# Numérique et IA dans l’Anthropocène

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Former, enseigner et apprendre dans le monde des IA

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EPISEN École Publique d'Ingénieurs de la Santé Et du Numérique

lacl

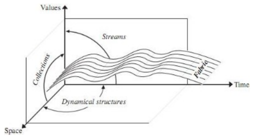
SLOW TECH Low Tech lab numérique de l'UPEC

EcoInfo POUR UNE INFORMATIQUE ÉCO-RESPONSABLE

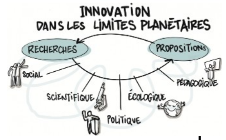
# 0 Prolegomena

**Where I'm speaking from (my knowledges are *situated* - [D. Haraway - 1988] ) :**

- **Position: research professor in computer science**
- **Research activities:**
  - `92-2014: design of declarative languages for DS`




  - `2014-   : digital technology and the Anthropocene`
- **Member of** Labos 1point5, EcoInfo (pour une informatique éco-responsable), GdR GPL (GdR Génie de la Programmation et du Logiciel)
- **Projects**




Slow Tech – Low Tech lab numérique de l'UPEC

# Word of clarification

## Disclaimer

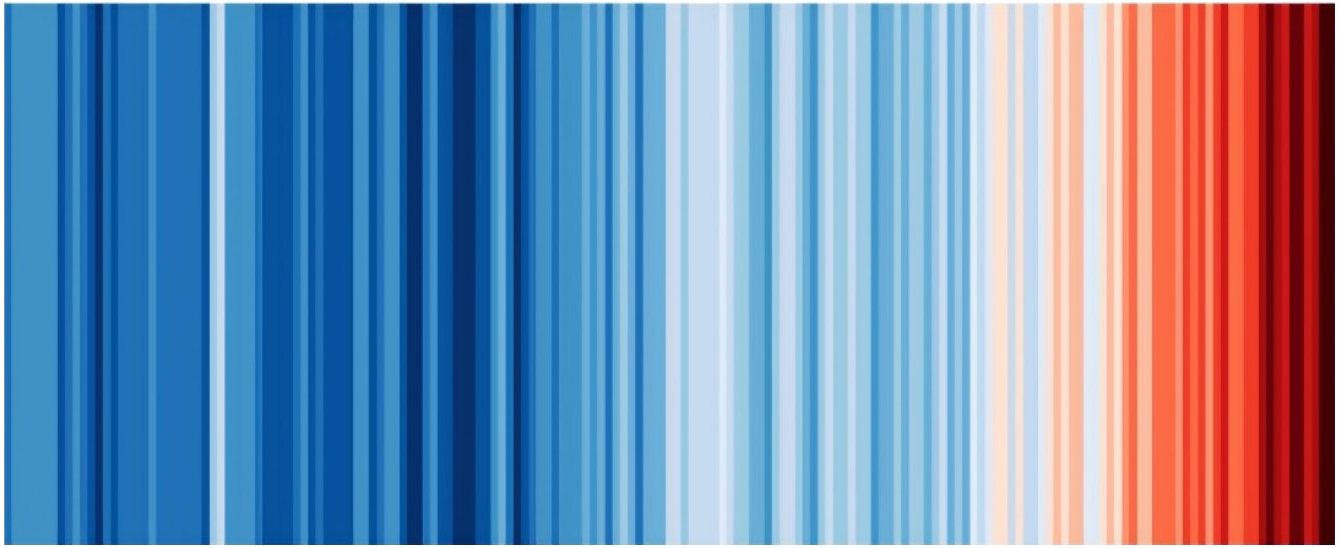
- A *broad* and *multidisciplinary subject* that draws on various academic fields
- Science in the making: unstabilized knowledge
- High degree of uncertainty at the root of controversies
- Collision between the long term (of research) and the short term (of news)

(*) the picture on the first slide is from [Source - 2018] that is pre Nov. 2022

# Outline of the talk

1. Current situation
2. Information and communication
   - Definition
   - ICT and GHG impact
   - Life cyce analysis (LCA) and Direct Effects
   - Second Order Indirect Effects
3. Mainstream (generative) AI
4. Conclusion

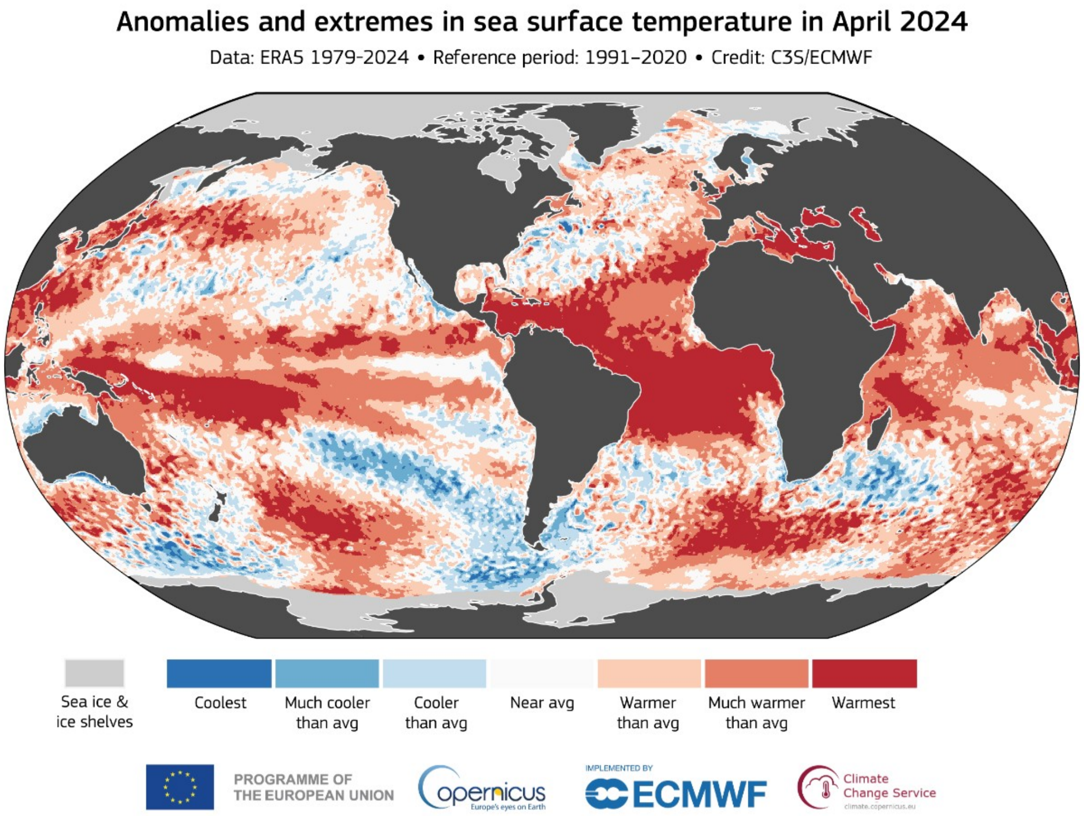
# 1 Current situation



[U. of Liverpool - Warming oceans and atmosphere visualized in new climate stripes study - 05/2025]

# A serious situation

- **Climate change widespread, rapid and intensifying (IPCC)**
  - Extreme temperatures
  - Drought conditions
  - Heatwaves
  - Fires
  - Flooding
  - Glacier melting
  - Permafrost melting
  - …
- **Relative to 1850/1900**
  - +1,15 °C (world)
  - +1,7 °C (France)




***[…] April 2024 is the eleventh consecutive month being the warmest for the respective month of the year. […]***

[Copernicus - 2024 - 11th consecutive warmets month globally]

# 2023-2025: first three-year average above 1.5°C

| Region | Anomaly (vs 1991-2020) | Actual temperature | Rank | Three highest anomalies |
|---|---|---|---|---|
| *Surface air temperature* | | | | |
| Globe | +0.59°C (+1.47°C vs pre-industrial) | 14.97°C | 3rd highest | 2024: +0.72°C<br>2023: +0.60°C<br>**2025**: +0.59°C |
| Global land | +0.86°C | 10.08°C | 2nd highest | 2024: +1.06°C<br>**2025**: +0.86°C<br>2023: +0.85°C |
| Europe | +1.17°C | 10.41°C | 3rd highest | 2024: +1.47°C<br>2020: +1.19°C<br>**2025**: +1.17°C |

**Key temperature statistics for 2025**

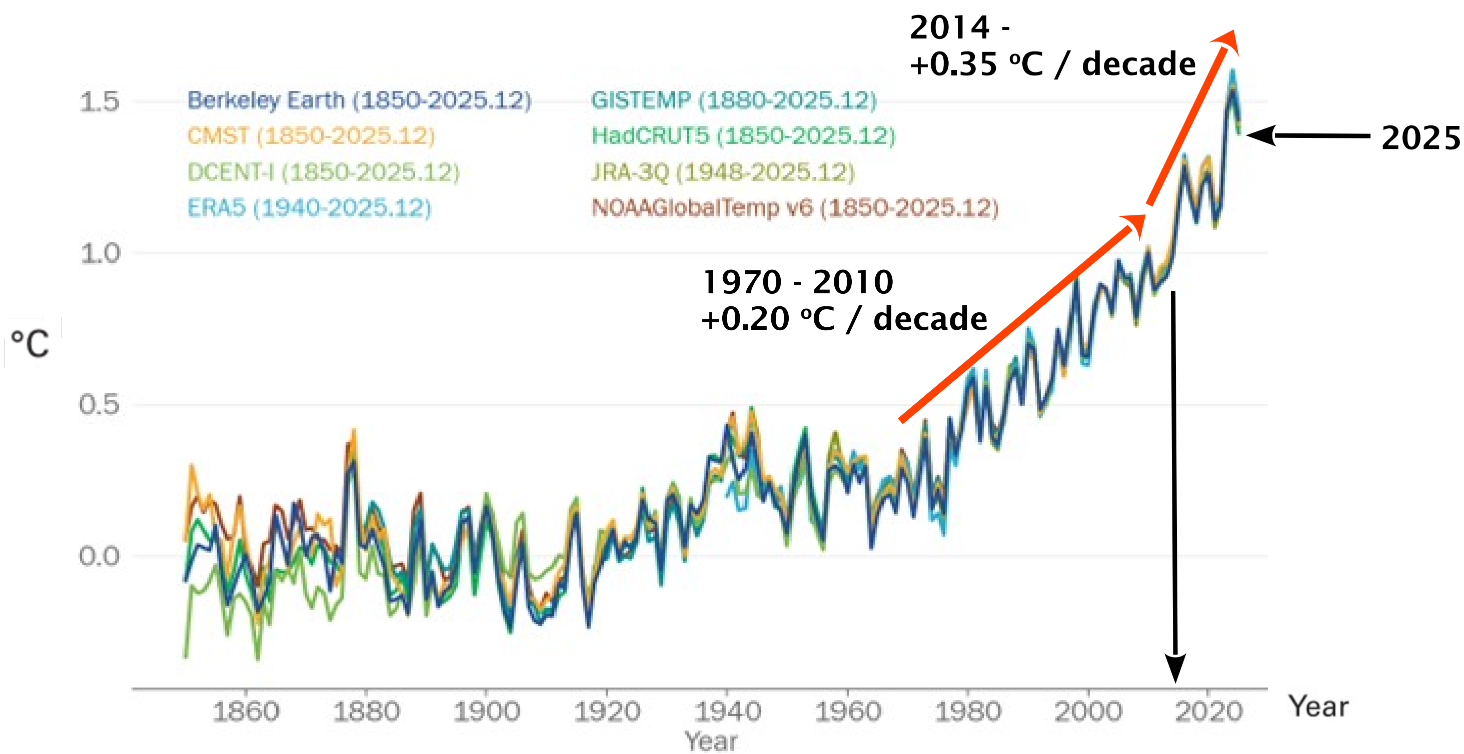
- **Past 11 years** have been **11 warmest on record**
- **January 2025** (+0,79ºC – reference 1991-2020) is the **warmest January ever recorded**
- **March, April and May were each the second warmest** for the time of year
- **Each month of the year, except Feb and Dec, was warmer than the corresponding month in any year before 2023**
- In 2025, annual surface air temperatures were above the 1991–2020 average across 91% of the globe, the same fraction as in 2024.
- 48% of the globe experienced much warmer than average annual temperatures
- Annual temperatures were the warmest over 9% of the Earth's surface relative to all years since 1979

[2026 - Global Climate for 2025 - COPERNICUS]

# Acceleration in temperature rise

Inspired by [J. Rockström - 2024 - The Tipping Points of Climate Change — and Where We Stand]

- Reference: pre-industrial period (1850-1900)
- Acceleration of warming since 2014
- At this rate, it will be +2 °C in 20 years and +3 °C by 2100




[G. Foster and S. Rahmstorf - GRL - 03/2026]
[2026 - WMO confirms 2025 was one of the warmest years on record - WMO]
[2024 - State of the Global Climate - UN]

# An acceleration that started in the 50's

Inspired by [J. Rockström - 2024 - The Tipping Points of Climate Change — and Where We Stand]

- All socioeconomic indicators show similar growth
- Turning point in 1950

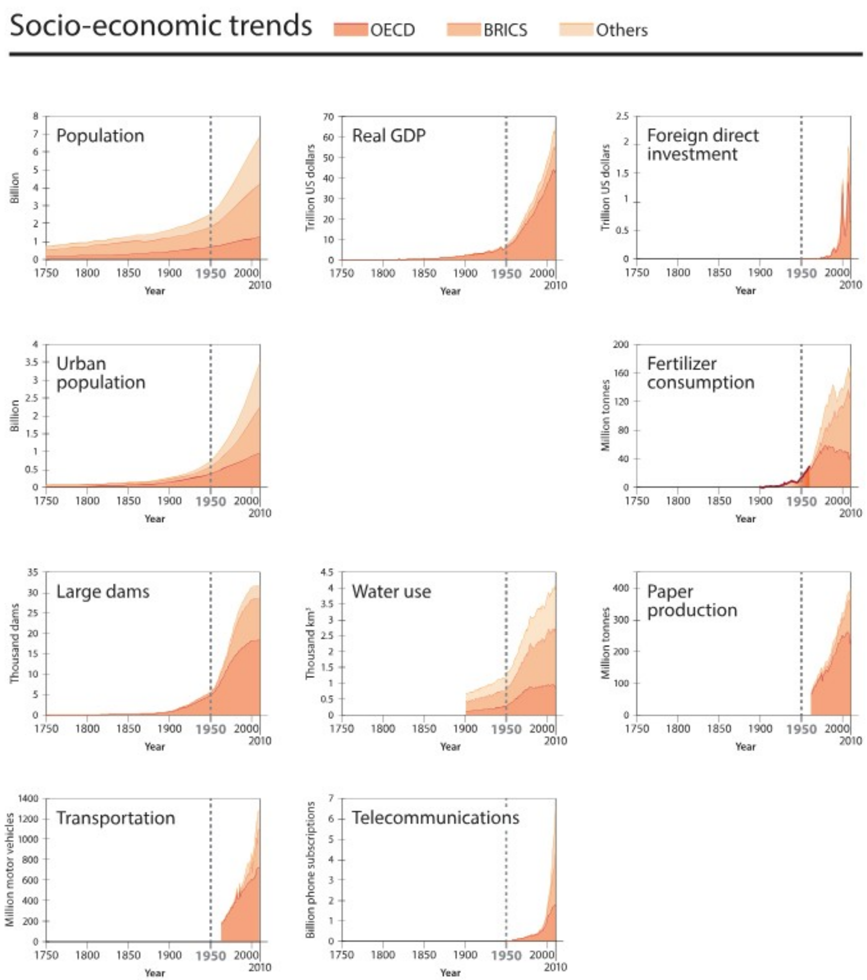



Figure 2. **Trends from 1750 to 2010** for ten of the socio-economic graphs (excluding primary energy use and international tourism) with three splits for: the **OECD countries**, the so-called **BRICS** (Brazil, Russia, India, China (including Macau, Hong Kong and Taiwan where applicable), and South Africa) countries, and **the rest of the world**

[Stephen et al. - The Anthropocene Review - 2018]

Inspired by [J. Rockström - 2024 - The Tipping Points of Climate Change — and Where We Stand]

## ❑ Similar situation for many Earth system indicators

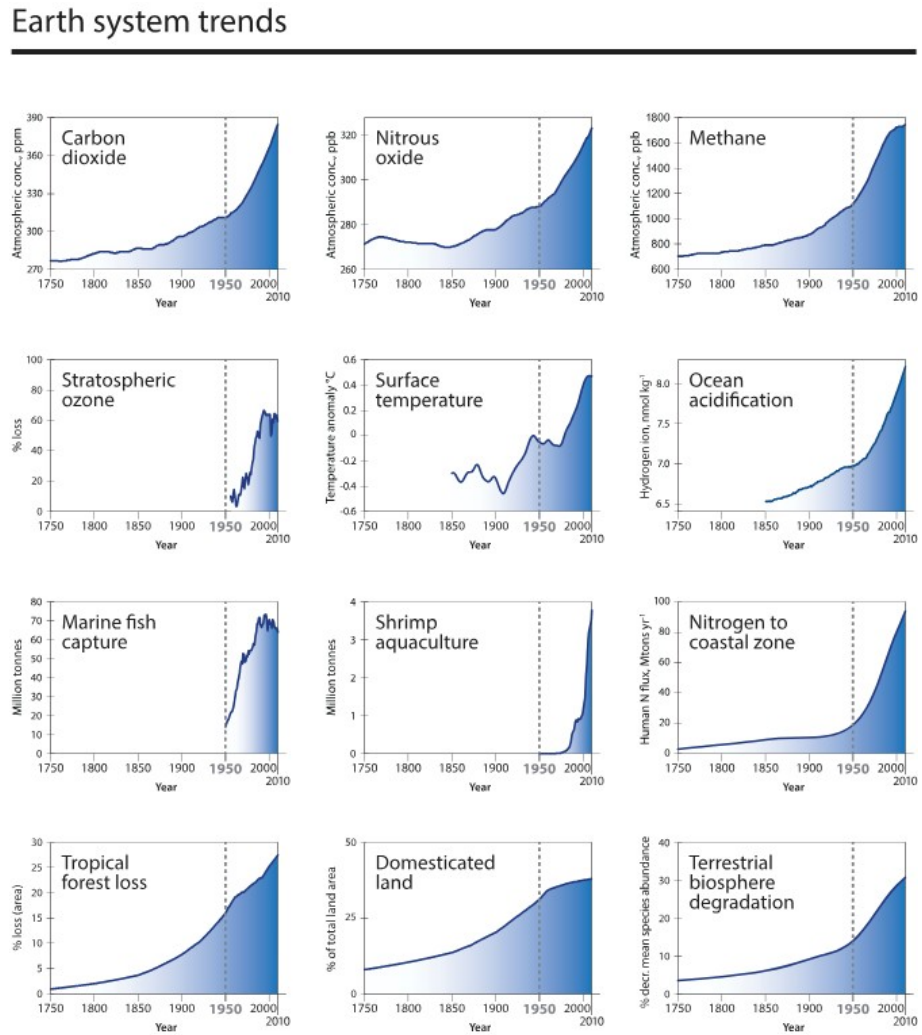


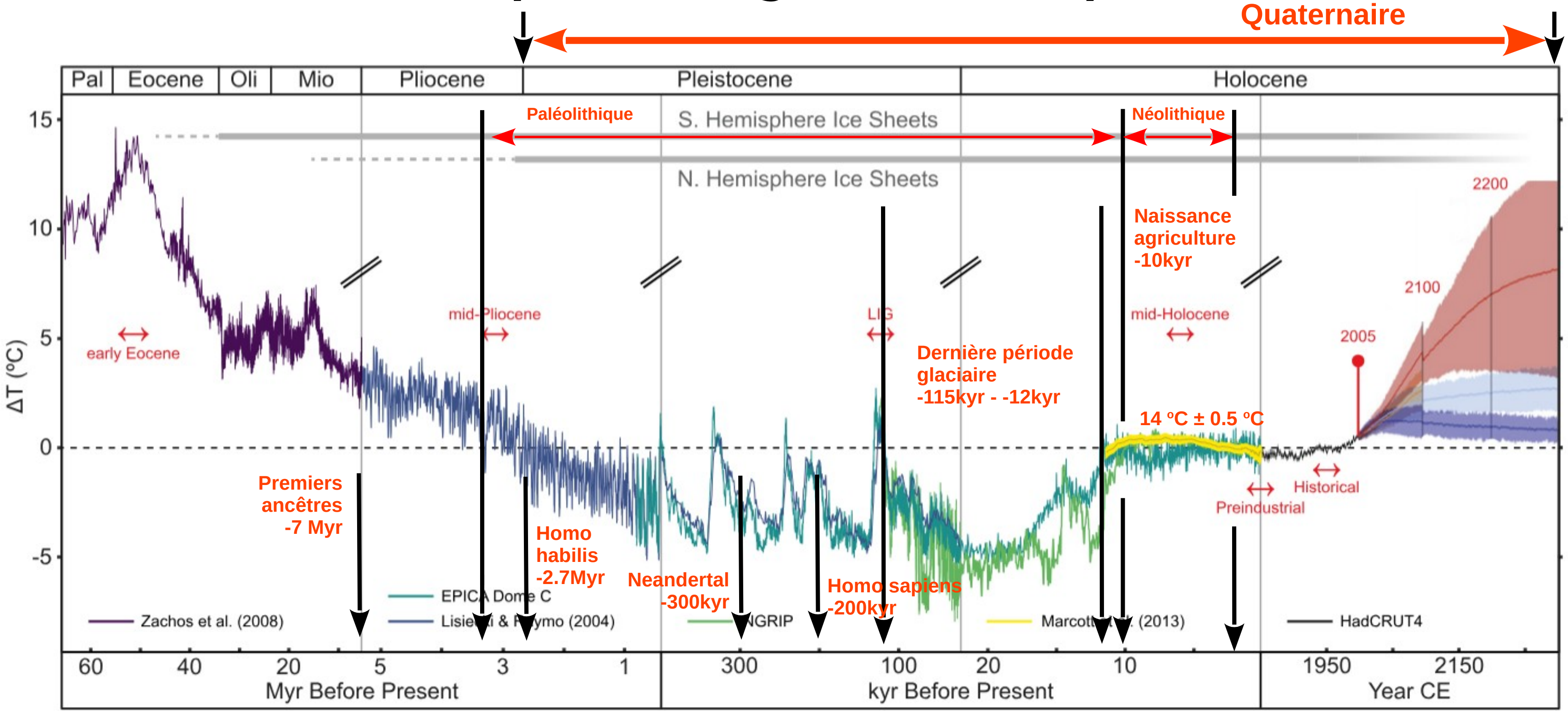

Figure 3. Trends from 1750 to 2010 in indicators for the structure and functioning of the Earth System. (1) **Carbon dioxide** from firn and ice core records (Law Dome, Antarctica) and Cape Grim, Australia (deseasonalised flask and instrumental records); spline fit. (2) **Nitrous oxide** from firn and ice core records (Law Dome, Antarctica) and Cape Grim, Australia (deseasonalised flask and instrumental records); spline fit. (3) **Methane** from firn and ice core records (Law Dome, Antarctica) and Cape Grim, Australia (deseasonalised flask and instrumental records); spline fit. (4) Maximum percentage total column **ozone** decline (2-year moving average) over Halley, Antarctica during October, using 305 DU, the average October total column ozone for the first decade of measurements, as a baseline. (5) **Global surface temperature anomaly** (HadCRUT4: combined land and ocean observations, relative to 1961–1990, 20 yr Gaussian smoothed). (6) **Ocean acidification** expressed as global mean surface ocean hydrogen ion concentration from a suite of models (CMIP5) based on observations of atmospheric CO2 until 2005 and thereafter RCP8.5. (7) **Global marine fishes capture production** (the sum of coastal, demersal and pelagic marine fish species only), i.e. it does not include mammals, molluscs, crustaceans, plants, etc. There are no FAO data available prior to 1950. (8) **Global aquaculture shrimp production** (the sum of 25 cultured shrimp species) as a proxy for coastal zone modification. (9) **Model-calculated human-induced perturbation flux of nitrogen** into the coastal margin (riverine flux, sewage and atmospheric deposition). (10) **Loss of tropical forests** (tropical evergreen forest and tropical deciduous forest, which also includes the area under woody parts of savannas and woodlands) compared with 1700. (11) **Increase in agricultural land area**, including cropland and pasture as a percentage of total land area. (12) **Percentage decrease in terrestrial mean species abundance** relative to abundance in undisturbed ecosystems as an approximation for degradation of the terrestrial biosphere.

[Stephen et al. - The Anthropocene Review - 2018]

# On a human scale

Inspired by [J. Rockström - 2024 - The Tipping Points of Climate Change — and Where We Stand]

## ❑ The Holocene: a period of great stability



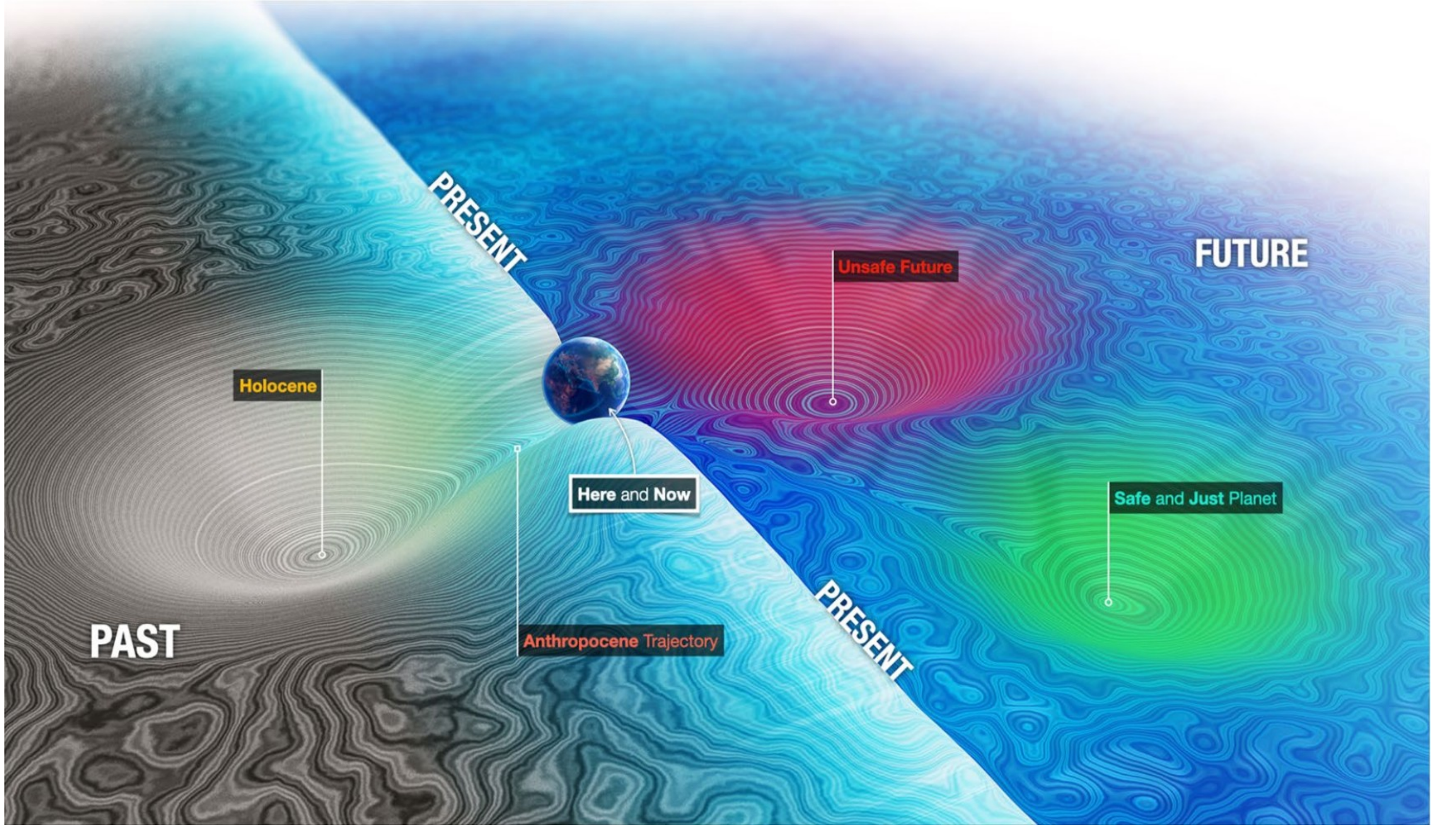

[Burke et al. 2018 - PNAS]

**Fig. 1.** Temperature trends for the past 65 Ma and potential geohistorical analogs for future climates. Six geohistorical states (red arrows) of the climate system are analyzed as potential analogs for future climates. For context, they are situated next to a multi-timescale time series of global mean annual temperatures for the last 65 Ma. Major patterns include a long-term cooling trend, periodic fluctuations driven by changes in the Earth's orbit at periods of 104–105 y, and recent and projected warming trends. Temperature anomalies are relative to 1961–1990 global means and are composited from five proxy-based reconstructions, modern observations, and future temperature projections for four emissions pathways (Materials and Methods). Pal, Paleocene; Mio, Miocene; Oli, Oligocene.

