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

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2025

Acknowledgement: This talk has been enriched by discussions with Françoise Berthoud, Sylvain Bouveret, Hadrien Cambazard, Serge Fenet, and Alexandre Gondran (among others). Many slides are from Sylvain Bouveret.

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)

$\leadsto$ These boundaries are defined by means of threshold values of control variables

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In 2009, 3 planetary boundaries were overstepped

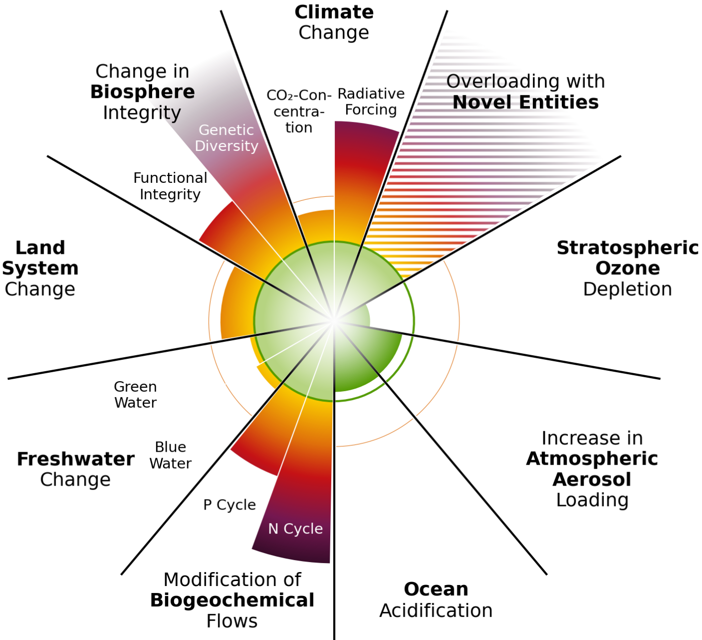
...and 2 were not yet quantified

Quiz

In (Science Advances, 2023):

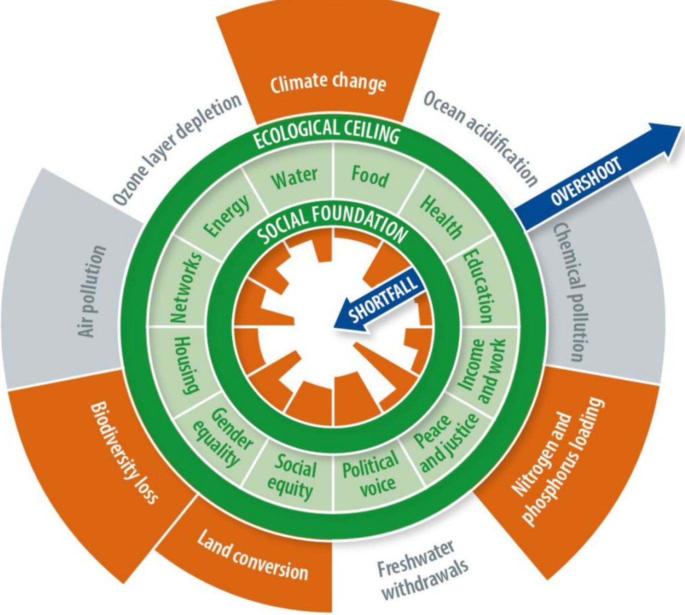
- Measures are introduced for the 2 remaining unquantified boundaries
- All boundaries are re-evaluated

How many boundaries are transgressed according to this study?



Planetary boundaries in 2023

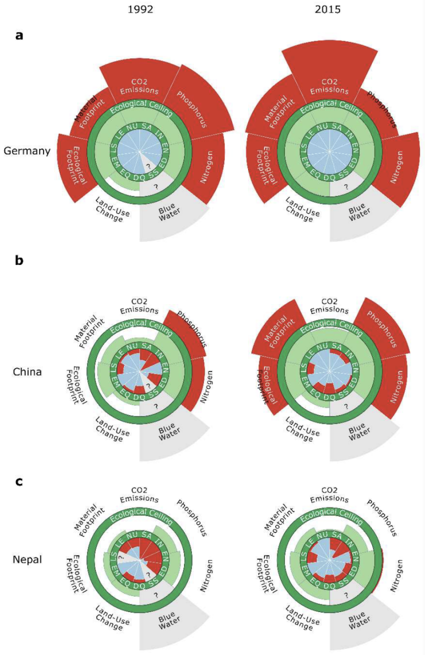
Image: Potsdam Institute for Climate Impact Research (PIK), CC BY 4.0



Kate Raworth's Doughnut:

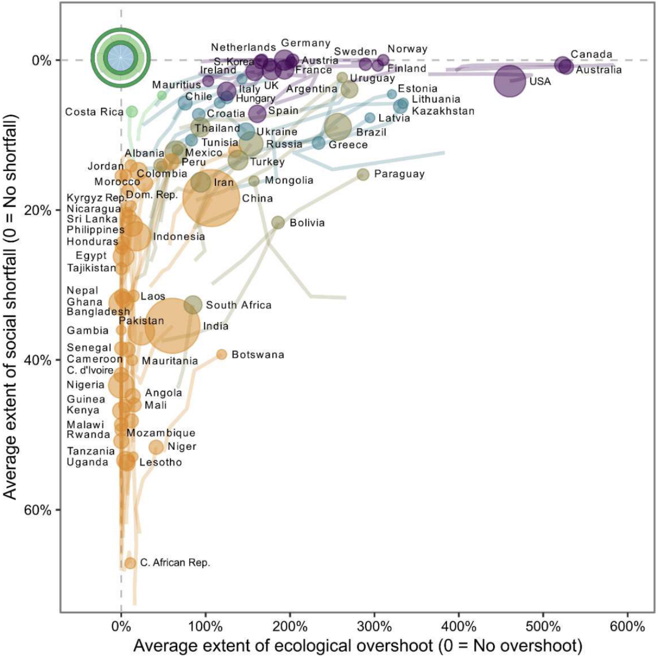
Combining planet's boundaries with social boundaries

Image by DoughnutEconomics - Own work, CC BY-SA 4.0



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
  $\rightsquigarrow$ Maximise efficiency and welfare
- This is a Constrained Optimization Problem!
  $\rightsquigarrow$ Can we use ICT to model and solve this problem?

Questions addressed in this course:

- 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:

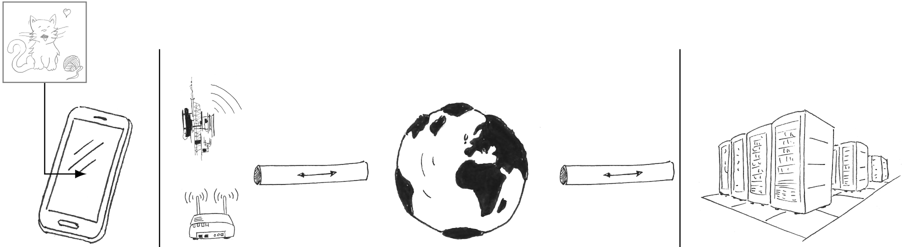
- Manufacture of electronic components whose purpose is not ICT
  $\rightsquigarrow$ *e.g.*, electronic components in cars
- Multimedia content industry
  $\rightsquigarrow$ *e.g.*, animated cartoons, music, etc

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)

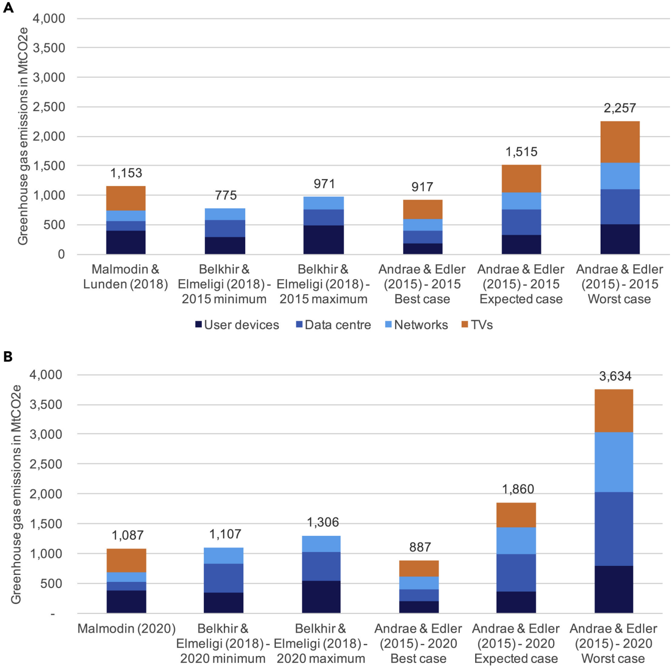


Terminals:	**Networks:**	**Datacenters:**
(smart)phones	boxes	servers
tablets	WIFI access points	other eq.
laptops	routers	
computers	antennas	
screens	pylons	
TVs	cables	
connected obj.	...	
...	See the animation of the New York Times	

Clearly, computer science is not virtual!

