Seminar at UCLouvain 2025

Green digitalization?

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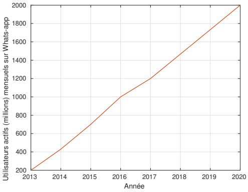
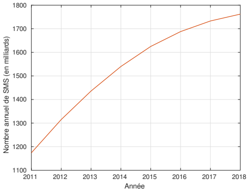
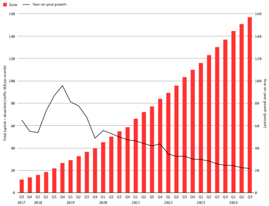
Section 1 : Some figures

Traffic increase



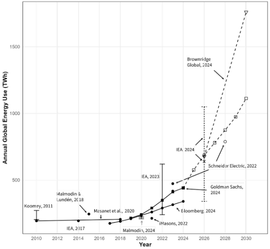


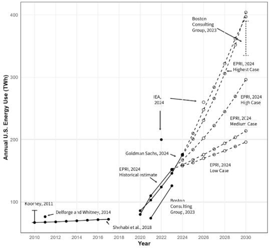


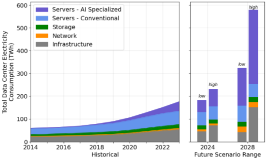
Tools accumulation without replacement

source : Statista2022, Ericsson Mobility Report

Data centers increase and become "computation" centers



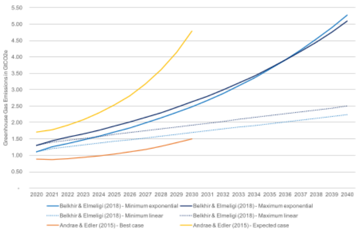


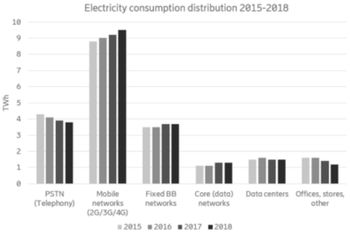


source : US data center energy usage report 2024 (Berkeley Lab)

Energy consumption for ICT

- ICT corresponds roughly to 3,5 to 4% of total GHG emissions
- Trend on energy consumption: direct consumption increases, some devices slightly decrease (less TV or Desktop PC)





source : D. Lunden, "Electricity consumption and operational carbon emissions of European telecom network operators," Sustainability, Feb. 2022 ; A. Andrae and T. Elder, "On the global electricity usage of communication technology: trends to 2030," Challenges, June 2015

Section 2 : Materials

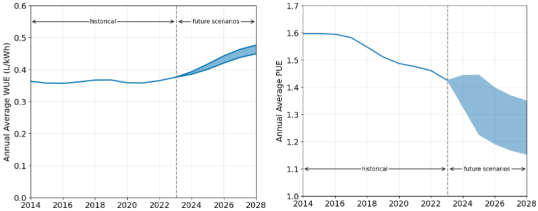
Dematerialization with ICT ?

- ICT is not virtual
- since a lot of devices and so of materials !

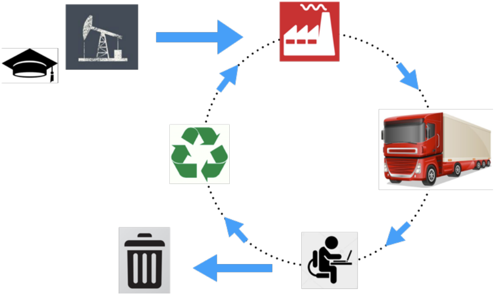


Figures on data center (2024)

- 460TWh
  - more than French nuclear plants
  - 2% of worldwide electricity production
- Issue: cooling
  - solution by free cooling with **water**: less energy but biodiversity issue and use conflict
  - ↪ Water Usage Effectiveness (WUE) around 0.4ℓ/kWh
  - ↪ best Power Usage Effectiveness (PUE) close to 1.1



Life Cycle Assessment (LCA)



→ Mining → manufacturing → transportation-distribution
→ Use
→ End of life

Use not necessary the biggest part!
depends on the considered system

Example: a device (laptop)

