Carbon and water footprints of computing infrastructures: evaluations and tendencies

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Infrastructure Workshop2025

Outline

- **Context**
- **Carbon footprint of Clouds**
- **Water consumption of Clouds**
- **Tendencies**

Context

Climate crisis

- **Planetary boundaries**
- **Decent and fair standard of living**

Computer science

- **Often presented as part of the solution to environmental problems (optimization, smart systems, planet models, etc.)**
- **But surely part of the problem.**

My scientific context

- **Researcher in computer science, distributed systems, started with grid computing…**
- **Energy consumption during use phase, environmental impacts**

Carbon footprint and energy consumption

What is the ICT part in the global carbon impact?

2.1 to 3.9% in 2021 (1.2 to 2.2 Gt CO2eq)

→ Forecast: +6% to 10% par an

["The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations'', C. Freitag, M. Berners-Lee, K. Widdicks, B. Knowles, G. Blair, A. Friday, *Patterns*, 2021.]

What is the ICT part in the electricity consumption of France?

11% in 2020 (52 TWh)

→ Forecast: 93 TWh in 2050 (+79%)

["Évaluation de l'impact environnemental du numérique en France et analyse prospective'', rapport ADEME – ARCEP, 2022.]

→ 65 TWh in 2020 including abroad data centers (+25% compared to without DC)

["Évaluation de l'impact environnemental du numérique en France'', rapport ADEME – ARCEP, 2025.]

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Carbon neutrality

FACEBOOK
Sustainability

Net Zero

reached net zero in operational GHG emissions

In 2020, we achieved net zero emissions in our operations by reducing emissions by 94 percent* and supporting carbon removal projects.

*from a 2017 baseline

Microsoft

2021 Environmental Sustainability Report

Our commitments

Carbon negative
By 2030, we will be carbon negative, and by 2050, we will remove our historical emissions since we were founded in 1975.

Reduce direct emissions
We will reduce our Scope 1 and 2 emissions to near zero by 2025 through energy efficiency work and by reaching 100 percent renewable energy.

100%
renewable energy

In 2020, we matched 100% of the electricity consumption of our operations with renewable energy purchases for the fourth consecutive year.

Google
Environmental Report

Environmental Progress Report

100%
renewable energy sourced for all Apple facilities

Carbon neutral
for corporate operations since April 2020

[Source : environmental reports of Facebook, Google, Microsoft and Apple, 2021]

GHG Protocol

Carbon footprint: 3 scopes

- **Scope 1:** emissions resulting directly from the company's activities, such as internal electricity generation, air conditioning refrigerant gas emissions, etc.

- **Scope 2:** emissions resulting from the company's energy consumption, typically purchased electricity and heating.

- **Scope 3:** (part of) everything else! i.e. purchases, business travel of employees and commuting, waste management…

[Source : https://ghgprotocol.org/standards-guidance]

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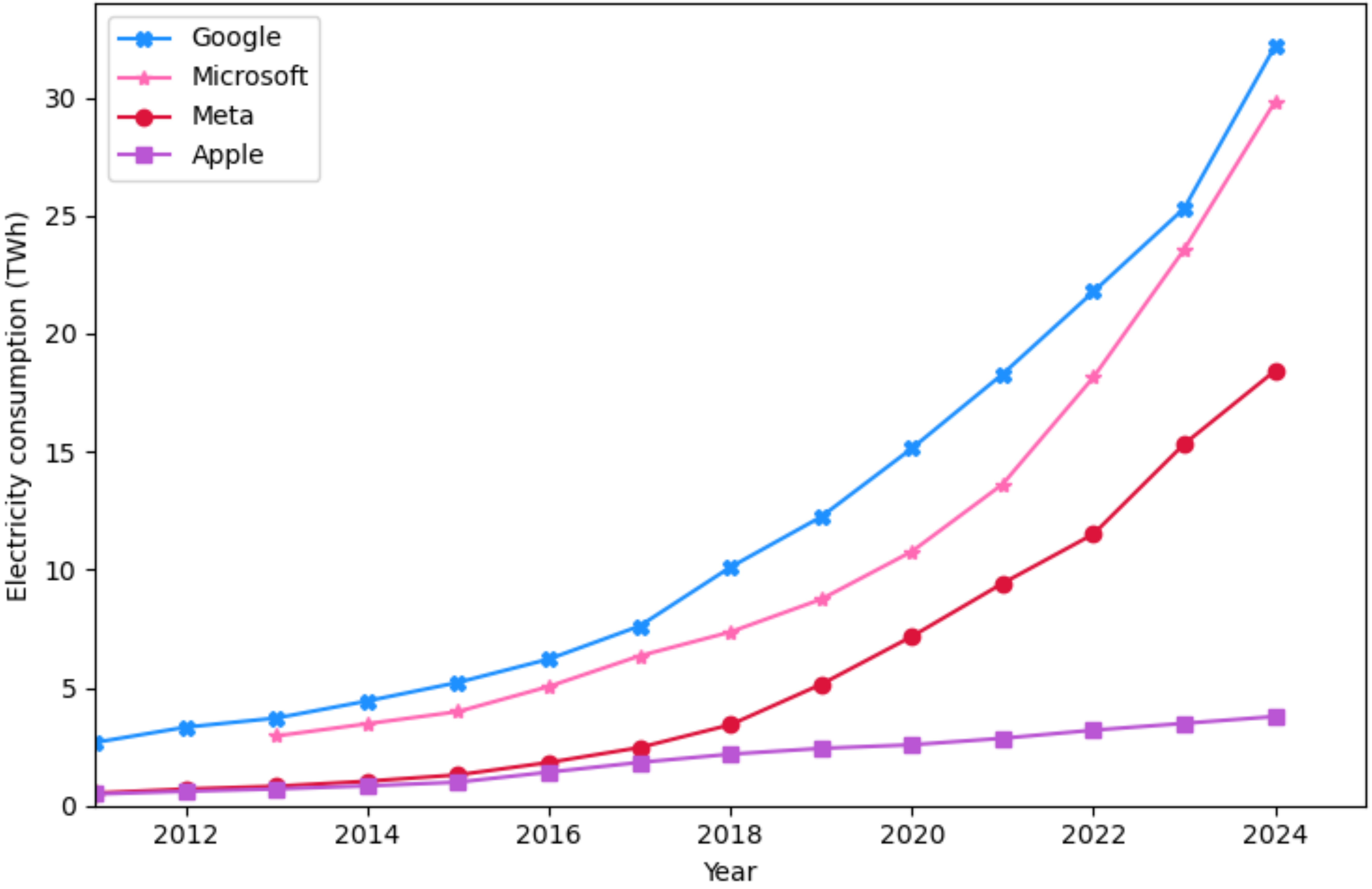
Electricity consumption of Clouds (scopes 1 & 2)



✕ 2 in 4 years

[“Power limits in data centers: what can we expect from improving energy efficiency and refreshing servers?”, Pablo Leboulanger, Anne-Cécile Orgerie, *IEEE International Conference on Cloud Engineering (IC2E)*, 2025, pp.1-12.]

[Sources: annual environmental reports of Google, Microsoft, Meta and Apple.]