Quiz:

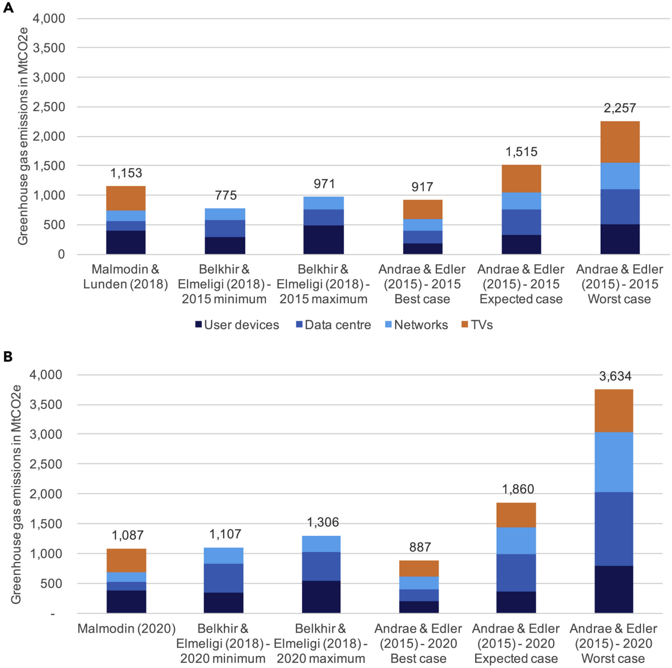
What approximate share of global GHG emissions does computer science account for?



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



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What about France?

In 2022, according to (ADEME, 2025):

- 4,4 % of GHG emissions
- 10% 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...

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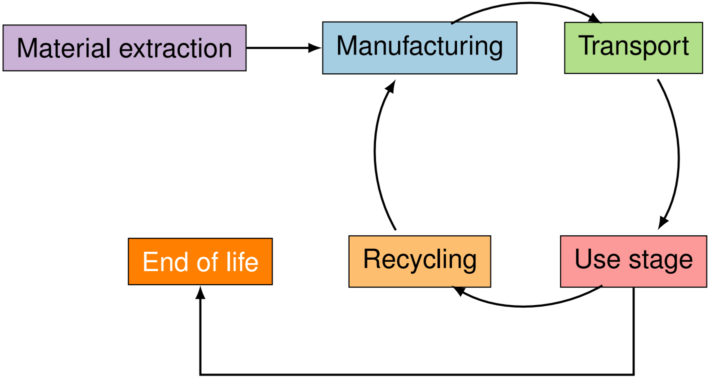
Why?

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

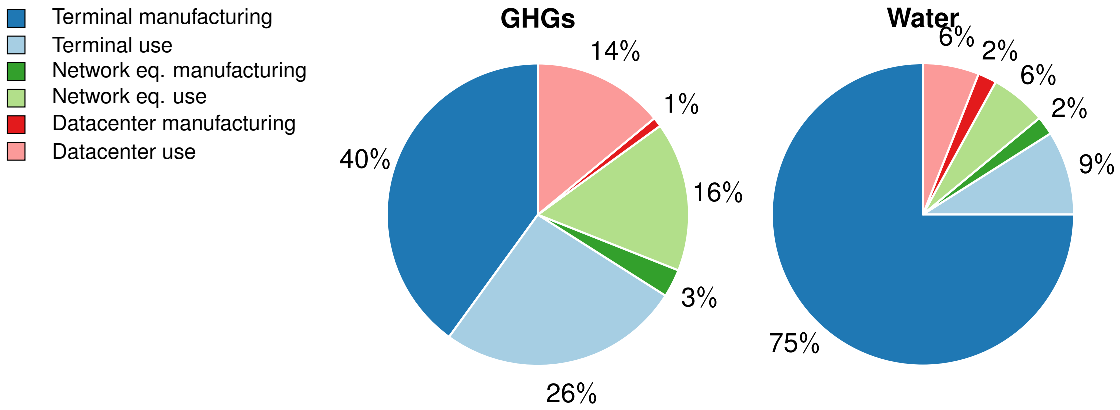
To better understand impacts, we have to analyse the whole life cycle



Quiz

- What step is the most impactful: manufacturing or use?
- Which tier is the most impactful: terminals, networks, or datacenters?

Impacts per source (GrenIT, 2019)



Plan

1. **Impacts of ICT on our planet's boundaries**
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The chemical elements of a smartphone

COMPOUND INTEREST

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

SCREEN

In (Indium) · Sn (Tin) · O (Oxygen)

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.

Al (Aluminium) · Si (Silicon) · O (Oxygen) · K (Potassium)

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.

Y (Yttrium) · La (Lanthanum) · Tb (Terbium) · Pr (Praseodymium) · Eu (Europium) · Dy (Dysprosium) · Gd (Gadolinium)

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.

ELECTRONICS

Cu (Copper) · Ag (Silver) · Au (Gold) · Ta (Tantalum)

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.

Ni (Nickel) · Dy (Dysprosium) · Pr (Praseodymium) · Tb (Terbium) · Nd (Neodymium) · Gd (Gadolinium)

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.

Si (Silicon) · O (Oxygen) · Sb (Antimony) · As (Arsenic) · P (Phosphorus) · Ga (Gallium)

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.

Sn (Tin) · Pb (Lead)

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

BATTERY

Li (Lithium) · Co (Cobalt) · O (Oxygen) · C (Carbon) · Al (Aluminium)

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.

CASING

C (Carbon) · Mg (Magnesium) · Br (Bromine) · Ni (Nickel)

