Responsible digital technologies (1)

Ethics, limits, and the color green

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Ethics and responsibility • Sustainability and limits • Possible paths

Goals

- Define what is responsible and sustainable technology;
- Train critical thinking skills sustainable-related data & solutions;
- Discover and manipulate tools to analyze digital technologies w.r.t. responsibility & sustainability.

Planning

- Lecture 1: Ethics, limits, and the color green
- Lab 1: designing within limits
- Lecture 2: Life Cycle Assessment 101
- Lab 2: Applied LCA
- Lecture 3: Measuring energy
- Lab 3: Software energy measurement (x2)

Evaluation

- Lab reports

For today...

In French, this class is named “**Numérique Responsable**”. Possible (mis)translations:

- Responsible digital technology
- Sustainable ICT
- GreenIT
- ...

Today’s plan:

- Define an ethic & responsibility framework;
- Define sustainability w.r.t. to digital technologies;
- Explore possible future paths & existing tools.

Ethics & responsibility

> What constitutes an ethical action? How do you choose to do the right thing?

> What does it mean to be responsible?

Goals of this section (hopefully):

1. Propose *some* answers to these questions.
2. Equip yourself to better navigate future ethical conundrum situations related to “Responsible Digital Technologies” as engineers.

Ethics & responsibility

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https://digistorm.app/p/9639962

Time to dust off the old guy

Max Weber (1864 - 1920) defines two forms of ethics[1]:

- Ethic of **responsibility**
- Ethic of moral **conviction**

[1] Weber. “Politik als Beruf” (1919).

Definitions

Ethic of responsibility:

- Concerned with the **means of action**
  - How efficient they are
  - Their **consequences**
- Accepts that means carry moral costs, and answers for them
- Pragmatism & compromise, **adjusts to circumstances**

E.g., politician and business leader: power == action == answer for it.

Ethic of conviction:

- Concerned with unconditional fidelity to a **value** or **norm**
  - Whatever the consequences
- Does not depend on context
- Responsible only for intention

E.g., science (value = truth) and religion (value = the sacred).

Each option has its limits

Ethic of responsibility

- Is it possible to be responsible without value?
- Navigate only reactively

Ethic of conviction

- Forgetting the impact, rigidity
- E.g. in tech: cornucopianism, technosolutionism

Example situations

Which side is **responsibility**, which is **conviction**?

Situation 1

When designing a conversational agent, an engineer measures how anthropomorphism affects vulnerable users and tunes the design accordingly (e.g., by changing its name to be gender-neutral).

Example situations

Which side is **responsibility**, which is **conviction**?

Situation 2

A security researcher finds a severe vulnerability and immediately publishes full exploit details because “the public has a right to know”.

Weber: what **justifies** a decision: fidelity to a value, or answering for consequences?[2]

We may follow one or the other ethic depending on the situation; both are complementary.

[2]Weber wrote about politics and science in 1919; the framework has since been updated to better motivate it w.r.t. modern scientific practices.

Now, who's **responsible** for a decision and its following consequences?

Example situation

Léa is a smartphone product manager.

She strongly believes in sustainable practices and is known for pushing for repairability at every design review. As product lead, she was responsible for choosing the battery and glass that go into the phone.

Under quarterly margin pressure, she signed off on gluing the battery in place and dropping the spare-parts contract to save two euros a unit. Did she have the information, tools, and authority to foresee what that would cost down the line?

Her sign-off cut the phone's lifespan from seven years to three, resulting in a wave of prematurely discarded devices. Under the EU's Ecodesign for Sustainable Products Regulation, her employer will likely pay a fine for the e-waste.

What is responsibility?

Multiple (independent, cumulative) meanings:[3]

Virtue: someone's *character, reputation or intentions*, evidenced by a *history* of doing what they think is right.

Role: the *duties* a person has: what they should or ought (not) to do.

Capacity: being able to *understand* what is required and to control one's conduct accordingly. *Also includes available tools*.

Outcome: a state *or an action* is rightfully attributable to you as something you did with full agency.

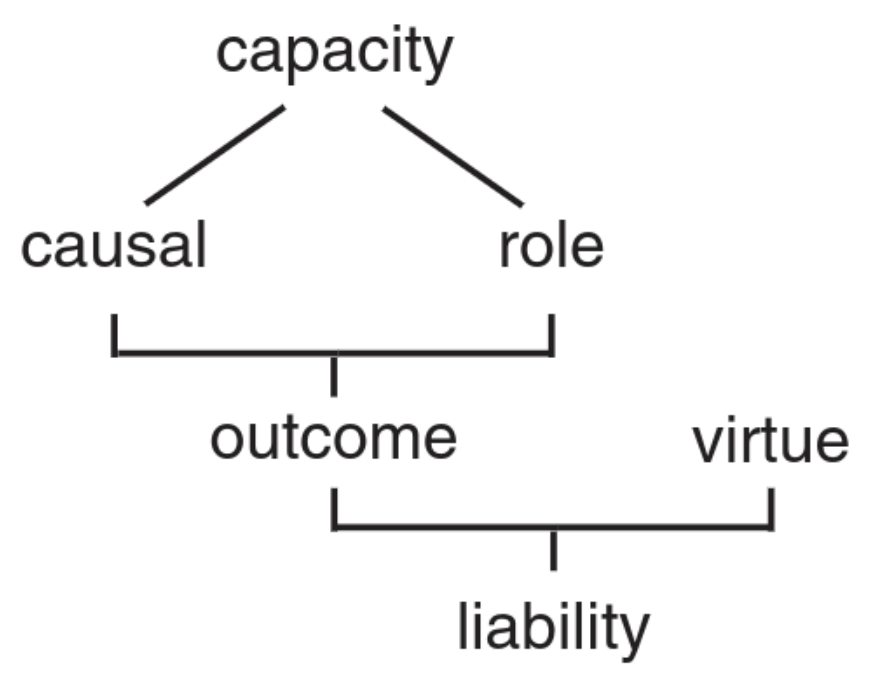
Causal: purely factual/descriptive, happens through you, no agency implied.

Liability: what must now be done to set things right (e.g., compensate, apologize, fix it). Usually said as "take responsibility" or "hold responsible".

[3]Vincent. "A Structured Taxonomy of Responsibility Concepts." Moral responsibility: Beyond free will and determinism (2011).

What is responsibility?

Not independent: **capacity** and **causal**/**role** responsibility motivate **outcome** responsibility. **Outcome** and **virtue** responsibility motivate **liability**.



Example situation

Léa is a smartphone product manager.

She strongly believes in sustainable practices and **is known for pushing for repairability** at every design review (**virtue**). **As product lead**, she was responsible for choosing the battery and glass that go into the phone (**role**).

Under quarterly margin pressure, she signed off on gluing the battery in place and dropping the spare-parts contract to save two euros a unit. **Did she have the information, tools, and authority to foresee what that would cost down the line?** (**capacity**)[4]

Her sign-off cut the phone's lifespan from seven years to three (**causally**), **resulting in a wave of prematurely discarded devices** (**outcome**). Under the EU's Ecodesign for Sustainable Products Regulation, ***her employer*** **will likely pay a fine for the e-waste** (**liability**).

[4]Here, mental **capacity** to be held responsible is assumed by default.

Evil Ethics 101

Start at the bottom of the graph, go up the branches.

A hyperscale AI data centre in a water-stressed basin. Local wells drop, the aquifer doesn't recover over the dry season, residents bring an action.

outcome **"The depletion isn't attributable to us."**

causal **"We don't operate the site, our colocation provider does"** (deny the act) or **"we are 2% of basin withdrawal, irrigation is 80%"** (deny the link).

role **"Others breached duties too"**; the Préfecture granted the authorisation, no water-intensity standard exists, the utility set the tariff, the customer specified the model size.

capacity **"There was no reporting standard, so we couldn't have known."** Or: **"the cluster autoscaled, nobody chose that training run's footprint."**

Limits of responsibility?

Many hands problem

> In some situations in which undesirable collective effects occur, it is very hard, if not impossible, to hold any individual reasonably responsible.[5]

Rare bird problem

> Explicit ethical deliberation virtually never occurs spontaneously [...]
>
> When prompted, engineers exhibited narrow conceptions of their responsibilities and frequently deflected ethical concerns to managers or legal systems.[6]

[5] Van de Poel, et al. "The problem of many hands: Climate change as an example." Science and Engineering Ethics (2012).

[6] Lange, et al. "Epistemic Trust as a Mechanism for Ethics Integration: Failure Modes and Design Principles from 70 Moral Imagination Workshops" (2026), citing Lee et al. (2019).

Beyond blame

As future engineers, “responsibility” should not (only) be used to point fingers.

Sense of responsibility	Function of attributing responsibility[7]
Backward-looking responsibility	
• Responsibility-as-blameworthiness	Retribution
• Responsibility-as-accountability	Maintaining moral community
• Responsibility-as-liability	Justice to victims
Forward-looking responsibility	
• Responsibility-as-obligation	Efficacy (who is best suited to handle the task; not at fault)
• Responsibility-as-virtue	Due care to others

Hence: this class is motivated by ...? system based on forward-looking responsibility; (hopefully) help

[7] Table source: Van de Poel, et al. “The problem of many hands: Climate change as an example.” Science and Engineering Ethics (2012).

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Hence: this class is motivated by forward-looking responsibility, to (hopefully) help future generations (of engineers).

[8] Table source: Van de Poel, et al. “The problem of many hands: Climate change as an example.” Science and Engineering Ethics (2012).

Concepts summary

How do you choose to do the right thing?

- Ethics of conviction (absolute norm) and ethics of responsibility (depends on consequences).
- Can be combined depending on individuals / situations.

What does it mean to be responsible?

- Responsibility is multi-faceted, and you may hold various flavors of it.
- Responsibility is linked with functions.
- This class on *responsible* digital technologies is motivated by forward-looking responsibility.

TL;DR tutorial (1)

Before a decision: **forward**-looking ownership.

- Don’t wait for the rare bird to sing, don’t let many hands excuse assigning none.
- AIRR framework[9]:
  - *Anticipate*: think through impacts before they happen
  - *Include*: bring in those affected, not just experts
  - *Reflect*: question assumptions and blind spots
  - *Respond*: stay able to change course as you learn

After something goes wrong: check capacity, causality, knowledge, freedom, wrong-doing before assigning **backward**-looking blame.