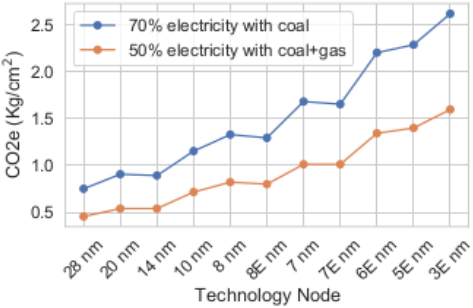
MacBook 2019: 16 inches, storage 521 Go, frequency 2,6 GHz

- Use phase during 4 years
- Carbon footprint of 394kgCO_2e
  - mining/manufacturing: 75%
  - transportation: 5%
  - use: 19%
  - end of life: 1%

Keep this laptop **4 times longer**
s.t use phase = manufacturing phase

Manufacturing energy consumption

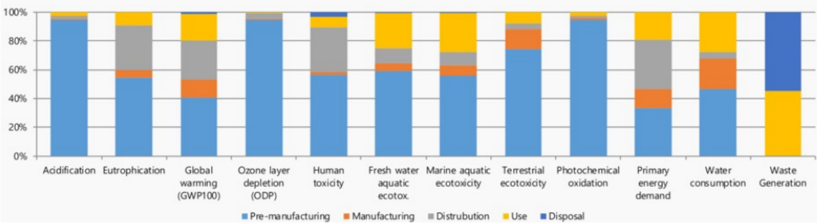
Be careful: new manufacturing process can be less efficient!
Example: **miniaturization** leads to speeder circuits for the same surface (and so the same thermal dissipation) but more complex industrial processing



source : S. Tamu and P. Nair, "The dirty secret of SSD: embodied carbon", preprint Arxiv, Jul. 2022

Global environmental cost

There is not only carbon footprint!