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

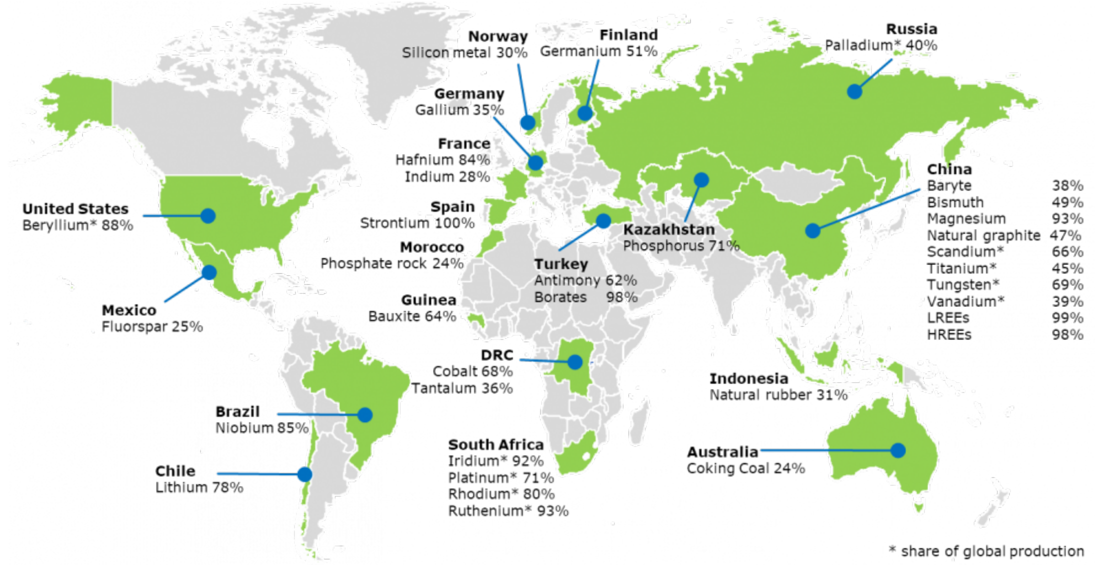
Unit impacts are increasing

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

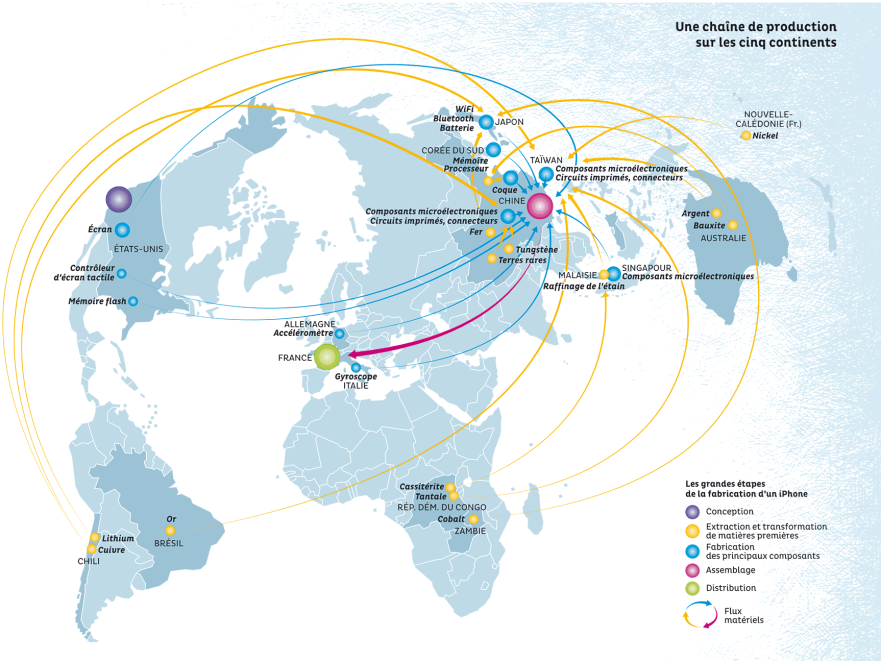
2 videos (in french) to watch:

- 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)



...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 ⇝ ultra-pure materials
  ⇝ massive use of chemical products and water
- *e.g.*, more than 150,000 tonnes of water per day for TSMC in 2019
  ⇝ 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?

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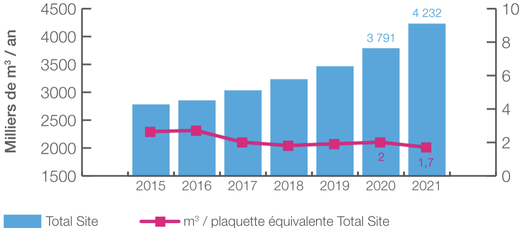

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Use stage of an ICT equipment

- What is the main impact of the use stage?

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- What is the main impact of the use stage? $\leadsto$ *Electricity consumption*
- How to translate an electricity consumption into impacts?

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- How to translate an electricity consumption into impacts? $\rightsquigarrow$ *It depends...*
- What is the most common source of energy used to generate electricity in the world?

Use stage of an ICT equipment

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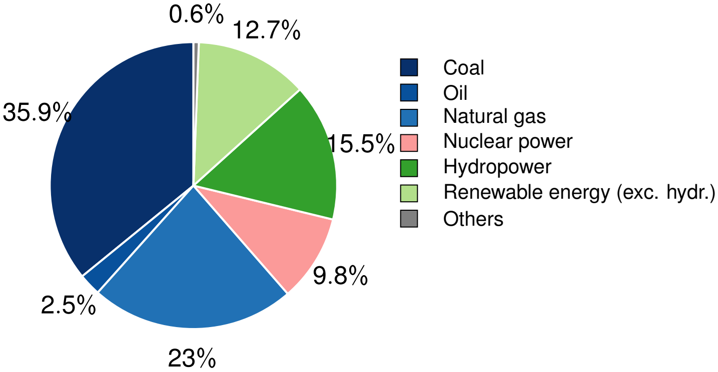
- What is the most common source of energy used to generate electricity in the world?

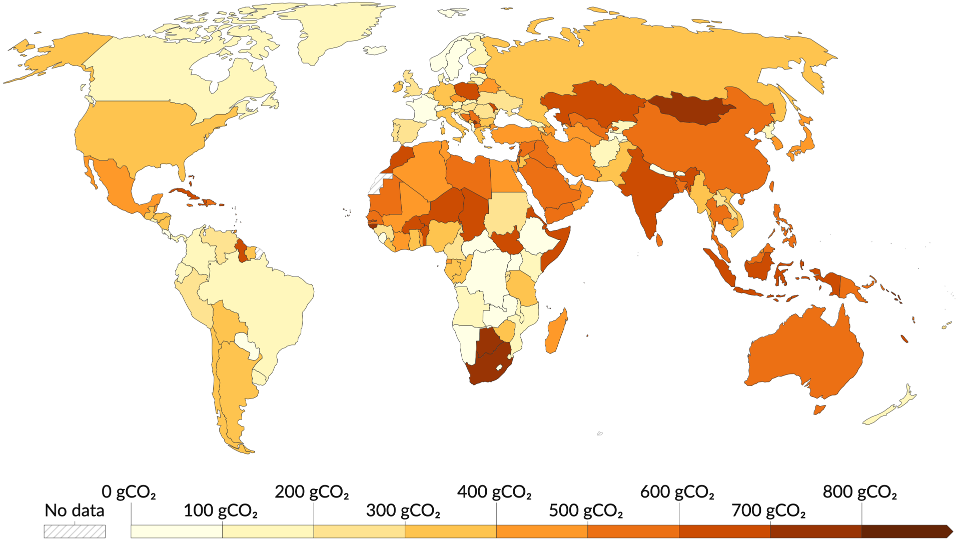


Is it the same in all countries?

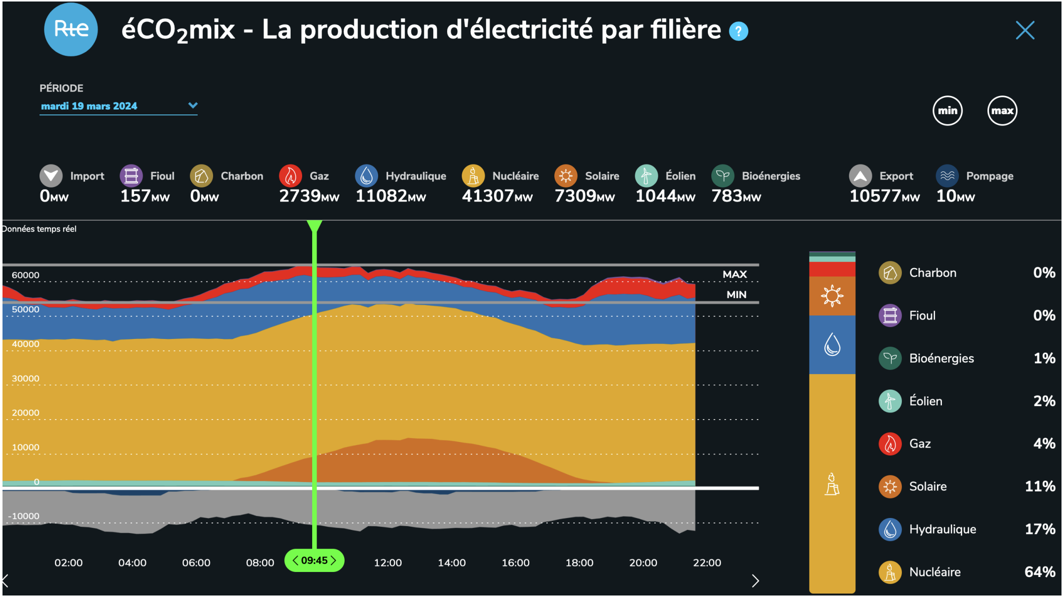
Carbon intensity of electricity generation, 2022

Carbon intensity is measured in grams of carbon dioxide-equivalents emitted per kilowatt-hour of electricity generated.

