1. Sustainability Concepts

Date	@September 2, 2025
Status	In progress

Video Lectures

1. What is sustainability?
2. How can we coordinate globally such a varied concept?
3. A framework to measure sustainability
4. Sustainable Development Goals and influence on companies

Extra - Links

https://unstats.un.org/sdgs/dataportal - SGD

https://databank.worldbank.org/source/sustainable-development-goals-(sdgs) - databank sgd

https://github.com/sdga2023 - world bank sgd

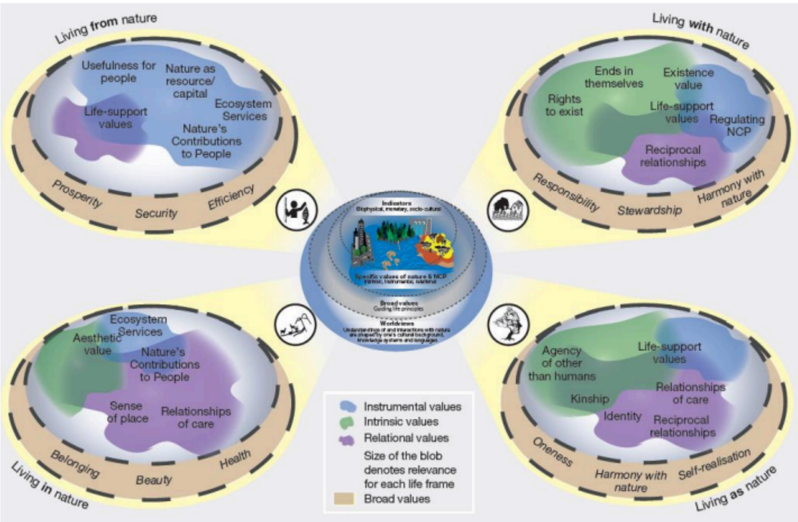
https://www.nature.com/articles/s41586-023-06406-9 - **Diverse values of nature for sustainability**

https://cdnapisec.kaltura.com/p/2503451/embedPlaykitJs/uiconf_id/47917953?iframeembed=true&playerId=kVideoTarget&entry_id=1_v5z5sj1k&flashvars[streamerType]=auto&v2Redirect=true&v2Redirecttranslate=true - rio declaration documentary

https://youtu.be/a1pdAO62bH0 - glimpse into draft ERSR 1 general requirements

https://www.nature.com/articles/s41893-019-0231-4 - **Income-based variation in Sustainable Development Goal interaction networks**

https://youtu.be/alVL89I-o5k - hoow will we know the sgd have succeeded in 2030



- "Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature."
- "The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations."
- "In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it."

Rio Declaration 1992

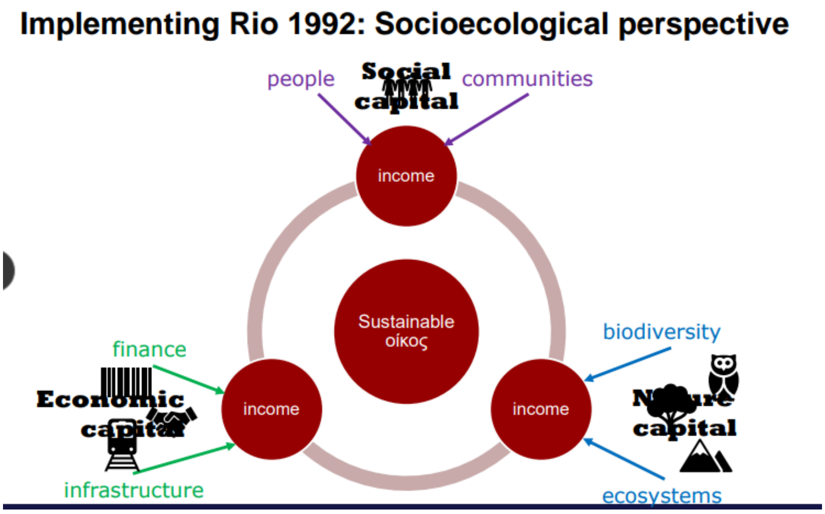
- "Human beings are at the centre of concerns for sustainable development..."
- "...equitably meet developmental and environmental needs of present and future generations."
- "... environmental protection shall constitute an integral part of the development process...."

What is at the origin of nowadays SDGs?
The modern sustainability concept emerged from interactions between economic development & environmentalism

- Consensus I: 1972 Stockholm Declaration
    - Our activities (particularly industrialization) are having an impact on the global environment
    - We need to assess the impact of our activities and manage them
- Consensus II: 1992 Rio Declaration
    - Reconcile Stockholm declaration with economic development & UDHR
    - needed for global security
    - needed to adhere to Universal Human Rights

Universal Declaration of Human Rights (1948)

- Article 1 – All human beings are born free and equal in dignity and rights.
- Article 2 – Everyone is entitled to all the rights and freedoms set forth in this Declaration, without distinction of any kind.
- Article 25 - Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family.



2. Life Cycle

Date	@September 9, 2025
Status	Done

Read the articles:

Additionally, you must read two articles. One scientific article Enhancing the practical implementation of life cycle sustainability assessment - proposal of a Tiered approach. In the tiered approach, you expand your efforts and data requirements through three tiers. Sustainability indicators for each tier are suggested.

The second, Environmental improvement through product development - a guide, is a suggestion for a simple approach to assess environmental sustainability of products. Read step 1 to step 3 i.e. pages 10-23.

More literature can be found under Supplementary literature

Study the self assessment:

After watching the video lectures and reading the articles, you should study the Self-assessment about life cycle approach..

Teaching session:

In the teaching sessions we will study an exercise about life cycle approach.

You will also test the assessment framework in a qualitative way. And finally, if not already done, finalize the group contract where you agree on the process for your group work.

IPAT (Conceptual frameworks)

- **Tema**: Modelo conceptual da sustentabilidade e impacto ambiental.
- **Fórmula central (IPAT)**:I=P·A·T

  I=P·A·TI = P \cdot A \cdot T

  Onde:
  - III = impacto ambiental
  - PPP = população
  - AAA = afluência (consumo per capita, ex: GDP/person)
  - TTT = tecnologia (impacto por unidade de valor económico)
- **Key points**:
  - População global está a crescer.
  - Afluência (consumo per capita) também cresce → maior pressão ambiental.
  - Para reduzir impacto total, **T** tem de melhorar (eficiência) por um fator de 4–20!
  - **Rebound effect**: maior eficiência → menor custo → pode aumentar o consumo.
  - Conclusão: não chega apenas inovar em tecnologia, é preciso gerir também consumo/demanda.
- **Takeaways**:
  - Impactos são causados principalmente por consumo humano.
  - Tecnologia ajuda, mas limites planetários exigem mudanças em estilos de vida e padrões de consumo.

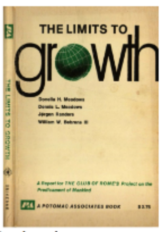
$$I = P \cdot A \cdot T = Pop \cdot \frac{GDP}{person} \cdot \frac{I}{GDP}$$

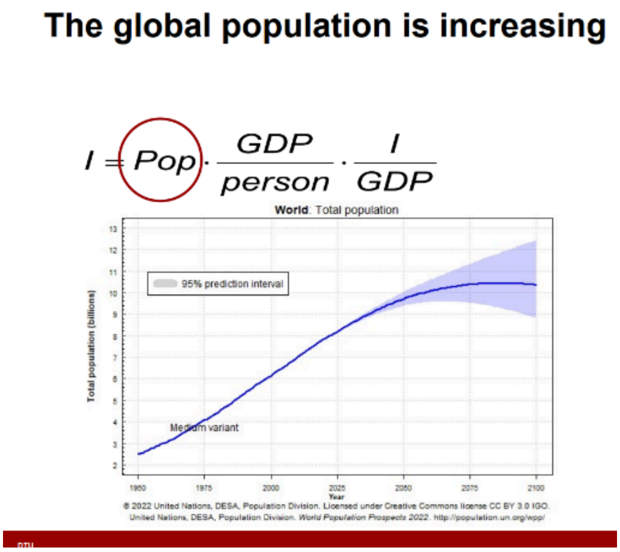
- I is the environmental impact
- *Pop* is the **global population**
- $\frac{GDP}{person}$ is the **Affluence**, the material standard of living
- $\frac{I}{GDP}$ is the **Technology factor** – environmental impact per created value

Ehrlich P, Holdren J (1971) Impact of population growth. Science 171, pp. 1212–1217.

Commoner B (1972) The environmental cost of economic growth. In Ridker RG (ed.) Population, Resources and the Environment, pp. 339- 63. U.S. Government Printing Office, Washington, DC.

Graedel and Allenby (1995) Industrial ecology. Prentice Hall, New Jersey.





The formula

$$I = Pop \cdot \frac{GDP}{person} \cdot \frac{I}{GDP}$$

Where:

- **I** = total environmental impact
- **Pop** = population size
- GDPperson\frac{GDP}{person}personGDP = **affluence** (consumption per capita, a measure of material standard of living)
- IGDP\frac{I}{GDP}GDPI = **technology factor** (impact per unit of economic output → how efficient/clean technology is)

Meaning

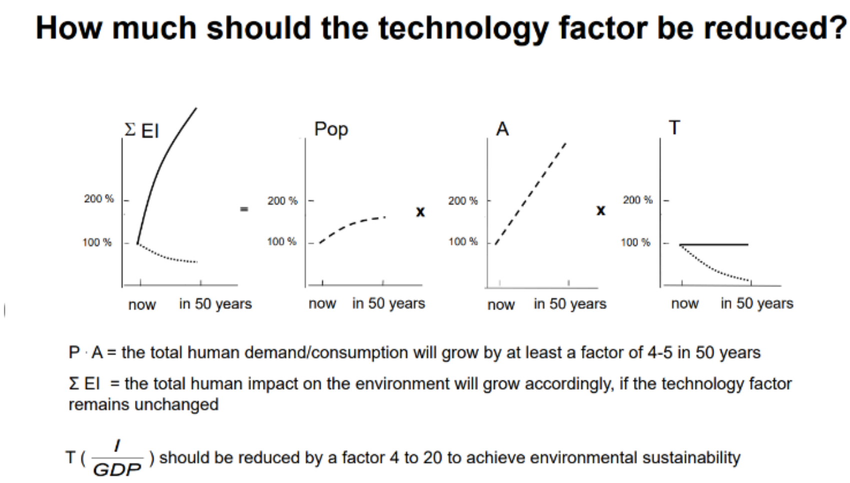
- As **population (Pop)** increases, the *baseline demand* rises.
- As **affluence (GDP/person)** rises, people consume more goods/services → more impact.
- Only by reducing the **impact per GDP unit** (better technology, cleaner production, efficiency gains) can total impact **I** be stabilized or reduced.

📈 **The graph**

- Shows **world population growth** from ~1950 to projections until 2100.
- Medium variant (blue line) suggests growth from ~2.5 billion in 1950 to ~10.5 billion mid-century, then leveling off.
- The shaded band = **95% prediction interval**, reflecting uncertainty (could be lower ~8.8 billion or higher ~12.4 billion by 2100).

🚨 **Implication**

- Even if technology improves, **population growth alone** pushes environmental impacts upward.
- When combined with rising affluence (people consuming more per capita), the pressure multiplies.
- To meet sustainability goals, the **technology factor (I/GDP)** must shrink massively (cleaner, more efficient tech, circular economy).



The logic

$$I = P \cdot A \cdot T$$

- **P (Population):** still growing, though slower → in ~50 years, +50% compared to now.
- **A (Affluence = GDP/person):** expected to at least **double** (200% in 50 years).
- **P × A:** together, this means **human demand/consumption could grow by a factor of 4–5**.

If **T (Impact per GDP unit)** stays the same, total environmental impact (ΣEI) will rise 4–5× — which is unsustainable.

🚨 **The requirement**

- To keep **ΣEI** stable or reduced, **T** must shrink dramatically.
- Specifically:

$$T = \frac{I}{GDP}$$

(the "technology factor")

must be reduced by **a factor of 4–20** within 50 years.

That means: for every dollar (or euro, krone) of GDP, the environmental impact has to become **4 to 20 times lower** than today.

🌍 **Interpretation**

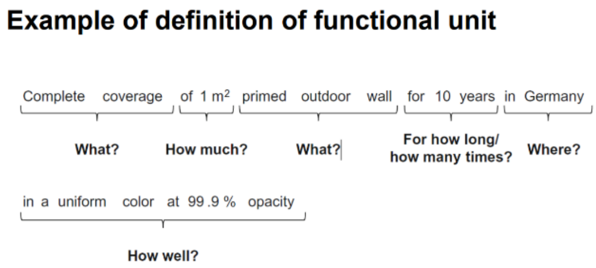
- **Factor 4–20**: wide range, because it depends on population growth path, economic development, and planetary boundaries.
- Essentially, we need **radical efficiency gains** + **cleaner production** + **circularity**.
- But: even huge efficiency improvements might not be enough if consumption (A) keeps rising unchecked → that's where the "rebound effect" comes in.

> Take aways
>
> - The global environmental impact is driven by human consumption and demands
> - We can achieve some reduction of the impact by technology development, which should be a factor 4-20 more efficient
> - But we also need to address the human consumption by it self

FU (Functional Unit) Definition

- **Tema**: O que é uma unidade funcional (FU) numa Análise de Ciclo de Vida (LCA).
- **Key points**:
  - FU é a **base de referência** que define a função de um produto/sistema.
  - Permite comparar produtos diferentes que cumprem a mesma função.
  - Exemplo: comparar **1 litro de tinta** vs. **pintar 10 m² de parede durante 10 anos**. A FU não é o produto em si, mas a *função prestada*.

    - Sem FU clara, a comparação é enganadora.
- **Conceito-chave**: FU assegura que análises LCA são comparáveis e focadas na utilidade real.



> Packaging of 1000L of beer and keeping it fresh during transportation, retail and storage for up 1 year in denmark

- should serve as a drinking device
- must fufil all legislative requirements to food packaging
- amount packaged
- properties to keep it fresh
- positioning properties (easy to open , lig

> providing a 500 lux light to an office working place in a average 4 houre per dau, 230 days per year for 5 years in denmark

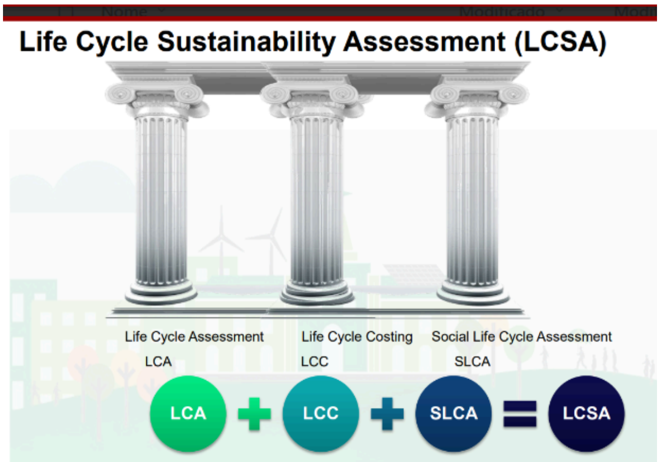
- provide a sufficient light - 500 lux
- direct light
- avoid glare
- CE labelled
- different positioning
- design
- Color temperature of the light

Framework and LCA

- Definition of goal of assessment - "what is the question?"
    - Scoping of system
    - Collection of data on emissions and resource use
    - Translation of emissions into environmental impacts
    - Interpretation of results - answer to the question
- **Tema**: Estrutura da LCA (Life Cycle Assessment) e avaliação de sustentabilidade.
- **Key points**:
    - Ciclo de vida → de "cradle to grave" (extração de matérias-primas → produção → uso → fim de vida).
    - **LCA (ISO 14040/44)**:
        1. Definir objetivo e âmbito da análise.
        2. Recolha de dados (emissões, consumo de recursos).
        3. Tradução em impactos ambientais.
        4. Interpretação dos resultados.
    - LCA foca-se em **comparar serviços equivalentes** (ex: garrafa de vidro vs. PET).
    - Evita *problem shifting*: reduzir um impacto mas aumentar outro.
    - **Extensão**: LCSA (Life Cycle Sustainability Assessment) =
        - LCA (ambiente) + LCC (custos) + SLCA (social).
    - **Frameworks importantes**:
        - **MECO** (Materials, Energy, Chemicals, Others): organiza causas de impacto por fase do ciclo de vida.