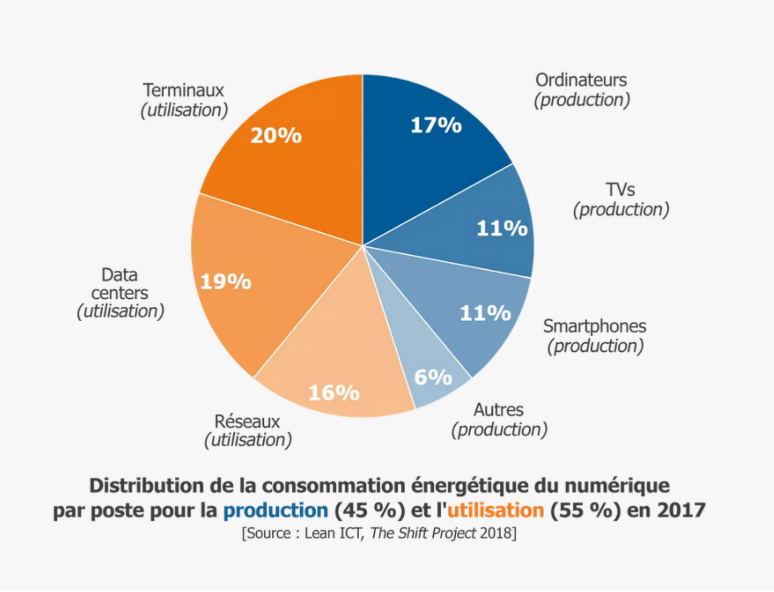


Product Environnmental Footprint (PEF) can be defined

Indicateur de l'impact	Unité	Normalisation	Pondération	Facteur d'aggréation
Changement climatique – total	Kg CO2 eq.	$8.10^{E}+03$	21.06	0,026 mPt/kg CO2 eq
Changement climatique – combustibles fossiles				
Changement climatique – biogénique				
Changement climatique – occup sol + transfo				
Appauvrissement de la couche d'ozone	Kg CFC 11 eq.	$5.36^{E}-02$	6.31	1176 mPt/kg CFC11 eq.
Acidification	mol H+ eq.	$5.56^{E}+01$	6.20	1,1 mPt/mol H+ eq.
Eutrophisation				
Eutrophisation – aquatique, eaux douces	Kg P eq.	$1.61^{E}+00$	2.80	17 mPT/kg P eq.
Eutrophisation – aquatique marine	Kg N eq.	$1.95^{E}+01$	2.96	1,5 mmPt/kg N eq.
Eutrophisation – terrestre	mol N eq.	$1.77^{E}+02$	3.71	0,21 mPt/mol N eq
Formation d'ozone photochimique	Kg NMVOC eq.	$4.06^{E}+01$	4.78	1,2 mPt/kg NMVOC eq
Epuisement des ressources abiotiques				
idem – minéraux et métaux	Kg Sb eq.	$6.36^{E}-02$	7.55	1186 mPt/kg SB eq.
idem – combustibles fossiles	MJ, net calorific value	$6.50^{E}+04$	8.32	0,0013 mPt/MJ
Besoin en eau	M³ world eq. deprived	$1.15^{E}+04$	8.51	0,0074 mPt/m³ depriv.
Emission de particules fines	Disease incidence	$5.95^{E}-04$	8.96	0,012 mPt/kBq U-235 eq.
Rayonnements ionisants, santé humaine	kBq U235 eq.	$4.22^{E}+03$	5.01	0,00045 mPt/CTUe
Ecotoxicité (eaux douces)	CTUe	$4.27^{E}+04$	1.92	
Toxicité humaine				
Toxicité humaine, effets cancérigènes	CTUh	$1.69^{E}-05$	2.13	1260385 mPt/CTUh
Toxicité humaine, effets non cancérigènes	CTUh	$2.30^{E}-04$	1.84	80114 mPt/CTUh
Impacts liés à l'occupation des sols / Qualité du sol	dimensionless	$8.19^{E}+05$	7.94	0,000097 mPt/Pt

source : Life Cycle Assessment for Mobile Products, Samsung, 2018

ICT energy consumption chart



Section 3 : Application to wireless networks

Solutions "for" or "by" these networks

- Solution 1: *GreenIT*

$$\textbf{Energy efficiency} = \frac{\textbf{performance metric}}{\textbf{consumed energy}}$$

  - Relative goal (less GHG per unit)
  - Rebound effect (number of units increases)
  - This technical answer may be not enough to fix the problem
- Solution 2: *IT for Green*
  - Deported goal (less GHG but elsewhere)
  - Enablement effect with deportation of energy efficiency
  - This technical answer may be not enough to fix the problem
- Solution 3: Sufficiency
  - Consumed energy/power is pre-fixed
  - Avoid rebound effect, ensure enablement effect
  - <u>but</u> limits of uses/needs to be defined. By whom?

Efficiency = Optimization ; Sufficiency = Way of Life

source: F. Feher, A. Heller, and G. Markus, "Dictatorship over needs", 1983

Rebound effect or Jevons' paradox

- when a technology efficiency improves
- use phase increases

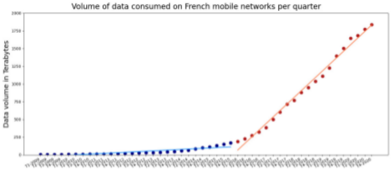
and finally global energy consumption increases as well

Rebound effect characterization [Combaz-Coupechoux2022]

Scope	Effect	5G Examples
First order	Embodied footprint	Production of 5G equipments and devices
	Operational footprint	Operation of networks, devices, data centers
	Disposal footprint	Equipments and devices end-of-life
Second order	Induction	5G motivates the sale of VR headsets
	Optimization	More efficient data transfer
	Substitution	Visio-conferencing replaces meetings
	Direct rebound	More mobile data are consumed
Third order	Indirect rebound	Footprint during time saved in data transfer
	Economy-wide rebound	Structural changes in production patterns and consumption habits
	Systemic transformation	5G modifies the way people are working and living

Examples from ICT

- Improvement of machine learning algorithms
  - Increase of apps using them
  - Increase of computed data
- Improvement of electronic devices and batteries
  - Increase of use for mobile phones
  - but phone autonomy keeps the same
- Improvement of mobile networks
  - Increase of data exchange



source : P. Ciblat, J. Combaz, M. Coupechoux, K. Marquet, and A.-C. Orgerie, "Environmental impacts of 5G (part 1)", 1024 newsletter, April 2024

