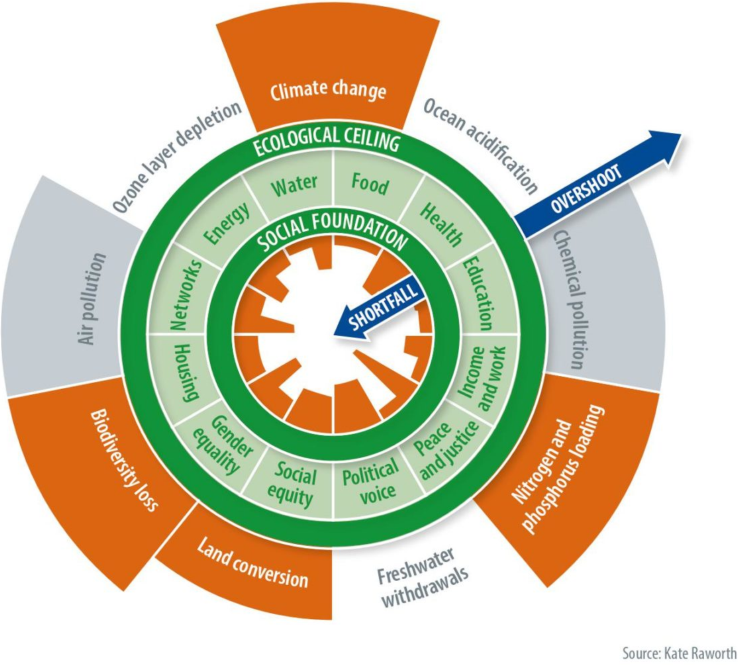
Can OR help us meet everyone's needs within the planet's boundaries?

Christine Solnon (CITI, INSA Lyon / INRIA)

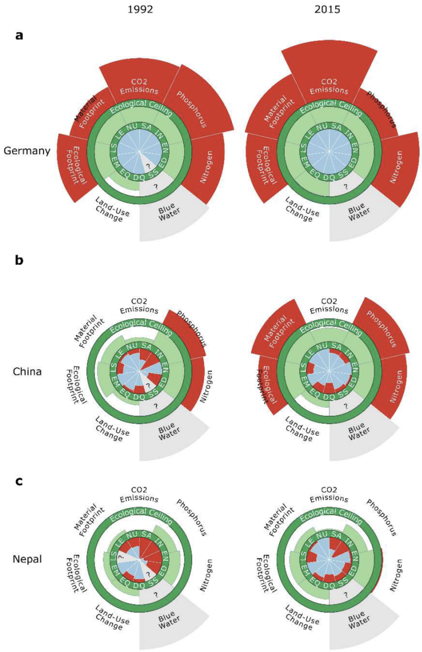
GreenDays 2025

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.



Kate Raworth's Doughnut:

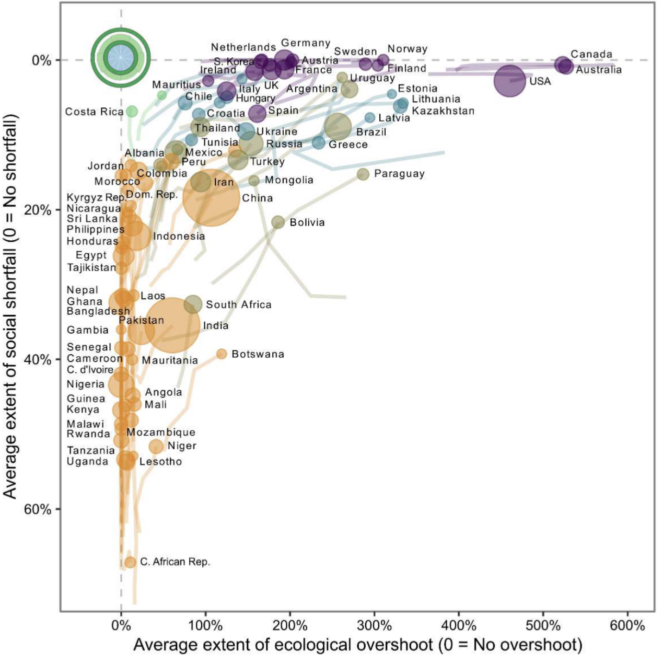
- 9 planet's boundaries
- 12 social boundaries



Doughnuts depend on:

- Countries
  ⇝ Germany vs China vs Nepal
- Time
  ⇝ 1992 vs 2015

See (Fanning et al, 2022) for more details



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

Can OR 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 OR to model and solve this problem?

Warning: I assume you already know ICT has huge impacts on planet's boundaries

For example, in France in 2022 (ADEME, 2025):

- 4.4% of GHG emissions
- 10% of electricity consumption

with an unsustainable growth rate...