[9] Stilgoe, et al. “Developing a framework for responsible innovation.” Research Policy (2013).

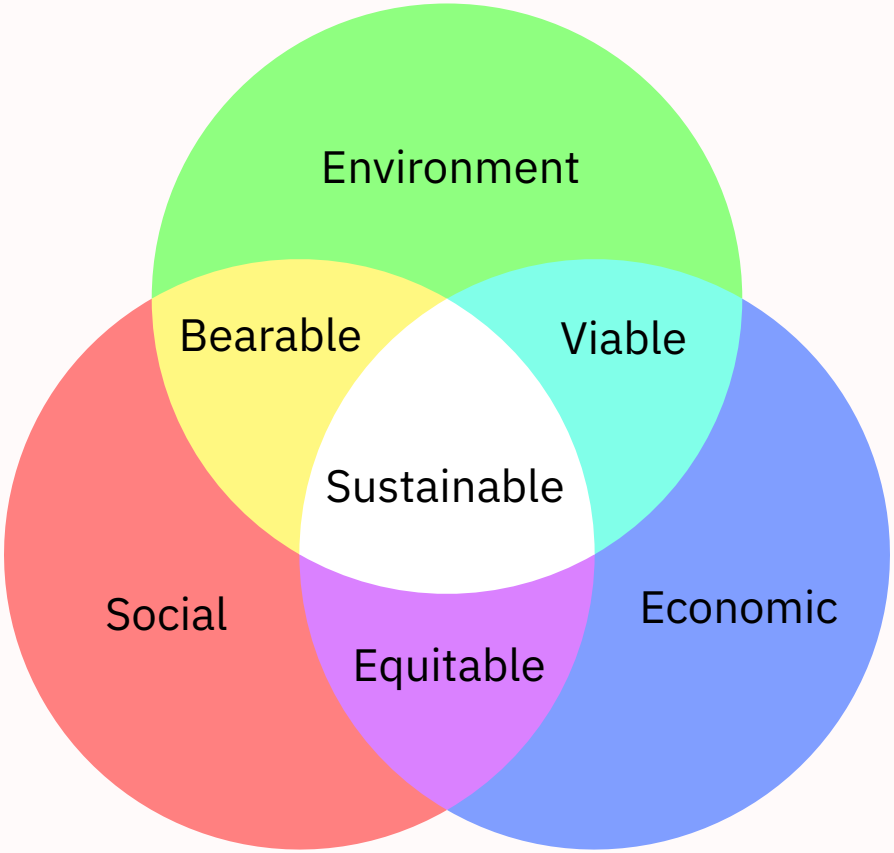
TL;DR tutorial (2)

- *Transparency*: if my choice were made public, would I be comfortable defending and explaining it?
- *Exemplarity*: could my choice serve as a (positive) example in any other similar situation?
- *Reciprocity*: if I were the one bearing the consequences of my choice, would I still consider it the right choice?[10]

[10] Ordre des Ingénieurs du Québec. “Guide de pratique professionnelle” (2026). https://gpp.oiq.qc.ca/L_ethique.htm

Sustainability, limits, and ICT

Sustainability



Sustainable development

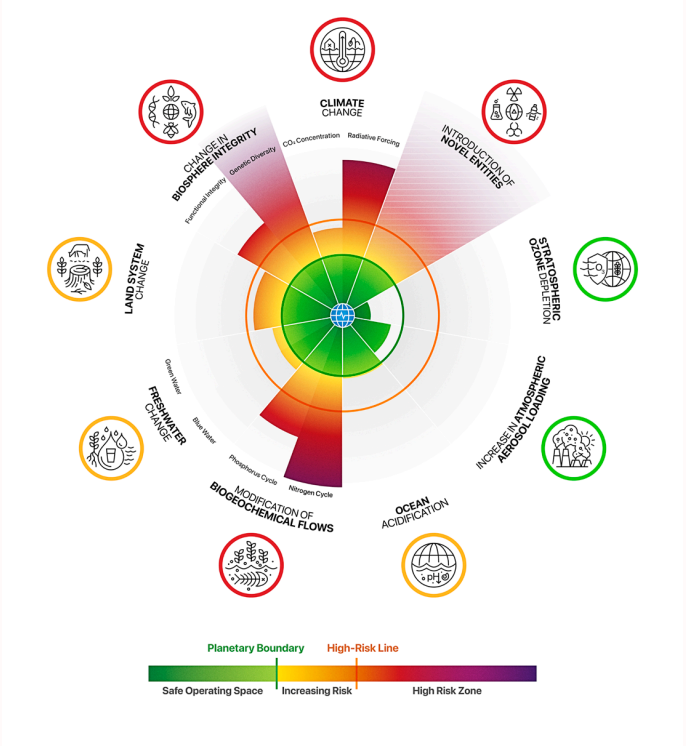
> Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.[11]

(Keep this definition in mind for later use.)

[11] Brundtland. “Our common future world commission on environment and development” (1987).

Most depressive slide of the deck, I promise

> The 2025 PHC report concludes that seven out of nine Planetary Boundaries have been breached.[12]



[12] Kitzmann, et al. "Planetary Health Check 2025: A scientific assessment of the state of the planet" (2025).

(I lied) Planetary boundaries details

Boundary (control variable)	Boundary[13]	2025 value[14]	Status
Climate - CO_2	350 ppm	423 ppm	**Breached**
Climate - radiative forcing	+1 W/m²	+2.97 W/m²	**Breached**
Biosphere - HANPP	10%	30%	**Breached**
Biosphere - extinction rate	10 E/MSY	100-1000 E/MSY	**Breached**
Land system - forest cover	75%	59%	**Breached**
Freshwater - blue/green water	12.9% / 12.4%	22.6% / 22%	**Breached**
Biogeochem. flows - P / N	6.2 / 62 Tg/yr	18.2 / 165 Tg/yr	**Breached**
Ocean acidification - Ω_{arag}	2.86	2.84	**Breached**
Novel entities	0% untested	untested release ongoing	**Breached**
Aerosol loading - ΔAOD	0.10	0.063	**Safe**
Stratospheric ozone	277 DU	285.7 DU	**Safe**

[13] Rockström, et al. “Planetary boundaries: exploring the safe operating space for humanity.” Ecology and Society (2009).

[14] Kitzmann, et al. “Planetary Health Check 2025: A scientific assessment of the state of the planet” (2025).

Wait, isn’t sustainability supposed to be more than one pillar?

Sustainable, for what, and for whom?

We generally focus on the environmental/ecological point of view, but sustainability is nothing without its social & economic aspects.

> One should always ask: Sustain what, for whom, for how long, and at what cost?
> [15]

[15] Tainter. “A framework for sustainability.” World Futures: The Journal of General Evolution (2003).

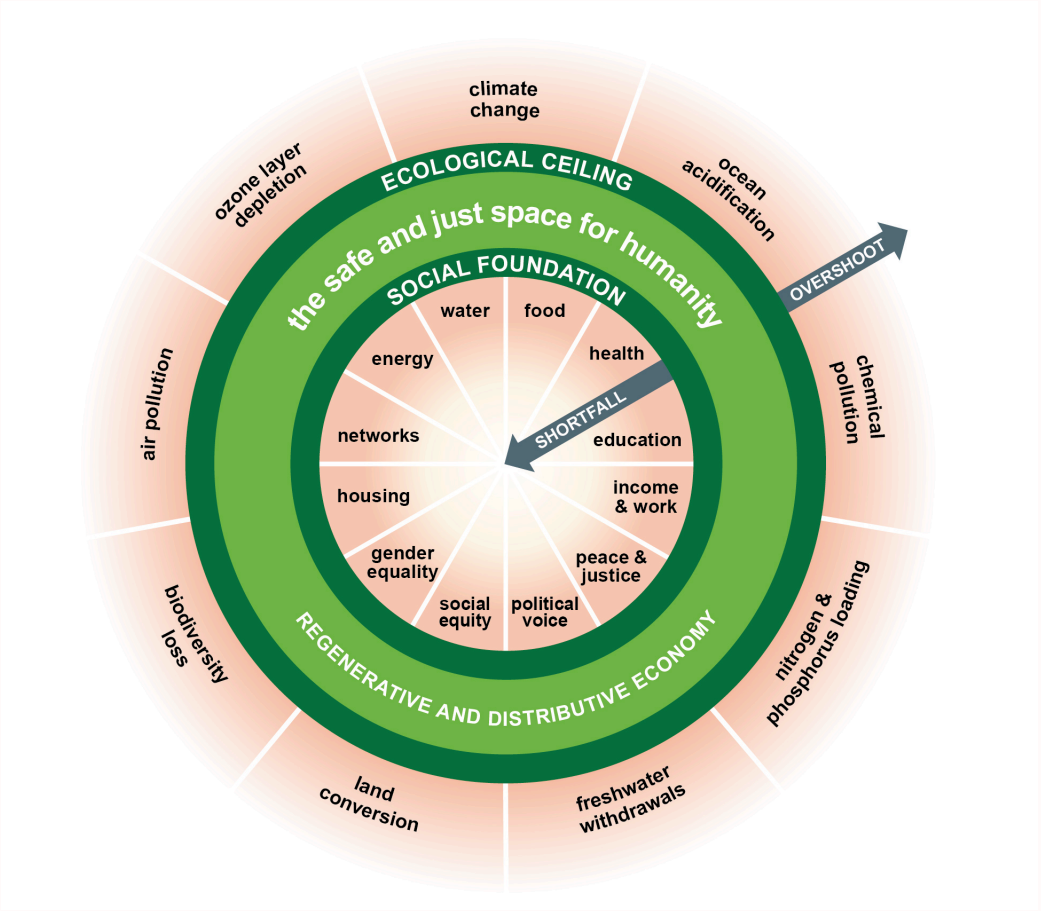
Sustainable, for what, and for whom?

Example:

- Collect and refurbish ICT equipment, typically after 3 - 4 years of use[16]
- Give them a second life in the Global South
- Can this practice serve as a sustainability goal or does it instead entrench current power structures?