# A system at risk of losing its resilience?

Inspired by [J. Rockström - 2024 - The Tipping Points of Climate Change — and Where We Stand]

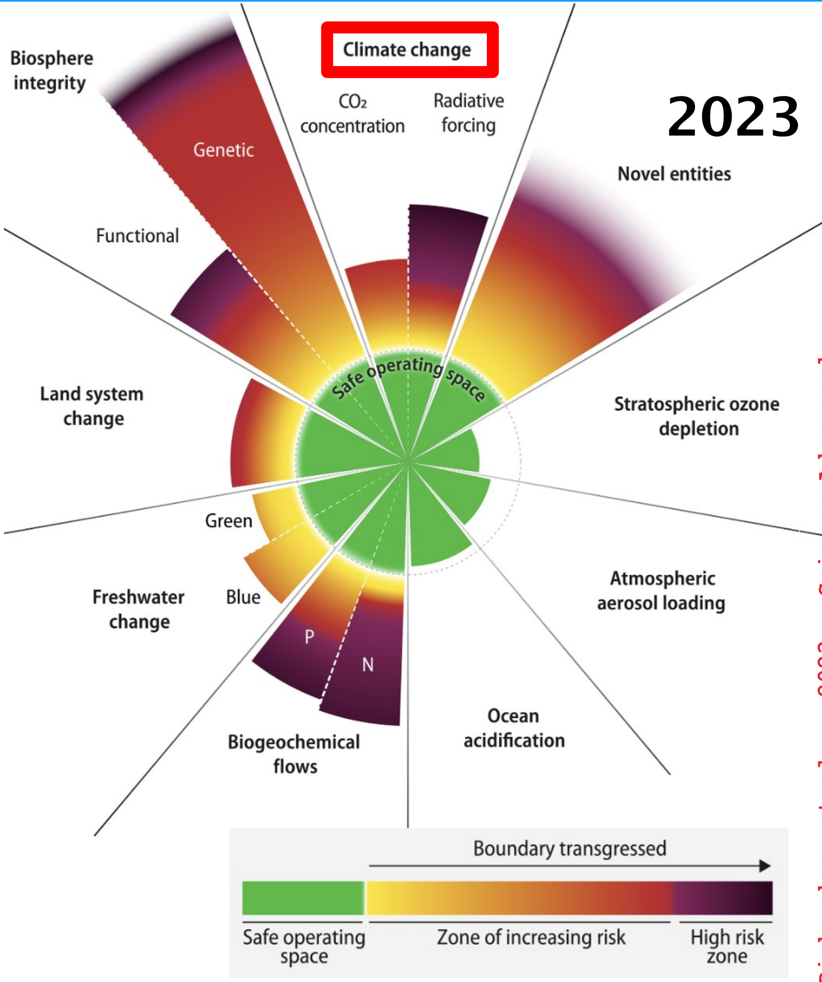
- ❑ **"Are we pushing the system out of its Holocene attraction basin?"** [J. Rockström - 2024]




[J. Rockström et al. - 2024 - The Tipping Points of Climate Change — and Where We Stand]

# Planetary boundaries to keep the planet in a safe zone

- **Planetary boundaries**
  - "The **planetary boundaries** framework delineates the **biophysical and biochemical systems** and **processes** known to **regulate the state of the planet within ranges** that are historically known and scientifically likely to **maintain Earth system stability and life-support systems conducive to the human welfare** and societal development experienced during the Holocene."
- **Regulation during > 3B years**
  - **Interactions between the geosphere and biosphere have controlled environmental conditions**
  - **Holocene state of earth (last 11 000 years) have been rather stable**

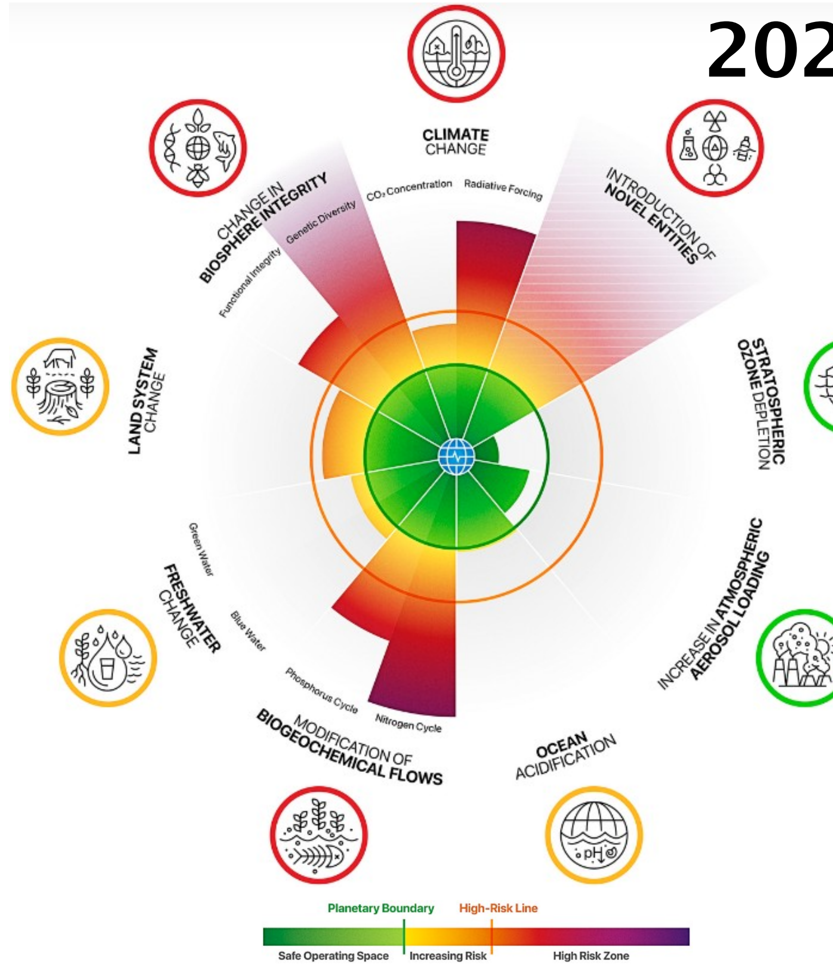



[K. Richardson et al. - 2023 - Science Advances]

# Planetary boundaries to keep the planet in a safe zone

- …7 have already been crossed
  1. Climate change

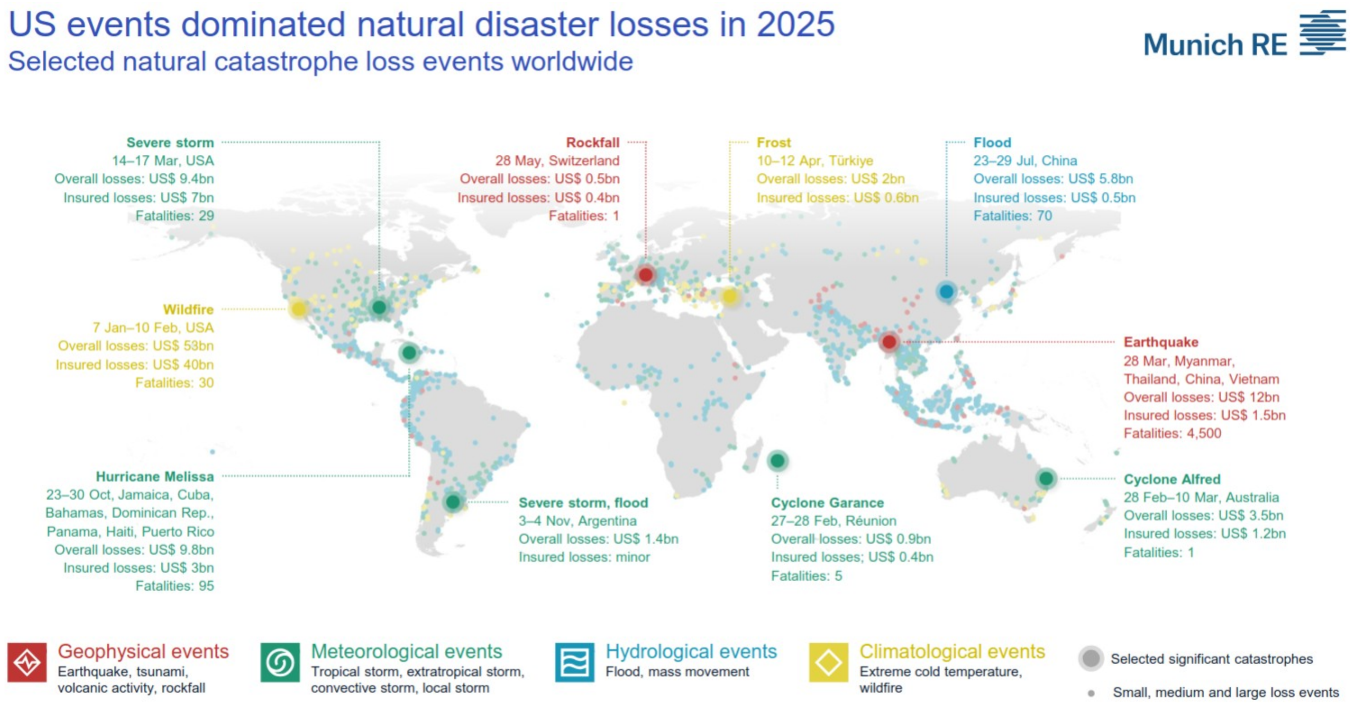
- But also
  2. Novel entities
  3. Stratospheric ozone depletion
  4. Atmospheric aerosol loading
  5. Ocean acidification (2025/09)
  6. Biochemical flows (N/P)
  7. Freswater change
  8. Land-system change
  9. Biosphere integrity




[2025 - Seven of nine planetary boundaries now breached - ocean acidification joins the danger zone]

[B. Sakschewski et al - 2025 - Planetary Health Check]

# The cost of climate disasters in 2025

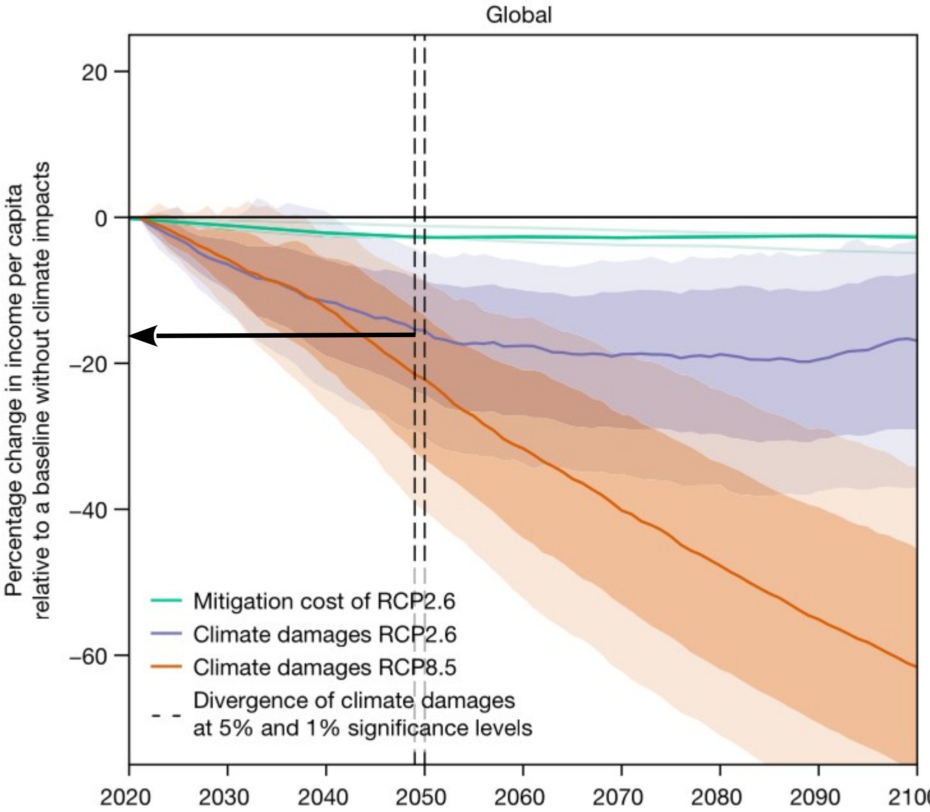



[T. Blunck - Devastating wildfires and intense thunderstorms exacerbate losses for insurers - 2026]

- According to reinsurer Munich RE
  - $224B cost for the damages
  - Costliest claims year to date regarding non-peak perils: **Wildfires, flooding and severe thunderstorms account for almost all insured losses**
  - Insured losses once again above the US$ 100bn mark; total global losses lower than the 10-year average
  - Hurricane Melissa devastates Jamaica; **USA dodges direct hurricane hit for first time in ten years**
  - **Fatalities totalling 17,200 significantly higher than in 2024**, but below long-term average
  - **Climate change does not let up: 2025 one of the warmest years ever**

# The cost of mitigating the effects

- **The projected cost of damage is estimated to be six times greater than the cost of mitigation (to meet the Paris Agreement targets)**
- **6 x 6 trillions US$/year in 2050**
- **18% drop in GDP by 2050**




[Kotz et al. - Nature - 2024]

- Fig. 1 | **The commitment and divergence of economic climate damages versus mitigation costs.** Estimates of the projected reduction in income per capita from changes in all climate variables based on empirical models of climate impacts on economic output with a robust lower bound on their persistence [...] under a low-emission scenario compatible with the **2 °C warming target** and a **high-emission scenario** (**SSP2**-RCP**2.6** and **SSP5**-RCP**8.5**, respectively) are shown in purple and orange, respectively. Shading represents the 34% and 10% confidence intervals reflecting the likely and very likely ranges, respectively (following the likelihood classification adopted by the IPCC), [...]

# Remaining stock of $CO_2$

## ❑ IPCC modelization (AR6 – 2021 – p20/21)

**B.5.2** For every 1000 $GtCO_2$ emitted by human activity, global surface temperature rises by 0.45°C (best estimate, with a *likely* range from 0.27 to 0.63°C). The best estimates of the remaining carbon budgetsfrom the

[39] Net zero GHG emissions defined by the 100-year global warming potential. See footnote 9.

**Subject to Copyedit** p.20

are 500 $GtCO_2$

Approved Summary for Policymakers IPCC AR6 SYR

beginning of 2020 are 500 $GtCO_2$ for a 50% likelihood of limiting global warming to 1.5°C and 1150 $GtCO_2$ for a 67% likelihood of limiting warming to 2°C[40]. The stronger the reductions in non-$CO_2$ emissions the lower the resulting temperatures are for a given remaining carbon budget or the larger remaining carbon budget for the same level of temperature change[41]. {3.3.1}

**In 2021…**

[IPCC – 2023 – 6th Assesment Report]

# Remaining stock of $CO_2$

- To avoid tipping: only use the available CO2 stock!
- IPCC modelization(2021)

B.5.2 For every 1000 $GtCO_2$ emitted by human activity, global surface temperature rises by 0.45°C (best estimate, with a *likely* range from 0.27 to 0.63°C). The best estimates of the remaining carbon budgetsfrom the

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**Subject to Copyedit** p.20

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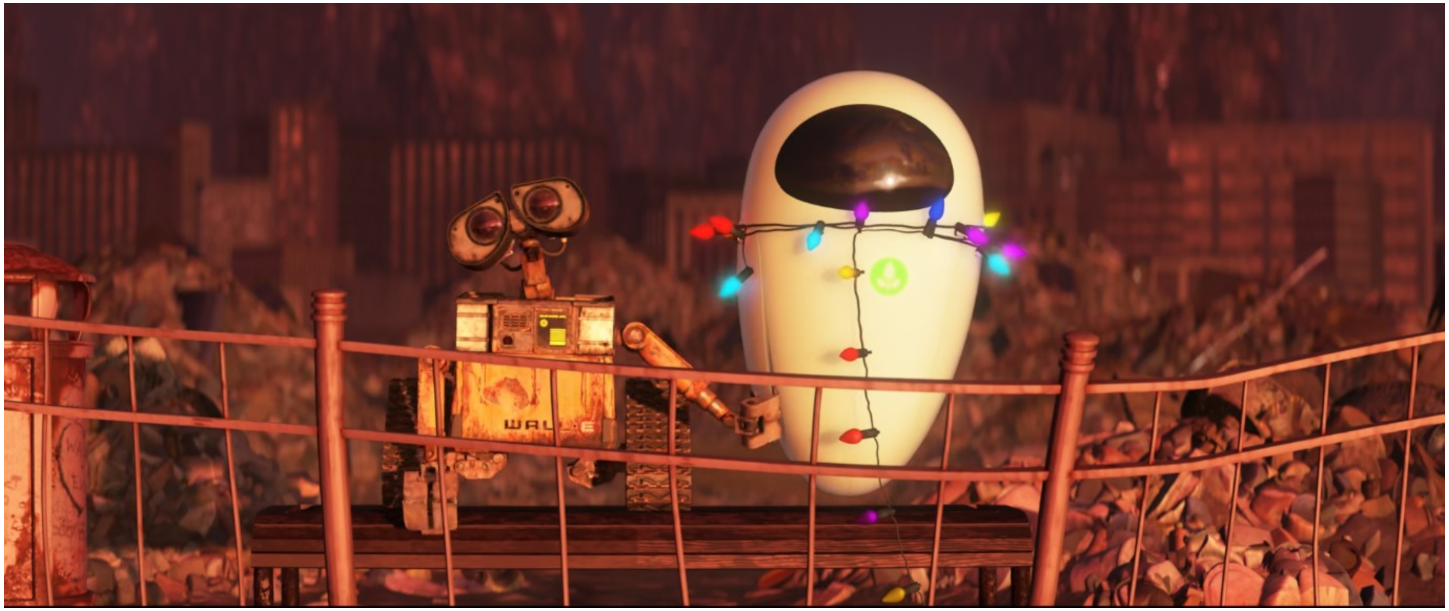
- $CO_2$ remaining stocks (in 2025) to comply with the Paris Agreement (SSP1-1.9) - +1,5 °C with a 50 % likelyhood
  - 2025: 130 Gt (exhausted in 3 years if $CO_2$ emissions stay at 2024 level)
  - 2024: 200 Gt
  - 2023: 275 Gt (+1,7 °C: 625 Gt, +2 °C: 1 050 Gt)

[P. Foster et al - 2024]

# 2 ICT




[A. Stanton - Wall·E - 2008]

# 2.1 Definition

**« Mal nommer un objet, c'est ajouter au malheur de ce monde »**

**"To misname things is to contribute to the world's miseries"**

[A. Camus - 1944]

# ICT: wherever there is silicon, computations?


**George Kedenburg III** @GK3

i just had to download a software update for my shoes which are now getting a charge on their USB-C wireless charging mat

we're living in the future!!! 🤯

Traduire le post

7:19 PM · 17 févr. 2019 depuis San Francisco, CA

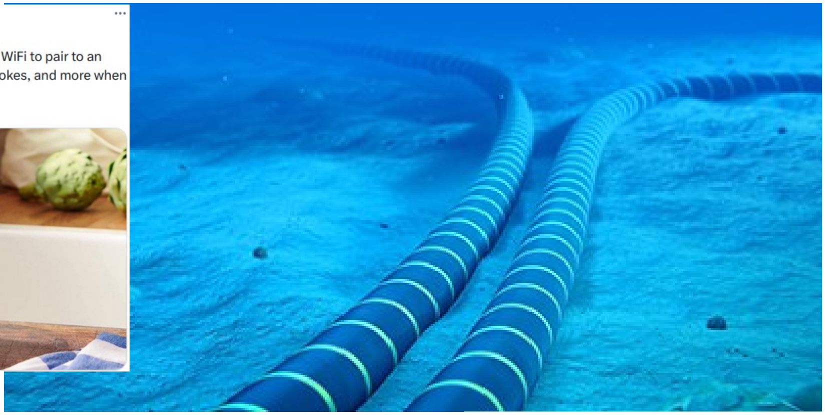
[Twitter - 2019]

**Tom Warren** @tomwarren

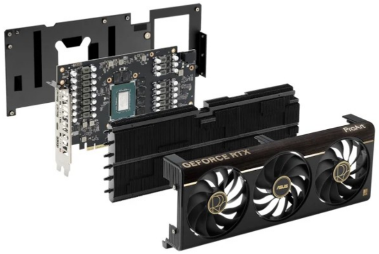
Amazon has created a $55 soap dispenser that has WiFi to pair to an Alexa speaker. Why? To "automatically play songs, jokes, and more when you wash" 😂 theverge.com/2021/8/3/22607...

Traduire le post

[Twitter - 2021]

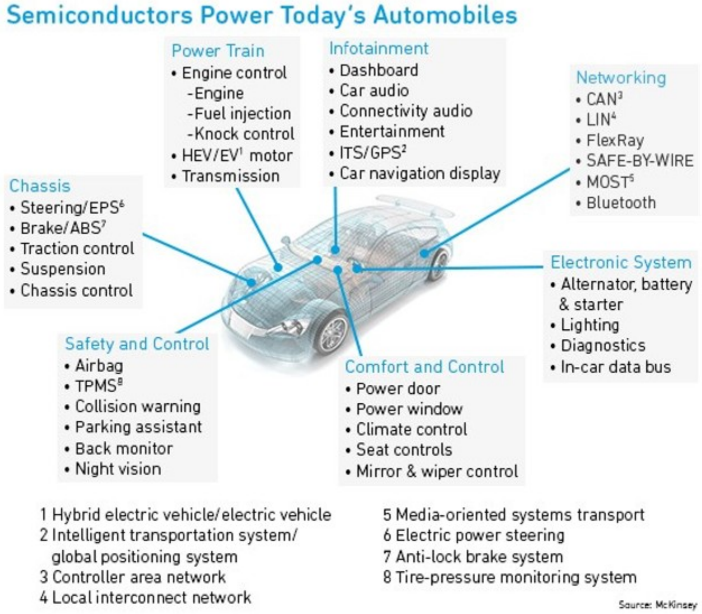


[Telecom Review - 2020]




[ASUS RTX 5080]

[Guardian - 2018]




[2021 - Semiconductor Engineering 2021]

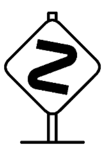
# ICT – definition issues

- **Technical definition (and not *sociotechnical*)**

  « An ecosystem that brings together all the devices used to manipulate information in electronic form »

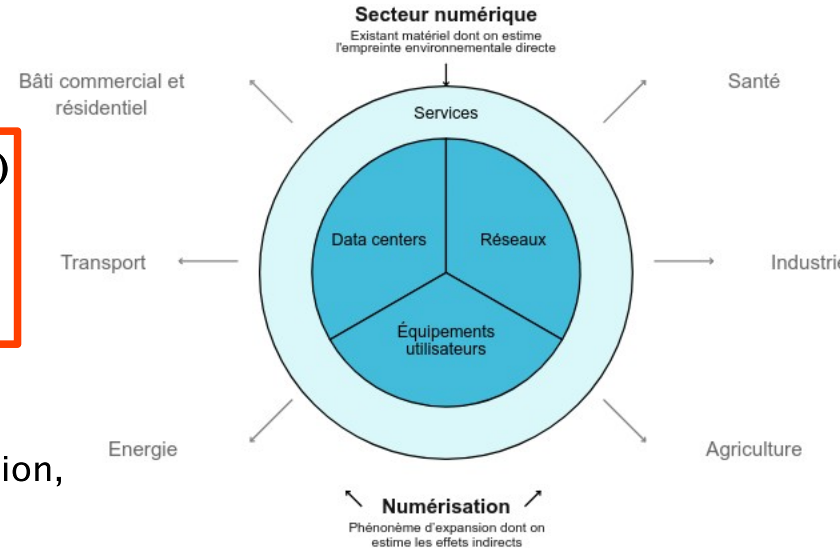
- **Two outlines according to [OECD]** [G. Roussilhe - 2022]

  - The digital object in 3-tiers



    1) ***Data Centers*** **– (data-storage and computing)**
    2) **User devices**
    3) **Networks**

  - A process: the digitalisation of activities
    - Business, agriculture, construction, transportation, industry, healthcare, education...
    - → the effects that come with all the changes brought by digital technology




[G. Roussilhe - 2022]

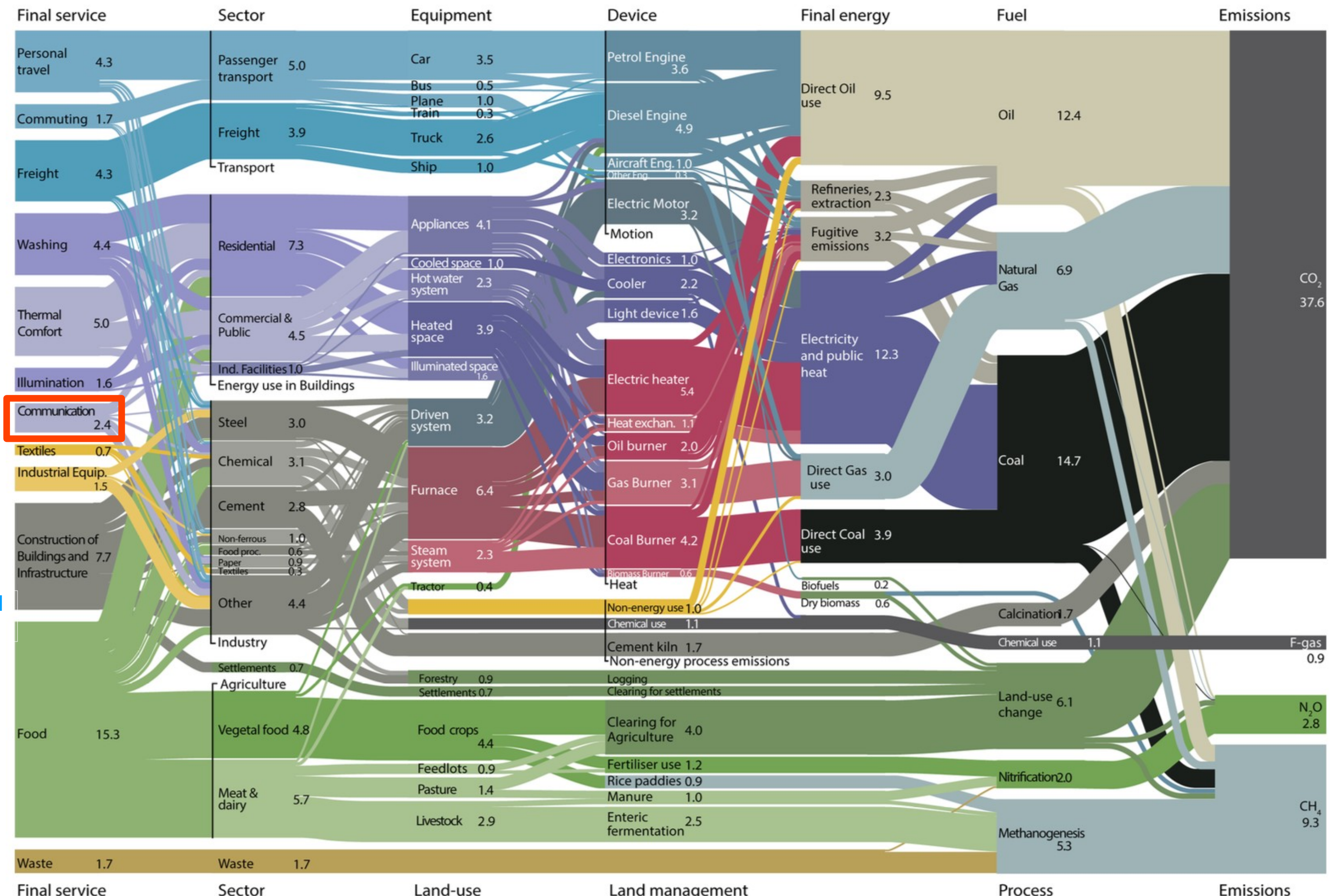
# 2.2 Trajectory

# Part of ICT in world GHG emissions

**Numérique**

**2 - 4% GHG**

[Freitag et al - 2021]

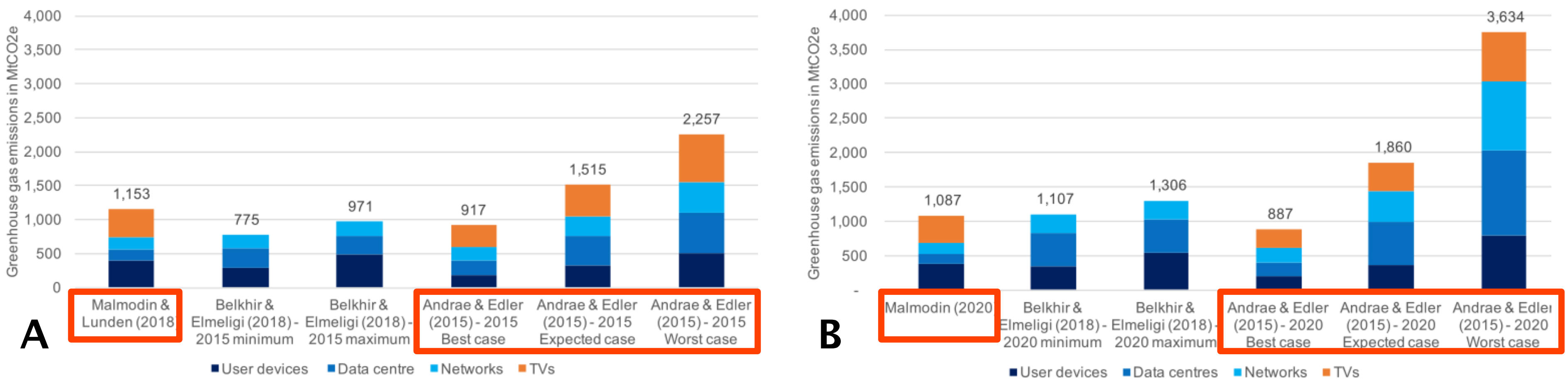



Total GHG emissions (2010): 50.6 Pg (Gt) $CO_2e$

[Bajželj et al - 2013]

UPEC | EPISEN | lacl | EcoInfo

# Part of ICT in world GHG emissions: distribution




[Freitag et al - 2021]

**Figure 2. Estimates for global ICT's carbon footprint in 2015 and 2020**

(A) Estimates for global ICT's carbon footprint in 2015. (B) Estimates for global ICT's carbon footprint in 2020. Note that for Malmodin and Lundén's[8,9] estimates, TV includes TV networks and other consumer electronics, whereas for Andrae and Edler's[3] estimates, only TVs themselves and TV peripherals are included. Belkhir and Elmeligi[7] did not include TVs. Malmodin and Lundén's[8,9] original estimates for the ICT and entertainment and media sector includes paper media, which we have excluded here.