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

Integrated Assessment Model (IAM):

Classical economic model (Ramsey model)
$\rightsquigarrow$ Economic growth

\+ Climate model (FAIR model)
$\rightsquigarrow$ Rising CO_2 concentrations lead to unrestrained global warming

\+ Carbon tax model and backstop technologies
$\rightsquigarrow$ Climate-change policies reduce emissions

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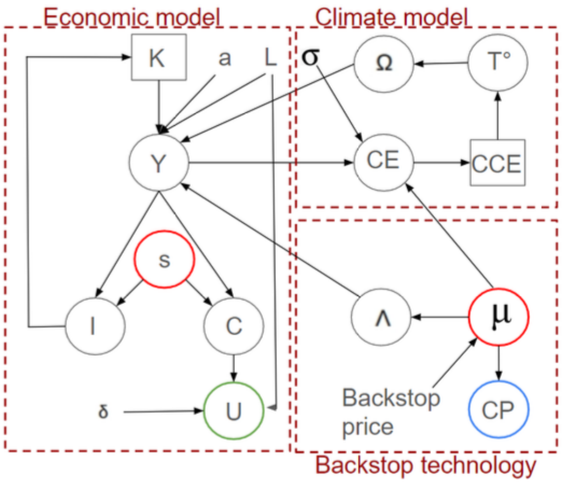
Description of DICE (Nordhaus, 2023)



(image from Alexandre Gondran)

Economic Ramsey 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 FAIR 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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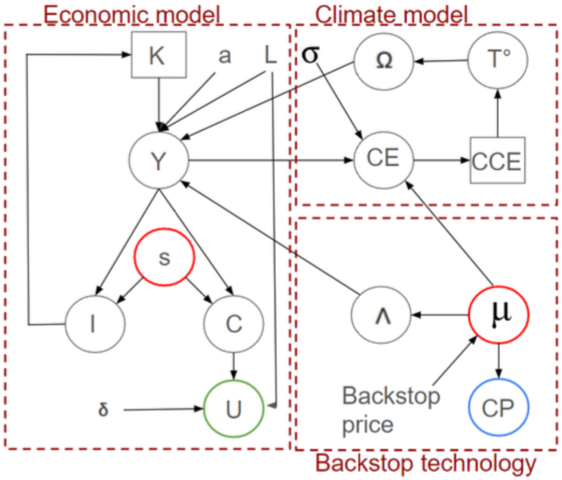

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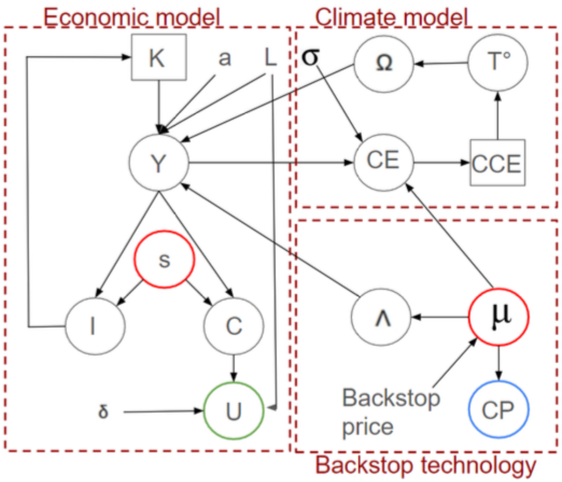

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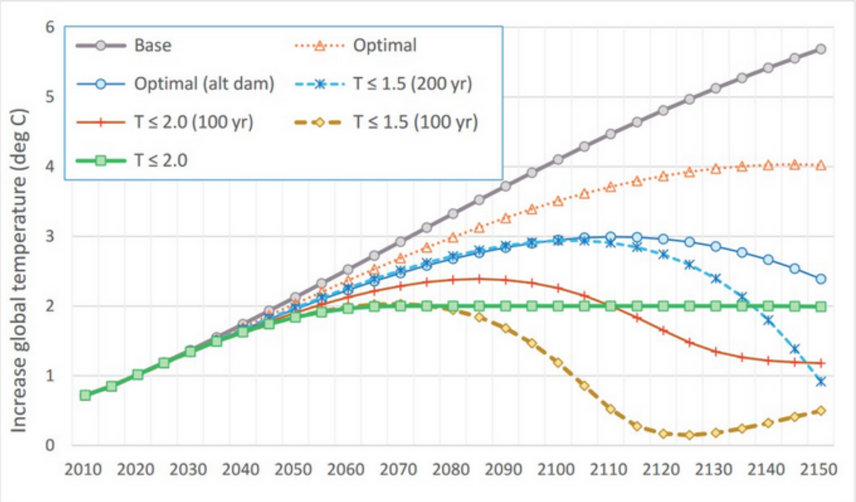
- T° = temperature
- Λ = carbon tax
- CP = carbon price
- μ = emissions control rate

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**

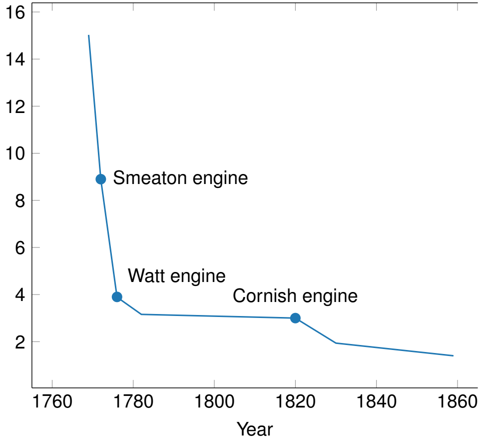
  $\rightsquigarrow$ Technological optimism

Which technological advances have reduced our impacts?