Our World in Data



What about France? (Source = RTE)



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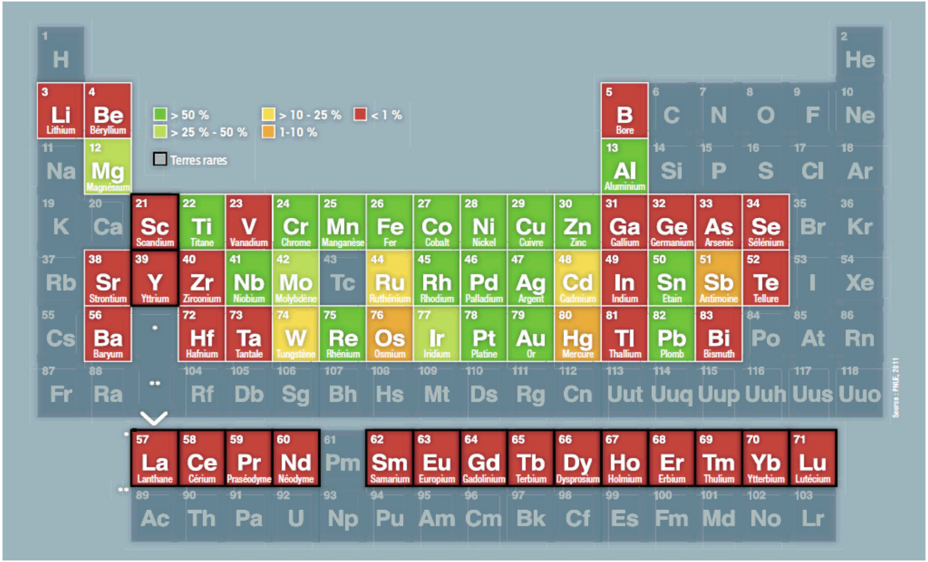
From life to waste

- Equipment no longer used $\rightsquigarrow$ 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/[...]

And when wastes are not collected?

- Stored at home
- Landfilled
- Burned
- Illegal treatment

Quiz:

How many non-used smartphones have you at home?

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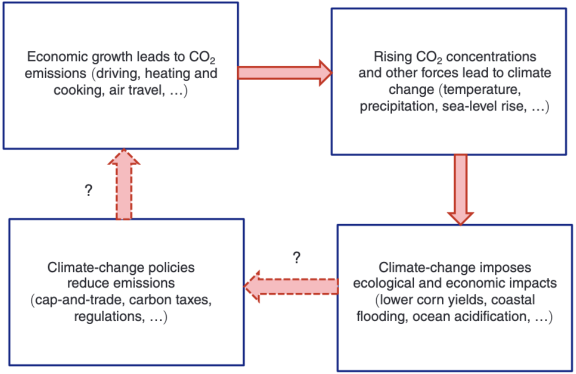
The answer of William Nordhaus: DICE

Structure of DICE (Nordhaus, 2019)



Integrated Assessment Model (IAM)
= Economic model (Ramsey model)
+ Climate model (FAIR model)

If we continue along our current path of virtually no policies, then the dashed arrows will fade away, and the globe will continue on the dangerous path of unrestrained global warming

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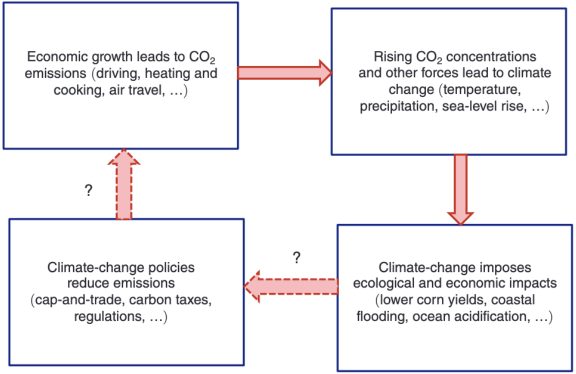

Integrated Assessment Model (IAM)
= Economic model (Ramsey model)
+ Climate model (FAIR model)
+ Carbon tax model

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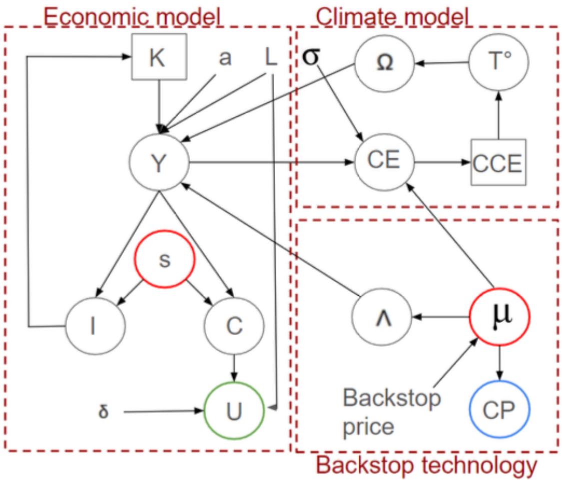
Solution: Introduce backstop technology

Description of DICE (Nordhaus, 2023)



(image from Alexandre Gondran)

Economic model:

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

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 Ω, CE, CCE, T°, and Y

Backstop technology:

Contraints between Λ, μ, 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

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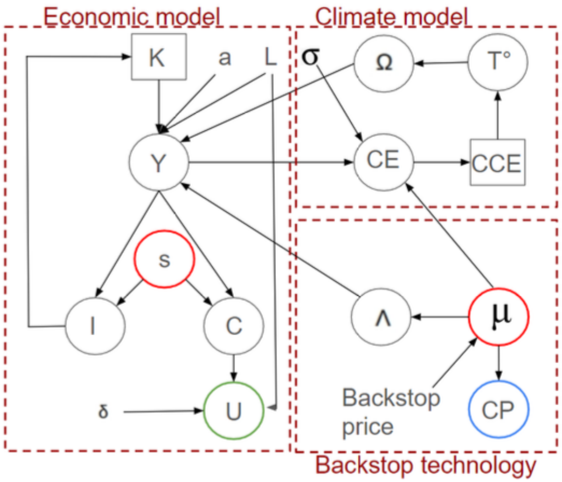

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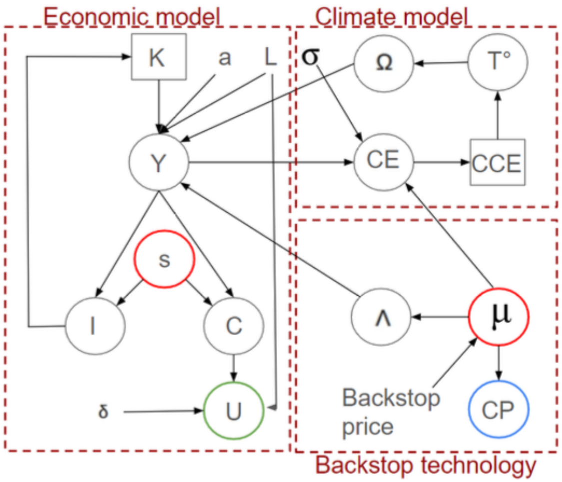

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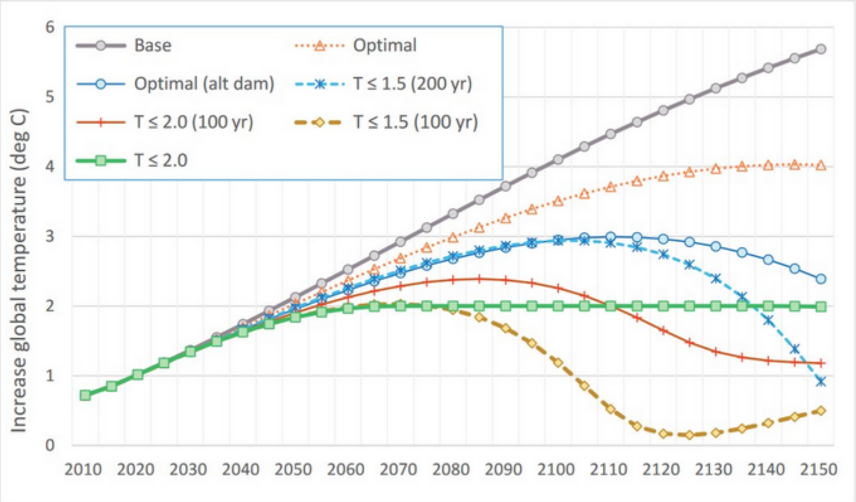
C = consumption	T° = temperature
s = saving rate	Λ = carbon tax
Y = GDP	CP = carbon price
K = capital	μ = emissions control rate

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: $\Omega[t] = 0.003467 \times T^{\circ}[t]^2$
  $\rightsquigarrow$ GDP decreases of 1% (resp. 4%, 9%) when T° increases of 2° (resp. 4°, 6°)

  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 ρ translates future costs into present value
  $\rightsquigarrow$ ρ 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?

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What do you think of these hypothesis?

We often focus on solving, but the modelling step is way more important...