[16] Example taken from: Mühlberg. “Sustaining security and safety in ICT: A quest for terminology, objectives, and limits.” Eighth Workshop on Computing within Limits (2022).

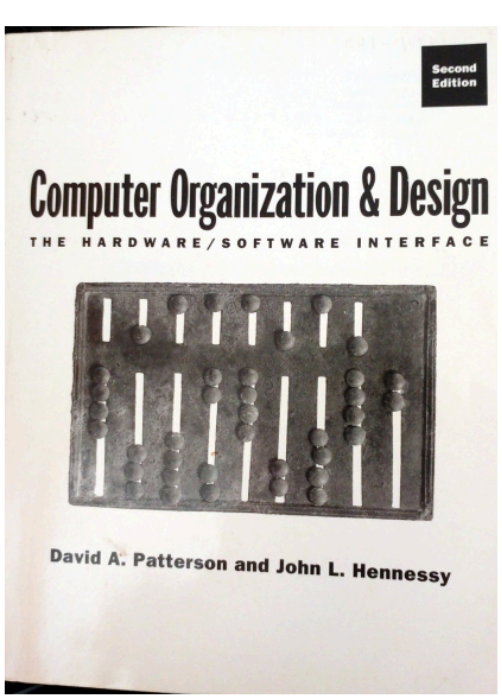
The doughnut

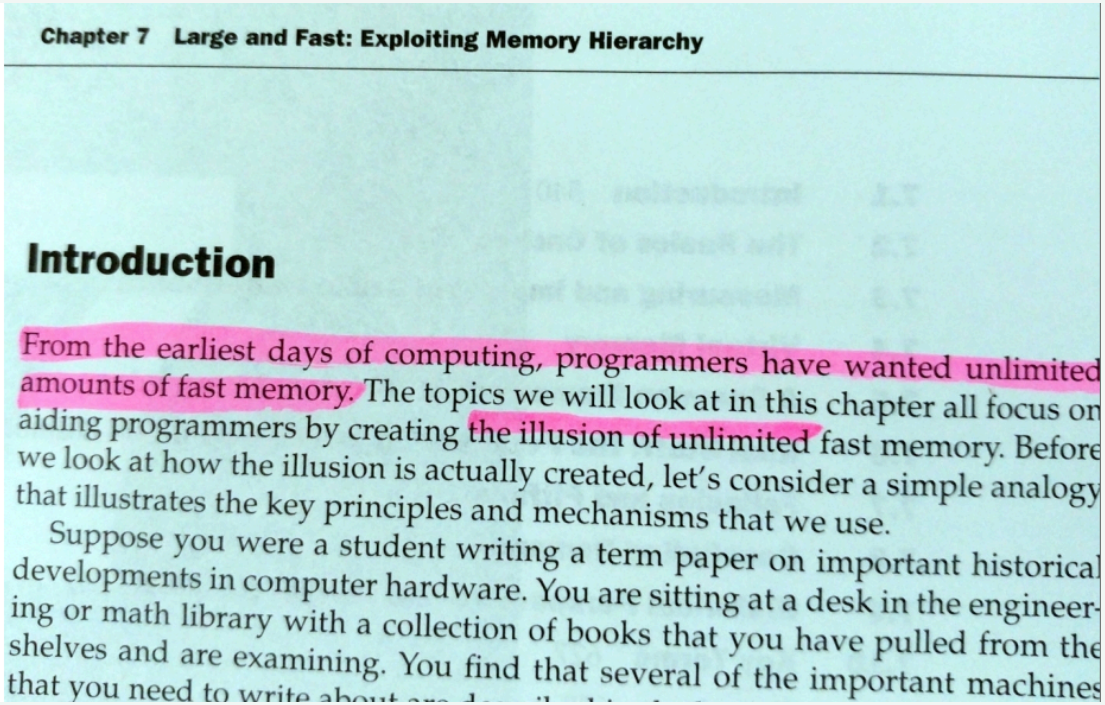


Doughnut economics : Two concentric rings: an inner **social foundation** (food, water, health, education, income, housing, political voice, gender equality, ...) and an outer **environmental ceiling** (planetary boundaries). In between: the **safe and just space for humanity**.

Raworth. “A safe and just space for humanity: can we live within the doughnut?” Oxfam (2012).

Alright, alright, what about ICT then?





Patterson and Hennessy, “Computer Organization and Design”, 1993. Photo: Florence Maraninchi.

=> ICT is **tangible**;

The ✨cloud✨ has actual consequences in the physical world.

ICT effects

Direct (first-order):

- Extraction
- Fabrication
- Distribution/installation
- Usage
- End-of-life

Indirect (higher order):

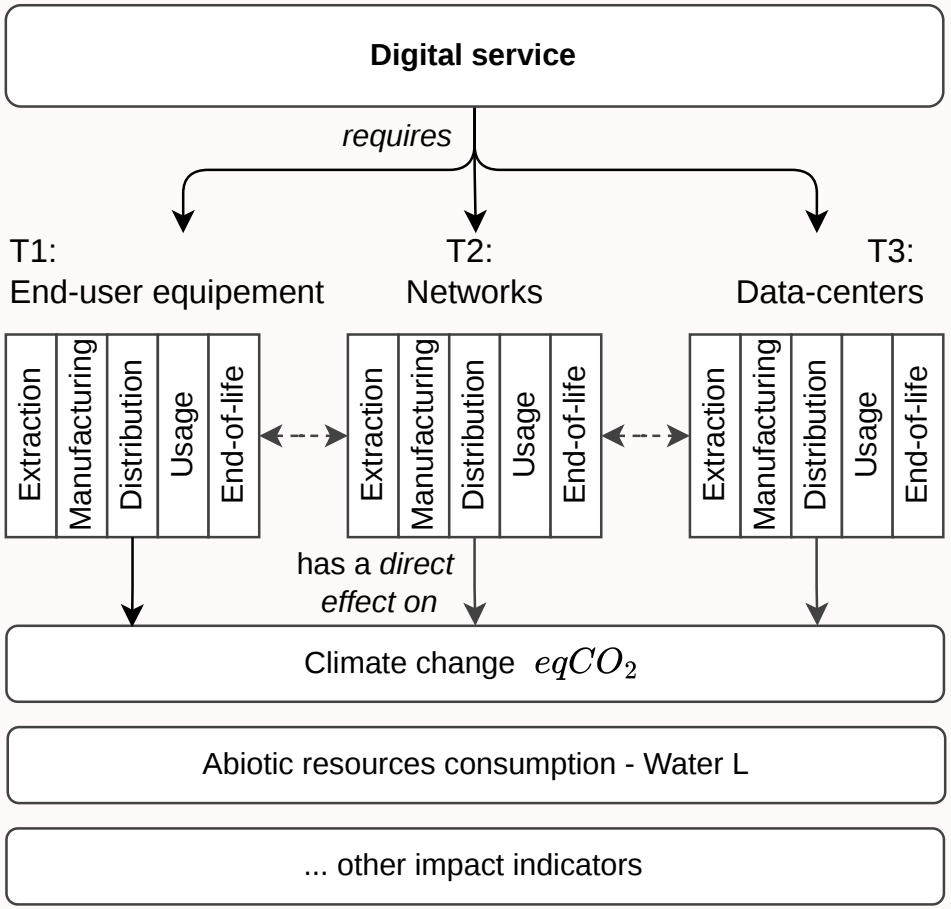
- Induction
- Substitution
- Optimization
- Direct rebound
- Indirect rebound
- Macro-economic rebound
- Social change

This list of effects and their taxonomy is from a recent ADEME report.[17]

[17] ADEME. “Évaluation environnementale des effets directs et indirects du numérique pour des cas d’usages” (2026).

Multiple taxonomies exist and are currently debated in research circles. For this class, we'll focus only on that one as the concepts are similar enough.

Direct effects through the complete life cycle



Direct effects example 1: water during fabrication

STMicroelectronics' Crolles chip fab used ~4.23M m^3 of water in 2021. How many French residents' yearly water needs is that equivalent to?[18]

- Around 150 residents
- Around 1,000 residents
- Around 20,000 residents
- Around 80,000 residents
- Around 150,000 residents

[18] Questions adapted from: Bouveret, et al. "Quiz sur les impacts environnementaux du numérique." EcoInfo (2025). (Figures updated when possible.)

[19] STMicroelectronics. "Sustainability Report" (2023). https://www.st.com/content/dam/about-us/sustainability/stmicroelectronics-sustainability-report-2023.pdf

[20] Lao, et al. "Panorama des services et de leur performance." Office français de la biodiversité (2022). https://www.eaufrance.fr/sites/default/files/documents/rapport_sispea_2022_vf.pdf

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- Around 150 residents
- Around 1,000 residents
- Around 20,000 residents
- **Around 80,000 residents**
- Around 150,000 residents

- 4,232,000 m³ of water in 2021[22]
- Roughly corresponds to 78,370 French residents for a year[23]

[21] Questions adapted from: Bouveret, et al. "Quiz sur les impacts environnementaux du numérique." EcoInfo (2025). (Figures updated when possible.)

[22] STMicroelectronics. "Sustainability Report" (2023). https://www.st.com/content/dam/about-us/sustainability/stmicroelectronics-sustainability-report-2023.pdf

[23] Lao, et al. "Panorama des services et de leur performance." Office français de la biodiversité (2022). https://www.eaufrance.fr/sites/default/files/documents/rapport_sispea_2022_vf.pdf

Direct effects example 2: end-of-life & e-waste

How many old smartphones do you have sitting in a drawer at home?

- 0
- 1 or 2
- 3 or 5
- Too many to admit

Direct effects example 2: end-of-life & e-waste

Worldwide, including *all* electrical & electronic equipment[24]:

- E-waste generated: 62 billion kg
- Formally collected & recycled: 13.8 billion kg
- Collected/recycled outside formal systems: 16 billion kg
- Managed by **self-employed/informal individuals**[25]: 18 billion kg
- Disposed of as residual waste (waste bins/landfill/ incinerated): 14 billion kg

[24] Baldé, et al. "Global e-waste monitor 2024" (2024).
[25] "For whom?"

