

## **3IF - REVE (Ressources, Enjeux du Vivant, Énergie)**

**Can ICT help us meet everyone's needs within the planet's boundaries?**

Christine Solnon (CITI, INSA Lyon / INRIA)

2026

Acknowledgement: This talk has been enriched by discussions with Françoise Berthoud, Sylvain Bouveret, Aurélie Bugeau, Hadrien Cambazard, Serge Fenet, Alexandre Gondran, Anne-Laure Ligozat, and Sophie Quinton (among others).

Many slides are from Sylvain Bouveret.

# REVE : Ressources, Enjeux du Vivant & Énergie (1/2)

**Objectif : Consolider la réflexion menée dans ETRE au FIMI**

→ Focus sur les métiers du numérique

**Équipe pédagogique :**

- Guillaume Beslon
- Lionel Morel (responsable pédagogique de l'EC)
- Nour Osta
- Christine Solnon

# REVE : Ressources, Enjeux du Vivant & Énergie (2/2)

## 3 séminaires :

- Limites planétaires, quelles réponses numériques ?
- Enjeux du vivant, quelles implications pour le numérique ?
- Quelle matérialité du numérique ? Quel cadre d'action pour l'ingénieur ?

## 4 séances de TD/TP adressant des questions complémentaires :

- Situer le numérique : Démythification autour de la matérialité du numérique (2h)
- Bilan Carbone : Méthodes et limites (2h)
- World3 : Modélisation du "système-terre", choix de société, risques systémiques (2h)
- Agriculture et Numérique : Ex. d'intrication de la technique au sein d'enjeux de société (4h)

## Évaluation :

DS sur l'ensemble des méthodes et connaissances vues en séminaire ou en TD/TP

## 9 Planetary Boundaries (**Nature, 2009**)

### **Goal: Ensure a safe operating system for humanity**

- Climate change
- Ocean acidification
- Stratospheric ozone depletion
- Biogeochemical flows (nitrogen and phosphorus cycles)
- Freshwater use
- Land system change (e.g., deforestation)
- Biosphere integrity (biodiversity loss)
- Novel entities (chemical pollution)
- Atmospheric aerosol loading (microscopic particles in the atmosphere)

→ These boundaries are defined by means of threshold values of control variables

In 2009, 3 planetary boundaries were overstepped

# 9 Planetary Boundaries (**Nature, 2009**)

**Goal: Ensure a safe operating system for humanity**

- **Climate change**
- Ocean acidification
- Stratospheric ozone depletion
- **Biogeochemical flows (nitrogen and phosphorus cycles)**
- Freshwater use
- Land system change (e.g., deforestation)
- **Biosphere integrity (biodiversity loss)**
- Novel entities (chemical pollution)
- Atmospheric aerosol loading (microscopic particles in the atmosphere)

~> These boundaries are defined by means of threshold values of control variables

**In 2009, 3 planetary boundaries were overstepped**

# 9 Planetary Boundaries (**Nature, 2009**)

## Goal: Ensure a safe operating system for humanity

- **Climate change**
- Ocean acidification
- Stratospheric ozone depletion
- **Biogeochemical flows (nitrogen and phosphorus cycles)**
- Freshwater use
- Land system change (e.g., deforestation)
- **Biosphere integrity (biodiversity loss)**
- Novel entities (chemical pollution)
- Atmospheric aerosol loading (microscopic particles in the atmosphere)

→ These boundaries are defined by means of threshold values of control variables

**In 2009, 3 planetary boundaries were overstepped**

...and 2 were not yet quantified

# Quiz

In ([Planetary Health, 2025](#)):

- Measures are introduced for the 2 remaining unquantified boundaries
- All boundaries are re-evaluated

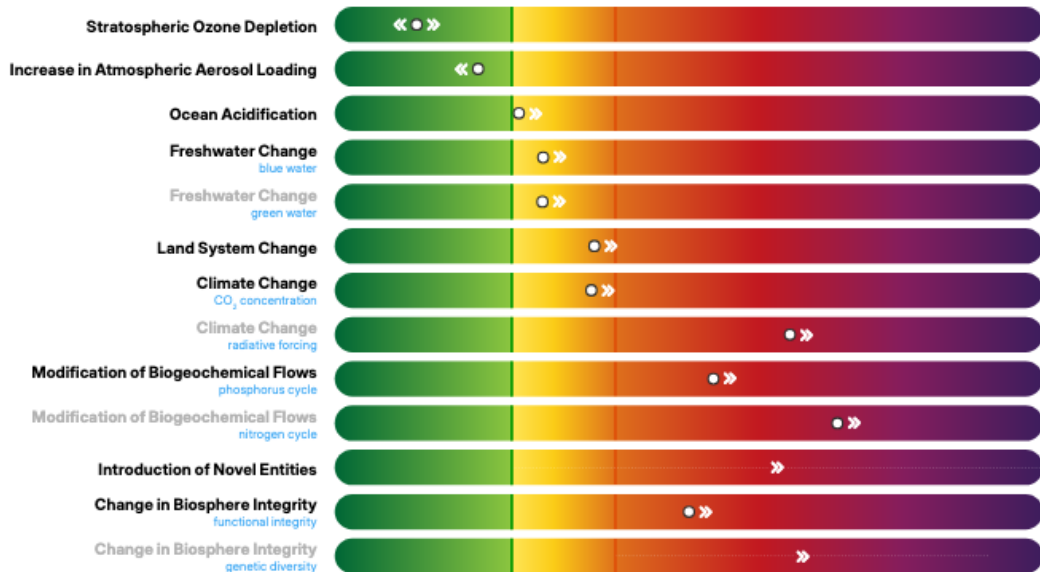
**Which boundaries are NOT transgressed according to this study?**

To answer, flash the QRcode or:

- Go to [wooclap.com](https://wooclap.com)
- Enter code IF2026



# Planetary boundaries according to Planetary Health, 2025





## Kate Raworth's Doughnut:

Combining planet's boundaries with social boundaries

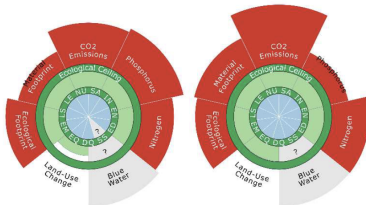
Image by [DoughnutEconomics](#) - Own work, CC BY-SA 4.0

1992

2015

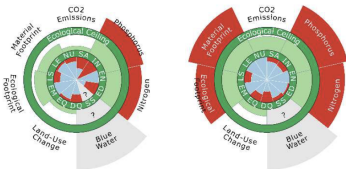
a

Germany



b

China



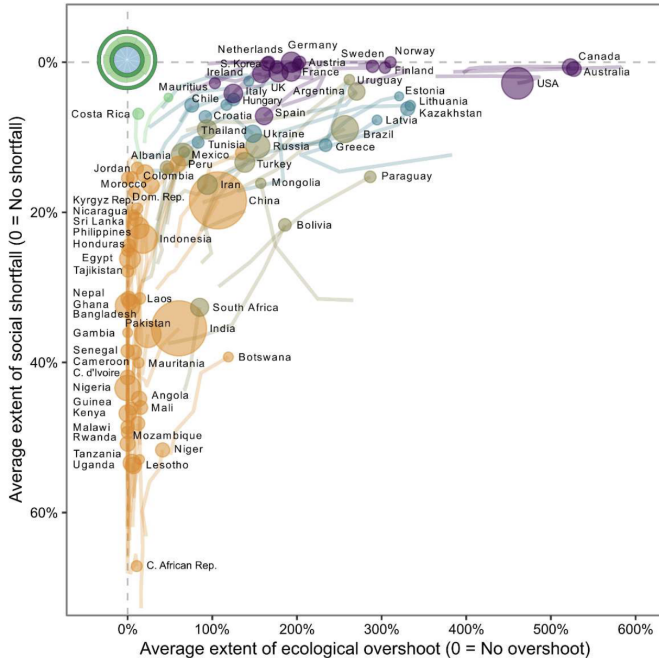
c

Nepal



We observe very different doughnuts depending on countries and time

See [Fanning et al, 2022](#) for more details



Dynamics of countries from 1992 to 2015 (Fanning et al, 2022)

# Can ICT help us meet everyone's needs within the planet's boundaries?

## OK: Our planet has limits, and some people are lacking access to life's essentials

(This was already well stated by [Meadows et al, 1972](#))

- We need to ensure that planet and social limits are not overpassed  
    ~> Maximise efficiency and welfare
- This is a Constrained Optimization Problem!  
    ~> Can we use ICT to model and solve this problem?

## Questions addressed in this talk:

- What are the impacts of ICT on our planet's boundaries?
- Can we use ICT to ensure that planet and social limits are not overpassed?

# Overview of the talk

## 1 Impacts of ICT on our planet's boundaries

- Material extraction and manufacturing
- Use stage
- End of life

## 2 Can we use ICT to ensure that planet and social limits are not overpassed?

## 3 Discussion

# What is ICT?

## OECD's answer:

- ICT manufacturing industries
  - 2610 Manufacture of electronic components and boards
  - 2620 Manufacture of computers and peripheral equipment
  - 2630 Manufacture of communication equipment
  - 2640 Manufacture of consumer electronics
  - 2680 Manufacture of magnetic and optical media
- ICT service industries
  - 4651 Wholesale of computers, computer peripheral and software
  - 4652 Wholesale of electronic and telecom. equipment and parts
  - 5820 Software publishing
  - 61 Telecommunications
  - 62 Computers programming, consultancy and related activities
  - 631 Data processing, hosting and related activities; Web portals
  - 951 Repair of computers and communication equipment

**This answer is often used to define ICT... Is it a problem?**

# What is ICT?

## The OECD definition doesn't include:

- Manufacture of electronic components whose purpose is not ICT  
    ~> *e.g.*, electronic components in cars
- Multimedia content industry  
    ~> *e.g.*, animated cartoons, music, etc

See [Roussilhe, 2022](#) for more details

## Actually, digital technologies are nearly everywhere...

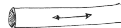
...but we often only consider the “pure” ICT sector when evaluating its impact

# The 3 tiers of ICT (or the journey of a photo posted on a social network)



## **Terminals:**

(smart)phones  
tablets  
laptops  
computers  
screens  
TVs  
connected obj.  
...



## **Networks:**

boxes  
WIFI access points  
routers  
antennas  
pylons  
cables  
...  
See [animation 1](#) and [animation 2](#)



## **Datacenters:**

servers  
other eq.

# Clearly, ICT is not virtual!

## Quiz:

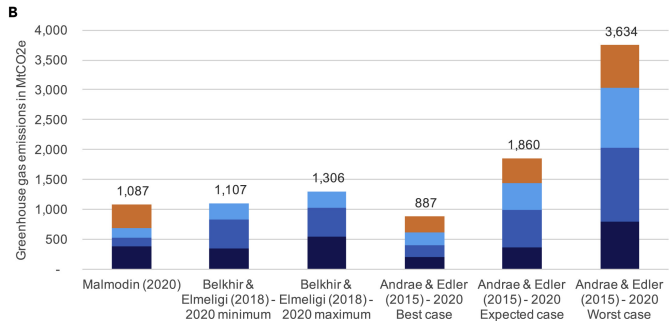
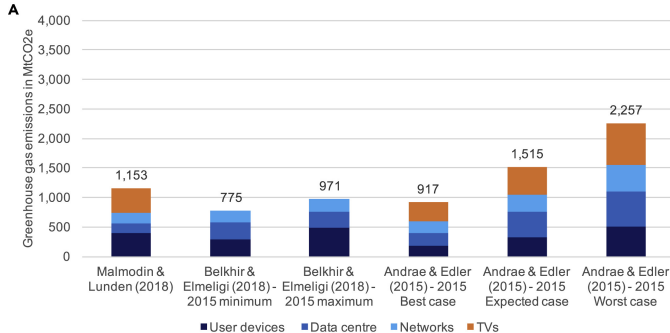
In your opinion, what approximate share of global GHG emissions does ICT account for?