Life cycle of the modelling step (source = Countermod French Working Group)

Before starting modelling, clearly define the following points:

- Goal $\rightsquigarrow$ What is the question to be answered by the model?
- Scope $\rightsquigarrow$ What are the hypothesis, preconditions, limits, ...?
- Potential consequences $\rightsquigarrow$ What may be done with this model (by you, and others than you)?
- Different stakeholders $\rightsquigarrow$ What are their contribution, interest, bias, ...?
- Assessment methods $\rightsquigarrow$ How to evaluate the quality and relevance of the model?

During modelling: Iterative process

- Build an initial model
- While the model is not good enough: improve it and simplify it

After:

- Transparency: Open data/source/hypothesis/limits ...
- Explainability: How to interpret the results?
- Make it reusable

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

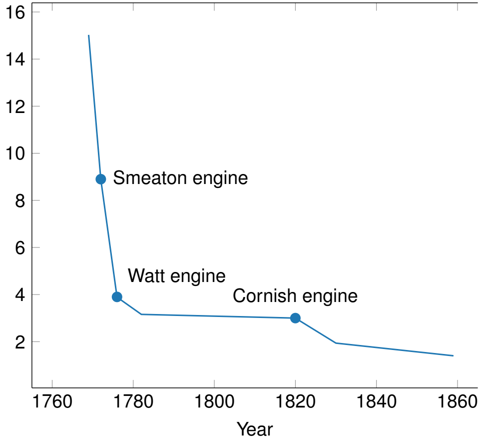
Quiz

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)

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)

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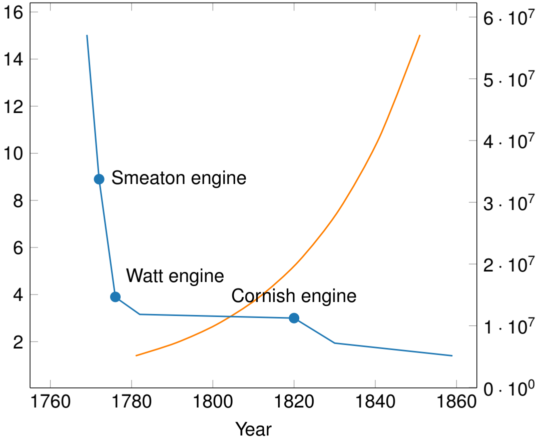

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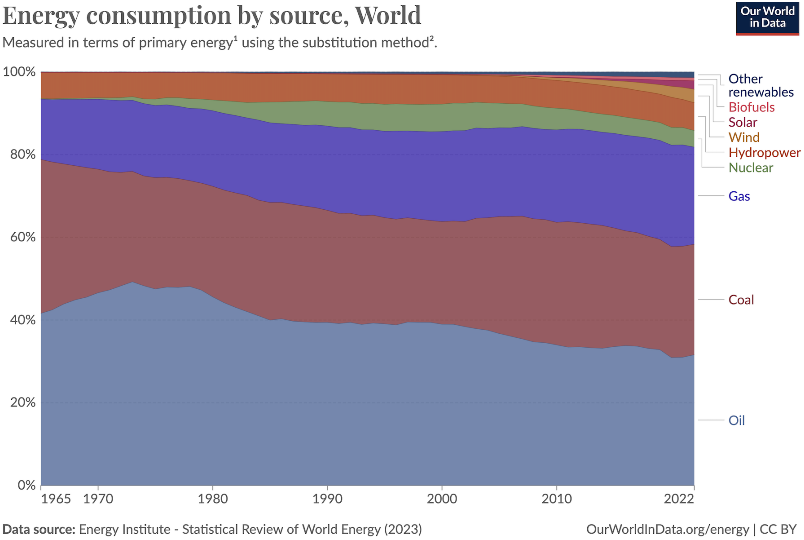

coal+gas+oil decrease from 93.4% in 1965 to 81.8% in 2022... but what's the catch?

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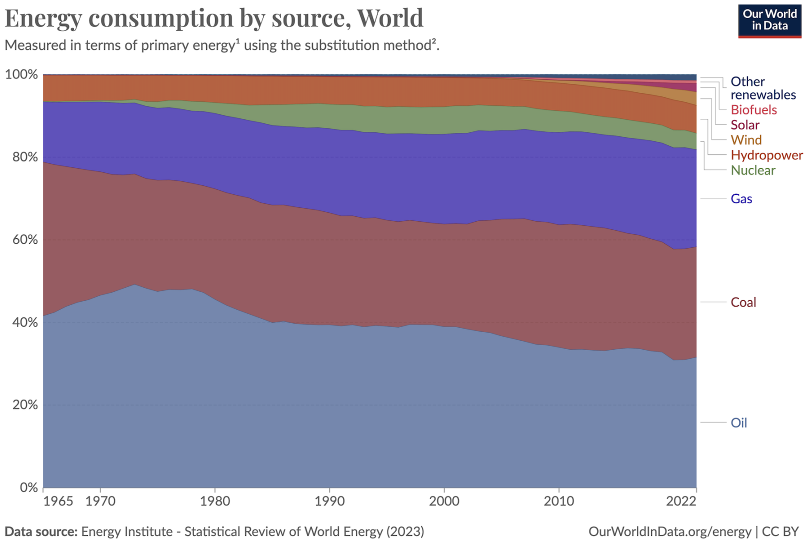

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These are percentages
⇝ Look at absolute values!

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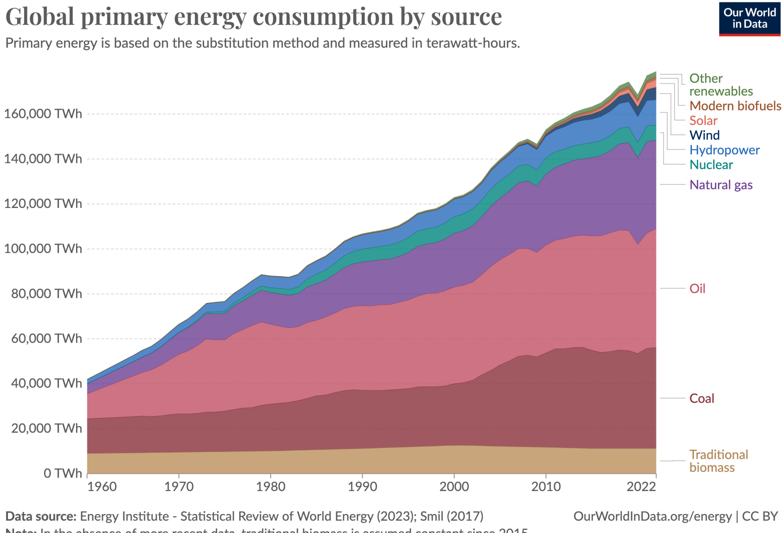

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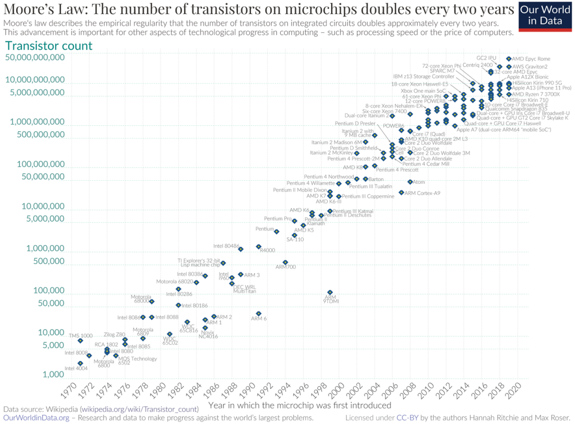
Do you see a transition?

Which technological advances have reduced our impact?

Improving computer processors?