« [We estimate] the carbon footprint for ICT, including TVs and other consumer electronics, rises to 1.2–2.2 $GtCO_2e$ (2.1%–3.9% of global GHG emissions) in 2020 with ca. 30% coming from embodied emissions and 70% from use phase emissions. We stress once more that these are rough estimates with a significant degree of uncertainty. »

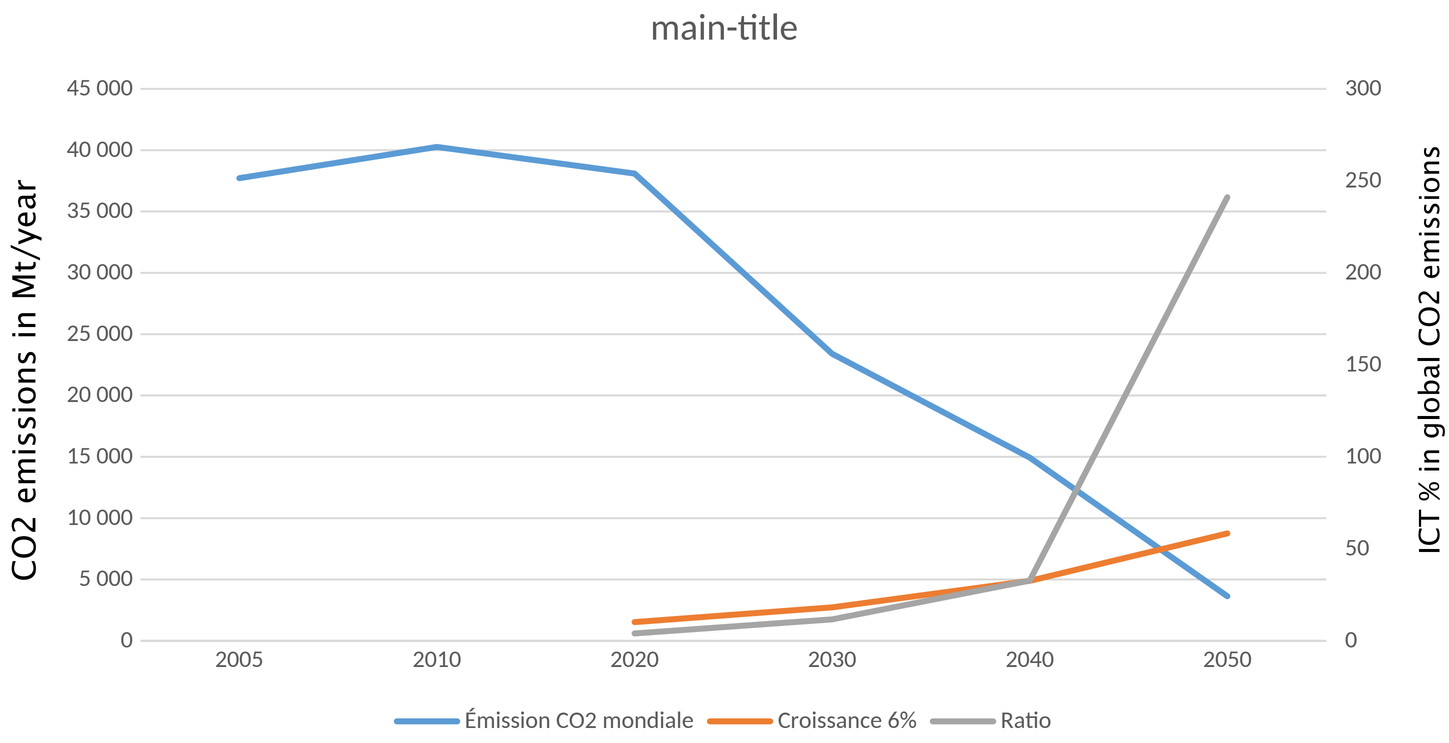
- Before 11/2022 and the release of mainstream AI with LLMs

UPEC EPISEN lacl EcoInfo

# ICT share of GHG emission

Analysis suggested by D. Trystram, Y. Malot & G. Raffin (UGA/France)

## ❑ SSP1-1.9 scenario and minimal ICT growth (6%)

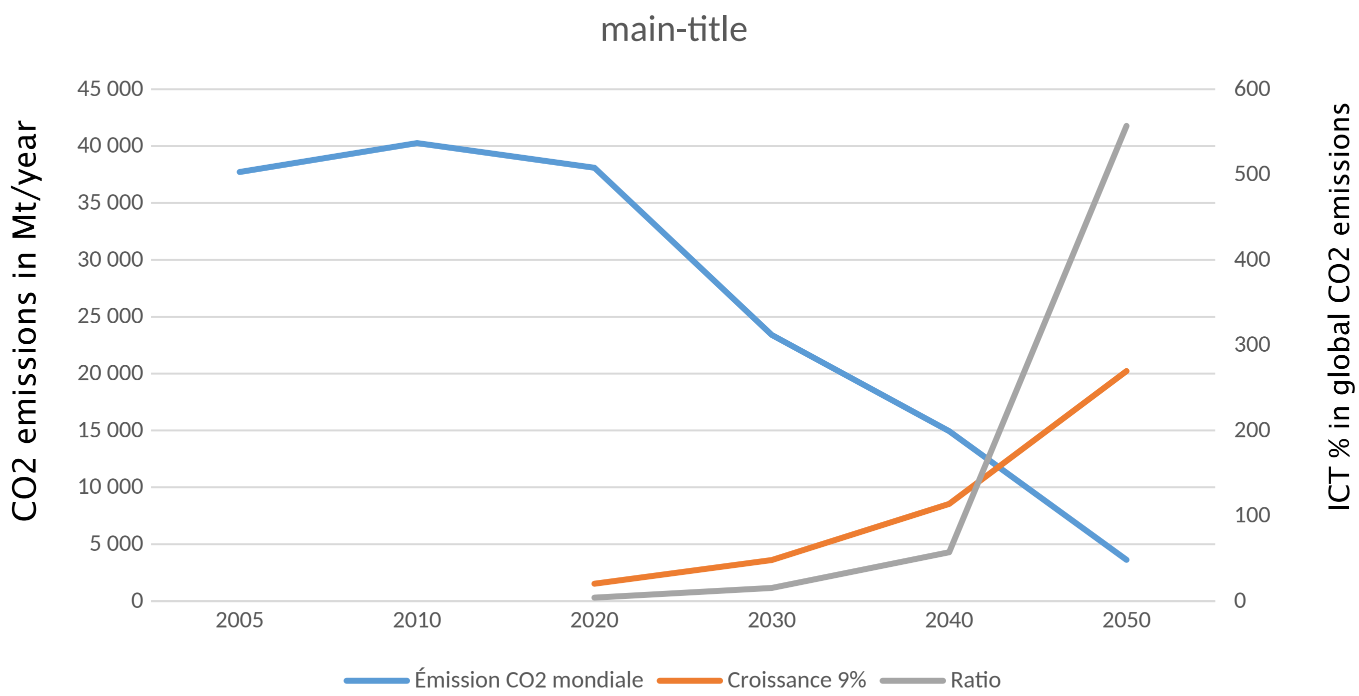



*Left ordinate are MT of CO2 emission per year. Right ordinate are percentages for the grey curve.*

# ICT share of GHG emission

Analysis suggested by D. Trystram, Y. Malot & G. Raffin (UGA/France)

## ❑ SSP1-1.9 scenario and higher limit ICT growth (9%)

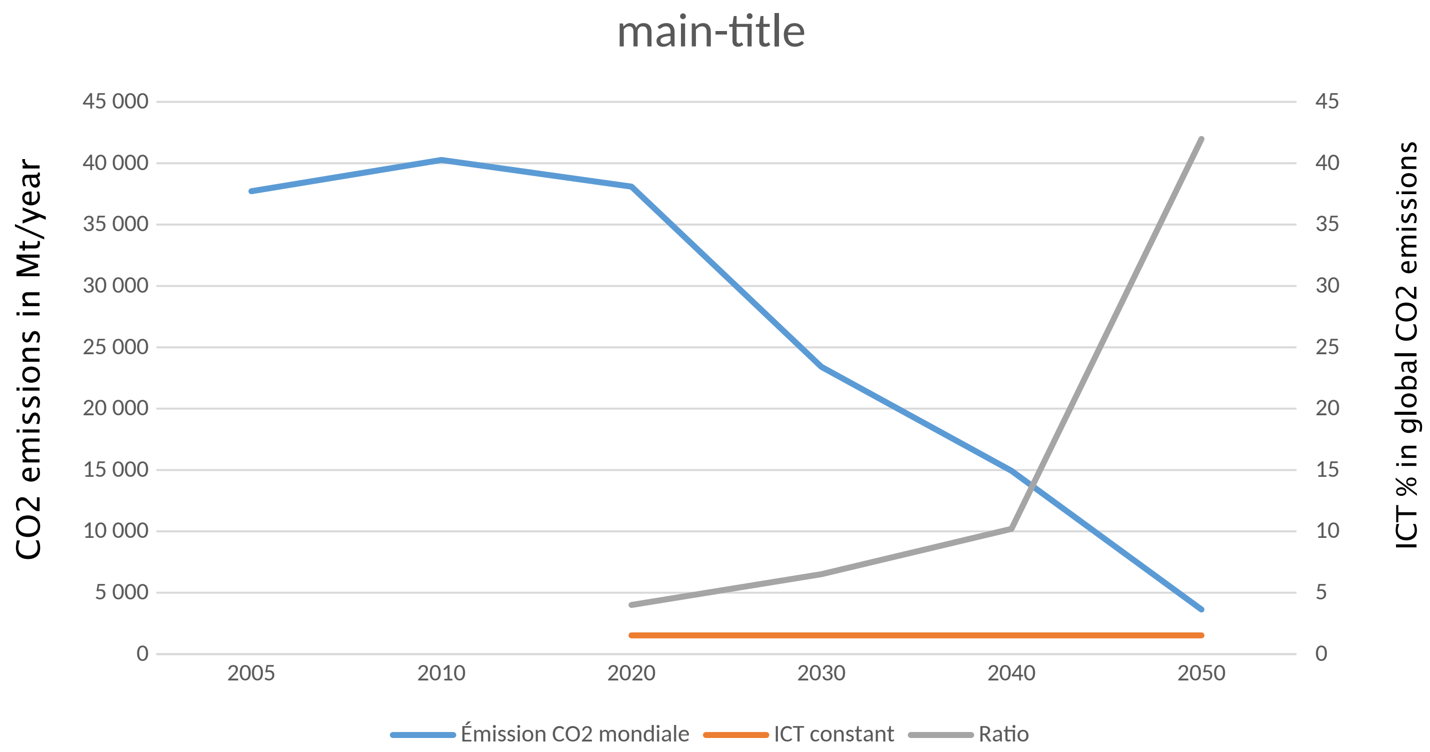



*Left ordinate are MT of CO2 emission per year. Right ordinate are percentages for the grey curve.*

# ICT share of GHG emission

Analysis suggested by D. Trystram, Y. Malot & G. Raffin (UGA/France)

## ❑ SSP1-1.9 scenario constant ICT share (6%)

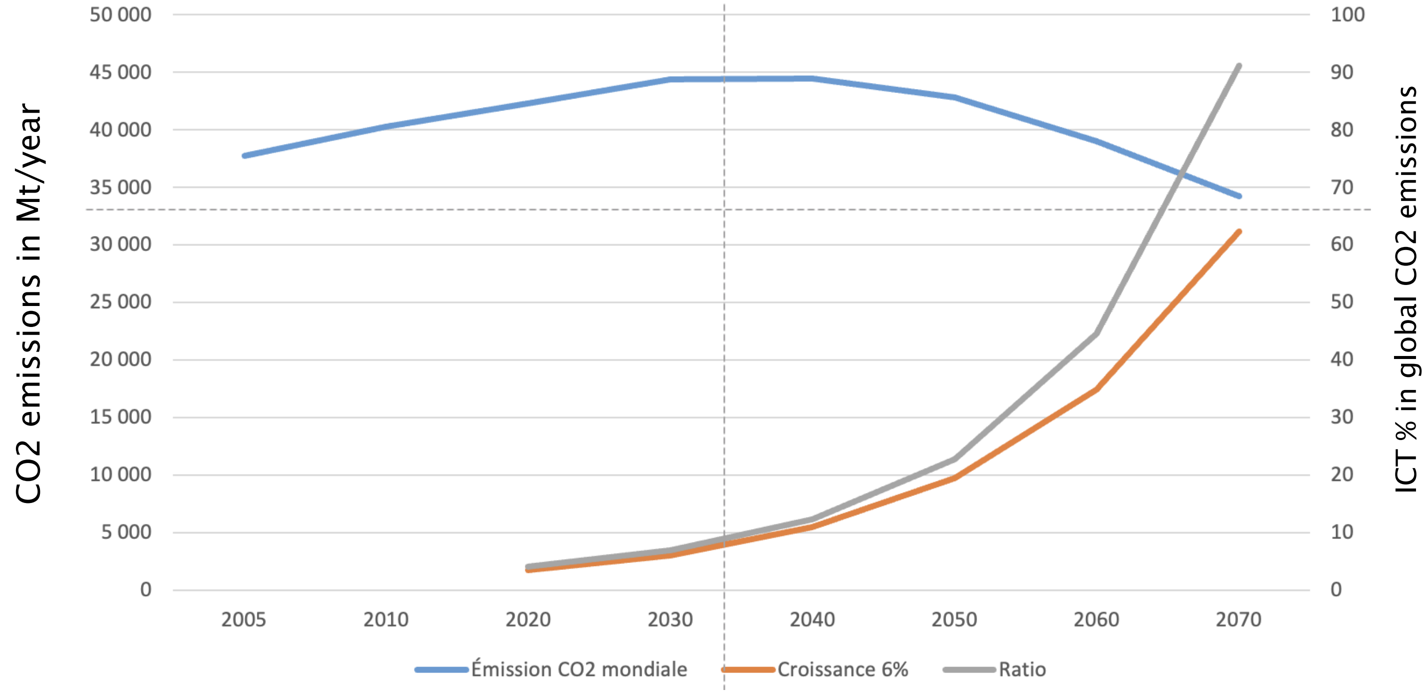



*Left ordinate are MT of CO2 emission per year. Right ordinate are percentages for the grey curve.*

# ICT share of GHG emission

Analysis suggested by D. Trystram, Y. Malot & G. Raffin (UGA/France)

- SSP2-4.5 scenario (business as usual) and minimal ICT growth (6%)

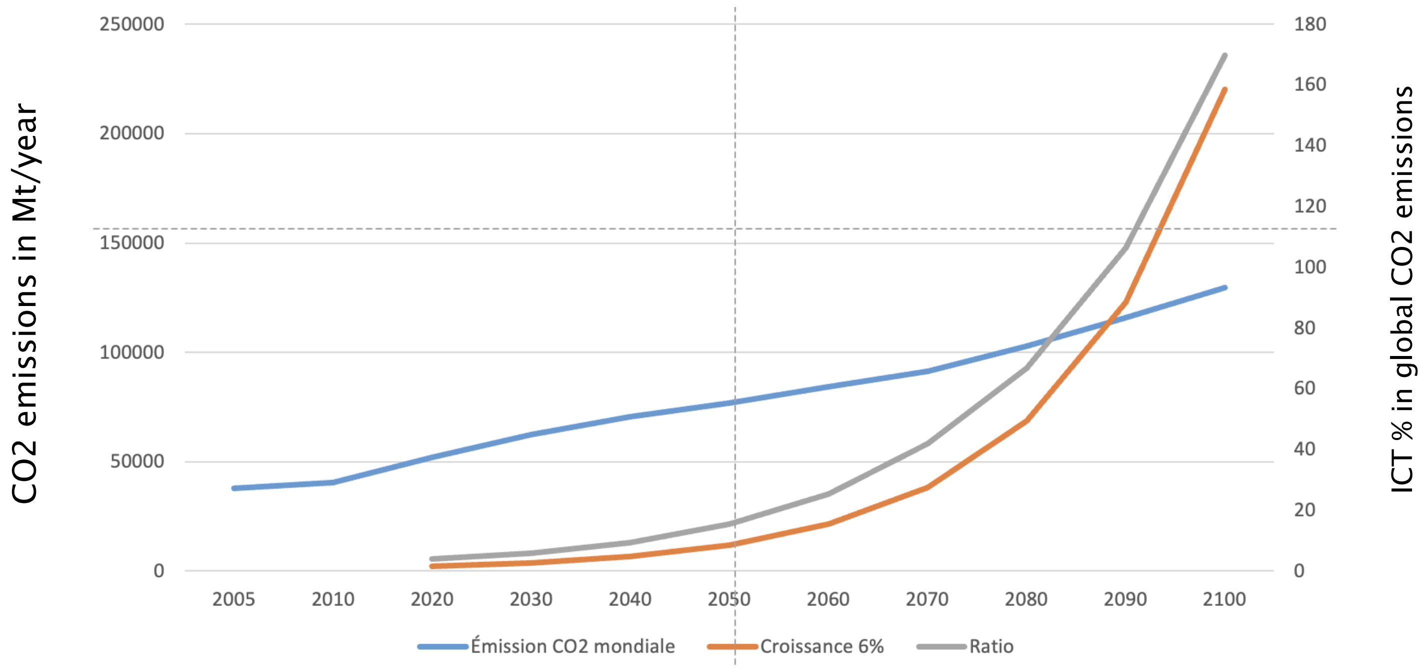



*Left ordinate are MT of CO2 emission per year. Right ordinate are percentages for the grey curve.*

# ICT share of GHG emission

Analysis suggested by D. Trystram, Y. Malot & G. Raffin (UGA/France)

- SSP3-7 scenario (regional rivalry) and minimal ICT growth (6%)



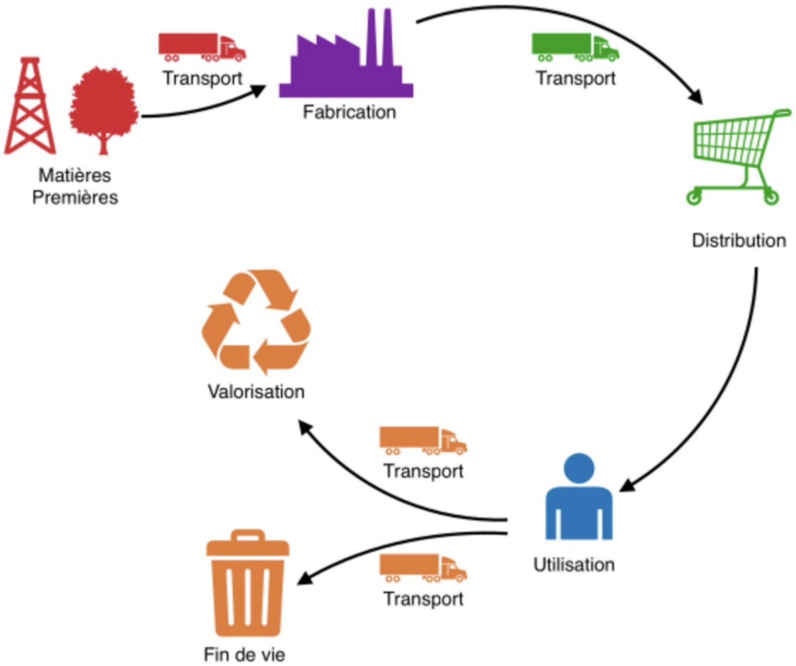

*Left ordinate are MT of CO2 emission per year. Right ordinate are percentages for the grey curve.*

# 2.2 1st and 2nd order effects

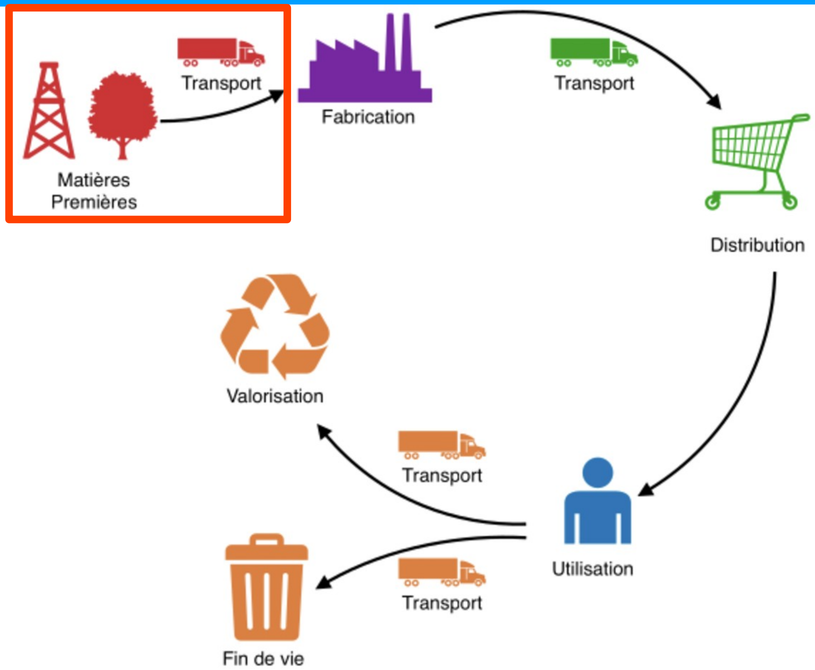
| Type | Perimeter | Effect | Examples |
|---|---|---|---|
| 1st order **Direct** | Technology Itself | Life Cycle Impact Of Hardware | production (energie, resources), use (energie), end-of-life (pollution) |
| 2nd order **Indirect** | Use and applications | Optimization | smart-* |
| | | Substitution | dematerialization - walkman + photo -> smartphone |
| 3rd order **Structural Behavioral** | Consumer Producers | obsolescence induction | 5G printer -> paper |
| | | direct rebound and indirect | devices, uses consumption |
| | Economy | economic growth | new markets |
| | | acceleration | e-commerce (24/7), logistics |
| | Society | reconfiguration | Über |

[N.C. Horner et al. - 2016]
[J. Combaz - 2023 - EJCP]

# 2.3 First order effects



# 2.3.1 Raw material



# A physical and political ICT

- DRC andcolombite-tantalite (coltan)
  - Source of Tantale (Ta)
  - Excellent electrical/heat conductor
  - Used in capacitors and 80% in electronics
  - DRC owning 60% of world's reserve
  - 2019: produces 40% of global supply
  - 8,6% loss of forest cover since Y2k

[Ethical consumer - 09/2025]

  - Area of significant conflict
    - 30 years of war
    - 7 millions of displaced people (UN data)
    - Over 10 000 deaths

[WP - 10/2025]

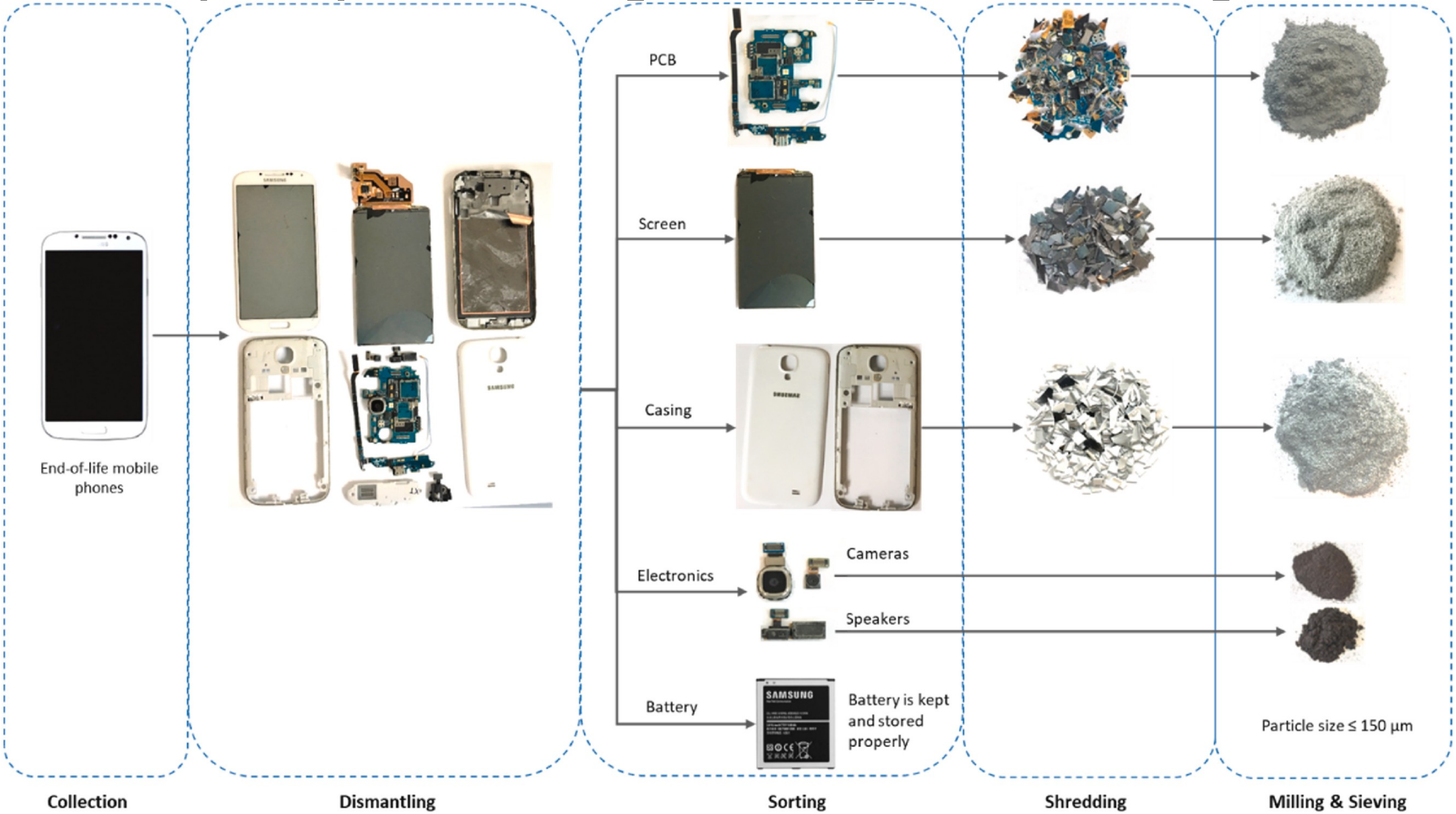
A coltan mine operated by *Société minière de Bisunzu* (SMB) near Rubaya, in eastern Democratic Republic of Congo, in August 2019. BAZ RATNER / REUTERS – in [Le Monde - 29/08/2024] accessed on 11/3/2024

- Cobalt
  - 80% of world's reserve
  - 30% extracted using traditional methods

[Electronic watch - 10/2023]

# Desperately Seeking Elements

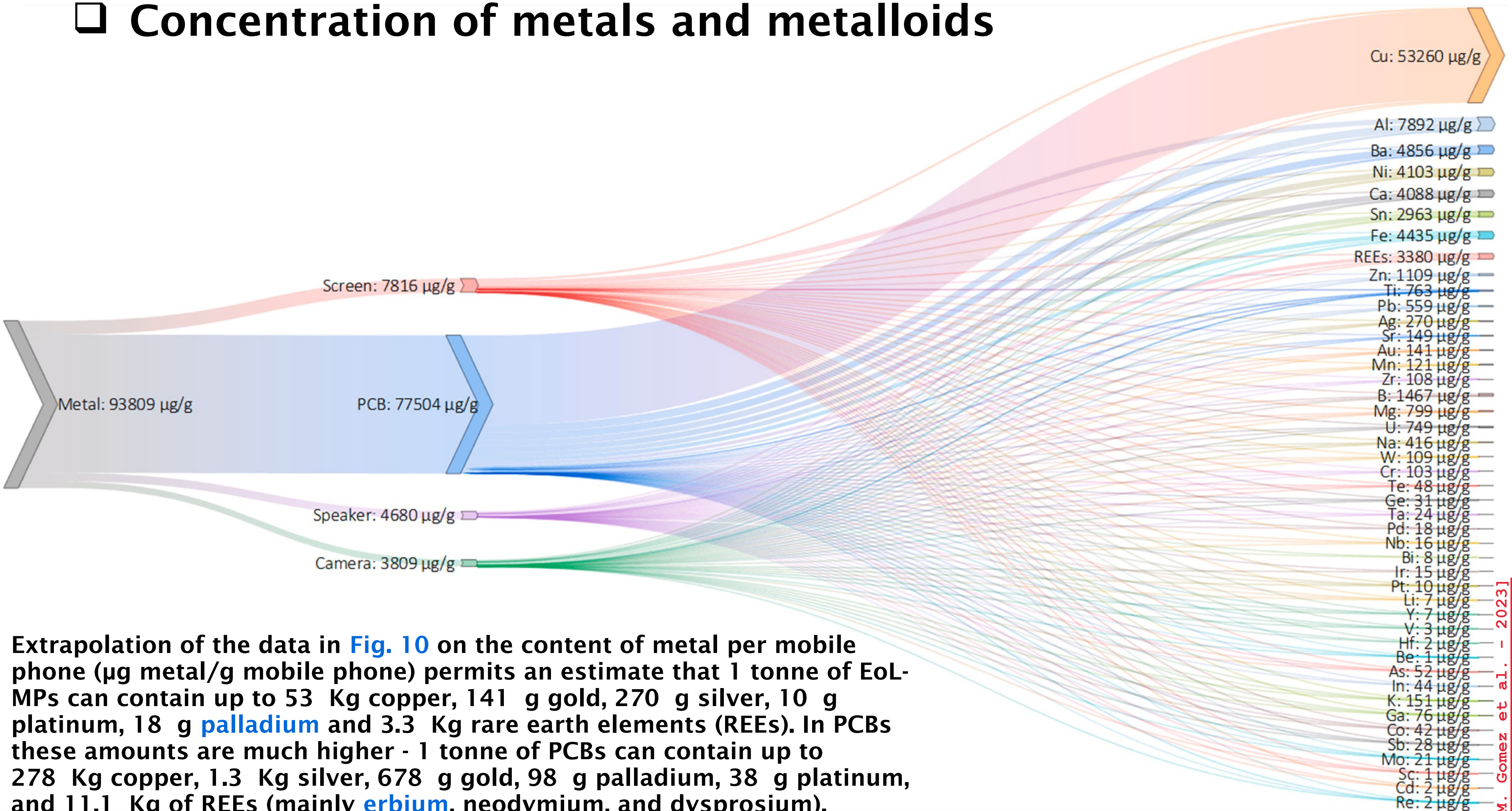
## ❑ Analysis by dismantling, crushing, and screening




[M. Gomez et al. - 2023]

# Significant dispersion of elements

## ❑ Concentration of metals and metalloids

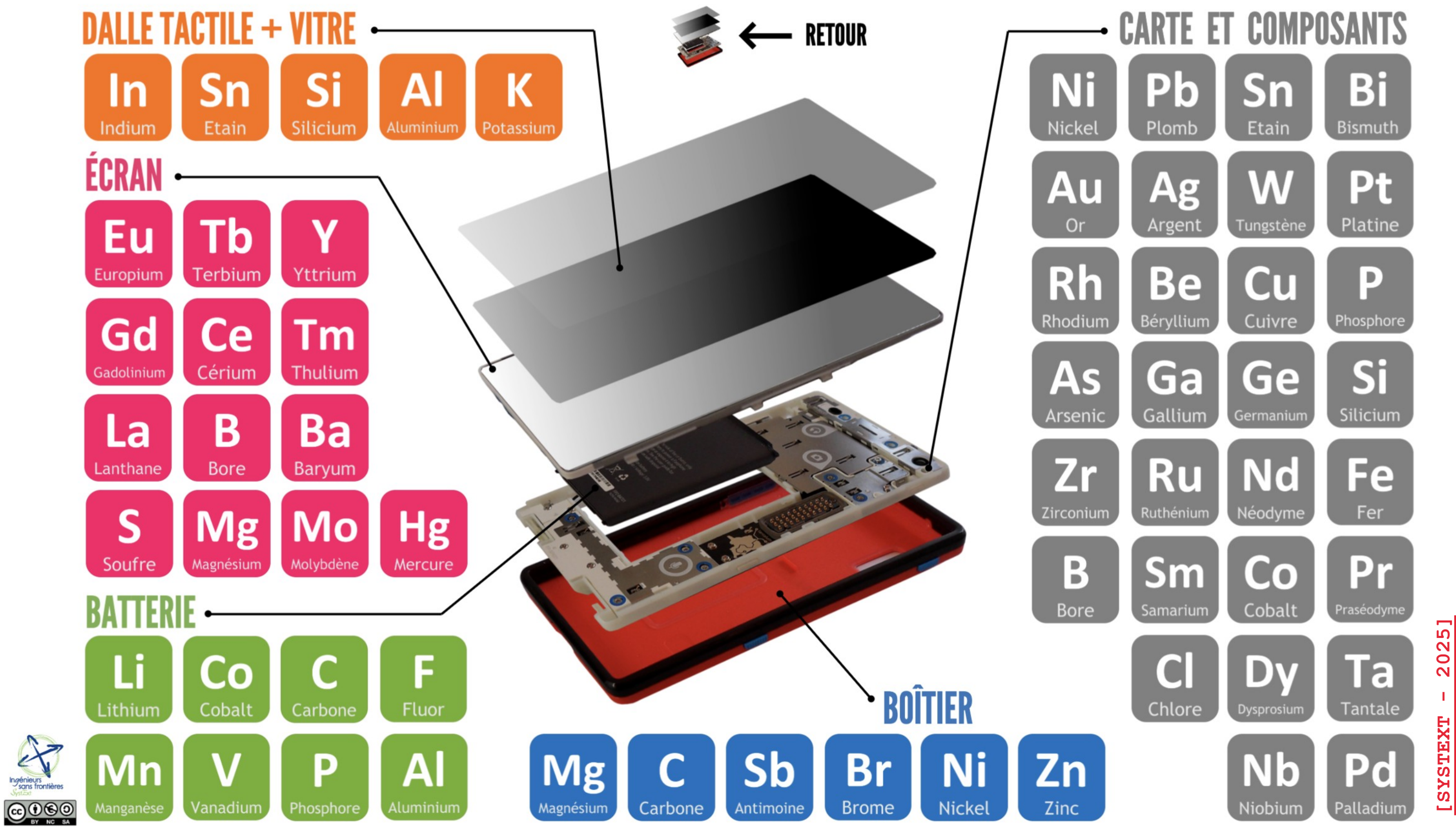



[M. Gomez et al. - 2023]

