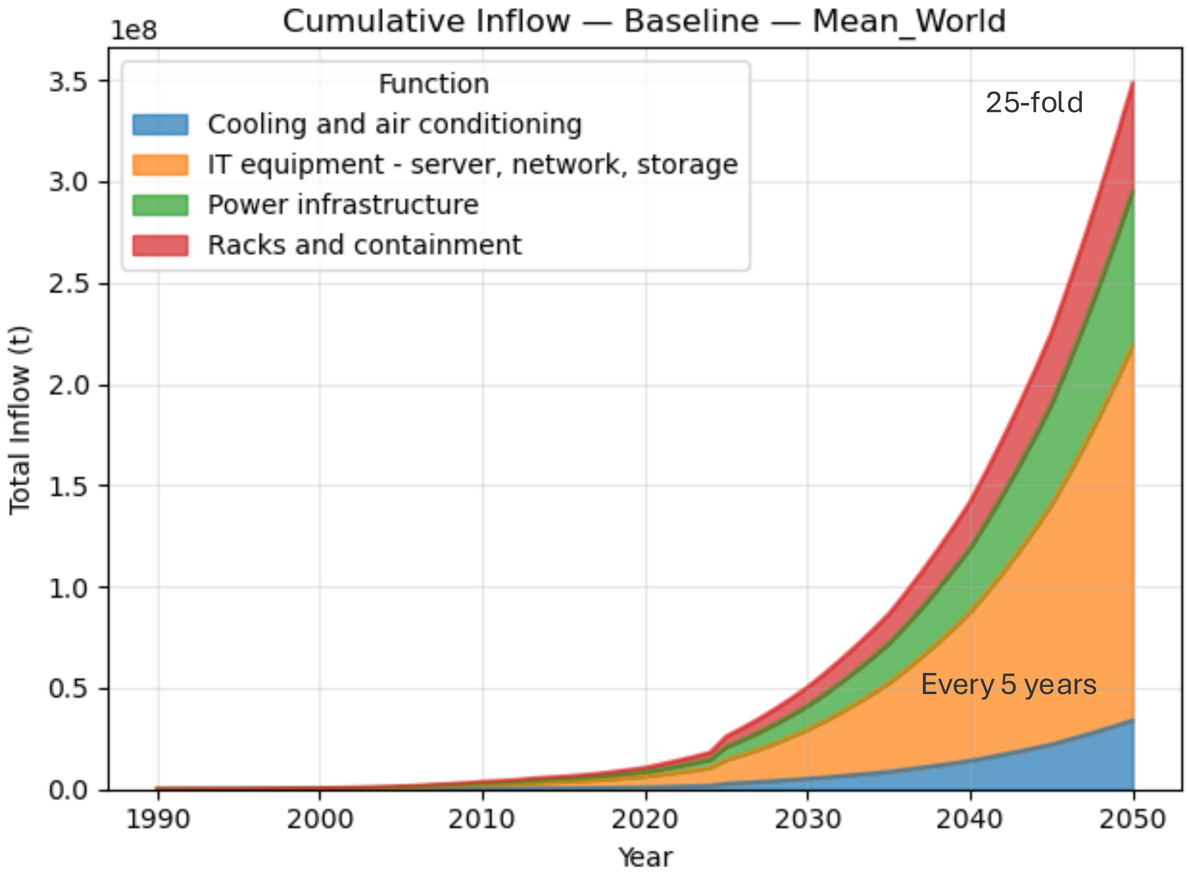
Gallium High speed (e.g. chip), “replacing” Si

