Seminar Lincs 2025

Green digitalization?

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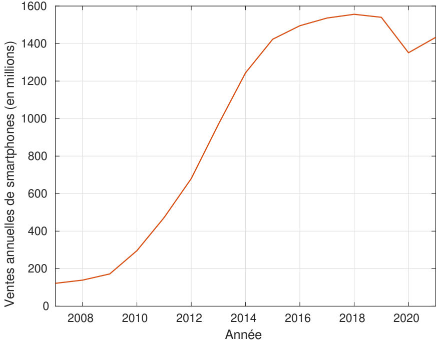
Section 1 : Some figures

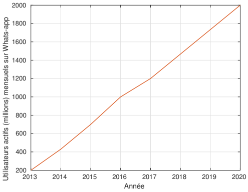
Some data to start...

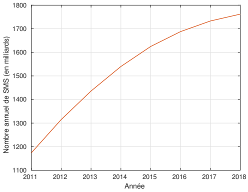
At worldwide: 67% of people get a mobile phone (+2% a year while +1.1% in population)

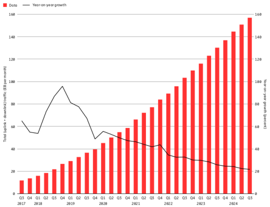


source : Statista2022, WeAreSocial

but traffic increase



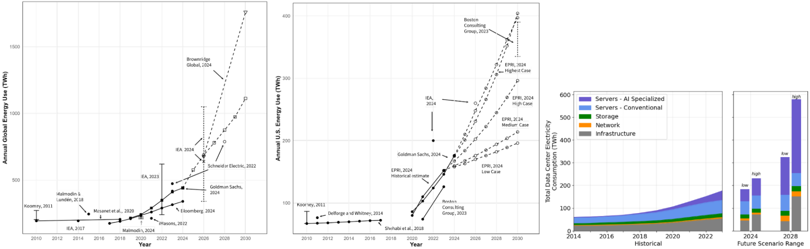




Tools accumulation without replacement

source : Statista2022, Ericsson Mobility Report

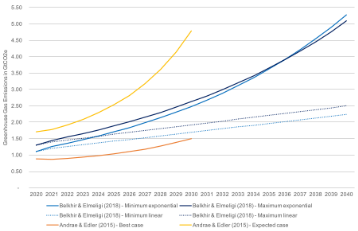
but data centers increase and become "computation" centers

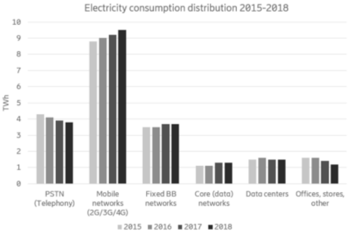


source : US data center energy usage report 2024 (Berkeley Lab)

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

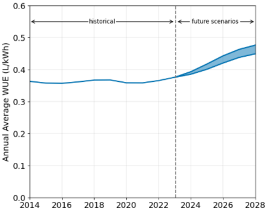
Section 2 : Materials

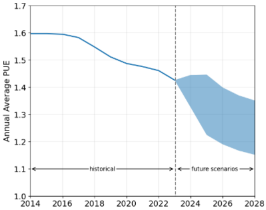
Dematerialization with ICT ?

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

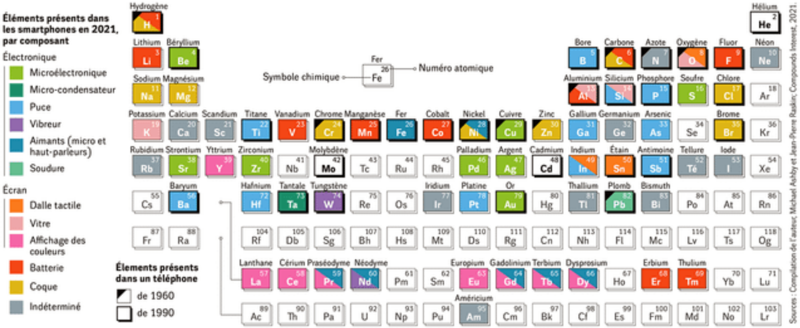
Figures on data center (2024)

- 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

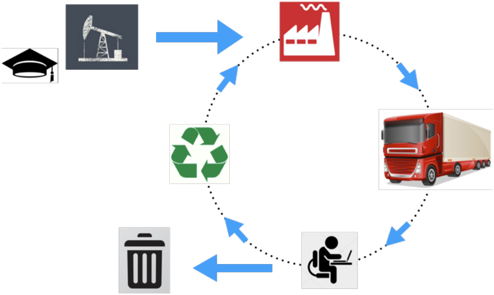




Materials and mining



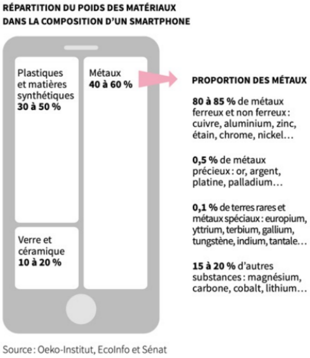
Life Cycle Assessment (LCA)

