CS4800: Designing Sustainable ICT Systems

Lecture 2: Defining Sustainability

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Lecturer: Przemysław Pawełczak
Authors: Alex Nedelcu, Przemysław Pawełczak

CS4800-EWI@tudelft.nl

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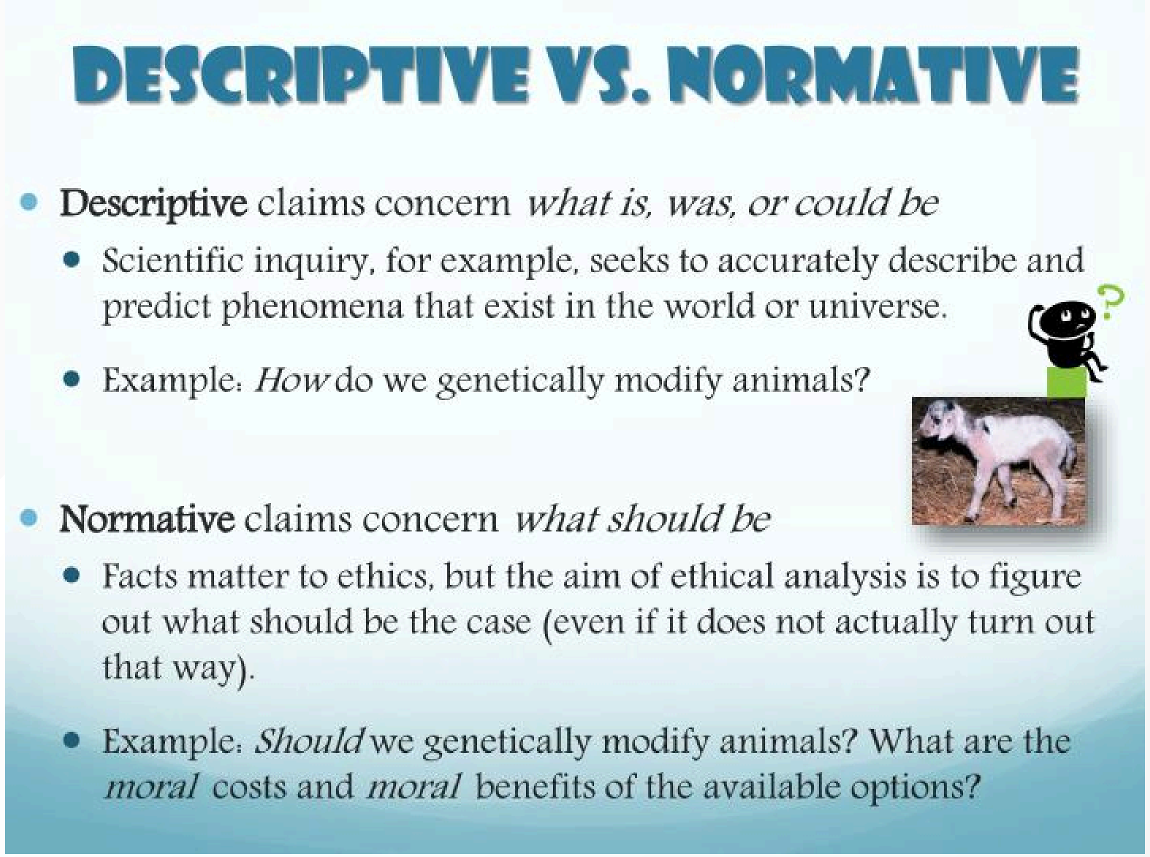
What will you learn in this lecture?

Week 1.2: Defining Sustainability

- Conceptualizing sustainability
- Defining sustainable ICT systems
- Frameworks for sustainability: planetary boundaries, circular economy, digital sufficiency
- Sustainability indicators: global warming potential, emissions reporting, carbon/energy/material/water intensity

Sustainability: history and context

- From Latin *sustinēo* - to uphold, support, maintain, or preserve
- *Silvicultura oeconomica* (1713): long-term responsible use of forest resources
- Normative concept: not how the world is, but how it should be



Descriptive vs normative claims

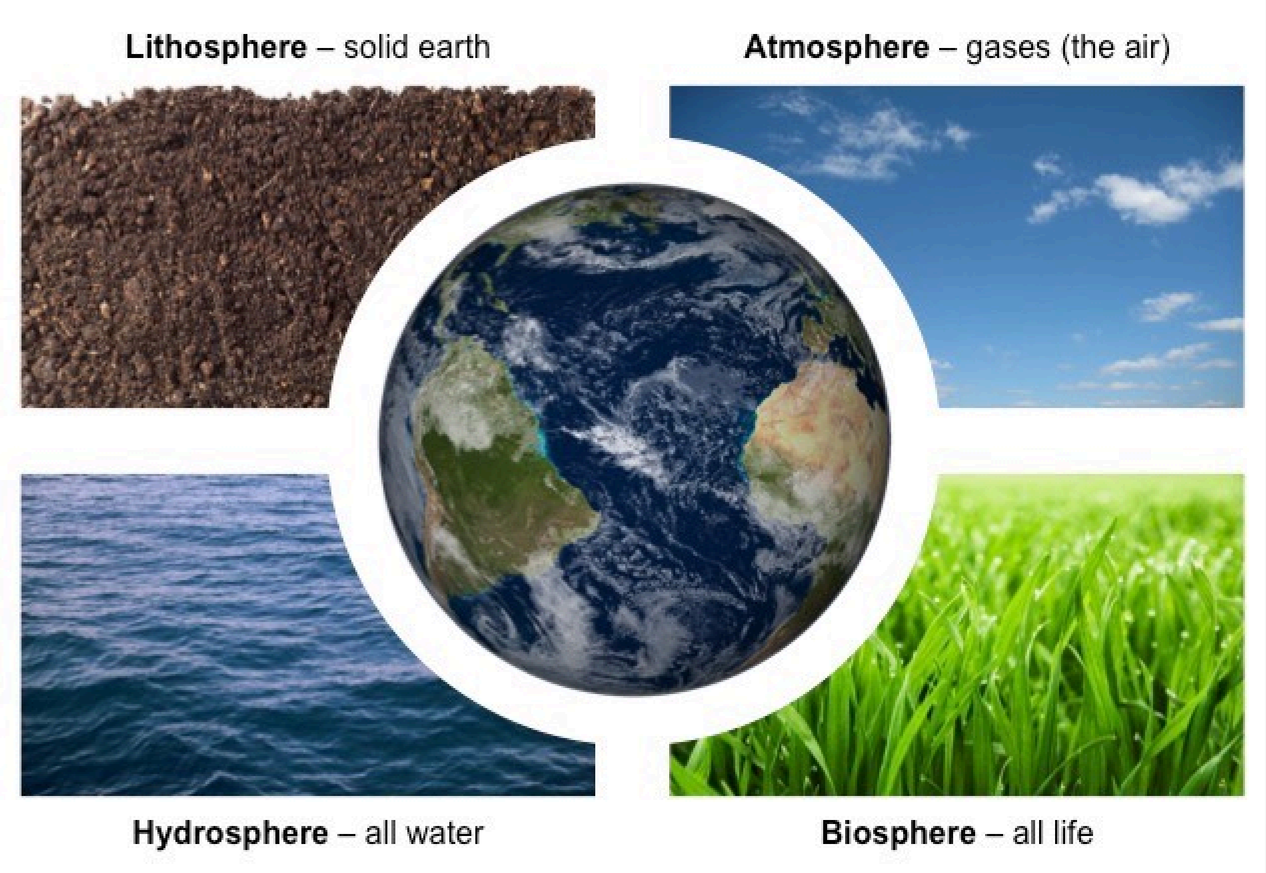
Definitions: sustainable development

- Brundtland Commission (1987): meet the needs of the present without compromising the ability of future generations to meet their own needs
- Natural Step (1989): limit extraction and artificial substances, preserve environment while meeting human needs

Gro Brundtland, Norwegian prime minister and chair of the Brundtland Commission

Definitions: planetary spheres, impacts

1. Atmosphere: greenhouse gas emissions
2. Hydrosphere: over-extraction, nitrogenation
3. Pedosphere: industrial agriculture
4. Lithosphere: over-mining
5. Biosphere: habitat loss
6. Anthroposphere: debt burden