Direct effects example 2: end-of-life & e-waste

Assuming 100% collection and recycling rates, what percentage of the demand for iron, aluminum, and copper would have been met (worldwide, 2019)?

- 30%
- 60%
- 90%

[26] Bouveret, et al. “Quiz sur les impacts environnementaux du numérique.” EcoInfo (2025).

Direct effects example 2: end-of-life & e-waste

Assuming 100% collection and recycling rates, what percentage of the demand for iron, aluminum, and copper would have been met (worldwide, 2019)?

- 30%
- **60%**
- 90%

- Demand: 39 Mt
- Maximum recycling potential: 25 Mt[27]

[27] Bouveret, et al. “Quiz sur les impacts environnementaux du numérique.” EcoInfo (2025).

Induction effect

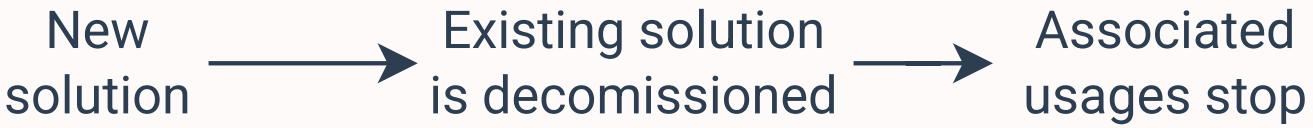
Induction effect: An increase in the level of energy or resource consumption that was caused or enabled by the emergence of “new options” arising from technological change.[28]

Example: Smart electricity meter => new possibility of collecting consumption data + interfacing with connected-home systems => enabling home-automation services => buying additional equipment.

[28] Lange, et al. “The induction effect: why the rebound effect is only half the story of technology’s failure to achieve sustainability.” Frontiers in Sustainability (2023).

Substitution effect

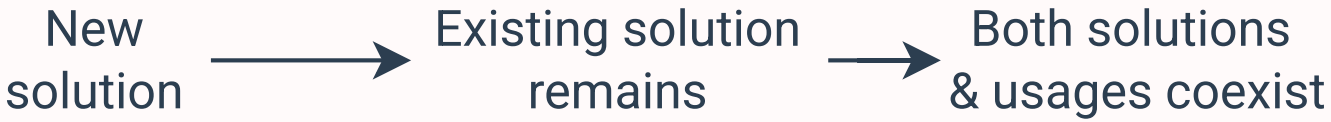
Substitution effect: a technology replaces a pre-existing one, which is then decommissioned. Generally, it's a more environmentally efficient technology.



Example: An e-commerce platform substitutes an in-store purchase process with a dematerialized one => avoids the transport needed for customers to travel to the store.

Substitution effect

Stacking effect: if the previous solution remains



Example: A brick & mortar store adds an e-commerce website => both solutions are used at the same time.

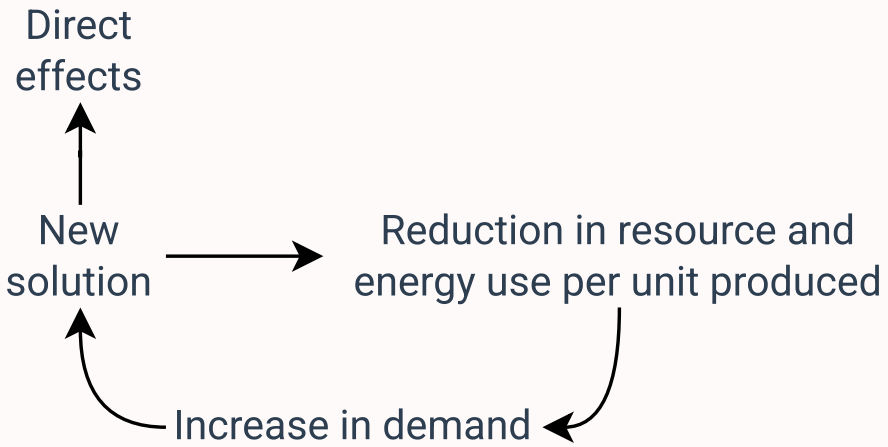
Optimization effect

Optimization effect: modifications to a solution allowing it to use fewer resources (materials, energy, money, ...) for a constant quantity produced or consumed.

> **Example:** A system that analyzes a plot of land and identifies its exact irrigation needs targets an optimization effect: the quantity of water per unit of surface area.

Direct rebound effect / Jevons paradox

Direct rebound effect: users of a solution react to an improvement in the efficiency of an activity by increasing their consumption of that same activity (in terms of energy and/or resources).



Example: Connected thermostat => efficiency gains by optimizing a home's heating system => Less energy (€) for the same thermal comfort => higher heating temperature, longer heating periods, heating rooms that weren't heated before...

Rebound: relative vs. absolute decoupling

Decoupling: Growing a service while its impact grows *slower* (**relative**) or *shrinks* (**absolute**).[29]

- **Relative decoupling**: impact *per unit of service* falls. Total impact can still rise if usage grows faster (= rebound).
- **Absolute decoupling**: *total* impact falls.

[29] Parrique, et al. "Decoupling Debunked." European Environmental Bureau (2019).

Direct rebound effect

Between 2011 and 2026, significant progress was made in the digital field. During that same period, according to the website httparchive.org, by approximately how much was the average loading time of a web page on a desktop computer reduced?

- By 100
- By 20
- By 10
- By 1

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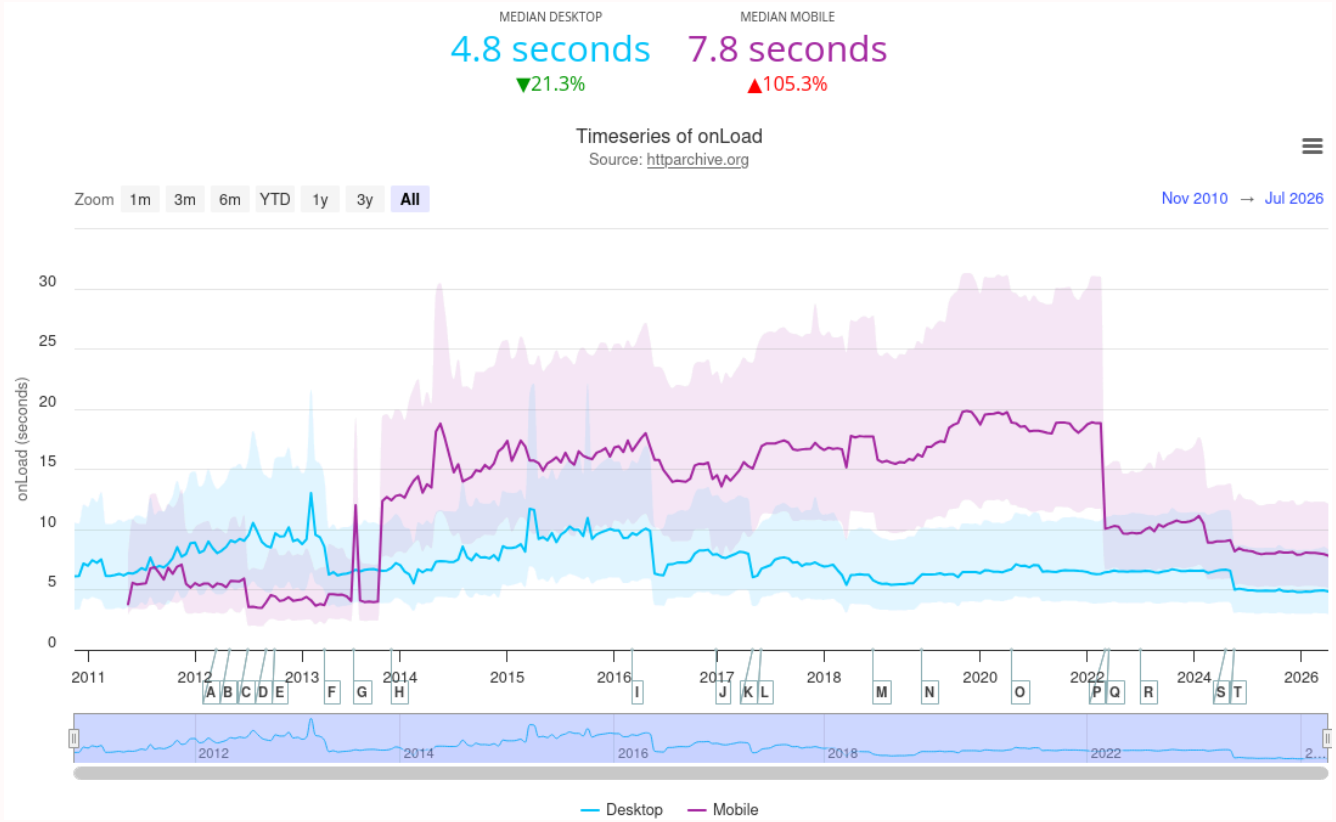
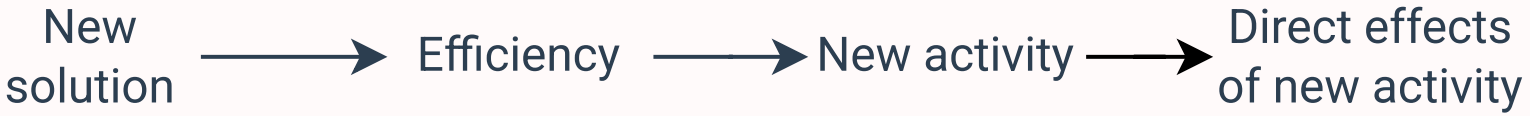
Direct rebound effect



Source: https://httparchive.org/reports/loading-speed#ol (July 2026)

Indirect rebound effect

Indirect rebound effect: users of a solution react to an increase in the efficiency of one activity by increasing their consumption of a **different** activity. More specifically: time rebound, space rebound, or income effect.



Indirect rebound effect

Is it better for the environment to work from home or in person?

[30]Kiko, et al. “Evaluation of direct and indirect effects of teleworking on mobility: the case of Paris.” Transportation Research Record (2024).

Indirect rebound effect

Is it better for the environment to work from home or in person?