**Extrapolation of the data in Fig. 10 on the content of metal per mobile phone (µg metal/g mobile phone) permits an estimate that 1 tonne of EoL-MPs can contain up to 53 Kg copper, 141 g gold, 270 g silver, 10 g platinum, 18 g palladium and 3.3 Kg rare earth elements (REEs). In PCBs these amounts are much higher - 1 tonne of PCBs can contain up to 278 Kg copper, 1.3 Kg silver, 678 g gold, 98 g palladium, 38 g platinum, and 11.1 Kg of REEs (mainly erbium, neodymium, and dysprosium).**

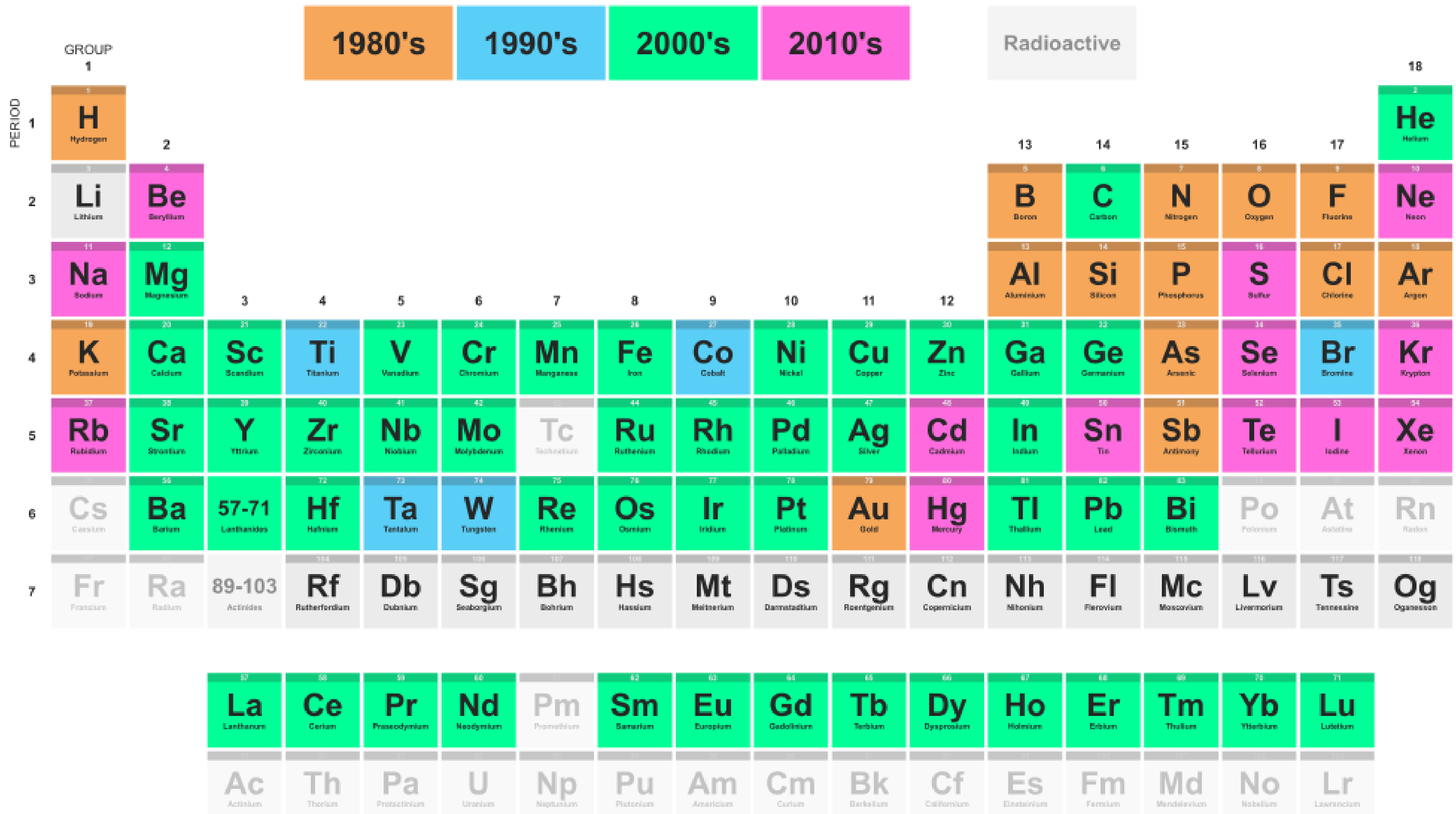
# Smarphone: a mine in your pocket

- The elements contained in a smartphone (66% of the periodic table)



# “*Purer than pure*” – the evolution of materiality

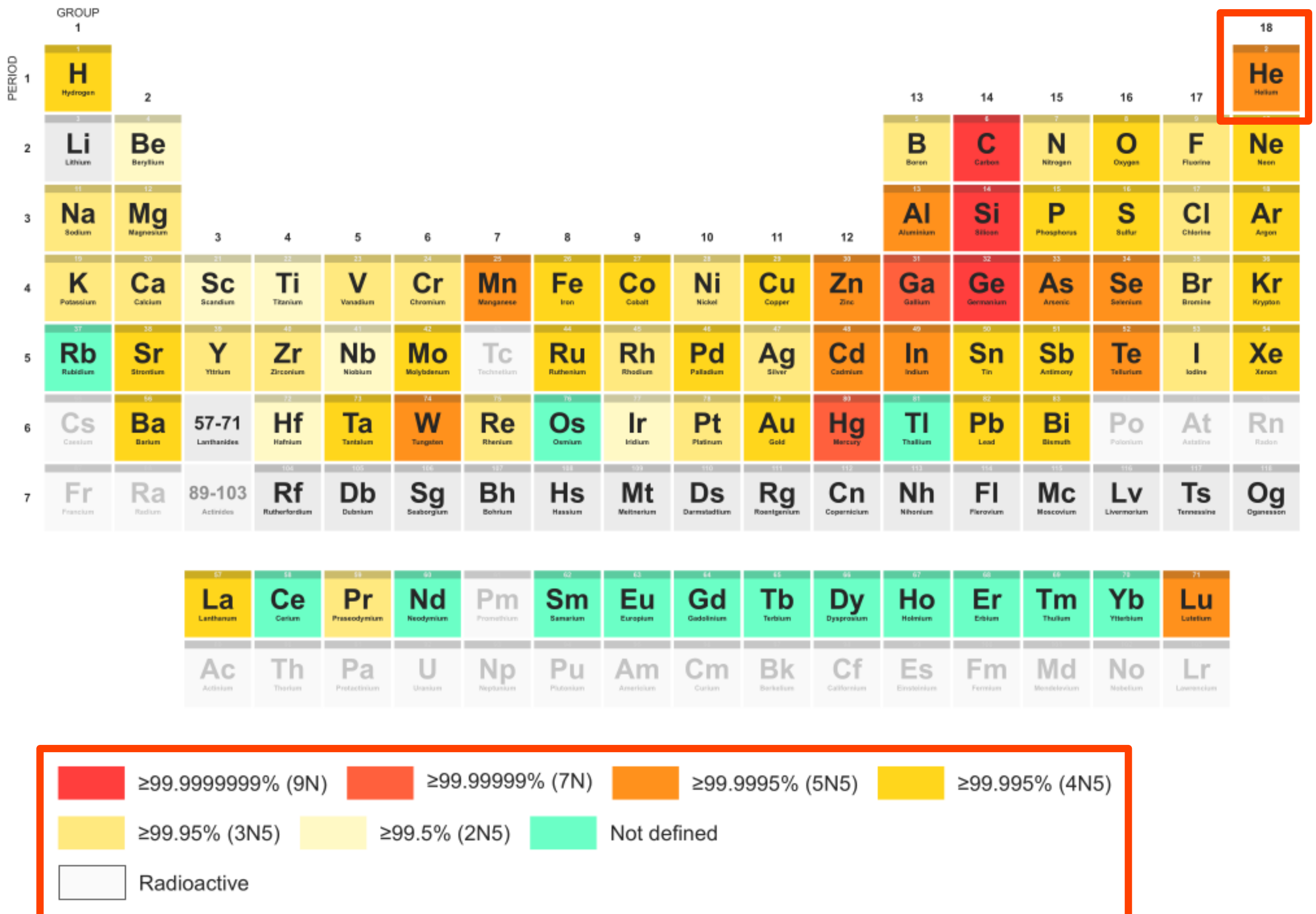
❑ **Elements in the semiconductor industry 80’s – 2010’s**




[G. Roussilhe et al. - 09/2025]

# "*Purer than pure*" – the evolution of materiality

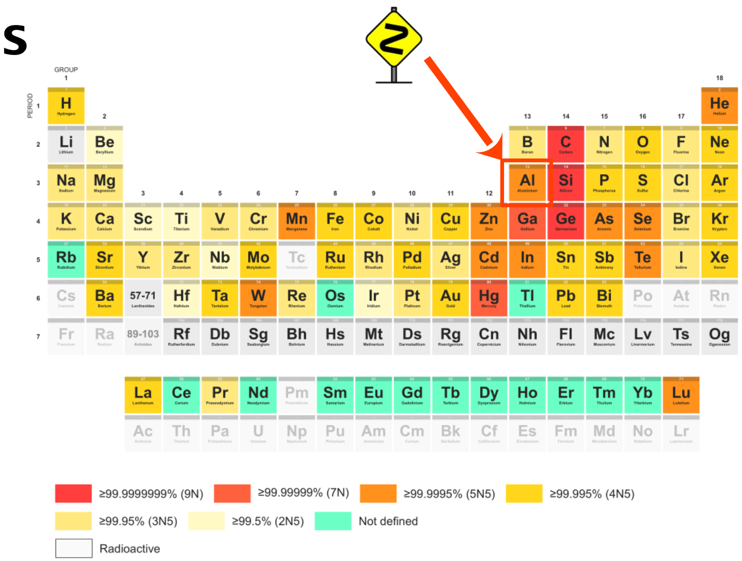
## ❑ Purity requirements for the elements




[G. Roussilhe et al. - 09/2025]

# "*Purer than pure*" – the evolution of materiality

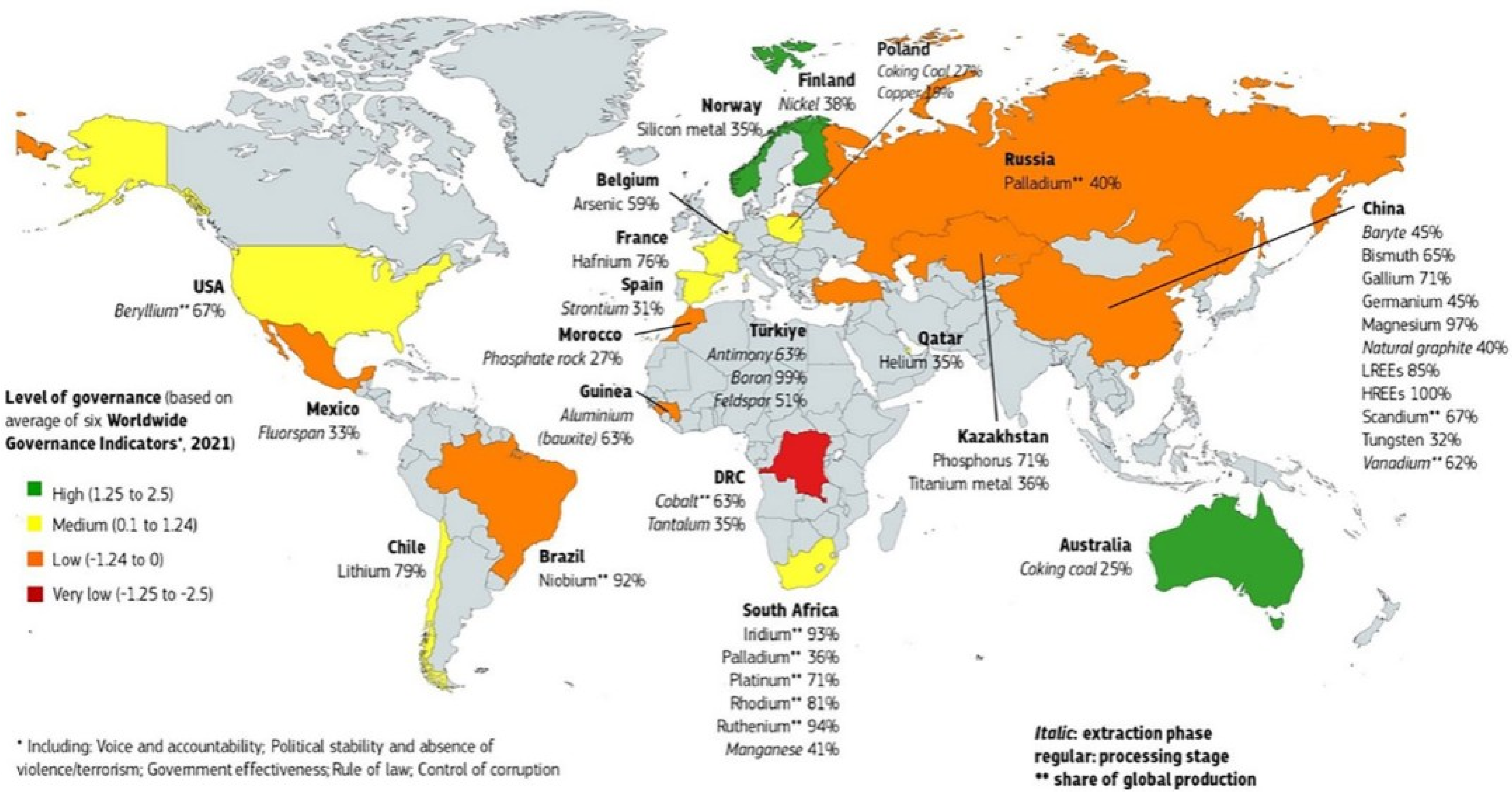
- ❑ **Purity requirements for the elements**
  - ❑ **Al(uminium) - industry**
    - ❑ *Industry grade*: 99% (2N)
    - ❑ 64 Mt consumed worldwide
    - ❑ 5% to 10% for electronics sector
  - ❑ **Al(uminium) - semiconductor**
    - ❑ *Semiconductor grade*: 99.9995 (5N5)
    - ❑ Purification is a multi-step process
    - ❑ Energy-intensive process (electrolysis/segreation)
    - ❑ 3 x electrolysis requiring 13 MWh/ton
    - ❑ 5 companies hold 79% of the market for 5N5 Al




[G. Roussilhe et al. - 09/2025]

# Geopolitics and governance of the elements

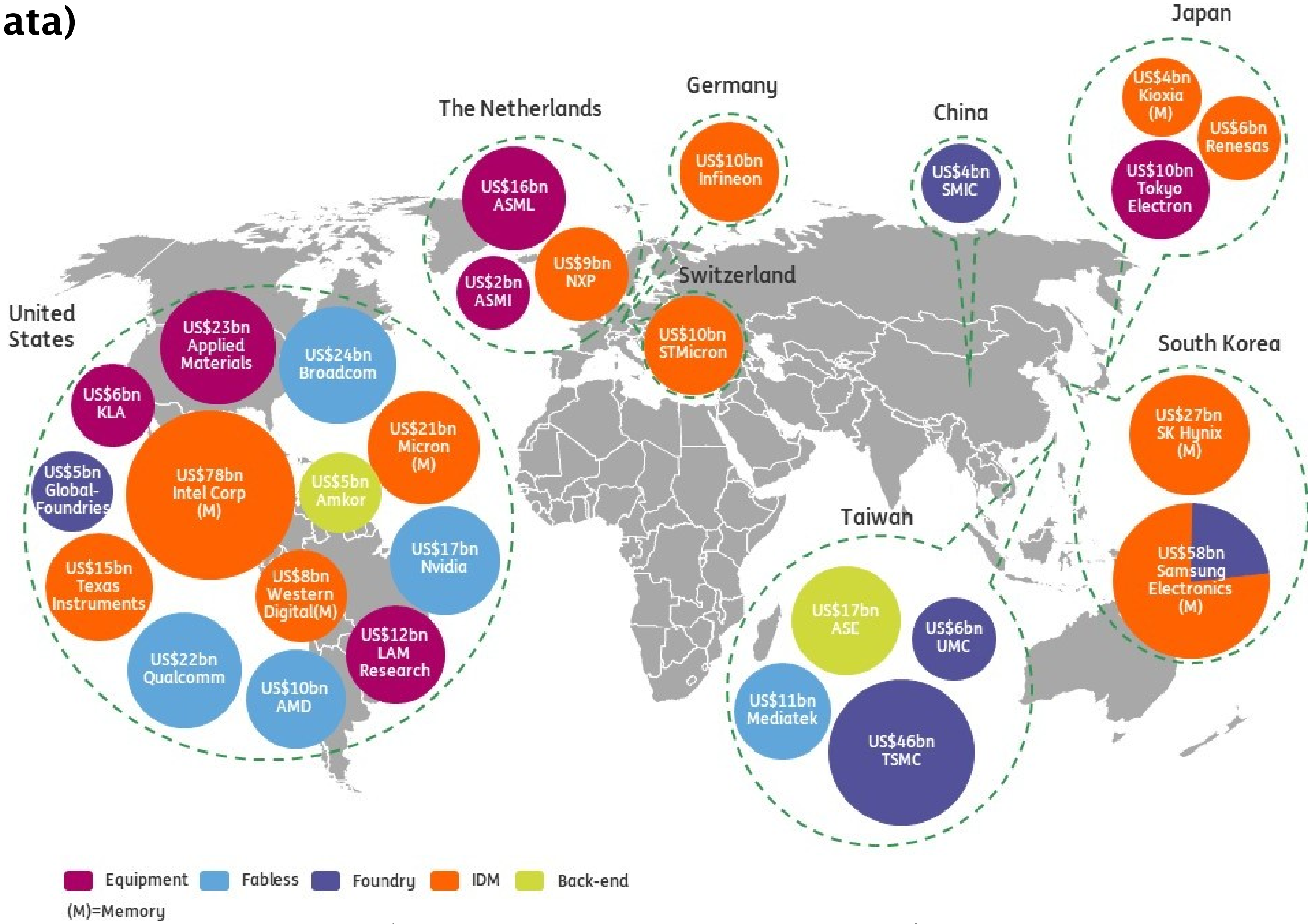
## ❑ Main EU suppliers of essential raw materials




[R. Zoboli - Investing in Critical Raw Materials for the Clean-Tech Transition in the EU - 12/2025]

# Concentration of semiconductor companies

- **Major companies in the semiconductor industry**
  **(2020 data)**




[ING - 2020]

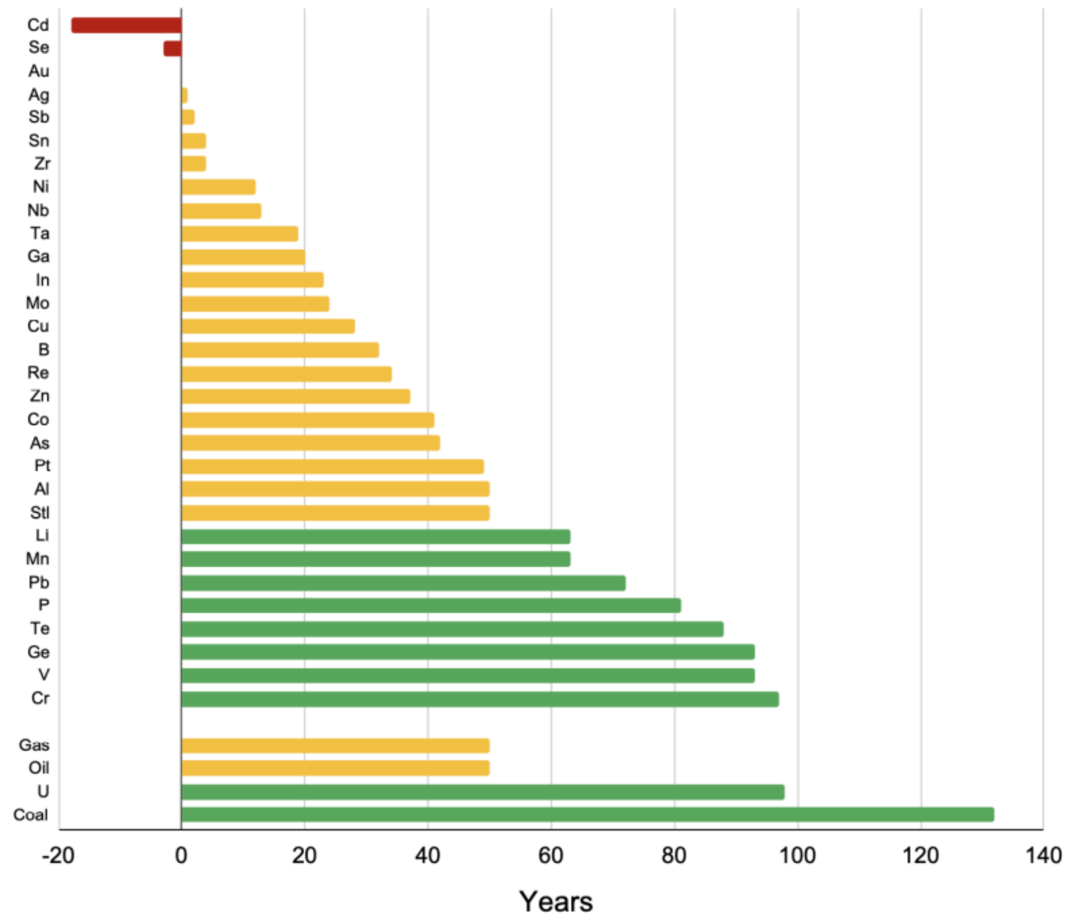
# Years projected before peak extraction

**Critical material and energy resources**

[…] The abscissa indicates the **year of peak**. **Red is for past peaks**, **yellow for peaks within half a century**, **green for peaks beyond that delay**.

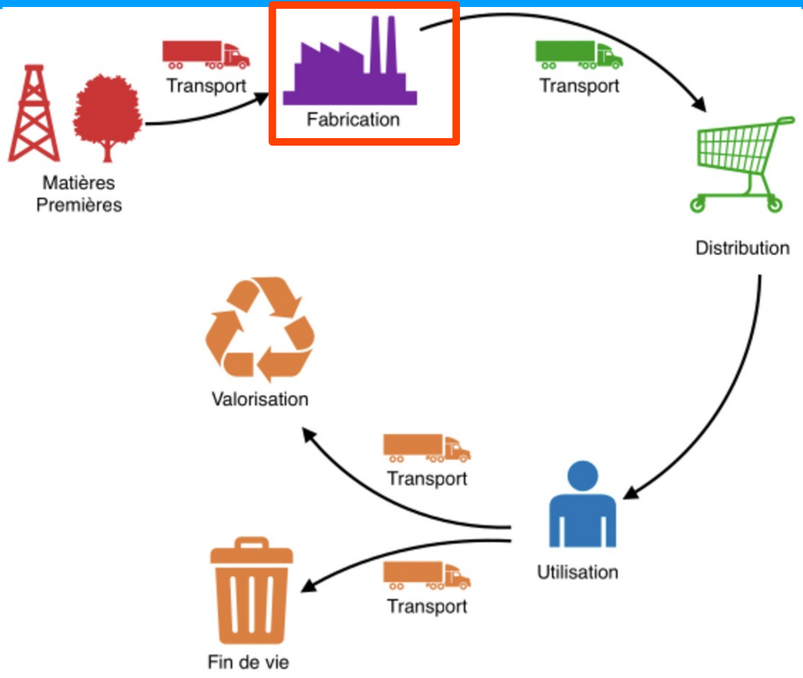
Many material stocks (e.g. phosphorus, **rare earth elements**) are projected to **peak within decades** [...], as will several metals. For instance, copper (Cu) could peak within 30-50 years [...].

For legibility, out of 92 elements, only a few ones representative of the elements which **peak within 200 years** are plotted. Data for ecosphere boundaries, which do not correspond to year predictions, are not plotted here.



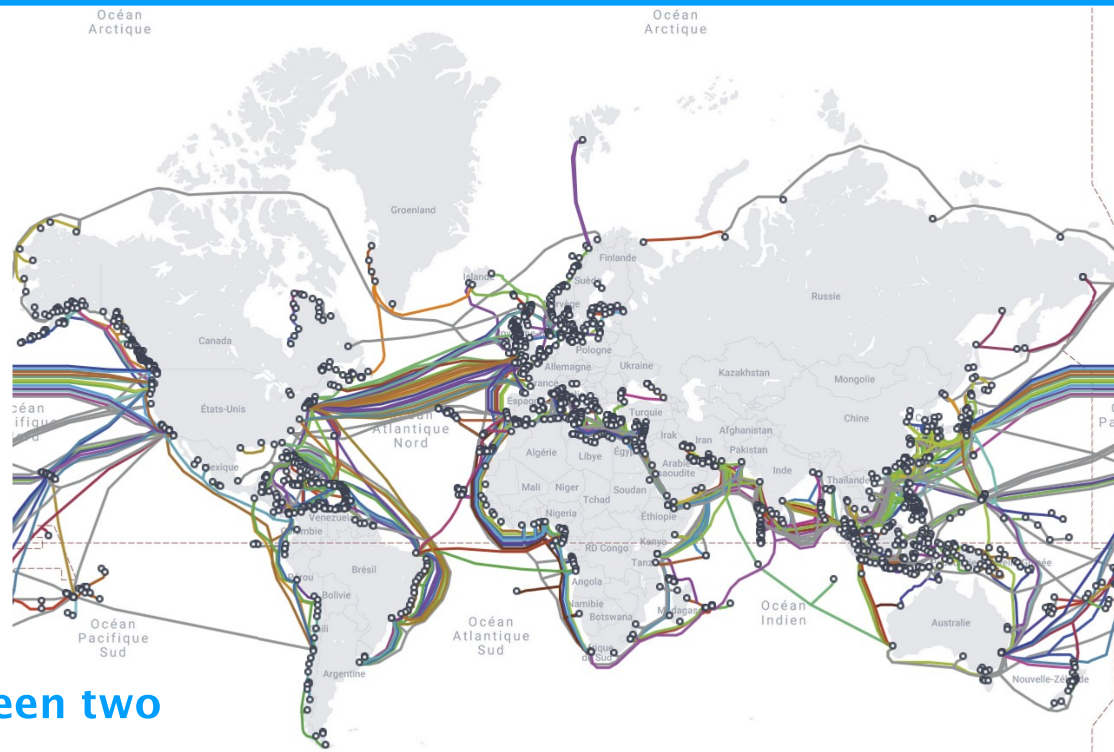

[J. Halloy et al. - The Physics of Sustainability: Material and Power Constraints for the Long Term - 12/2025]

# 2.3.2 Manufacturing



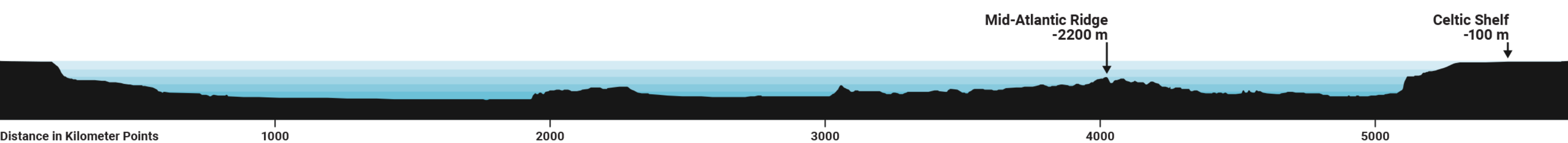
# A global network requiring a lot of cables

- **En 2025**
  - **1,48M km of cables**
  - **574 active cables**
  - **Of variable length**
    - 131km (Ireland – UK)
    - to 20k km (Asia-America)
  - **Laying100k km of cables per year**
  - **Cost of a campaign between two continents: NY → Irlande, Microsoft, $300m**



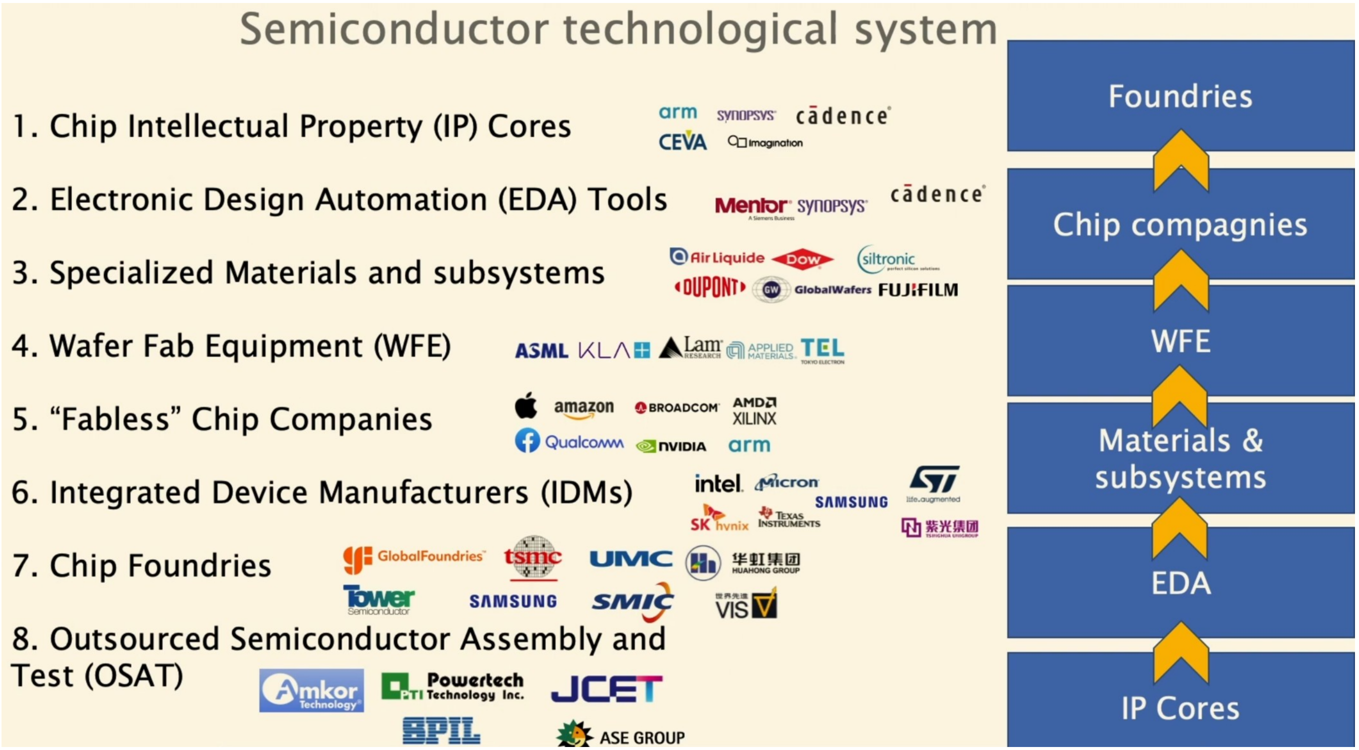

[Submarine Cable Map - 2025]