- **Quantitative Sustainability Framework**: liga etapas do ciclo de vida a áreas de impacto (recursos, ambiente, económico, social/saúde, transição).

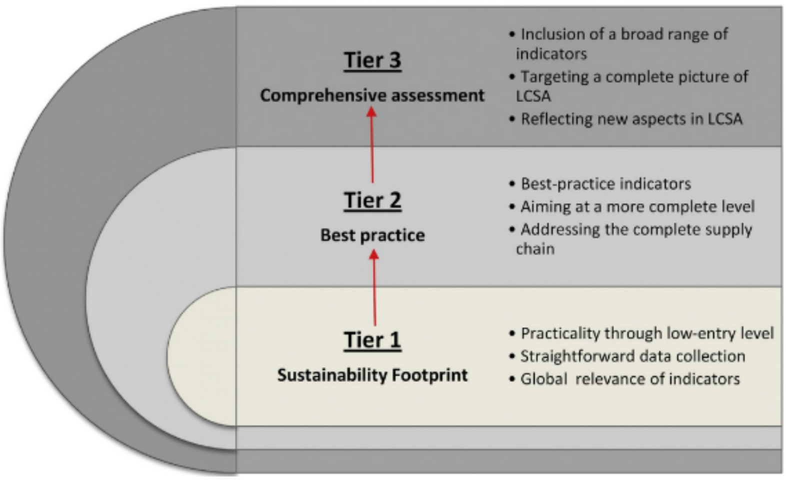
- **Fórmulas/novos termos**:
  - Impact categories: emissões → *impact factors* → indicadores (ex: CO_2 eq., SO_2 eq.).
  - Normalização: traduz impactos para *mPE* (miliperson-equivalents).



The 3 Pillars of LCSA

- **LCA (Life Cycle Assessment)** → Environmental side
  - Measures climate change, carbon footprint, pollution, resource use.
- **LCC (Life Cycle Costing)** → Economic side
  - Tracks costs across the whole life cycle (production, use, disposal).
- **SLCA (Social Life Cycle Assessment)** → Social side
  - Considers working conditions, human health, community impacts.

Together (LCA + LCC + SLCA) = LCSA → a holistic view of sustainability across all three dimensions.



The 3 Tiers of LCSA (maturity levels)

- **Tier 1 – Sustainability Footprint**
  - *Entry level*. Quick, simple assessment.
  - Uses a **small set of globally relevant indicators** (like CO_2 footprint, total cost, maybe one or two social risks).
  - Aim = practicality → easy to collect data, give a first impression.
- **Tier 2 – Best Practice**
  - More detailed and **supply-chain oriented**.
  - Uses "best-practice indicators" (widely accepted methods in LCA, LCC, SLCA).

- Goal = cover the **whole supply chain**, not just the product's main stages.
- A middle ground between simple and comprehensive.

- **Tier 3 – Comprehensive Assessment**
  - *Full picture*.
  - Includes a **broad range of indicators** (all environmental, social, and economic categories possible).
  - Captures new aspects as sustainability science evolves (like biodiversity loss, planetary boundaries, social equity).
  - Very data-intensive, but gives the **most complete LCSA**.

The MECO framework

	Life Cycle Stage				
Causes of Environmental Impact	Extraction of raw materials	Manufacturing stage	Use stage	Disposal stage	Driver for:
Materials					Depletion of natural resources
Energy					Climate change, acidification, photochemical ozone formation etc.
Chemicals					Human and ecological toxicity Ozone depletion
Others					E.g. land use, water use, social impacts etc.

What MECO stands for

- **M = Materials**
- **E = Energy**
- **C = Chemicals**
- **O = Others** (land use, water use, social impacts, etc.)

How it works

- The framework is a **matrix**:
  - Rows = **causes of impact** (M, E, C, O).
  - Columns = **life cycle stages** (Extraction of raw materials → Manufacturing → Use → Disposal).
  - Final column = shows which **environmental problems** these causes drive (e.g. depletion, climate change, toxicity).
- By filling in the table, you **map the main hotspots** of a product/system:
  - Where are the biggest material demands?
  - Which stage consumes the most energy?
  - Are harmful chemicals used/released?
  - What "other" issues matter (e.g. water use, land use, noise, social impacts)?

- **FU** → define *como* comparar.
- **LCA** → avalia impactos ambientais ao longo de todo o ciclo de vida.
- **IPAT** → mostra matematicamente a relação entre população, consumo e tecnologia no impacto ambiental.

	Life Cycle Stage				
Sustainability Impact area	Extraction of raw materials	Manufacturing stage	Use stage	Disposal stage	Measured by:
Resources					Use of biotic and abiotic resources Circular economy indicators
Environment					Climate change, Carbon footprint Absolute boundaries
Economic					Costs
Social/Health					Socioeconomic impacts, health impacts
Transition					Qualitative or semiquatitative assessment

- **Áreas de impacto da sustentabilidade** (linhas):
  - **Resources** → uso de matérias-primas, água, energia.
  - **Environment** → emissões, poluição, alterações climáticas.
  - **Economic** → custos diretos/indiretos.
  - **Social/Health** → condições de trabalho, saúde humana, impactos sociais.
  - **Transition** → mudanças qualitativas ligadas a circularidade, inovação, etc.
- **Etapas do ciclo de vida** (colunas):
  - **Extraction of raw materials** → extração de recursos naturais.
  - **Manufacturing stage** → transformação e fabrico.
  - **Use stage** → fase de utilização pelo consumidor.
  - **Disposal stage** → fim de vida (reciclagem, incineração, aterro).
- **Medido por** (última coluna):
  - Dá exemplos de **métricas típicas** em cada linha:
    - *Resources* → uso de recursos bióticos/abióticos, indicadores de economia circular.
    - *Environment* → pegada de carbono, mudança climática, limites planetários.
    - *Economic* → custos.
    - *Social/Health* → impactos socioeconómicos e na saúde.
    - *Transition* → avaliação qualitativa/semicuantitativa (ex: maturidade tecnológica, adaptabilidade).

- LCA is a comparative method that assess the environmental impacts of a product or system throughout its life cycle
- It is important to precisely define the object of assessment
- Life Cycle Sustainability Assessment aims to additionally include the economic and the social impacts
- In this course we do not apply LCSA, but aim to cover all aspects in a life cycle perspective through a simplified approach

Sustainability Impact area	Extraction of raw materials	Manufacturing stage	Use stage	Disposal stage	Measured by
Resources	**Metals (aluminium, copper, rare earths), plastics; non-renewable**	Energy/material intensive for LED and electronics	Low additional resources; only electricity	Metals recyclable, plastics often downcycled; DK e-waste collection helps	Abiotic resource use, circularity indicators
Environment	Mining impacts: land use, local pollution	CO_2 footprint from electronics production (often in Asia)	Main load = electricity consumption (DK grid mix relatively green)	Toxic components if mishandled; recycling reduces footprint	Carbon footprint, climate change, toxicity indicators
Economic	Costs from resource extraction	Higher production costs vs incandescent/halogen	Very cost-effective: high efficiency, long lifetime	Some e-waste handling cost, partly offset by recovered metals	Life Cycle Costs (purchase + use + disposal)
Social/Health	Mining linked to poor labor conditions (rare earths, cobalt, etc.)	Assembly labor issues, OSH risks	Positive: better lighting → comfort, productivity, eye health; risk if glare/flicker	Safe disposal in DK, risk in informal recycling abroad	Socioeconomic and health impact indicators

Sustainability Impact area	Extraction of raw materials	Manufacturing stage	Use stage	Disposal stage	Measured by
Transition	Reliance on critical raw materials	Supports shift to efficient lighting technologies	Large energy savings (80–90% vs incandescent)	Circular design limited; design for disassembly could improve	

DETAILED SUMMARY OF THE THREE MODULES (IPAT + Functional Unit + LCA Framework)

1. IPAT Framework — Understanding the drivers of global environmental impact

(*Module 2 IPAT*)

The IPAT equation is introduced as a **causal model** describing how human activities generate environmental impacts:

I = P × A × T

Where:

- **I** = total environmental impact
- **P** = population
- **A** = affluence (material consumption per person, often proxied by GDP/capita)
- **T** = technology factor (environmental impact per unit of economic value created)

What the slides emphasize:

1. **Population is increasing globally** (page 4).
   Even if per-capita impact stayed constant, total impact rises with population growth.
2. **Affluence is increasing even faster** (page 5).
   As economies develop, consumption intensity grows (more products, more energy, more mobility).
3. **Environmental impact must *decrease*, not just stabilize** (page 6).
   In the context of climate change and planetary boundaries, the global impact must go down dramatically.
4. **P × A will increase 4–5× within 50 years** (page 7).
   This means:
   → If technology efficiency (T) stays the same, impact multiplies by 4–5×.
   → To achieve sustainability, **technology must become 4–20× more efficient**.
5. **Consumption is also a critical lever** (page 8).
   Two concepts highlighted:
   - **Rebound effect**: efficiency gains lower cost → people consume more → impact rises again.
   - **Rising human demand** continues to push impacts upward.

Core insight:

Environmental sustainability cannot rely on “better technology” alone.

We must address **demand, behaviour, and consumption patterns**, not just efficiency.

2. Functional Unit — Defining *exactly* what is being assessed

(*Module 2 FU definition*)

The Functional Unit (FU) is the **central reference** of any comparative assessment (LCA, LCC, SLCA).

It guarantees that comparisons are fair, meaningful, and scientifically valid.

Key ideas from the slides:

A. **Start with the use context** (page 4)

Questions to define context:

- What is the product used for?
- What service does it deliver?
- For whom?
- How long and how often?
- Where is it used (geography)?
- What quality level is required?

B. **Identify obligatory vs. positioning properties** (page 5)

- **Obligatory properties** — essential features that define the product (legal, technical, functional requirements).
- **Positioning properties** — attractive features that differentiate one product from competitors.

Both help constrain the functional unit definition.

C. **Purpose of the Functional Unit** (page 6–7)

The FU must:

1. Be based on the actual **function** delivered, not the product itself.
2. Be **quantitative**: specify a measurable amount of service.
3. Ensure **equivalence** when comparing systems (e.g., same service, same performance level, same duration).

D. Example from the slides (page 8)

"Complete coverage of **1 m²** of **primed outdoor wall**, for **10 years**, in **Germany**, with **99.9% opacity**."

The example shows how a FU answers:

- What? → 1 m² wall coverage
- How much? → full coverage
- How well? → 99.9% opacity
- How long? → 10 years
- Where? → Germany

This level of detail avoids misleading comparisons.

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3. LCA Framework — Assessing sustainability from cradle to grave

(*Module 2 framework and LCA*)

This module explains the **logic, scope, and structure** of Life Cycle Assessment (LCA):

A. Life Cycle Thinking (pages 3–4)

The value chain is seen as a continuous flow **from raw material extraction → manufacturing → distribution → use → disposal**.

This prevents focusing only on one stage and missing impacts elsewhere.

B. How LCA conceptualizes a product system (page 5)

There are two spheres:

1. **Technosphere** — human-made system: extraction, production, transport, energy use, waste treatment.
2. **Ecosphere** — the natural environment that receives emissions and provides resources.

Resources flow *from* the ecosphere into the technosphere;

Emissions and waste flow *back* to the ecosphere.

C. The Four Steps of LCA (page 7)

1. **Goal definition** — what question are you answering?
2. **Scope/system boundaries** — what processes are included? Geographic/time scope?
3. **Inventory analysis (LCI)** — collect data on emissions, energy, materials, waste.
4. **Impact assessment (LCIA)** — convert flows into environmental impacts (CO_2, toxicity, eutrophication, etc.).
5. **Interpretation** — explain results, uncertainties, and recommendations.

D. LCA is service-driven (page 8)

The comparison is based on **service delivered**, not object.

Example:

A reusable glass bottle versus 30 cartons.

To compare them fairly, they must deliver the **same volume of drink** under the **same conditions**.

E. LCA avoids problem shifting (page 10)

A proper LCA considers:

• All life cycle stages

• All environmental impact categories

• Resource use

• Toxicity and human health

Preventing situations where reducing CO_2 accidentally increases toxic pollution or rare resource depletion.

F. Beyond LCA — Life Cycle Sustainability Assessment (page 11)

LCSA =

• **LCA** (environment) +

• **LCC** (life cycle economic costs) +

• **SLCA** (social impacts, e.g., labor rights, community effects)

This produces a full triple-bottom-line sustainability assessment.

G. Social LCA categories (page 14)

Stakeholder groups include:

• Workers

• Local communities

• Value-chain actors

• Consumers

• Society

• Children

Each includes indicators such as:

• Fair wages

• Health & safety

• Working conditions

• Child labor prevention

• Access to resources

• Security of living conditions, etc.

H. MECO Framework (page 16)

Breaks down impacts by **stage** and **impact drivers**:

Stages:

• Raw material extraction

• Manufacturing

• Use

• Disposal

Drivers:

• Materials (resource depletion)

• Energy (climate, acidification, etc.)

• Chemicals (toxicity)

• Others (land use, water, social aspects)

I. Quantitative Sustainability Framework (page 17)

This applies indicators across life cycle stages for:

• **Resources** (abiotic/biotic, circularity)

• **Environment** (carbon footprint, boundaries)

• **Economic costs**

• **Social/health impacts**

• **Transition indicators** (qualitative adaptation readiness)

FINAL INTEGRATED TAKEAWAY

IPAT tells us *why* sustainability challenges grow (impact = population × consumption × technology).

Functional Unit tells us *what exactly* we are assessing (the service, quantified).

LCA tells us *how* to measure the sustainability of that service across all life cycle stages.

These three modules together give the conceptual foundation for any life cycle–based sustainability study.

Question 1

What does the I=PAT equation represent?

Question 1 options:

a. That the environmental impact (I) is a function of the power consumption (P), the area used for producing the power (A) and the efficiency of the technology used to produce it (T)
b. That the overall environmental impact (I) is a function of how many people we are (P), how wealthy we are (A), and the environmental efficiency of our technologies (T)
c. That the environmental impact (I) is a function of how much we produce (P), the age of our production equipment (A), and the amount of time we use our products (T)

Question 2

How much should the factor T decrease, in order to compensate for increasing P and A and an already large I?

Question 2 options:

a. It should decrease by a factor 2
b. It should decrease by a factor 4-20
c. It should decrease by a factor of at least 10

Question 3

The Rebound effect may counterbalance the technological improvements causing consumers to buy even more products.