Scope 2

2. What is the emission factor for renewable energy?

Renewable energy, such solar, wind, geothermal, and hydropower, have no direct emissions at the point of electricity generation, and therefore use an emission factor of zero in scope 2. Nuclear-generated electricity is also carbon-free at the point of generation. While electricity generated from biogenic resources such as biomass, biofuels and biogas can be considered renewable, these electricity generation resources are not zero emissions at point of combustion. Based on the Corporate Standard, any CH4 or N2O emissions from biogenic energy sources use shall be reported in scope 2, while the CO2 portion of the biofuel combustion shall be reported outside the scopes.

[Source : Scope 2 Frequently Asked Questions, GHG Protocol, 2025]

Carbon-Free Energy Highlights

- 100% of electricity consumed by Amazon was matched with renewable energy sources in 2024, for the second consecutive year
- Since 2020, Amazon has been the world's largest corporate purchaser of renewable energy annually
- World's largest corporate buyer of offshore wind energy in 2024, according to BloombergNEF
- 100% of energy used by active Echo, Fire TV, and Ring devices worldwide was matched with operational wind and solar capacity in 2024
- 621 total renewable energy projects announced globally as of January 2025—including 124 new projects in 2024—representing 34 GW of carbon-free energy capacity, which can produce 91,000 GW hours of carbon-free electricity annually
- 219 solar projects and 83 wind farms, totaling 302 utility-scale wind and solar projects as of January 2025
- 319 on-site rooftop solar systems at our fulfillment centers and stores as of January 2025

[Source : Amazon Sustainability Report, 2024]

PPA et EAC

Power Purchase Agreement

- Power purchase contract, long term (10 to 25 years)
- Company commits to purchase renewable electricity directly from an energy producer
- Fixed price over the period (by contract), accounting in the carbon footprint
- Driving investment in new renewable energy installations

Energy Attribute Certificates (aka RECs, SRECs, TRCs)

- Tradable ‘certificates’ issued by electricity producers when it produces 1 MWh of renewable electricity
- Unbundle from the physical electricity, sell separately
- Variable price, accounting in the carbon footprint
- Risk of double counting the environmental gains

Buying renewable energy (scope 2)

Location	Renewable energy technology	Size (MW)
Australia	PV	0.5
Brazil	Wind	0.5
China mainland	PV	195
China mainland	Wind	130
Denmark	PV	42
Denmark	Wind	17
India	PV	16
Israel	PV	5
Japan	PV	12
Mexico	Wind	0.8
Rooftop solar projects	PV	5.0
Power for Impact projects	PV	7
Singapore	PV	54
Taiwan	PV	1
Turkey	PV	4
Arizona, U.S.	PV	62
California, U.S.	Biogas fuel cell	4
California, U.S.	PV	144
Illinois, U.S.	Wind	112
Nevada, U.S.	PV	320
North Carolina, U.S.	PV	164
Oregon, U.S.	Microhydro	3
Oregon, U.S.	PV	125
Oregon, U.S.	Wind	200
Texas, U.S.	Wind	25
Virginia, U.S.	PV	134
	Total	**1,782**

Maiden, North Carolina: Grid mix versus Apple-sourced renewable energy

Electricity use in 2024: 466 million kWh

Emissions avoided in 2024: 117,800 million MT CO_2e[4]

Default grid mix	%
Gas	41
Nuclear	38
Coal	9
Renewable	9
Hydro	3

Source: eGRID 2022.

Apple actual renewable energy allocation	%
Apple's solar projects	68
Apple's wind projects	32

Source: 2024 energy data.

China: Grid mix versus Apple-sourced renewable energy

Electricity use in 2024: 214 million kWh

Emissions avoided in 2024: 126,800 million MT CO_2e[10]

Default grid mix	%
Coal	63
Hydro	17
Renewable	11
Nuclear	5
Gas	3

Source: IEA Electricity Information 2022, www.iea.org/data-and-statistics/data-product/electricity-information.

Apple actual renewable energy allocation	%
Apple's solar projects	50
Apple's wind projects	50

Source: 2024 energy data.

[Source : Apple Environmental Progress Report, 2025]

Buying renewable energy (scope 2)

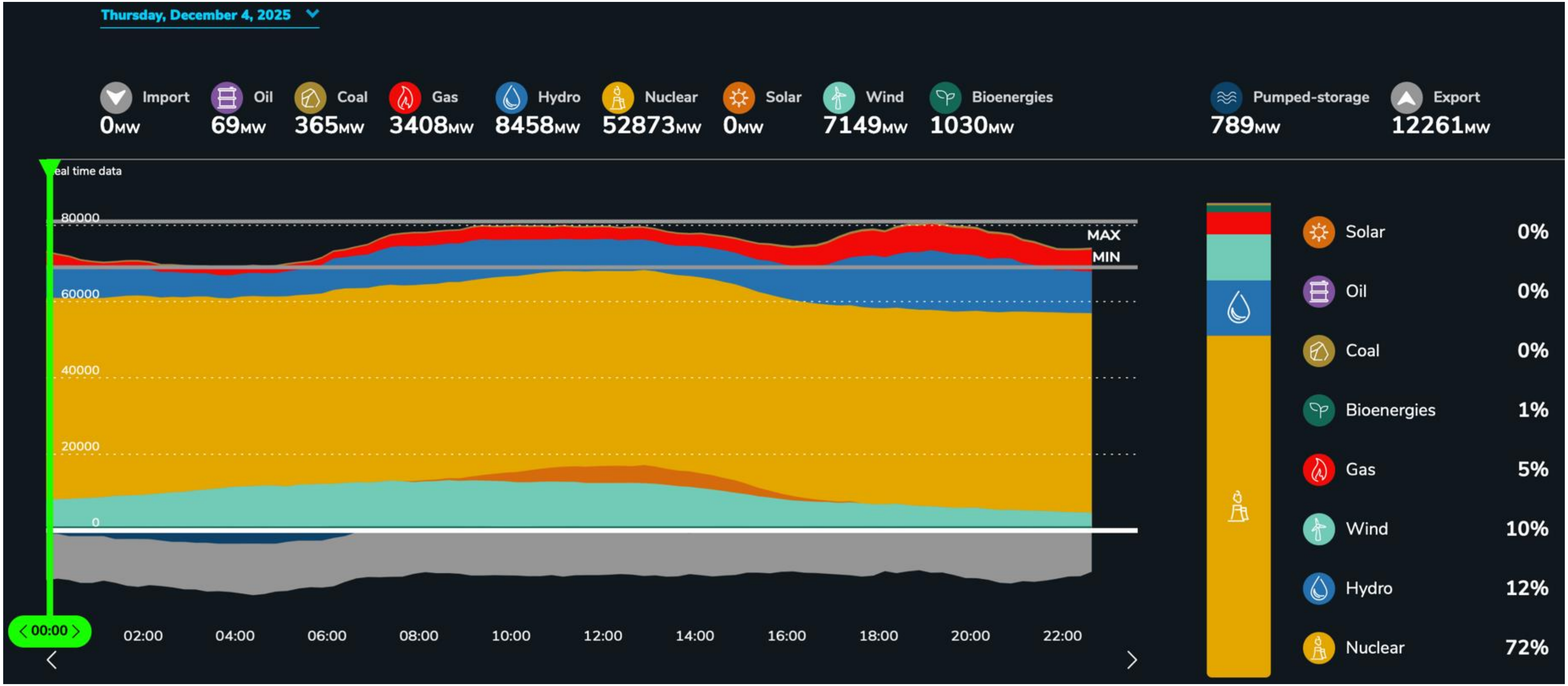
Meta example in 2024

Electricity Consumption					
Electricity Consumption by Facility (in MWh)					
	2020	**2021**	**2022**	**2023**	**2024**
Total electricity consumption	7,170,000	9,420,839	11,508,131	15,325,314	18,423,634
Electricity from grid (%)	100%	>99%	>99%	>99%	>99%
Data centers total	6,966,000	9,117,122	11,167,416	14,975,435	18,061,781