Law of Moore (Source: Our World in Data)



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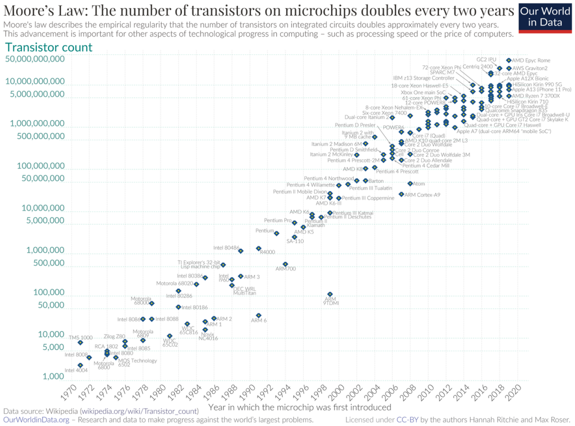
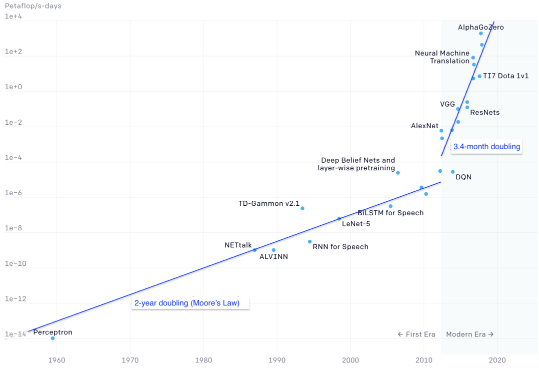
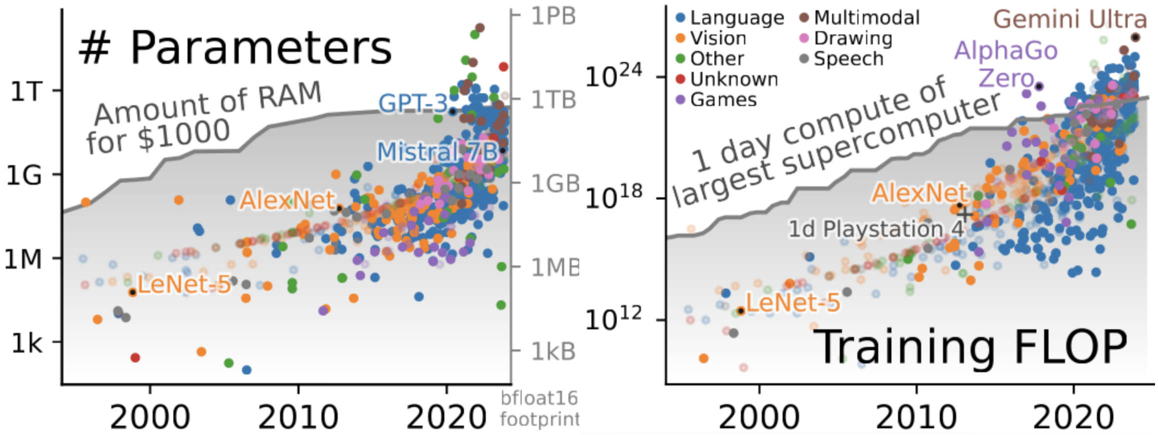


Training cost of an AI (source: OpenAI)

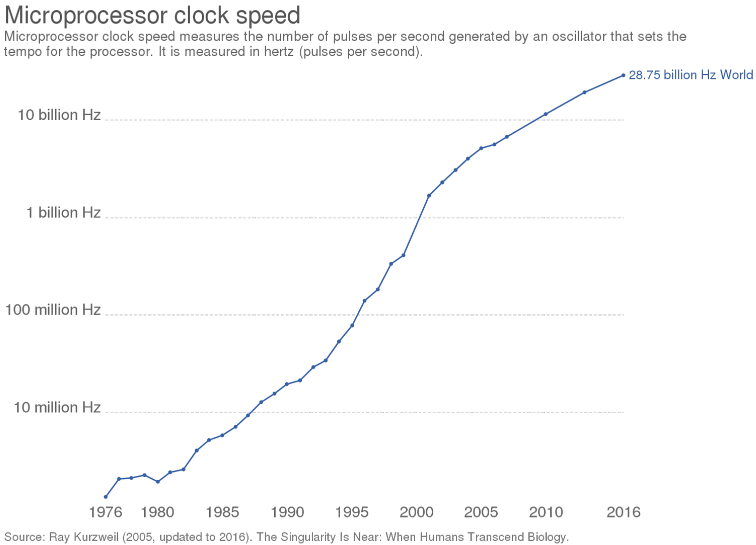


- What happened in 2012?
- What made it possible?

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



Other exponential rates related to Moore's law



- 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?**

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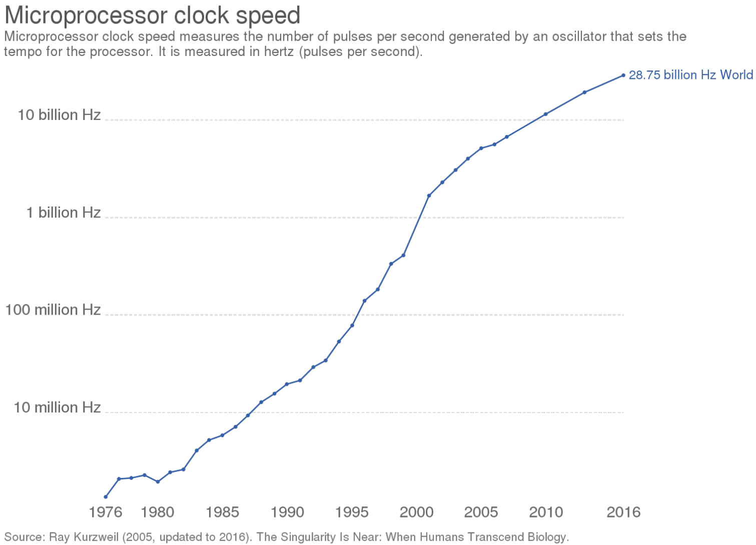

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Image by Our World In Data - CC BY 3.0

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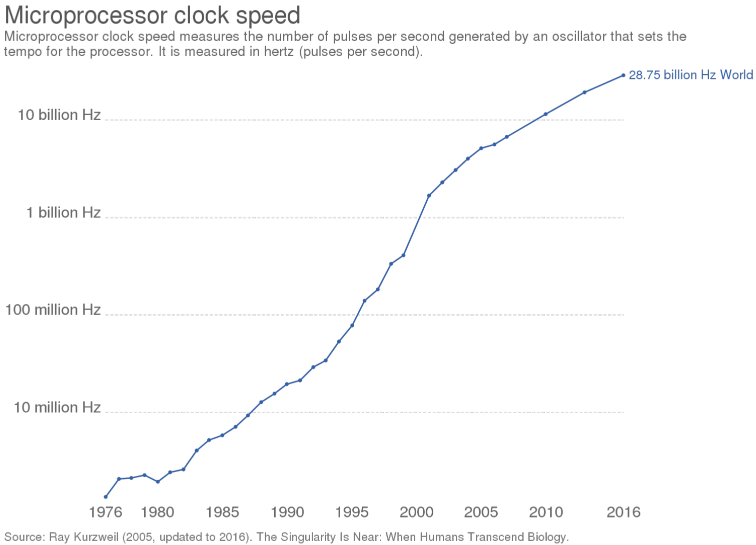

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The Great Moore's Law Compensator

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:
  $\rightsquigarrow$ 12$\times$ memory and 3$\times$ processing power as Office 2000
- The end of Windows 10 support could turn 240 million PCs into e-waste (Caddy and Jessop, 2023)

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)

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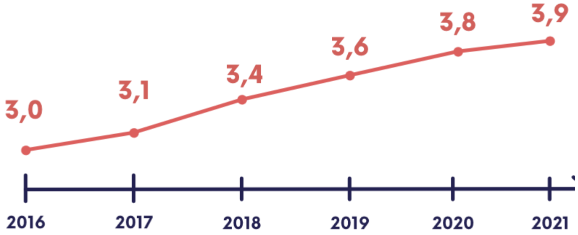
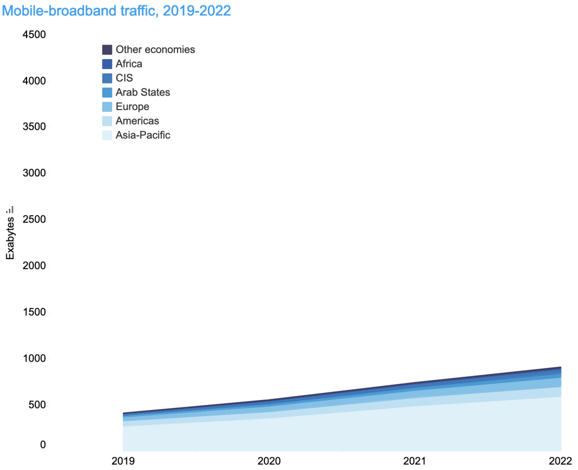
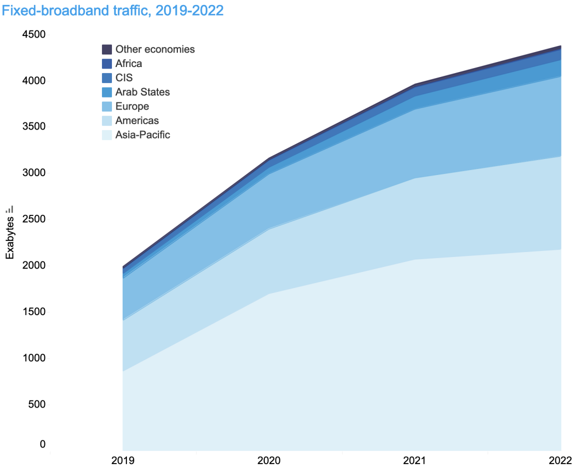
And yet, the energy consumed by fixed and mobile networks is increasing by an average of 5% each year (period 2016-2020):