Enablement effect

Thanks to ICT, other domains decrease (strongly) their energy consumption

Some figures: 1gCO_2e consumed in ICT avoids 10gCO_2e elsewhere [GSMA2019] ; fanciful figure [Roussilhe2021]

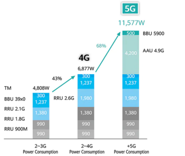
- self-driving cars but public transportation more efficient
- logistics (vehicle management in Livorno harbor with 250km container ship distance gain)
- smart farming (salmon farming in Norway required 5G even 6G)
- remote working

→ Problem with unsafe results except for limited areas

→ Topic with high imagination: praise of the promise

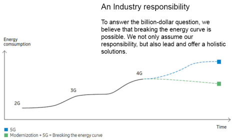
Some real figures

Basestation or network on use phase

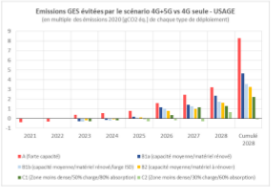


Typical maximum power consumption of a single 5G base station

Source: Huawei



Source: Ericsson



Network decommissioning with frequency re-use

source : Huawei, Ericsson, Arcep

State of the art on energy consumption

Until 5G, it was not a crucial topic

- Energy consumption
  - Issue for health
  - Issue for battery autonomy
- Mining resource: nothing to report

Example:

- Books did not provide global figures

  P. Nicopolitidis et al., "Wireless Networks", 2003
  N. Tripathi, J. Reed, "Cellular Networks", 2014
- Same thing in Wikipedia (except for 5G)
- Some figures on applications

  A. Shehabi, "Energy and Greenhouse gas implications of internet video streaming in the US", 2014
  M. Deltour et al. "Carbon footprint: streaming vs DVD", Telecom internship, 2020

Since 2020, exponential growth for this kind of analysis

Types of energy

- P_{tx}: transmission energy (so far, the only one considered)
- $P_{\mathrm{circuitry}}$: circuitry energy
  - $P_{\mathrm{processing}}$: processing energy (decoding, sync, $\cdots$)
  - P_{hardware}: hardware energy (power amplifier, ADC/DAC)
- $P_{\mathrm{manufacturing}}$: manufacturing energy (related to LCA)

Efficiency for P_{tx}

$$E_{\mathrm{tx,file}} = \frac{LP_{\mathrm{tx}}}{n_{\mathrm{tx}} B \log_2\left(1 + \gamma \frac{P_{\mathrm{tx}}}{n_{\mathrm{tx}} B N_0}\right)}$$

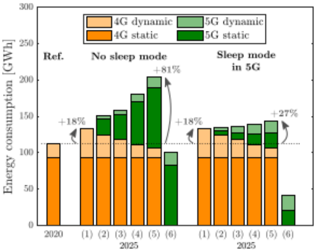
- Efficiency in transmit energy E_{tx}: yes
  - Bandwidth and carrier frequency (B)
  - Multiple antennas (MIMO) (n_{tx})
    - ↪ Multiplexing, Beamforming, Relaying (*RIS*)
  - Interference management (γ)
    - ↪ Intra-user (OFDM), Inter-user (xDMA/NOMA)
- Efficiency in consumed energy per device: ?
- Efficiency in consumed energy for manufacturing: ?

Other ideas for 6G but only in efficiency or decarbonization

- Distributed storage to limit core network access
- Harvested (solar/wind) energy

Example 1: macroscopic analysis (data-driven)

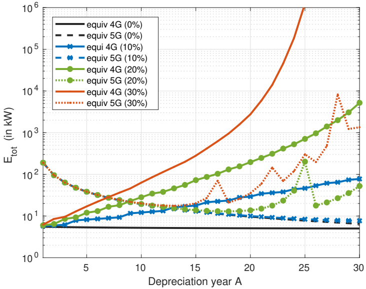
- 4G model: $P_{4g} = P_0 + \alpha R$
- 5G model: $P_{5g} = \beta P_{4g}(B_{5g}/B_{4g})^{.95}(S_{5g}/S_{4g})^{.1}$ with S flows
- Traffic (sleeping mode)



source : L. Golard et al., "Evaluation and projection of 4G and 5G RAN energy footprints : the case of Belgium for 2022-2025," Annals of Telecoms, 2024 ; B. Debaillie, C. Desset, F. Louagie, "A flexible and future-proof power model for cellular base stations", VTC 2015