- Improving the efficiency of steam engines?
- Renewable energies?
- 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)?



Jevons's Paradox:

- 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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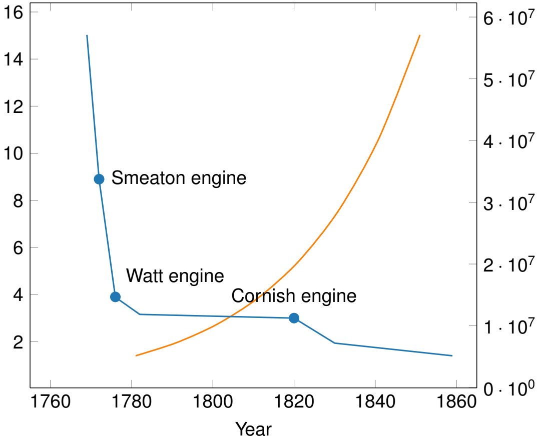

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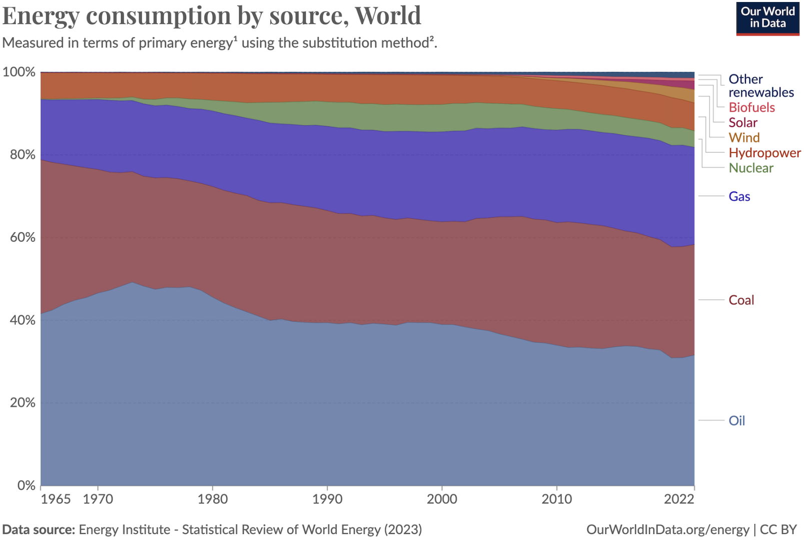
Renewable energies (source = Our World in Data)?



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

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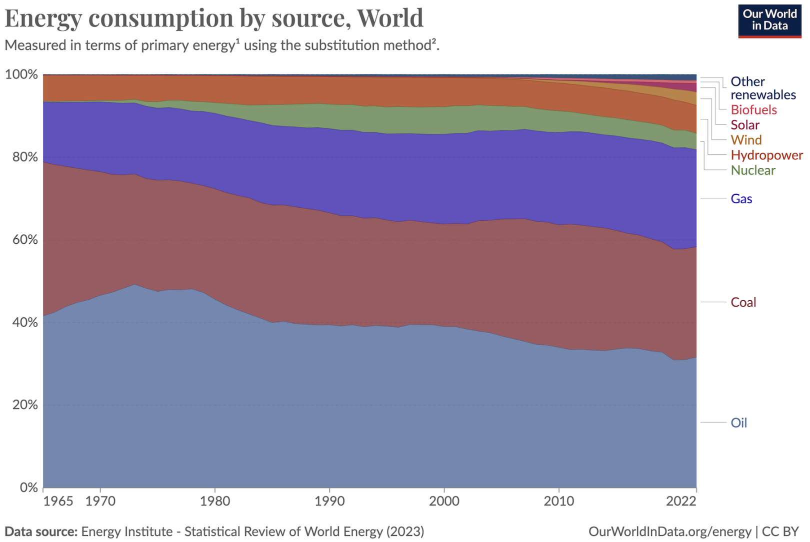

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These are percentages
⇝ Look at absolute values!

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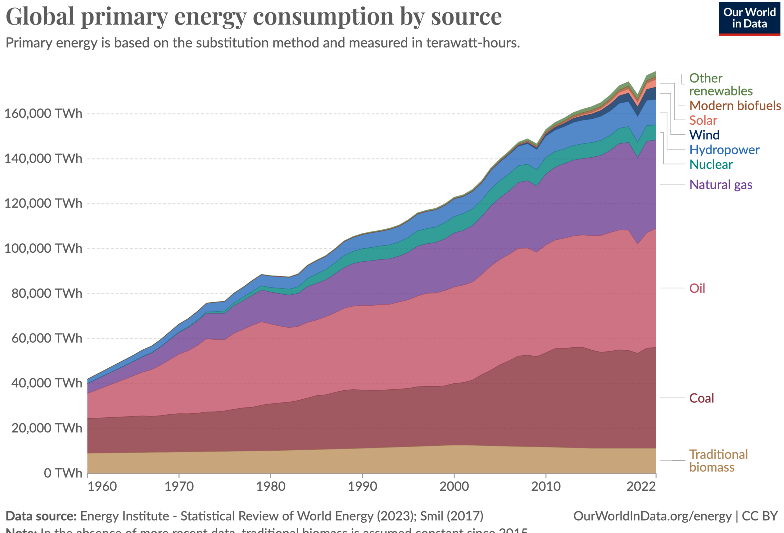