## To answer:

To answer, flash the QRcode or:

- Go to [wooclap.com](https://wooclap.com)
- Enter code IF2026

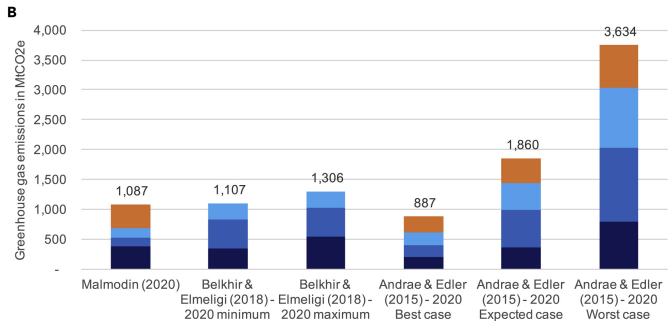
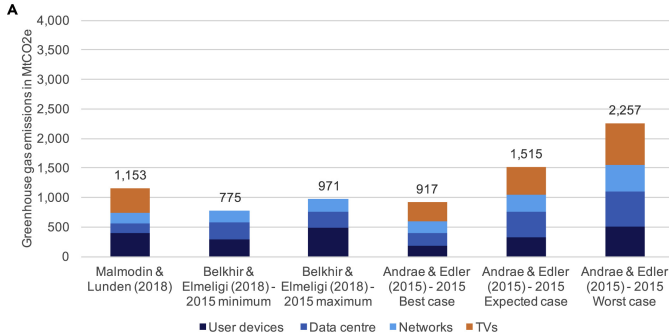




## Carbon footprint of ICT worldwide

Different studies in 2015 (top) and 2020 (bottom) compared in Freitag et al 2021:

- ICT (excluding TV) = 2 to 4% of GHG emissions
- Comparable to air transport



## Carbon footprint of ICT worldwide

Different studies in 2015 (top) and 2020 (bottom) compared in Freitag et al 2021:

- ICT (excluding TV) = 2 to 4% of GHG emissions
- Comparable to air transport

## What about France?

In 2022, according to ADEME, 2025:

- 4,4 % of GHG emissions
- 11% of electricity consumption

# A few trends...

## Evolution from 2010 to 2025:

- GHGs  $\times 3.1$
- Water  $\times 2.4$

## Projected trends from 2020 to 2030 in the business-as-usual scenario of (Ademe, 2023):

- Increase of 45% of the GHGs

Why?

# A few trends...

## Evolution from 2010 to 2025:

- GHGs  $\times 3.1$
- Water  $\times 2.4$

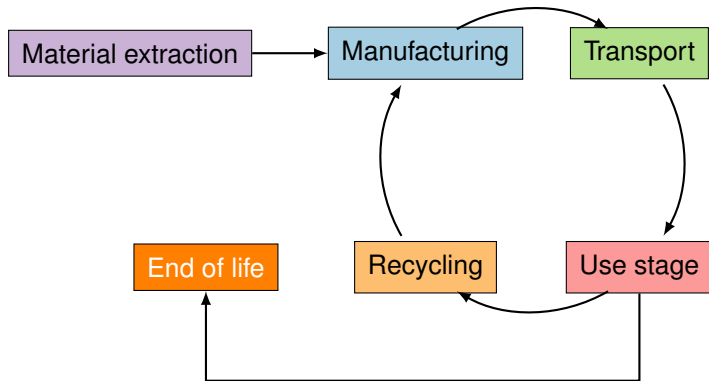
## Projected trends from 2020 to 2030 in the business-as-usual scenario of (Ademe, 2023):

- Increase of 45% of the GHGs

## Why?

- Connected objets  $\times 48$
- Screen size  $\times 2$
- Emerging countries are increasing their equipment level
- ...
- And generative AI!

# Life Cycle



To better understand ICT's impacts, we have to analyse the whole cycle

# Quiz

In your opinion, what is the main source of GHG emissions for ICT?

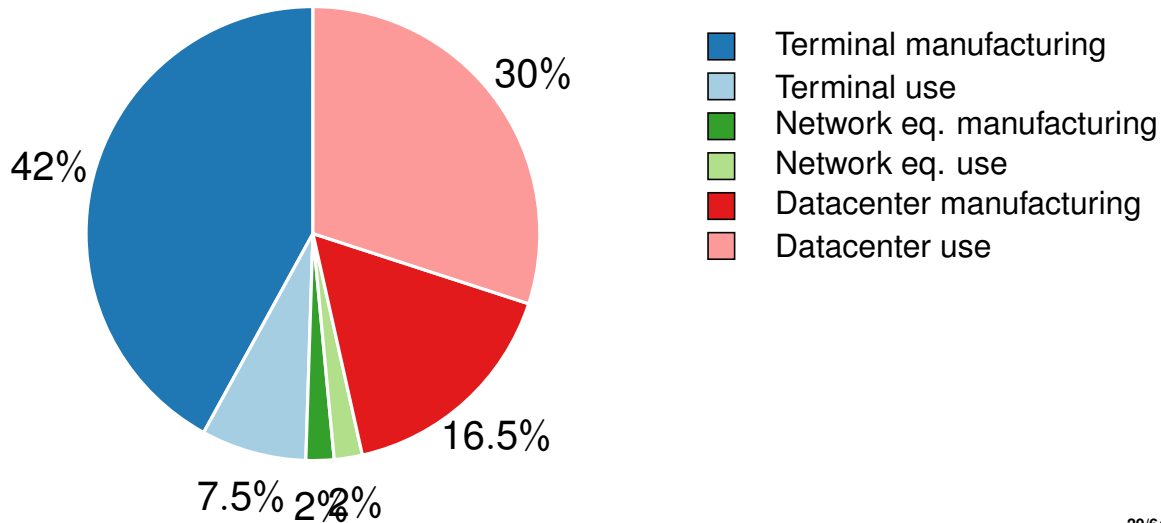
To answer:

To answer, flash the QRcode or:

- Go to [wooclap.com](https://wooclap.com)
- Enter code IF2026



## GHG emissions per source in 2022 in France ([ADEME, 2025](#))



# Various impacts per source in 2022 in France (ADEME, 2025)

|                                                   | Epuisement des<br>ressources abiotiques<br>naturelles - éléments - kg | Epuisement des<br>ressources abiotiques<br>naturelles - fossiles - MJ | Acidification - mol H+<br>eq. | Ecotoxicité - CTUe | Changement climatique<br>- kg CO2 eq. | Radiations ionisantes -<br>kBq U235 eq. | Emissions de particules<br>fines - Disease<br>occurrence | Création d'ozone<br>photochimique - kg<br>NMVOC eq. | MIPS - kg | Consommation<br>d'énergie primaire - MJ |
|---------------------------------------------------|-----------------------------------------------------------------------|-----------------------------------------------------------------------|-------------------------------|--------------------|---------------------------------------|-----------------------------------------|----------------------------------------------------------|-----------------------------------------------------|-----------|-----------------------------------------|
| TIER 1 – Fabrication,<br>Distribution, Fin de vie | 85,7%                                                                 | 17,0%                                                                 | 41,5%                         | 50,7%              | 42,1%                                 | 18,3%                                   | 25,3%                                                    | 44,2%                                               | 54,6%     | 16,1%                                   |
| TIER 1 - Utilisation                              | 0,1%                                                                  | 37,9%                                                                 | 6,7%                          | 2,9%               | 7,5%                                  | 45,9%                                   | 27,7%                                                    | 6,7%                                                | 4,6%      | 38,6%                                   |
| TIER 2 – Fabrication,<br>Distribution, Fin de vie | 5,6%                                                                  | 1,4%                                                                  | 2,5%                          | 2,9%               | 1,8%                                  | 1,9%                                    | 2,0%                                                     | 3,1%                                                | 4,4%      | 1,5%                                    |
| TIER 2 - Utilisation                              | 0,1%                                                                  | 7,9%                                                                  | 1,6%                          | 1,1%               | 2,0%                                  | 9,4%                                    | 6,0%                                                     | 2,1%                                                | 0,9%      | 8,0%                                    |
| TIER 3 – Fabrication,<br>Distribution, Fin de vie | 8,4%                                                                  | 7,3%                                                                  | 14,9%                         | 15,8%              | 16,5%                                 | 4,3%                                    | 9,7%                                                     | 14,6%                                               | 15,5%     | 7,2%                                    |
| TIER 3 - Utilisation                              | 0,1%                                                                  | 28,5%                                                                 | 32,8%                         | 26,6%              | 30,3%                                 | 20,3%                                   | 29,4%                                                    | 29,4%                                               | 20,0%     | 28,6%                                   |

# Plan

## 1 Impacts of ICT on our planet's boundaries

- Material extraction and manufacturing
- Use stage
- End of life

## 2 Can we use ICT to ensure that planet and social limits are not overpassed?

## 3 Discussion

# The chemical elements of a smartphone

**Elements colour key:** ● Alkali metal ● Alkaline earth metal ● Transition metal ● Group 13 ● Group 14 ● Group 15 ● Group 16 ● Halogen ● Lanthanide

## SCREEN



**Touch: Indium tin oxide**  
Used in a transparent film over the phone's screen that conducts electricity. This allows the screen to function as a touch screen. This is the major use of indium.



**Glass: Alumina and silica**  
On most phones the glass is aluminosilicate glass, a mix of aluminium oxide and silicon dioxide. It also contains potassium ions which help strengthen it.



**Colours: Rare earth metals**  
A variety of rare earth metal-containing compounds are used to help to produce the colours in a smartphone's screen. Some of these compounds are also used to help reduce light penetration into the phone. Many of the rare earths occur commonly in the Earth's crust, but often at levels too low to be economically extracted.

## BATTERY



Most phones use lithium-ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Sometimes other metals, such as manganese, are used in place of cobalt. The battery casing is often made of aluminium.

## ELECTRONICS

**Wiring and microelectronics**  
Copper is used for wiring, and for micro-electrical components along with gold and silver. Tantalum is the major component in micro-capacitors.



**Microphones and vibrations**  
Nickel is used in the microphone and for electrical connections. Rare earth element alloys are used in magnets in the speaker and microphone, and the vibration unit.



**The silicon chip**  
Pure silicon is used to manufacture the chip, which is then oxidised to produce non-conducting regions. Other elements are added to allow the chip to conduct electricity.



**Connecting electronics**  
Tin and lead were used in older solders; newer, lead-free solders use a mix of tin, copper and silver.



## CASING



Magnesium alloy is used to make some phone cases. Many others are made of plastics, which are carbon-based. Plastics will also include flame-retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.