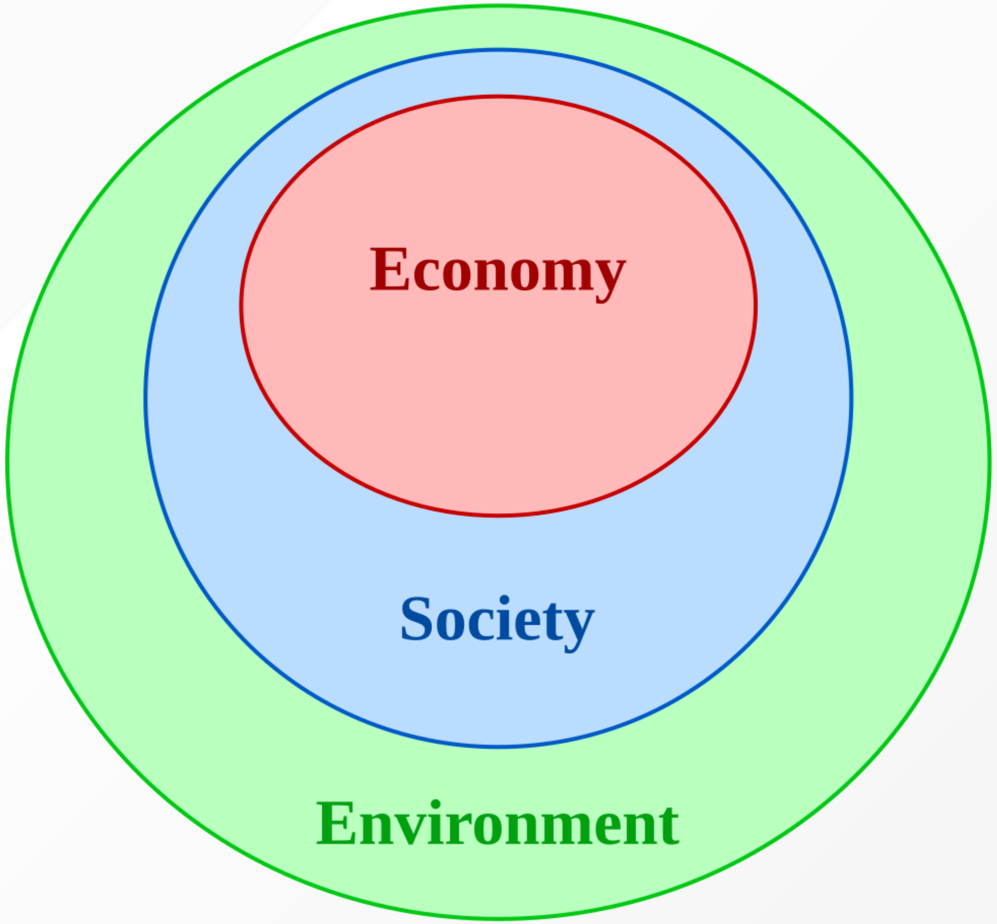
Four recognized planetary spheres

Definitions: dimensions of sustainability

Rio Declaration (1992): three dimensions (environmental, social, economic)

1. **Environmental**: stewardship of natural resources for future generations
2. **Social**: ability of society to continue existing without structural obstacles
3. **Economic**: policies that support long-term viability without present-day damage

Hierarchy: environmental sustainability overarching → we will focus on it when we talk about sustainability



Hierarchy of the dimensions of sustainability

Defining sustainable ICT systems

Aspects shared by previous definitions:

1. Sustainability is an objective to be reached
2. Sustainability involves the protection of the planetary system
3. Sustainability involves judicious use of resources

-> **Sustainable ICT systems minimize impact on natural resources while meeting societal needs**

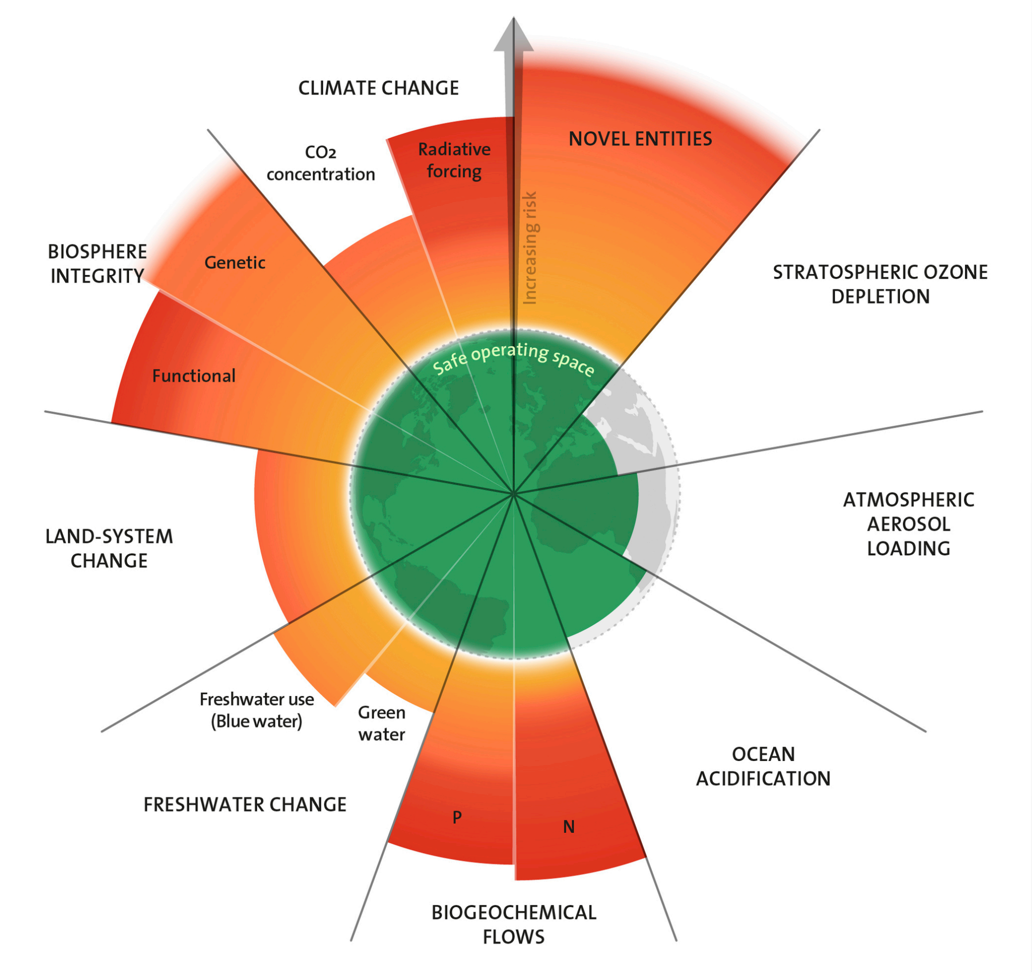
Hacker voice: I'm in

What frameworks can we use to think about sustainability?

Planetary boundaries

Stockholm Resilience Centre (2009): safe limits for human pressure on critical processes

1. Climate change: 429.64 ppm CO_2
2. Biosphere integrity
3. Ocean acidification
4. Nitrogen, phosphorus flows
5. Freshwater change
6. Land system change
7. Stratospheric ozone depletion
8. Atmospheric aerosol loading
9. Novel entities: e.g. microplastics