Market-Based vs. Location-Based										
Scope 2 Emissions (in metric tons CO_2e)										
	2020		**2021**		**2022**		**2023**		**2024**	
	Market-based	Location-based	Market-based	Location-based	Market-based	Location-based	Market-based	Location-based	Market-based	Location-based
Total facilities GHG emissions	9,000	2,718,000	2,487	3,080,194	273	3,921,611	1,658	5,141,350	1,358	5,967,348
Data centers total	2,000	2,650,000	2,487	2,987,964	273	3,821,450	733	5,036,131	135	5,862,614

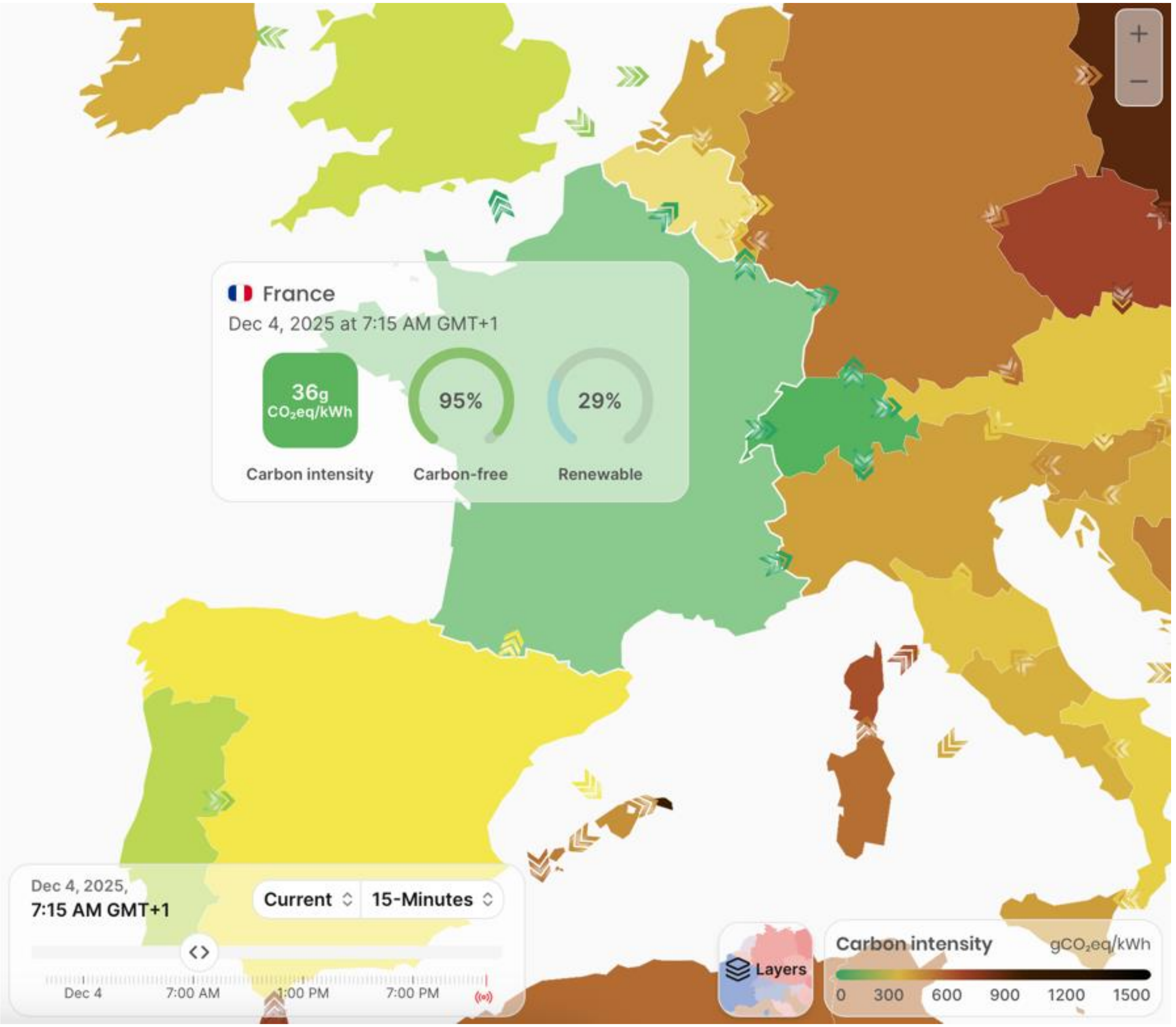
[Source : Sustainability Report – Environmental Data Index, Meta, 2025]