[Fibre Systems - 11/2025]



# The semiconductor technological system

- **Interdependence between materials, physics, chemistry and power/energy**
- ***Technical system:* computers needed to build computers**



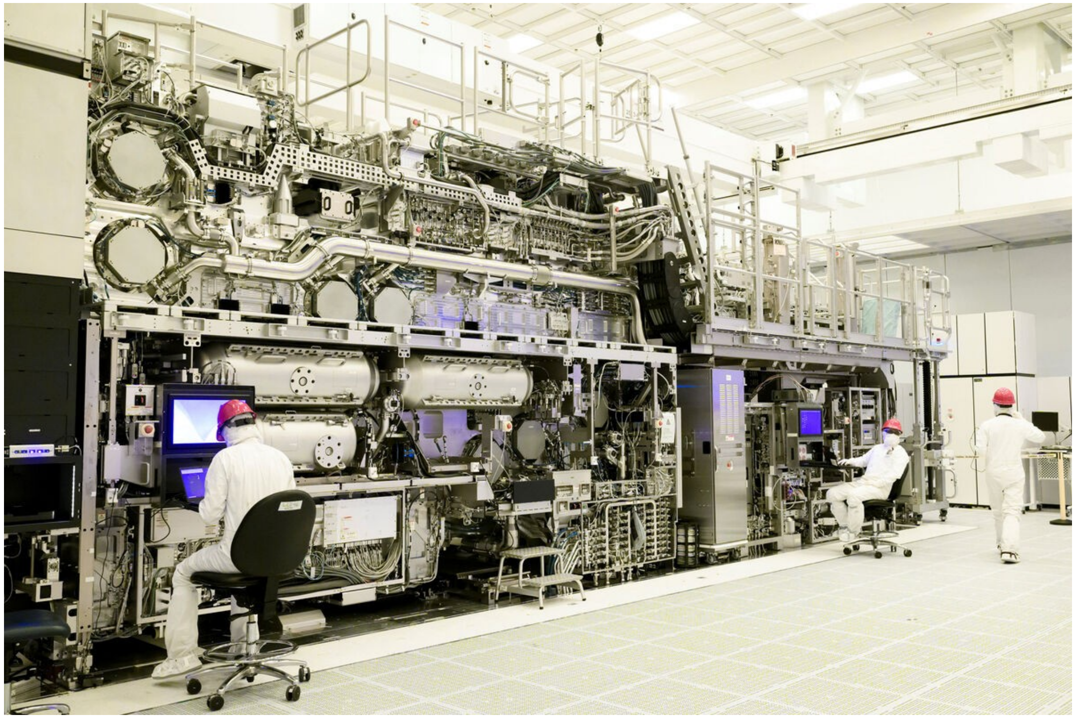

[J. Halloy - 2024]

# The semiconductor technological system

- Example : ASML (Pays-Bas)
- Leading supplier (> 80%) of semiconductor equipment
- 2024: m.cap 345 B€ ; Revenue 28 B€ ; net profit 7,6 B€

- 5 months manufacturing
- 100 000 parts
- 2km of cables
- Cost: 100-150 M€
- Only firm able to handle 3nm process

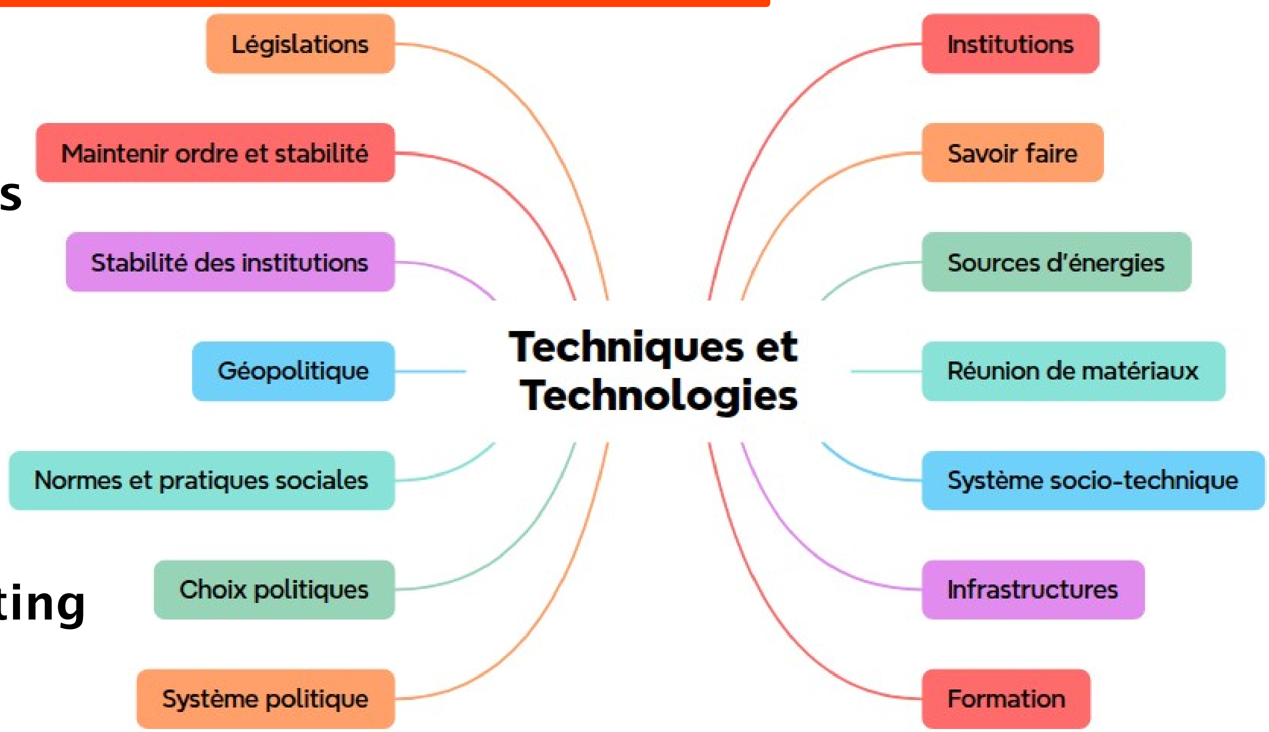
- High NA EUV photolithography system at an Intel facility in Oregon, US



[Usine Nouvelle - 2024]

# Un système technologique

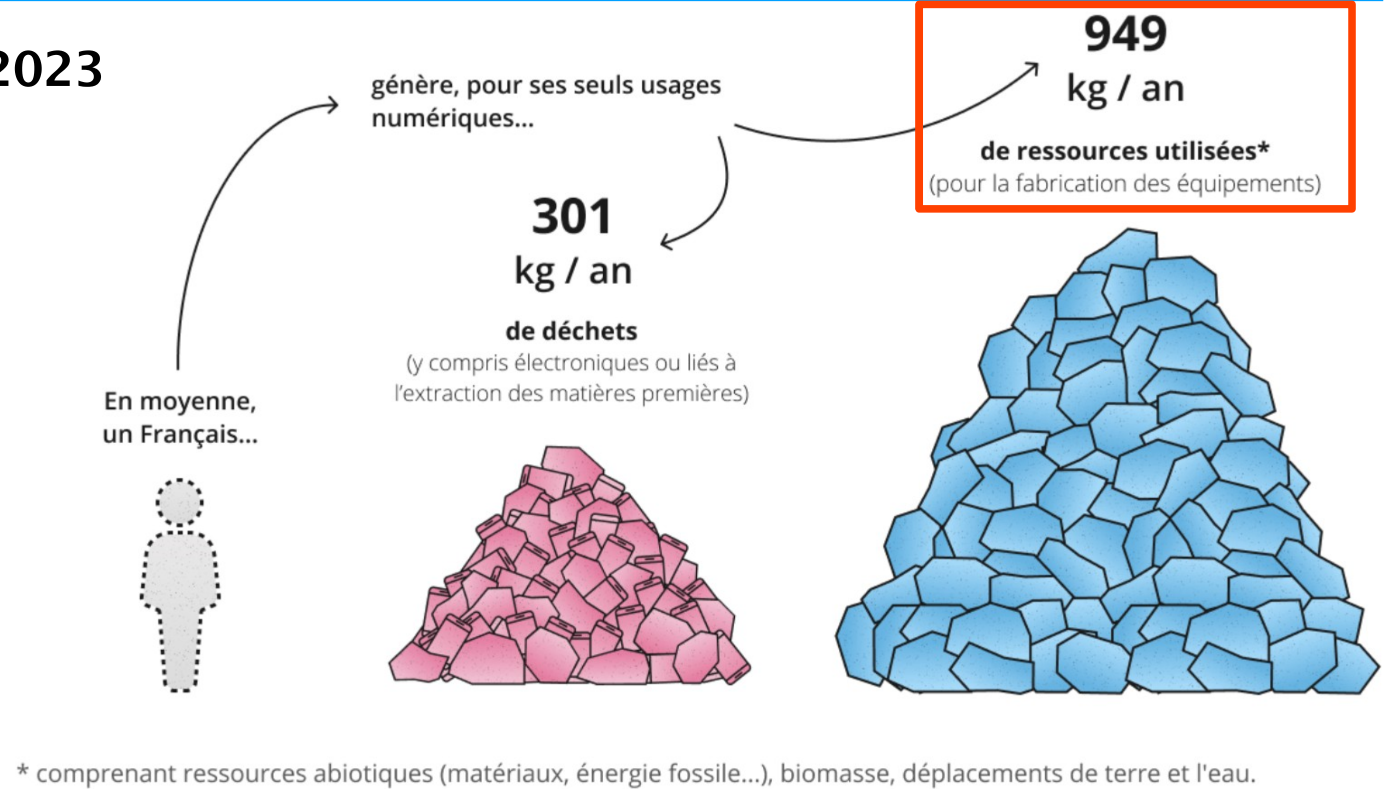
- Systeme
  - Complicated (made up of a large number of elements)
  - Fragile and vulnerable (one part goes missing and nothing works anymore)
  - Reduces or even destroys the robustness of the system
- Techniques and technologies operate in systems
- Form dense, intertwined networks composed of numerous interacting heterogeneous elements




[J. Halloy - 2022 - Du vivant aux technologies zombies et inversement]

# France: use of resources

- ARCEP study, 2023

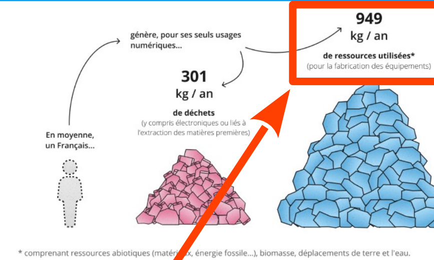



[ARCEP - Étude 2023]

# France: use of resources

- ARCEP study 2023
- ADEME study 2025
- The more we progress...
- ...the greater the measured impact is


[ADEME - 2025]




[ARCEP - Étude 2023]

# Overview of a DC


[Vectorstock]

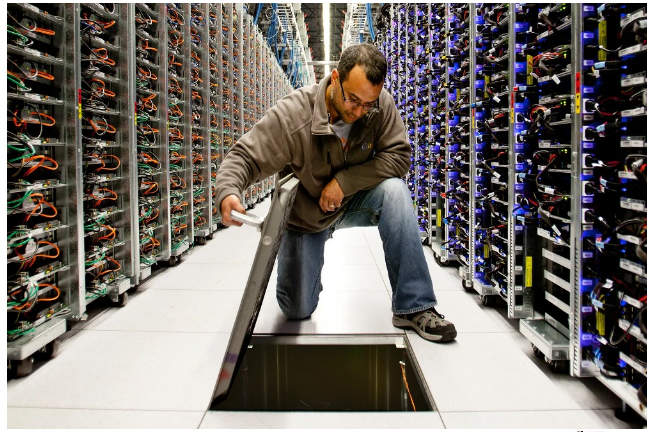
# Physical views of a Google DC in New Albany

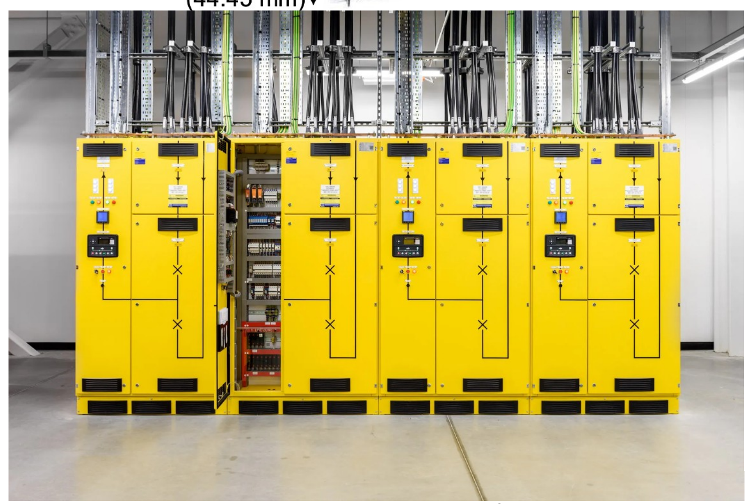
- Site: 70 acres (28ha - 283 000 m²) → land artificialization
- DC: 139 000 m²
- Power: 3 x 64MW (192 MW) – density of 3.23 kW/m²

[Vantage DC - 2025]

[DC - Google]

# Physical views of a DC



[D.W. Demetriou - 2025]

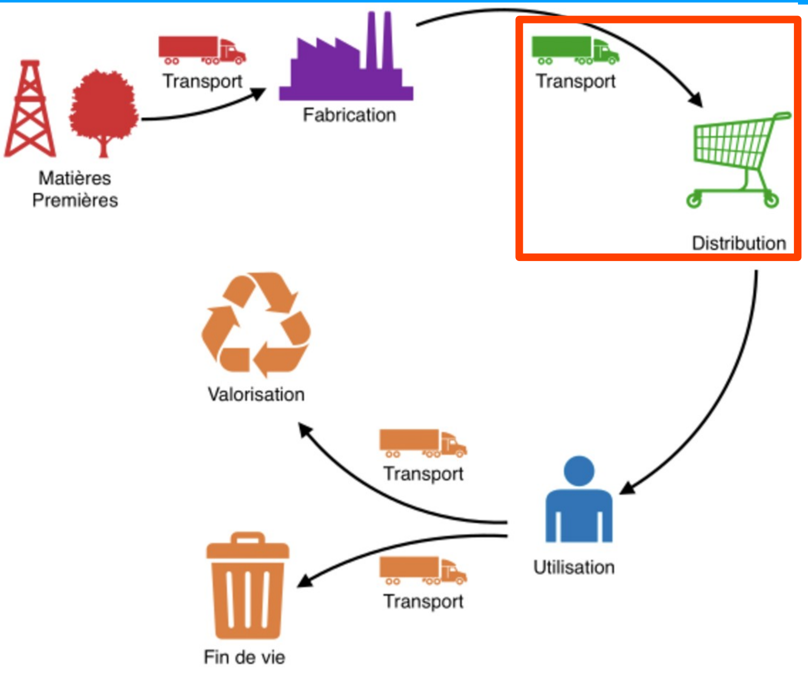
[DC - Google]

# Birth of a DC: Ai campus in Fouju (south of Paris)

- ❑ **Facts and figures**
  - ❑ Located in Fouju (Seine-et-Marne)
  - ❑ Covers 70 hectares
    - 12 buildings
    - 2 electrical stations
    - Various buildings (training, technical support)
    - Common areas
    - Green spaces
  - ❑ Two phases
    1) → 2028 : 3 buildings DC + training, 700 MW capacity
    2) → 2029 : +9 DC, 1,4 GW capacity
- ❑ **Cost : 35B euros (8B for the first phase)**

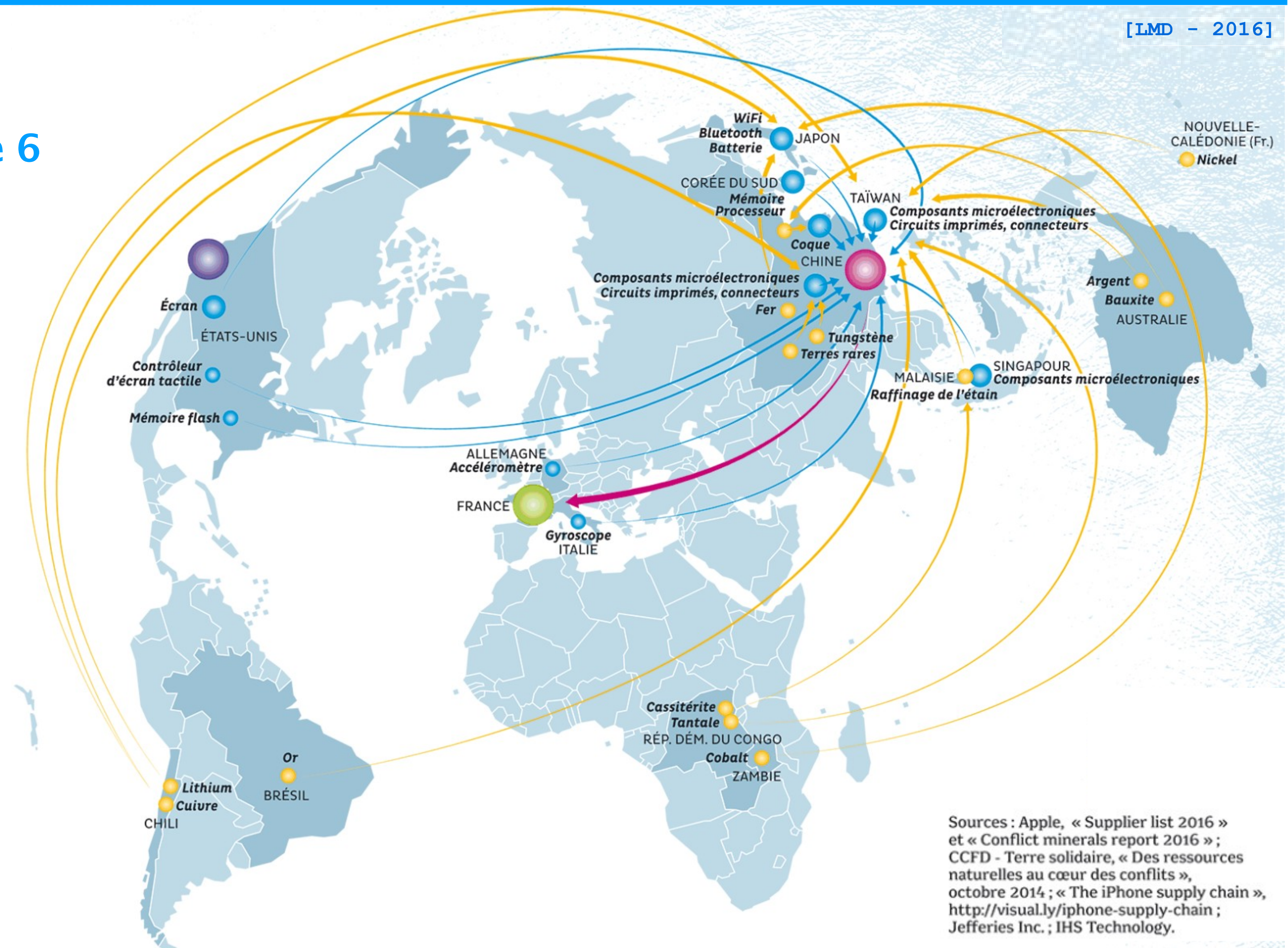
[CNDP - 2025]

# 2.3.3 Distribution

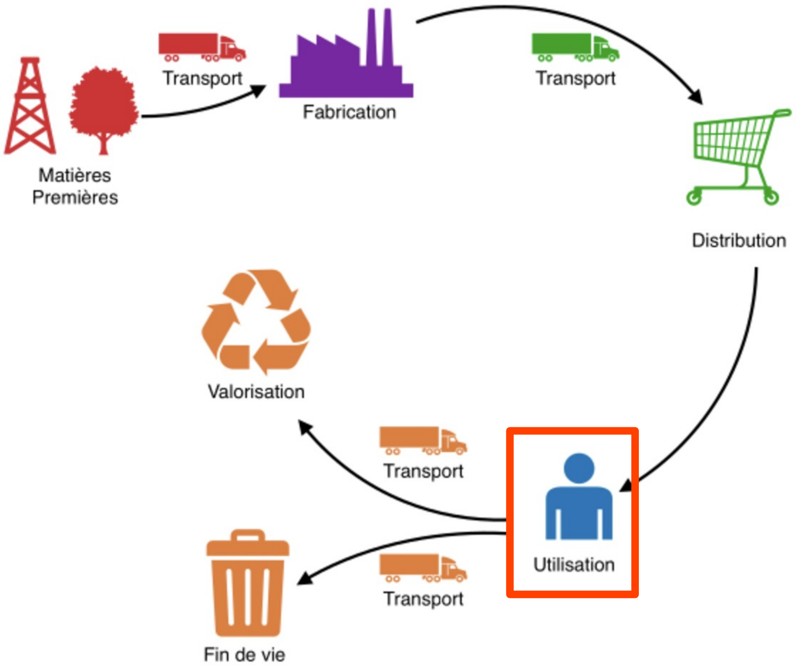


# A smartphone travels (a lot)

- Data 2016
  - Apple iPhone 6




# 2.3.4 Use



Transport
Fabrication
Transport
Matières
Premières
Distribution
Valorisation
Transport
Utilisation
Transport
Fin de vie

# The materiality ICT – Worldwide and France

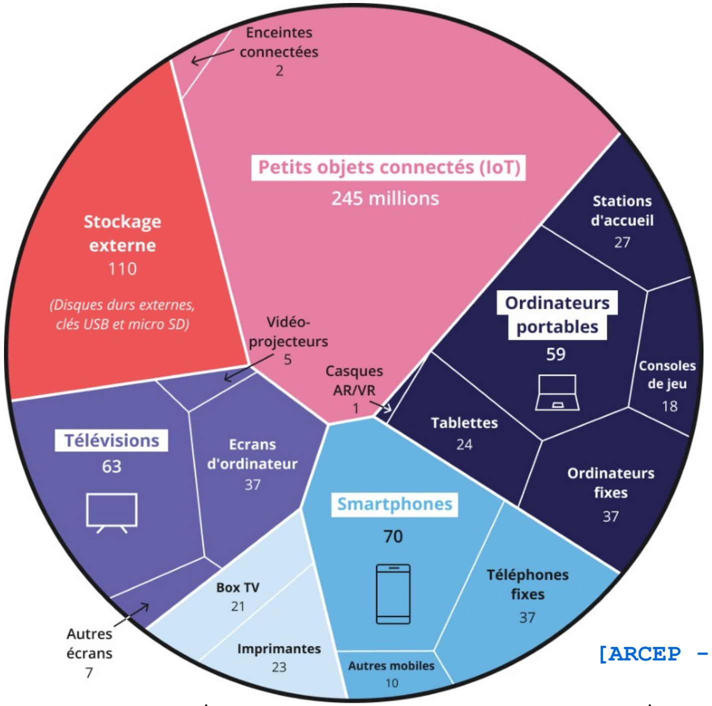
- Some figures (worldwide)
  - 34 B devices
  - 5,5B users [ITU – 2024]
  - 5,5% of global electricity consumption
  - 2-4% of GHG, growing at 6-9% / year

[Freitag et al – 2021]

- 3-tier
  - DC
    - **67 million servers**
    - **1,5% of global electricity** (IEA – 2025)
  - Devices
    - **3.5B smartphones**
    - > 3B screens
    - Between 10 and 30B IoT devices
  - Network
    - **1B internet boxes**
    - 10M relay antennas

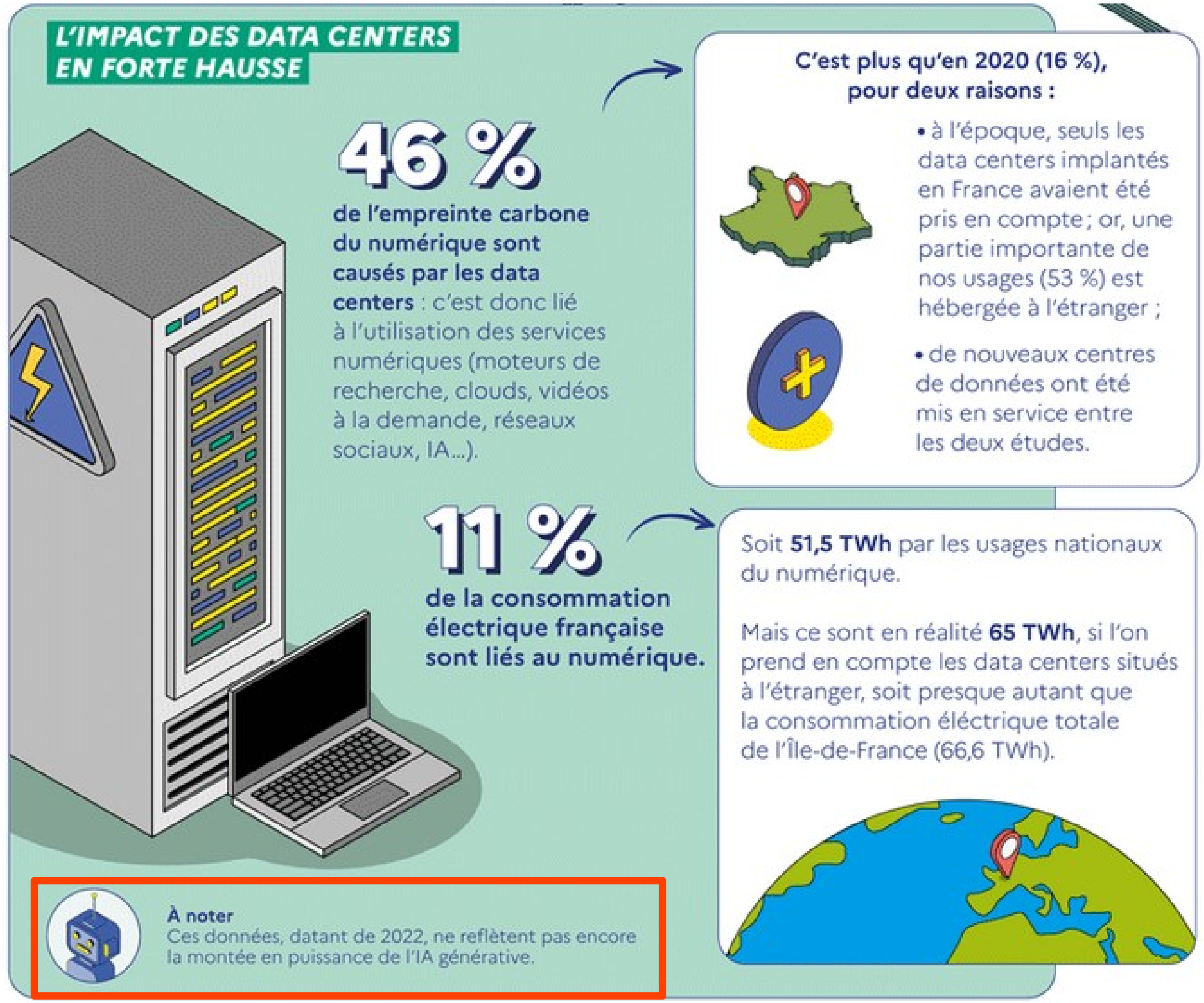
[Bordage – 2019] [TSP – 2018]

- France (updated 2022 data)
  - 11% of electricity consumed [ADEME – 2025]
    - 51,5 TWh for domestic use
    - 65 TWh including DC outside France
  - > 800M user devices (2020)




[ARCEP – 2023]

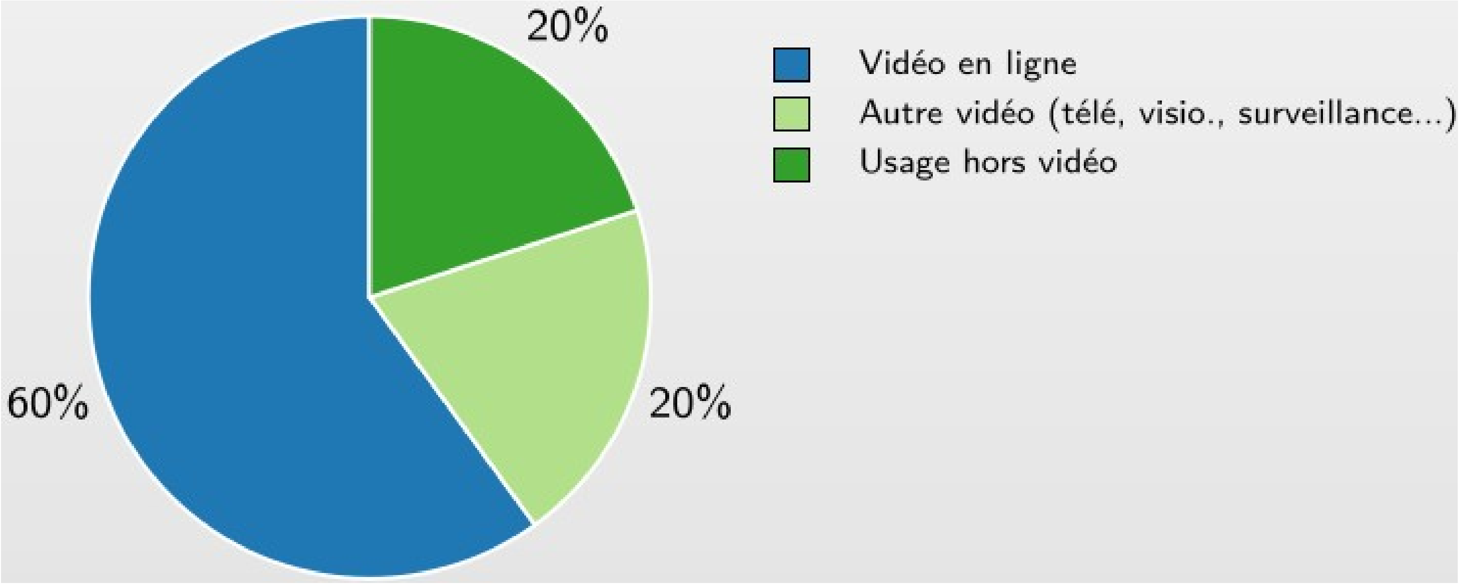
# The materiality of digital technology – Worldwide


[ADEME - 2025]