Quantifying human pressures on each planetary boundary

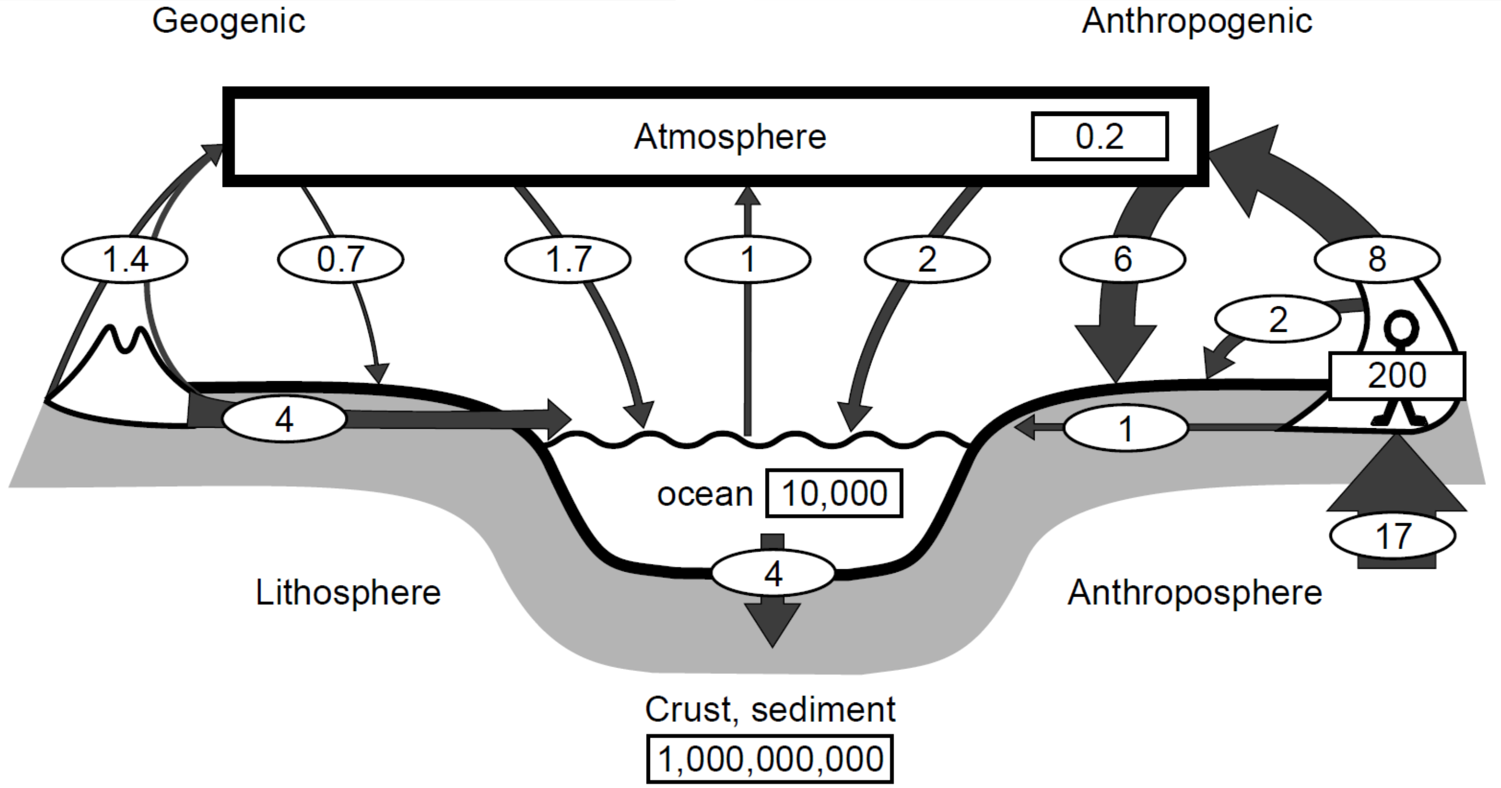
Precautionary principle

- Complex planetary system → great uncertainties in calculating exact limits
- Rio Declaration (1992): if we risk serious damage, insufficient certainty is not a reason to delay preventive measures

Burden of proof vs precautionary principle reasoning

Tools: material flow analysis

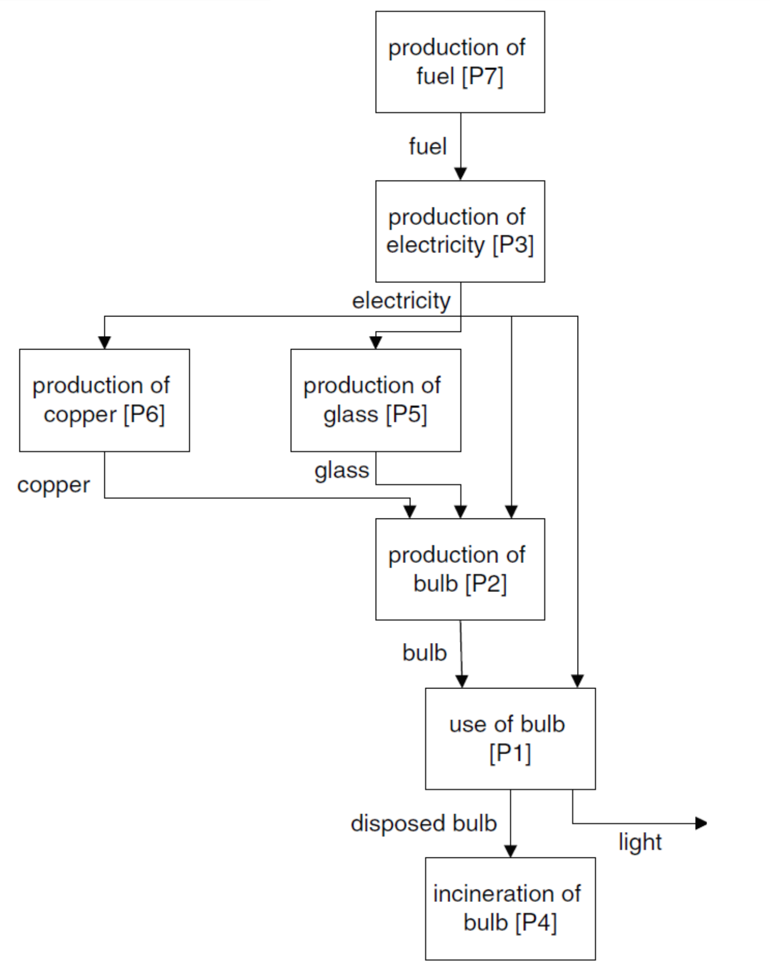
- Developed to measure physical impact of human society on natural systems
- Calculates how individual substances (C, N, P) or materials (steel, plastics) travel through world
- Systematic [assessment](#) of stocks and flows



Example: global cadmium stocks and flows in the 1980's in kilotons - note human-made flows on the right

Tools: lifecycle analysis

- Environmental footprint: total human pressure on natural environment
- Individual product footprint: calculated through lifecycle analysis
- Environmental impact calculated for every activity: materials sourcing, manufacturing, distribution, decommissioning etc



Example: flowchart of incandescent lightbulb lifecycle

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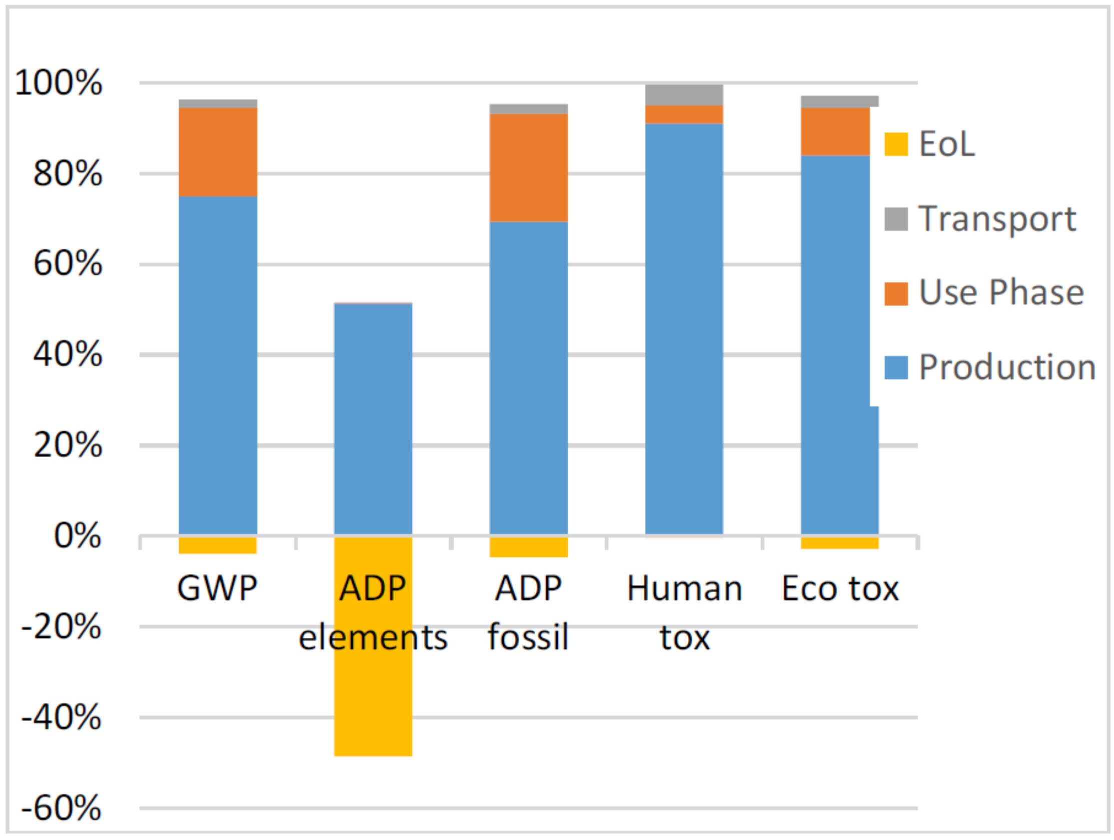
Example: Fairphone LCA