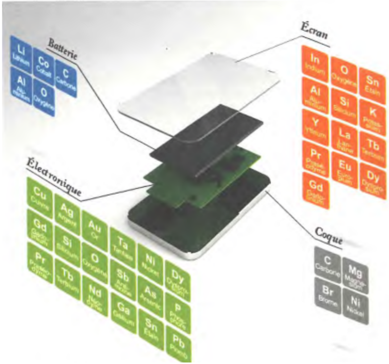


→ Mining → manufacturing → transportation-distribution
→ Use
→ End of life

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

Example 1: a device (mobile phone)





source : G. Pitron (right)

- 70kgCO_2e for a smartphone
- 10kgCO_2e for a dumbphone

Example 2: 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

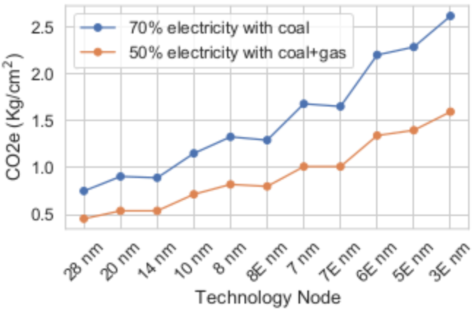
Example 3: an application (email)

Hard to estimate *precisely* the carbon footprint for an email

- 6mgCO_2e for 1MB email [Aslan2018]
- 2mgCO_2e for 1MB email on Renater [Ficher2021]
  but without storage and LCA
- with storage and LCA: 20gCO_2e for 1MB email [Ademe2011]

Manufacturing energy consumption

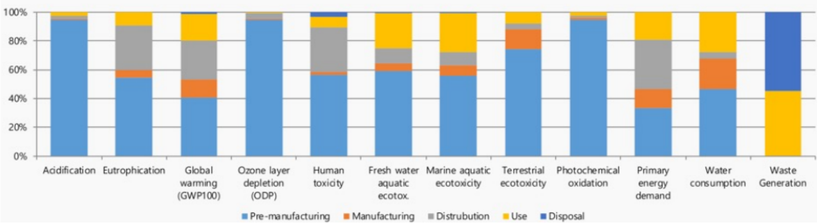
Be careful: new manufacturing process can be less efficient!
Example: **miniaturization** leads to speeder circuits for the same surface (and so the same thermal dissipation) but more complex industrial processing



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!

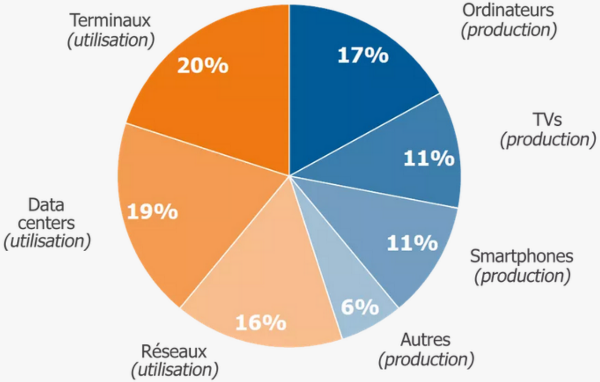


Product Environnmental Footprint (PEF) can be defined

Indicateur de l'impact	Unité	Normalisation	Pondération	Facteur d'aggréation
Changement climatique – total Changement climatique – combustibles fossiles Changement climatique – biogénique Changement climatique – occup sol + transfo	Kg CO2 eq.	8.10^{E}+03	21.06	0,026 mPt/kg CO2 eq
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 Eutrophisation – aquatique marine Eutrophisation – terrestre	 Kg P eq. Kg N eq. mol N eq.	 1.61^{E}+00 1.95^{E}+01 1.77^{E}+02	 2.80 2.96 3.71	 17 mPT/kg P eq. 1,5 mmPt/kg N eq. 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 idem – combustibles fossiles	 Kg Sb eq. MJ, net calorific value	 6.36^{E}-02 6.50^{E}+04	 7.55 8.32	 1186 mPt/kg SB eq. 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 Toxicité humaine, effets non cancérigènes	 CTUh CTUh	 1.69^{E}-05 2.30^{E}-04	 2.13 1.84	 1260385 mPt/CTUh 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



Distribution de la consommation énergétique du numérique par poste pour la production (45 %) et l'utilisation (55 %) en 2017

[Source : Lean ICT, *The Shift Project* 2018]