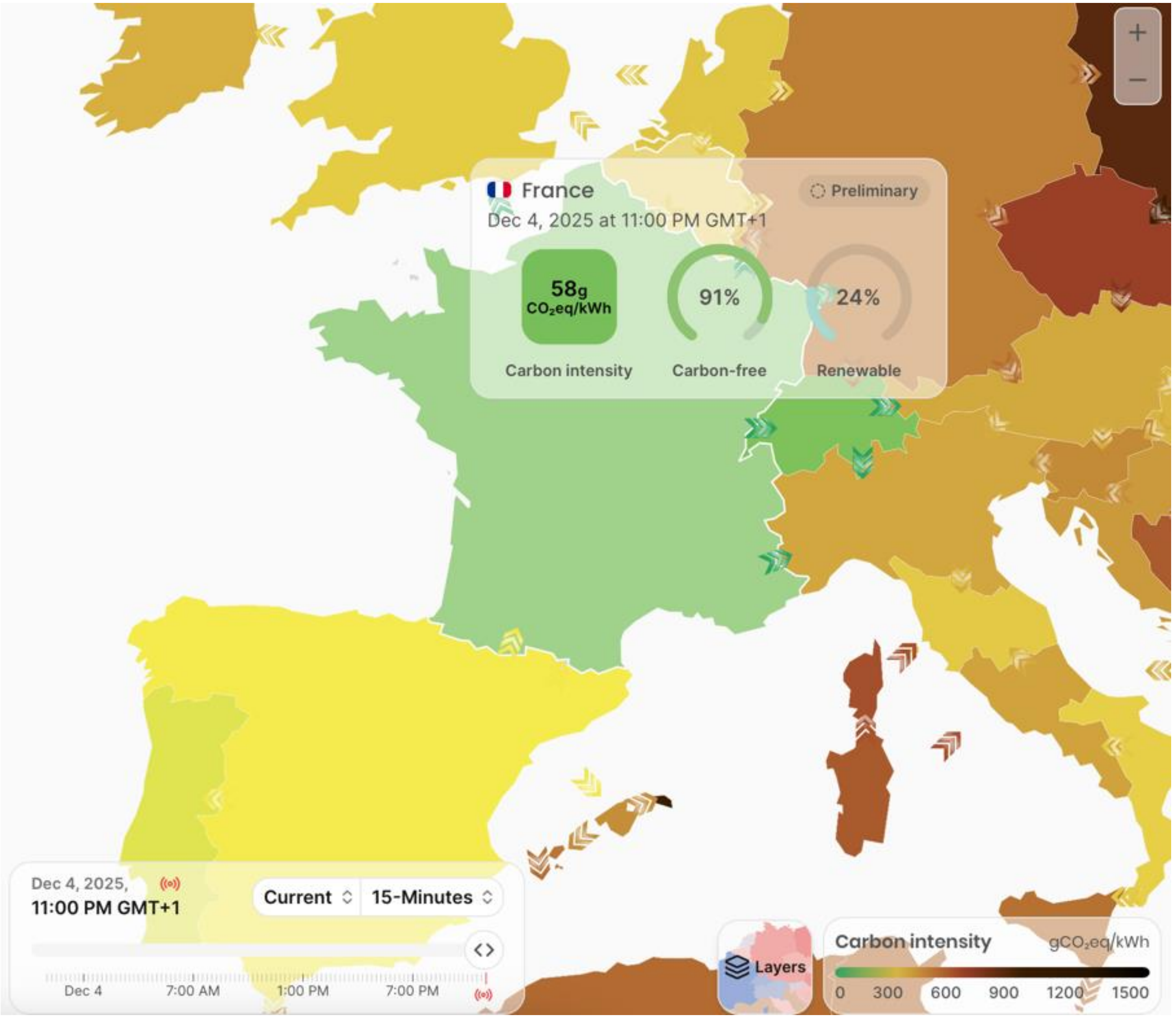
Example of electrical mix in France



[Source : Eco2mix, RTE, 2025]

Temporal variability and electricity imports/exports





[Source : ElectricityMaps, 2025]

Ireland case

x 121

Ireland has around 121 data centres operated by 24 providers

Data centres are termed **'large energy users'**

Around one-fifth of Ireland's corporation taxes income is linked to companies in the ICT sector including data centres – in 2023 that's around €4billion

2015
Data centres used **5% (1.2 TWh)** of Ireland's electricity

2023
Data centres used **21% (6.3 TWh)** of Ireland's electricity

A five-fold increase in power demand in just 8 years

+1 TWh

The rise in electricity use by data centres is around **1 TWh** per year – outpacing new renewable electricity sources

[Source : "The future of data centres in Ireland", Kate Walsh, Senior Parliamentary Researcher (Environmental Science), 2025]

Grid stability

Threat of cascading power outage

Data Center Alley, a 30-square-mile stretch outside Washington D.C. and home to more than 200 data centers, consumes roughly the same electricity as Boston. So power company officials were alarmed when a big chunk of those centers - 60 of them - suddenly dropped off the grid one day last summer and switched to on-site generators.

The mass reaction was triggered by a standard safety mechanism across the data center industry, intended to protect computer chips and electronic equipment from damage caused by voltage fluctuations. But it caused a huge surge in excess electricity, according to federal regulators and utility executives.

The magnitude of the imbalance forced grid operator PJM and local utility Dominion Energy (D.N), to scale back output from power plants to protect grid infrastructure and avoid a worst-case scenario of cascading power outages across the region.

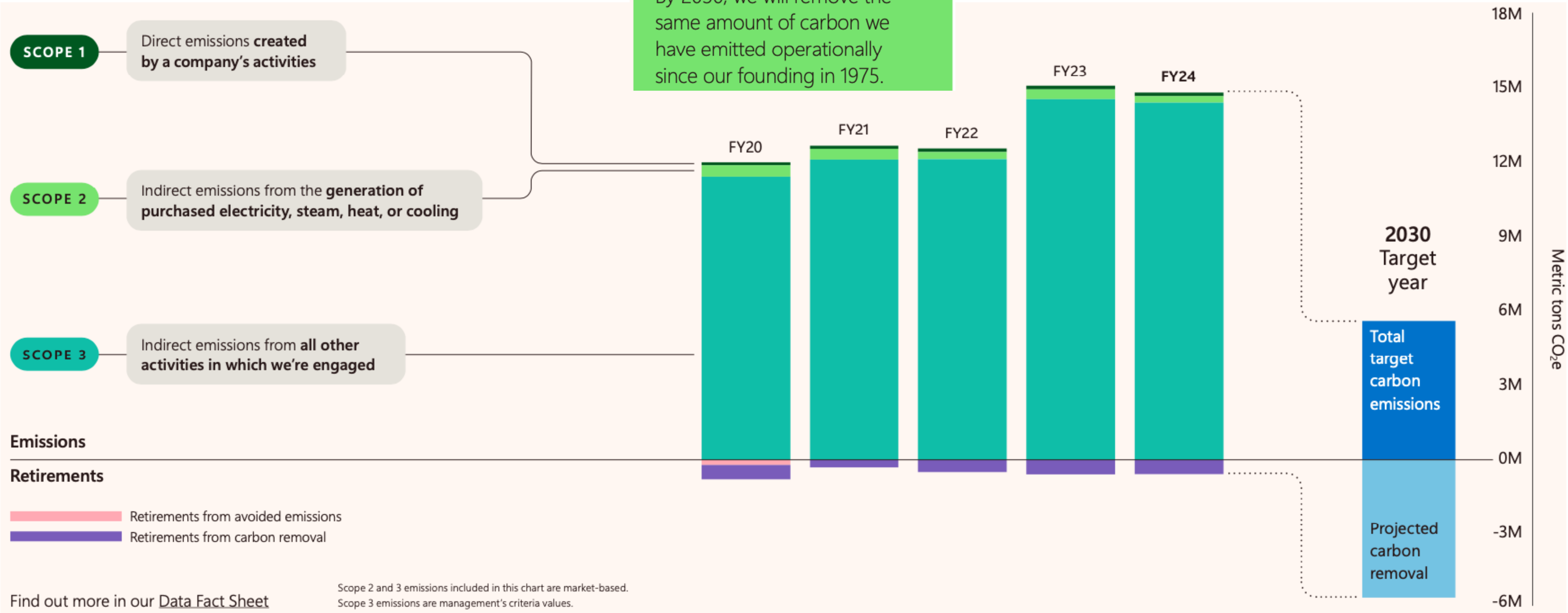
The near-miss - reported here in detail for the first time - forced federal regulators to recognize a new vulnerability of America's electrical grid: unannounced disconnections by data centers.

[“Big Tech’s data center boom poses new risk to US grid operators”, Tim McLaughlin, Reuters, 2025]

Microsoft example

Carbon negative

By 2030, Microsoft will cut its emissions by more than half compared to 2020 and remove more carbon than it emits. By 2050, we will remove the same amount of carbon we have emitted operationally since our founding in 1975.



[Source: 2025 Environmental Sustainability report, Microsoft, 2025.]