Example 2: microscopic analysis (model-driven)

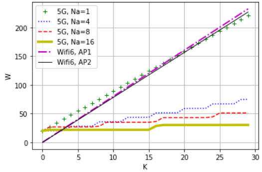
- 4G model: 4 antennas, already 10 depreciation years
- 5G model: 100 antennas
- Manufacturing taken into account (especially antennas cost)



source : P. Ciblat, "A propos du MIMO massif dans un contexte de sobriété numérique," Gretsi, 2022

Example 3: xG vs. Wifi

- Use phase ($E_{\text{tx}} + E_{\text{processing}} + E_{\text{hardware}}$)
- Teleworking case (one user per Access Point in Wifi)



Extension to distributed Wifi as cellular network not easy

- No handover in Wifi
- Security level not the same
- Coverage guarantee not the same
- Provider not the same

source : M. Hentati, T. Chahed, P. Ciblat, M. Coupechoux, and S. Najeh : "5G vs Wifi6 downlink power consumption comparison for teleworking use case", IEEE International Conference on Communications and Networking, Nov. 2023

Example 4: BTS model

Since 2009, lot (15) of models in State-of-the-Art but

- with different clusterings
- with different analysis for dependency

Unified framework is missing to compare and to see the lack

$$P_{\mathrm{BS}} = \sum_{s=1}^{N_s} (P_{\mathrm{AFN},s} + P_{\mathrm{PA},s} + P_{\mathrm{RFE},s} + P_{\mathrm{BB},s} + P_{\mathrm{ULP},s}) + P_{\mathrm{PSC}} + P_{\mathrm{BH}}$$

with N_s sectors

- Antenna Feeding Network (AFN)
- Power Amplifier (PA)
- Radio Front-End (RFE) Unit
- Baseband (BB) PHY Processing Unit
- Upper-Layer Packet (ULP) Processing Unit
- Power Supply and Cooling (PSC)
- Control and Network Backhaul (BH)

Example 4: BTS model [Tombaz2011]

$$
\begin{cases}
\sum_{s=1}^{N_s} (P_{\mathrm{PA},s} + P_{\mathrm{AFN},s}) = aP_{\mathrm{tx}} \\
\sum_{s=1}^{N_s} P_{\mathrm{RFE},s} + \sum_{s=1}^{N_s} P_{\mathrm{BB},s} + P_{\mathrm{PSC}} = b_{\mathrm{radio}} \\
P_{\mathrm{BH}} = b_{\mathrm{BH}} + yR_{\mathrm{BS}}
\end{cases}
$$

with y proportion of backhaul devoted to this BTS traffic

Example 4: BTS model [Desset2012, Golard2024]

Extension of EARTH model [Auer2011]

$$\begin{cases} \sum_{s=1}^{N_s} (P_{\text{PA},s} + P_{\text{AFN},s}) = MN_s(1-\sigma_{\text{feed}})\bar{P}_{\text{PA}} = M(1-\sigma_{\text{feed}})\bar{P}_{\text{out}}/\eta_{\text{PA}} \\ \sum_{s=1}^{N_s} P_{\text{RFE},s} = N_s P_{\text{AFE},s} = N_s \sum_{i \in I_{\text{RF}}} P_{i,\text{ref}} \prod_{x \in X} \left(\frac{x_{\text{act}}}{x_{\text{ref}}}\right)^{s_{i,x}} \\ \sum_{s=1}^{N_s} P_{\text{BB},s} + P_{\text{BH}} = N_s P_{\text{DBB},s} = N_s \sum_{i \in I_{\text{BB}}} P_{i,\text{ref}} \prod_{x \in X} \left(\frac{x_{\text{act}}}{x_{\text{ref}}}\right)^{s_{i,x}} \\ P_{\text{PSC}} = N_s \left(M(1-\sigma_{\text{feed}})\bar{P}_{\text{out}}/\eta_{\text{PA}} + P_{\text{AFE},s} + P_{\text{DBB},s}\right) \\ \times \left((1+\zeta_{\text{Cool}})(1+\zeta_{\text{DC-DC}})(1+\zeta_{\text{AC-DC}}) - 1\right) \end{cases}$$

Future 1: 6G

Honestly, no learning about 5G controversy to design 6G. The show must go on.