(source = Arcep, 2023)

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



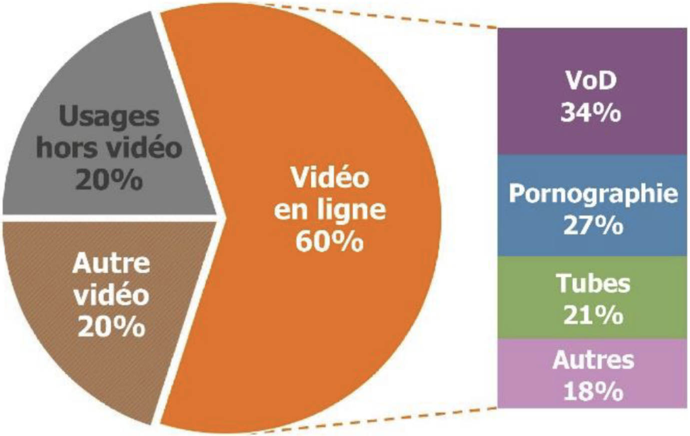


(1 Exabyte = 10^{12} Megabytes)

$\rightsquigarrow$ Multiplication by more than 2 in 4 years...

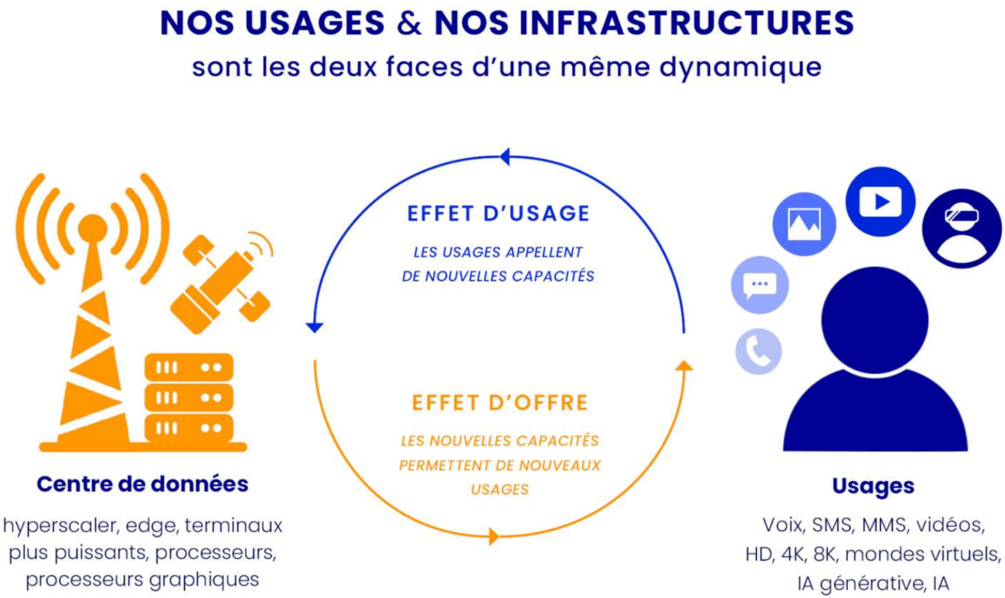
And all this to do what?

Repartition of data flows in 2018 in the world:

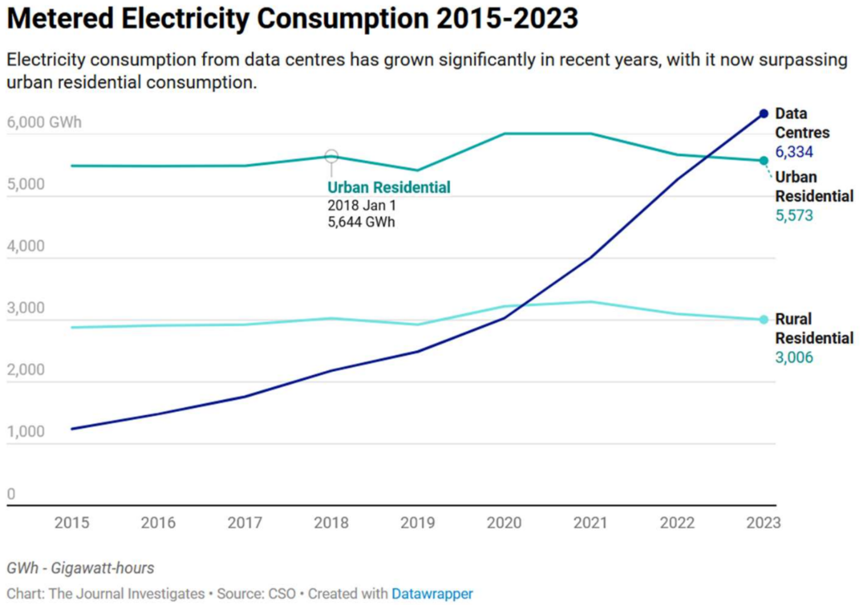


(source = Shift Project, 2019)

Usages et infrastructures : les deux faces d’une même pièce (Shift Project, 2025)



Le cas de l'Irlande (Shift Project, 2025)



The explanation for these paradoxes? The rebound effect!

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

(figure from Françoise Berthoud)

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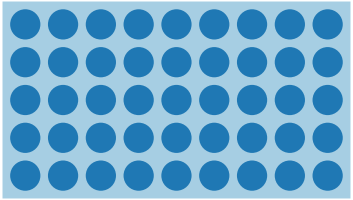

Resource: material, energy, time, money...

Stuff that consumes resource

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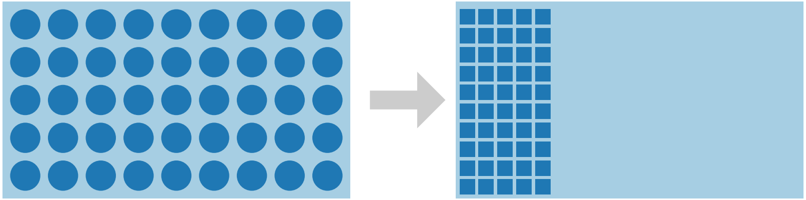

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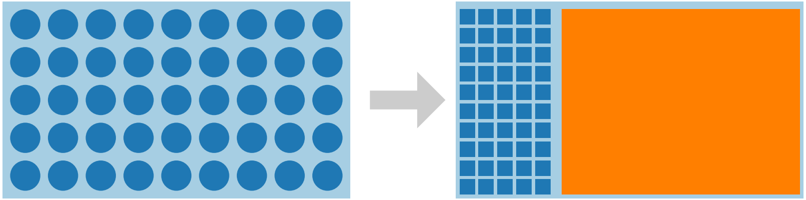

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Freed resource

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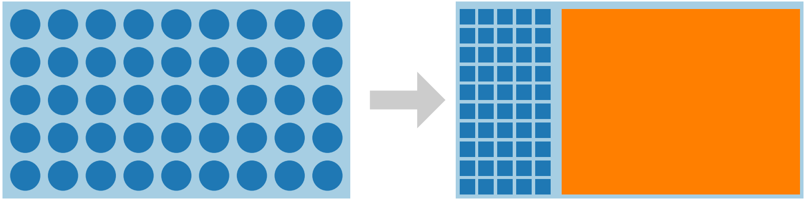

Resource: material, energy, time, money...