External contractor quantified product's environmental footprint over impact categories:

1. Climate change (GDP)
2. Material use (ADP elements)
3. Fossil fuel use (ADP fossil)
4. Human toxicity (Human tox)
5. Environmental toxicity (Eco tox)

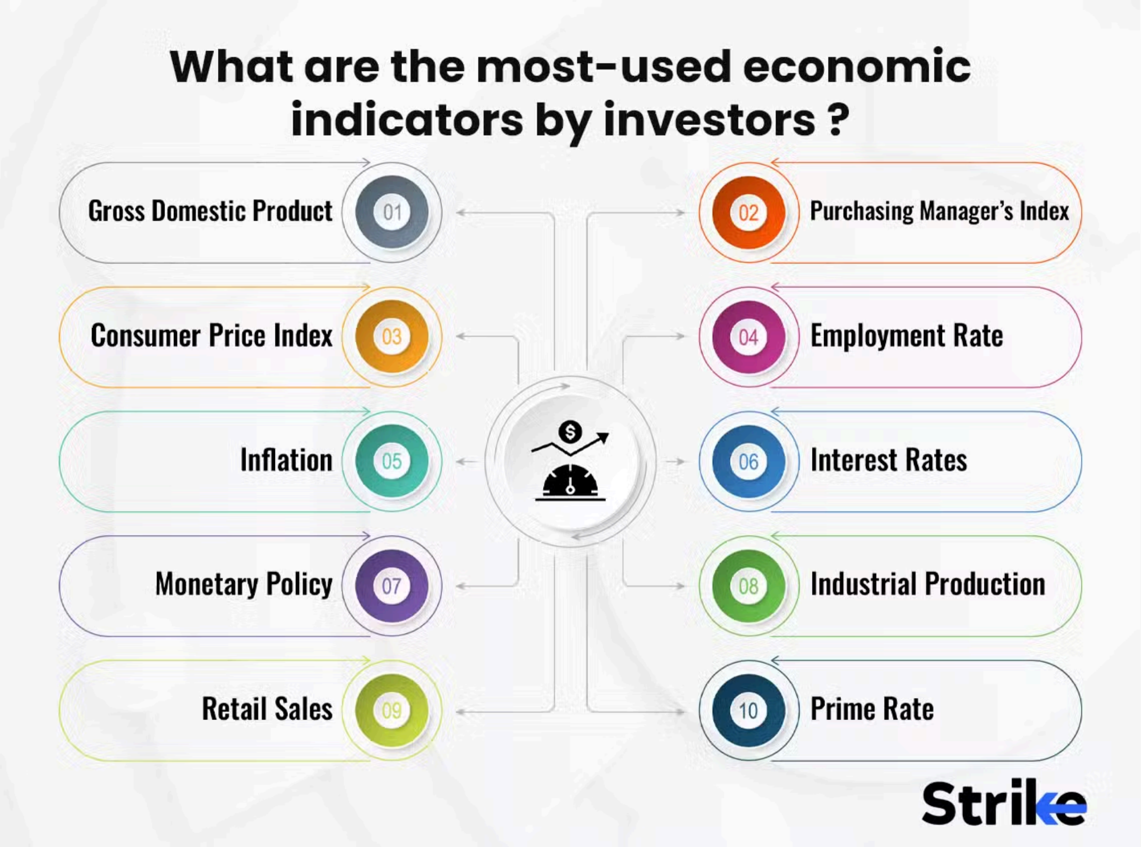
Highest impact observed during production phase, distributed across components



Relative impact (as percent of total) for each lifecyle phase on various impact categories

Sustainability indicators

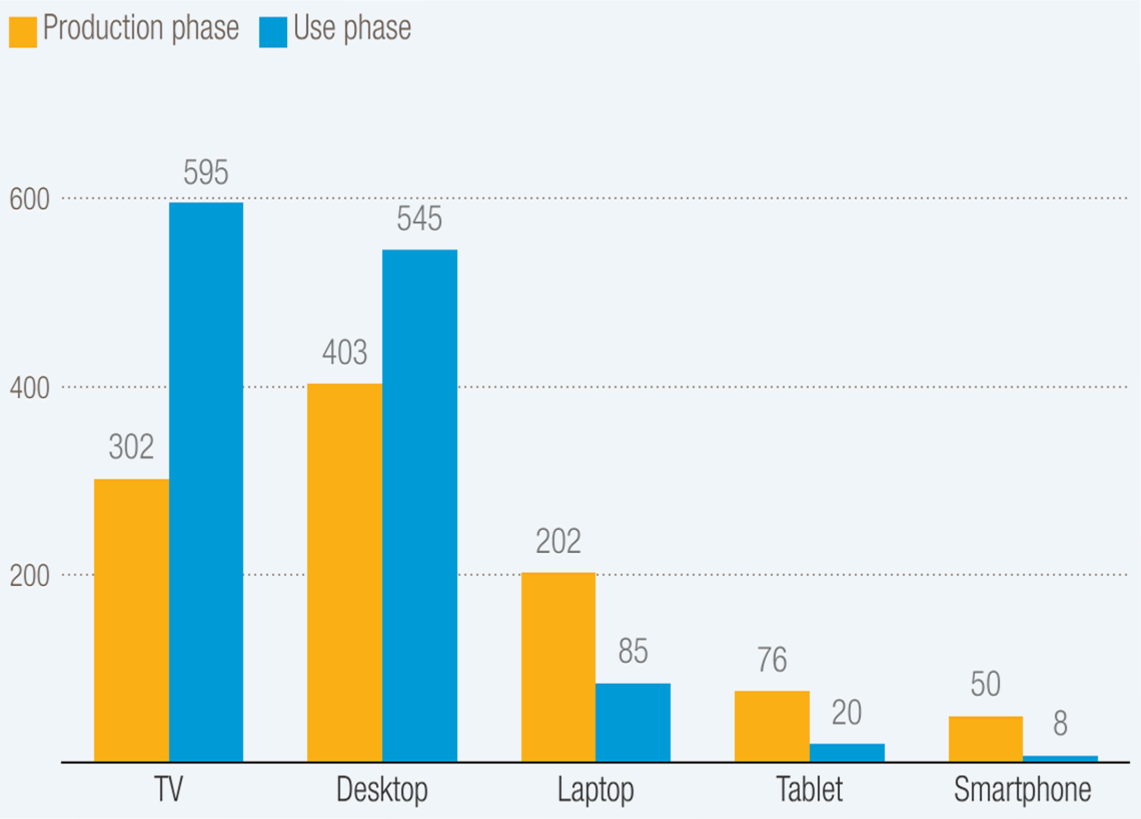
- No universal standard for studying sustainability
- Competing indicators developed
- Indicator: quantitative/qualitative measure of how close we are to a target



Various economic indicators

Sustainability indicators: global warming potential

- Global warming potential: multiple of warming caused by same mass of CO_2 (GWP=1)
- Use GWP to calculate mass of CO_2 that would warm the planet as much as the mass of studied gas: CO_2-eq
- Use CO_2-eq to calculate carbon intensity: impact of a unit of product or service on climate change