Examples:

- Zeppelin with solar panels to replace basestations on ground. Energy cost in that paper: 0.
- Reflecting Intelligent Surfaces (RIS), so adaptive electro-magnetic mirror. Energy cost in that paper: 0.

sources : D. Renga and M. Meo, "Can High Altitude Platforms make 6G sustainable," IEEE Com Mag, 2022 ; M. Di Renzo, "Smart Radio Environnment empowered by RIS: state of the art and the road ahead," JSAC, 2020

6G: for which applications?

Reminder:

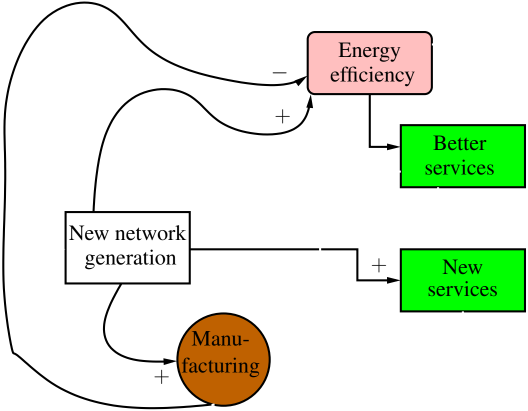
- Bibop launching (1993): P. Meyer, "imaginez-vous au restaurant ou dans la rue, environné d'écervelés qui se font appeler? En 2000, un million d'appareils à striduler n'importe quand, n'importe où et pour n'importe quoi"
- First works on 3G (1991): data transmission while fixed Internet only for researchers
- First works on 4G (2001): touch screen does not work well

Advocated applications:

- 3G: videophone, video streaming (advertising, news, $\cdots$), online shopping, mms, video meeting, $\cdots$
- 4G: virtual meeting, informed shopping (via localization), $\cdots$
- 5G: Smart farming, Autonomous car, $\cdots$
- 6G: ?

Usually, ultra-light business map

Systemic chart for 6G



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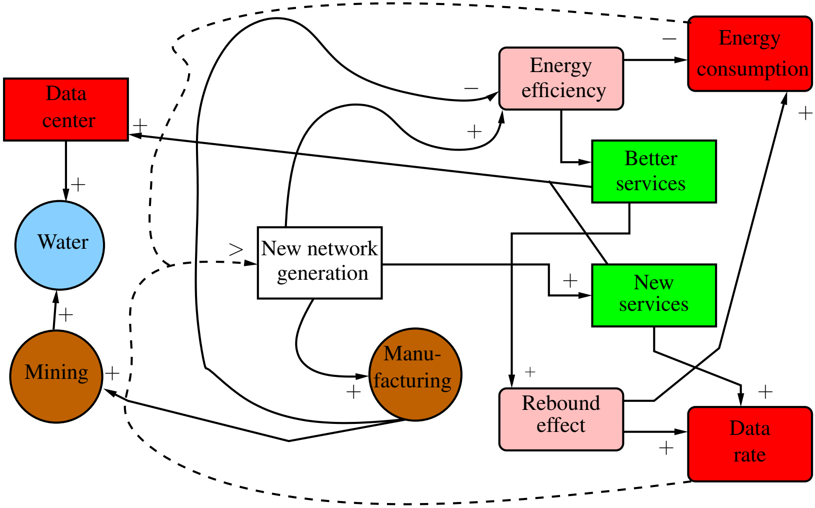
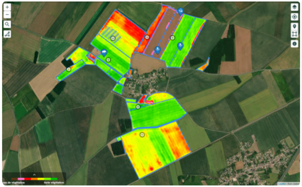
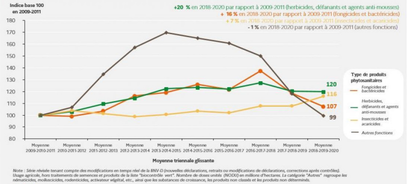