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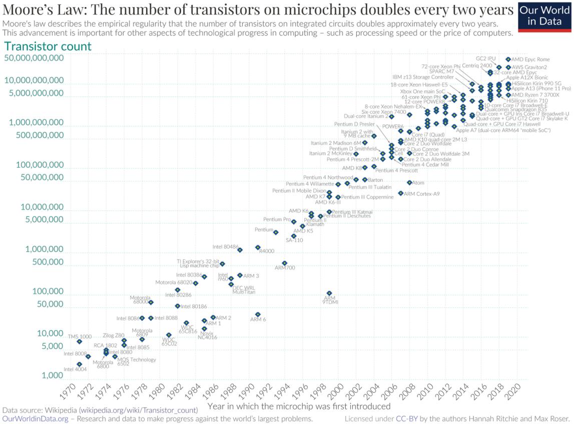
Do you see a transition?

Which technological advances have reduced our impact?

Improving computer processors?

Law of Moore (Source: Our World in Data)



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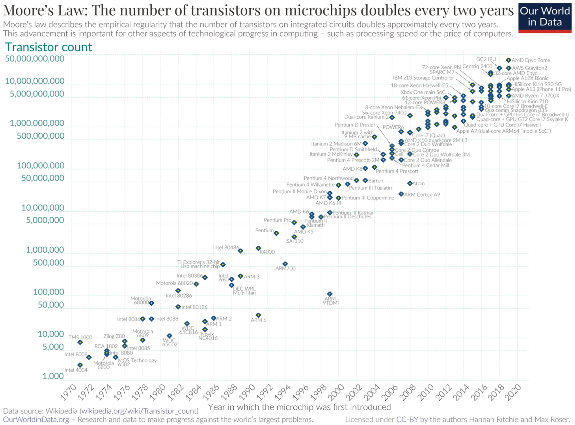
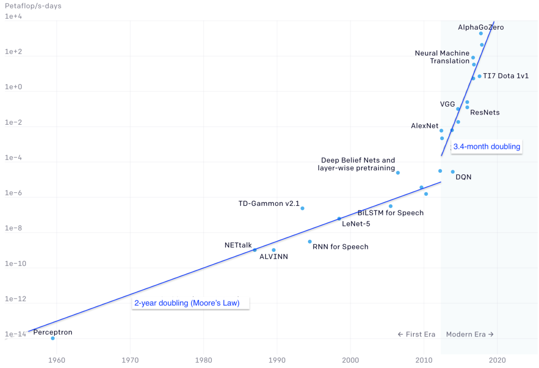
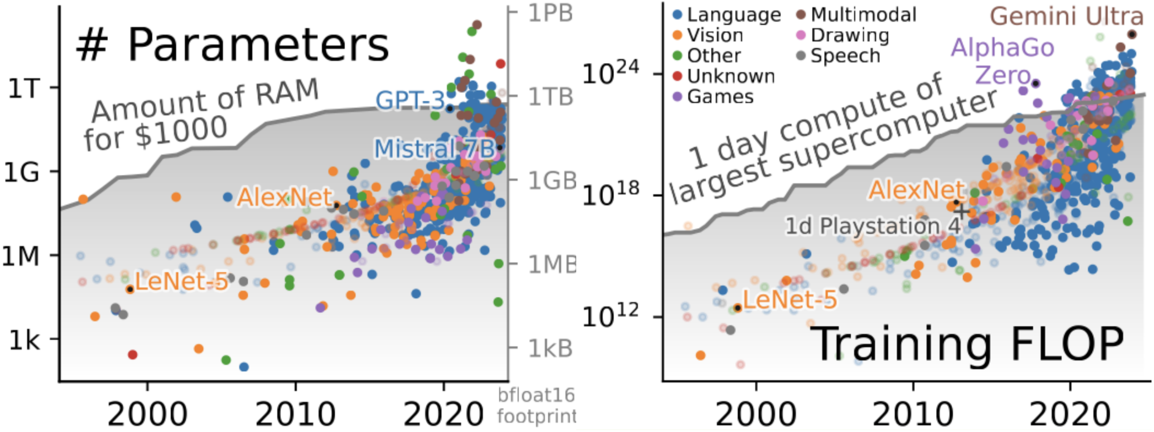


Training cost of an AI (source: OpenAI)