Average lifecycle emissions of electronic devices in kg CO_2-eq

Carbon accounting

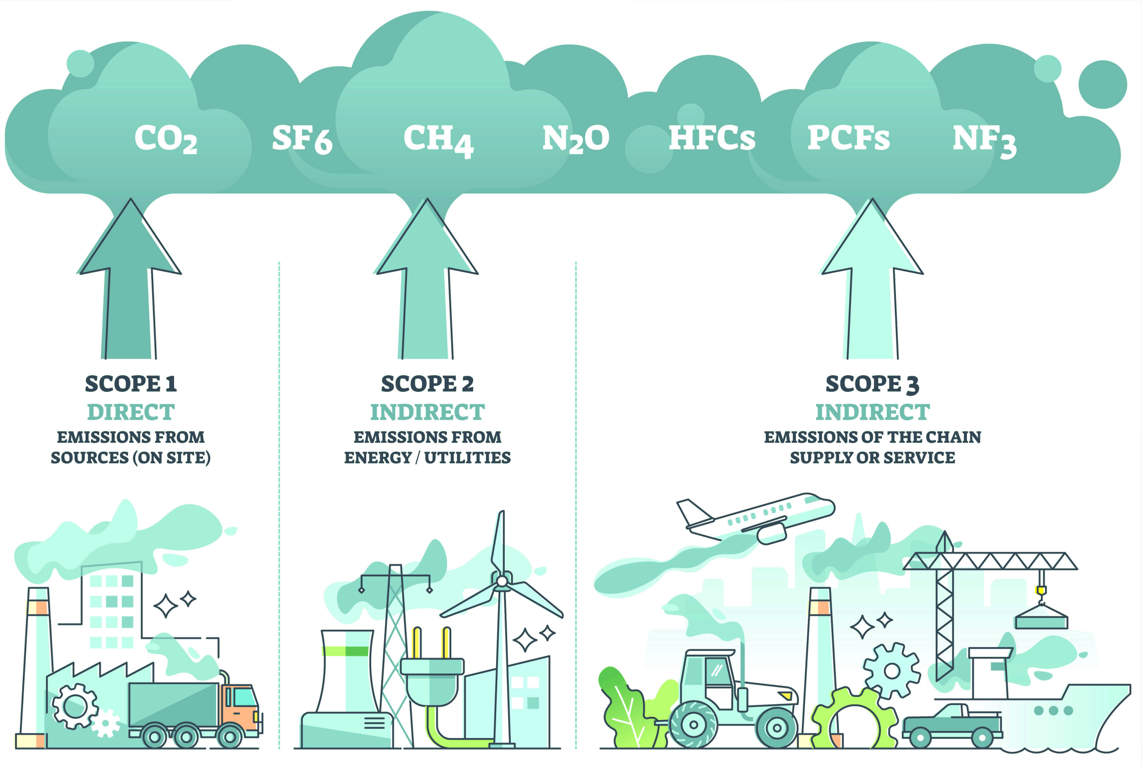
- Tracks an organization's carbon emissions
- National (US, NL) and international (EU ETS) monitoring and reporting

- GHG Protocol: define organizational boundary, then apply scopes:

  Scope 1: sources owned/controlled by company

  Scope 2: energy consumed by company

  Scope 3: indirect emissions, upstream (e.g. manufacturing of goods purchased by company) or downstream (e.g. decommissioning goods sold by company)



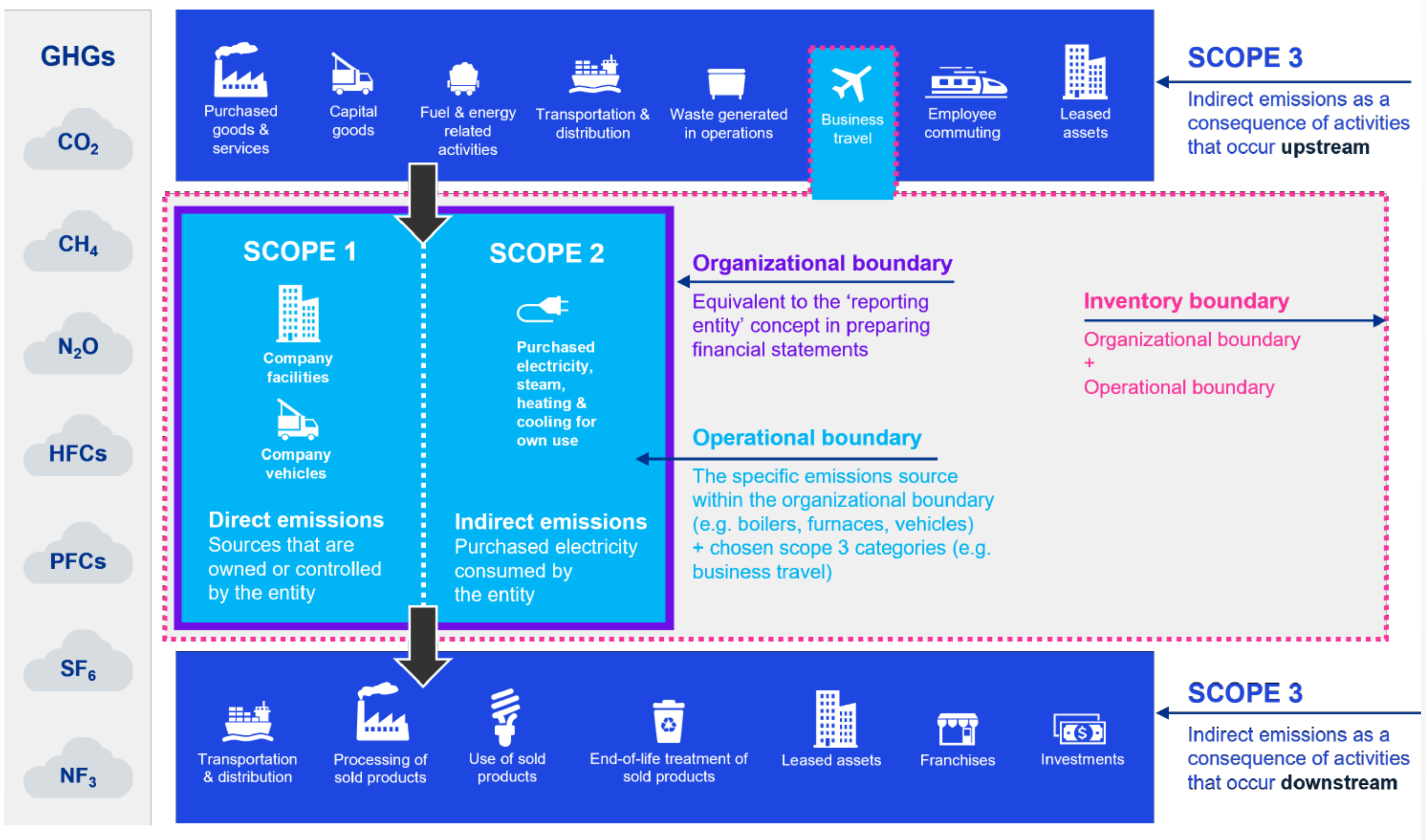
Scope 1, 2, and 3 emissions

Carbon accounting: GHG inventory

- Total emissions for each scope: multiply activities by carbon intensity:

$$CO_2eq = \text{Activity} \cdot \text{Carbon intensity} \cdot \text{GWP}$$

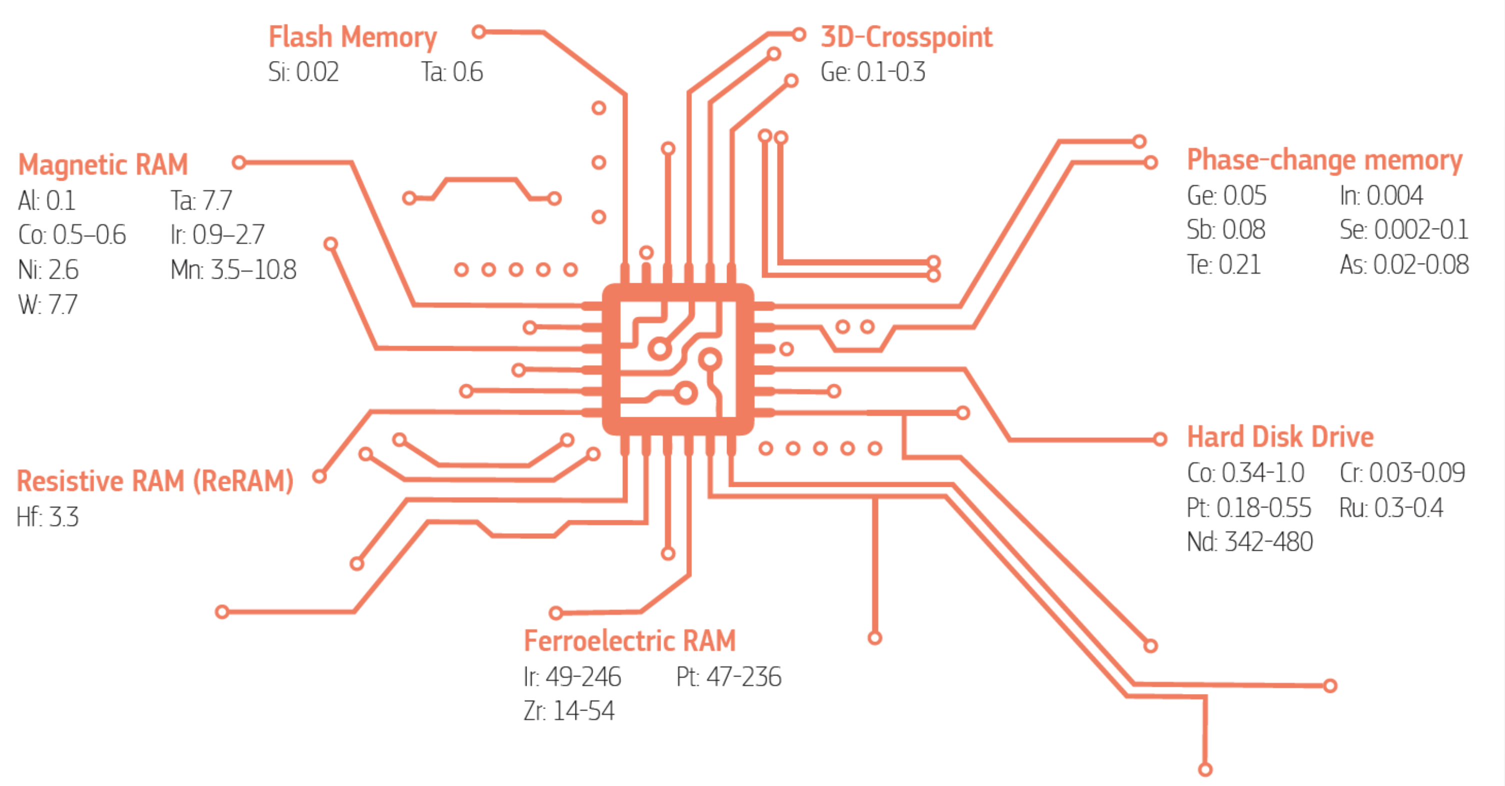
- Emissions data placed in company GHG inventory
- Calculations not always precise: data uncertainty, standard carbon intensity factors, (rarely) malicious underreporting



Organizational boundary and emissions scopes

Sustainability indicators: material intensity

- EU 3rd Raw Materials Scoreboard: total historical global material use (biomass, fossil fuels, metal ores, non-metallic minerals) has exceeded 90 billion tons
- Critical raw materials: supply risk, economic importance
- Significant increase in material use for ICT projected: Pt, Nd, Co, Rb, Cr, Se

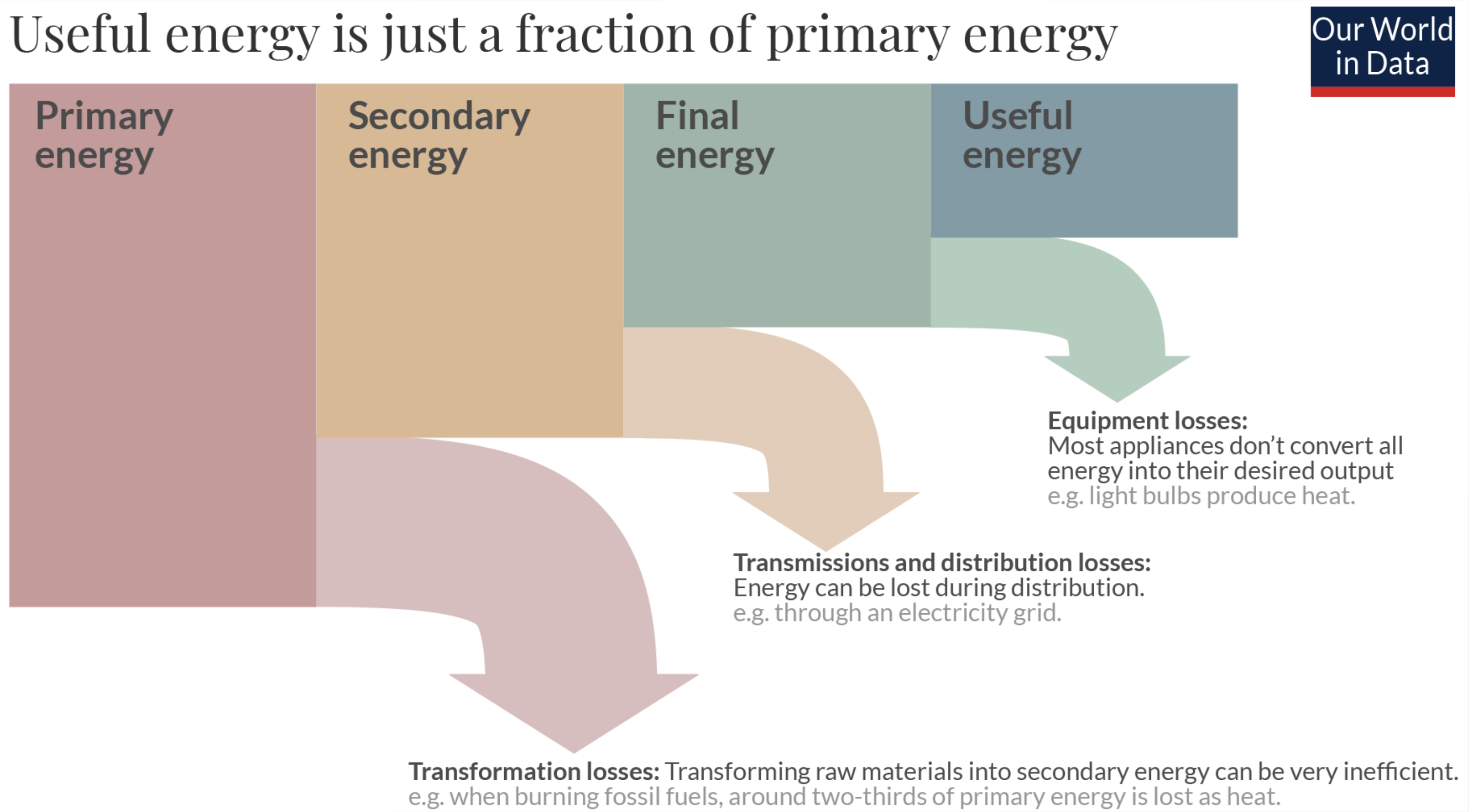


Material intensity for memory technologies (tons/zettabyte)

Sustainability indicators: energy intensity

1. **Primary energy**: found in nature, e.g. chemical energy in coal or oil
2. **Secondary energy**: transportable, e.g. electricity, liquid fuels
3. **Final energy**: used by consumer
4. **Useful energy**: actually used for desired output, e.g. light from lamp

-> (Primary) energy intensity: energy required per unit of product/service



Differentiating primary, secondary, final, and useful energy

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Sustainability indicators: water intensity

- All life needs water to exist
- Various indicators used to calculate impact of human system on hydrosphere
- Water intensity: water consumed per unit of product/service
- Not all water used by a process is consumed! Some can be returned as grey water