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Water consumption

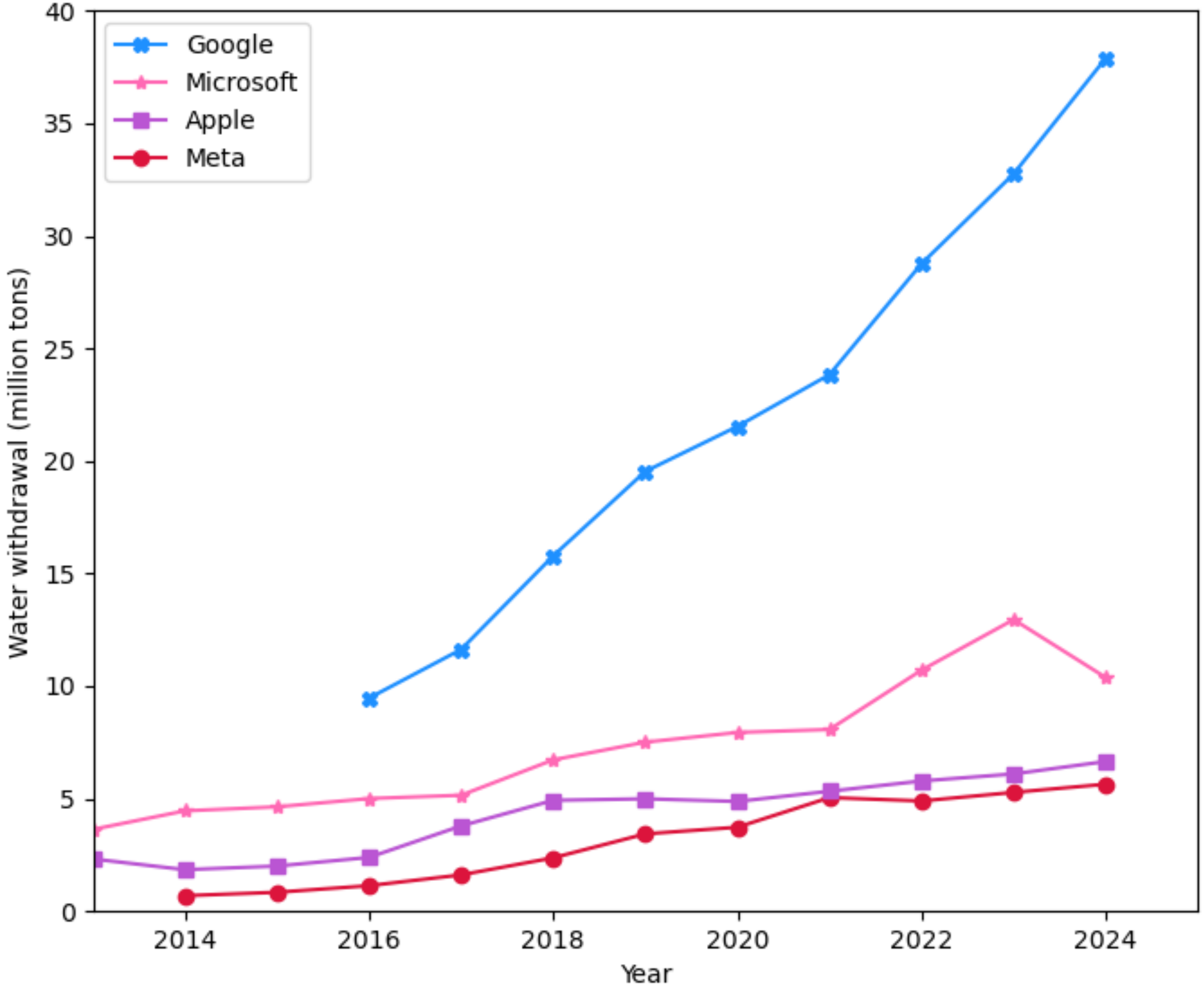
No water (GHG-like) protocol

- Scope 1: on-site water consumption for cooling
  - Withdrawn water: water ‘used’ (bought or taken from a source)
  - Discharged water: waste water
  - Consumed water = withdrawn water - discharged water (including evaporated)
- Scope 2: water consumption for electricity production
- Scope 3:
  - DC building
  - IT equipment manufacturing
  - Etc.

Water issues are local and seasonal (water stress)

[“*De l'eau dans les nuages*”, Sylvain Bouveret, Aurélie Bugeau, Anne-Cécile Orgerie, Sophie Quinton, Annales des Mines - Enjeux Numériques, 2024.]

Water consumption of Clouds (scope 1)



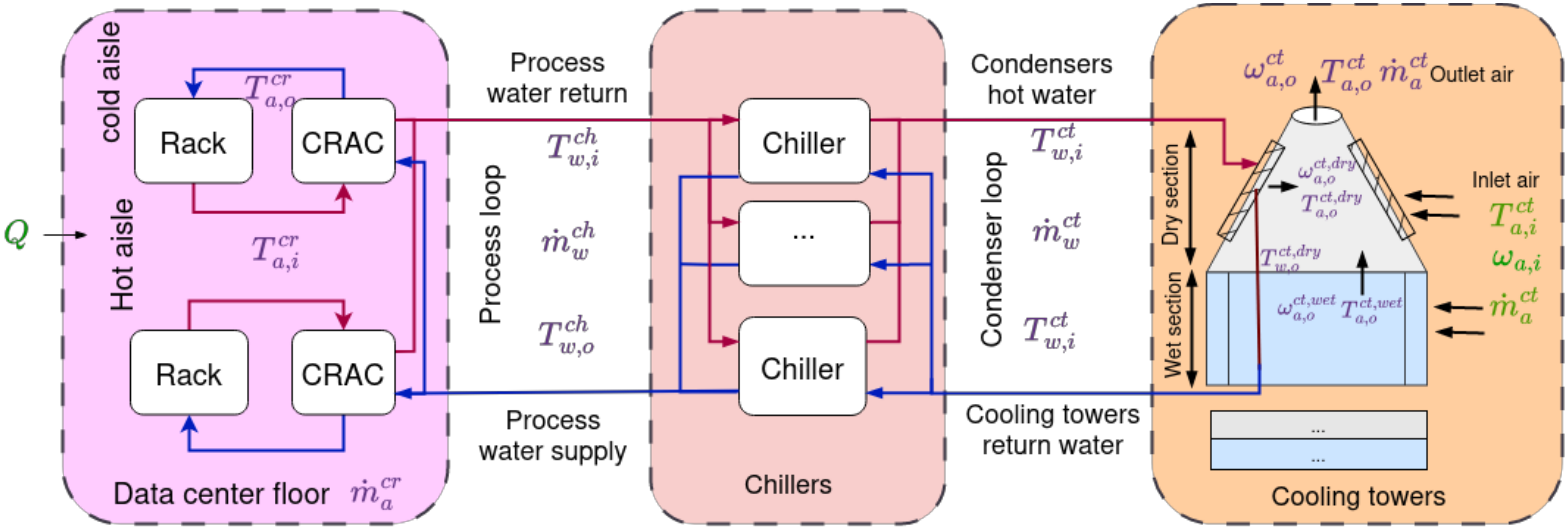
*"Starting in FY24, reported values incorporate an **updated approach** based on water use efficiency metrics to estimate how much we withdraw and consume for datacenter locations where data actuals are not available, as outlined in the methodology section of our Data Fact Sheet. **Prior years were not adjusted to reflect this change** due to data availability limitations."*

[Source: 2025 Environmental Sustainability Report, Microsoft, 2025]

[Sources: annual environmental reports of Google, Microsoft, Meta and Apple.]