# Network

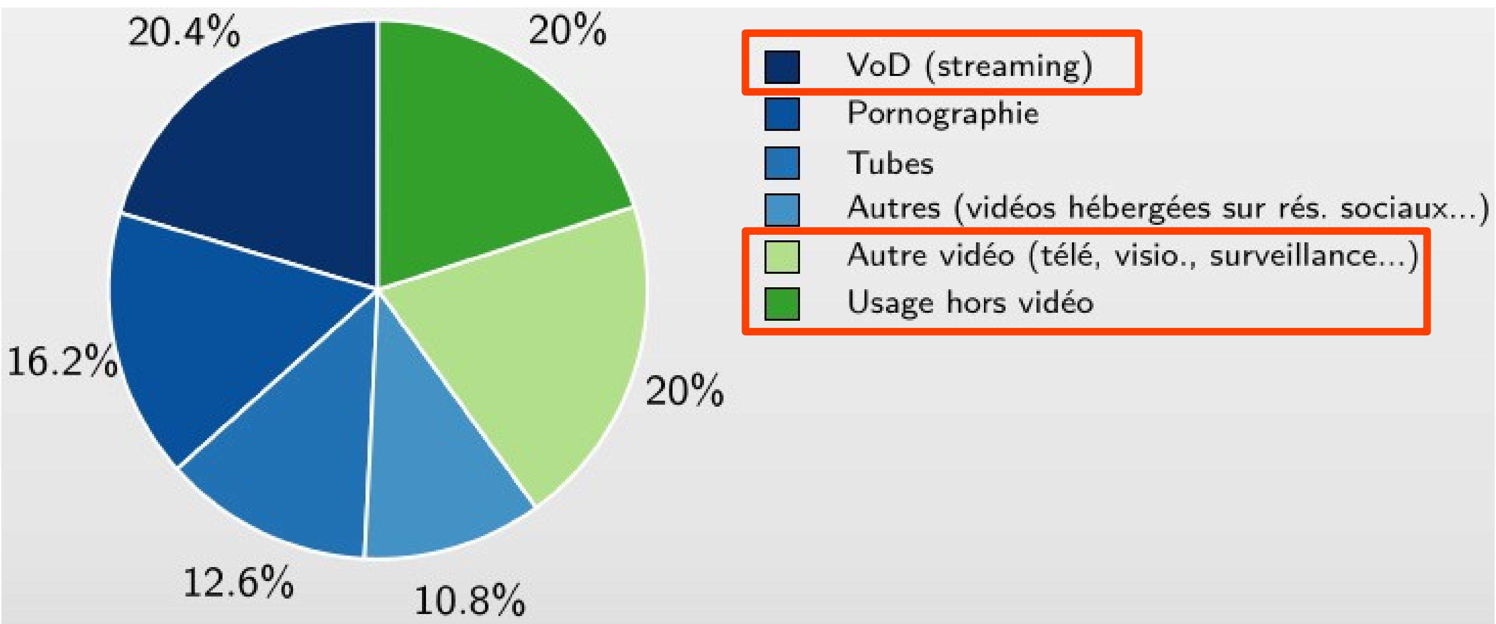
- Worldwide (data S. Bouveret citing Statista & Cisco)
  - 2019 – world IP traffic  (proj.): 1,66 Zo ($10^{21}$ bytes)
  - 2017 – world IP traffic: 1,5 Zo (500 times more in 15 ans)
  - 2002 – 3,2 Eo
- Traffic distribution




[S. Bouveret - 2024]

# Network

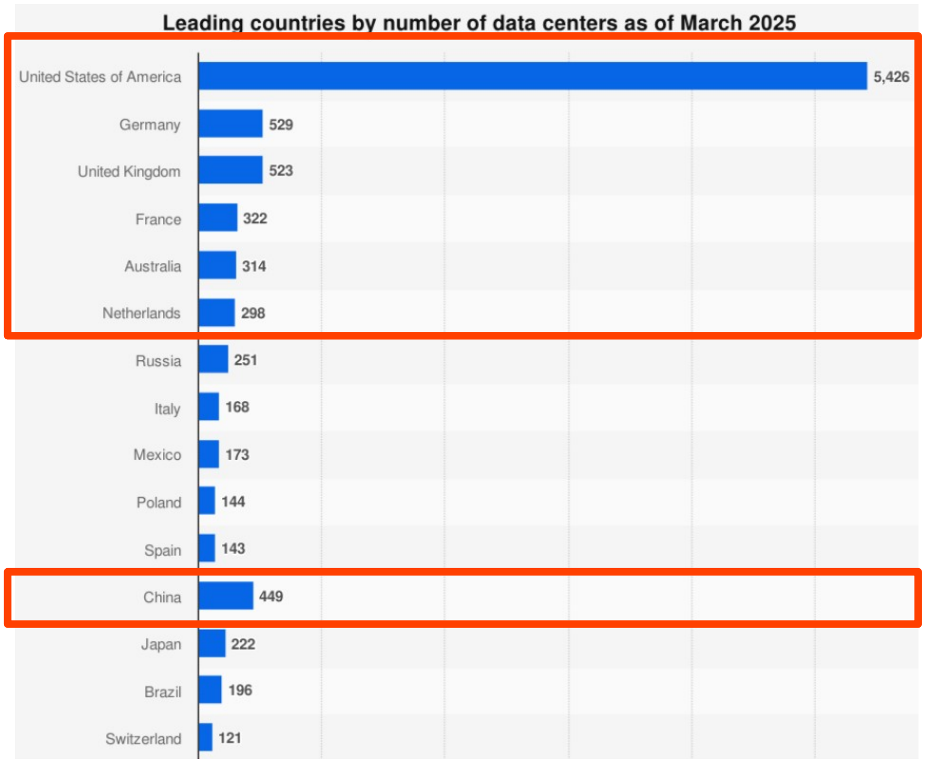
- Dans le monde (données S. Bouveret citant Statista & Cisco)
  - 2019 – world IP traffic (proj.): 1,66 Zo ($10^{21}$ bytes)
  - 2017 – world IP traffic: 1,5 Zo (500 times more in 15 ans)
  - 2002 – 3,2 Eo
- Traffic distribution

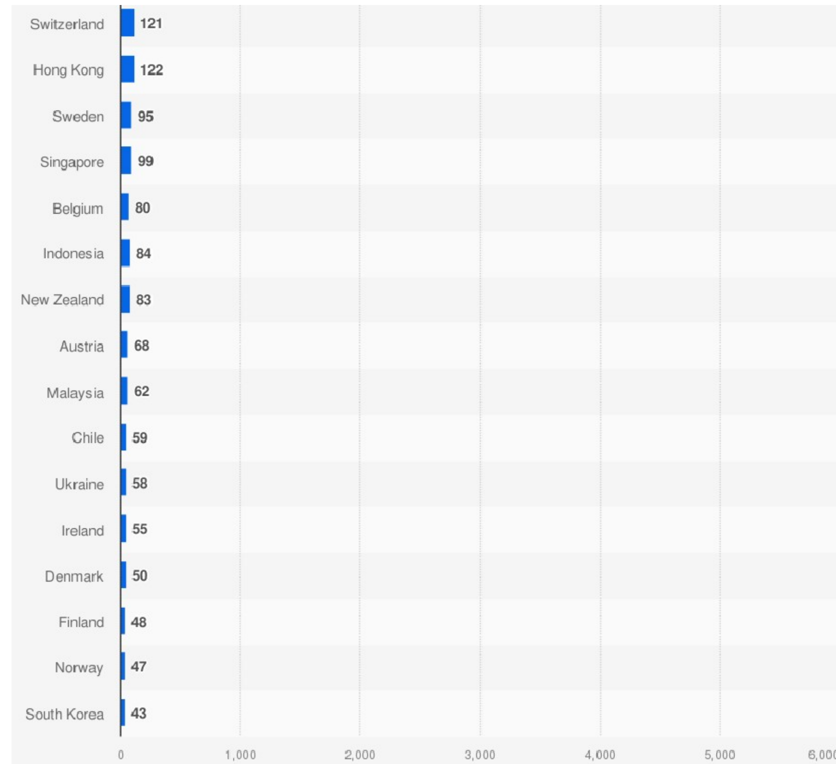



[S. Bouveret – 2024]

# DC locations around the world

❑ An *uneven* geographical distribution of sites

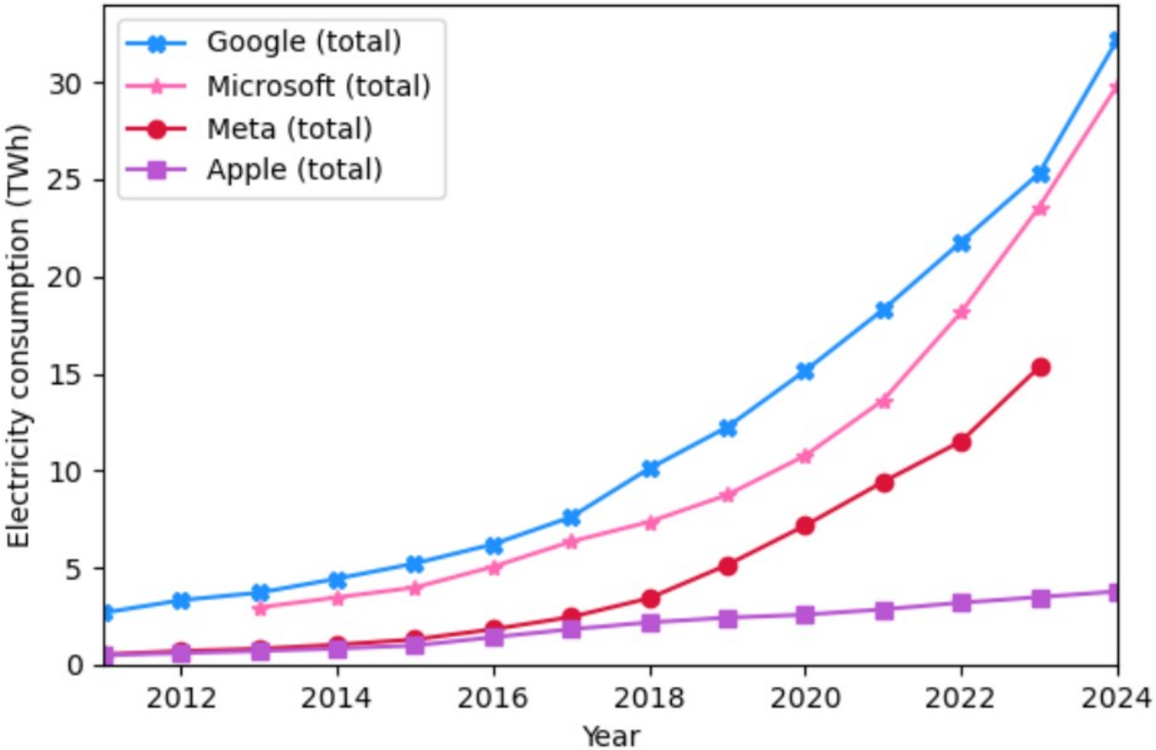



[Statista - 03/2025]

# Strong growth in demand

- Analyse of data 2012-2024
- Source: environmental reports from firms
- Analysis: P. Leboulanger and A.-C. Orgerie (2025)



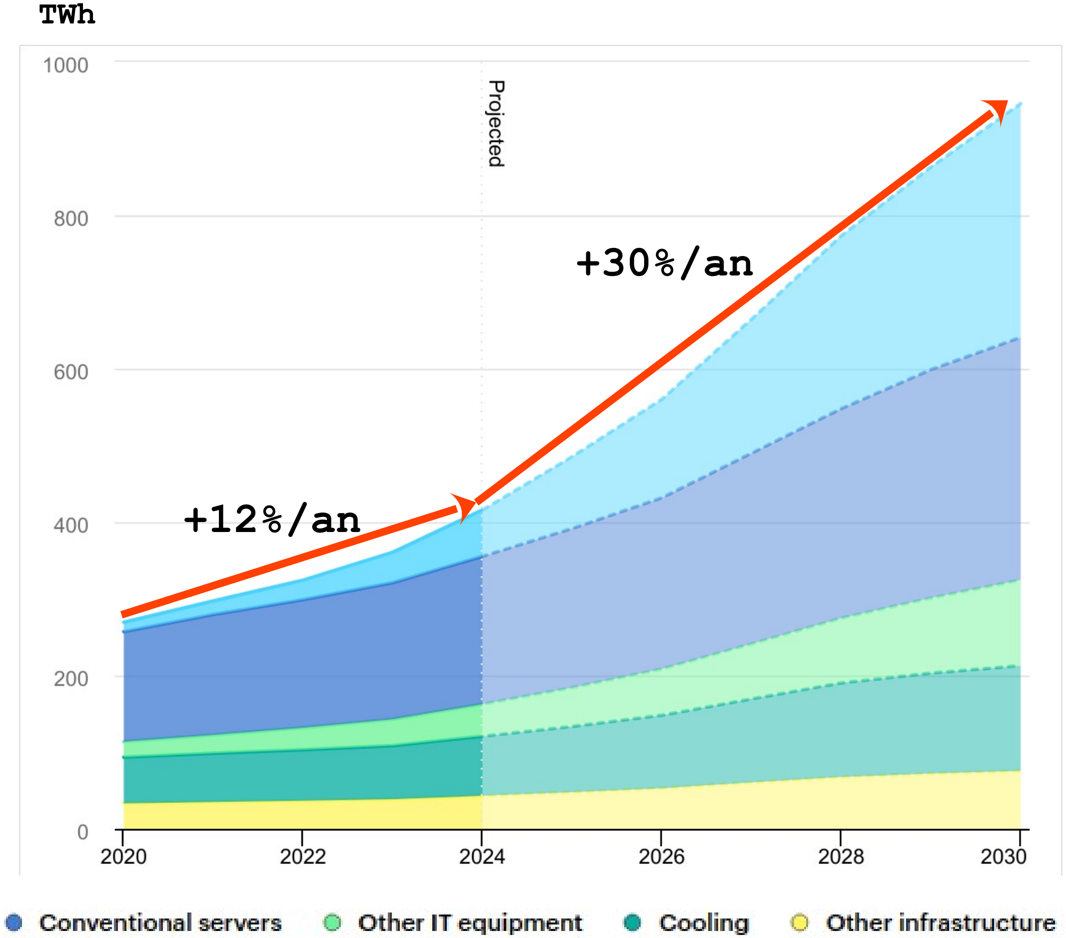

[IC2E - P. Leboulanger & A.-C. Orgerie - 2025]

# DC consumption projections (*base case*)

- 2024: 415 Twh
- 2030
  - 945 Twh (x2)
  - 3% of world consumption

- 12% growth/an → 2017
- 30% growth post 2024

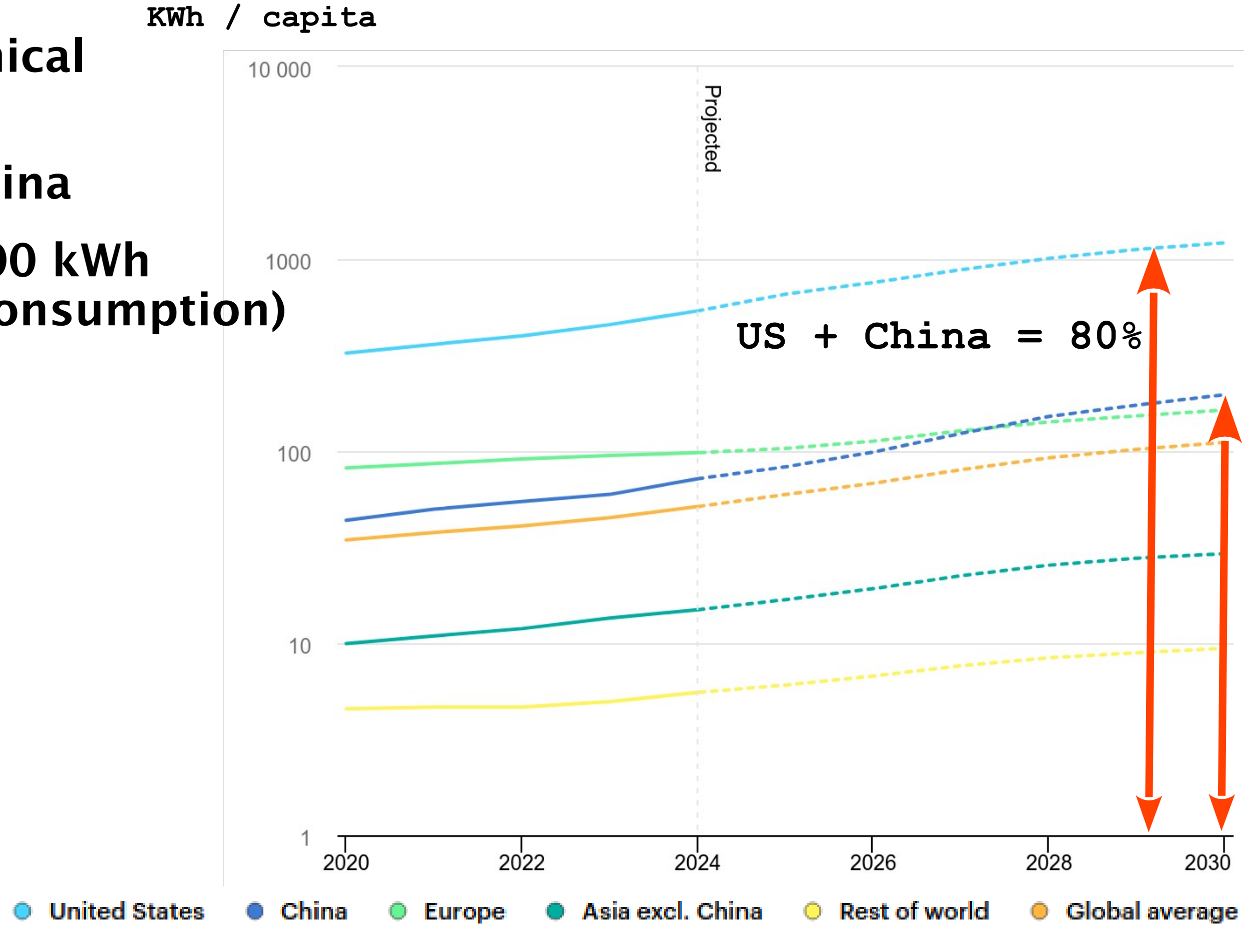
- growth 4x faster than overall consumption




[IEA - Energy And AI - 04/2025]

# *Per capita* DC consumption projections

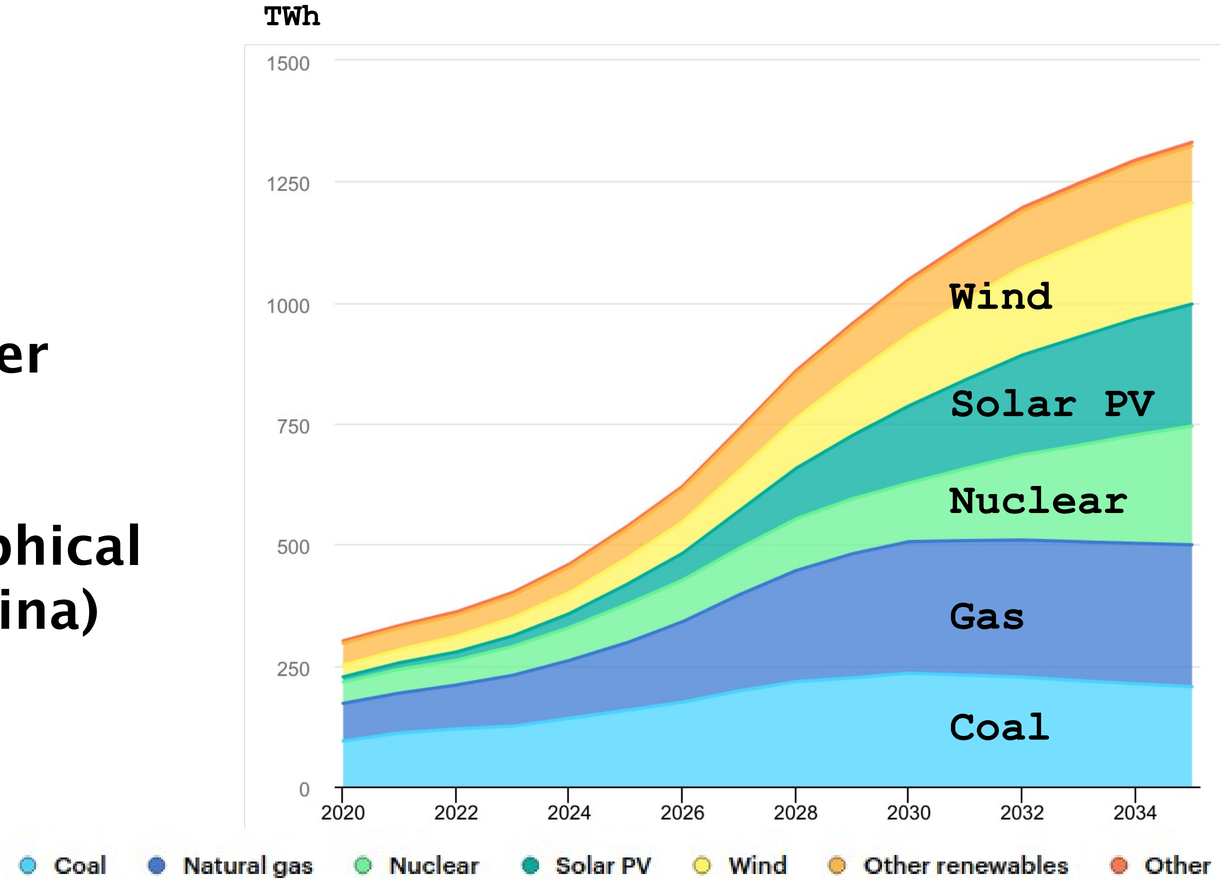
- Significant geographical variations
- 80% growth: US + China
- US : 540 kWh → 1,200 kWh (10% of household consumption)




[IEA - Energy And AI - 04/2025]

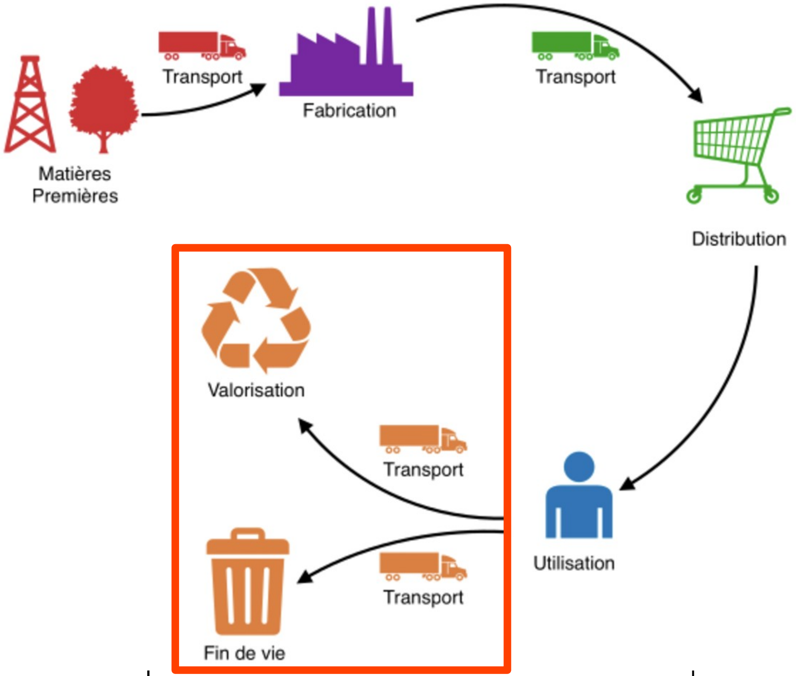
# Energy source projections for DC

- 30 %: Coal
- 27 %: Renewable
- 26 %: Natural gas
- 15 %: Nuclear power
- *Location-based*
- Significant geographical disparity (US vs China)




[IEA - Energy And AI - 04/2025]

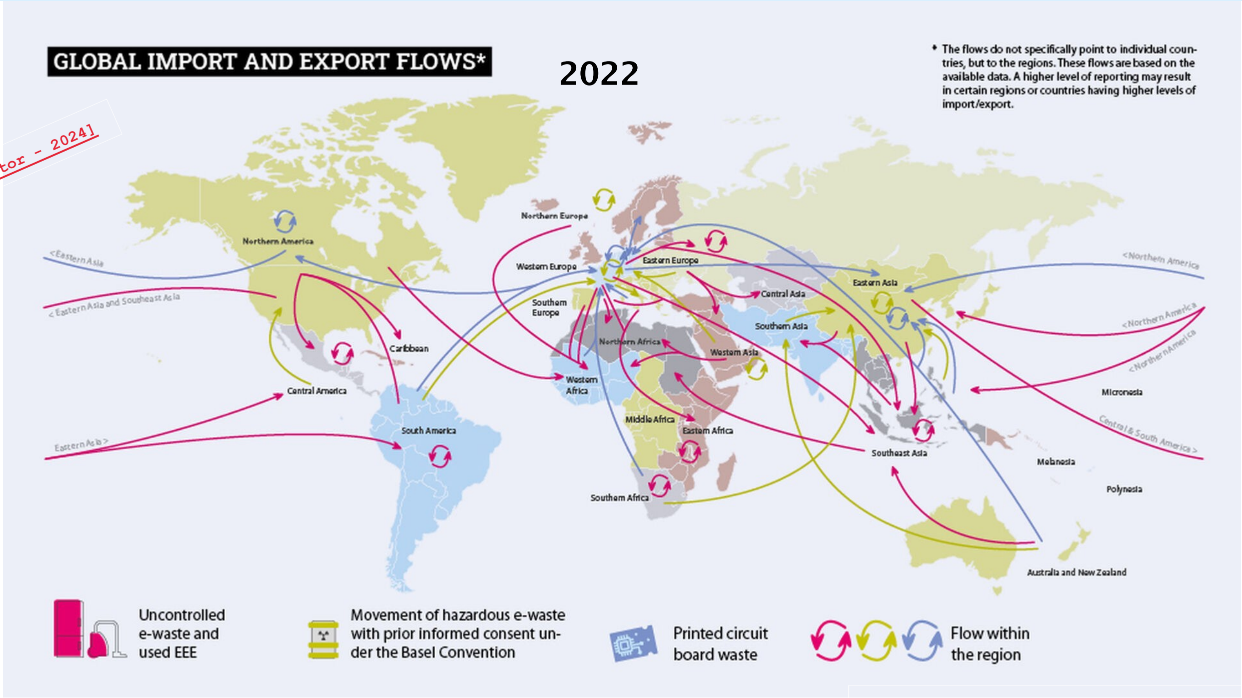
# 2.3.5 End of life



# Flow of WEEE

- Flow of WEEE
  - 2019 : 53Mt WEEE
  - 2022 : 62Mt WEEE (+16%)
  - 7.8 Kg / earthling
  - Growth > 2Mt / year
  - 17%-22 % properly handled
  - What about the 80%
  - Since 2010, growth of WEEE if 5 times faster than collection and recycling

[E-Waste Monitor - 2024]




[Waste Management - 2022]

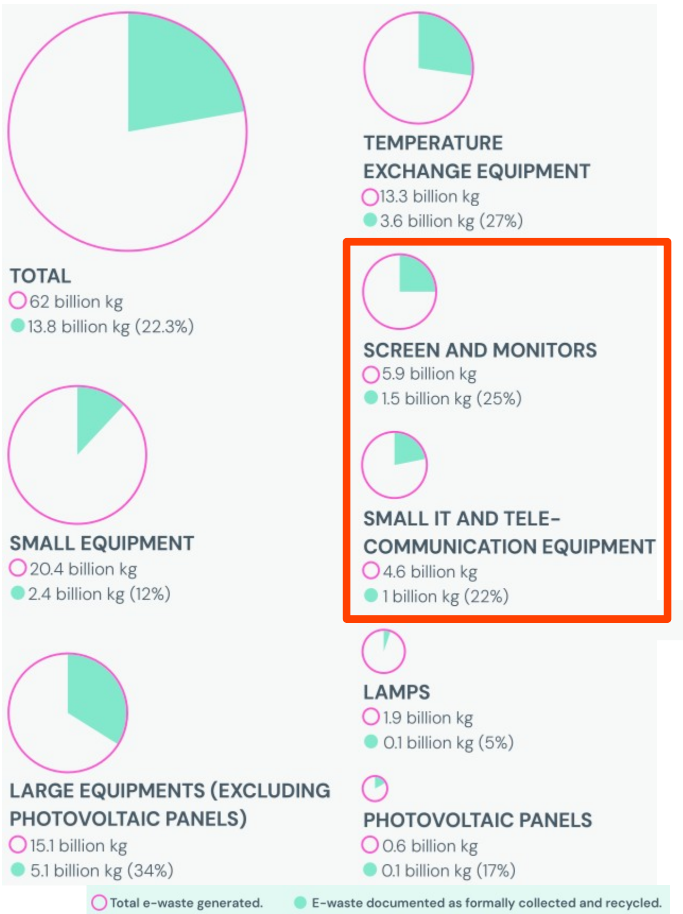
- Flow of WEEE
  - From North to South
  - 10% crosses borders

Informal sector

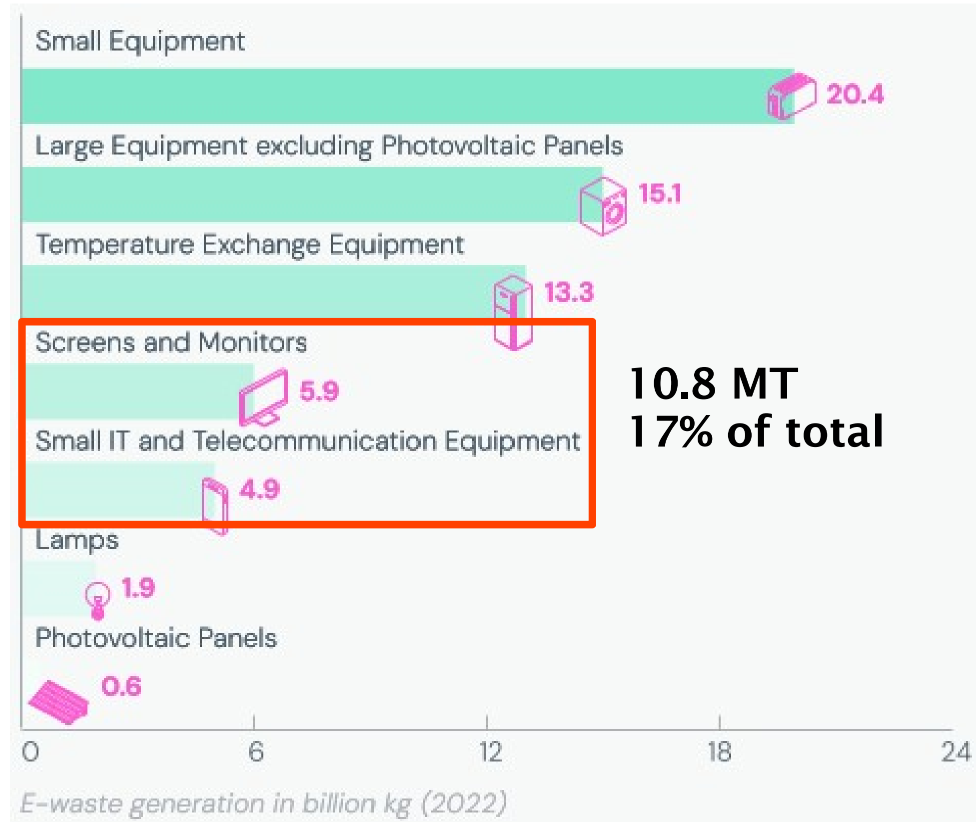
- 13M of women
- 19M children (age >=5)

- **Pollution and destruction are not negative externality but rather the conditions to make low-cost digital technology possible.**

# Part of ICT in WEEE




**Produced / collected and recycled**




**Part of ICT**

[E-Waste Monitor - 2024]

# Hidden part of WEEE

- ❑ **Agbogbloshie landfill (Accra, Ghana)**

[France Inter - 2024] photo Giv Anquetil

[France Info - 2020] photo MUNTAKA CHASANT/SOLENT NE/SIPA

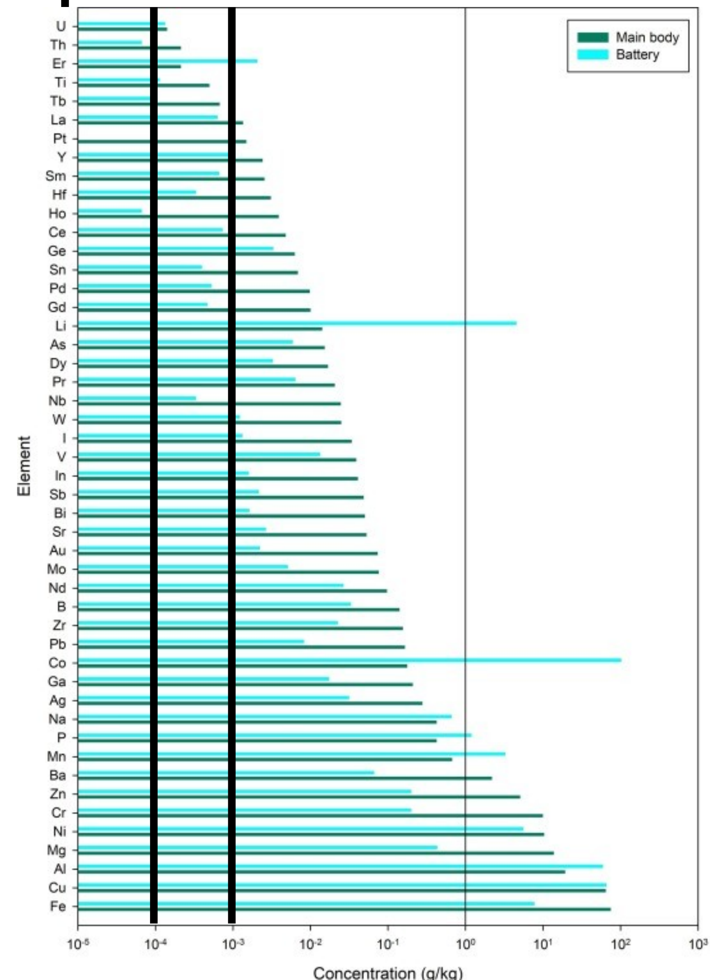
- ❑ **Wiped out in 2021**
- ❑ **Relocated in the neighboring district of Old Fadama**

# Worth of smartphone components

- ❑ **Elements contained in a smartphone with their concentration**
- ❑ **Obtained by grinding and sieving**
- ❑ **$1.10^{-3}$g = mg**

Highlights

- 850 mobile phones processed with minimal pre-processing and industrial shredding.
- In mobile phone bodies, with 278 g/kg of metals, Au is 82.1% of the total price.
- The economic value of recovered metals from 1 kg of phone bodies is $13.41.
- Batteries contained 524 g/kg of metals, with Co, Al, and Cu being dominant elements.
- 1 kg of batteries is valued at $11.37, containing high-value metals like cobalt and gold.