Question 3 options:

a. True
b. False

Yes, the rebound effect occurs because technological improvements often will reduce the price of the products, making money accessible to buy more of the same product or buy other products. This may cause an increase in environmental impact, or reduce the environmental improvement

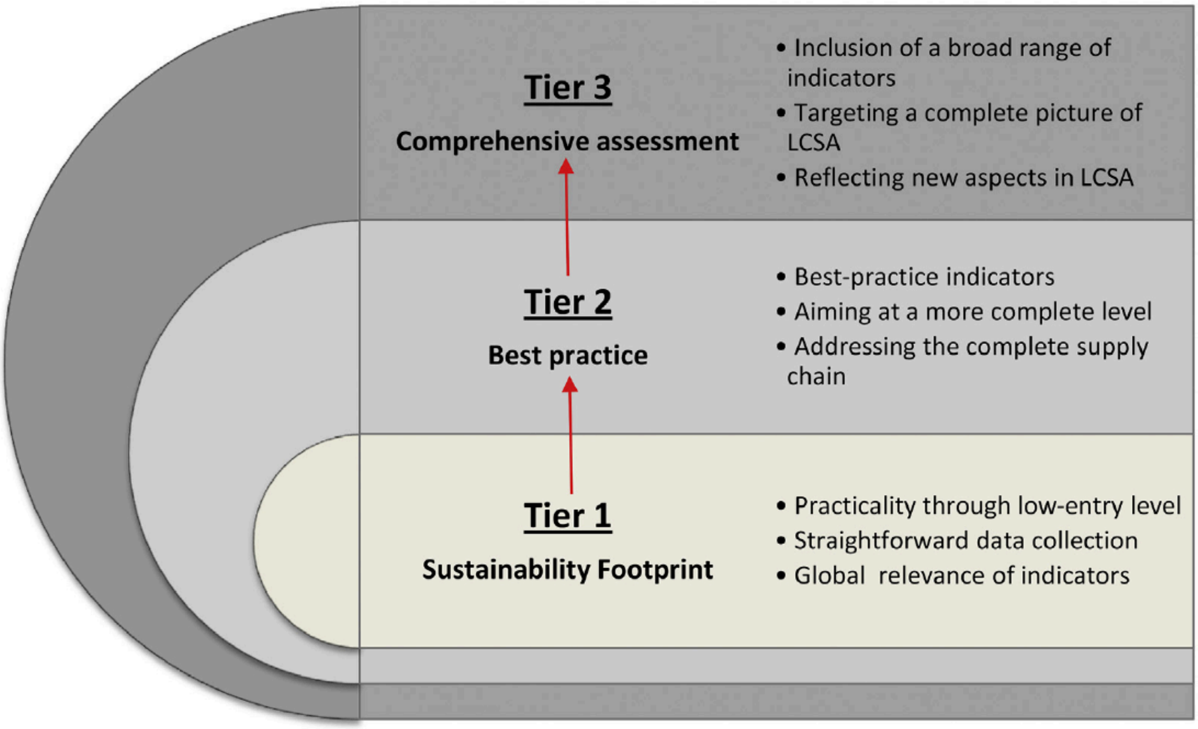
Question 4

The object of assessment in sustainability assessment focus on the service that the product, system or technology provides?

Question 4 options:

a. True
b. False

Question 5



In the suggestion for a stepwise Life Cycle Sustainability Assessment by Neugebauer et al. there are some suggestion for which indicators should be included at each step. Below are the social indicators. Please order them according to which tier they belong starting with the lowest tier.

2 Health

3 Human rights

1 Fair wages

Hide Check my answer

Fair wage is one of the most applicable indicators considered within SLCA. It also describes perfectly a necessity to fulfil basic needs. Therefore it is the first level indicator

Health has been broadly addressed within SLCA and LCA literature and bynumerous institutions, like WHO or OECD. Therefore, they have considered it a tier 2 indicator.

Human rights are normally expressed by different subtopics, e.g. child labour, forced labour, discrimination and equity and therefore it is a more complex indicator to be considered at level 3.

Question 6

How will environmental sustainability be addressed in this course?

Question 6 options:

a. You will assess the impact on the nine boundaries of the planetary boundaries framework
b. You will assess impact on climate change through a carbon footprint and relate this result to the absolute boundaries (earth's carrying capacity) for climate change
c. You will apply a life cycle impact assessment including several different environmental impact categories and relate them to their absolute boundaries

Yes, climate change is the most commonly known impact and is the subject of concern for most companies. Therefore, the focus of this course is on climate change.

Question 7

The environmental aspects is represented by LCA or life cycle assessment

The economic aspect is represented by LCC or life cycle costing

The social aspects is represented by SLCA or social life cycle assessment

Question 8

The functional unit quantifies the product/system/technology e.g. in terms of it's efficiency, for example as kg CO_2 emitted/km driven for a car?

Question 8 options:

a. True

b. False

Correct, the functional unit is a quantification of the service provided by the product/system/technology. In the case of a car it could e.g. be 1 person transported 1 km every day for 10 years. It does not represent a relative value that includes the CO_2 emitted.

4. Carbon Footprint and Environmental Indicators

Date	@September 23, 2025
Status	In progress

In this module you will:

Studies before:

1. Be taught about environmental indicators
2. Practice calculating carbon footprint of gasoline vehicles compared to electric vehicles

Teaching session:

1. Practice calculating carbon footprint of coffee
2. Assessing yourself on your ability to calculate carbon footprints

Follow the sequence of activities as described below:

Studies before teaching session:

4.1 Video lecture: Environmental indicators

Watch the video lecture Introduction to environmental indicators.

4.2 Video lecture and exercise: Carbon footprint of gasoline vehicles compared to electric vehicles

Download the Spreadsheet template: Carbon footprint of gasoline vehicles compared to electrical vehicles and have it open while you you watch the video lecture Determining the carbon footprint of human activity, Gasoline vs electric vehicles.

In the video lecture you will be guided in how to compare the carbon footprint of gasoline vehicles and electric vehicles.Fill in the ochre/brown highlighted empty cells in the spreadsheet, when you are guided of how to do so in the video lecture.

Please note that a few fields/processes numbers have been updated between the video and the current spreadsheet uploaded here. You should insert the process number corresponding to the given *Activity name* in the spreadsheet.

Download Spreadsheet solutions: Carbon footprint of gasoline vehicles compared to electrical vehicles and compare with your filled spreadsheet template.

Teaching session:

4.3 Exercise: Carbon footprint of coffee

In the teaching session we will focus one the Exercise: Carbon footprint of coffee.

For the exercise we are going to use the Spreadsheet template about coffee.

4.4 Self-assessment

After the above mentioned exercise, we will focus on the Self-assessment and study the different questions in the self-assessment.

Use the last question in the self-assessment to upload your spreadsheet from the above described exercise about carbon footprint of coffee (4.3) and click *Submit* when you have finished your first try at the self-assessment.

When you have submitted the self-assessment, you will receive a spreadsheet with the solutions to the exercise about carbon footprint of coffee at the bottom of the feedback page. Use the solutions to compare with your own results.

You can study the self-assessment as many times as you prefer (eg until you have all the right answers).

The exercises and self-assessment is solely for practicing and you will not be assessed on your results.

Why performing a carbon footprint

- Because climate change has among the highest environmental impact on humans and ecosystems, especially in developing countries
- Because many other environmental impacts are correlated to climate change
  co-benefits for many other types of impacts (except water and sometimes land use)
  ... and once you get the carbon footprint tool, you get impacts on humans & ecosystems

- Because it is useful: It helps identify hotspots in production process and compare products & scenarios per unit of consumption/function
- Because we have a lot of data available to quantify the GHG emission for more than 20,000 processes
- Because it is relatively simple: every engineers and everybody able to do multiplication and additions can do it
- Because you will be able to apply it in your case study in module 8 and then use it in your professional life
- Because you will use the carbon footprint tool at the exam

Detailed Summary

The session explains **why** carbon footprints matter, **how** to calculate them, and **how to interpret results**. It mixes lecture content with hands-on exercises (cars + coffee) to teach you the practical workflow of Life Cycle Assessment (LCA) applied specifically to **Greenhouse Gas emissions (GHG)**.

---

1. Why carbon footprints matter (pages 4–5)

Climate change has the highest environmental pressure on humans and ecosystems. Many other environmental impacts correlate with GHG emissions, so reducing carbon often produces **co-benefits** (except water and land in some cases).

A carbon footprint = **sum of all GHG emissions** across a product/system, converted to **CO_2-equivalent** using IPCC GWP100 factors (e.g., CH_4 ≈ 27× CO_2, N_2O ≈ 273× CO_2, SF_6 ≈ 24,300× CO_2). This allows different gases to be compared on the same scale.

The method is popular because:

- Data availability is huge (20k+ processes in ecoinvent).
- It's structured, quantitative, and simple to compute.
- Hotspots become clear, helping compare scenarios and guide decisions.
- You'll need it for your case study and your exam.

---

2. How a carbon footprint is calculated (page 6–8)

The tool is basically a formula:

Carbon footprint = Σ (Activity Amount × Emission Factor)

for a **functional unit** (FU), e.g., 1 vehicle-km or 1 cup of coffee.

Workflow:

1. **Collect input data** (materials, energy, transport, etc.).
2. **Find GHG emission factors** in ecoinvent (kg CO_2e per kg, per kWh, per km, etc.).
3. **Convert all quantities to the FU**.
4. Multiply **Q × EF**, sum everything.

The slides show the example of a car with:

- steel use
- gasoline combustion
  all converted to kg CO_2e per 1 vehicle-km.

---

3. Case study: Gasoline vs Electric Vehicles (pages 7, 13–15)

Key insight: An EV is only "clean" if the electricity is clean.

Carbon footprint comparison graph (page 13):

- Gasoline vehicle = highest footprint per km (dominated by *use phase* emissions).
- EV with **wind or PV electricity** = lowest footprint.
- EV with **hard-coal electricity** = worse than gasoline.
- Manufacturing of EVs is higher due to batteries, but still offset by clean electricity.

Sensitivity analysis (pages 14–15):

- Cumulative footprint grows linearly with distance.
- Per-km footprint decreases with lifetime.

- EV advantage grows with:
  - higher mileage
  - cleaner electricity
  - lower battery manufacturing impact

---

4. Interpretation principles (page 11)

When analyzing results, always ask:

- Which **processes** or **life-cycle stages** dominate?
- Can these stages be improved?
- Are there surprising results? If yes, don't ignore them — it means a parameter or assumption matters more than expected.

You must understand why differences happen; otherwise, it's either a mistake or a missed insight.

---

5. Coffee carbon footprint exercise (pages 17–23)

You calculate the footprint **per cup** of coffee using:

- 11.5 g green beans
- roasting energy
- electricity consumption of coffee maker
- hot water heating (major contributor)
- transportation (truck + ship)
- end-of-life incineration
- long lifetime of coffee machine shared between users

The exercise trains you to:

- find correct ecoinvent processes
- convert all units to a per-cup FU
- calculate t-km for transport
- compare different electricity mixes (DK, EU, wind, PV, hard coal)
- compare Robusta vs Arabica coffee

The comparison graph (page 20) shows:

- Roasted coffee beans dominate.
- Electricity in use phase can be very important, depending on the electricity mix.
- Aluminum capsules also add significant impact.
- Wind/PV mixes drastically lower the footprint.
- Hard coal makes it worse.

---

6. Sensitivity analysis for coffee (page 22)

You test:

- DK electricity (default, very clean)
- Hard-coal electricity (very high footprint)
- EU mix (medium)
- PV electricity
- 100% wind electricity
- Robusta vs Arabica

Main takeaway:

The footprint of a cup of coffee can vary by **almost a factor of 2** depending mainly on the **electricity mix** and **coffee type**.

---

7. Normalized LCA damage comparison (page 16)

Using Impact World+, the slides show damage categories:

- human health

- ecosystems
- resource use

EVs outperform gasoline in almost all categories when powered by clean electricity. Hard-coal EVs perform worse in almost every category.

8. Module workflow

Throughout the teaching session:

- You learn the method.
- Apply it to cars.
- Apply it to coffee.
- Then you use the same method for your **WAGER case study** in module 8.

In one tight line

The document teaches you the rationale, math, databases, and interpretation skills needed to calculate and analyze the carbon footprint of any product, demonstrated using cars and coffee.

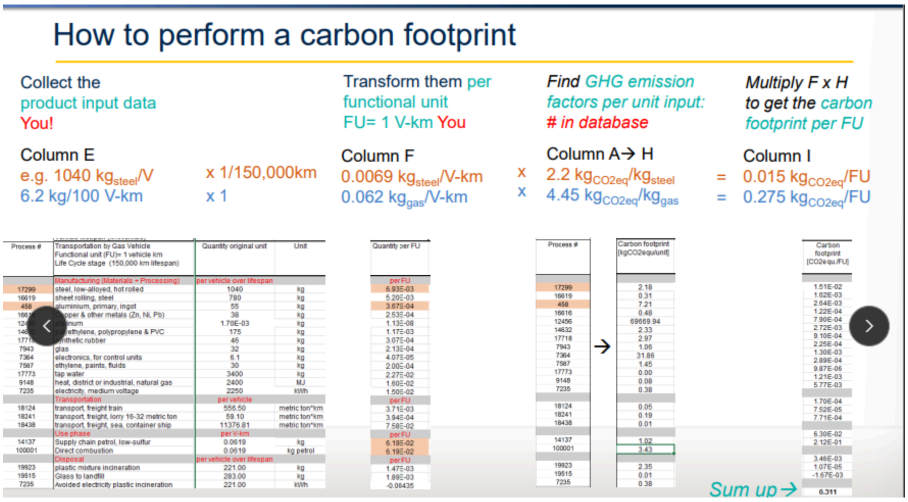
Carbon Footprint: at personal and product levels

A carbon footprint is the weighted sum of greenhouse gas (GHG) emissions caused by an individual, event, organization, service, or product, expressed as carbon dioxide equivalent. GHG emissions are weighted based on their global warming potentials (GWP100, as defined by the Intergovernmental Panel on Climate Change, AR6, Tables 7.15 and 7.SM.7)

Greenhouse Gas	GWP100
Carbon Dioxide (CO_2)	1 kg_{CO2e}/kg_{CO2}
Methane biogenic (CH_4)	27 kg_{CO2e}/kg_{CH4}
Methane fossil (CH_4)	29.8 kg_{CO2e}/kg_{CH4}
Nitrous Oxide (N_2O)	273 kg_{CO2e}/kg_{N2O}
Hydrofluorocarbons (HFC-32)	771 kg_{CO2e}/kg_{HFC}
Perfluorocarbons (PFC-14)	7380 kg_{CO2e}/kg_{PFC}
Sulphur Hexafluoride (SF_6)	24300 kg_{CO2e}/kg_{SF6}

Amount of inputs per functional Unit (e.g. kg/vehicle-km)		*GHG Emission factors per unit input:*		*Carbon footprint per FU*
Q	X	*E*	=	*F*
kg_{steel}/V-km	x	kg_{CO2eq}/kg_{steel}	=	kg_{CO2eq}/FU
kg_{gas}/V-km	x	kg_{CO2eq}/kg_{gas}	=	kg_{CO2eq}/FU

DATABASE → ECOINVENT



transport to measure how much distance vehicles travel. For example, 1 bus driving 10 km equals 10 vehicle-km. It's often used to quantify service supply, traffic volume, emissions, or maintenance needs.

Environmental Indicators – Carbon Footprint

Learning objectives

- Relate human activity to climate change using causal frameworks.
- Calculate carbon footprint by aggregating substances with different global warming potentials (GWP).
- Compare carbon footprint to other environmental indicators.

Global warming context

- Based on IPCC 2019: risks of exceeding +1.5°C warming by 2100 under business-as-usual.
- Health disparities: climate change increases risks of both heat- and cold-related impacts.

Frameworks and models

- DPSIR model (Drivers–Pressures–State–Impact–Response) links causes and effects of indicators.
- Applied to transport: vehicles → GHG emissions → radiative forcing → temperature rise → biodiversity loss, DALYs lost.