Modeling cooling systems

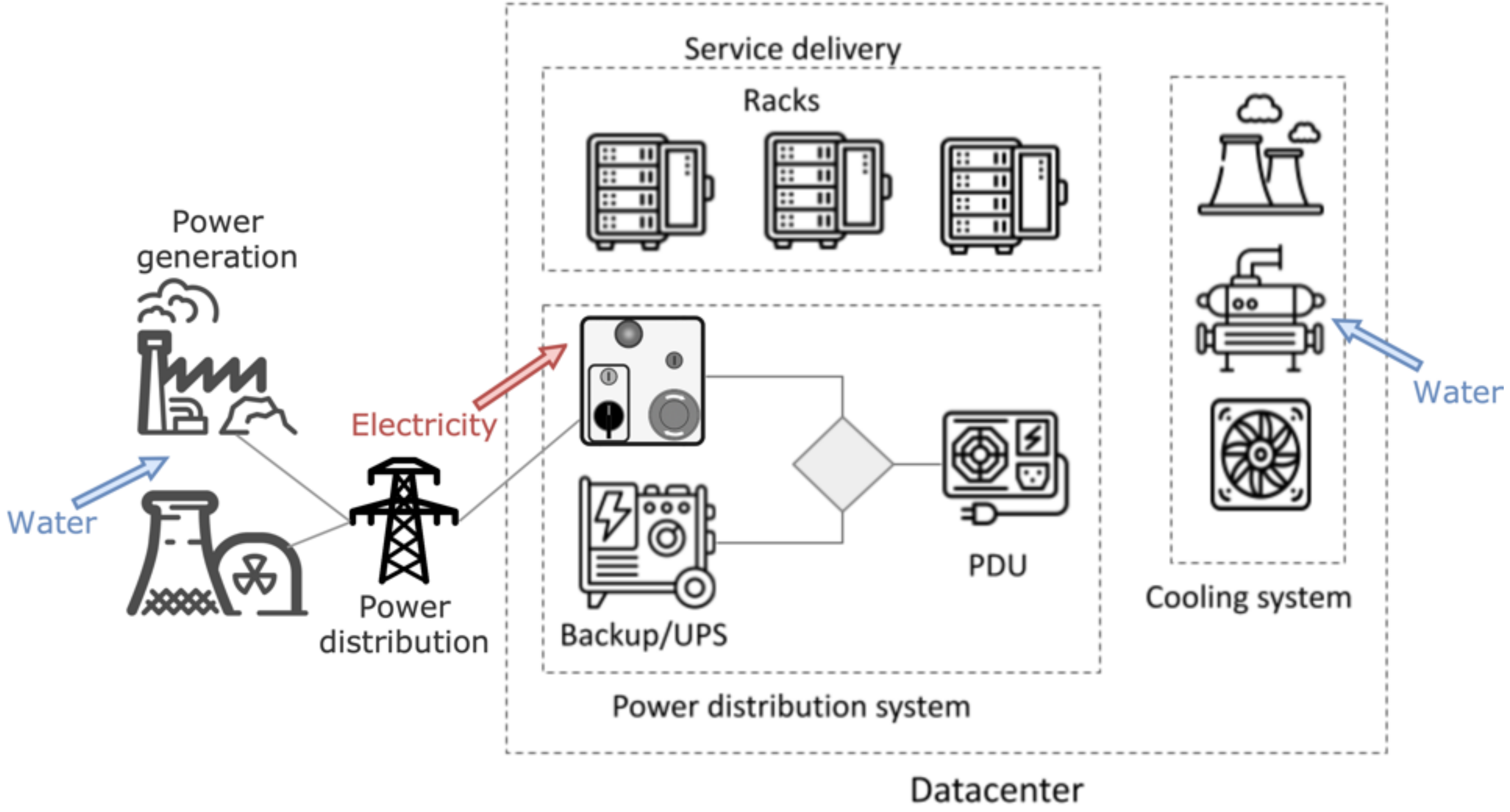
Thermodynamic modeling



[“FlexCoolDC: Datacenter Cooling Flexibility for Harmonizing Water, Energy, Carbon, and Cost Trade-offs”, W. E. Gnibga, A. Chien, A. Blavette, A.-C. Orgerie, *ACM International Conference on Future and Sustainable Energy Systems*, 2024.]

Linked energy and water consumptions (scopes 1 & 2)

Water consumption of electricity production (scope 2)

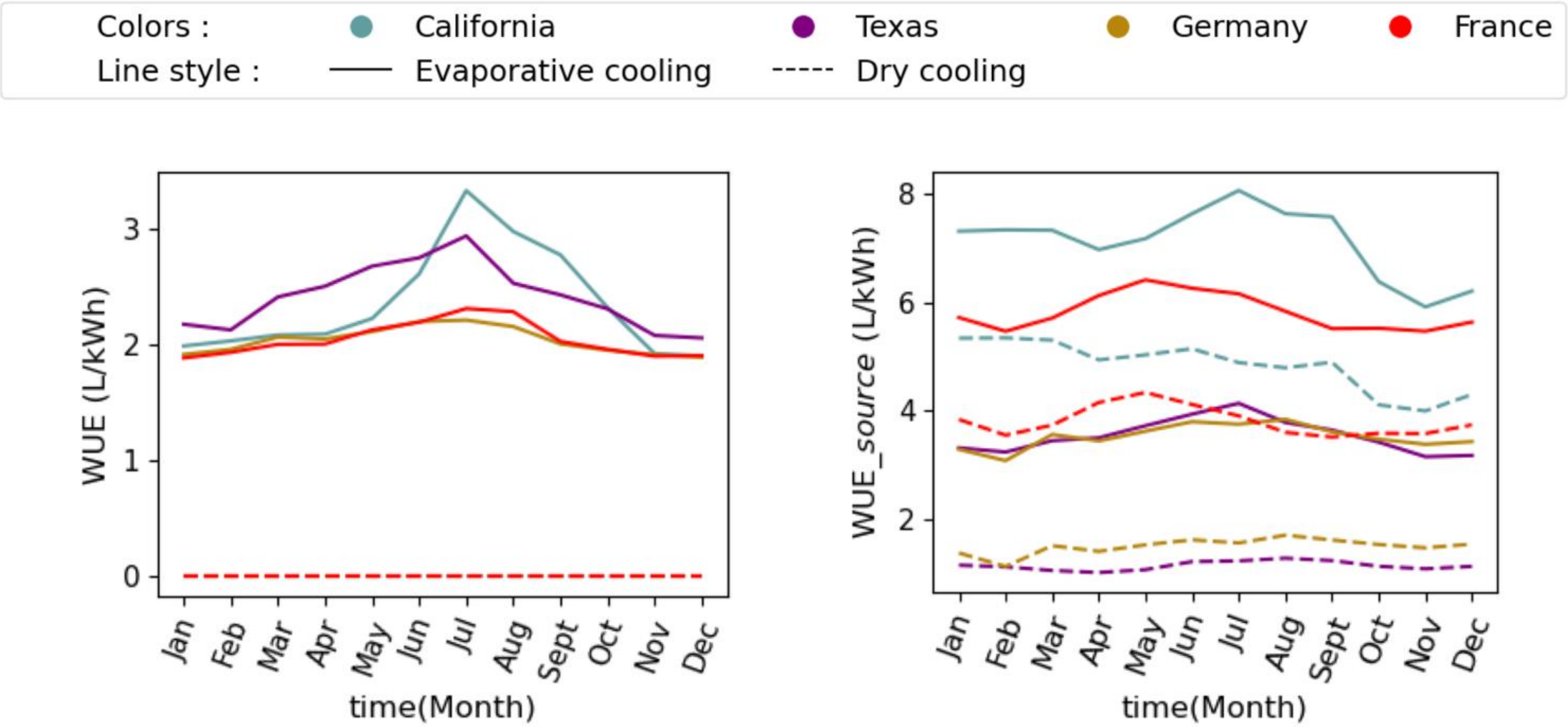


In France, for a 20MW DC, with evaporative cooling: Water consumption for the cooling $\times$ 2.8 = water consumption for the electricity production for the same DC