Section 3 : Application to wireless networks

Future wireless networks

A new generation each 10 years

- 2G: first digital generation: design for voice
- 3G: data (mobile Internet on the street: what an idea?)
- 4G: high data rate (touch screen saves the idea)
- 5G:
  - Very high data rate (eMMB) : cellular network
  - Low Latency and high reliability (URLLC) : automation
  - Massive connectivity (mMTC) : Internet of Things (IoT)
- 6G: under progress

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
  - but 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

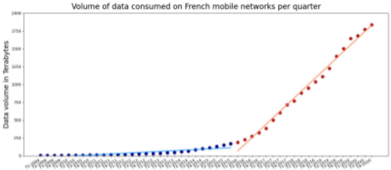
and finally global energy consumption increases as well

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]

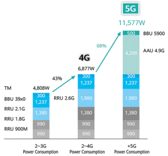
- self-driving cars but public transportation more efficient
- logistics (vehicle management in Livorno harbor with 250km container ship distance gain)
- smart farming (salmon farming in Norway required 5G even 6G)
- remote working

→ Problem with unsafe results except for limited areas

→ Topic with high imagination: praise of the promise

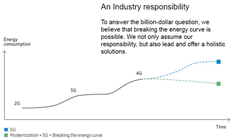
Some real figures

Basestation or network on use phase

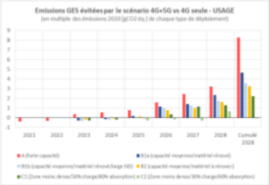


Typical maximum power consumption of a single 5G base station

Source: Huawei



Source: Ericsson

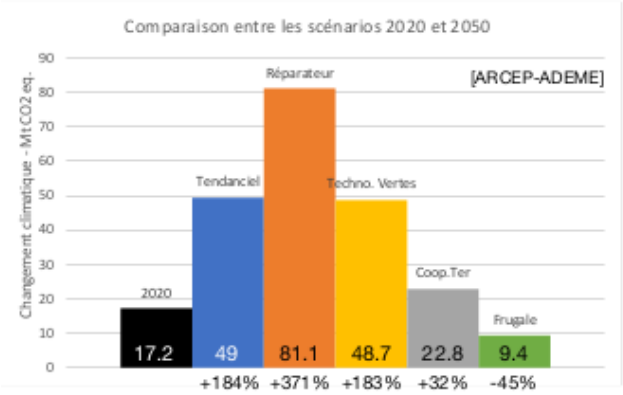


Network decommissioning with frequency re-use

source : Huawei, Ericsson, Arcep

Some perspectives

Scenarios 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)
- $P_{\mathrm{processing}}$: processing energy (decoding, sync, $\cdots$)
- $P_{\mathrm{circuitry}}$: circuitry energy (power amplifier, ADC/DAC)
- $P_{\mathrm{manufacturing}}$: manufacturing energy (related to LCA)

Efficiency for P_{tx}

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

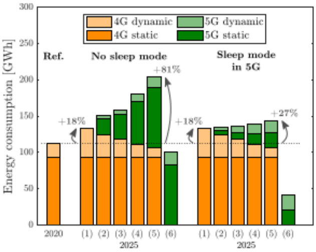
- Efficiency in transmit energy E_{tx}: yes
  - Bandwidth and carrier frequency (B)
  - Multiple antennas (MIMO) (n_{tx})
    - ↪ Multiplexing, Beamforming, Relaying (*RIS*)
  - Interference management (γ)
    - ↪ Intra-user (OFDM), Inter-user (xDMA/NOMA)
- Efficiency in consumed energy per device: ?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

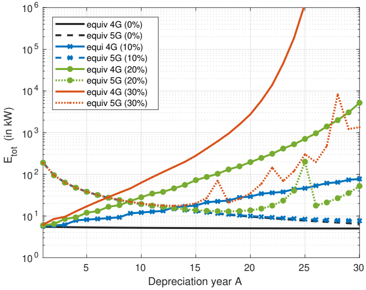
- 4G model: $P_{4g} = P_0 + \alpha R$
- 5G model: $P_{5g} = \beta P_{4g}(B_{5g}/B_{4g})^{.95}(S_{5g}/S_{4g})^{.1}$ with S flows
- Traffic (sleeping mode)



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

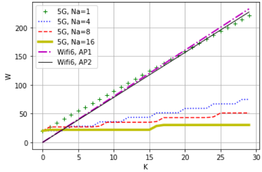
- 4G model: 4 antennas, already 10 depreciation years
- 5G model: 100 antennas
- Manufacturing taken into account (especially antennas cost)



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

Example 3: xG vs. Wifi

- Use phase ($E_{\text{tx}} + E_{\text{processing}} + E_{\text{circuitry}}$)
- 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