Carbon footprint definition

- Weighted sum of greenhouse gas (GHG) emissions from a product, service, event, or person.
- Expressed in CO_2-equivalents ($kgCO_2e$).
- Uses 100-year Global Warming Potentials (GWP100, IPCC AR6):
  - CO_2 = 1
  - CH_4 biogenic = 27
  - CH_4 fossil = 29.8
  - N_2O = 273
  - HFC-32 = 771
  - PFC-14 = 7380
  - SF_6 = 24300

Examples: footprints per capita

- **Denmark** (consumption-based): ~8,000 $kgCO_2$/year from CO_2, ~46 kg from CH_4, smaller amounts from N_2O and fluorinated gases.
- **USA**: much higher totals (≈10,340 $kgCO_2e$/person/year).

How to build an energy & carbon balance

1. Define the **functional unit (FU)** (e.g., 1 km driven, 1 cup of coffee).
2. Collect **composition and consumption data** (kg, kWh, liters per FU).
3. Find **GHG and energy factors** in databases.
4. Calculate **footprints per FU** (MJ non-renewable energy, $kgCO_2e$).

5. Sum contributions, interpret results, and identify hotspots.

Applications and case studies

- Energy and CO_2 balance of gasoline vs. electric vehicles.
- Sensitivity studies: impact of vehicle lifetime on footprint.
- Coffee cup exercise: accounting cultivation, processing, shipping, heating water.

Interpretation principles

- Compare scenarios across life cycle stages.
- Identify critical pollutants and phases.
- Use sensitivity and uncertainty analyses to test robustness.
- Always ask *why* differences appear—either it's an error, or it reveals an important insight.

🌍 Carbon Footprint Cheat Sheet

Definition

- Total GHG emissions of product/service/person, in **$kgCO_2e$**.
- Based on **GWP100** (100-year global warming potential).

Main GWP100 values (IPCC AR6)

- CO_2 = 1
- CH_4 (biogenic) = 27 | (fossil) = 29.8
- N_2O = 273
- HFC-32 = 771
- PFC-14 = 7380
- SF_6 = 24,300

Framework: DPSIR

Drivers → Pressures → State → Impact → Response

(e.g., Cars → GHG → Radiative forcing → Temp rise → Biodiversity/health loss)

Per Capita Footprints

- Denmark ≈ 8,000 $kgCO_2e$/year
- USA ≈ 10,300 $kgCO_2e$/year

How to calculate

1. Define **Functional Unit** (FU) (e.g., 1 km drive, 1 cup coffee).
2. Collect data (kg, kWh, liters per FU).
3. Use emission/energy factors.
4. Compute CO_2e + energy use.
5. Identify hotspots, compare scenarios.

Applications

- Gasoline vs. EVs (lifetime matters).
- Coffee cup (cultivation, transport, heating water).

Interpretation tips

- Compare life cycle stages.
- Check critical gases/phases.
- Do sensitivity + uncertainty analysis.
- Always ask *why* results differ → error or insight.

1. What is a **Functional Unit (FU)?**

- The FU defines the *basis of comparison* (e.g., *1 cup of coffee*, *1 km driven*, *1 T-shirt*).
- All inputs (materials, energy) and outputs (emissions) are converted relative to this FU.

- Example in this file: **FU = 1 cup of coffee**.

2. Units in the file

- **Mass-based**: kg (e.g., coffee beans per cup).
- **Volume-based**: liters (e.g., water used per cup).
- **Energy-based**: kWh, MJ (e.g., electricity to heat water).
- **Product-based**: unit (e.g., 1 coffee machine).

Each process in *Selected processes* has a reference product unit (kg, liter, unit), and its carbon footprint is given in **kgCO_2e per reference unit**.

3. Conversion to the FU

Steps to convert any input into FU terms:

1. **Determine consumption per FU**

   Example:

   - Coffee beans = 15 g per cup = 0.015 kg/FU
   - Water = 0.125 L per cup
   - Electricity = 0.06 kWh per cup

2. **Find emission factor** (from database/Ecoinvent):

   - Coffee beans = 5.66 kgCO_2e / kg
   - Electricity (DK mix) ≈ 0.3 kgCO_2e / kWh
   - Water (tap) ≈ 0.0003 kgCO_2e / L

3. **Multiply and sum**:

   $\text{Contribution} = \text{Quantity per FU} \times \text{Emission factor}$

   Example for coffee beans:

   $0.015\,\text{kg} \times 5.66\,\frac{\text{kgCO}_2\text{e}}{\text{kg}} = 0.085\,\text{kgCO}_2\text{e per FU}$

4. From FU to total carbon footprint

Once you have the footprint per FU (e.g., per cup), you can scale:

- **Per day** (if 2 cups/day):

  $2 \times 0.12\,\text{kgCO}_2\text{e} = 0.24\,\text{kgCO}_2\text{e/day}$

- **Per year**:

  $0.24 \times 365 \approx 87.6\,\text{kgCO}_2\text{e/year}$

- **Per household** (if 2 drinkers):

  $87.6 \times 2 = 175\,\text{kgCO}_2\text{e/year}$

5. General Formula

Total footprint (kgCO_2e/FU)=

$\text{Total footprint (kgCO}_2\text{e/FU)} = \sum_i \left(\text{Quantity of input}_i \times \text{Emission factor}_i\right)$

Question 1

1. Input data:

Complement the file "12100 QS Module 4 coffee carbon footprint template F24b.xlsx" you have just downloaded, **filling in the ochre/brown cells with missing data** in rows 21 to 43, following the indications below:

a. you need to **find the process numbers for the missing processes in cells A23 and A25**. For this, you will need to use the other two tabs "selected processes" that identifies the number of the ecoinvent processes that you use for this case study, and "Ecoinvent data that contains Global Warming scores in kg CO2 equivalent for 21000+ industrial and agricultural processes (that will be useful for your case study). Since this is a commercial database you can only use or share it within DTU and cannot distribute it elsewhere.

Go to the "selected processes" Tab. You want to **find the ecoinvent process number for "coffee green bean production, robusta" for the rest of the world.** For this, go to the ecoinvent data tab and search for "coffee green bean production, robusta". Find the process for the rest of the world (RoW). Write down the process number in column A, and **enter it in cell A5 of the selected process tab**. Also **enter this same process number in cell A23 of the "Carbon footprint calculator" tab**. The process name and carbon footprint data are automatically populated,

b. Complement the quantity per **FU=1 cup of coffee** **for the missing cells from column F**. Be careful that that .input data have different units and need to be all transformed into a per cup amount.

c**. For transportation**, impacts available in ecoinvent are calculated per t-km (t x km), i.e. **per t transported over a km**. To calculate the number of t-km transported by sea freight for the coffee green beans, multiply the distance by the weight of green beans per cup (you have calculated that above), and divide it by the conversion factor of 1000 kg/t you find in cell B17.

d. Also **complete in cell I23**, the calculation of the carbon footprint of the coffee green beans per cup

2. Carbon footprint analysis

Look at the carbon footprint and respective results in columns I and J and on the graph of column V on the right. Comment in the text below **A) what is the total footprint in kg CO2 equivalent, and B) what are the dominant processes?**

Question 2

3. Sensitivity analysis with electricity mix and type of coffee

Let us make a sensitivity analysis, changing from the default DK electricity grid (limited carbon since an important contribution of wind electricity), to:

1) a high footprint electricity from 100% hard coal rows (**fil cell A52** based on the different electricity offered at the bottom of the "selected processes" tabs),

2) an average EU electricity mix (**Fill cell A79**),

3) a photovotaic electricity production (**Fill cell A106**),

4) a 100% wind electricity production with the default **robusta** coffee (**Fill cell A133**),

5) a cup of **arabica**, coffee with wind electricity (**Fill cells A158 and A160**).

Look at the carbon footprint graph of column V on the right**. Discuss in the text field below how far the carbon footprint of this cup of coffee changes with the type of coffee and the source of electricity.**

Save your file carefully adding your student number in the file name. Based on this spreadsheet file result, you will be asked further questions in the self-assessment quiz, and required to upload the spreadsheet. You will then get a solution sheet you can compare with your own results.

P.S. once you are done, you can go to the top of column U, and BO and click on the + in the grey zone over the top. This will expand hidden column and show that in addition to the carbon footprint we directly get for free results for human health, ecosystem impacts and cumulative non-renewable energy demand. We will use them in module about social - and health dimensions.

Your morning coffee

A morning coffee might be essential for many people. But what are the most important inputs contributing to the CO2 and energy balance of a cup of roasted coffee.

You want to calculate the energy and CO2 balance of a cup of roasted coffee. To have a cup of coffee (1 cup is 1 dl = 0.1 liters), you need 11.5 grams of roasted coffee grounds. Coffee needs to be cultivated, treated, processed, and added to hot water. Hot water requires 0.12 kWh per liter water and 0.028 kWh per cup. Complement the file "Energy and carbon balance coffee data 1d.xlsx" with missing data and calculation as follows:

a. Complement the quantity per **cup of coffee (FU)** for the missing cells from column B

b. Get the data from the Ecoinvent aggregated file for the few missing processes for Aluminium primary at plant, electricity production mix and transport, transoceanic freight ship (see exact process on excel template and look them in file "EHS672_Activity 3.3.2 Ecoinvent Energy and CO2 data 1a.xlsx")

c. Calculate the non-renewable primary energy and the fossil CO2

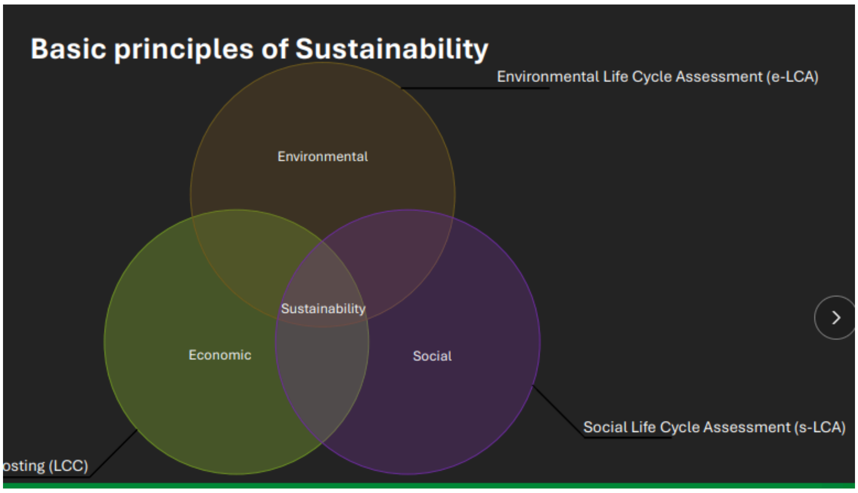
d. Based on your results, then select the three correct answers below

5. Economic Dimensions

Date	@September 30, 2025
Status	In progress

Learning objectives - Questions

- What is the meaning of life cycle costing (LCC)?
- Which are the basic parameters that we should consider to estimate LCC?
- What are the assumptions and limitations of LCC estimation?
- How can I perform an LCC analysis for my case study?
- How can I quantify the different compounds of LCC for my case study?



Sustainability Tools for Society I

The lecture by Prof. Karyn Morrissey frames companies as central actors in building sustainable economic systems. Sustainability is not only about minimizing environmental impacts but also enhancing social and economic well-being. Structured tools are needed—because if you can't measure something, you can't manage it.

Lecture Overview

The focus is on the life-cycle economics of gasoline cars versus electric vehicles (EVs), quantifying household costs across their lifespan. It also considers variations in electricity sources, ownership models such as leasing, and wider societal and equity issues.

Toolbox of Methods

The main sustainability tools presented are: multi-criteria decision analysis (MCDA), material flow analysis (MFA), life cycle assessment (LCA), input–output models, sustainability indicators and indices, cost–benefit analysis (CBA), and optimisation methods. Each tool provides a different perspective—environmental, social, or economic.

Material Flow Analysis (MFA)

MFA maps the inputs and outputs of materials in process chains, showing how the economy is embedded in and dependent on the environment. Many countries publish economy-wide MFA accounts that form the basis for sustainability monitoring.

Input–Output Models (IO)

IO models describe the interdependencies between economic sectors, calculating impacts on employment and Gross Value Added (GVA). Environmentally extended input–output analysis (EEIO) connects consumption activities with environmental pressures.

Direct and Indirect Effects in IO

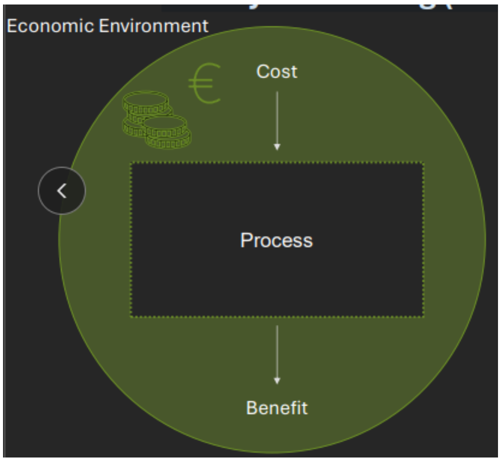
IO models capture both direct effects (immediate impacts of expenditure in a sector) and indirect effects (ripple effects through supplier industries). Multipliers are used to quantify the overall impacts of sectoral changes on the economy.

Cost–Benefit Analysis (CBA)

CBA compares projects by assigning monetary values to both costs and benefits. It often incorporates outputs from LCAs and IO models to make sustainability choices more tangible in economic terms.

Life Cycle Cost Assessment (LCCA)

LCCA extends the concept of cost analysis by including all expenses over an asset's lifespan: purchase, operation, maintenance, and disposal. It shifts the focus from environmental footprints to economic decision-making for both producers and consumers.



Life Cycle Costing (LCC)

- LCC began in the 1950s in the United Kingdom and was related with the construction of buildings.
- The 1973 energy crisis led to its wider adoption.
- Life Cycle Costing of the investment or a product is compatible with environmental LCA.

- **What do we want to achieve?**

  Estimation of the total cost throughout asset's life including, planning, design, acquisition, support cost, and other costs directly attributable to owing using the asset.

- **How we can achieve it?**

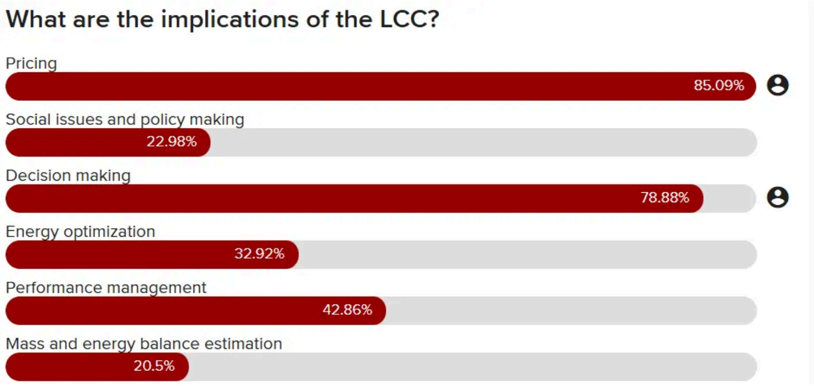
  Recording of the initial investment cost (equipment, facilities, etc.), lifetime, total operating cost for the entire lifetime, and total profits. Including also cost for waste treatment.