**These chemical elements are coming from mines:**

- Top: *Chino Copper Mine* (New Mexico), diameter 2,8km, depth 410m
- Bottom: *Bagger 288* excavator, lignite mining (Germany), 13500T, length 240m, height 96m, Alim. 16,5MW



# Reality of the mineral industry

## An element is never found in its pure state in nature

- Extremely low concentration (e.g., 1g/T for gold)
- A host of very toxic associated elements (e.g., mercury, arsenic, barium... for gold)

## Metal recovery is more than just extraction

- Concentration, then chemical extraction, then refining
- Each of these steps is highly energy-intensive, requires a great deal of water, and is extremely polluting

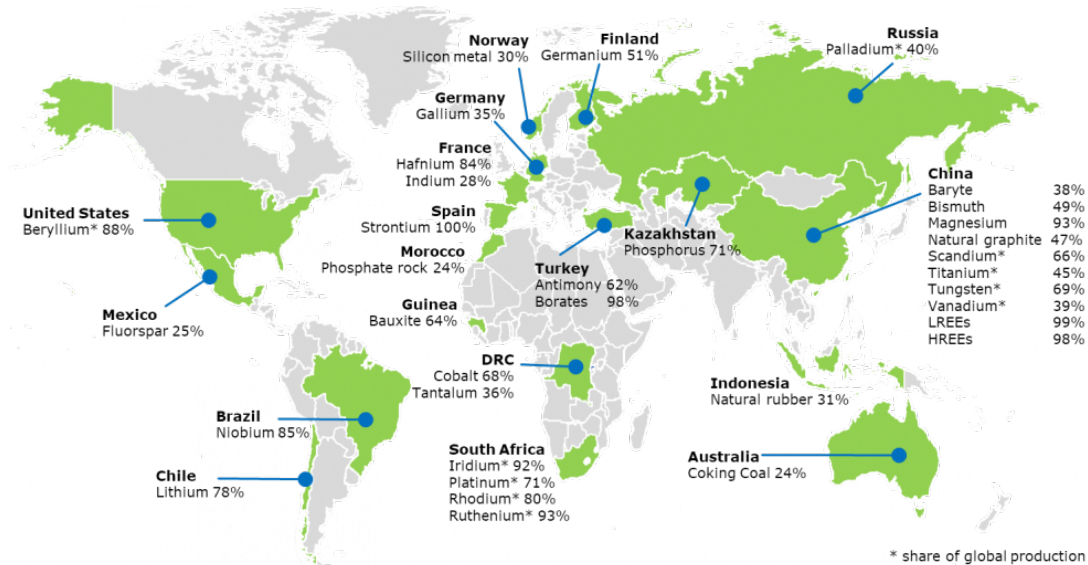
## Unit impacts are increasing

- Concentration declines  $\Rightarrow$  energy / water / toxic products to be used increase

## 2 videos (in french) to watch:

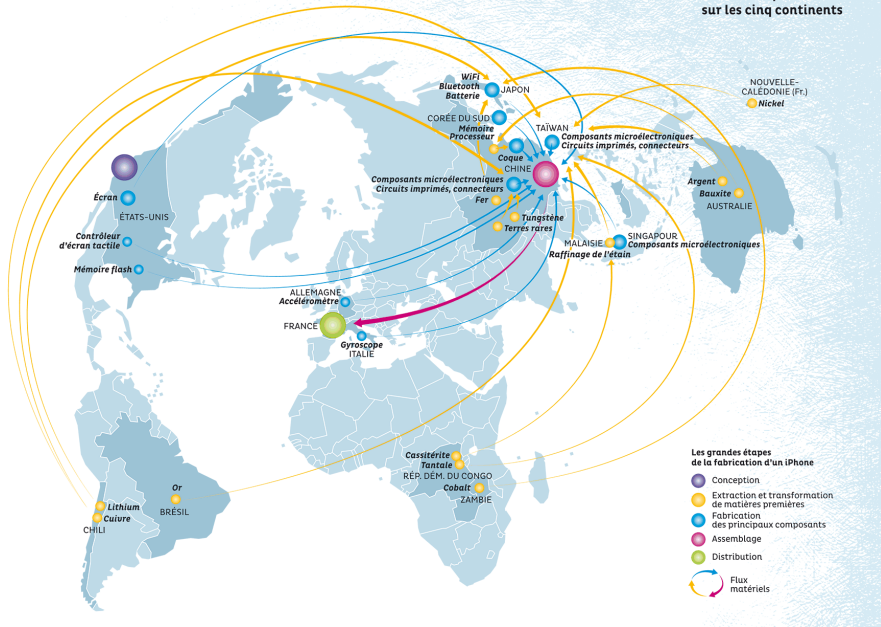
- On the mining issue: [Aurore Stéphant](#)
- On materials for the energy transition: [Olivier Vidal](#)

# From extraction...



Diverse geographical origins with numerous underlying geopolitical and human problems ([Report EC, 2018](#))

## Une chaîne de production sur les cinq continents



...to  
manufacturing,  
assembling and  
distributing

Source: [Le Monde Diplomatique](#), 2015

# Focus on semiconductors

## 75% of global chip production is in East Asia

- Very small number of actors (Samsung in Korea and TSMC in Taiwan for 7nm)
- Extremely accurate process  $\leadsto$  ultra-pure materials  
 $\leadsto$  massive use of chemical products and water
- e.g., more than 150,000 tonnes of water per day for [TSMC in 2019](#)  
 $\leadsto$  Major problem at Taiwan in 2021 (see [Mediapart](#))

## Closer from here: STMicroelectronics in Crolles (between Grenoble and Chambéry)

- 4,232,000 tonnes of water in 2021  
(according to [ST](#))
- Total consumption increases, even  
though unit consumption decreases

What are the potential use conflicts?

# Focus on semiconductors

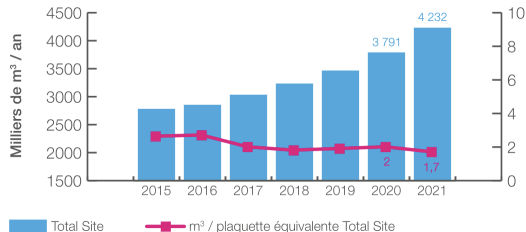
## 75% of global chip production is in East Asia

- Very small number of actors (Samsung in Korea and TSMC in Taiwan for 7nm)
- Extremely accurate process  $\leadsto$  ultra-pure materials  
 $\leadsto$  massive use of chemical products and water
- e.g., more than 150,000 tonnes of water per day for **TSMC in 2019**  
 $\leadsto$  Major problem at Taiwan in 2021 (see [Mediapart](#))

## Closer from here: STMicroelectronics in Crolles (between Grenoble and Chambéry)

- 4,232,000 tonnes of water in 2021 (according to [ST](#))
- Total consumption increases, even though unit consumption decreases

What are the potential use conflicts?



# Plan

## 1 Impacts of ICT on our planet's boundaries

- Material extraction and manufacturing
- Use stage
- End of life

## 2 Can we use ICT to ensure that planet and social limits are not overpassed?

## 3 Discussion

# Use stage of an ICT equipment

- What is the main impact source of the use stage?

# Use stage of an ICT equipment

- What is the main impact source of the use stage?  
    ~> *Electricity consumption*

# Use stage of an ICT equipment

- What is the main impact source of the use stage?  
    ~> *Electricity consumption*
- How to translate an electricity consumption into impacts?

# Use stage of an ICT equipment

- What is the main impact source of the use stage?  
~> *Electricity consumption*
- How to translate an electricity consumption into impacts?

## Quiz:

What is the most common source of energy used to generate electricity in the world?

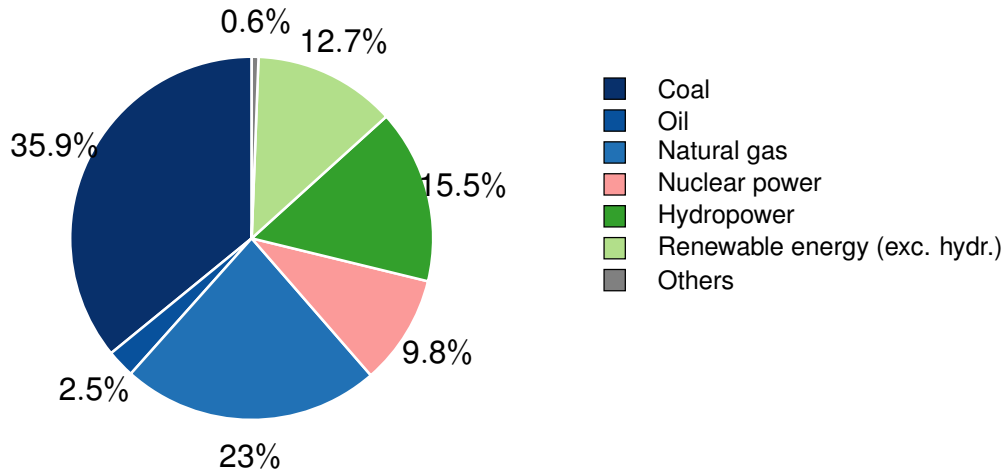
## To answer:

To answer, flash the QRcode or:

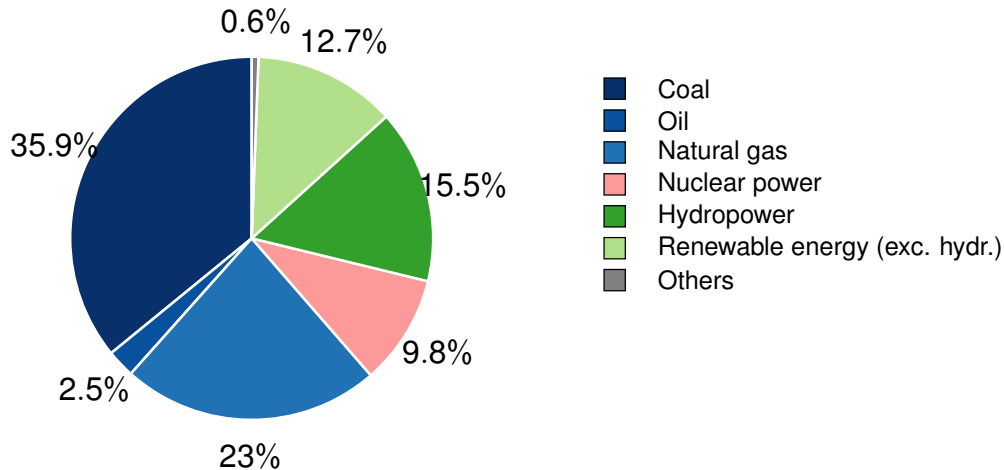
- Go to [wooclap.com](https://wooclap.com)
- Enter code IF2026



## Sources of electrical energy (International Energy Agency, 2021)



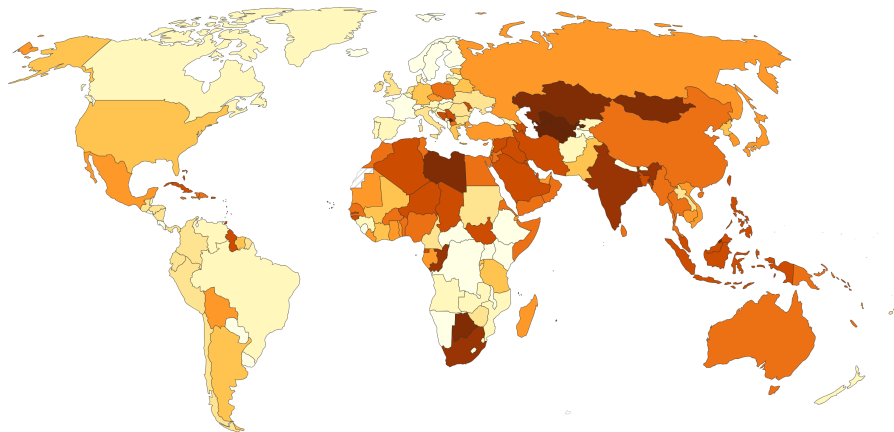
## Sources of electrical energy (International Energy Agency, 2021)