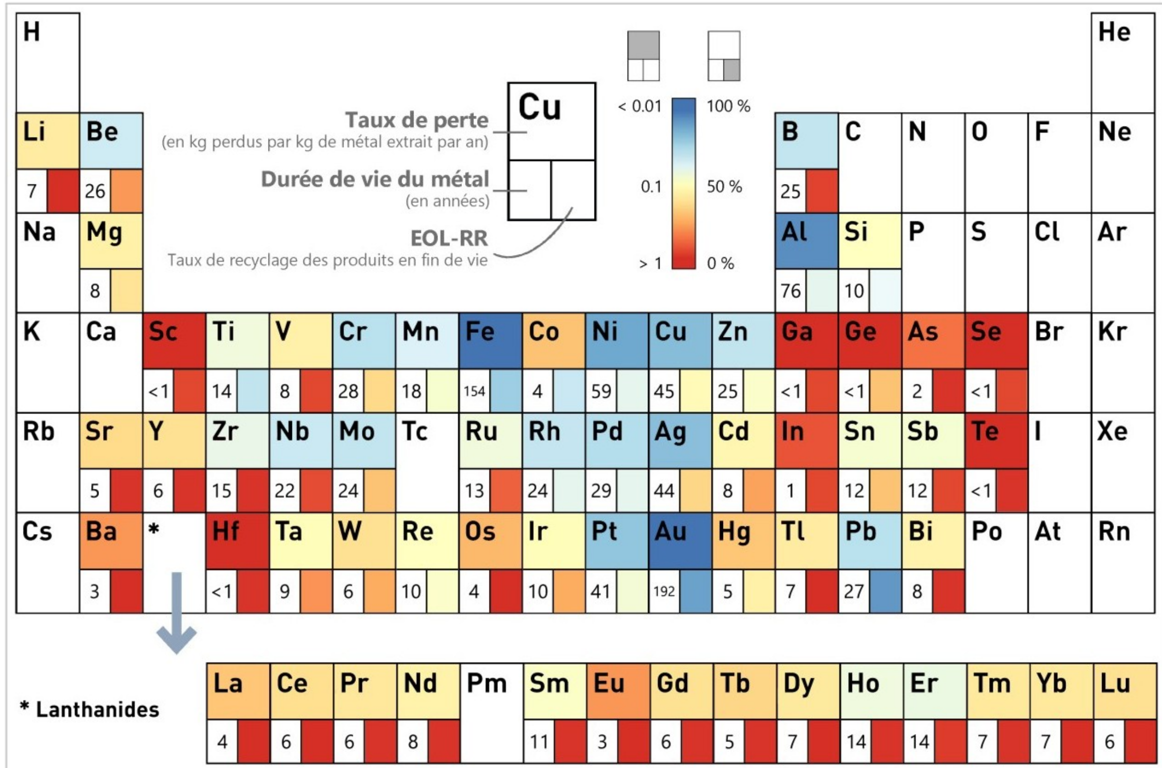

[Morell et al. - 2025]

# Poorly recycled digital technology

- **Loss rate, lifetime and EOL-RR of 61 metals**

[A. Charpentier et al. - 2022]

  - ***Loss rate*: the rate at which extracted metal becomes unavailable for further use**
  - ***Lifespan*: average duration of use in the economy (from extraction to disposal)**
  - ***EndOfLife-Recycling Rate***

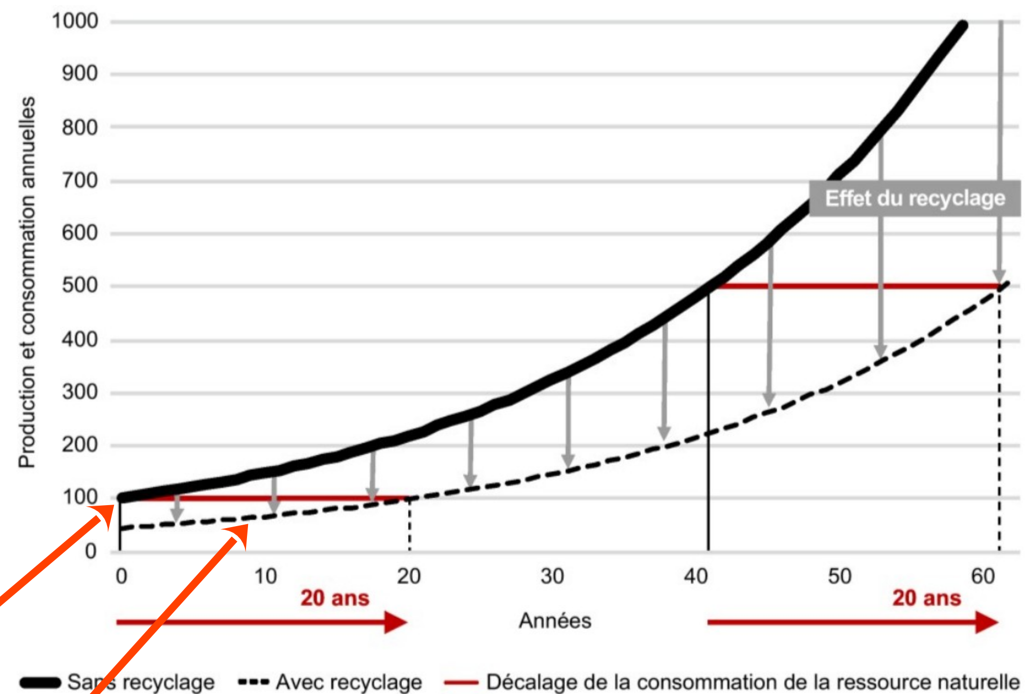



[SYSTEXT - 2024 - p107]

# Recycling that only delays depletion

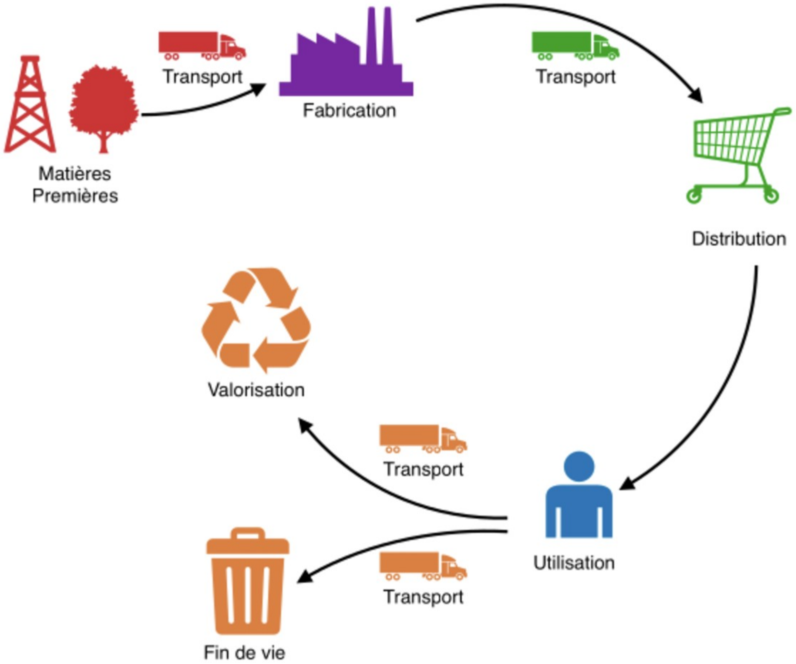
- In a context of growth, recycling only causes a shift in time.
- Asumptions :
  - Constant annual consumption growth rate of 4%.
  - End-of-life recycling rate (EOL-RR) of 80%.
  - Metal residence time in the economy of 10 years.
- Solid curve: change in global consumption of a metal.
- Consumption represents 100 equivalent units for year 1 and 500 units for year 41.
- No recycling: all metal comes from primary resources, so primary production coincides with the solid curve.
- If recycling: only part of the metal comes from primary resources (the rest of consumption is provided by recycled metal), so primary production corresponds to the dotted curve.

[SYSTEXT - 2024 - p164]

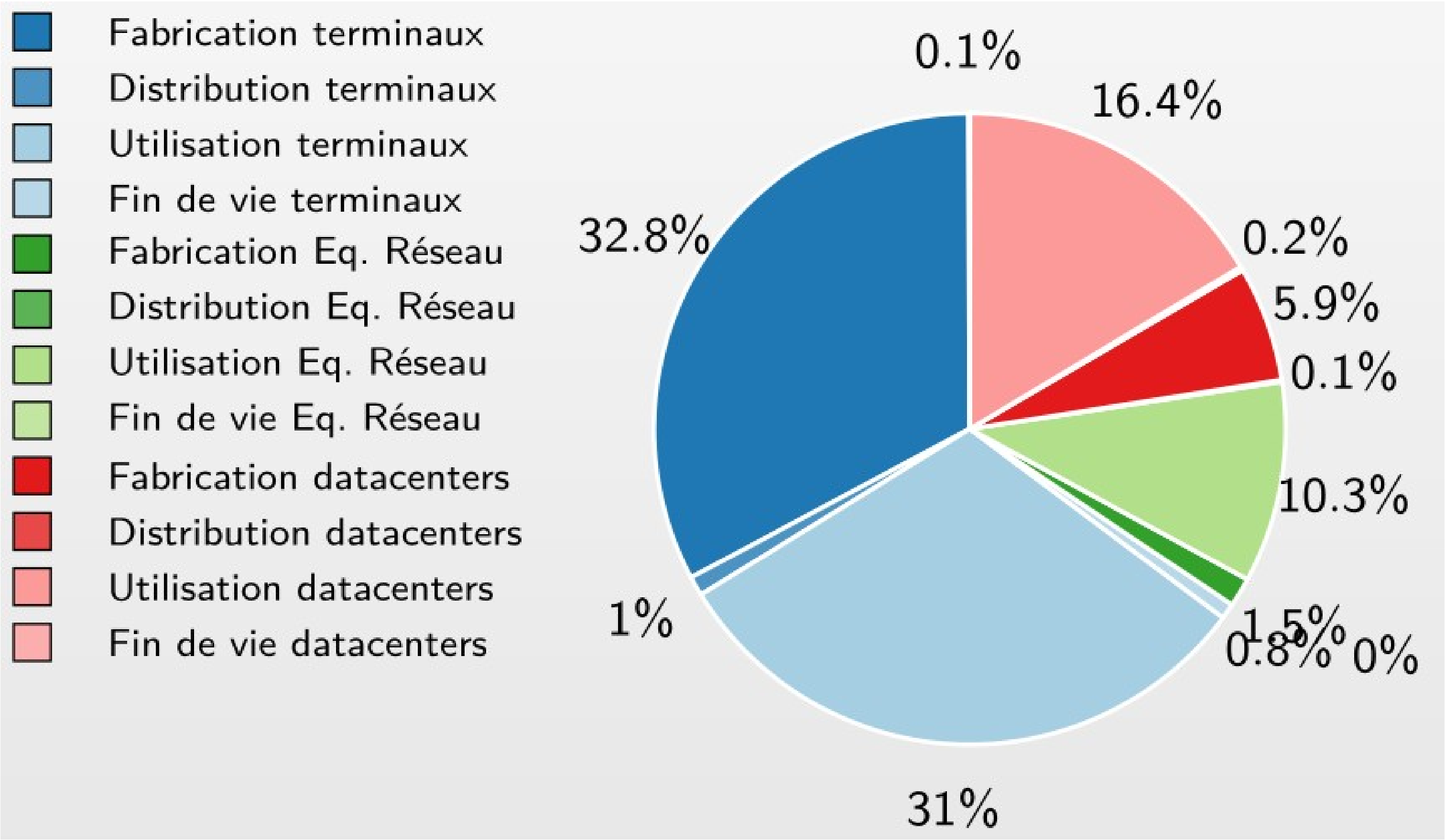



- Global consumption increases by 4% each year → the share of production that comes from primary resources also increases by 4% each year, even though the amount of recycled metal is also growing exponentially (gray downward arrows between the two curves). Thus, after 20 years, primary production in the case of recycling corresponds to 100 units, whereas it would amount to just over 200 units in the absence of recycling.
- Similarly, after 60 years, primary production with recycling corresponds to 500 units, whereas it would amount to more than 1,000 units without recycling. In other words, the curve with recycling for year 60 is equal to the curve without recycling for year 41.
- Conclusion: Based on these assumptions, the depletion of primary resources is only delayed by 20 years, even if the amount recycled increases exponentially (e.g., in year 40, the amount of metal recycled is five times higher than in year 1).

# 2.3.6 Additional data



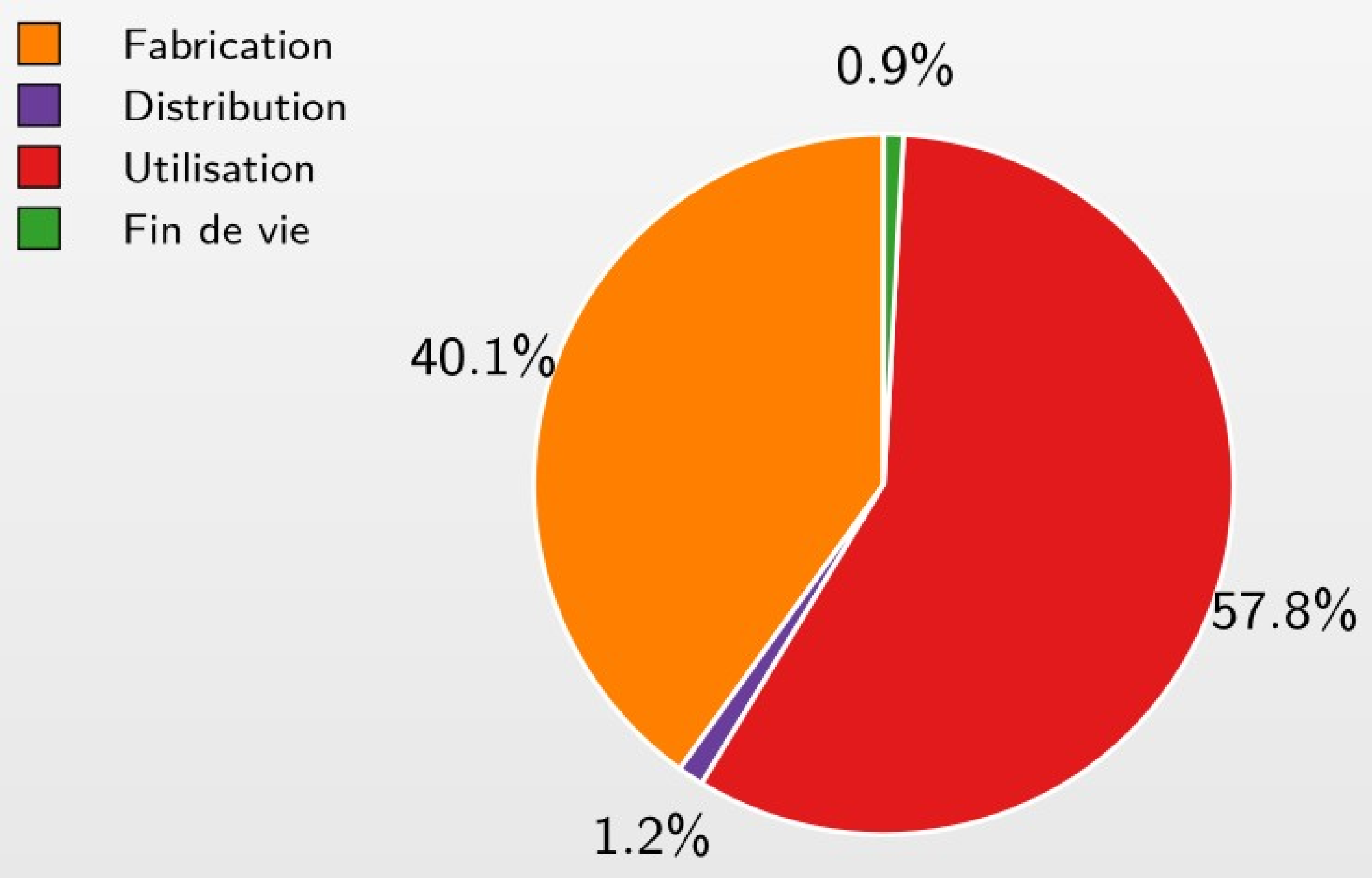
# Emissions by product (Europe)




[S. Bouveret - 2024]

[Bordage et al. - 2021 - p 35]

# Emissions by life cycle stage (Europe)




[S. Bouveret - 2024]

[Bordage et al. - 2021 - p 35]

# 2.4 Second order effect

| Type | Perimeter | Effect | Examples |
|---|---|---|---|
| 1st order **Direct** | Technology Itself | Life Cycle Impact Of Hardware | production (energie, resources), use (energie), end-of-life (pollution) |
| 2nd order **Indirect** | Use and applications | Optimization | smart-* |
| | | Substitution | dematerialization - walkman + photo -> smartphone |
| 3rd order **Structural Behavioral** | Consumer Producers | obsolescence induction | 5G printer -> paper |
| | | direct rebound and indirect | devices, uses consumption |
| | Economy | economic growth | new markets |
| | | acceleration | e-commerce (24/7), logistics |
| | Society | reconfiguration | Über |

[N.C. Horner et al. - 2016]
[J. Combaz - 2023 - EJCP]

# Effets indirect

- **Optimization, efficienciency**

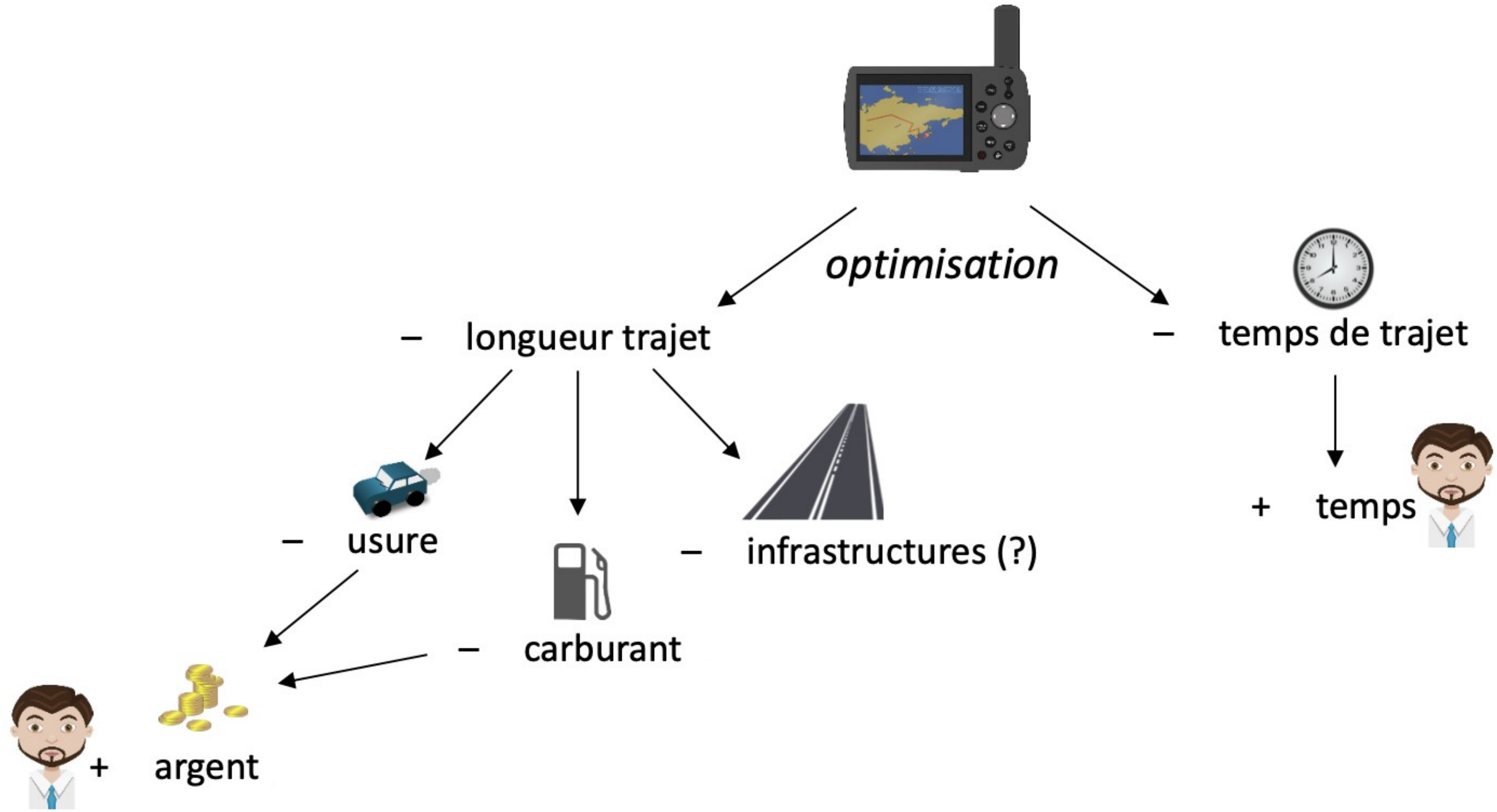
| Type | Perimeter | Effect | Examples |
|---|---|---|---|
| 1st order **Direct** | Technology Itself | Life Cycle Impact Of Hardware | production (energie, resources), use (energie), end-of-life (pollution) |
| 2nd order **Indirect** | Use and applications | Optimization | smart-* |
| | | Substitution | dematerialization - walkman + photo -> smartphone |
| 3rd order **Structural Behavioral** | Consumer Producers | obsolescence / induction | 5G / printer -> paper |
| | | direct rebound / and indirect | devices, uses consumption |
| | Economy | economic growth | new markets |
| | | acceleration | e-commerce (24/7), logistics |
| | Society | reconfiguration | Über |

[J. Combaz - 2023 - EJCP]

- **Indirect effect that may result from better resource allocation or streamlining of processes**
- **Technical process but with potential social consequences (e.g., Linky meter, which helps optimize consumption)**
- **This is generally a positive effect**

[G. Roussilhe - 2022 - Blog]

# Example : GPS




[J. Combaz - 2023 - EJCP]

# Indirect effects

## ❑ Substitution

| Type | Perimeter | Effect | | Examples | |
|---|---|---|---|---|---|
| 1st order **Direct** | Technology Itself | Life Cycle Impact Of Hardware | | production (energie, resources), use (energie), end-of-life (pollution) | |
| 2nd order **Indirect** | Use and applications | Optimization | | smart-* | |
| | | Substitution | | dematerialization - walkman + photo -> smartphone | |
| 3rd order **Structural Behavioral** | Consumer Producers | obsolescence | induction | 5G | printer -> paper |
| | | direct rebound | and indirect | devices, uses consumption | |
| | Economy | economic growth | | new markets | |
| | | acceleration | | e-commerce (24/7), logistics | |
| | Society | reconfiguration | | Über | |

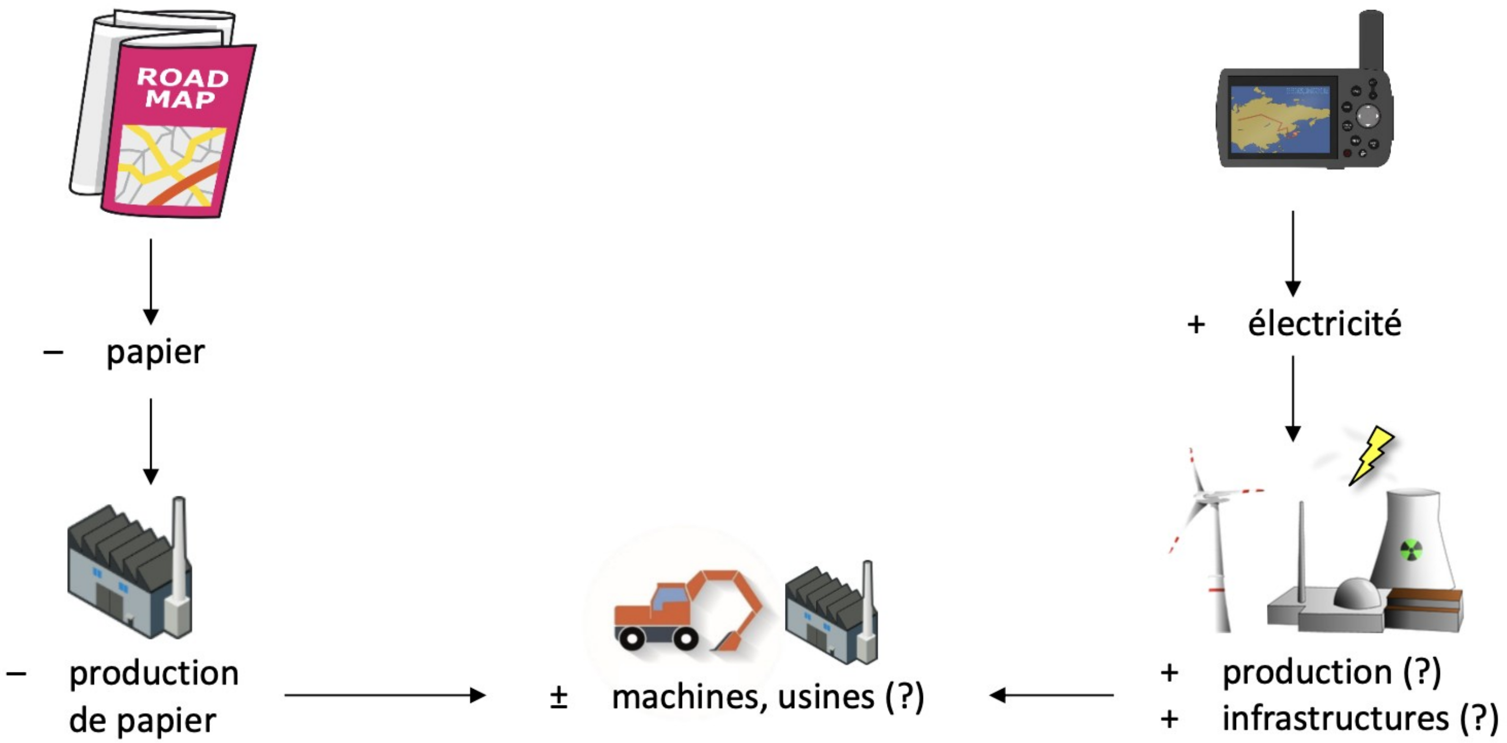
[J. Combaz - 2023 - EJCP]

- ❑ Indirect effect consisting of replacing a product or service with a product or service that has a lower environmental impact (e.g., switching from CRT to LCD screens).
- ❑ The paradigmatic example is the smartphone (which produces *substitution*, *accumulation*, and *extension*, even *symbiosis*).

Everything in this picture is now in your pocket.