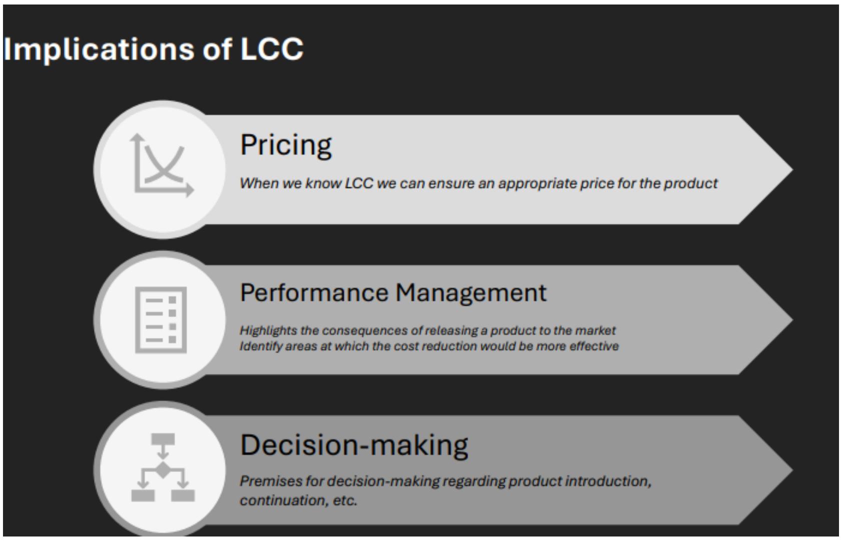
- **Why we want to achieve it?**

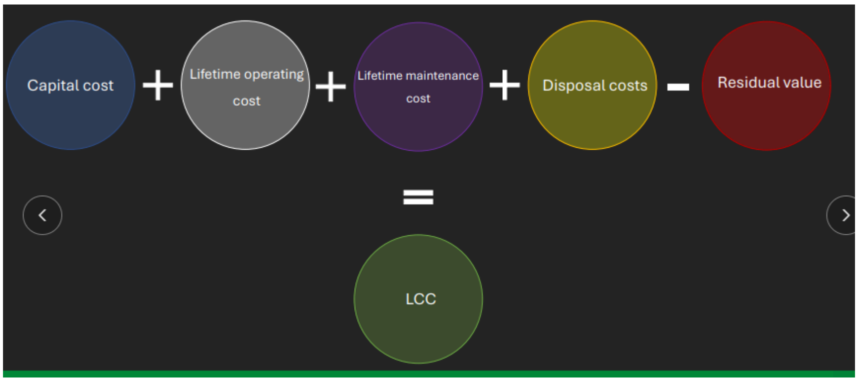
  Economic feasibility is one the most important criterion for implementing an investment. LCC allows the optimum decisionmaking accounting the entire Life Cycle of a product.

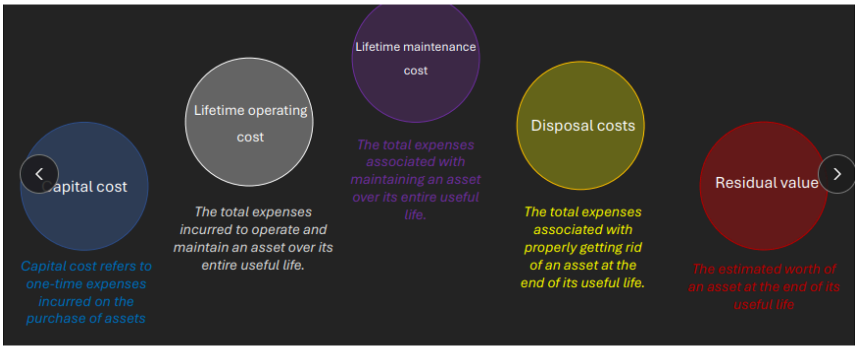
Objectives

- Assist management in smartly managing the total cost through the product's life cycle
- Identify areas in which the cost reduction would be more efficient
- Estimation of cost impacts of alternative designs and support options
  - It's really helpful to low technology issues (repair VS replacement)









ANNUAL DEPRECIATIION

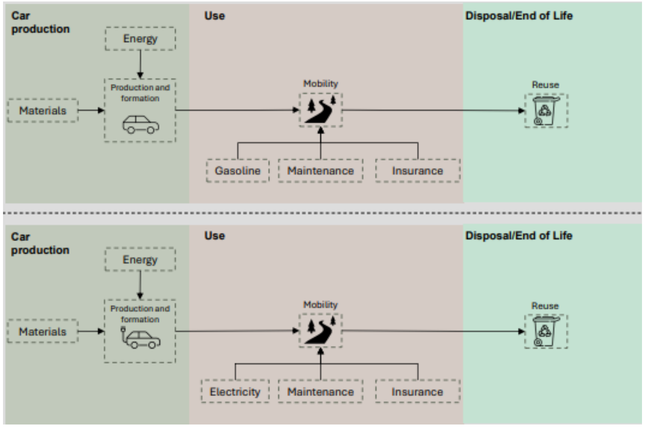
$$\text{Annual Depreciation} = \frac{\text{Capital Cost} - \text{Residual Value}}{\text{Useful Lifetime}}$$

Reflecting how much value is lost over time

Advantages of LCC	Disadvantages of LCC
Improve forecasting – Applying Life Cycle Costing (LCC) enables a more accurate estimation of the total cost associated with a procurement.	**Time consuming** – LCC can become extended or more complex due to rapid changes in technology.
Improved awareness – Enhances management's understanding of the cost drivers and the resources required for the procurement.	**Costly** – The longer the project's lifetime, the higher the operating costs incurred over time.
Performance trade-off against cost – The LCC technique not only focuses on cost but also considers other factors such as the quality of goods and the level of service provided.	**Technology** – Technology always changes day to day, making estimation uncertain.

Case Study Setup

A practical example is presented through a comparison of household lifetime costs between gasoline cars and EVs using LCA.



Gasoline Car vs Electric Car

Side-by-side comparison highlights how each option performs economically and environmentally.

Scenario 1: Electricity Prices

Explores how variations in electricity costs alter the long-term economic outcomes of owning an EV.

Social and Environmental Justice Issues

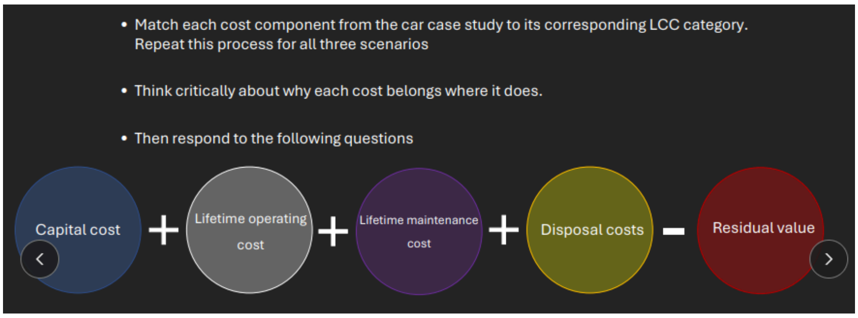
Although EVs are cheaper over their lifecycle, high upfront costs exclude many low-income households from accessing these savings. This highlights the importance of equity when interpreting results.

Scenario 2: Leasing

Leasing is explored as an alternative ownership model. A life-cycle cost analysis of leasing can show whether this model lowers barriers to EV access.

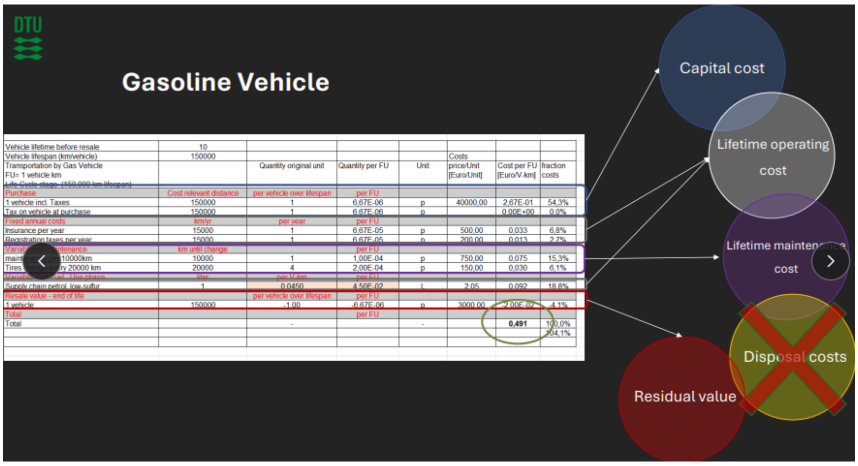
Result and Theory of Fairness

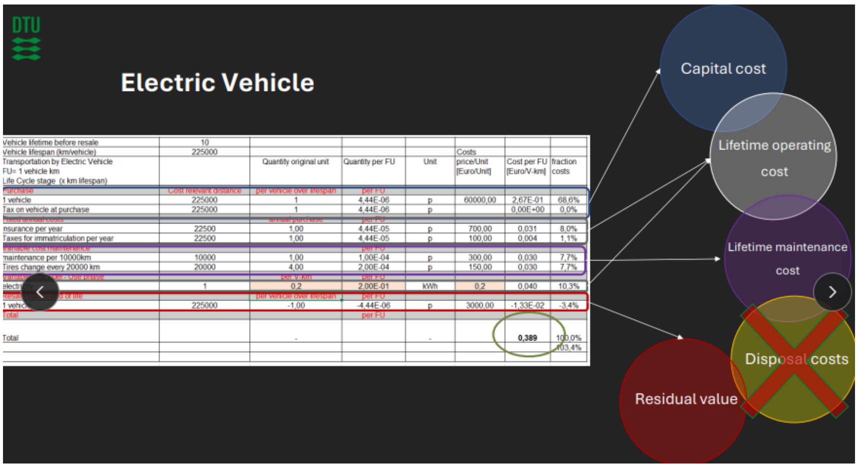
Sam Vimes' "Boots" theory of socioeconomic unfairness is introduced: people with fewer resources are forced to buy cheaper, lower-quality goods repeatedly, ultimately spending more in the long run. Similarly, EV affordability highlights how long-term savings may remain inaccessible to those unable to afford the initial investment.

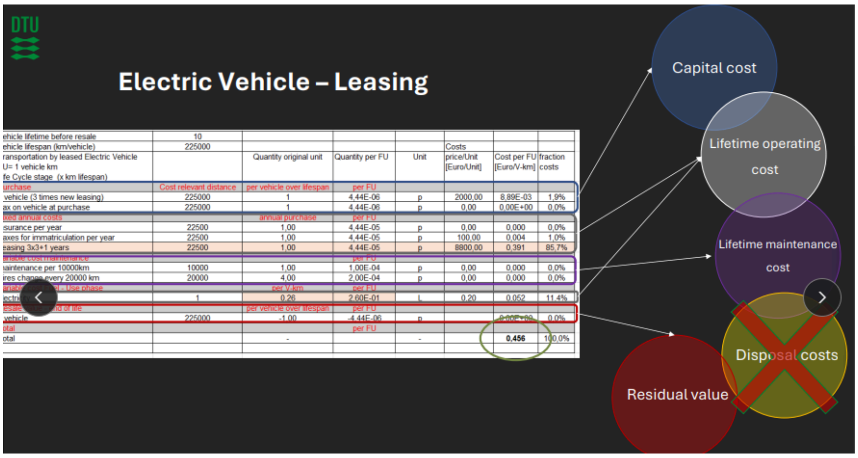


TIRE CHANGE → MAINTENANCE

ELECTRICITY & PETROL → lifetime operating cost







Economic feasibility and Scaling effects

- **Reduction of "per unit" fixed cost**
  - Increased production leads to the spread of the fixed cost over more output.
- **Reduction of "per unit" variable cost**
  - The scale expansion increases the efficiency of the production process.

BUT… What is the connection?

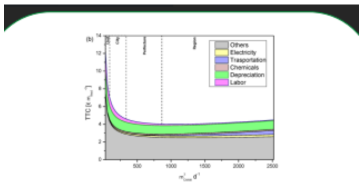
$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n$

- C_t= Cost in scale ttt
- S_t= Capacity in scale ttt

- n= Scaling factor ≈ 0.67 (two-thirds rule)

Figures shown:

- Graph of cost per unit decreasing with increased capacity (showing components: Others, Electricity, Transportation, Chemicals, Depreciation, Labor).
- Diagrams:
  - Economic cost decreases with experience (FOAK → NOAK).
  - Technological performance increases with experience.
  - Environmental impact decreases with experience.



Sustainability assessment tools Finland.pdf

SUSTAUNABILITY ASSESSEMENT TOOLS FINLAND

Companies are central to sustainable economic systems since they generate environmental impacts, economic activity, and social development. Many tools exist to assess sustainability, but their fit for company-level use is less clear. The study reviews seven tools —MCDA, MFA, LCA, IO models, sustainability indicators, CBA, and optimisation—and evaluates their comprehensiveness. It also looks at how Finnish companies actually use them. MCDA appears most promising but still requires input from other methods. In practice, Finnish firms mostly use sustainability indicators and indices, with LCA occasionally applied in construction. There's a big gap between what research discusses and what companies use.

1. Introduction

The paper roots sustainability in the Brundtland definition and Rio 1992. Companies are key actors, but they both face challenges (biofuel controversies, resource intensity) and opportunities (eco-innovation). Sustainability reporting is widespread, but actual strategic application is weaker. SMEs, which dominate in Finland (98% of enterprises), lack resources to use complex tools. Finland, while committed to ambitious sustainability targets, still shows high carbon footprints—making this a timely context to study tool use.

2. Material and Methods

The study has three parts: (1) evaluate common tools found in research, (2) review company use in Finland, (3) compare the two.

2.1 Tools to assess sustainability – a review

- **MCDA**: Helps compare alternatives with multiple objectives, handles trade-offs well, good for combining environmental, economic, and social aspects.
- **MFA**: Tracks material and energy flows through systems; good for quantifying but narrow in scope.
- **LCA & Life-cycle methods**: Covers cradle-to-grave impacts; extensions include LCC (economic), SLCA (social), LCSA (integrated). Widely standardised but often complex.
- **IO Models**: Map interdependencies across the economy; EEIO links consumption to environmental impacts. Often applied at regional or national levels.
- **Sustainability Indicators & Indices**: Simplify and communicate trends (e.g., CO_2, GDP). Widely used in reporting, but not analytical methods by themselves.
- **CBA**: Weighs costs and benefits in monetary terms; extended CBA can try to value ecosystem services, though controversial.
- **Optimisation**: Mathematical models to find "best" outcomes under constraints; strong for quantitative analysis, but often expert-driven.

2.2 The assessment criteria for the tools

Tools were evaluated under four dimensions:

- Transparency (clarity, negative aspects, justification, results),
- Flexibility (ability to adapt criteria, iterate, integrate new ideas),
- Consensus building (multiple perspectives, early engagement, conflict recognition),
- Operability (measurable criteria, trade-offs, actionable plans, uncertainty handling).

MCDA scored highly, but no single tool met all criteria.

2.3 The review of company-level sustainability assessment

Looked at 127 Finnish companies in energy, hotels/restaurants, mining, and construction. Checked sustainability reports and websites for evidence of tool use.

3. Results and Discussion

3.1 Assessment of tools in research

- MCDA, LCA, CBA, and optimisation perform fairly well across criteria.
- MFA and indicators/indices are less comprehensive.
- Each tool has strengths but also clear limitations—none alone is sufficient.

3.2 Tools applied by Finnish companies

Reality check:

- Indicators and indices are used by ~60–70% across sectors.
- LCA used only in construction (17%).
- Other tools (MCDA, MFA, IO, CBA, optimisation) almost never used.
- Larger companies tend to publish sustainability reports; SMEs rarely do.

3.3 Utilisation of tools to support assessments

Despite academic interest, companies rarely implement these tools. Possible reasons: lack of resources, expertise, or incentives. Transparency in reporting is also lacking.