[“FlexCoolDC: Datacenter Cooling Flexibility for Harmonizing Water, Energy, Carbon, and Cost Trade-offs”, W. E. Gnibga, A. Chien, A. Blavette, A.-C. Orgerie, *ACM International Conference on Future and Sustainable Energy Systems*, 2024.]

Evaluating water consumption of DCs (scopes 1 & 2)

Simulations for a 20 MW DC with location-based method (scope 2)



[“FlexCoolDC: Datacenter Cooling Flexibility for Harmonizing Water, Energy, Carbon, and Cost Trade-offs”, W. E. Gnibga, A. Chien, A. Blavette, A.-C. Orgerie, *ACM International Conference on Future and Sustainable Energy Systems*, 2024.]

Data transparency

Amazon strategised about keeping its datacentres' full water use secret, leaked document shows

*"Amazon defends its approach and has taken steps to manage how efficient its water use is, but it has faced criticism over **transparency**. Microsoft and Google regularly publish figures for their water consumption, but Amazon has never publicly disclosed how much water its server farms consume.*
*When designing a campaign for water efficiency, the company's cloud computing division **chose to account for only a smaller water usage figure that does not include all the ways its datacentres use water so as to minimise the risk to its reputation, according to a leaked memo** seen by SourceMaterialand the Guardian."*

[Luke Barratt and Rosa Furneaux, The Guardian, Oct. 25, 2025.]

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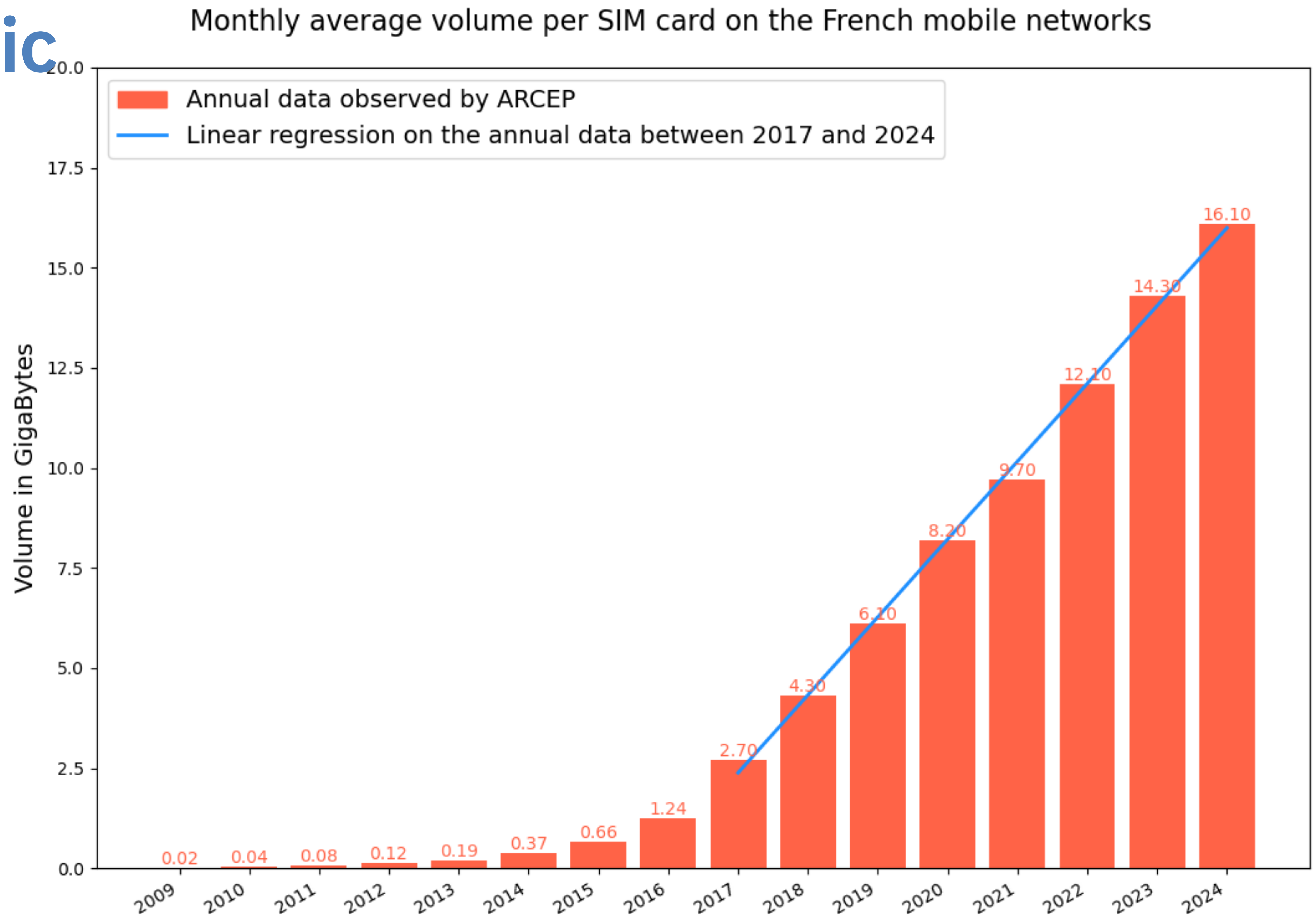
More and more traffic



In Q4 2014 :

- **71.7 million** SIM cards in France (prepaid and subscription, without MtoM)
- average monthly data consumption per SIM card: **0.46 GB/month**

In Q4 2024 :

- **83.8 million** SIM cards
- **16.6 GB/month** (**✕35 in**  **0 years per SIM card**)

[Source: "*Effets environnementaux de la 5G (partie 2) : Applications envisagées et acteurs impliqués*", Philippe Ciblat, Jacques Combaz, Marceau Coupechoux, Kevin Marquet, Anne-Cécile Orgerie, 1024 : Bulletin de la Société Informatique de France, 2024.]