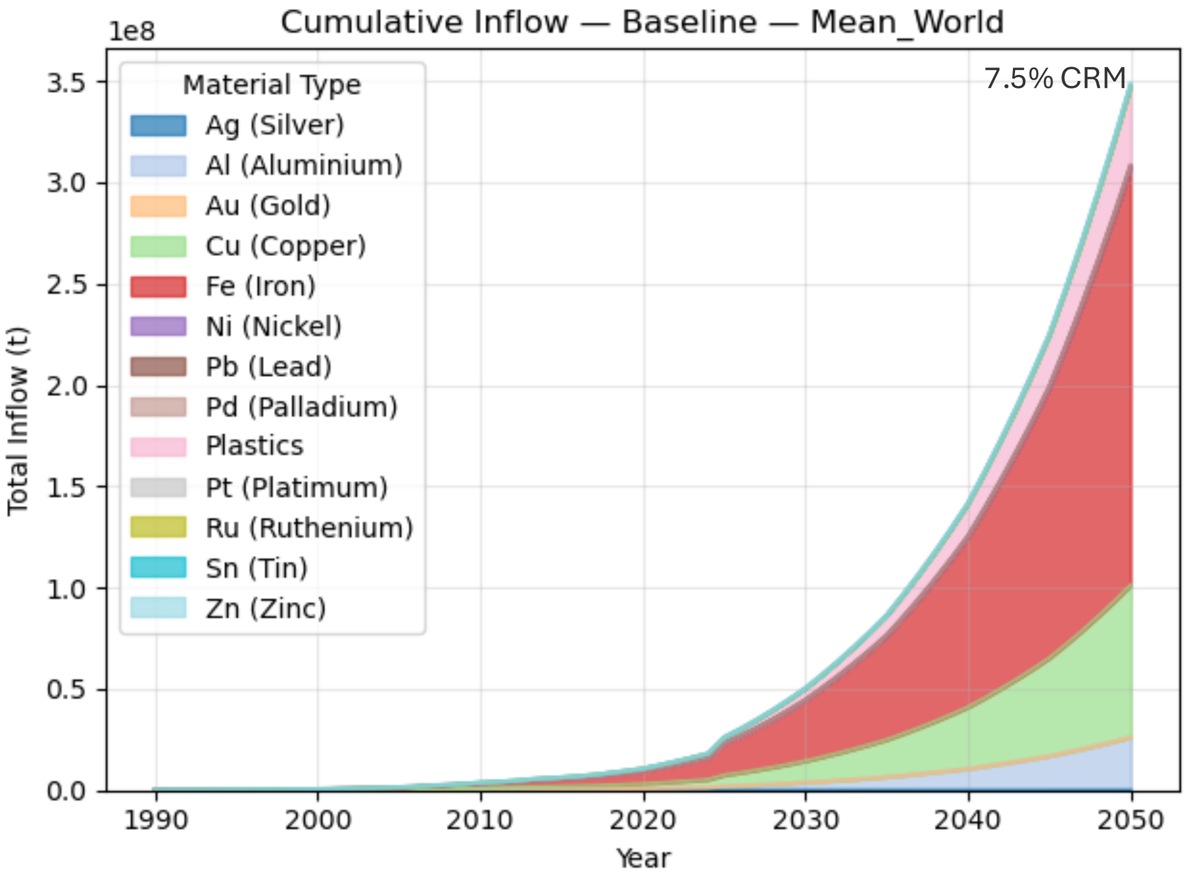
Dysprosium Neodymium

rare earth-strong permanent magnet- cooling system (fans, drive, motors)

https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-electronics/critical-minerals-in-servers-and-data-storage/

Projected Material Demand: Increase Significantly





Emerging material has to model through sensitivity test

Will Data Centres Increase Our Dependence on Certain Countries for Critical Minerals?