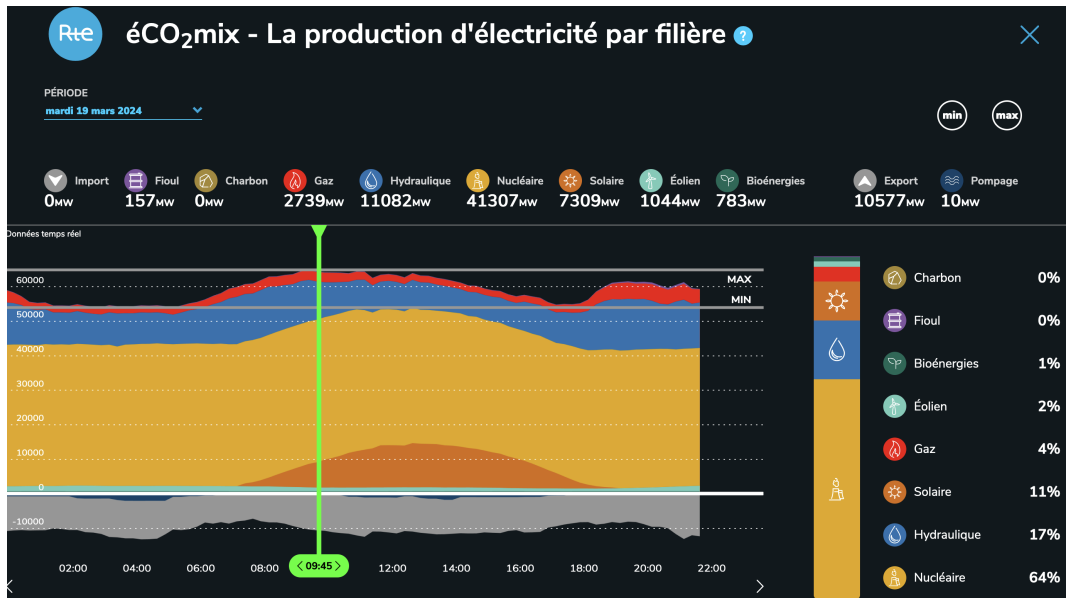
Is it the same in all countries?

# Lifecycle carbon intensity of electricity, 2025

Measured in grams of carbon dioxide-equivalents<sup>1</sup> emitted per kilowatt-hour<sup>2</sup> of electricity generated. Emissions are estimated on a lifecycle basis, including upstream, supply chain and manufacturing stages, and cover all greenhouse gases.



# What about France? (Source = RTE)



# Plan

## 1 Impacts of ICT on our planet's boundaries

- Material extraction and manufacturing
- Use stage
- End of life

## 2 Can we use ICT to ensure that planet and social limits are not overpassed?

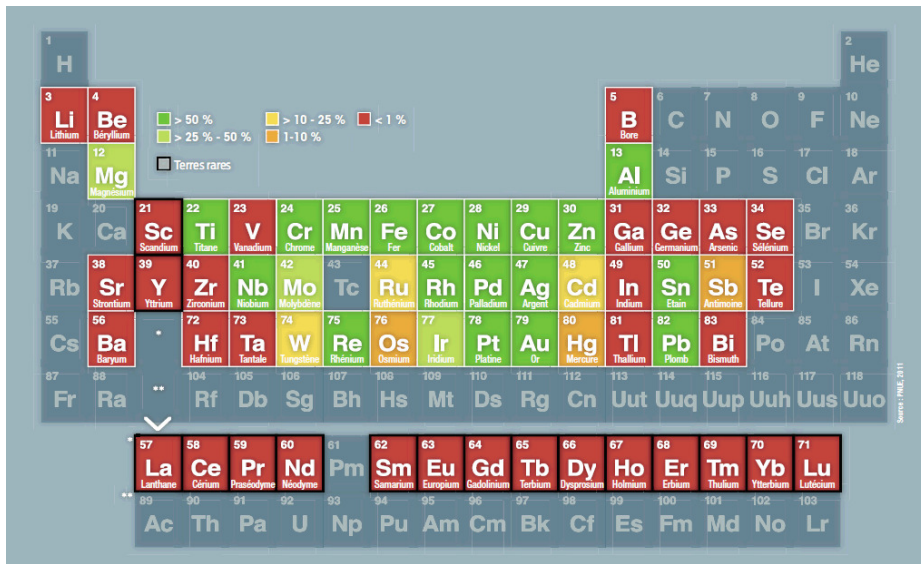
## 3 Discussion

# From life to waste

- Equipment no longer used  $\leadsto$  Waste
- Digital equipment  $\subseteq$  Waste electrical and electronic equipment (WEEE)
- World (2019): WEEE collection  $\approx 17\%$  (by weight)
- France (2019): WEEE collection  $\approx 50\%$  (by weight)

But a collected equipment is not necessarily recycled!

# Recyclability of materials



Source: [https://www.alternatives-economiques.fr/\[...\]](https://www.alternatives-economiques.fr/[...])

# And when wastes are not collected?

- Stored at home
- Landfilled
- Burned
- Illegal treatment

## Quiz:

How many non-used smartphones have you at home?

## To answer:

To answer, flash the QRcode or:

- Go to [wooclap.com](https://wooclap.com)
- Enter code IF2026



# Overview of the talk

- 1 Impacts of ICT on our planet's boundaries
- 2 Can we use ICT to ensure that planet and social limits are not overpassed?
- 3 Discussion

# The answer of William Nordhaus: DICE (Nordhaus, 2019)

## Integrated Assessment Model (IAM):

Classical economic model (Ramsey model)

~> Economic growth

+ Climate model (FAIR model)

~> Rising CO<sub>2</sub> concentrations lead to unrestrained global warming

+ Carbon tax model and backstop technologies

~> Climate-change policies reduce emissions, and allow "sustainable" growth

# The answer of William Nordhaus: DICE (Nordhaus, 2019)

## Integrated Assessment Model (IAM):

Classical economic model (Ramsey model)

~> Economic growth

+ Climate model (FAIR model)

~> Rising CO<sub>2</sub> concentrations lead to unrestrained global warming

+ Carbon tax model and backstop technologies

~> Climate-change policies reduce emissions, and allow "sustainable" growth

# The answer of William Nordhaus: DICE (Nordhaus, 2019)

## Integrated Assessment Model (IAM):

Classical economic model (Ramsey model)

~> Economic growth

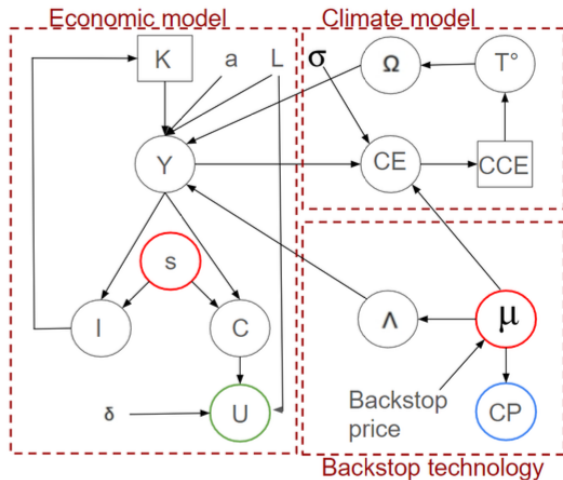
+ Climate model (FAIR model)

~> Rising CO<sub>2</sub> concentrations lead to unrestrained global warming

+ Carbon tax model and backstop technologies

~> Climate-change policies reduce emissions, and allow “sustainable” growth

# Description of DICE (Nordhaus, 2023)



## Economic model:

$$\max \sum_t (1 - \beta)^t U[t]$$

$$\text{s.t. } U[t] = L[t]^\phi \times \frac{C[t]^{1-\phi}}{1-\phi}$$

$$C[t] = (1 - s[t]) \times Y[t]$$

$$K[t + 1] = (1 - \delta) \times K[t] + s[t] \times Y[t]$$

$$Y[t] = a[t] \times L[t]^{1-\gamma} \times K[t]^\gamma$$

## Climate model:

Constraints between  $\Omega$ ,  $CE$ ,  $CCE$ ,  $T^\circ$ , and  $Y$

## Backstop technology:

Constraints between  $\Lambda$ ,  $\mu$ ,  $CP$ ,  $Y$  and  $CE$

## Input data and variables (indexed by time):

$L$  = population (input)

$a$  = productivity (input)

$U$  = utility

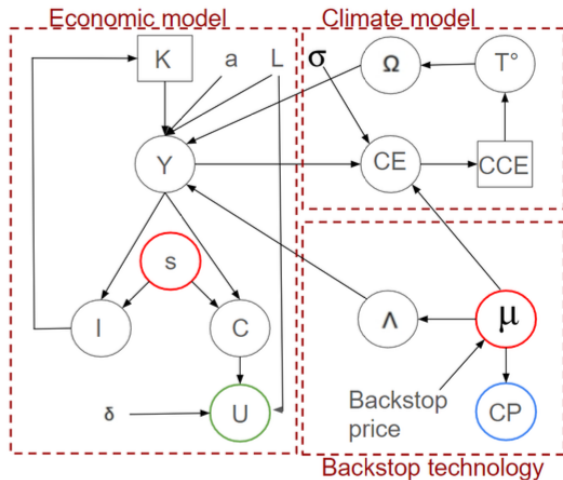
$C$  = consumption

$s$  = saving rate

$Y$  = GDP

$K$  = capital

# Description of DICE (Nordhaus, 2023)



(image from Alexandre Gondran)

## Economic model:

$$\max \sum_t (1 - \beta)^t U[t]$$

$$\text{s.t. } U[t] = L[t]^\phi \times \frac{C[t]^{1-\phi}}{1-\phi}$$

$$C[t] = (1 - s[t]) \times Y[t]$$

$$K[t + 1] = (1 - \delta) \times K[t] + s[t] \times Y[t]$$

$$Y[t] = (1 - \Omega[t]) \times a[t] \times L[t]^{1-\gamma} \times K[t]^\gamma$$

## Climate model:

Constraints between  $\Omega$ ,  $CE$ ,  $CCE$ ,  $T^\circ$ , and  $Y$

## Backstop technology:

Constraints between  $\Lambda$ ,  $\mu$ ,  $CP$ ,  $Y$  and  $CE$

## Input data and variables (indexed by time):

$L$  = population (input)

$a$  = productivity (input)

$U$  = utility

$C$  = consumption

$s$  = saving rate

$Y$  = GDP

$K$  = capital

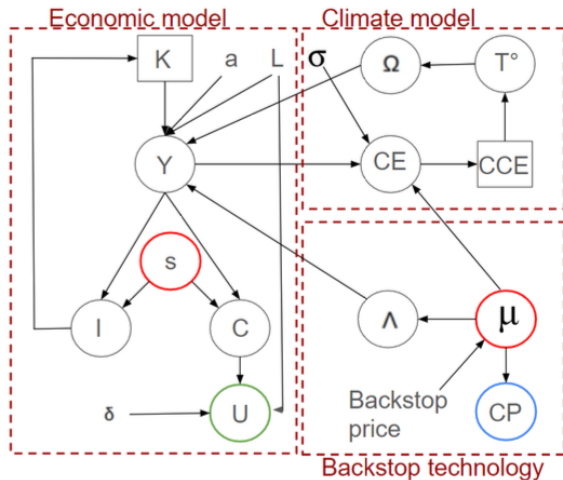
$\Omega$  = climate damage

$CE$  = carbon emissions

$CCE$  = cumulated CE

$T^\circ$  = temperature

# Description of DICE (Nordhaus, 2023)



(image from Alexandre Gondran)