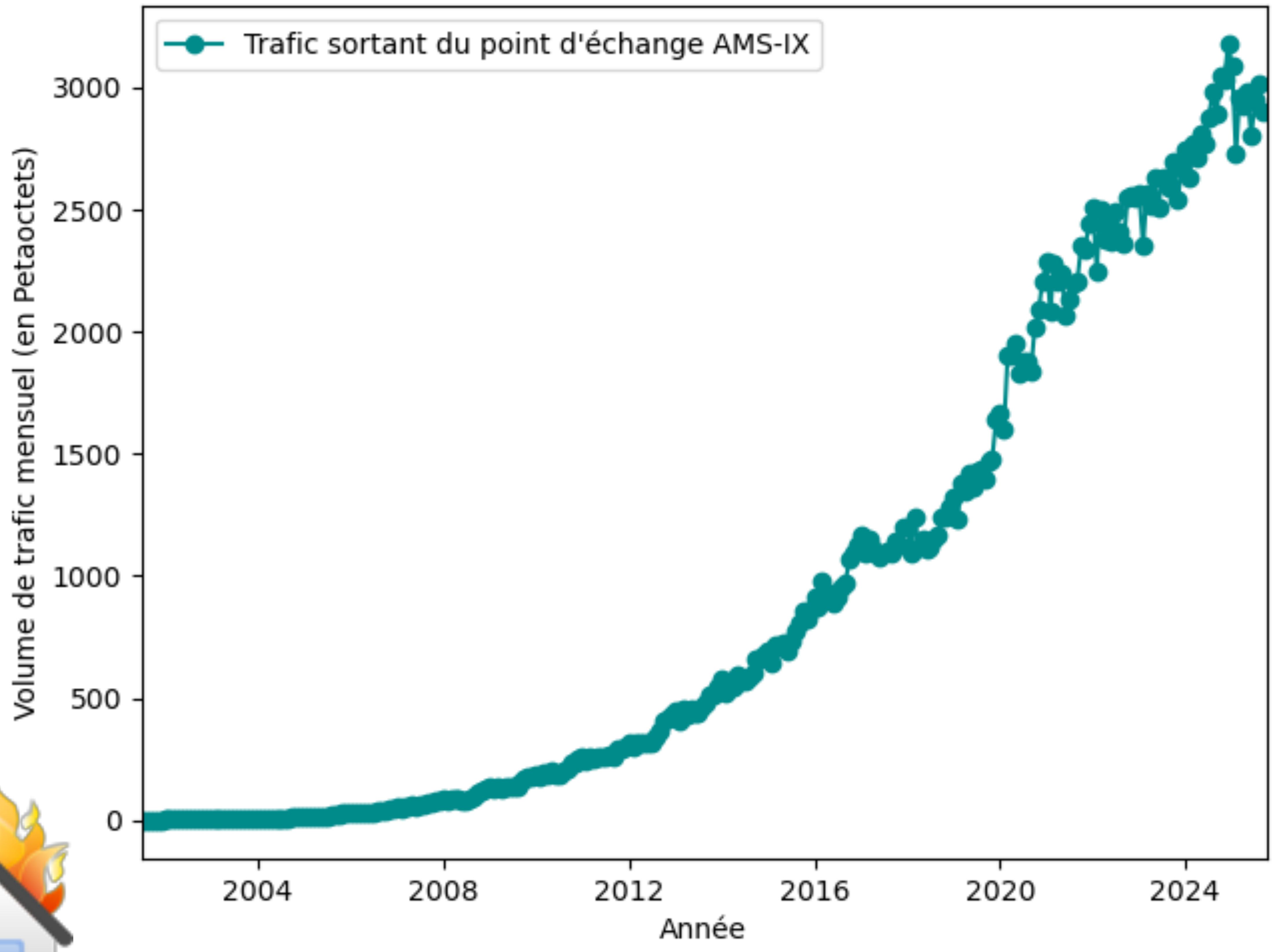
Wired networks

- July 2001: 0.69 Po

- Oct. 2001: 1.06 Po
- Nov. 2004: 10.64 Po
- Oct. 2008: 109.95 Po
- Oct. 2016: 1,070 Po

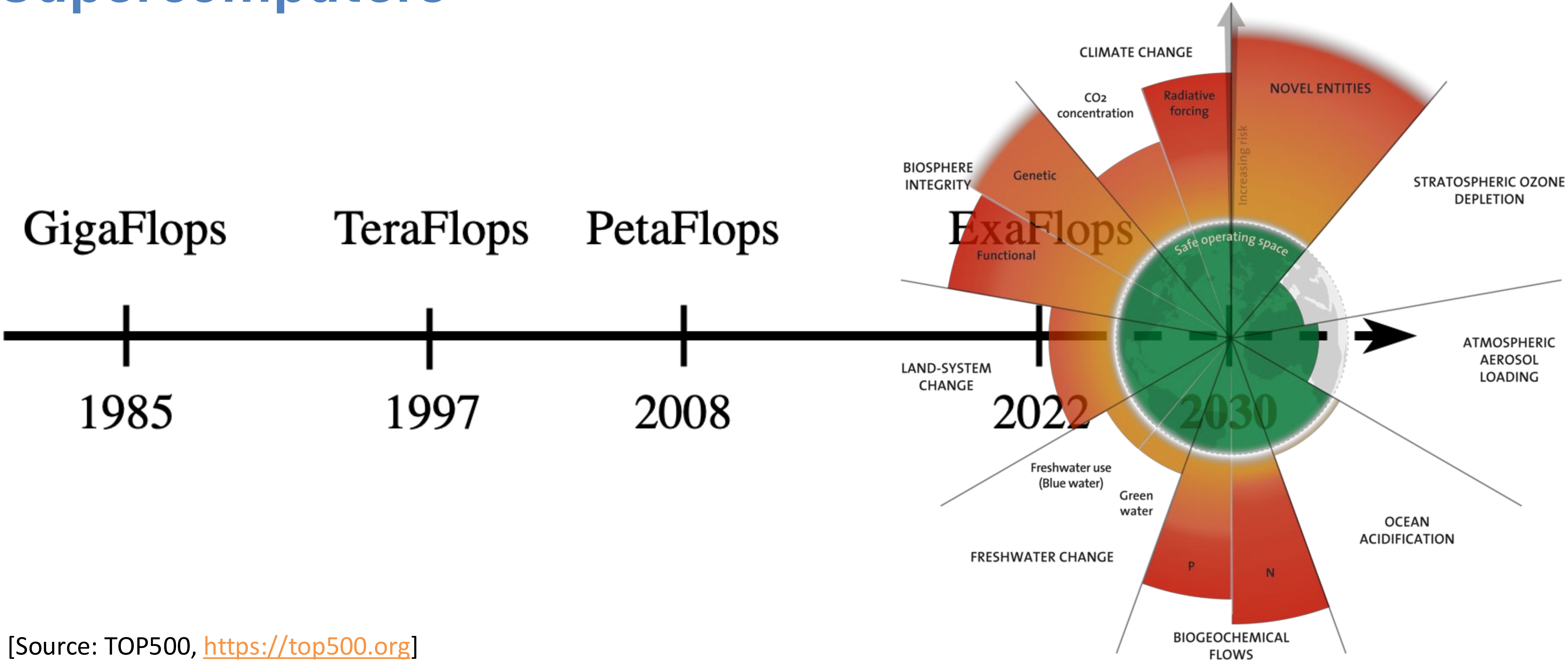
- Dec. 2024: 3,180 Po
- Sept. 2025: 2,900 Po

→ **4 orders of magnitude more in a bit more than 20 years**



[Source : https://www.ams-ix.net/ams]

Supercomputers



[Source: TOP500, https://top500.org]

[Source : Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023.]

https://people.irisa.fr/Anne-Cecile.Orgerie/

cnrs

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EcoInfo