It depends[31]:

- Videoconferencing has a lower energy, time, and cost footprint than travel
- These gains can be re-allocated:
  - Additional trips for reasons other than work
  - May choose to live farther from their workplace (longer commutes)
  - Reduced traffic congestion => increased car use among non-teleworkers.

[31] Kiko, et al. "Evaluation of direct and indirect effects of teleworking on mobility: the case of Paris." Transportation Research Record (2024).

Macro-economic rebound & societal transformation

Macro-economic rebound & societal transformation: Transformations of the economy and society at large scales.

- Macro-economic: investment, labor productivity, or market actor behavior.
- Societal transformations: cultural habits, public policy, organizational modes, social norms, or value systems

Example: Digital home-sharing platform (e.g., Airbnb) => changed the nature of the rental housing stock in many cities. Initially thought for short-term tourist visits, shifted long-term rental stock towards short-term => reduced housing supply for residents / relocated households outside the city.

A note on rebound effects

- Rebound is not only about **end-user** behavior.
- **Other actors** have their motivations to generate or amplify rebound effects.
  - In that case, growth is the goal.
  - Efficiency/performance optimization is deliberately used to achieve it.[32]

[32] Morand, et al. “When rebound effect is not a side effect: analyzing sociotechnical contexts of digital technologies.” (2026).

A note on rebound effects - AI training example

- Deep learning models require significant resources to train (e.g., water, metal, energy)[33]
- **AI companies' claim**: algorithm optimization / frequent hardware updates could mitigate[34] or even reduce the carbon footprint of AI training.[35]

[33] Morand, et al. "When rebound effect is not a side effect: analyzing sociotechnical contexts of digital technologies." (2026).

[34] Wu, et al. "Beyond efficiency: Scaling AI sustainably." IEEE Micro (2024).

[35] Patterson, et al. "The carbon footprint of machine learning training will plateau, then shrink." Computer (2022).

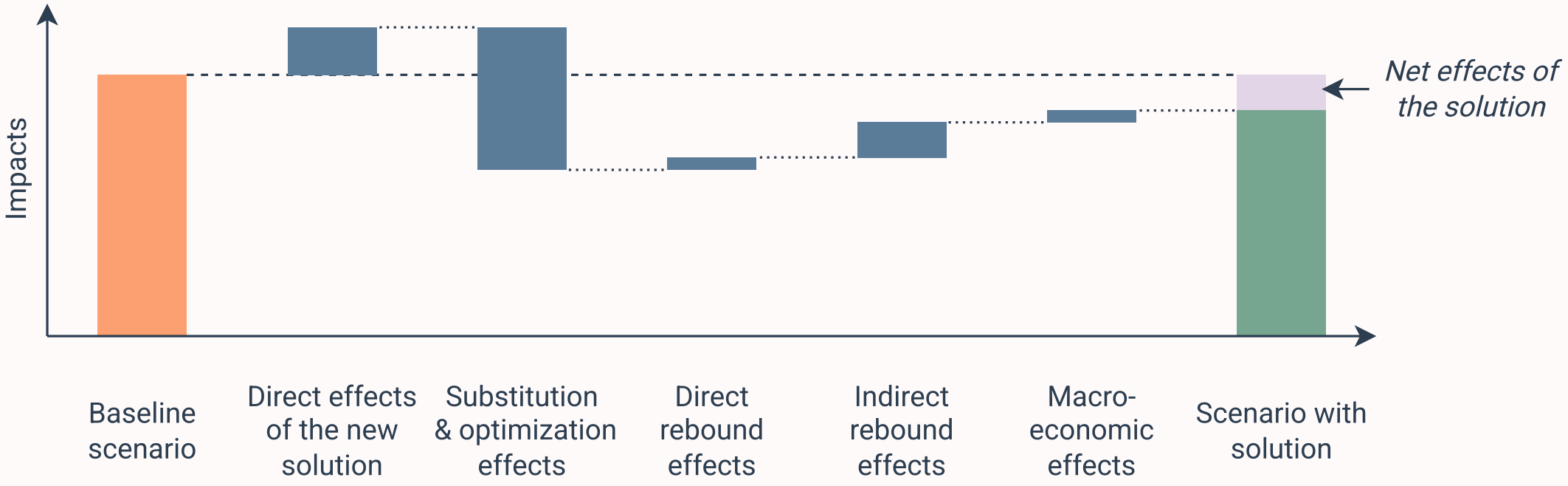
A note on rebound effects - AI training example

- The field follows a “bigger is better” paradigm => scaling laws tie more data/ compute to better benchmark performance => gains are reinvested into bigger models.
- Energy efficiency mainly serves to remove scaling bottlenecks (power, cost, reputational risk) => **intended enablement** =/= unintended rebound effect.

Same concept for the deployment of new technologies: e.g., 5G; mobile network operators *need* the intended enablement to grow/profit/survive.[36]

[36] Morand, et al. “When rebound effect is not a side effect: analyzing sociotechnical contexts of digital technologies” (2026).

Taking all effects into account



Mapping ICT onto the planetary boundaries

To complete:

Boundary	Direct	Indirect
Climate change		
Biosphere integrity		
Land-system change		
Freshwater change		
Biogeochemical flows	-	
Novel entities		-

Mapping ICT onto the planetary boundaries

Boundary	Direct	Indirect
Climate change	Fabrication, usage (GHG/ energy)	Optimization, substitution (↓, e.g. smart grids) vs. Induction, direct/indirect/ macro-economic rebound (↑)
Biosphere integrity	Extraction (habitat loss), end-of-life (toxics)	Macro-economic rebound / social change (land conversion driven by ICT-enabled markets)
Land-system change	Extraction, distribution/ installation (data centers, network infra)	Induction (new land uses enabled by connectivity)

Boundary	Direct	Indirect
Freshwater change	Fabrication (chip-fab water), usage (cooling)	Optimization (precision irrigation, ↓) vs. rebound (↑ output → ↑ withdrawal)
Biogeochemical flows	-	Induction / macro-economic rebound (ad-driven consumption, e-commerce) vs. optimization (precision agriculture, ↓ fertilizer)
Novel entities	Fabrication (PFAS, novel compounds), end-of-life (e-waste chemicals)	-

Boundary	Direct	Indirect
Ocean acidification	-	Same chain as climate change (via CO_2)
Aerosol loading / ozone	Fabrication (historical CFCs, phased out)	-

What about other sectors?

Global numbers:

- Goal (to limit global warming to +1.5°C): 2 t CO_2 / year / person.
- France (2024): 8.2 t CO_2 / year / person.[37]

ICT:

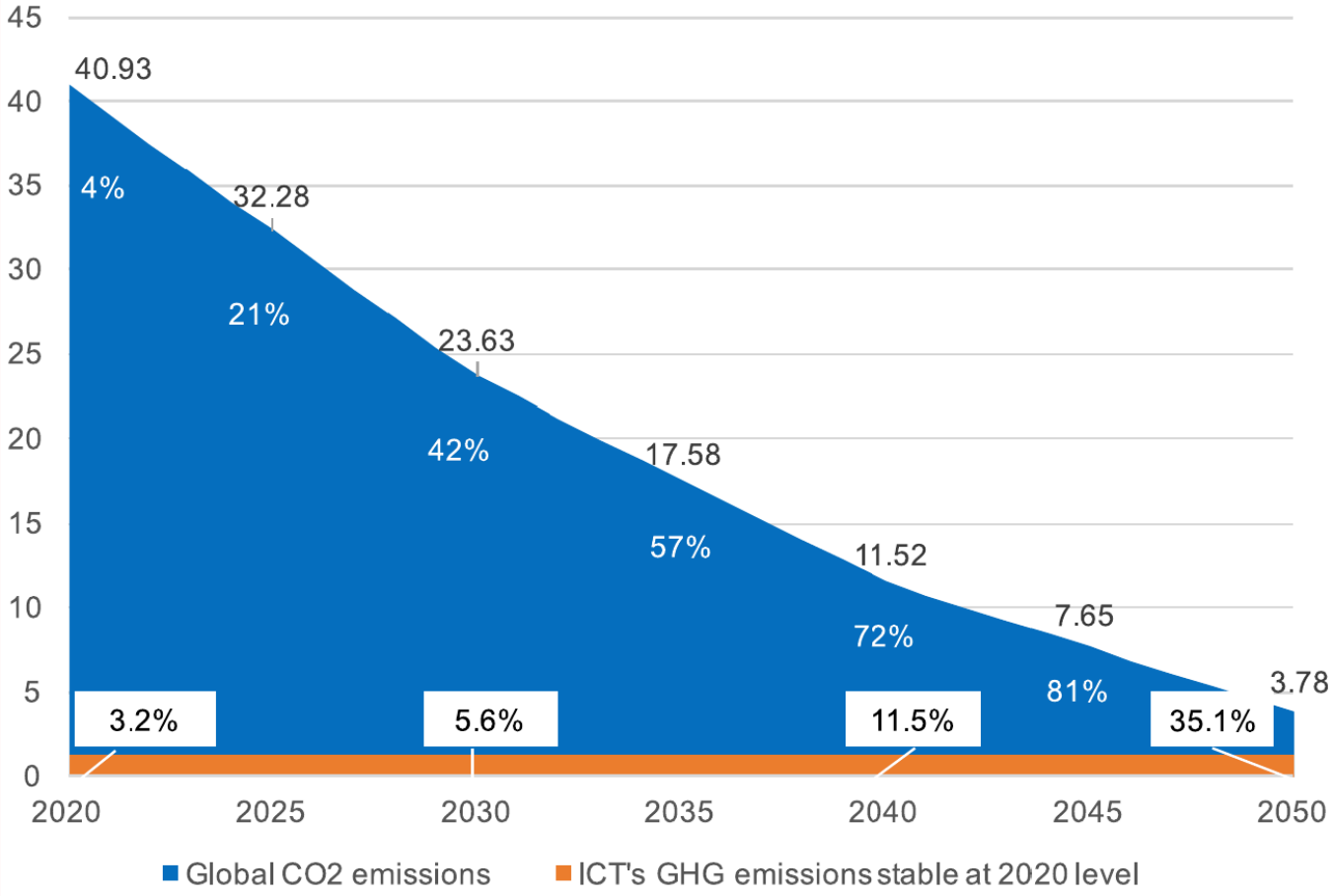
- France: 4.4% of the carbon footprint (2022).[38]
- World: between 2.1% - 3.9% of the carbon footprint (2021).[39]

[37] Statisque publique de l'énergie, des transports, du logement et de l'environement (SDES). "L'empreinte carbone de la France de 1990 à 2024" (2024).