3.4 Suggestions for future research

Propose "company-oriented sustainability trials" where experts help firms run streamlined versions of tools. Web-based simplified tools (e.g., openLCA) could help bridge the gap, especially for SMEs.

3.5 Conclusions

No tool is comprehensive. Combining tools is often best (e.g., MCDA + LCA + CBA). Finnish companies mostly stick to indicators and reporting, with limited use of advanced methods. Bridging research and practice requires simplified tools, expert-company collaboration, and small-scale trials that make sustainability assessments feasible without heavy investment.

MarinePolicy_IO.pdf

The role of the marine sector in the Irish national economy: An input–output analysis

Karyn Morrissey & Cathal O'Donoghue (2013)

Introduction

Ireland had some estimates of the marine sector's direct value (about €1.44 billion GVA and 17,000 jobs in 2007), but these don't capture how marine industries connect with the wider economy. Sectors don't operate in isolation: they rely on suppliers (backward linkages) and provide inputs to others (forward linkages). Input–Output (IO) analysis, developed by Leontief, allows these linkages to be quantified. This study disaggregates Ireland's 2007 IO table to include 10 detailed marine subsectors (fishing, seafood processing, oil & gas, marine engineering, construction, boat building, maritime transport, auxiliary services, marine tourism, marine retail).

Data

To build the marine IO table, three data types were combined:

- **Type 1 (public)**: official statistics (e.g., fisheries, transport).
- **Type 2 (restricted)**: confidential census/survey data from the CSO (turnover, GVA, employment).

- **Type 3 (non-public)**: new company surveys for sectors not captured in national datasets (e.g., marine tourism, marine retail).

Methodology

Standard IO models link sectoral inputs and outputs mathematically (Leontief inverse). Backward linkages measure how much a sector pulls from upstream suppliers. Forward linkages (via Ghosh model) measure how much a sector pushes into downstream production. Multipliers (for production and employment) show ripple effects of a €1 or €100,000 investment.

Results

Linkages within the marine sector

Three marine subsectors were among the strongest in Ireland for backward linkages:

- **Seafood processing** (1.26)
- **Maritime transport** (1.09)
- **Water construction** (1.06)

This means each euro of output induces significant upstream demand. For example, €1 of seafood processing generates €0.26 in supplier demand (most through indirect supply chains).

Forward linkages

Only maritime transport had strong forward linkages (1.20). This reflects Ireland's dependence on shipping for imports and exports—other sectors rely heavily on it as an input. Other marine sectors sell mainly to final consumers (e.g., tourism, retail) and thus have weak forward linkages.

Production-inducing effects

Overall, the marine sector had a production multiplier of 6.31. That means every €1 invested in marine industries generated €6.31 across the economy. The biggest spillovers were to **construction, financial services, and wholesale trade**—three of Ireland's largest sectors.

Employment-inducing effects

Water construction ranked very high nationally: every €100,000 invested created 0.9 full-time jobs (FTE). Across the 10 marine subsectors combined, about 3 FTEs per €100,000 invested were supported. The strongest downstream job effects were again in construction and business services, showing marine industries fuel broader employment.

Using the I–O framework for policy analysis

By quantifying which sectors have strong linkages, IO analysis identifies where public investment could have the biggest impact. For example:

- **Maritime transport** emerges as a strategic cluster candidate (ties to IT, insurance, finance, exports).
- **Seafood processing and water construction** also show high backward pull on domestic suppliers.
- Employment benefits are larger than expected in services and knowledge-based marine sectors, not just fishing and aquaculture.

Discussion

Although the marine sector contributed only ~1% of GVA in 2007, IO analysis shows it has **high backward linkages, strong multipliers, and notable employment effects**. Its future potential lies not just in traditional fishing or shipping, but in innovation areas like marine biotech, renewable energy, and marine education/R&D. Policymakers can use these findings to design regional marine clusters, target investment, and create coherent strategies (e.g., Ireland's *Sea Change Strategy*).

This paper shows how IO models reveal the hidden connective tissue of an economy. The Irish marine sector, modest in size, turns out to be a surprisingly powerful lever when viewed through linkages and multipliers.

SAMS_Mauritius_pub.pdf

Exploring the distributional impact of investment in the port sector on households in Mauritius: A social accounting matrix approach

Karyn Morrissey, Shakeel B. Burthoo-Barah, Mukesh Dawoonauth, Pasquale Lucio Scandizzo (2019)

Introduction

Mauritius is an upper middle-income country with strong growth, but also rising unemployment and inequality. The richest 20% of households earn almost half of national income, while the poorest 20% share just over 5%. The government wants the *Ocean*

Economy—its 2.3 million km² maritime zone—to drive both growth and equity. A major part of this strategy is investment in Port Louis, the country's main seaport. Ports are seen as growth engines globally, but their *distributional effects* (who actually benefits) are less studied. This paper asks:

1. What is the overall contribution of the port sector?
2. What are the short- and long-term economic impacts of new investments?
3. How are the benefits distributed across education groups and household income classes?

Proposed development scenarios for the Port Sector

The Port Master Plan (2016) sets out two scenarios:

- **Conservative scenario (US$1.089 billion over 10 years):** upgrades like a new container gate, an oil jetty, coal import facilities, fish landing complex, cruise terminal, marinas, and small breakwaters.
- **Optimistic scenario (US$1.332 billion over 20 years):** larger breakwater, petroleum hub, and new shipyard.

Both scenarios assume baseline investments (~US$520m) already underway. Port Louis handles 99% of Mauritius's trade and is key to trans-shipment, bunkering, and tourism.

Social Accounting Matrix (SAM)

A SAM is like an expanded Input–Output (IO) model but includes flows between households, government, and corporations. It can trace how investment shocks ripple through the economy, including distribution of wages and household income.

The Mauritian SAM (2015) is an **85×85 matrix** covering 30 activities, 30 goods/services, 7 income factors, 6 institutions, capital formation, rest of the world, and 7 environmental sectors. For this study:

- Labour income is split by education (primary, lower secondary, higher secondary, university).
- Households are split into **poor (deciles 1–2), lower middle (3–5), higher middle (6–9), and wealthy (10th decile)**.

Distributional aspects of a SAM

- **Short term:** modelled as a shock to the *construction sector* (during port building).
- **Medium/long term:** modelled as a shock to *maritime transport* (once port is operational).

This allows the study to see who gains at different stages.

Results

- **Short run (construction shock):**
  - Huge boost to output (US$4.5bn for conservative; US$5.5bn for optimistic).
  - Wages shift: employees with *primary education* see their share rise from 20% to 30%.
  - Poor households' share of income rises slightly (from 1% to 2%); lower-middle households also gain.
  - Wealthier households see their share stagnate or fall slightly.
- **Medium to long run (maritime transport shock):**
  - Again large yearly gains (US$4.5bn and US$5.5bn in output).
  - Wages now benefit mostly *university-educated workers* (44% share). Primary education workers' share drops to 17%.
  - Wealthy households increase their share from 33% to 36%, while poor households remain stuck at 1%.
  - Inequality therefore persists and may even worsen in the long term.

Discussion

Short-term port investment helps poorer groups (more construction jobs, lower-skilled work). But once operational, benefits concentrate among highly educated workers and wealthy households. This mirrors broader debates: growth doesn't automatically reduce poverty or inequality.

The authors recommend **complementary redistributive policies** (e.g., targeted training, fiscal transfers) if Mauritius wants its Ocean Economy expansion to deliver inclusive growth.

Methodologically, SAM has limitations: assumes fixed prices, constant returns, and no crowding-out effects. But for a country like Mauritius, with high unemployment and spare capacity, SAM is more realistic than CGE models for short-medium term analysis.

In short: the port sector can supercharge Mauritius's economy, but without redistribution policies, the gains will mostly flow to the top.

Method	What it does	Strengths	Weaknesses / Limits	Examples / Contexts
MCDA (Multi-Criteria Decision Analysis)	Compares options when multiple objectives (economic, social, environmental) must be weighed. Uses scoring and weighting to evaluate trade-offs.	Transparent trade-off handling, can integrate quantitative + qualitative data, flexible.	Needs expert/stakeholder input, can be subjective (weighting).	Academic review: seen as most comprehensive for company use. Useful in project prioritisation (e.g. energy, transport).
MFA (Material Flow Analysis)	Tracks physical flows of materials/energy in a system (input–output in tonnes, joules).	Clear picture of resource use, waste streams, circularity. Good for environmental accounting.	Narrow: does not cover economic or social aspects, mostly physical flows.	National economy-wide MFA accounts; used to link economy ↔ environment.
LCA (Life Cycle Assessment)	Assesses environmental impacts of a product/system "cradle-to-grave" (from raw materials to disposal).	Standardised (ISO), widely recognised, holistic environmental view.	Complex data needs; typically focused on environment, less on cost/social.	Gasoline vs EV case study (lecture). Widely used in construction, manufacturing.
LCCA (Life Cycle Cost Assessment / Costing)	Calculates total costs over lifetime: purchase, operation, maintenance, disposal.	Good for financial decision-making, complements LCA. Useful to compare ownership vs leasing.	Does not include environmental/social impacts unless combined with other tools.	Applied in EV vs gasoline cost comparison. Common in infrastructure/project finance.
CBA (Cost–Benefit Analysis)	Expresses all costs and benefits (ideally including environmental/social) in monetary terms.	Simple economic decision rule (if benefits > costs, do it). Can integrate results from LCA/IO.	Monetisation of non-market impacts (e.g. ecosystem services) is controversial. Risk of ignoring distributional issues.	Used in policy appraisal, environmental projects, transport projects.
Indicators & Indices	Aggregate data into simplified measures (e.g., CO_2 per capita, HDI, sustainability indices).	Easy communication, tracking trends over time.	Not analytical tools; may hide trade-offs and complexity.	Most common in Finnish companies (60–70% use). Widespread in sustainability reporting.
Input–Output Models (IO / EEIO)	Economic tables showing inter-sector linkages; Environmentally Extended IO adds resource/emission flows.	Captures ripple effects (direct, indirect impacts). Can calculate multipliers for GDP, jobs, emissions.	National/regional scale; less detail at company level; assumes fixed technology, no price effects.	Ireland marine economy IO (seafood, shipping, construction). Finnish review.
SAM (Social Accounting Matrix)	Expanded IO that includes households, government, institutions, distribution of income.	Shows how benefits are distributed across groups (poor vs rich, low vs high education).	Still linear, no price responses; can overestimate short-term effects.	Mauritius port sector study: showed poor gain short-term, rich gain long-term.
Optimisation Models	Mathematical models that search for the "best" solution under constraints (minimise cost, maximise sustainability).	Strong for quantitative planning (energy, logistics, waste).	Data-intensive, technical, often inaccessible to SMEs, "black-box" feel.	Mentioned in reviews as academic-heavy; not widely used in Finnish companies.

6. Planetary Boundaries and Absolute Sustainability

Date	@October 7, 2025
Status	Done

In this module about Planetary boundaries and absolute sustainability the focus is on:

1. Understanding the need for an absolute sustainability perspective on technology and how to quantify the sustainability challenge to our technology
2. Understanding the planetary boundaries as a framework for evaluation of absolute sustainability
3. Understanding the use of absolute environmental sustainability assessment methods (AESA) .. and importantly
4. Applying an absolute sustainability assessment on the mobility exercise from previous modules

Studies before teaching session:

10.1 From relative to absolute sustainability

Read the article Sustainability in manufacturing – relative and absolute perspectives with specific focus on Sections 2 and 3.

Watch video lecture: From relative to absolute sustainability

10.2 Planetary boundaries and absolute sustainability

Read the article Planetary boundaries: Guiding human development on a changing planet for a presentation of the Planetary boundaries framework.

Watch video lecture: Planetary boundaries and absolute sustainability

10.3 Absolute Environmental sustainability assessment methods

Watch video lecture: Absolute environmental sustainability assessment (AESA) for assessing absolute environmental sustainability

Read the article Reflecting the importance of human needs fulfilment in absolute sustainability assessments for a deeper understanding of the allocation step of the AESA method and ethical considerations behind different allocation principles.

10.4 Absolute environmental sustainability metrics

For an introduction of other absolute metrics for environmental sustainability, watch video lecture: Examples of other absolute sustainability metrics

Teaching session:

In the teaching session we will discuss central elements from the lectures that you have watched and we will work on an absolute environmental sustainability assessment of different mobility forms, building on the electromobility exercise from previous modules. Based on your results, we will discuss the potential for future individual transport systems that are sustainable in absolute terms and not just better than what we have today.

From Relative to Absolute Sustainability

1. The Sustainability Challenge

The lecture opens with the **IPAT equation**, a fundamental relationship describing environmental impact:

$I = P \times A \times T$

Where:

- **I** = Environmental impact
- **P (Population)** = number of people
- **A (Affluence)** = material standard of living (consumption per person)
- **T (Technology)** = environmental impact per unit of GDP or created value

This model was introduced by Ehrlich & Holdren (1971) and later refined by Commoner (1972) and Graedel & Allenby (1995).

Meaning:

Even if technology improves (lower T), if population and affluence keep increasing, total environmental impact (I) may still rise. This is the core sustainability dilemma.

Trends mentioned:

- Global population is projected to stabilize around **10 billion**.
- **Affluence** (especially in industrializing nations) continues to grow rapidly.
- Many current environmental impacts already **exceed sustainable levels** (climate change, biodiversity loss, etc.).

Thus, the challenge becomes:

> "How can we decouple growth in population and wealth from environmental degradation?"

2. Eco-Efficiency

Eco-efficiency expresses how effectively we deliver value with minimal environmental harm.

It is **the reciprocal of the technology factor (T)** in the IPAT equation.

$$\text{Eco-efficiency} = \frac{\text{Delivered Service or Value}}{\text{Environmental Impact}} = \frac{1}{T}$$

Eco-efficiency=Environmental ImpactDelivered Service or Value=T1

So, improving technology to lower emissions per product or service **increases eco-efficiency**.

Example:

Switching from incandescent bulbs to LEDs dramatically improves eco-efficiency because it delivers the same light with less energy.

Measurement tool:

Eco-efficiency is quantified through **Life Cycle Assessment (LCA)** — evaluating total environmental impact across a product's full life cycle.

Key message:

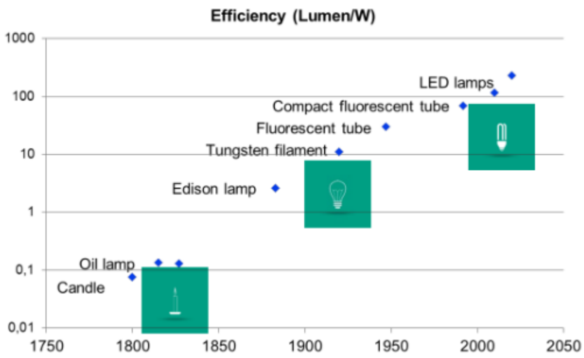
To maintain or improve quality of life while the population and economy grow, eco-efficiency must increase **much faster** than affluence and population.

3. Developments in Efficiency – The Lighting Example

Reference: Franceschini, S. (2015), *Eco-innovation dynamics and sustainability*.

Lighting technologies illustrate the progress in eco-efficiency:

- Transition from **candles → incandescent → fluorescent → LED** reduced energy use per lumen drastically.
- Yet total **global light consumption increased** as light became cheaper and more accessible — a **rebound effect**.