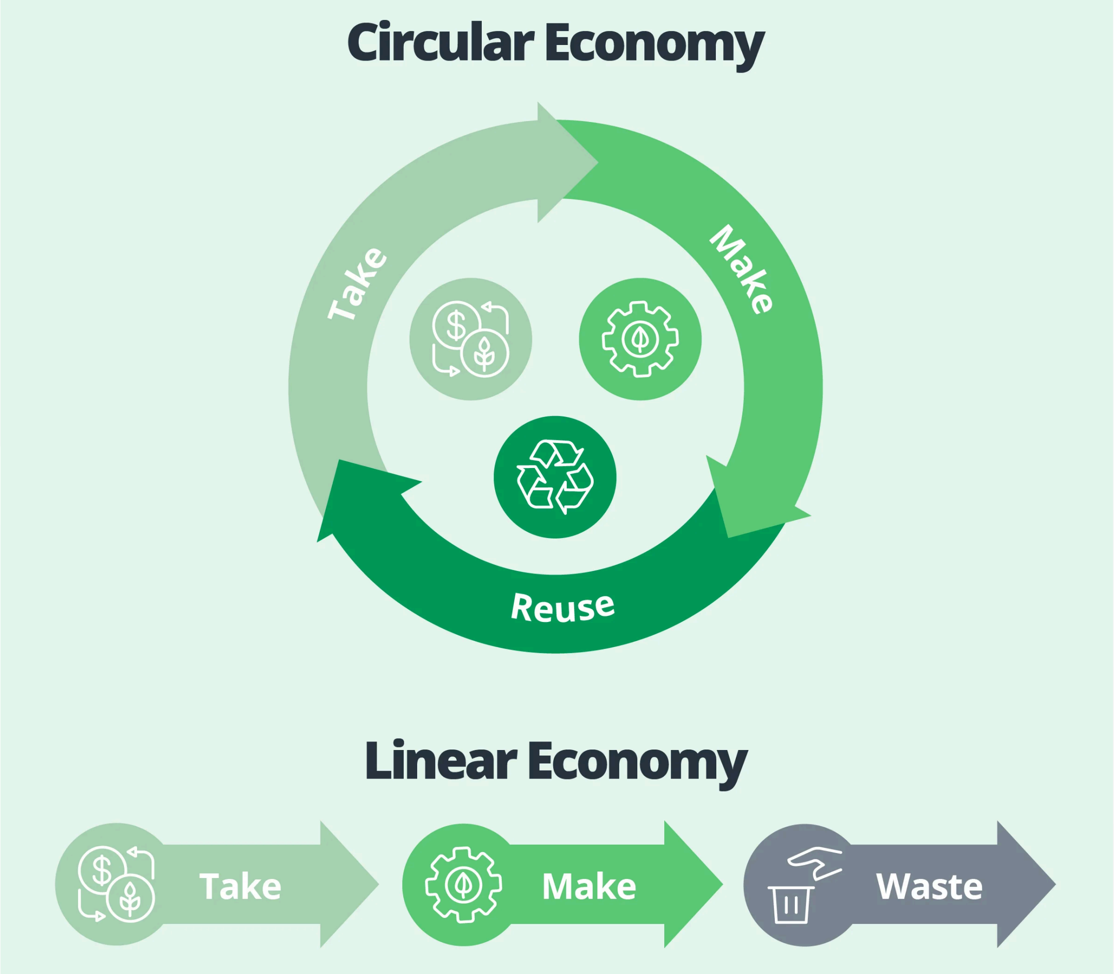
Water footprint of various food products

Sustainability indicators: others

- Various others indicators developed to quantify human interventions in natural systems: e.g. biodiversity, ocean acidification
- Not directly relevant to ICT systems

Circular economy: definitions

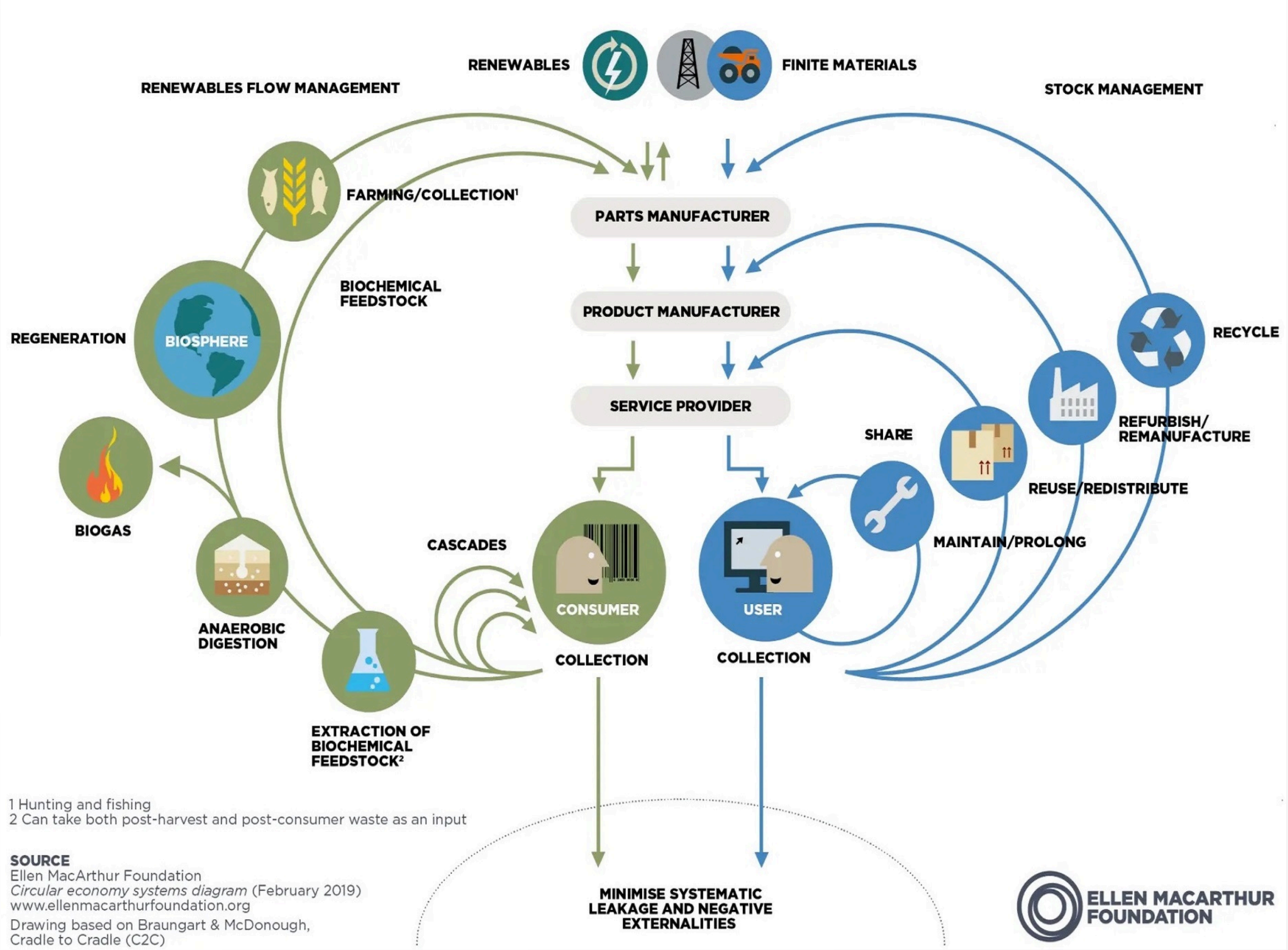
- No universally-accepted definition
- Ellen MacArthur Foundation: economic system with closed loop products/services, allows for long life, reuse, refurbishment, repair, recycling
- China: generic term for reducing, reusing and recycling activities conducted in process of production, circulation and consumption
- Contrast with linear economy: resources processed into products, eventually waste ("take, make, waste")



Circular vs linear economy

Circular economy: principles

- Butterfly diagram: closed loop economy
- Nine R's: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover
- Deliberate, reflective design applied to products
- Produce fewer products? What about manufacturing jobs?
- Still aims for economic growth! What about energy coupling?



Butterfly diagram of the circular economy

Circular economy: decoupling, rebound effects

- Reducing material, energy intensity of products → cost goes down
- Cost goes down → more products can be purchased with same income
- More products purchased → total impacts may actually increase!