## Economic model:

$$\max \sum_t (1 - \beta)^t U[t]$$

$$\begin{aligned} \text{s.t. } U[t] &= L[t]^\phi \times \frac{C[t]^{1-\phi}}{1-\phi} \\ C[t] &= (1 - s[t]) \times Y[t] \\ K[t+1] &= (1 - \delta) \times K[t] + s[t] \times Y[t] \\ Y[t] &= (1 - \Omega[t]) \times (1 - \Lambda[t]) \times a[t] \times L[t]^{1-\gamma} \times K[t]^\gamma \end{aligned}$$

## Climate model:

Constraints between  $\Omega$ ,  $CE$ ,  $CCE$ ,  $T^\circ$ , and  $Y$

## Backstop technology:

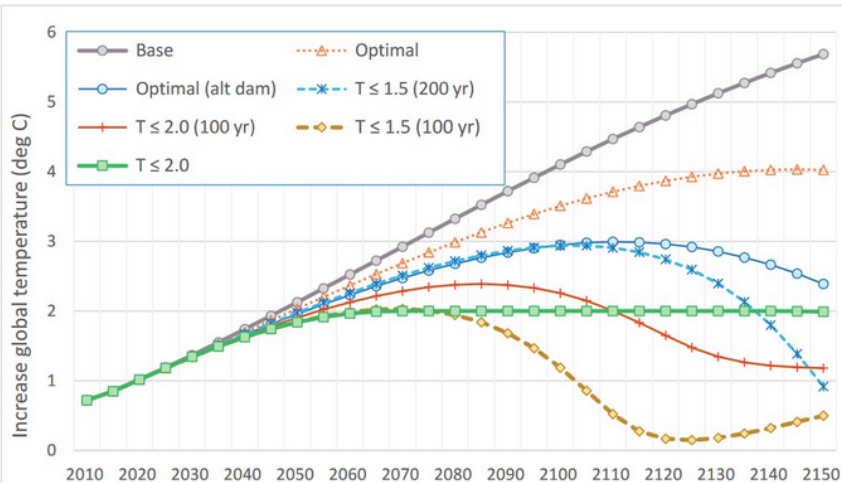
Constraints between  $\Lambda$ ,  $\mu$ ,  $CP$ ,  $Y$  and  $CE$

## Input data and variables (indexed by time):

|                            |                                |
|----------------------------|--------------------------------|
| $L$ = population (input)   | $\Omega$ = climate damage      |
| $a$ = productivity (input) | $CE$ = carbon emissions        |
| $U$ = utility              | $CCE$ = cumulated CE           |
| $C$ = consumption          | $T^\circ$ = temperature        |
| $s$ = saving rate          | $\Lambda$ = carbon tax         |
| $Y$ = GDP                  | $CP$ = carbon price            |
| $K$ = capital              | $\mu$ = emissions control rate |

## Conclusions of DICE 2018: Optimal solution (from a cost-benefit perspective)

- Cost of reducing carbon emissions = \$ 3000 billions
- Increase of temperature of 4° in 2150, causing damages of \$ 15000 billions



**2018 Nobel Memorial  
Prize in Economic  
Sciences**

Image from [Nordhaus, 2018](#)

# Some hypothesis of DICE

- Objective function = Welfare, evaluated by consumption
- Everything is evaluated in a same unit (wrt GDP)
- The damage function which evaluates climate impacts is:  $\Omega[t] = 0.003467 \times T^\circ[t]^2$   
 $\leadsto$  GDP decreases of 1% (resp. 4%, 9%) when  $T^\circ$  increases of  $2^\circ$  (resp.  $4^\circ$ ,  $6^\circ$ )  
*According to Nordhaus, 87% of the USA's GDP would be "negligibly affected by climate change", because it takes place in "carefully controlled environments". See ([Keen et al, 2023](#)) for more details.*
- The discount rate  $\rho$  translates future costs into present value  
 $\leadsto \rho$  reflects the importance attached to the well-being of future generations  
In other words: huge damage way off in the future  $\Leftrightarrow$  little damage nowadays  
When  $\rho = 4\%$ , 50 times less for a 100 year damage than a present one
- Assume that the price of carbon-free technologies will decline over time (whatever we invest in technology) to reach carbon-neutral economy in 2060

What do you think of these hypothesis?

# The DICE model assumes that technology will allow us to be carbon-neutral in 2060

## Quiz

Which of the following technological advances has actually reduced our impact?

- Improving the efficiency of steam engines
- Hydro-electricity
- Renewable energies (others than hydro-electricity)
- Improving computer processors
- Improving the energy efficiency of networks (2G, 3G, 4G, 5G, fiber)

## To answer:

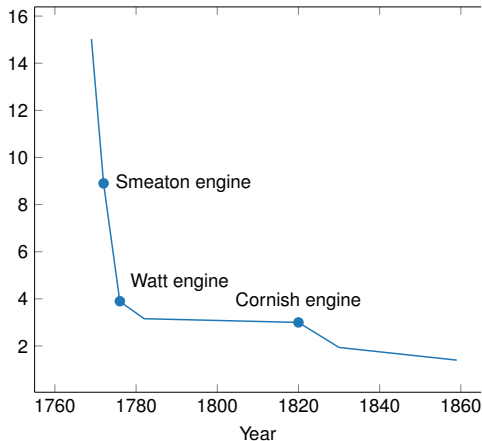
To answer, flash the QRcode or:

- Go to [wooclap.com](https://wooclap.com)
- Enter code IF2026



# Which technological advances have reduced our impact?

Improving the efficiency of steam engines (source = [Jevons 1866](#)) ?

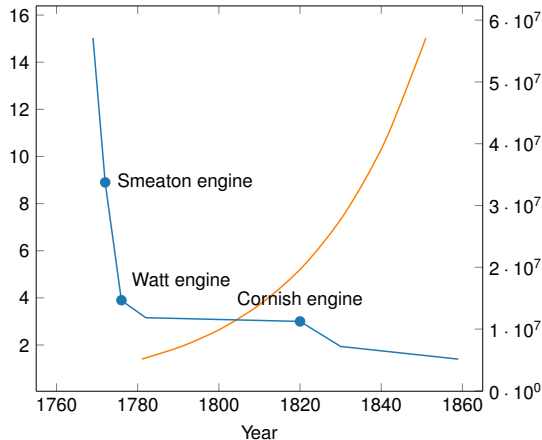


## Paradoxe of Jevons:

- Evolution of energy efficiency (number of pounds of coal needed to raise  $10^6$  pounds of water by one foot)
- Evolution of total consumption (number of tonnes of coal consumed in the UK per year)

# Which technological advances have reduced our impact?

Improving the efficiency of steam engines (source = [Jevons 1866](#)) ?



## Paradoxe of Jevons:

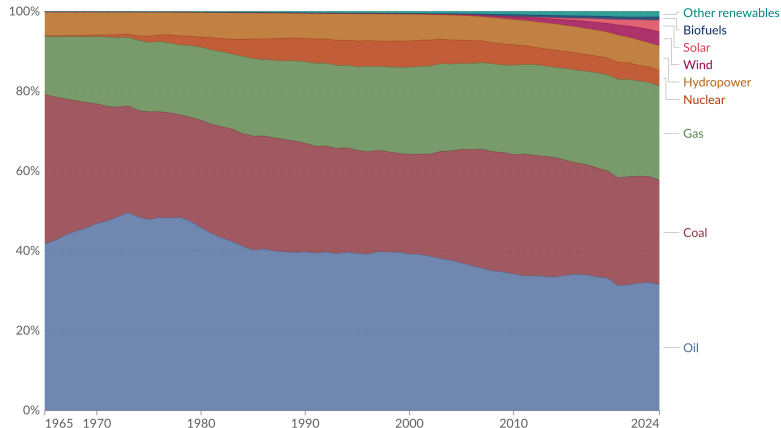
- Evolution of energy efficiency (number of pounds of coal needed to raise 10<sup>6</sup> pounds of water by one foot)
- Evolution of total consumption (number of tonnes of coal consumed in the UK per year)

# Which technological advances have reduced our impact?

Renewable energies (source = [Our World in Data](#)) ?

## Energy consumption by source, World

Measured in terms of primary energy<sup>1</sup> using the substitution method<sup>2</sup>.



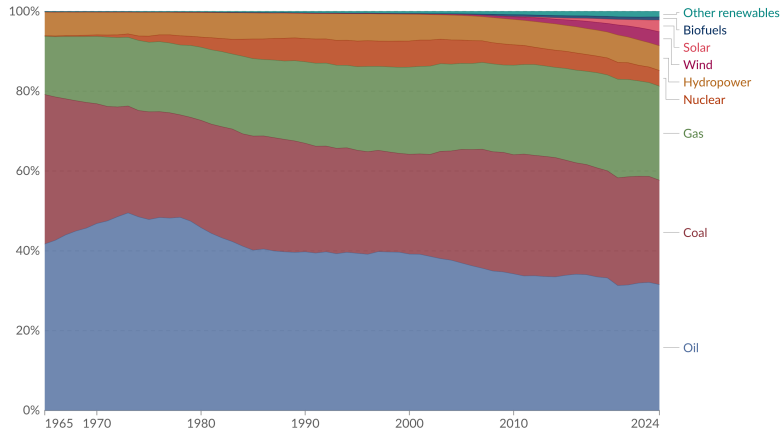
coal+gas+oil decrease from 93.4% in 1965 to 81.3% in 2024... but what's the catch?

# Which technological advances have reduced our impact?

Renewable energies (source = [Our World in Data](#)) ?

## Energy consumption by source, World

Measured in terms of primary energy<sup>1</sup> using the substitution method<sup>2</sup>.



Our World  
in Data

coal+gas+oil decrease from  
93.4% in 1965 to 81.3% in  
2024... but what's the catch?

These are percentages  
~> Look at absolute values!

Data source: Energy Institute - Statistical Review of World Energy (2025)

Note: "Other renewables" include geothermal, biomass, and waste energy.

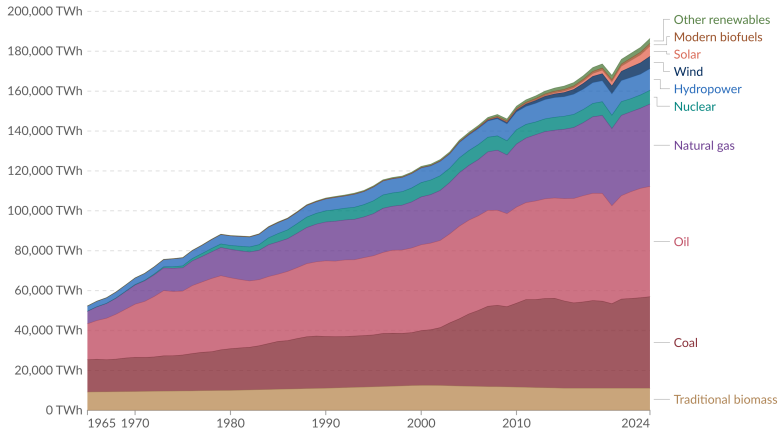
[OurWorldinData.org/energy](https://OurWorldinData.org/energy) | CC BY

# Which technological advances have reduced our impact?

Renewable energies (source = [Our World in Data](#)) ?

## Global primary energy consumption by source

Primary energy<sup>1</sup> is based on the substitution method<sup>2</sup> and measured in terawatt-hours<sup>3</sup>.