[38] Brilland, et al. "Evaluation de l'impact environnemental du numérique en France." ADEME (2025).

[39] Freitag, et al. "The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations." Patterns (2021).

What about other sectors?



ICT emissions, assuming the 2020 level (adjusted for truncation error) remains stable until 2050, and global CO2 emissions reduced in line with 1.5+ C under scenario SSP2-19

Source: Freitag, et al. “The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations.” Patterns (2021).

Is ICT The Answer?

Two approaches[40]

- **Green ICT**
  - Measures/estimations/modeling of (mainly) energy consumption
  - Optimization (software, hardware, communication)
- **ICT for Green**
  - Optimizations of existing non-IT domains (e.g., supply chain, smart-*)
  - New domains (e.g., car-sharing platform)

[40] Maraninchi. "Planetary Limits, Anti-Limits in Computer Systems And The Missing Scenarios" (2024).

Is ICT The Answer?

The GeSI SMARTer2030 report claims that, by 2030, ICT-enabled emission savings in other sectors (relative to ICT's own carbon footprint) amount to roughly:

- x2
- x5
- x9.7
- x15

[41] Global eSustainability Initiative (GeSI). "SMARTer2030: ICT Solutions for 21st Century Challenges." (2015).

Is ICT The Answer?

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- x2
- x5
- **x9.7**
- x15

- ICT's own estimated footprint (2030): 1.25 Gt CO_2e
- Claimed savings enabled elsewhere: 12.08 Gt CO_2e
- A **20% reduction** of global CO_2 emissions by 2030[42]

[42] Global eSustainability Initiative (GeSI). "SMARTer2030: ICT Solutions for 21st Century Challenges." (2015).

Is ICT The Answer?

The European Commission seems to generally agree:

> Digital technologies are a critical enabler for attaining the sustainability goals of the Green Deal in many different sectors.[43]

[43] European Commission. “The European Green Deal.” (2019).

however.

Is ICT The Answer?

Scientists are a bit less enthusiastic:

> The Green Deal does not provide a detailed roadmap for how these technologies will in fact deliver against these goals, nor figures regarding expected savings to be achieved [...] there is no evidence in the multi-decade history of ICT-driven efficiency savings that enablement works for reducing overall emissions.[44]

Worse:

- The International Telecommunication Union (ITU) published a report on 200 leading digital companies: 1.4% increase in GHG between 2022 and 2023.[45]

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[44] Freitag, et al. "The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations." Patterns (2021).

[45] International Telecommunication Union. "Greening Digital Companies" (2025).

Is ICT The Answer?

Also:

- GeSI is sponsored by several large ICT companies
- The ICT footprint is probably underestimated
- The rebound effect is not taken into account in the 12.08 Gt CO_2e figure[46]

[46] https://smarter2030.gesi.org/downloads/Full_report.pdf

Is ICT The Answer?

Not *the* answer. A part of the problem & could be a part of the solution.

Can’t help but try, though.

Summary

- Planetary limits motivate deep transformation in multiple sectors.
- ICT *does* have real-world effects, both direct and indirect.
- While not the leading resource-consuming sector, ICT still needs to reduce its impacts.
- ICT can help to build solutions but it is also a gigantic enabler of the problem it's trying to fight.

And now what?

Possible paths

> Sustainability is an active condition of problem solving, not a passive consequence of consuming less.[47]

Disclaimers:

1. No perfect technical solution (approximations, trade-offs, complex effects).
2. No scientific consensus *on engineering processes* & taxonomy applied to sustainable ICT (see next slides).

Main goals:

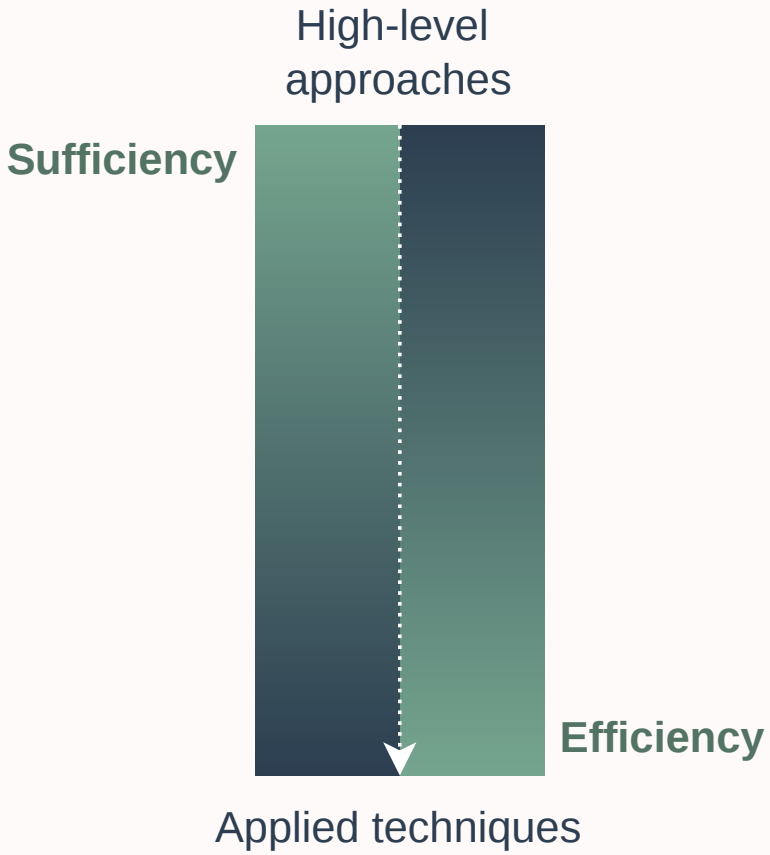
- Identify **high-level design** approaches.
- Give you possible **tools** and **methods** to navigate your future work as **engineers**.

[47] Tainter. "Social complexity and sustainability." Ecological Complexity (2006).

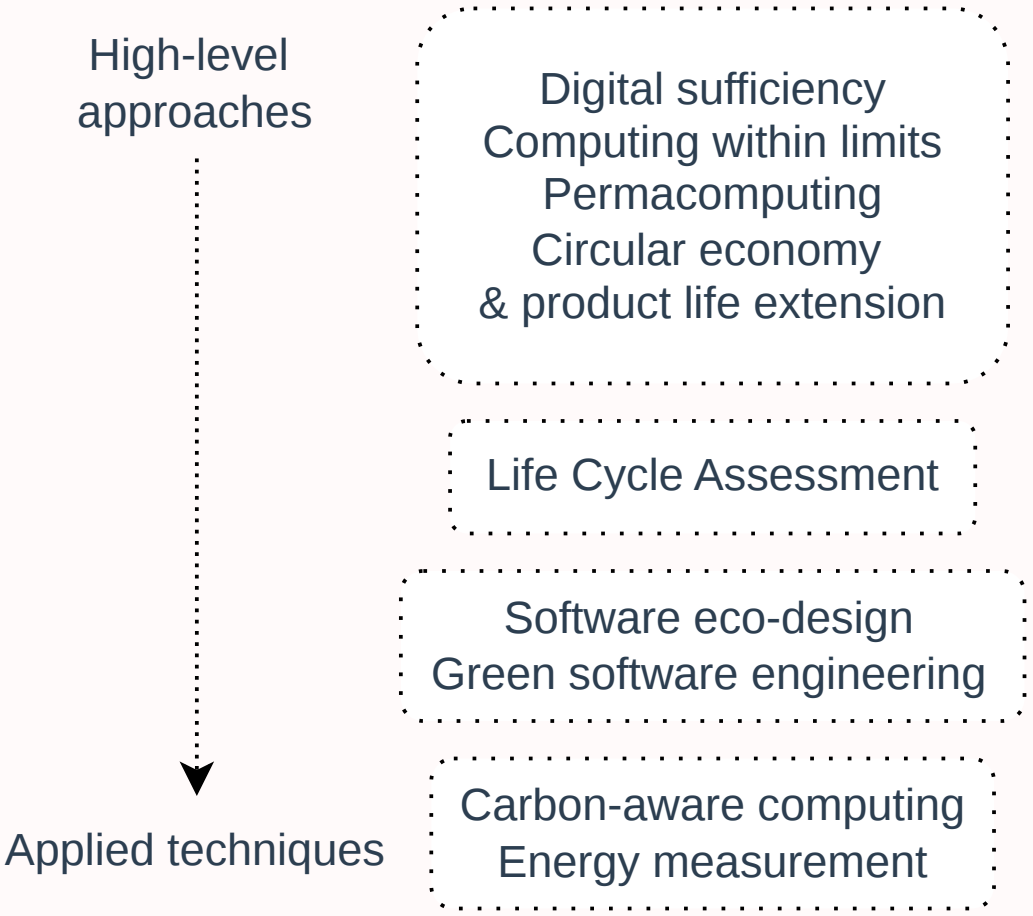
Approaches

Sufficiency
Do we need it, how much?

Efficiency
Given we're building it, how do we do it with less impact?



Approaches


High-level approaches
Digital sufficiency
Computing within limits
Permacomputing
Circular economy
& product life extension
Life Cycle Assessment
Software eco-design
Green software engineering
Carbon-aware computing
Energy measurement
Applied techniques

Approaches

High-level approaches

Digital sufficiency
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Applied techniques

Next lectures!

Digital sufficiency

> **"Digital sufficiency":** Strategies aiming for an *absolute* reduction of the material & energy use of digital systems.[48]

Via:

- *Hardware* sufficiency: fewer, longer-lived devices
- *Software* sufficiency: lightweight, undemanding software
- *User* sufficiency: usage behavior (what/how much/how often)
- *Economic* sufficiency: business models not reliant on growth

[48] Santarius, et al. "Digital sufficiency: conceptual considerations for ICTs on a finite planet." Annals of Telecommunications (2023).