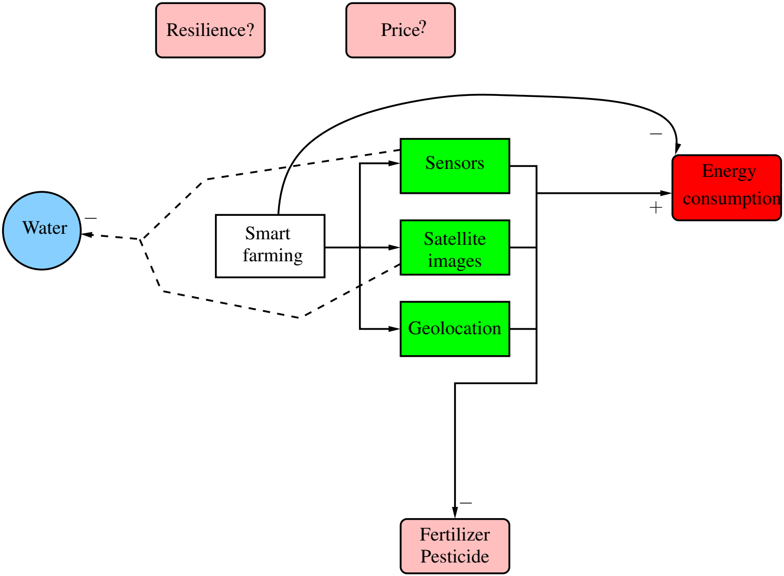
Future 2: smart farming

- Sensing, monitoring (communication & control)
  - ↪ geolocation, satellite image, local sensors, data network, computation for decision-making → large techno-structure
- Goals
  - ↪ First, increase of yields
  - ↪ Second, fertilizer/water decrease <u>but</u> failure of Ecophyto plan

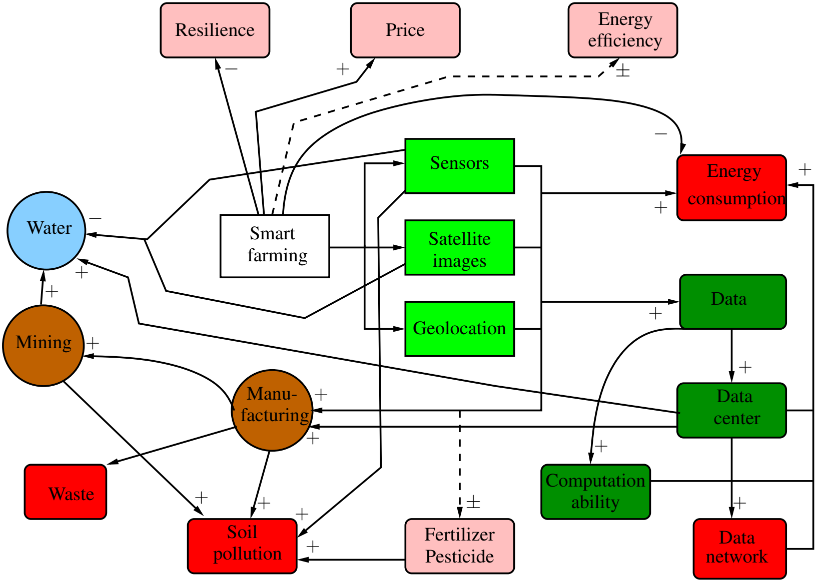



source: https://blog.spotifarm.fr ; http://www.ofb.gouv.fr ; J. Oui, "Produire une faute -conforme-. Outils numériques et normes environnementales en agriculture", Sociologies Pratiques, 2024

Systemic chart for smart farming



Systemic chart for smart farming



Other future questions

- Large-scale network optimization with limited energy
  - Use scheduling (rather than slot scheduling)
  - Standard optimization use
- Use selection : net neutrality?
- Uses/Needs in Democracy? law or just costs $\cdots$