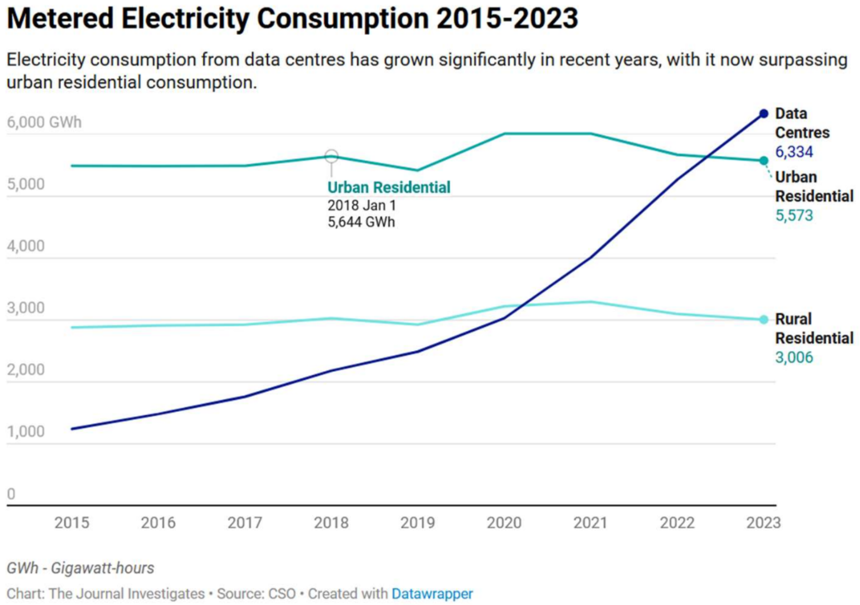


- What happened in 2012?
- What made it possible?

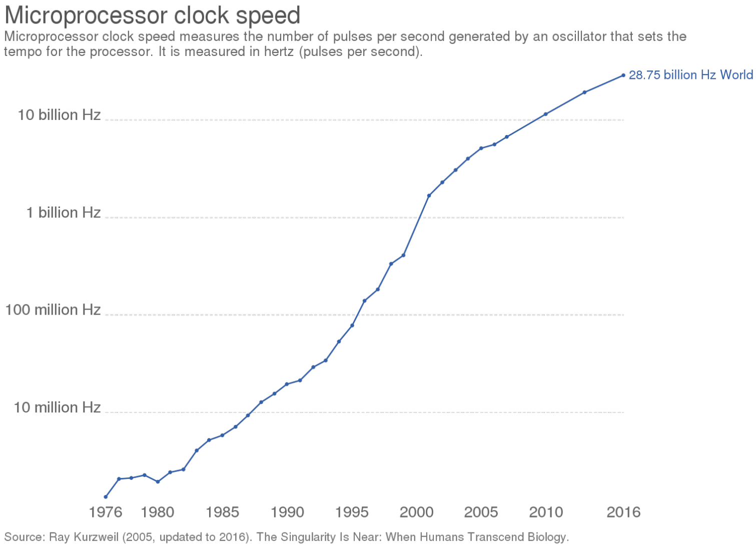
Explosion in AI model size (Varoquaux et al, 2025)



Evolution of Electricity Consumption in Ireland (Shift Project, 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?**

Image by Our World In Data - CC BY 3.0

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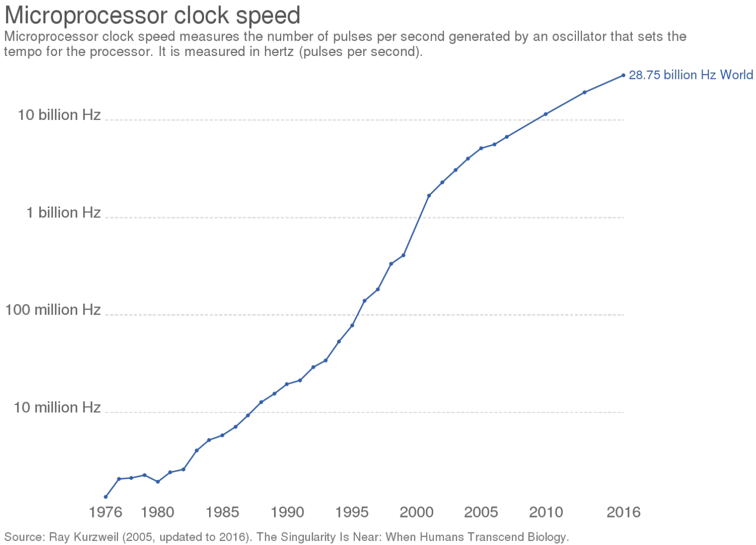

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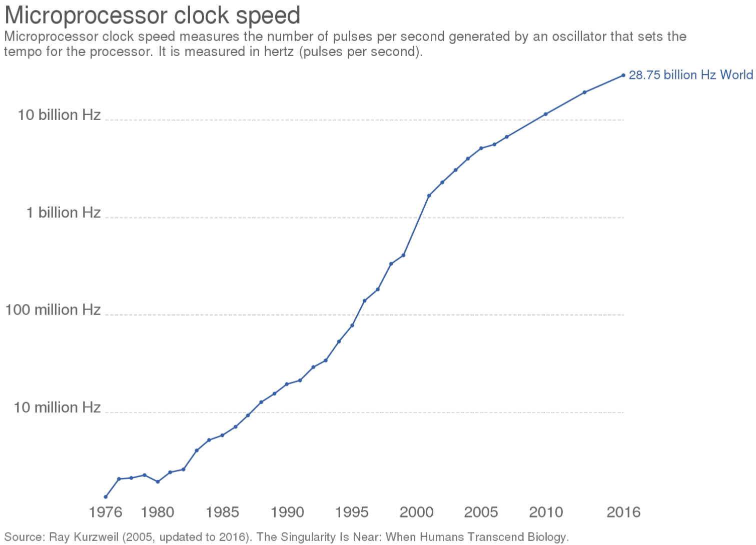