Computing within limits

3 principles[49]:

- **Question growth**. Is our work:
  - reliant on growth?
  - seeking to make growth happen?
  - contributing to growth?
- **Consider models of scarcity**
  - What will happen when X is missing? (e.g., electricity, clean water, internet access)
- **Reduce energy and material consumption**

[49] Nardi, et al. "Computing within limits." Communications of the ACM (2018).

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Remember AAIR:
Anticipate + **Reflect**.

[50] Nardi, et al. “Computing within limits.” Communications of the ACM (2018).

Computing within limits: growth & anti-limits

> **"Anti-limit"[51]:** Both a promise and a hypothesis, built into a system's design, that some resource will grow as needed.

Some examples:

- Unlimited cloud storage
- "Always available" cloud services regardless of client count
- Betting on a more efficient machine "soon"
- Allow for unlimited functional extensions...

Hence: Green ICT (optimize) and ICT for Green (use ICT to green other sectors): **limited-by-construction IT** (systems deliberately designed to *not* scale indefinitely).

[51] Maraninchi. "Let us not put all our eggs in one basket." Communications of the ACM (2022).

Computing within limits: growth & anti-limits

Design (counter-)example: Mastodon provides a built-in way of deleting old posts.

Computing within limits: growth & anti-limits

> **“Extensibility”:** A software engineering and systems design principle that provides for future growth.

- Usually a desirable property
- As seen previously, infinite future growth should be questioned / not be enabled technically
- Hence: design systems that are *not* scalable, on purpose?

Computing within limits: growth & anti-limits

Design examples:

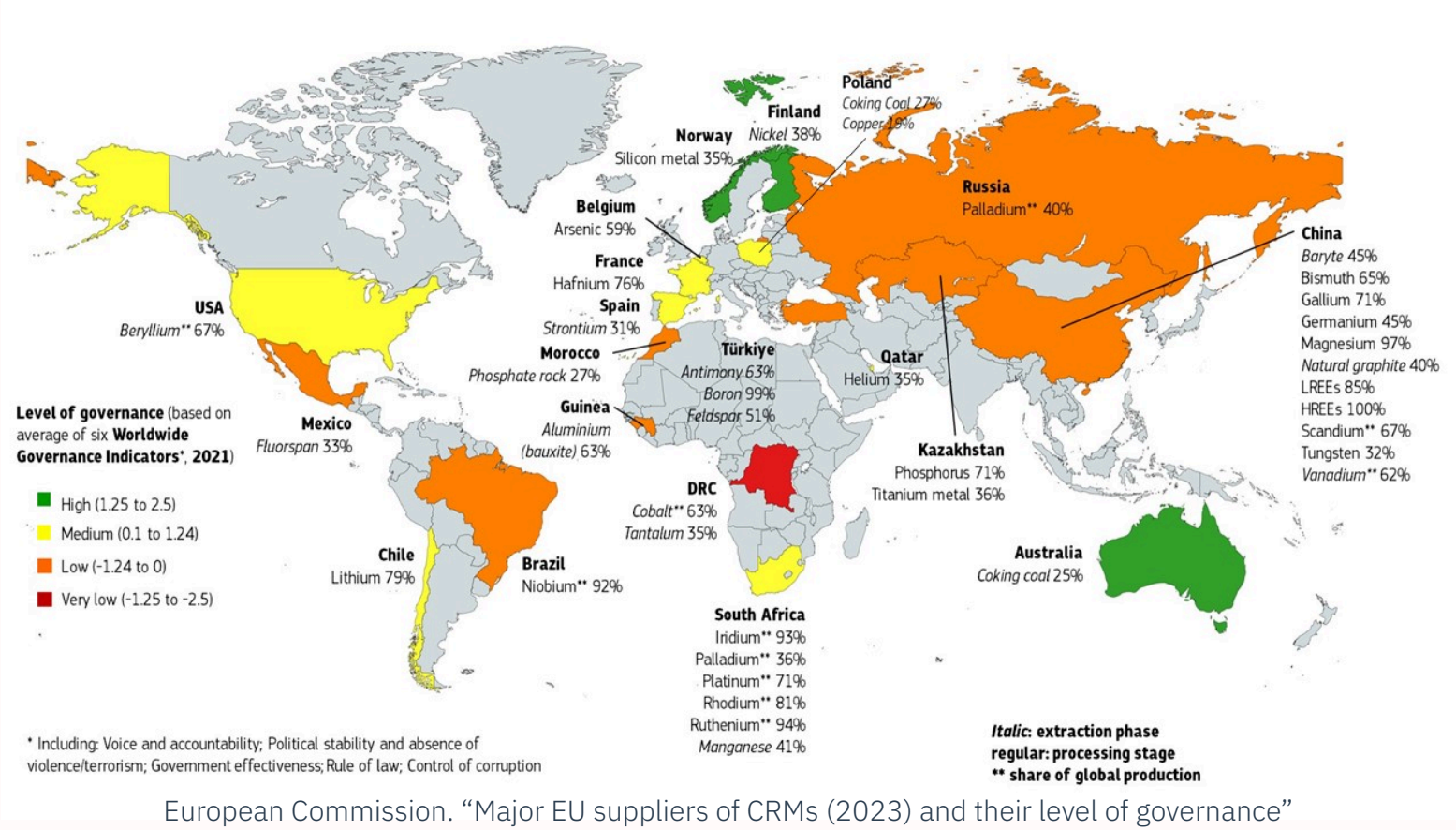
- Strict feature set
- In software development: “maintenance mode”
  - Feature complete, focus on debug & security patches
  - If something radically new is required, new project

Tangential: *requirements engineering*.[52]

[52] https://en.wikipedia.org/wiki/Requirements_engineering

Computing within limits: scarcity

Limits are not only directly related to environmental impacts.



European Commission. "Major EU suppliers of CRMs (2023) and their level of governance"
https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials

Computing within limits: scarcity

Limits are not only directly related to environmental impacts.

- Supply chain disruptions
- Permanent Internet access
- Electricity price
- New regulations (e.g., security)

(Software) design examples:

- Local-first[53]
- Offline-first

[53] Siffre, et al. "Local Computing vs. Cloud Computing: An Empirical Study of Energy Consumption." IEEE/ACM International Conference on Utility and Cloud Computing (2025).

Permacomputing

“Permacomputing”: applying permaculture principles to computing (e.g., durability, care, salvage, appropriate scale).[54]

Similar principles to digital sufficiency/computing within limits (e.g., minimize CPU/RAM/storage/energy budgets by design, offline-first / don’t assume permanent connectivity).

[54] https://permacomputing.net

Permacomputing

But also:

- **Salvage & reuse**: explicitly target existing/obsolete hardware over the newest (also see circular economy & extending product lifetime[55])
- **Stable, open formats**: interoperability/future-proofing (also see Sustainable Interaction Design[56]).

[55] Bakker, et al. "Products that go round: exploring product life extension through design." Journal of Cleaner Production (2014).

[56] Blevis. "Sustainable interaction design: invention & disposal, renewal & reuse." SIGCHI Conference on Human Factors in Computing Systems (2007).

Permacomputing

Design examples:

- **Everything Is A Computer**: “Documenting re-usability of vapes found on the ground”.[57]
- Low-tech Magazine’s **solar-powered website** (goes offline when there is not enough sun in Barcelona).[58]

[57] https://bbs.permacomputing.net/thread/6/%5bdiscuss%5d-documenting-re-usability-of-vapes-found-on-the-ground--8/ & “Repurposing Disposable Vape Batteries: The Why, The How, and the Vape Synth” https://www.youtube.com/watch?v=QmgaqjXy8qE

[58] De Decker. “How to build a low-tech website.” Low-tech Magazine (2018). https://solar.lowtechmagazine.com

Summary: high-level design checklist

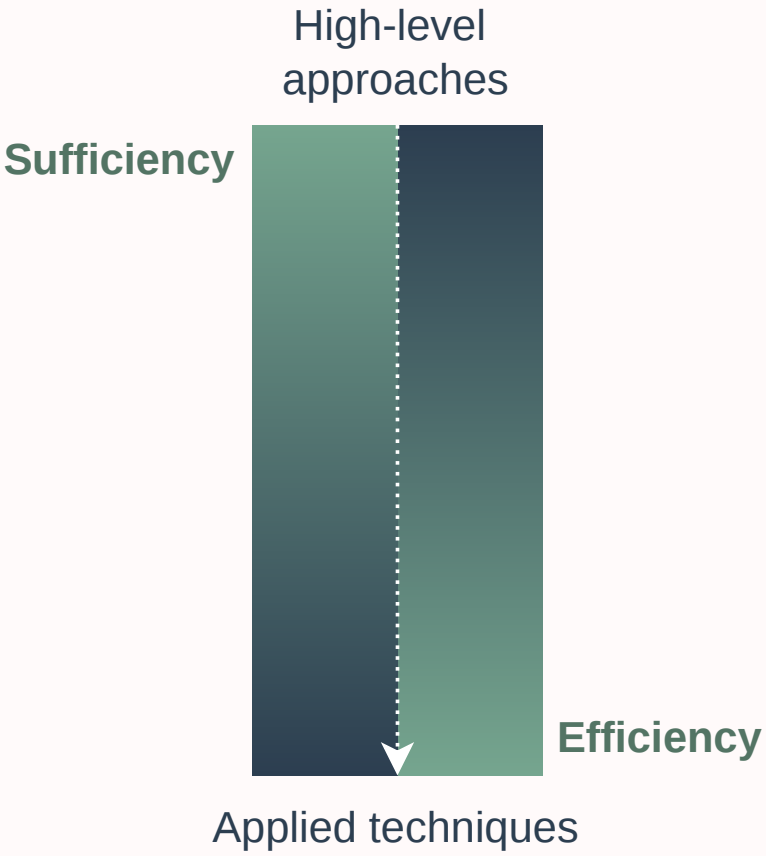
From digital sufficiency & computing within limits:

- Do we need it? (at all, how often)
- How does it relate to growth?
- What will happen when X is not available anymore?
- Do we rely on anti-limit patterns?
- What is the targeted feature set?