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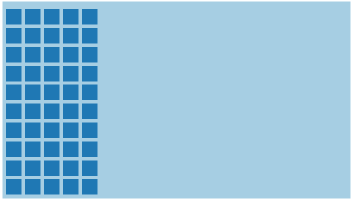
Freed resource

What do we do with this freed resource?

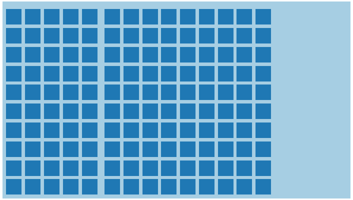
(figure from Françoise Berthoud)

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



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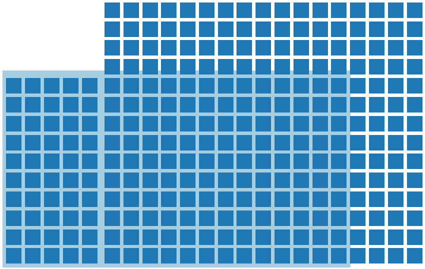

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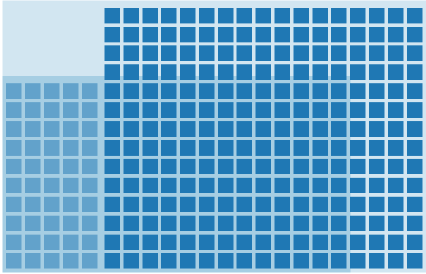

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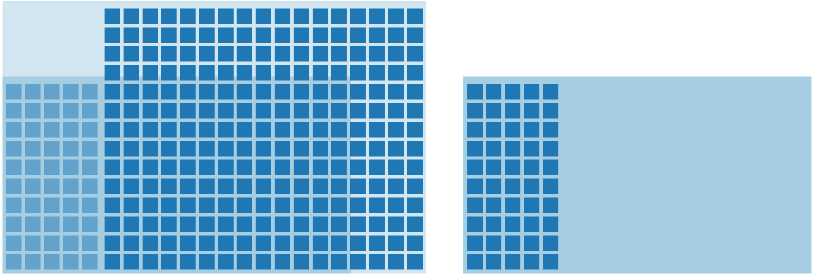

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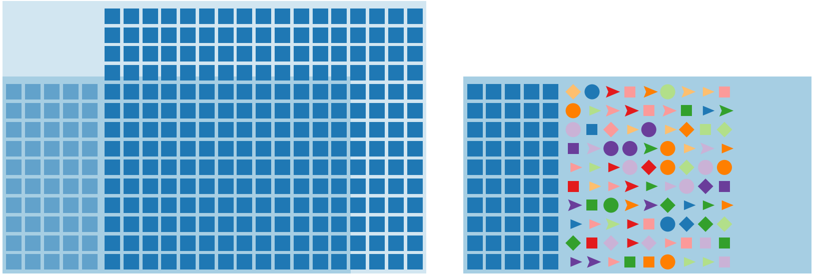

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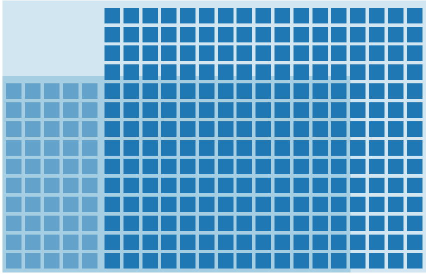

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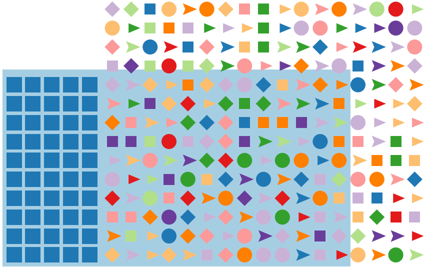

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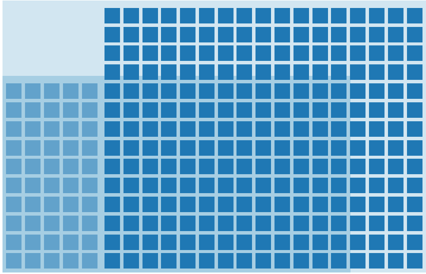

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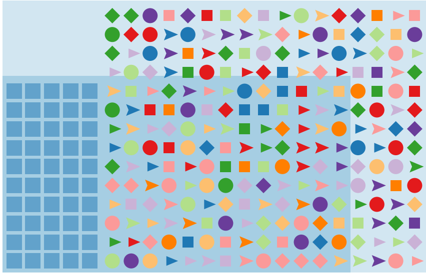

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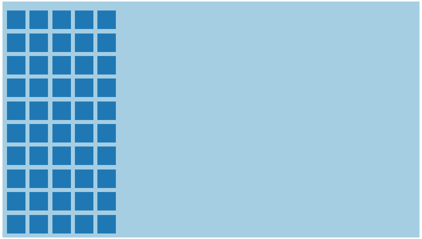
Rebound effect

What we should (probably) do:



Rebound effect

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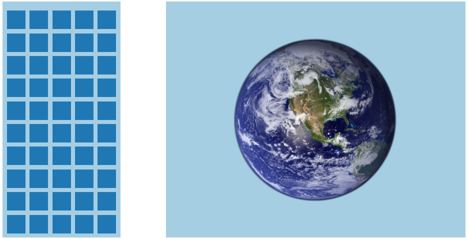

Taxonomy of effects (inspired from Horner et al, 2016)

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

Example: GPS system with user-submitted travel times

- 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
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2nd order	Indirect: unique service	Optimisation
		Substitution

Example: GPS system with user-submitted travel times

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

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3rd order		Direct rebound

Example: GPS system with user-submitted travel times

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

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2nd order	Indirect: unique service	Optimisation
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3rd order		Direct rebound
	Indirect: Complementary services	Indirect rebound

Example: GPS system with user-submitted travel times

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

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

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	Indirect: Economy	Structural changes

Example: GPS system with user-submitted travel times

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

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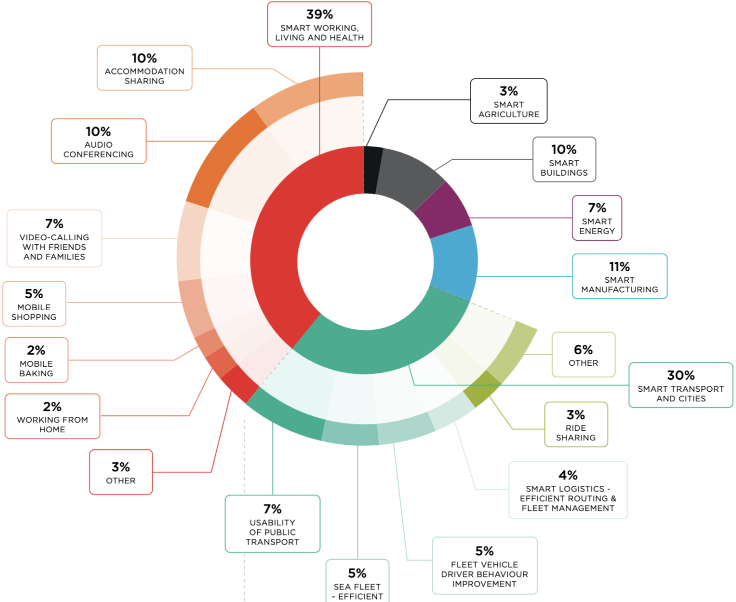
	Indirect: Economy	Structural changes
	Indirect: Society	Systemic changes

Example: GPS system with user-submitted travel times

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

What about smart X (with $X \in \{$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.

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Example: Working from home

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

Study of Ademe: decrease of 271 kg eq CO_2 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_2 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

- 6 planetary boundaries (over 9) are overpassed...
  ...and many people still havn't decent life conditions
  $\rightsquigarrow$ We must react urgently
- Evaluating accurately the direct impacts of ICT is difficult
  $\rightsquigarrow$ We should consider the whole life-cycle
  $\rightsquigarrow$ Extraction and manufacturing are the most impacting steps
- Models are not neutral
  $\rightsquigarrow$ Hypothesis should be carefully chosen and well explained
  $\rightsquigarrow$ Some problems cannot be modelled at all (and we should not try to model them)
- Efficiency improvement $\not\Rightarrow$ Overall impact reduction
  $\rightsquigarrow$ It is often the contrary due to rebound effects!
- Indirect and rebound effects are difficult to quantified, but they are generally devastating
  $\rightsquigarrow$ 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?