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4. Development in Consumption

Even though lighting efficiency improved enormously, **the total global energy spent on light** has remained relatively constant for centuries:

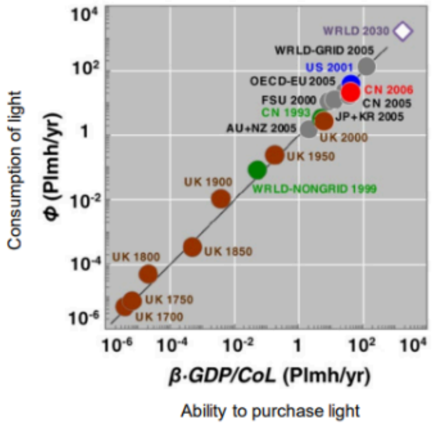
- Around **0.72% of world GDP** goes to light.
- About **0.54% of GDP** is used for energy associated with lighting.

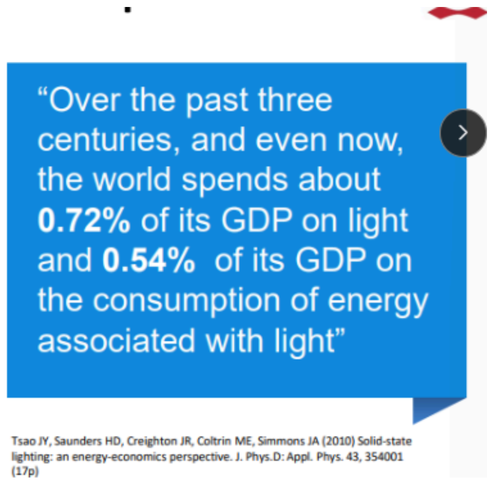
(Source: Tsao et al., 2010)

Insight:

Efficiency gains often lead to increased consumption (people use more because it's cheaper). This is known as the **Jevons Paradox**.

So, improving eco-efficiency alone doesn't guarantee sustainability.





5. Relative vs Absolute Sustainability

- **Relative sustainability** compares alternatives:

  "Product A is *more sustainable* than Product B."

  LCA is excellent for this — it quantifies **relative improvements** (less impact per unit).

- **Absolute sustainability** asks:

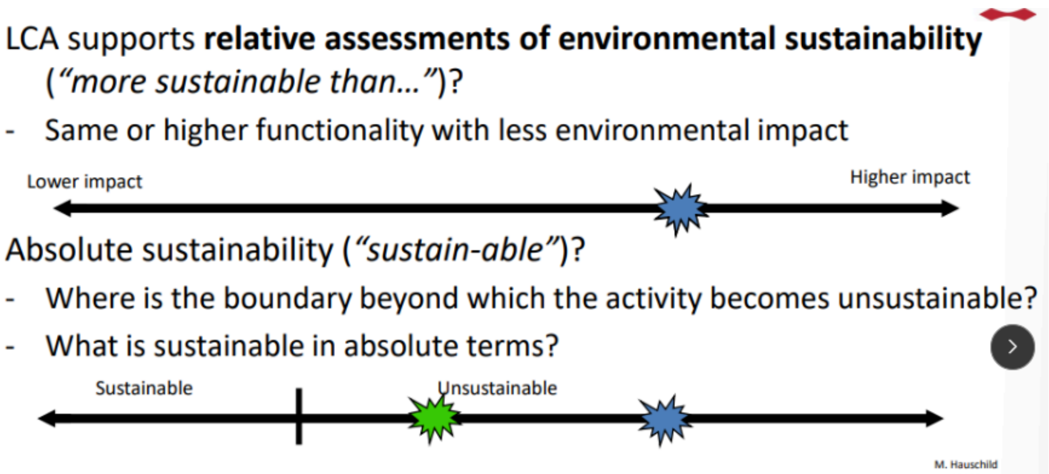
  "Is this activity sustainable in an absolute sense?"

  That means checking whether total environmental impact stays **within planetary limits**.

Example:

You can reduce emissions by 30%, but if the safe limit for the system is already surpassed, even that reduced level is still **unsustainable**.

This moves the question from **"better than before"** to **"safe enough for the planet."**



6. A Sustainable Level of Impact

Sustainability means meeting present needs **without compromising** the ability of future generations to meet theirs.

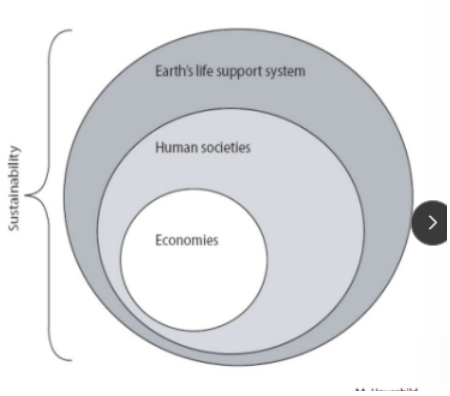
But what exactly are "needs," and for how many people?

Here enters the **Planetary Boundaries (PB)** concept — a **top-down approach** defining the *maximum sustainable level of environmental impact* Earth can tolerate before crossing dangerous thresholds.

Examples of boundaries include:

- Climate change (CO_2 concentration, radiative forcing)
- Nitrogen and phosphorus cycles
- Land-system change
- Freshwater use
- Biodiversity loss

By quantifying safe operating limits, PBs provide the **absolute reference points** missing in traditional LCAs.



- **Eco-efficiency** = created value / environmental impact.
- Sustainability demands massive gains in eco-efficiency.
- **Relative sustainability** (LCA-based) helps choose better options.
- But we must adopt an **absolute sustainability** perspective — ensuring our total impact remains within the Earth's ecological capacity.
- The **Planetary Boundaries framework** provides a scientific way to define these absolute thresholds.
- Ultimately, sustainability requires not just doing *less harm*, but doing **enough good to remain within safe planetary limits** — i.e., becoming **eco-effective**, not merely eco-efficient.

IPAT equation → need for eco-efficiency → limits of relative comparison → planetary boundaries → absolute sustainability

This shift parallels the move in environmental science from *"doing things better"* to *"doing things within limits."*

Sustainability in Manufacturing – Relative and Absolute Perspectives.

1. Overview

- **Author:** Prof. Michael Zwicky Hauschild
- **Institution:** Technical University of Denmark, Head of Centre for Absolute Sustainability
- **Conference:** IMEC 2022 – Japan Machine Tool Builders' Association
- **Goal:** To define what *sustainable manufacturing* really means when judged not only by efficiency, but by **planetary limits**.

---

2. Core Idea

Hauschild argues that:

> It is not enough for technology or manufacturing to become more sustainable — it must be sustainable in absolute terms.

Even as eco-efficiency (service per environmental impact) improves, total global impact keeps increasing due to growing population and affluence.

Therefore, industry must shift from *relative comparisons* ("better than before") to *absolute thresholds* ("within safe planetary limits").

---

3. Definitions of Sustainability

a) **Brundtland Definition (1987)**

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

This focuses on *human needs*, but is vague about:

- Which needs (basic vs luxury)
- How many people
- Environmental preconditions

b) **Triple Bottom Line (John Elkington, 1997)**

- Sustainability = balance between:
  - **People** (social)
  - **Planet** (environment)
  - **Profit** (economic)

This business-oriented model separates the three dimensions but treats them as equal.

c) Planetary Boundaries and Absolute Sustainability

- Modern sustainability thinking *nests* economy and society **within** the environment (not next to it).
- The **environment sets limits**—the economy and society must function inside those biophysical constraints.

This shift is illustrated as:

- **Old model (A):** Three independent "pillars."
- **New model (B):** Nested systems — planet → society → economy.

---

4. Historical Development of Absolute Limits

Limits to Growth (Meadows et al., 1972)

- First to simulate human–environment interactions.
- Predicted three possible futures:
  1. **Stabilized world** (sustainable feedback)
  2. **Overshoot and collapse** (the dominant trend without intervention)
- Introduced the idea of *finite Earth systems* and resource limits.

Paris Agreement (2015)

- Sets an **absolute limit**: keep global temperature rise **below 1.5 °C**.
- Represents a *quantified environmental boundary*—a condition for planetary stability.

Planetary Boundaries Framework (Rockström, Steffen et al.)

- Identifies **nine critical Earth system processes** that regulate climate and ecosystems:
  1. Climate change
  2. Biosphere integrity (biodiversity)
  3. Land-system change
  4. Freshwater use
  5. Biogeochemical flows (nitrogen, phosphorus)
  6. Ocean acidification
  7. Stratospheric ozone depletion
  8. Atmospheric aerosols
  9. Novel entities (chemical pollution)

Exceeding these thresholds risks destabilizing Earth's systems.

Currently, **at least three are already beyond safe levels.**

---

5. The Sustainability Challenge – Quantitative View

The **IPAT equation** formalizes the problem:

$$I = P \times A \times T$$

Where:

- **I** = Environmental impact
- **P** = Population
- **A** = Affluence (GDP per person)
- **T** = Technology (impact per GDP)

To keep impact within limits, **T must fall sharply** as P and A rise.

Example: Climate Change

If emissions in 2030 must be half of 2020 levels,

and population +10%, GDP +30%, then:

$T_{2030} = \frac{I_{2030}}{P_{2030}A_{2030}} = \frac{0.5}{1.1 \times 1.3} = 0.35$

So **technology must become ~3× cleaner** in ten years to stay under 1.5 °C.

Some sectors may need reductions by factors of **4 to 50** depending on assumptions.

---

6. Eco-Efficiency and Life-Cycle Assessment (LCA)

Eco-efficiency is formally:

$\text{Eco-efficiency} = \frac{\text{Delivered Value or Function}}{\text{Environmental Impact}} = \frac{1}{T}$

Eco-efficiency=Environmental ImpactDelivered Value or Function=T1

Measured through **ISO 14045** and **LCA**, because:

- LCA covers **the full life cycle** (raw material → manufacturing → use → end of life).
- Avoids **problem shifting** (reducing impact in one stage while increasing it in another).
- Evaluates multiple **impact categories**: global (climate), regional (acidification), local (water, land).

Hauschild emphasizes the three **scopes of impact accounting**:

- **Scope 1:** Direct emissions from owned operations.
- **Scope 2:** Purchased energy.
- **Scope 3:** Upstream/downstream supply chain, including waste and transport.

A proper LCA aggregates all three to ensure completeness.

---

7. From Relative to Absolute Sustainability

Relative (Current Industry Focus)

- “More sustainable than what came before.”
- Driven by **eco-efficiency**.
- Example: lighting technology.
  - Efficiency improved by >100× from candles to LEDs.
  - Yet total electricity use for lighting **increased** (rebound effect).
  - Lower cost → higher use → **backfire effect**.

Absolute (Needed)

- Evaluates if total impact remains **within the global safe operating space**.
- Requires translating planetary limits into **company or product-level boundaries**.

Hauschild and colleagues (Bjørn, Ryberg, Hjalsted, etc.) developed methods to **allocate** the total pollution space among actors:

- **Grandfathering:** all reduce by same percentage (Science Based Targets).
- **Per capita allocation:** divide limits by population (Nykvist et al.).
- **Alternative ethical principles:** egalitarian, capability-based, etc. (Hjalsted et al. 2020).

Allocation choices greatly influence the results, as shown in **laundry-washing case studies**:

- Even with major efficiency gains, the scenario can remain unsustainable if it exceeds its allocated share of the safe operating space.

---

8. Key Figures Explained

Figure 1:

Evolution from “Triple Bottom Line” to “Nested Model” — environment as the ultimate constraint.

Figure 2:

The nine **Planetary Boundaries** and their safe operating zones.

Figure 3:

Life-cycle and Scope 1–3 system boundaries in eco-efficiency analysis.

Figure 4–5:

Allocation of the safe operating space to companies or sectors, demonstrating that sustainability depends on how the total planetary limit is divided.

9. Sustainable Manufacturing – Proposed Definition

> Sustainable manufacturing is manufacturing that helps meet the needs of present and future generations within the tolerance levels of our planet's regulating systems (climate and ecosystems).

So, manufacturing cannot be called sustainable in isolation — it must be judged by whether its **products enable sustainable lifestyles** and respect **planetary limits**.

10. Takeaways

1. **Eco-efficiency ≠ sustainability.** Efficiency alone can lead to rebound effects.
2. **Absolute sustainability** demands linking impacts to **scientific limits**.
3. **LCA** is the essential tool for measuring environmental intensity across life cycles.
4. **Allocation of safe operating space** is the next frontier — both ethical and methodological.
5. **Manufacturing's role**: provide human well-being while keeping total impacts inside the planetary boundary system.

Old Paradigm	New Paradigm
"Less bad"	"Good enough"
Relative improvement	Absolute threshold compliance
Triple bottom line	Nested Earth system model
Efficiency (T↓)	Effectiveness within limits
Decoupling focus	Planetary boundary alignment

Hauschild's message, in essence:

> Sustainability science must move from comparing shades of green to defining the green line we must not cross.

Planetary Boundaries and Absolute Sustainability

1. The Sustainability Challenge – Keeping the Planet in the Holocene

Hauschild begins by reminding us that human civilization evolved during the **Holocene epoch**, a period of remarkable climate stability over roughly 12,000 years.

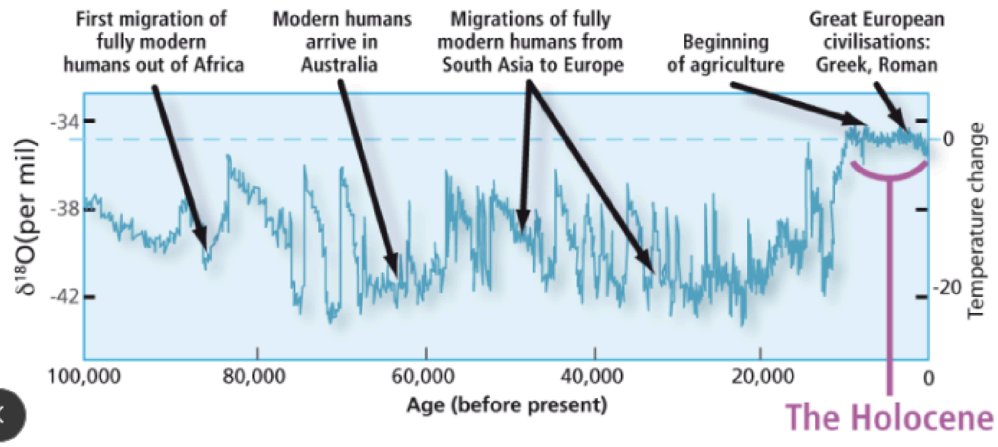
This stability is what allowed agriculture, urbanization, and complex societies to emerge.

However, human activity is now pushing the Earth into a new epoch — the **Anthropocene** — characterized by human-driven changes to climate and ecosystems.

Core idea:

The challenge of sustainability is essentially **to keep the Earth within the conditions of the Holocene**, because this is the only climate regime in which modern civilization has proven viable.

Reference: *International Geosphere-Biosphere Programme (IGBP)* – "Global Change / Anthropocene".