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Image by Our World In Data -

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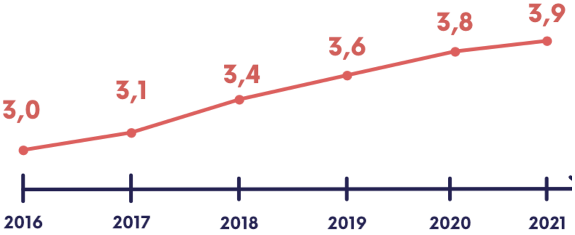
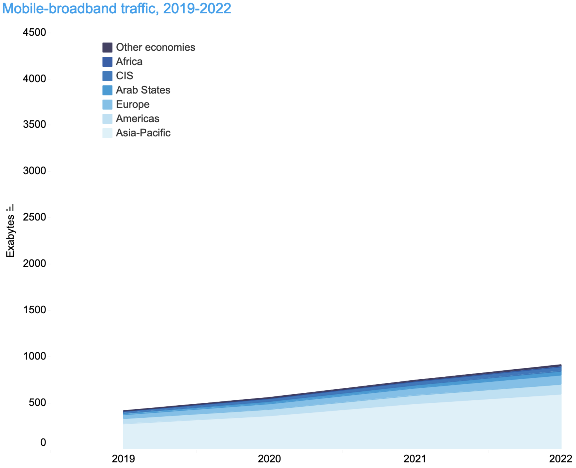
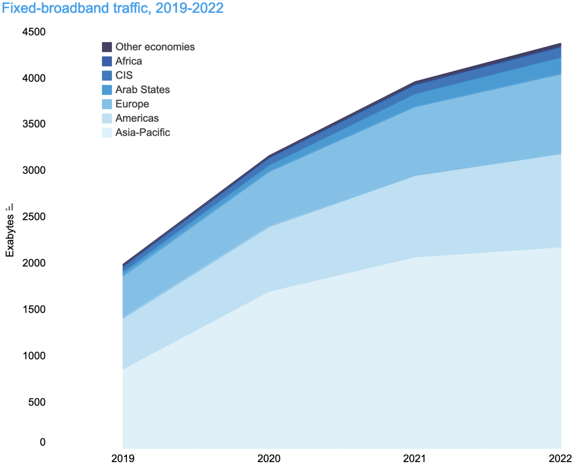
And yet, the energy consumed by fixed and mobile networks is increasing by an average of 5% each year (period 2016-2020):



(source = Arcep, 2023)

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



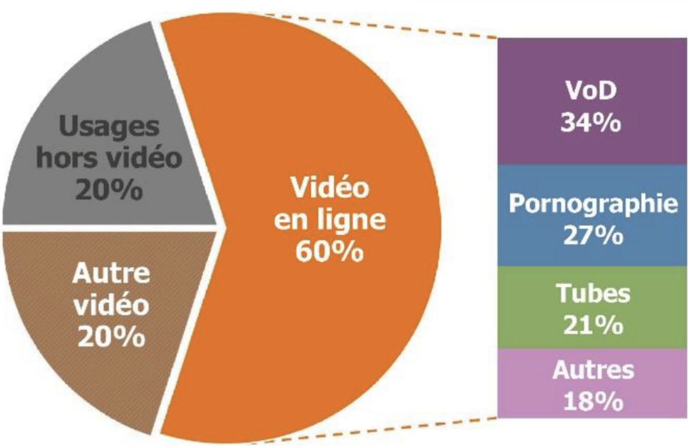


(1 Exabyte = 10^{12} Megabytes)

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

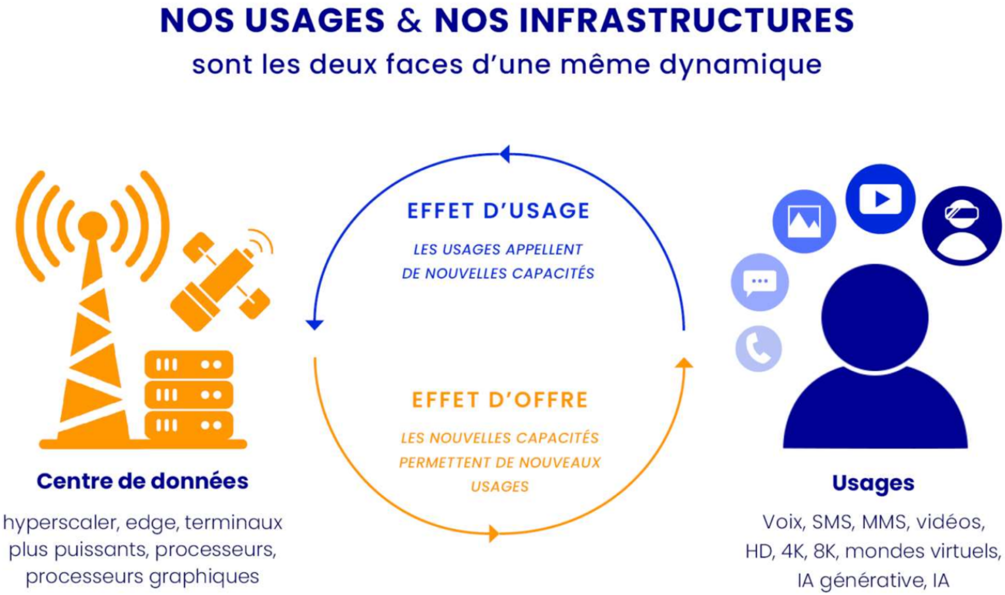
And all this to do what?