Our World  
in Data

coal+gas+oil decrease from  
93.4% in 1965 to 81.3% in  
2024... but what's the catch?

These are percentages  
→ Look at absolute values!

Data source: Energy Institute - Statistical Review of World Energy (2025); Smil (2017)

Note: In the absence of more recent data, traditional biomass is assumed constant since 2015.

[OurWorldinData.org/energy](https://OurWorldinData.org/energy) | CC BY

## Improving computer processors?

Moore's Law: The number of transistors on microchips doubles every two years

Our World  
in Data

50,000,000,000



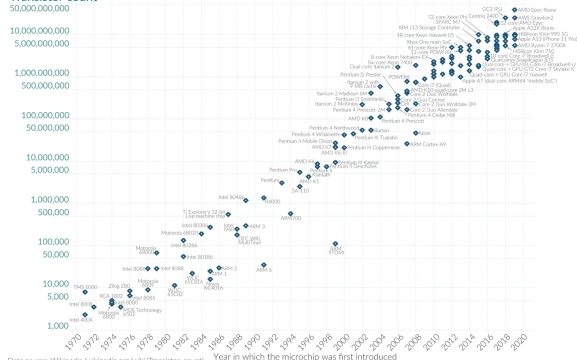
## Improving computer processors?

## Law of Moore (Source: [Our World in Data](#))

Moore's Law: The number of transistors on microchips doubles every two years

This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

### Transistor count

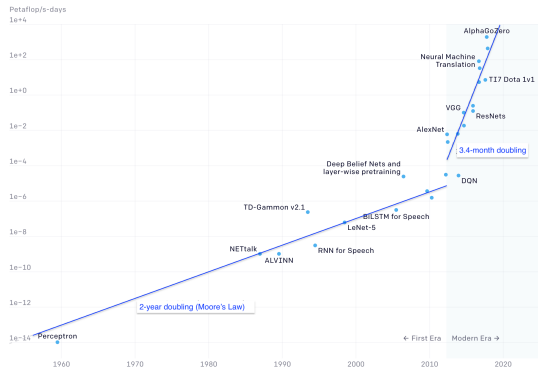


Data source: Wikipedia ([wikipedia.org/wiki/Transistor\\_count](https://wikipedia.org/wiki/Transistor_count))

OurWorldinData.org – Research and data to make progress against the world's largest problems.

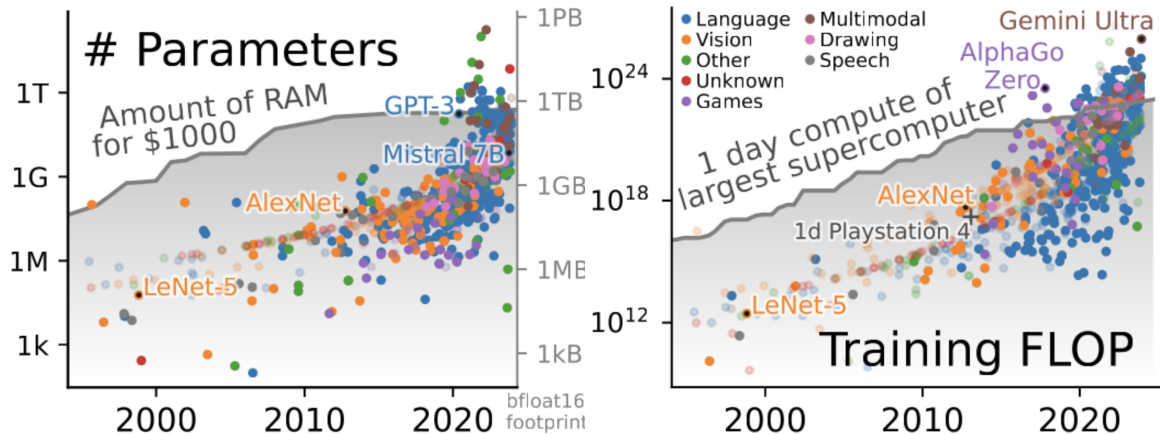
Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

## Training cost of an AI (source: [OpenAI](#))



- What happened in 2012?
- What made it possible?

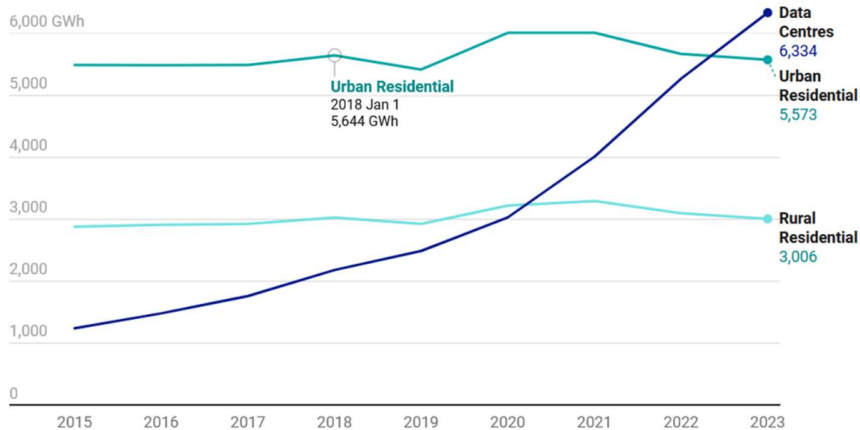
# Explosion in AI model size (Varoquaux et al, 2025)



# Evolution of Electricity Consumption in Ireland (Shift Project, 2025)

## Metered Electricity Consumption 2015-2023

Electricity consumption from data centres has grown significantly in recent years, with it now surpassing urban residential consumption.



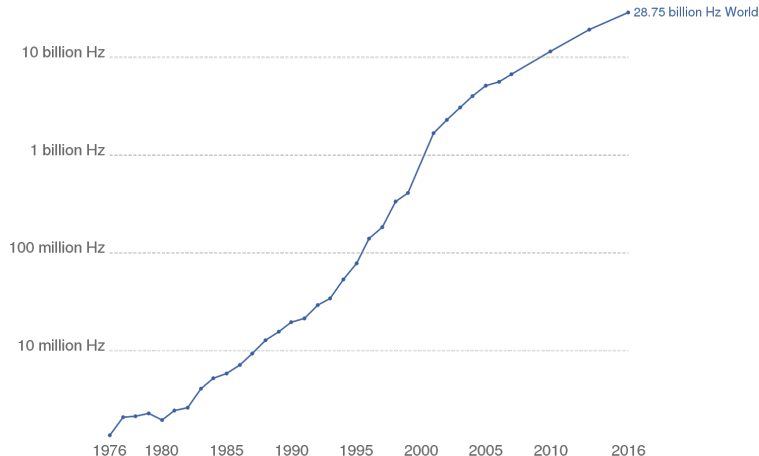
GWh - Gigawatt-hours

Chart: The Journal Investigates • Source: CSO • Created with [Datawrapper](#)

# Other exponential rates related to Moore's law

## Microprocessor clock speed

Microprocessor clock speed measures the number of pulses per second generated by an oscillator that sets the tempo for the processor. It is measured in hertz (pulses per second).



Source: Ray Kurzweil (2005, updated to 2016). The Singularity Is Near: When Humans Transcend Biology.

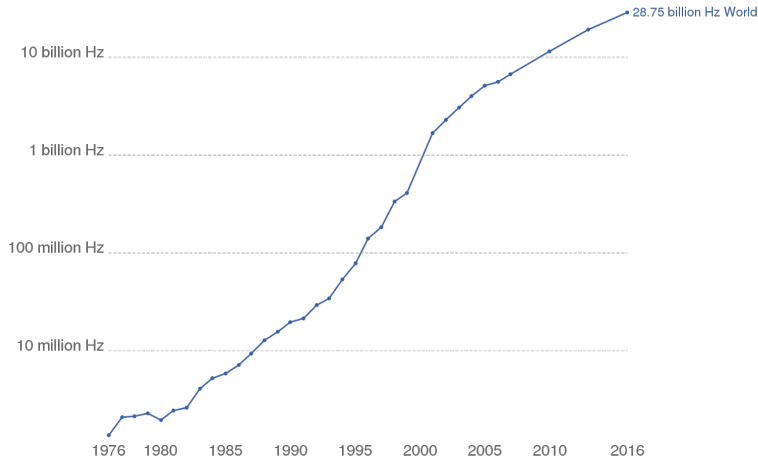
- Similar evolution for microprocessor speed  
And also: energy consumption, memory capacity, number of pixels, ...
- But exponential growth can't go on forever due to physical limits!
- Do softwares run faster and are they less impactful thanks to these hardware improvements?

Image by Our World In Data - [CC BY 3.0](#)

# Other exponential rates related to Moore's law

## Microprocessor clock speed

Microprocessor clock speed measures the number of pulses per second generated by an oscillator that sets the tempo for the processor. It is measured in hertz (pulses per second).



Source: Ray Kurzweil (2005, updated to 2016). The Singularity Is Near: When Humans Transcend Biology.

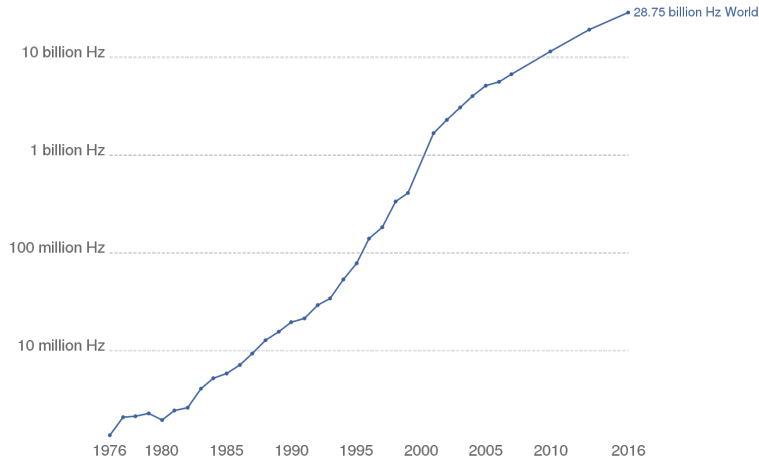
- Similar evolution for microprocessor speed  
And also: energy consumption, memory capacity, number of pixels, ...
- But exponential growth can't go on forever due to physical limits!
- Do softwares run faster and are they less impactful thanks to these hardware improvements?

Image by Our World In Data - [CC BY 3.0](#)

# Other exponential rates related to Moore's law

## Microprocessor clock speed

Microprocessor clock speed measures the number of pulses per second generated by an oscillator that sets the tempo for the processor. It is measured in hertz (pulses per second).



Source: Ray Kurzweil (2005, updated to 2016). The Singularity Is Near: When Humans Transcend Biology.

- Similar evolution for microprocessor speed  
And also: energy consumption, memory capacity, number of pixels, ...
- But exponential growth can't go on forever due to physical limits!
- **Do softwares run faster and are they less impactful thanks to these hardware improvements?**

Image by Our World In Data - [CC BY 3.0](#)

# The Great Moore's Law Compensator

## Law of Wirth, 1995

*Software is getting slower more rapidly than hardware is becoming faster*

## What Intel giveth, Microsoft taketh away (Kennedy, 2007)

For example:

- Microsoft Office 2007 on Windows Vista:  
~ 12× memory and 3× processing power as Office 2000
- The end of Windows 10 support could turn 400 million PCs into e-waste  
(Green Alliance Blog, 2025)

## All this mainly leads to obsolescence...

Just try to install recent apps on a 10 year old smartphone!