[G. Roussilhe - 2022 - Blog]

# Example  : GPS



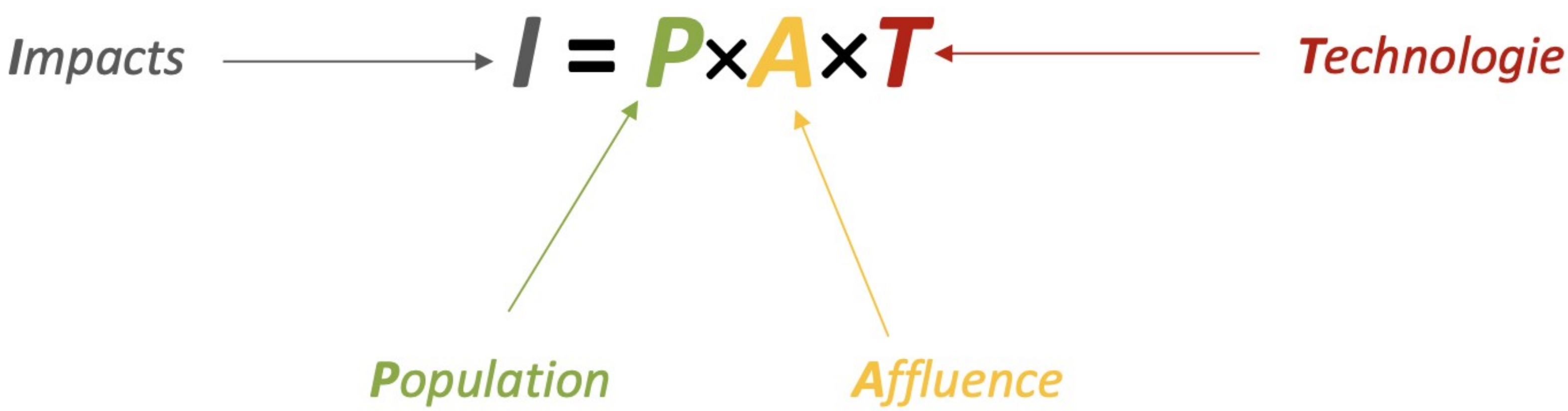

[J. Combaz - 2023 - EJCP]

# Rebound effect (Jevons' paradox – 1865)

- **Direct**
  - More efficient use of resources (efficiency gains) increases consumption (e.g., steam engines, cars, insulation in Germany, etc.).
- **Indirect**
  - Indirect rebound effect when gains made in one area generate consumption in another area
- **The drive for efficiency can lead to rebound effects due to reinvested savings or reduced guilt about consuming other products**

# Understanding the impact

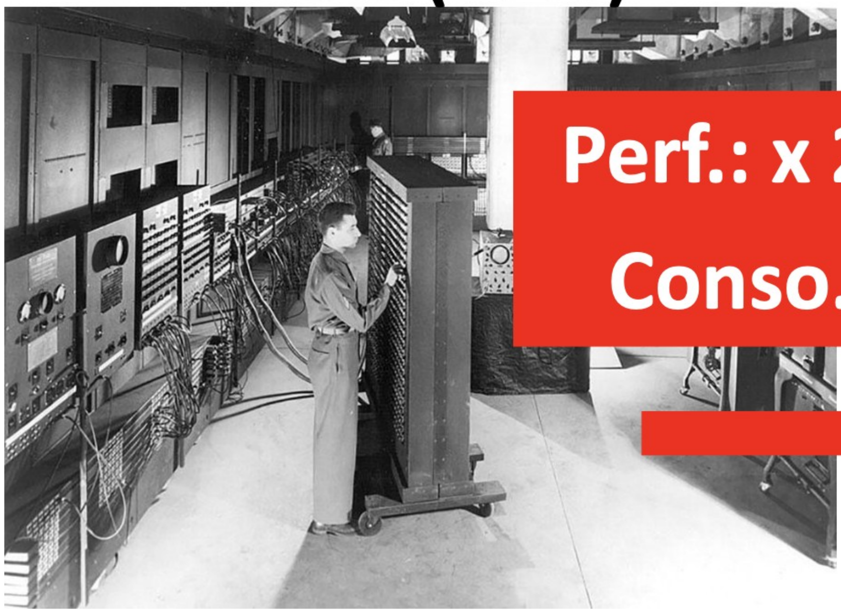
- Variation on Kaya's equation



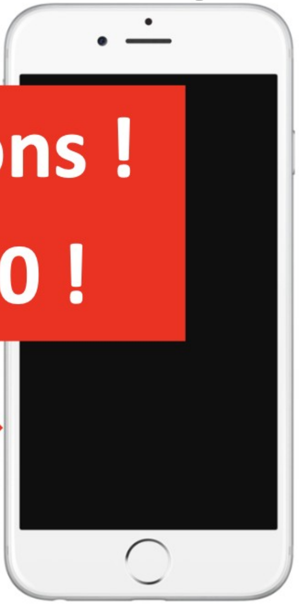

[J. Combaz - 2023 - EJCP]

# Rebound effect: from the ENIAC to the iPhone 6

## ENIAC (1945)



## iPhone 6 (2014)



**Perf.: x 260 millions !**

**Conso. : ÷ 75 000 !**

ENIAC (1945):

- Poids : 30 t
- Dim. : 30,5 m × 2,4 × 0,9 (167 m²)
- Conso. : 150 kW
- Perf. : ~500 FLOPS

iPhone 6 (2014):

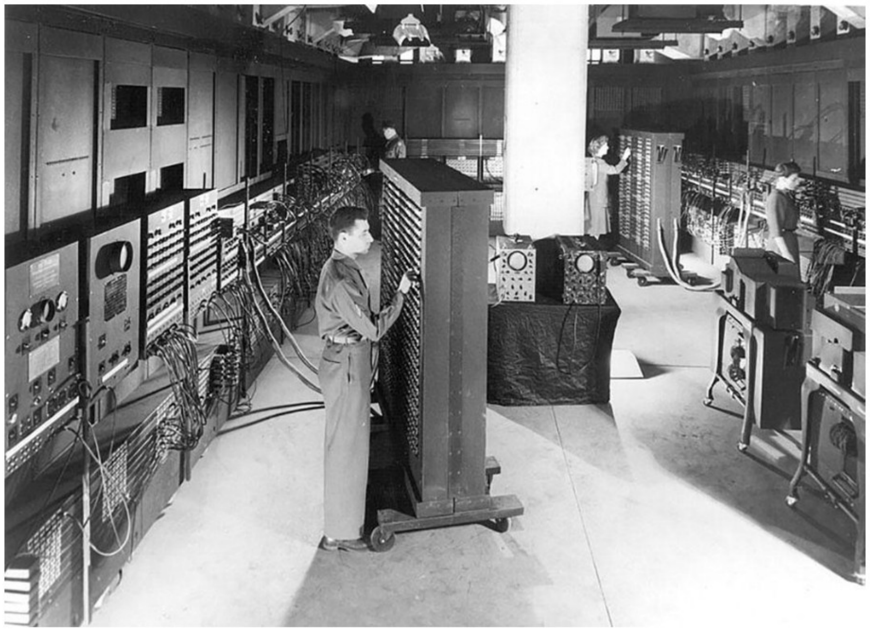
- Poids : 130 g
- Dim. : 158,1 × 77,8 mm × 7,1 mm
- Conso. : ~2 W
- Perf. : ~130 GFLOPS

imag

[J. Combaz - 2023 - EJCP]

# Rebound effect: from the ENIAC to the iPhone 6

**ENIAC**




**150 kW (in operation)** → **×1,7 millions** → **260 GW (continuously)**

[J. Combaz - 2023 - EJCP]

# IT for green : « *Enabling effects* »

- Enabling effects: induction of positive indirect effects by technology
- Do we have *enabling effects* for digital technology?


[L'esprit critique - S3E30]

# IT for green : « *Enabling effects* »

- **Enabling effects: induction of indirect effects using tech.**
- **À ce jour on dispose de**
  - **Two studies that mention effects of this type for digital technologies:** [GESI -2015] [GSMA - 2019]
  - **These studies suffer from significant methodological weaknesses:** [G. Roussilhe et al. - 2023] [G. Roussilhe - 2022 - Blog]
  - **These studies do not take into account *indirect rebound effects*.**

### 3.1 Enabling effects

To the best of our knowledge, no scientific publication so far has provided an assessment of the global (current or potential) enabling effects of digitization for GHG emissions mitigation[2]. Still, two claims have been widely shared amongst stakeholders and tech companies since 2015: that digitization could reduce global GHG emissions by up to 20% (12 GtCO2e) in 2030 according to GeSI [16], a partnership of companies from the ICT sector; and that mobile communication technologies enabled the avoidance of 2.1 GtCO2e in 2018 according to GSMA [17], the association representing the interests of mobile operators worldwide. Both reports show major methodological flaws and their results should be used with extreme caution, as we explain below.

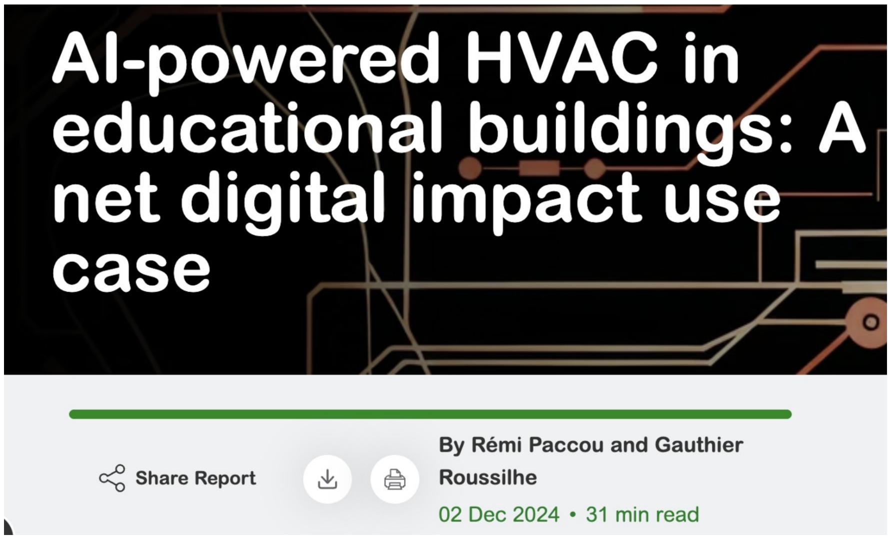
[G. Roussilhe et al. - 2023]

# IT for green : « *Enabling effects* »

- Enabling effects: induction of indirect effects using tech.
- À ce jour on dispose de
  - Two studies that mention effects of this type for digital technologies: [GESI -2015] [GSMA - 2019]
  - These studies suffer from significant methodological weaknesses: [G. Roussilhe et al. - 2023] [G. Roussilhe - 2022 - Blog]
  - These studies do not take into account *indirect rebound effects*.
- In general
  - The work focuses on the benefits
  - Has results that contradict observation
  - Is based on optimistic assumptions
- Analysis of methodological weaknesses [G. Roussilhe - 2022 - Blog]

# A net positive effect of digitization

❑ **Study conducted in 2024 by R. Paccou and G. Roussilhe**




[R.Paccou & G. Roussilhe - 2024]

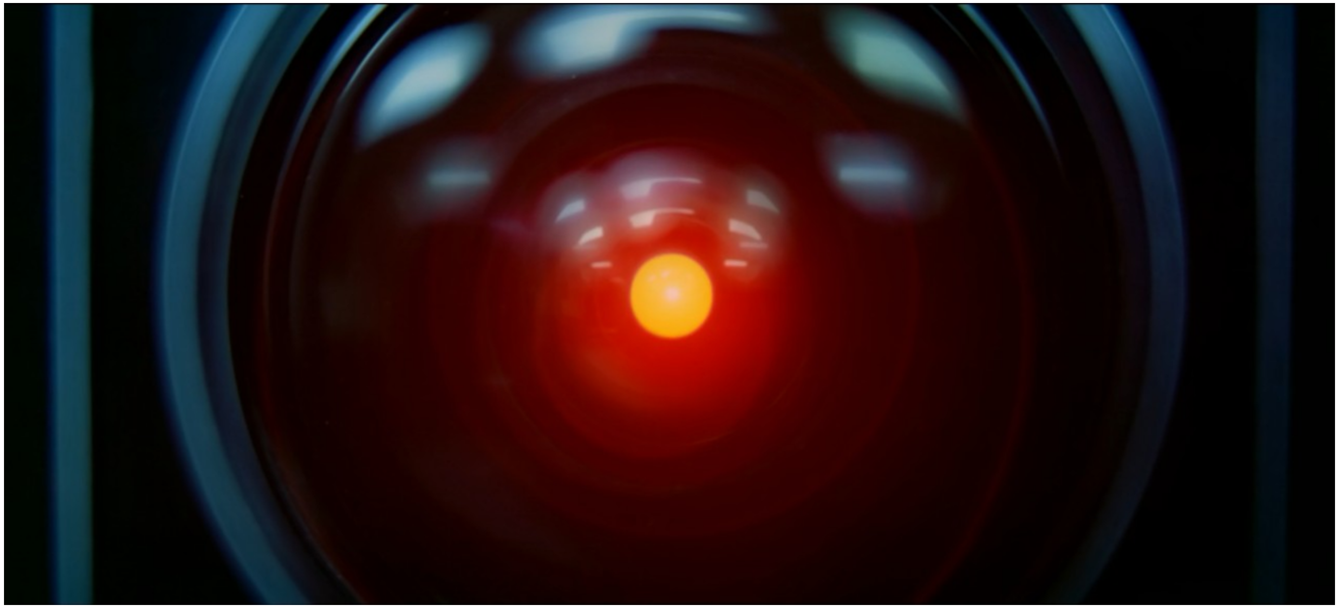
## Conclusions

### Key Insights On The Results

**Key Insight 1:** Demonstrating Significant Positive Impacts with a Favorable Carbon Cost-Benefit Ratio of 1:60 per year

Our study reveals the substantial potential of AI-Powered HVAC systems in buildings, showcasing notable energy savings and carbon emission reductions. Between 2019 and 2023, we observed a 3.12% reduction in district heating consumption and an impressive 8.93% decrease in electricity consumption. These improvements translated to significant carbon emission reductions: 109.87 $tCO_2e$ from district heating and 149.30 $tCO_2e$ from electricity, totaling 259.17 $tCO_2e$ over the four-year period. The results indicate a favorable 1:240 carbon cost-benefit ratio per year, highlighting the efficiency of the system. While these findings are encouraging, we recognize the importance of further research to validate these effects across diverse building types and geographical locations, paving the way for more widespread adoption and optimization of AI-powered HVAC systems.

# 3 And came mainstream AI



[S. Kubrick - 2001: A Space Odyssey - 1968]

# Multiple perspectives

- A subject at the intersection of multiple fields
  1) Legal (learning, use, data, etc.)
  2) Philosophical (intelligence, thinking, cognitive tasks, etc.)
  3) Economical (data centers, GPUs, global transformation, etc.)
  4) Social (surveillance, employment, training, etc.)
  5) Societal (arts, culture, human/algorithm relations, etc.)
  6) Political (ownership, decision-making, governance, etc.)
  7) Technological (global purpose technology)
  8) And… environmental (solutions, resources, impacts, etc.)

# 3.1 Definition attempt


[S. Jonze - Her - 2013]

# What are we talking about?

- According to the EU *Artificial Intelligence Act* (02/02/2025) [EU – 2025]

## Article 3: Definitions

Date of entry into force: 2 February 2025

According to: Article 113(a)

Inherited from: Chapter I

See here for a full implementation timeline.

SUMMARY +

For the purposes of this Regulation, the following definitions apply:

(1) 'AI system' means a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments; Related: Recital 12

# Socio-technologico-political definition

- According to EU *Artificial Intelligence Act* (02/02/2025)
- AFNOR: reuses EU's definition
- K. Crawford (NYU & Microsoft) "The atlas of AI" [K. Crawford - 2022]

I argue that AI is **neither artificial nor intelligent.** Rather, artificial intelligence **is both embodied and material**, made from **natural resources, fuel, human labor, infrastructures, logistics, histories, and classifications.** AI systems are not autonomous, rational, or able to discern anything without **extensive, computationally intensive training with large datasets or predefined rules and rewards.** In fact, **artificial intelligence** as we know it **depends entirely on a much wider set of political and social structures.** And due to the capital required to build AI at scale and the ways of seeing that it optimizes **AI systems are ultimately designed to serve existing dominant interests. In this sense, artificial intelligence is a registry of power.**

[...] how artificial intelligence is made, in the widest sense, and the economic, political, cultural, and historical forces that shape it. Once we connect AI within these broader structures and social systems, **we can escape the notion that artificial intelligence is a purely technical domain.** At a fundamental level, **AI is technical and social practices, institutions and infrastructures, politics and culture.** Computational reason and embodied work are deeply interlinked: **AI systems both reflect and produce social relations and understandings of the world.**

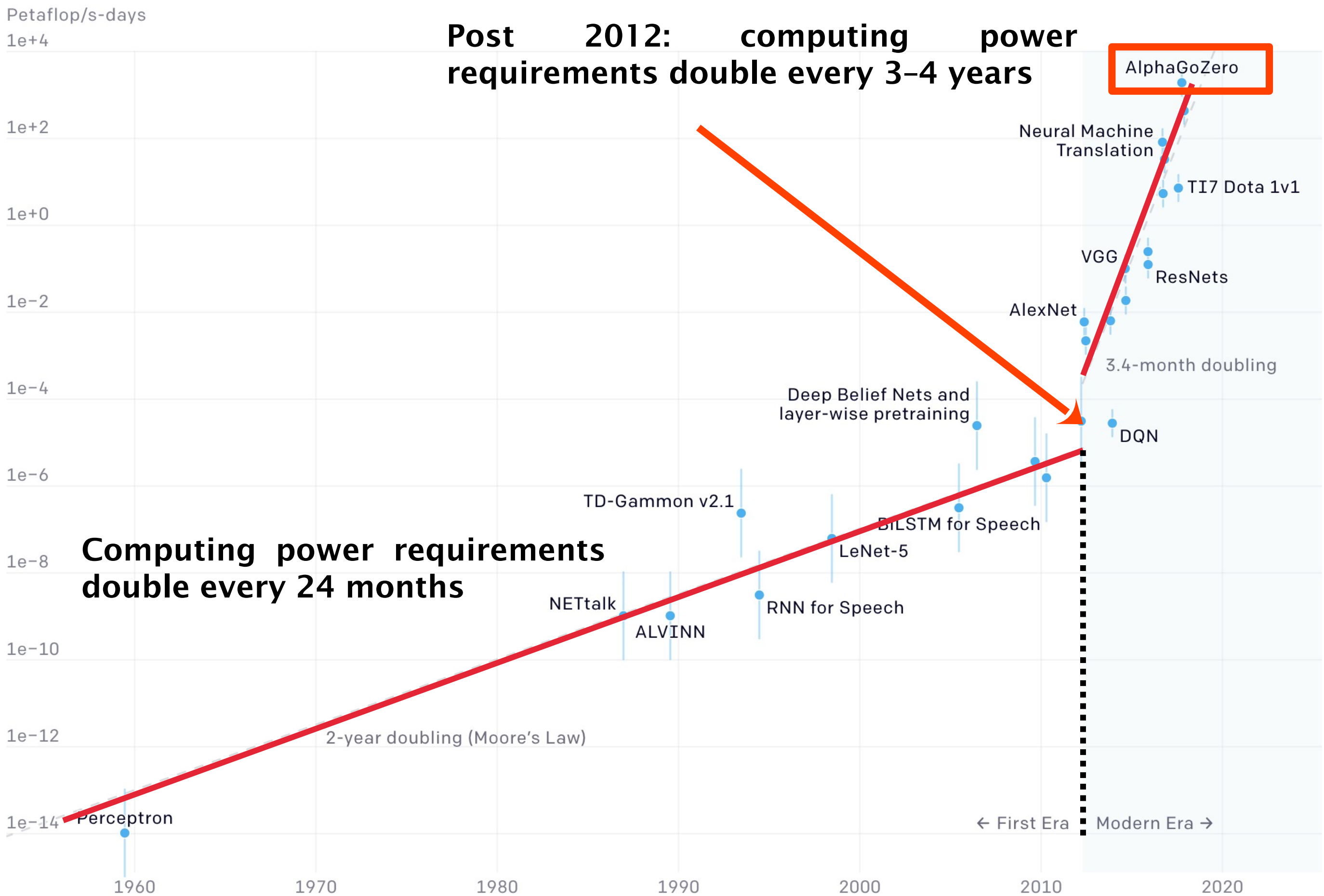
# 3.2 IA and resources

# The great acceleration since 2012

Mega = $10^6$
Giga = $10^9$
Tera = $10^{12}$
Peta = $10^{15}$
Exa = $10^{18}$
Zetta = $10^{21}$
Yotta = $10^{24}$

**Post 2012: computing power requirements double every 3-4 years**

**Computing power requirements double every 24 months**




[Blog AI Compute - 05/2018]

# Generative AI: the acceleration accelerates

```
Mega  = 10^6
Giga  = 10^9
Tera  = 10^12
Peta  = 10^15
Exa   = 10^18
Zetta = 10^21
Yotta = 10^24
```

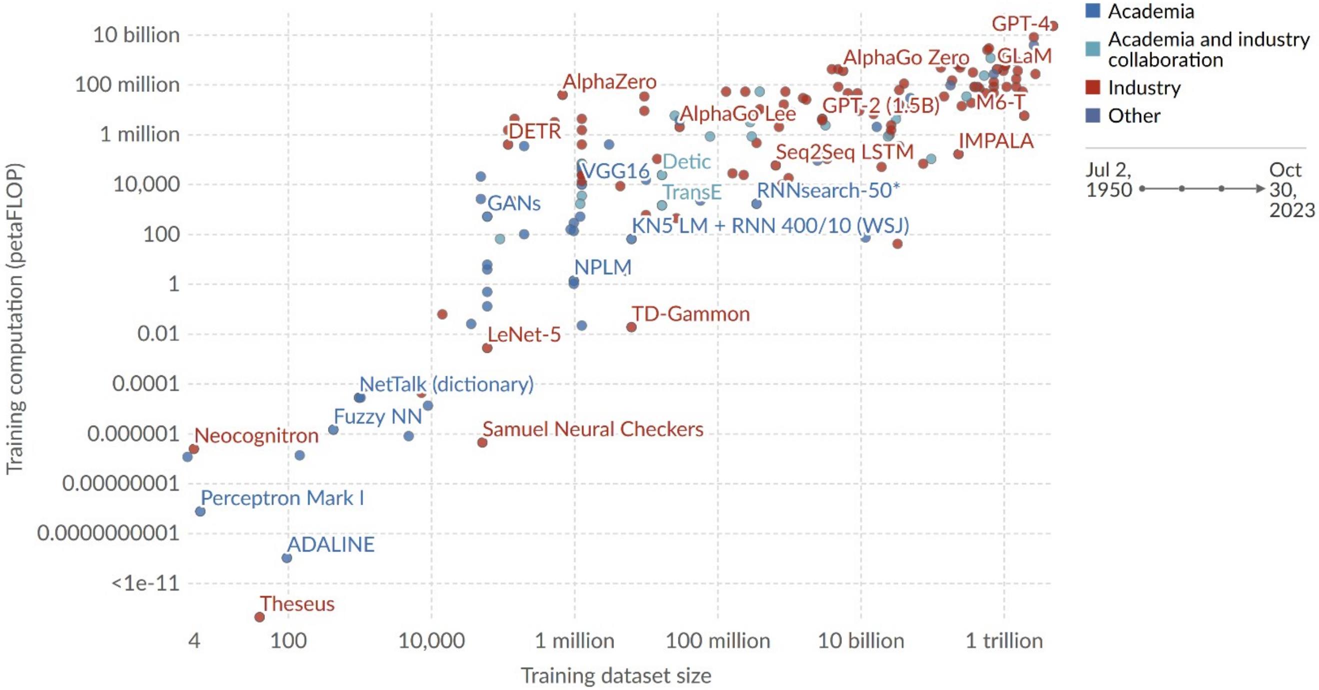
- The tsunami of generative AI (enables the rapid generation of text, images, multimedia, etc., and produces results that are statistically close to a model)
- See J. Sevilla *et al.* – 2022 on available models


[J. Sevilla et al – 2022]

# Large amount of data used

## Training computation vs. dataset size in notable AI systems, by researcher affiliation

Computation is measured in total petaFLOP, which is $10^{15}$ floating-point operations[1] estimated from AI literature, albeit with some uncertainty. Training dataset size refers to the volume of text that is employed to train a model effectively.




**Data source:** Epoch (2024)

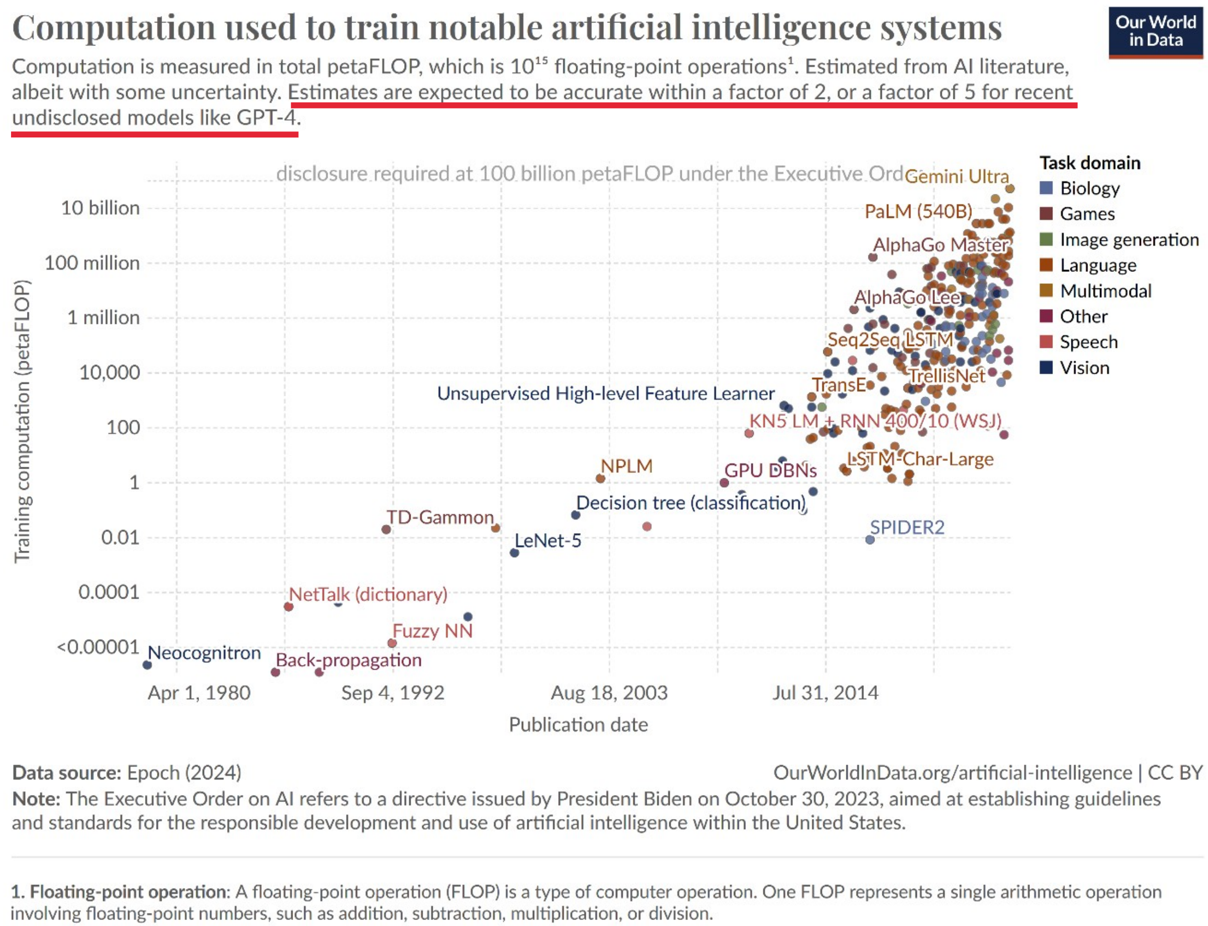
OurWorldInData.org/artificial-intelligence | CC BY

1. **Floating-point operation**: A floating-point operation (FLOP) is a type of computer operation. One FLOP represents a single arithmetic operation involving floating-point numbers, such as addition, subtraction, multiplication, or division.

# Generative AI: the acceleration accelerates

Mega = $10^6$
Giga = $10^9$
Tera = $10^{12}$
Peta = $10^{15}$
Exa = $10^{18}$
Zetta = $10^{21}$
Yotta = $10^{24}$

- GPT
  - 2018
  - 17 600 petaFLOPS
- ×84
- GPT-2
  - 2019
  - 1,49M petaFLOPS
- ×228
- GPT-3
  - 2020
  - 341M petaFLOPS (341 zetaFLOPS)
- ×61
- GPT-4
  - 21B petaFLOPS (21 yottaFLOPS)

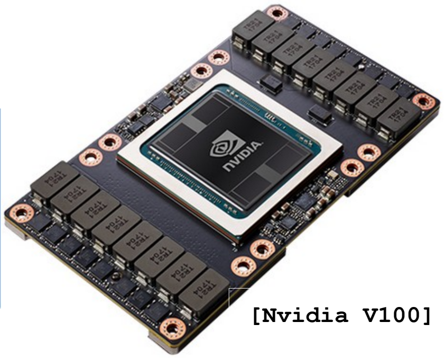



[C. Giattino et al - 2023]

# Training GPT-3 - OpenAI

- **Models are trained on GPUs**
- **Gpt 3 (a somehow old version)**
  - Data set used for training: 45 To of data
  - Computation time: 355 ans on a single V100
  - Model: 176B parameters
  - Training on 10k NVIDIA V100 (2017) by Microsoft
  - Durée: 10 jours
  - Training: 552 tons eCO2 and 1,2 GWh of electricity
  - 05/2024  : 10M users/day requiring 564 MWh of electricity

GPT-3



[Nvidia V100]

[D. Trystram & T. Ménissier - 2024]

# Using GPT - OpenAI

- ❑ Models are trained on GPUs
- ❑ Gpt 3 (a somehow old version)

GPT-3

[Nvidia V100]

- ❑ ~~05/2024 : 10M users/day requiring 564 MWh d'électricité~~
- ❑ 07/2025 : 2,5B prompts per day (according to S. Altman) [techCrunch - 07/2025]

- ❑ Look at [Stanford AI index - 2025] for additional informations

# Paradigm shift

- Ai requires resources
  - Training phase – 10%
  - Use phase (*inference*) – 90%
- Significant change
  - Previously, compiled code ran on data
  - Low resource consumption (near to zero marginal computing cost)

6/11/2025 - The Minds of Modern AI: J. Huang, G. Hinton, Y. LeCun & the AI Vision of the Future

[YT - 6/11/2025]

## The use phase

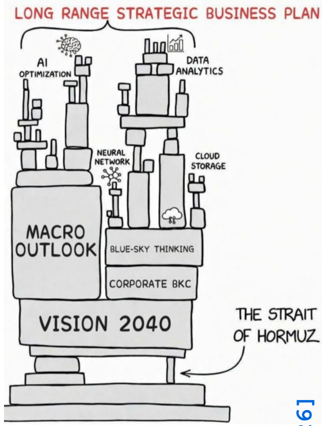
- Requires to take the (large) context into account
- Results generated in real time

# 4 Conclusion

[Lars Lundström - Äkta människor - 2012]

# Numérique : maladie infantile de nos sociétés ?

- **Le numérique (et l'IA), un géant aux pieds d'argiles**
  - Système socio-technique construit comme un *illimitisme*
  - Non-soutenable *par design*
    - Reposant sur des stocks non renouvelables
    - Nécessitant beaucoup d'énergie et de puissance
  - Impact environnemental important (du berceau au tombeau)
  - Soumis à une géopolitique complexe
- **Un chemin possible pour un futur collectif**
  - Prendre soin des infrastructures existantes
  - Innover par soustraction
  - Politiser les enjeux techniques
  - Dé-numériser ce qui est possible
  - Renforcer les architectures souveraines et sobres




He(lium)
Qatar: 34%

[USGS – 2026]

Lewis Carroll – Through the looking glass