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)



The explanation for these paradoxes? The rebound effect!

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

(figure from Françoise Berthoud)

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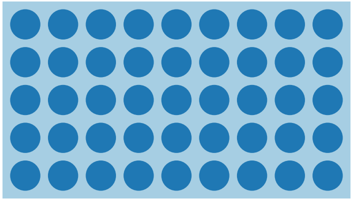

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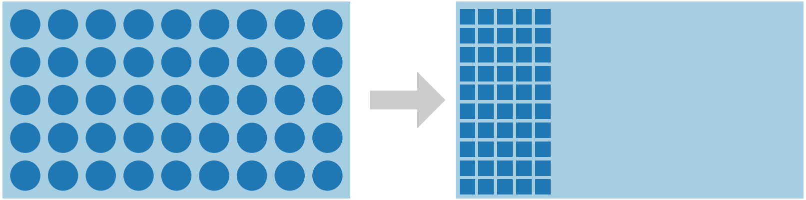

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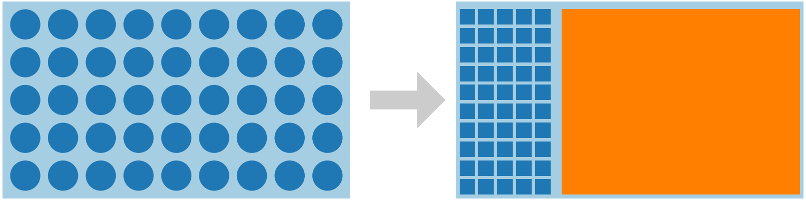

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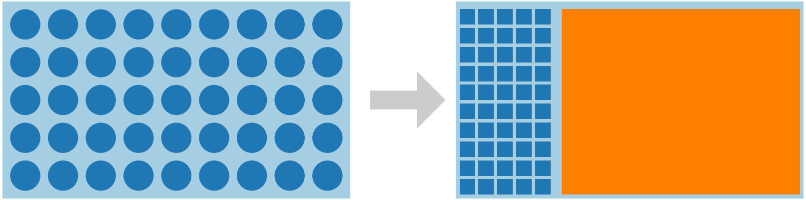

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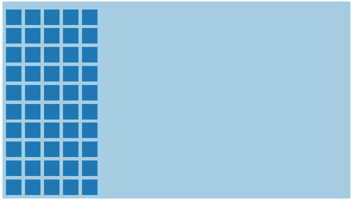
Freed resource

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)

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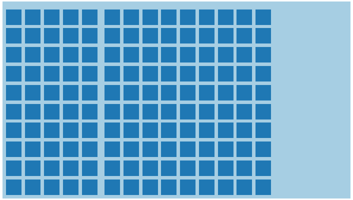

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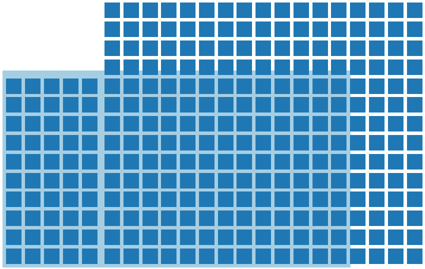

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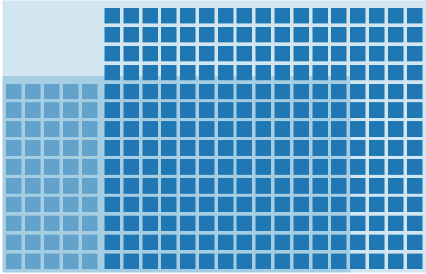

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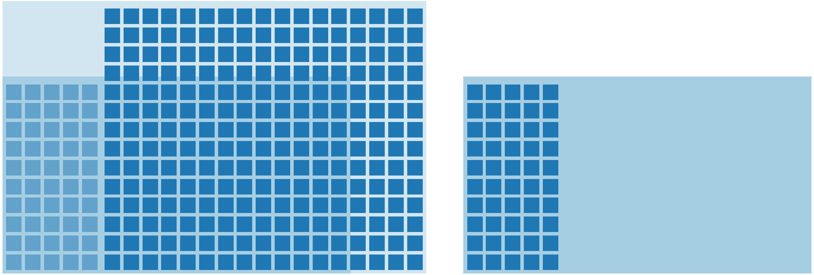

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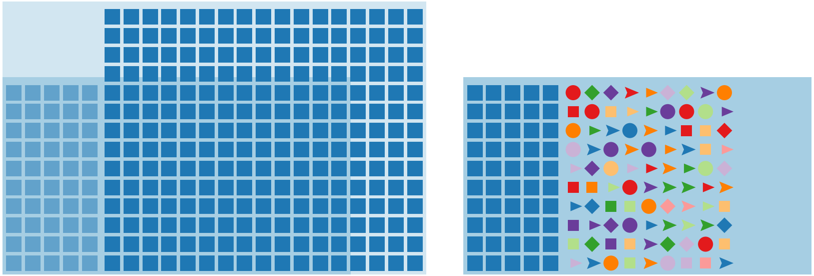