# Which technological advances have reduced our impact?

Improving the energy efficiency of networks (2G, 3G, 4G, 5G, fiber)?

## Network energy efficiency :

- 2G = 4.6 TWh/EB ; 3G = 2.14 TWh/EB ; 4G = 0.09 TWh/EB (source = [Sénat, 2020](#))
- 5G antennas are twice more efficient than 4G antennas (source = [Orange](#))
- Optical fiber consumes 4 times less KWh than copper (source = [Arcep, 2022](#))

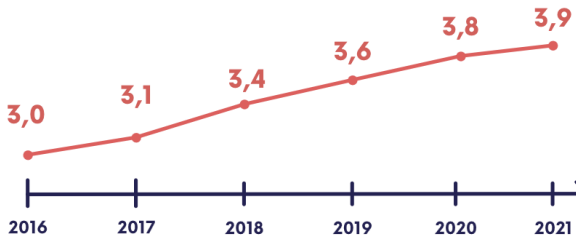
# Which technological advances have reduced our impact?

Improving the energy efficiency of networks (2G, 3G, 4G, 5G, fiber)?

## Network energy efficiency :

- 2G = 4.6 TWh/EB ; 3G = 2.14 TWh/EB ; 4G = 0.09 TWh/EB (source = [Sénat, 2020](#))
- 5G antennas are twice more efficient than 4G antennas (source = [Orange](#))
- Optical fiber consumes 4 times less KWh than copper (source = [Arcep, 2022](#))

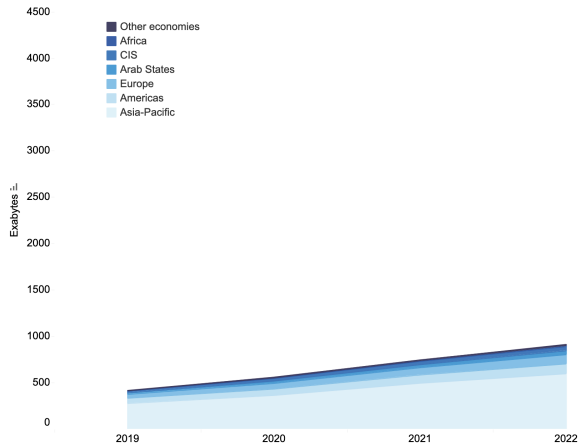
And yet, the energy consumed by fixed and mobile networks is increasing by an average of 5% each year (period 2016-2020):



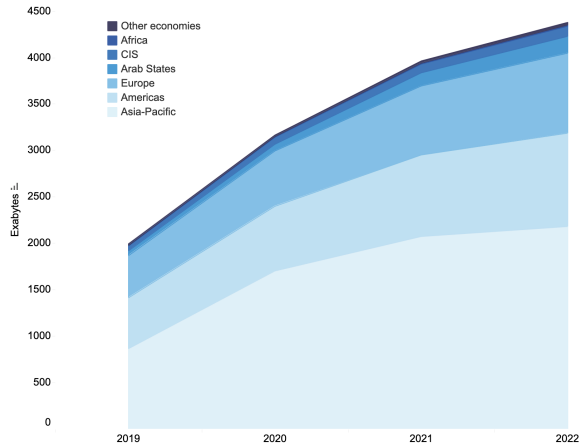
(source = [Arcep, 2023](#))

# Evolution of network use from 2019 to 2022 (source = [ITU](#))

Mobile-broadband traffic, 2019-2022



Fixed-broadband traffic, 2019-2022

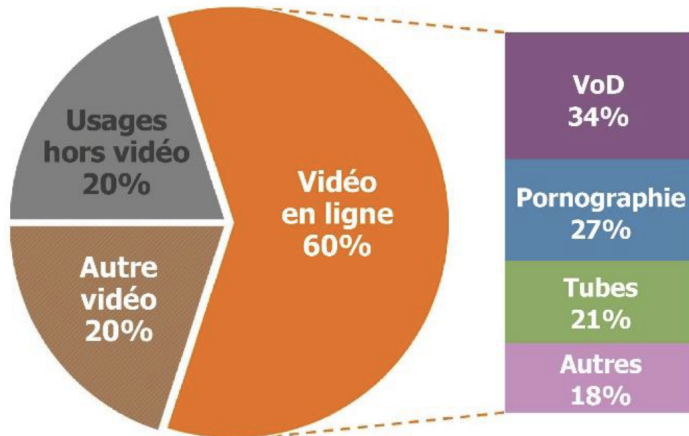


(1 Exabyte =  $10^{12}$  Megabytes)

~ Multiplication by more than 2 in 4 years...

# And all this to do what?

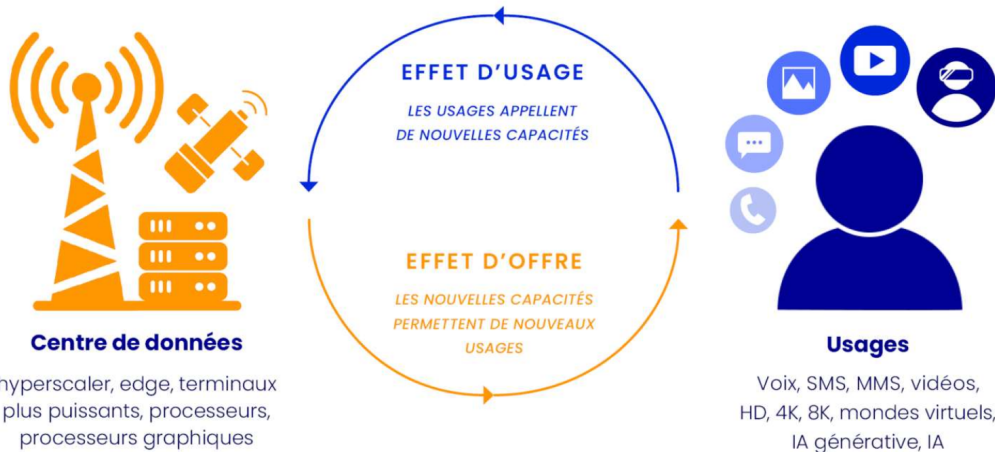
Repartition of data flows in 2018 in the world:



(source = [Shift Project, 2019](#))

## NOS USAGES & NOS INFRASTRUCTURES

sont les deux faces d'une même dynamique



# The explanation for these paradoxes?

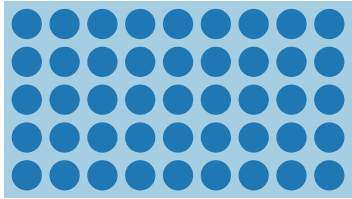
## The rebound effect!



Resource: material, energy, time, money...

# The explanation for these paradoxes?

## The rebound effect!



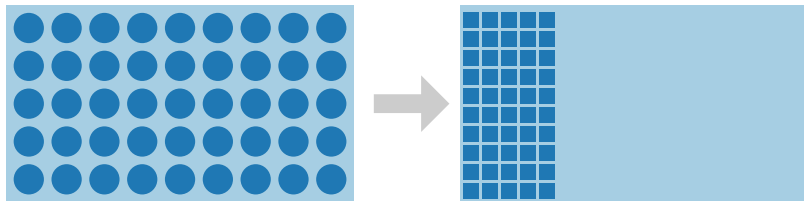
Resource: material, energy, time, money...



Stuff that consumes resource

# The explanation for these paradoxes?

## The rebound effect!



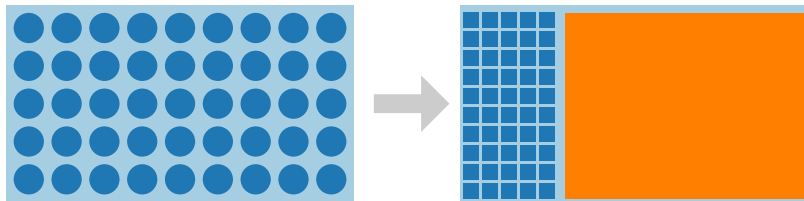
Resource: material, energy, time, money...

● Stuff that consumes resource

■ More efficient stuff that consumes resource

# The explanation for these paradoxes?

## The rebound effect!



Resource: material, energy, time, money...

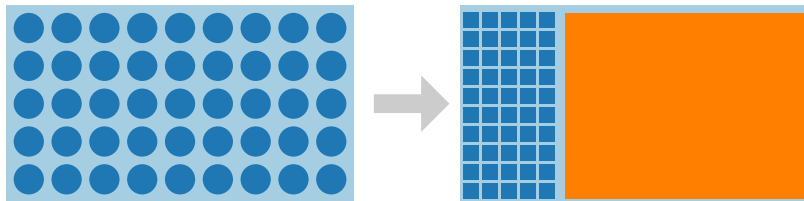
Stuff that consumes resource

More efficient stuff that consumes resource

Freed resource

# The explanation for these paradoxes?

## The rebound effect!



Resource: material, energy, time, money...



Stuff that consumes resource



More efficient stuff that consumes resource

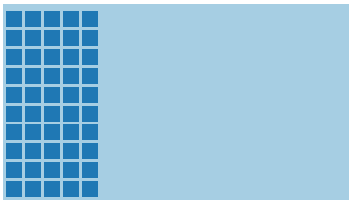


Freed resource

What do we do with this freed resource?

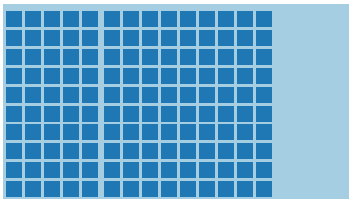
(figure from Françoise Berthoud)

# Rebound effect



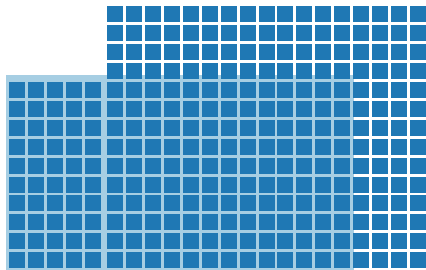
- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

# Rebound effect



- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

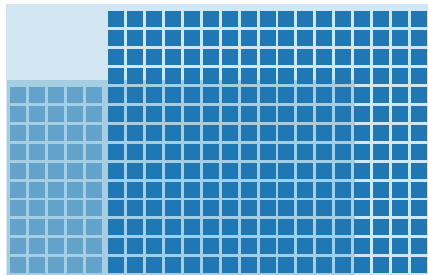
# Rebound effect



Backfire!

- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

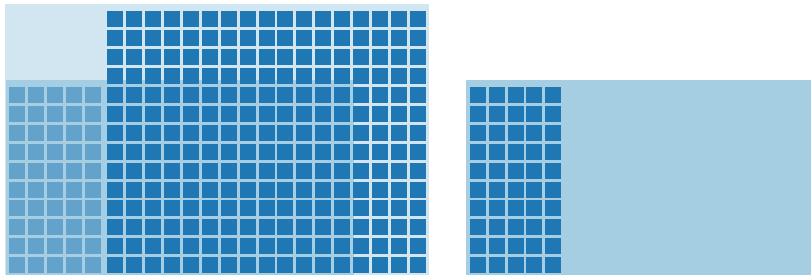
# Rebound effect



Backfire!

- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

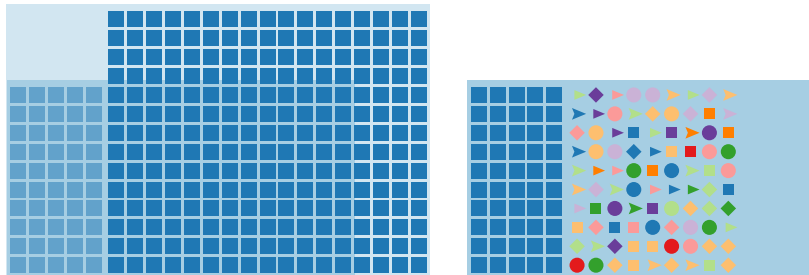
# Rebound effect



Backfire!

- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

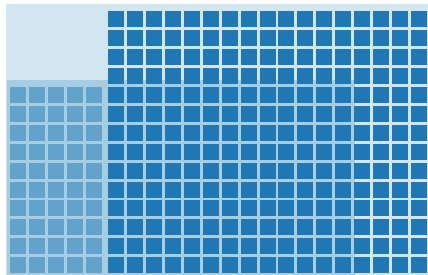
# Rebound effect



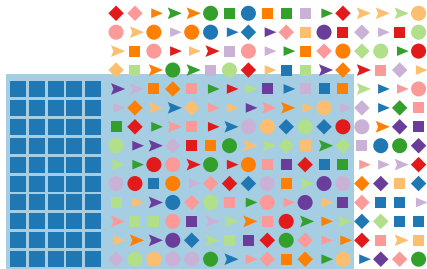
Backfire!

- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

# Rebound effect



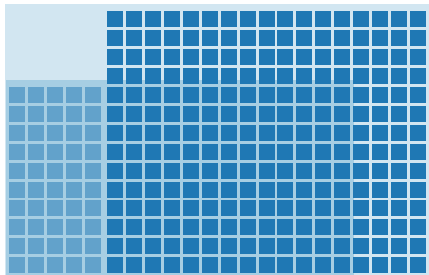
Backfire!



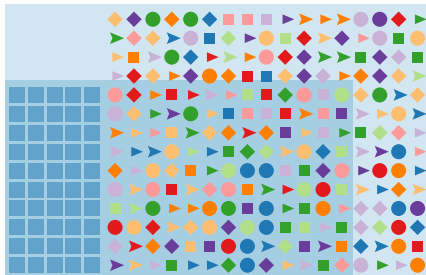
Backfire!

- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

# Rebound effect



Backfire!

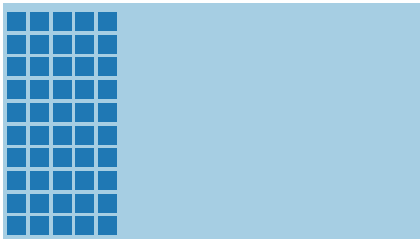


Backfire!

- We do more of the same thing (direct rebound effect)
- We use the freed resource to do something else (indirect rebound effect)

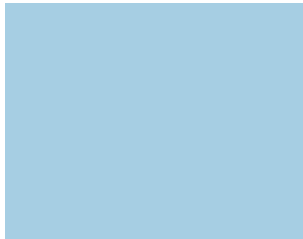
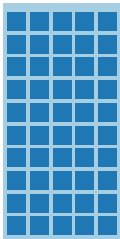
# Rebound effect

What we should (probably) do:



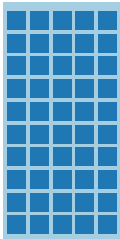
# Rebound effect

What we should (probably) do:



# Rebound effect

What we should (probably) do:



## Taxonomy of effects (inspired from [Horner et al, 2016](#))

| Type      | Scope  | Effect               |
|-----------|--------|----------------------|
| 1st order | Direct | Manufacturing impact |
|           |        | Use impact           |
|           |        | End of life impact   |

### Example: Waze

- Manufacturing of GPS, smartphones, antennas, servers, ...
- Use of GPS, smartphones, antennas, servers, ...
- End of life of GPS, smartphones, antennas, servers, ...

## Taxonomy of effects (inspired from Horner et al, 2016)

| Type      | Scope                    | Effect               |
|-----------|--------------------------|----------------------|
| 1st order | Direct                   | Manufacturing impact |
|           |                          | Use impact           |
|           |                          | End of life impact   |
| 2nd order | Indirect: unique service | Optimisation         |
|           |                          | Substitution         |

### Example: Waze

- Optimisation: Travel times and costs are decreased thanks to the routing system
- Substitution: Replacement of paper-based maps

## Taxonomy of effects (inspired from [Horner et al, 2016](#))

| Type      | Scope                    | Effect               |
|-----------|--------------------------|----------------------|
| 1st order | Direct                   | Manufacturing impact |
|           |                          | Use impact           |
|           |                          | End of life impact   |
| 2nd order | Indirect: unique service | Optimisation         |
|           |                          | Substitution         |
| 3rd order |                          | Direct rebound       |

### Example: Waze

- The number of travels increases because travel times and costs have decreased

## Taxonomy of effects (inspired from [Horner et al, 2016](#))

| Type      | Scope                            | Effect               |
|-----------|----------------------------------|----------------------|
| 1st order | direct                           | Manufacturing impact |
|           |                                  | Use impact           |
|           |                                  | End of life impact   |
| 2nd order | Indirect: unique service         | Optimisation         |
|           |                                  | Substitution         |
| 3rd order |                                  | Direct rebound       |
|           | Indirect: Complementary services | Indirect rebound     |

### Example: Waze

- Saved time and costs are re-invested in other activities that generate new impacts

## Taxonomy of effects (inspired from [Horner et al, 2016](#))

| Type      | Scope                            | Effect               |
|-----------|----------------------------------|----------------------|
| 1st order | Direct                           | Manufacturing impact |
|           |                                  | Use impact           |
|           |                                  | End of life impact   |
| 2nd order | Indirect: Unique service         | Optimisation         |
|           |                                  | Substitution         |
|           |                                  | Direct rebound       |
| 3rd order | Indirect: Complementary services | Indirect rebound     |
|           | Indirect: Economy                | Structural changes   |

### Example: Waze

- The system enables autonomous vehicles and causes growth of intelligent transportation system manufacturing

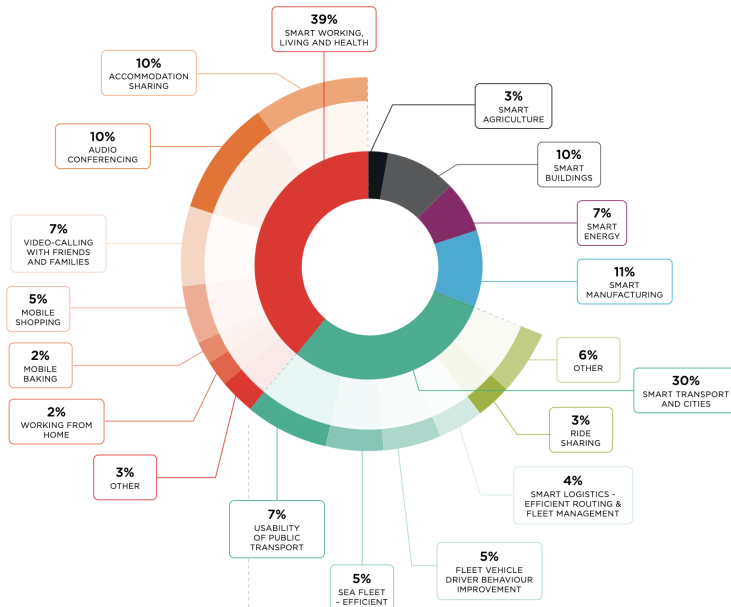
## Taxonomy of effects (inspired from [Horner et al, 2016](#))

| Type      | Scope                            | Effect               |
|-----------|----------------------------------|----------------------|
| 1st order | Direct                           | Manufacturing impact |
|           |                                  | Use impact           |
|           |                                  | End of life impact   |
| 2nd order | Indirect: Unique service         | Optimisation         |
|           |                                  | Substitution         |
|           |                                  | Direct rebound       |
| 3rd order | Indirect: Complementary services | Indirect rebound     |
|           | Indirect: Economy                | Structural changes   |
|           | Indirect: Society                | Systemic changes     |

### Example: Waze

- Cities modify traffic plans to increase travel times of routes that cross residential districts

# What about smart X (with $X \in \{\text{buildings, cities, energy, ...}\}$ )?



## Enabled Avoided Carbon Emissions by Category according to (GSMA, 2019)

*"Mobile networks enable rapid emission reductions while improving quality of life and supporting economic growth*

*(...)*

*reduce CO2 emissions by more than 2,000 million tonnes in 2018 alone"*

## But who is GSMA ?

*The GSMA represents the interests of mobile operators worldwide, uniting more than 750 operators with almost 400 companies in the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and internet companies, as well as organisations in adjacent industry sectors.*

## And how did they evaluate impacts?

*The overall approach to assessing the enabling impact is to multiply an avoided emissions factor by the relevant quantity metric. (...) Generally, we have not explicitly included rebound effects in the analysis.*

## But who is GSMA ?

*The GSMA represents the interests of mobile operators worldwide, uniting more than 750 operators with almost 400 companies in the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and internet companies, as well as organisations in adjacent industry sectors.*

## And how did they evaluate impacts?

*The overall approach to assessing the enabling impact is to multiply an avoided emissions factor by the relevant quantity metric. (...) Generally, we have not explicitly included rebound effects in the analysis.*

# Example: Working from home

**At first sight, that's good for the environment!**

Study of [Ademe](#): decrease of 271 kg eq CO<sub>2</sub> per year and per weekday of teleworking

**What about indirect effects?**

**Can you think of other (positive or negative) systemic effects?**

All this is extremely difficult to evaluate...

# Example: Working from home

**At first sight, that's good for the environment!**

Study of [Ademe](#): decrease of 271 kg eq CO<sub>2</sub> per year and per weekday of teleworking

**What about indirect effects?**

- (-) Augmentation of video flows
- (-) New energy consumption at home
- (-) Some travels are still done (shopping, children, etc)
- (-) Some new travels are done (e.g., sport)
- (+) Reduction of office size in case of flex-office

Ademe conclusion: -31% or +52% on direct effects depending on whether flexoffice is used or not

**Can you think of other (positive or negative) systemic effects?**

All this is extremely difficult to evaluate...

# Overview of the talk

- 1 Impacts of ICT on our planet's boundaries
- 2 Can we use ICT to ensure that planet and social limits are not overpassed?
- 3 Discussion

# Some take-away messages

- 7 planetary boundaries (over 9) are overpassed...  
...and many people still haven't decent life conditions  
    ~> We must react urgently
- Evaluating accurately the direct impacts of ICT is difficult  
    ~> We should consider the whole life-cycle  
    ~> Extraction and manufacturing are the most impacting steps  
    ~> But data center use is increasing at an unsustainable speed
- Models are not neutral  
    ~> Hypothesis should be carefully chosen and well explained  
    ~> Some problems cannot be modelled at all (and we should not try to model them)
- Efficiency improvement  $\nrightarrow$  Overall impact reduction  
    ~> It is often the contrary due to rebound effects!
- Indirect and rebound effects are difficult to quantify, but they are generally devastating  
    ~> Consider a holistic approach

# Discussion

## Some well known contributions of ICT to improve efficiency:

- Car sequencing
- Scheduling
- Pricing
- Picking
- Packing
- Vehicle Routing
- ... insert your favorite problem here ...

## Questions (some being beyond this talk):

- What are their positive and negative impacts on planet and social boundaries?
- Can we add constraints to forbid negative rebound effects?
- Should we collectively choose the constraints to be imposed to get back within planet and social boundaries, or go on our business as usually and suffer the consequences?
- What values do we want to defend? Do our ICT tools allow us to defend them?  
What values are carried by our tools?