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:

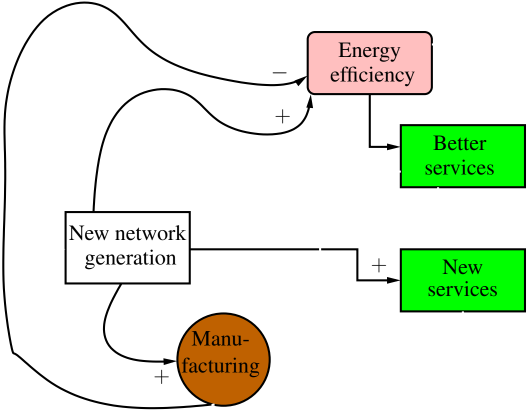
- Bibop launching (1993): P. Meyer, "imaginez-vous au restaurant ou dans la rue, environné d'écervelés qui se font appeler? En 2000, un million d'appareils à striduler n'importe quand, n'importe où et pour n'importe quoi"
- First works on 3G (1991): data transmission while fixed Internet only for researchers
- 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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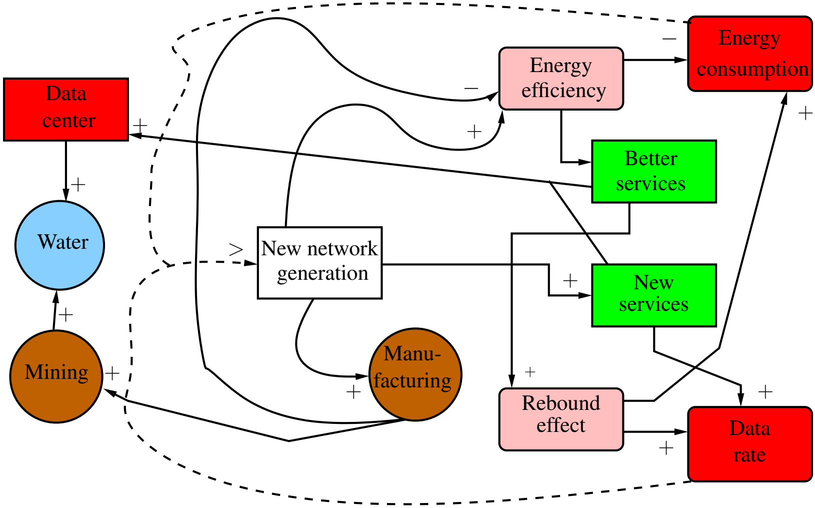
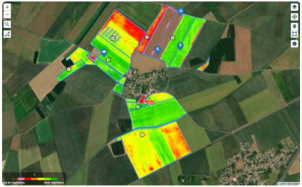
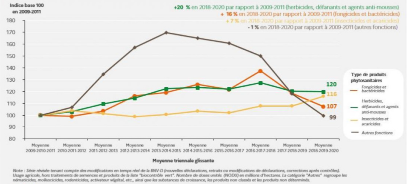


Future 2: smart farming

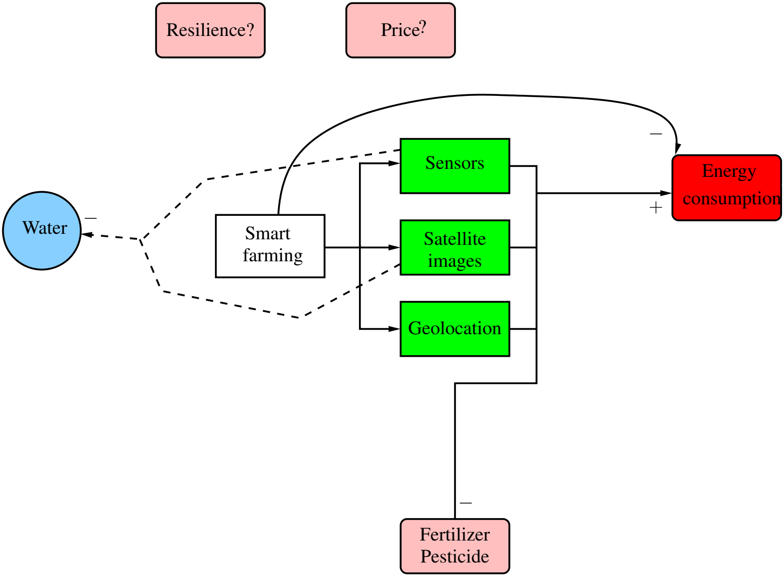
- Sensing, monitoring (communication & control)
  - ↪ geolocation, satellite image, local sensors, data network, computation for decision-making → large techno-structure
- Goals
  - ↪ First, increase of yields
  - ↪ Second, fertilizer/water decrease <u>but</u> failure of Ecophyto plan





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