From permacomputing & sustainable interaction design:

- What is the lowest-power, oldest hardware this could run on?
- Would that be good enough?
- Can we use / optimize for existing hardware?
- How will it work in a decade?
- Can we somehow extend its lifetime?

Approaches



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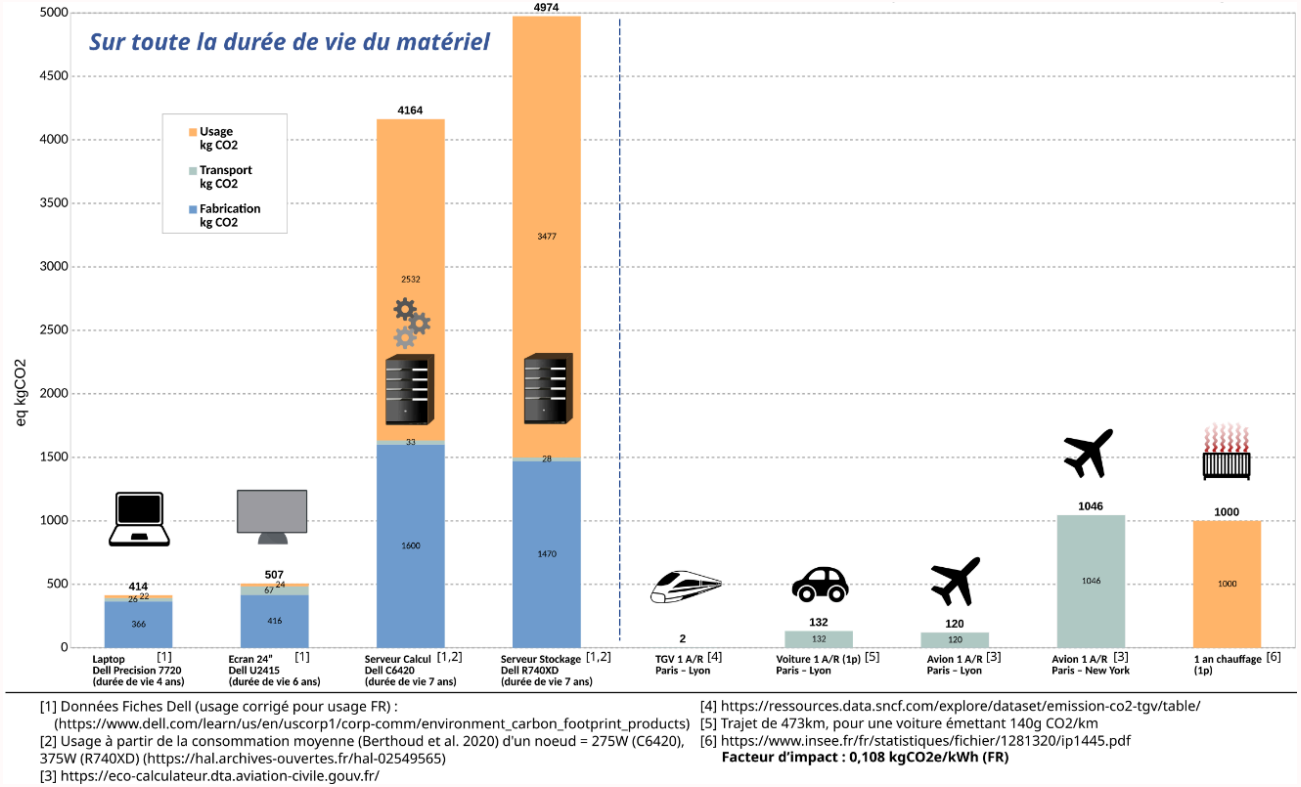
Software eco-design / green software



Jérémy Wambecke, Carole Plasson, and Laurent Bourgès (2020). From: Bonamy et al. “Je code: les bonnes pratiques en éco-conception de service numérique à destination des développeurs de logiciels.” (2022)

Software eco-design

Software eco-design: Engineering choices made throughout the software life cycle (design, development, deployment, maintenance) to reduce its environmental footprint.[59]

Lots of frameworks / guidelines / advice, often targeting (web) digital services with various levels of applicability.

Today, we'll focus on the **RGESN**.

[59] Bonamy, et al. "Je code: les bonnes pratiques en éco-conception de service numérique à destination des développeurs de logiciels." (2022).

Référentiel général d'écoconception de services numériques

RGESN (General Policy Framework for the Ecodesign of Digital Services)[60]

- Motivated by the 2021 "Réduire l'Empreinte Environnementale du Numérique" (REEN) law[61]. Authored by Arcep & Arcom (+ADEME, DINUM, CNIL, and Inria).
- 78 criteria (questions) with priority and (estimated) difficulty of implementation
- 9 thematic categories following the service's life cycle
  - "Strategy", "Specifications", "Architecture", "User experience and user interface (UX/UI)", "Content", "Frontend", "Backend", "Hosting", "Algorithms"

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[60] Arcep, Arcom et al. "Référentiel général d'écoconception de services numériques, version 2024." (2024). 🇫🇷https://ecoresponsable.numerique.gouv.fr/docs/2024/rgesn-mai2024/referentiel_general_ecoconception_des_services_numeriques_version_2024.pdf 🇬🇧https://www.arcom.fr/sites/default/files/2024-05/general_policy_framework_for_the_ecodesign_of_digital_services_version_2024.pdf

[61] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000044327272

RGESN: examples

- Content: 5.3 - Does the digital service use a definition adapted to the content and viewing context for each video?
- Hosting: 8.3 - Does the digital service use a hosting provider with a low PUE (Power Usage Effectiveness)?
- Algorithms: 9.1 - Has the digital service questioned the need for a training phase to avoid unsubstantiated and unreasonable usage?

🇬🇧https://www.arcom.fr/sites/default/files/2024-05/general_policy_framework_for_the_ecodesign_of_digital_services_version_2024.pdf

Other frameworks?

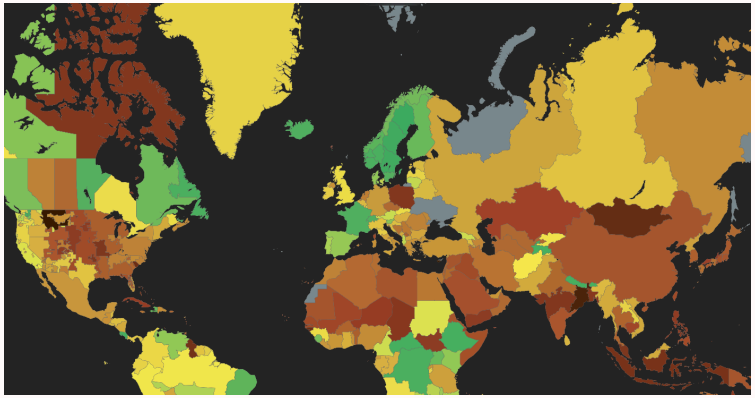
Other more-or-less known examples, citing/inspired by the RGESN:

- W3C's Web Sustainability Guidelines
  https://www.w3.org/TR/web-sustainability-guidelines/ (draft, 2026)
  - Complementary to the RGESN on technical aspects
  - Lacks clear indicators / thresholds
- Green IT Collective's eco-design guidelines, e.g., for the Web
  https://rweb.greenit.fr/en (2025)
  - Complementary & slightly more sexy
  - Less technical information

Carbon-aware computing

Carbon-aware / temporal workload shifting: Scheduling computation for *when* (and *where*) the electricity grid's carbon intensity is lowest, instead of running it immediately/locally by default.[62]

- **Time-shift**: Batch jobs / training runs / CI/CD pipelines are often *not* latency-critical.



- **Location-shift**: pick a data center located in a lower carbon intensity area.

[62] Wiesner, et al. "Let's wait awhile: how temporal workload shifting can reduce carbon emissions in the cloud." Middleware (2021).

Carbon-aware computing

- Already used by big digital companies (e.g., Microsoft[63], Google[64]) for their own workloads
- SDKs[65] and APIs exist for developers[66]

[63] https://news.microsoft.com/de-ch/2023/01/10/carbon-aware-computing-whitepaper/

[64] https://blog.google/innovation-and-ai/infrastructure-and-cloud/global-network/data-centers-work-harder-sun-shines-wind-blows/

[65] https://github.com/Green-Software-Foundation/carbon-aware-sdk

[66] https://app.electricitymaps.com/api/docs/reference

Summary

Green IT / software eco-design:

1. Requires a deep understanding of the technical stack;
   - What's possible? How to implement it optimally? Measure/monitor?
2. Is based on already established engineering practices;
3. Is intimately linked with other technical areas.

Examples:

- **DevOps**: carbon-aware deployments, monitored pipelines;
- **Security**: supply chain, update policies, cryptographic algorithms;
- **Privacy**-by-design: reduce the amount of collected data.

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- **Security**: supply chain, update policies, cryptographic algorithms;
- **Privacy**-by-design: reduce the amount of collected data.

=> We need skilled engineers for all of that. :)

Even more resources
(if the references in the slides were not enough).

Ethics

- 🇫🇷 Hottois. “Éthique de la responsabilité et éthique de la conviction” (1996).
- Comité National Pilote d’Ethique du Numérique. “Opinion 3 - Ethical issues of conversational agents.” (2022). https://www.ccne-ethique.fr/sites/default/files/2022-05/CNPEN%233-ethical_issues_of_conversational_agents.pdf

Sustainability

- Tolentino-Zondervan et al. “Moving cities up the R-ladder of circular economy: Learning from the construction and demolition sector “ (2026).
- Wikipedia. “Issues and problems with the power usage effectiveness” (2026). https://en.wikipedia.org/wiki/Power_usage_effectiveness#Issues_and_problems_with_the_power_usage_effectiveness
- 🇫🇷Valérie d’Acremont. “Santé, Technologies, Environnement : Quels compromis éthiques ?” conférence (2022) https://www.youtube.com/watch?v=oKcy_cY0QOw
- 🇫🇷Mathilde Saliou, interview de Boris Dolley (bureau de l’Open source de RTE). “Écosystème 4/7 : Numérique électrique, numérique responsable” Next (2026). https://next.ink/podcast/rediffusion-ecosysteme-4-7-numerique-electrique-numerique-responsable/