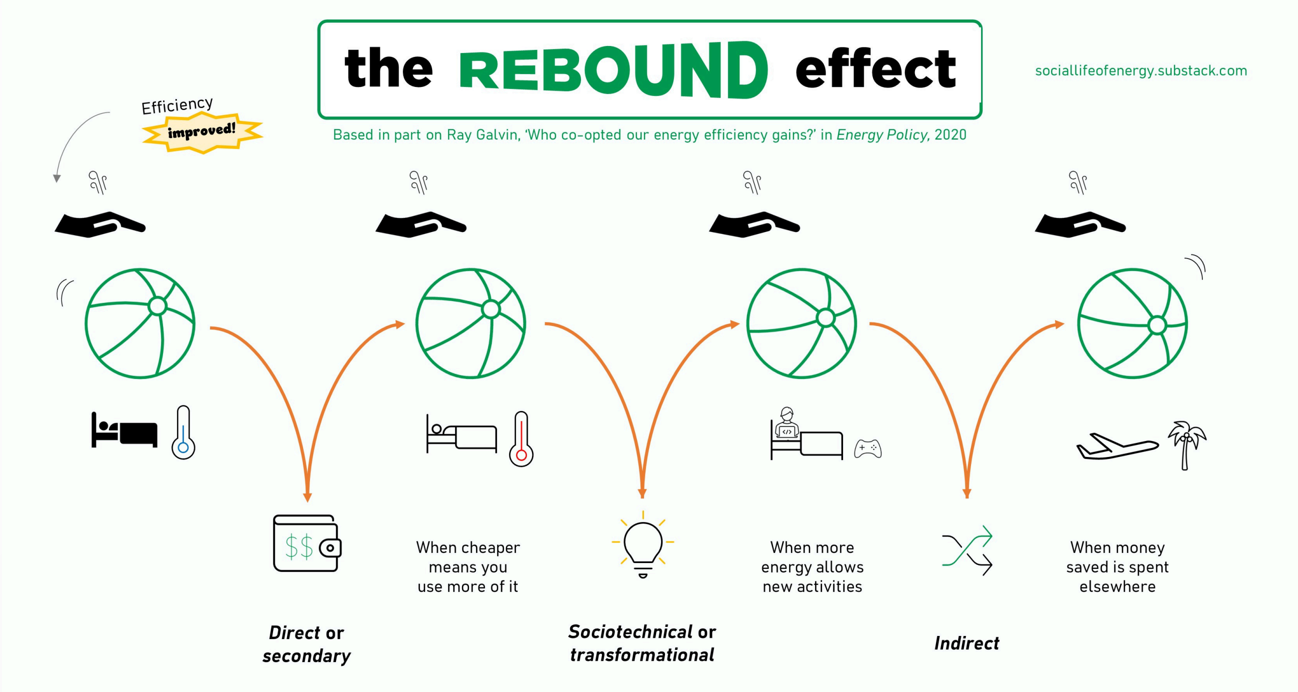


Illustration of the rebound effect

Digital sufficiency: introduction

Comprehensive framework for reducing ICT impacts:

1. *Consistency:* doing things better, avoiding waste
2. *Efficiency:* doing more with less, reducing intensity
3. *Sufficiency*: reducing total resource demand while maintaining performance

[Digital sufficiency](#) aims to directly or indirectly decrease the absolute level of resource and energy demand from the production or application of ICT.

Digital sufficiency: types of impacts

Taxonomy of ICT environmental impacts:

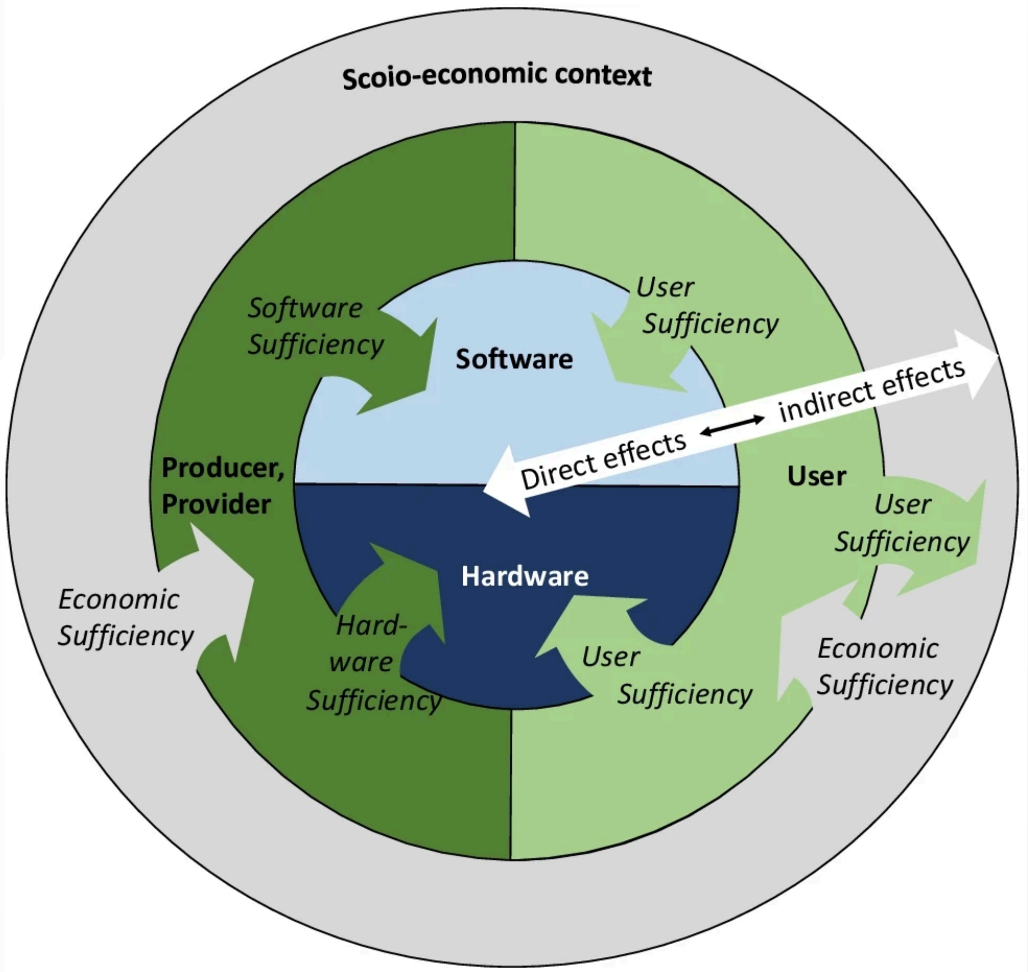
- **Direct effects**: resource extraction, insufficient environmental standards
- **Indirect effects**: increase in data volume eating up efficiency gains (e.g. 3G → 5G)
- **Indirect effects**: application of ICT systems has improved efficiency in other sectors
- **Induction effects**: new opportunities for production and consumption opened, additional resource demands generated

Overall impact complex: economic growth and affluence, but also environmental degradation!

Digital sufficiency: dimensions

Four dimensions of digital sufficiency:

1. Hardware: producing fewer, longer-lasting devices, which have minimum resource demand for their job
2. Software: reducing data volume and traffic, demand for computing power
3. User: frugal use of ICT, devices enable more sustainable lifestyle
4. Economic: use of ICT should improve living conditions, not necessarily economic growth



Dimensions of digital sufficiency

Sustainability frameworks and ICT systems

We apply these principles in the lectures to follow:

1. Estimating energy intensity of software (including AI), designing efficient software
2. Evaluating data center energy/carbon/water footprint
3. Studying material intensity of electronics, designing sufficient electronics

Sustainability frameworks allow us to quantify both ICT impacts and mitigation efforts!

Recap

- Sustainable ICT systems minimize environmental impacts while meeting societal needs
- Planetary boundaries set limits for human activities, uncertainty does not warrant inaction
- MFA, LCA, indicators used to quantify environmental impact of human activities
- Circular economy is part of the solution, but vulnerable to rebound effects
- Digital sufficiency comprehensively targets all levels of ICT environmental impacts

Exam(ple) questions

1. **In the lifecycle analysis of an electronic device (e.g. a phone), which phase usually has the highest environmental footprint?**
   a. Production
   b. Transport
   c. Use
   d. End of life

2. **Methane has a GWP of 20. A certain data center consumes 0.3kWh per unit of compute, and is powered by a power plant that emits 1kg of methane and 10kg of CO_2 per kWh produced. What is the carbon intensity of the data center in kgCO2-eq/compute?**
   a. 3kgCO2-eq/compute
   b. 6kgCO2-eq/compute
   c. 9kgCO2-eq/compute
   d. 20kgCO2-eq/compute

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   a. Production
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   ~~a. 3kgCO2-eq/compute~~
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   c. 9kgCO2-eq/compute
   ~~d. 20kgCO2-eq/compute~~

Feedback

- This is the first edition of the course - we need your feedback!
- Feedback on Lecture 2 slides/notes:

Announcements

- Project groups formed, one-person groups will be consolidated
- Tomorrow, 15:45-17:30: assignment 'office hours', we are available online for problems, ideas, or feedback
- Midterm presentation (mandatory, ungraded): formative assessment, expect feedback
  - Thursday, October 2, 15:45, EEMCS Hall G
  - Slides: introduction, chosen topic, group progress
- Final presentation (mandatory, graded):
  - Friday, October 24, 15:45-17:45, EEMCS Hall G
  - Format to follow
- Trying to switch Lecture 4 (Sustainable Cloud Computing) with Lecture 5 (Sustainable AI) to help groups with Sustainable AI assignment

Thank you for your attention!

Next lecture: Sustainable Software

Thursday, September 18, 15:45-17:30, EEMCS Hall F

- Sustainable software: concept, origins, landscape
- Experimental assessment of software energy efficiency
- Software development practices, impact on sustainability
- Energy efficiency differences across programming languages

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Questions?