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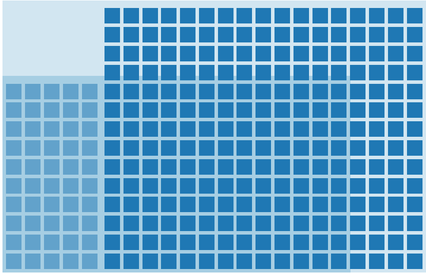

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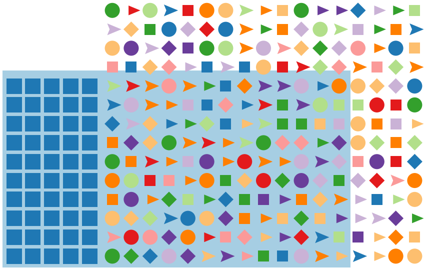

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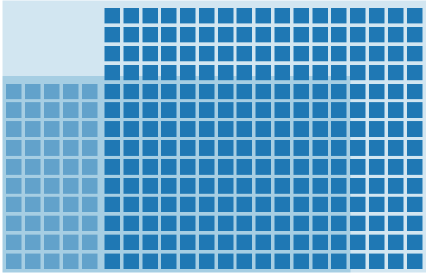

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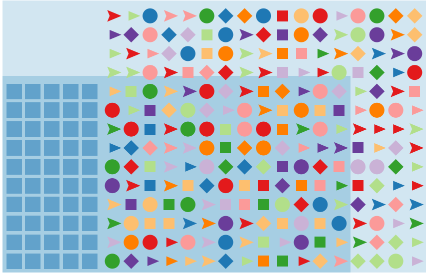

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Taxonomy of effects (inspired from Horner et al, 2016)

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, ...
  $\leadsto$ Analysis of GPS traces in data centers
- 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: 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

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

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

Example: GPS system with user-submitted travel times

- 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: 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)

Type	Scope	Effect
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2nd order	Indirect: Unique service	Optimisation
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3rd order		Direct rebound
	Indirect: Complementary services	Indirect rebound
	Indirect: Economy	Structural changes

Example: GPS system with user-submitted travel times

- The exploitation of personal GPS traces allows companies to send more relevant advertisements which increases online sales
- The system enables autonomous vehicles and causes growth of intelligent transportation system manufacturing

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

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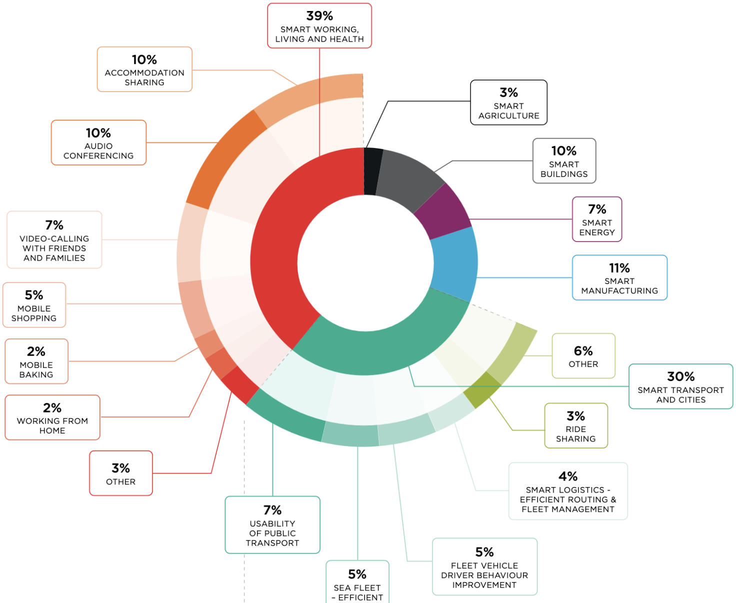
3rd order		Direct rebound
	Indirect: Complementary services	Indirect rebound
	Indirect: Economy	Structural changes
	Indirect: Society	Systemic changes

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...

Some take-away messages

- 6 planetary boundaries (over 9) are overpassed...
  ...and many people still haven't decent life conditions
  $\rightsquigarrow$ We must react urgently
- Mathematical models are not neutral
  $\rightsquigarrow$ Hypothesis should be carefully chosen and well explained
- Evaluating accurately the direct impacts of ICT is difficult
  $\rightsquigarrow$ We should consider the whole life-cycle
  $\rightsquigarrow$ Extraction and manufacturing are very impacting steps
  $\rightsquigarrow$ Electricity consumption of data centres has grown significantly in recent years
  But it is way more easy than evaluating indirect impacts due to systemic changes
- Efficiency improvement $\not\Rightarrow$ Overall impact reduction
  $\rightsquigarrow$ It is often the contrary due to rebound effects!
- Rebound effects are difficult to model and quantify, but they are generally devastating
  $\rightsquigarrow$ Consider a holistic approach

Discussion

Some well known contributions of OR 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 OR tools allow us to defend them? What values are carried by our tools?