A Small Contribution, but One That Could Still Deepen Existing Pressures

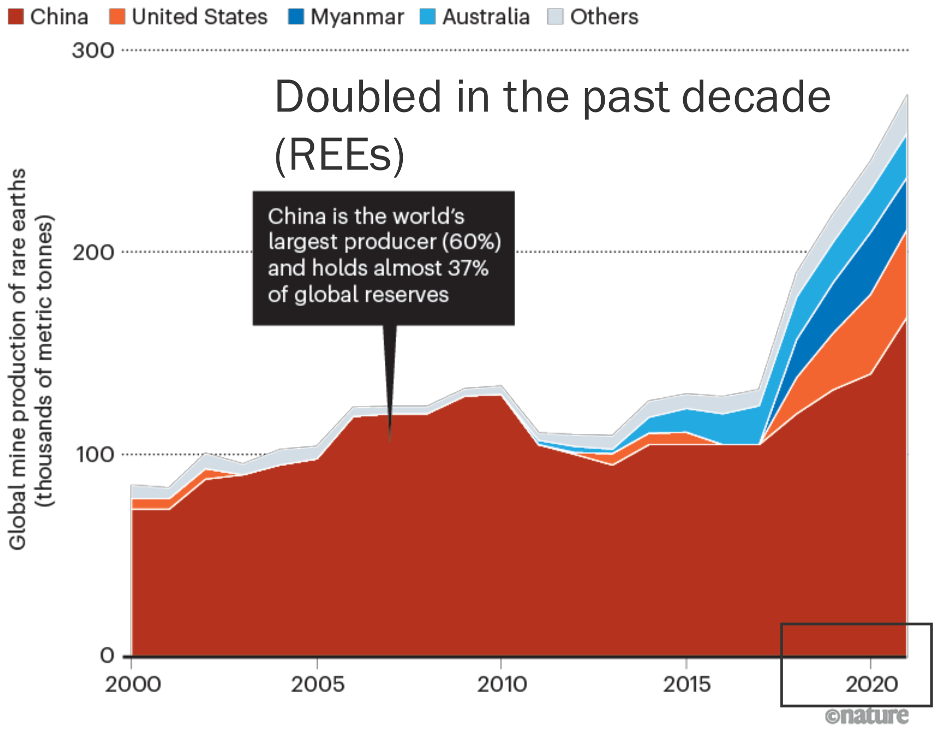
CRM	Import Reliance	**EU** consumption in 2020[a]	Others in 2050 (**EU**)[b]	DC Demand (**Europe**) in 2050
Bauxite (E) Aluminium (P)	89 % 58 %	16,146,077 4,980,933	110,000 – 130,000 (PVs)	106,065
Nickel (E) Nickel (P)	31 % 75 %	78,084 257,147	85,000 – 163,662 (Wind Turbine)	2,023
Palladium	High	20 (In 2024=39)	2 (ICT Devices)	13.60
Platinum		72	5-50 (Fuel cells for e-mobility)	0.29
Ruthenium		17.25	1-2 (Electrolyser)	0.31

On-going research. Please do not cite
[a]Values represent the 2016–2020 average from SCRREEN (2023) CRMS 2023 https://scrreen.eu/crms-2023/. Unit = t
[b]Foresight study from European Commission 2020

Rethinking Material Security as Demand Rises and for Environment: Shifting from More Mining to More Reuse

Circular Economy: Emphasis on Reusing and Recycling Materials

rather than relying on the continuous expansion of raw material extraction



Less than **1%** are currently recycled

Each tonne of REEs minning generates

- 9600-12000m^3 of gas containing sulphur dioxide
- 1.4 t of radioactive waste
- 1000 t of wastewater
- 2000 t of toxic mining waste

Cutting

- ✓ Emissions
- ✓ Pollution
- ✓ Supply risk and
- ✓ E-waste (in longer terms)

requires systemic design and data visibility across the ICT sector

https://www.nature.com/articles/d41586-023-02153-z

Beyond Recycling: Other Circular Economy Strategies

Close (loop material back into use)
Recycle
Recover
Slow (Extend product life)
Reuse
Repair
Refurbish
Remanufacture
Repurpose
Narrow (Reduce resource use)
Refuse
Rethink
Reduce

Data Centre

CE Strategies	CE
Zombie server removal (unused or idle servers)	**Narrow**
Consolidation (combining workload-fewer physical machines)	Narrow
Design efficiency (lightweight, modular)	Narrow
Lifetime extension (physical lifespan vs economic or reliability lifetime)	**Slow**
Redeployment/ cascade (older servers for lower priority workloads	Slow
Recycling	**Close**

Next: Explore its **implication on embodied energy & GHG** (and beyond) and the potential of **circular economy in mitigating**

https://circeular.org/wp-content/uploads/sites/21/2025/04/CircEUlar_D6.1_narratives_model_parameterisation.pdf

Key messages

- ICT must embody sustainability — not dismiss this responsibility by saying it enables it elsewhere.
- Direct DC footprint is real but small versus major emitting sectors.
- The indirect footprint (e.g. on the applied sector) of digitalisation may be larger and harder to regulate — needs research attention.
- Circular economy approach is essential — not enough attention

Thank you

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