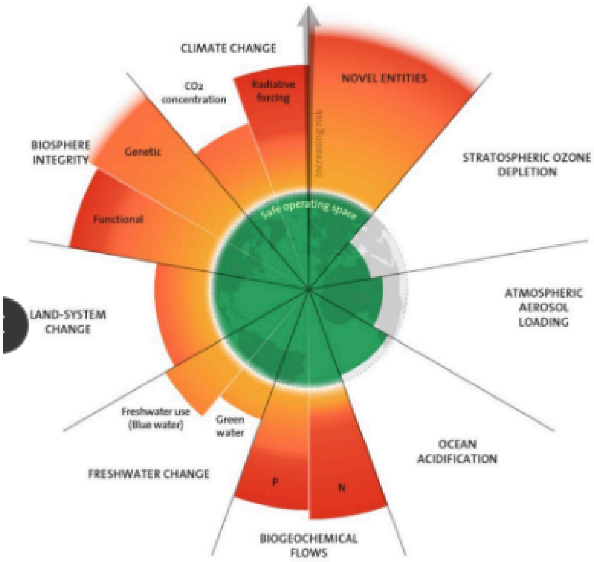
2. Planetary Boundaries (PBs)

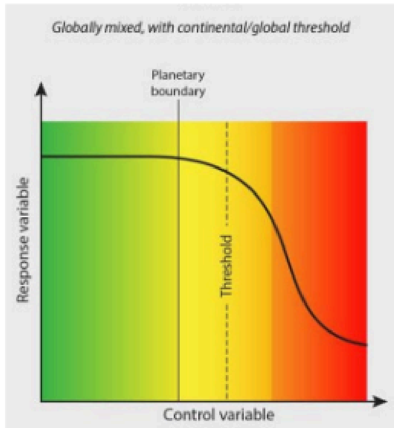
This concept, introduced by **Rockström, Steffen, Richardson, et al.** (2009, updated 2015 and 2023), provides a **scientific framework for defining the safe operating space for humanity**.

Definition

Planetary boundaries are **quantitative limits** on critical Earth-system processes that regulate the planet's stability.

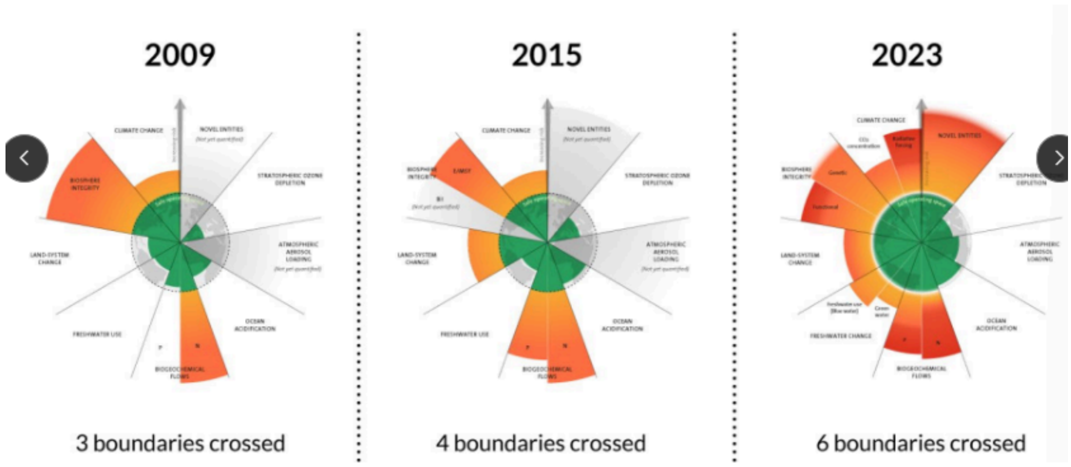
They mark the thresholds beyond which human activity could trigger **non-linear, potentially irreversible environmental change**.





Richardson K, Steffen W, Lucht W et al. (2023) Earth beyond six of nine planetary boundaries. Science Advances 9, eadh245.

if you increase the control variable you will pass the theresholds and see consequences. → feedback loops → stronger impacts



2023 → 6 boundaries crossed → growing risk → irreversible changes

3. The Nine Planetary Boundaries (Steffen et al., Science, 2015)

Each boundary represents an environmental process vital to Earth's self-regulation.

The 2015 framework identifies **nine** boundaries, of which several are already exceeded.

1. **Climate change** – measured via CO_2 concentration and radiative forcing.
2. **Biosphere integrity** – includes biodiversity loss and ecosystem degradation.
3. **Land-system change** – conversion of forests, croplands, etc.
4. **Freshwater use** – blue water withdrawals from rivers and aquifers.
5. **Biogeochemical flows** – disruption of nitrogen and phosphorus cycles.
6. **Ocean acidification** – linked to atmospheric CO_2 dissolution.
7. **Stratospheric ozone depletion** – due to synthetic halocarbons.

8. **Atmospheric aerosol loading** – particulate matter affecting climate and health.
9. **Novel entities** – chemical pollution (plastics, heavy metals, PFAS).

The **core boundaries** — *climate change* and *biosphere integrity* — are seen as **"planetary core systems"**, because they regulate all others.

4. Exceeding the Boundaries (2023 Update)

Richardson, Steffen, Lucht et al. (2023) report that **six out of nine boundaries have already been crossed**, indicating the Earth is now operating **beyond the Holocene stability zone**.

Breached boundaries include:

- Climate change
- Biosphere integrity
- Land-system change
- Biogeochemical flows (N & P)
- Freshwater use
- Novel entities

This means human activity has pushed the planet into an **unsustainable state**, with rising risks of abrupt, systemic collapse.

5. Absolute Sustainability

> **Meeting the needs of present and future generations within the biophysical boundaries of our climate and ecosystems — i.e., within the safe operating space of the Earth.**

This is the **bridge between Planetary Boundaries and sustainability science.**

Key idea:

- Relative sustainability asks *"is this better?"*
- Absolute sustainability asks *"is this enough?"*

Thus, a process or technology can only be sustainable if its **total impact remains within the global safe limits** derived from PBs.

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6. Absolute Boundaries for Social Sustainability

This slide raises a thought-provoking question:

> Can we also define absolute boundaries for social sustainability?

Whereas planetary boundaries are grounded in **natural science** (biophysical limits, measurable thresholds),

social sustainability involves **ethical and political negotiation** — defining fair access, well-being, and equity.

Hauschild contrasts:

- **Natural science:** measurable and model-based (CO_2 ppm, nitrogen flow, etc.)
- **Social science:** value-based and negotiated (justice, equality, decent living conditions).

This highlights a frontier in sustainability science: integrating **biophysical limits** with **social thresholds** (the "doughnut model" by Kate Raworth is an example).

to be sustainable we need to stay in the outer donut

- **Planetary boundaries** define the *limits* of pressure humanity can place on Earth systems that maintain stability.
- These boundaries include multiple dimensions, but the **core** are **climate change** and **biosphere integrity**.
- **Absolute sustainability** = fulfilling human needs today and in the future while staying **within** these planetary limits.
- The challenge is to translate these **global boundaries** into **sector, company, and product-level goals** (through LCA, eco-efficiency, and science-based targets).

Conceptual Connection with Lecture 1 and the 2022 Paper

Concept	Lecture 1	Lecture 2	2022 Paper
IPAT equation	Introduced (Impact = Population × Affluence × Technology)	Implicit background	Fully detailed
Eco-efficiency	Defined and linked to LCA	Replaced by planetary framing	Quantified via ISO 14045
Relative vs Absolute	Core topic	Revisited with planetary context	Expanded with allocation methods
Planetary Boundaries	Mentioned conceptually	Central framework	Integrated into manufacturing assessment
Holocene stability	Not discussed	Introduced as the "goal state"	Background for sustainability targets

Sustainability cannot be understood without planetary context.

The planet defines *what is possible*, and humanity must adapt its activities — including manufacturing, agriculture, and consumption — to remain within those physical limits.

That is **absolute sustainability**.

Planetary boundaries: Guiding human development on a changing planet

1. Overview

Purpose:

To update and expand the original **Planetary Boundaries (PB)** framework (first introduced in 2009 by Rockström et al.) and to provide a **scientific foundation for defining a "safe operating space for humanity."**

Core idea:

Earth's biophysical systems have limits. If human pressure pushes beyond these **boundaries**, the planet could leave the stable environmental conditions of the **Holocene** — the epoch during which modern civilization developed.

2. The Holocene and the Anthropocene

The **Holocene epoch** (last 11,700 years) provided unusually stable conditions: predictable temperature, rainfall, and sea levels.

This stability enabled agriculture, urbanization, and global economic expansion.

However, human activity has now become a **dominant geological force**.

We have entered the **Anthropocene**, an era where human actions (deforestation, greenhouse gases, nitrogen use, etc.) are reshaping planetary systems.

The challenge is to **maintain Holocene-like stability** even under this new human-dominated regime.

3. What Are Planetary Boundaries?

Planetary boundaries are **quantitative limits** for key Earth-system processes that regulate the planet's stability.

Crossing a boundary increases the risk of triggering **irreversible environmental change** and **tipping points**.

Each boundary defines:

1. A **control variable** (measurable indicator, e.g. CO_2 concentration, nitrogen fixation rate).
2. A **boundary value** (the proposed safe limit).
3. A **zone of uncertainty** (reflecting incomplete scientific knowledge).

When global indicators move beyond the safe zone, the corresponding boundary is considered **transgressed**.

4. The Nine Planetary Boundaries (2015 Update)

Earth-System Process	Control Variable(s)	Status (2015)	Notes
1. **Climate Change**	CO_2 concentration (ppm); Radiative forcing (W/m^2)	**Transgressed**	Core boundary; regulates energy balance of Earth.
2. **Biosphere Integrity**	(a) Genetic diversity (extinction rate) (b) Functional diversity (biosphere functioning)	**Transgressed**	Second core boundary; loss of species and ecosystems.

Earth-System Process	Control Variable(s)	Status (2015)	Notes
3. **Land-System Change**	% of global forest cover remaining	**Transgressed**	Deforestation altering surface reflectivity, water cycles.
4. **Biogeochemical Flows**	Nitrogen (N) & Phosphorus (P) cycles	**Transgressed**	Massive fertilizer use disrupts aquatic and terrestrial systems.
5. **Freshwater Use**	Blue water consumption (km³/year)	Within zone	Regional hotspots already critical.
6. **Ocean Acidification**	Mean surface ocean pH	Below boundary	Linked to CO_2 dissolution in seawater.
7. **Stratospheric Ozone Depletion**	O_3 concentration (DU)	Safe (recovered due to Montreal Protocol)	Success story of international environmental action.
8. **Atmospheric Aerosol Loading**	Particulate concentration	Unquantified	Regionally variable (e.g., South Asia).
9. **Novel Entities (Chemical Pollution)**	Concentration of synthetic compounds	Unquantified	Includes plastics, heavy metals, persistent organic pollutants.

Result:

By 2015, **four boundaries** were *beyond safe limits*:

- Climate change
- Biosphere integrity
- Land-system change
- Biogeochemical flows

Later studies (2023) show **six of nine** are now transgressed.

---

5. The "Core Boundaries" Concept

Two boundaries — **Climate Change** and **Biosphere Integrity** — are identified as **core** because they **fundamentally regulate the Earth system**.

Transgressing these could drive the planet into a new, less stable state that cascades across other systems.

They act like "planetary thermostats" — if these fail, stability in other boundaries becomes irrelevant.

---

6. Safe Operating Space for Humanity

The PB framework defines a **safe operating space**:

the range of environmental conditions within which human societies can continue to thrive.

It's **not about zero impact**, but about staying within the Earth's regenerative and buffering capacity.

Crossing boundaries doesn't guarantee disaster, but **increases the risk** of crossing **tipping points** (abrupt, irreversible change).

Analogy:

Think of each boundary as a guardrail on a winding mountain road — crossing it doesn't always mean immediate catastrophe, but it drastically increases the chance of falling off the cliff.

---

7. Interactions Among Boundaries

The boundaries are **interconnected**:

- For example, **land-use change** increases CO_2 emissions and decreases biodiversity.
- **Nitrogen pollution** can drive both **eutrophication** and **climate forcing** via nitrous oxide.
- Exceeding one boundary can make others easier to breach.

Hence, sustainability must consider the **Earth system as a whole**, not isolated sectors.

---

8. Importance for Policy and Sustainability Science

The PB framework provides a **scientific foundation for global sustainability goals**, including the UN's **Sustainable Development Goals (SDGs)**.

It shifts environmental governance from relative targets (e.g. "reduce emissions by 20%") to **absolute limits** ("stay below 1.5 °C").

Key policy implications:

- The **Paris Agreement (2015)** directly aligns with the climate boundary.
- National and corporate strategies (e.g. *Science-Based Targets initiative*) increasingly adopt PB logic.
- It connects **Earth-system science** with **economic planning** and **life-cycle assessment (LCA)**.

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9. Critiques and Challenges

- **Uncertainty:** Many boundaries are difficult to quantify (especially aerosols and novel entities).
- **Equity and ethics:** How should the global "safe space" be divided among nations and industries?
- **Complexity:** Interactions and feedbacks between systems are not yet fully understood.
- **Scalability:** Translating global boundaries into **regional, national, or company-level targets** remains complex (Hauschild and DTU researchers are working on this).

Despite these challenges, the framework remains the **most influential systems-based model** in sustainability science.

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10. Summary – What the Article Is About

This article establishes a **quantitative scientific framework for absolute environmental sustainability**.

It:

1. Identifies nine critical Earth-system processes.
2. Defines safe global limits for each.
3. Shows that human activity has already transgressed several of them.
4. Argues that maintaining Earth within these boundaries is essential for stable civilization.
5. Provides a foundation for integrating planetary limits into sustainability governance and industrial decision-making.

In essence:

> Steffen et al. (2015) is the scientific backbone of the "Planetary Boundaries" concept — the map of the Earth's ecological guardrails that define the safe operating space for humanity.

AESA for Assessing Absolute Environmental Sustainability

The lecture shows how **absolute sustainability**—staying within the Earth's biophysical limits—can be **quantified** for human activities, industries, or products.

The key idea is to link **LCA results** (which measure environmental impacts) with **Planetary Boundaries** (which define safe operating limits).

This combination forms **AESA**, a method to check if an activity is sustainable *in absolute terms*, not just "better than before."

What Is AESA? (Absolute Environmental Sustainability Assessment)

Definition:

AESA is a framework that evaluates whether the environmental impacts of an activity stay within its **allocated share** of the **safe operating space** defined by Planetary Boundaries (PBs).

Core Principle:

> Sustainability = Environmental impact ≤ Assigned share of the global safe operating space.

It uses **Life Cycle Assessment (LCA)** as its analytical foundation.

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3. Steps for Performing AESA

Hauschild summarizes the AESA procedure in four key steps:

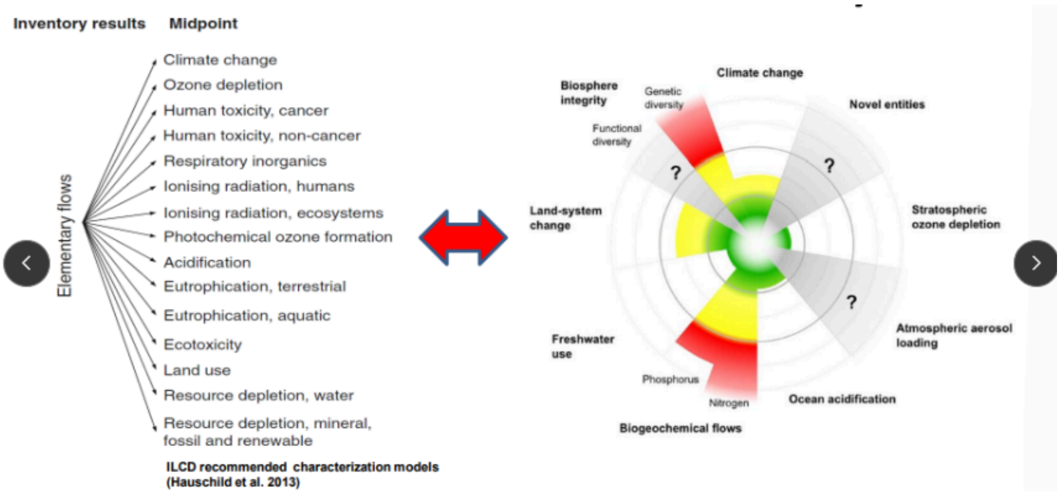
1. **Identify Biophysical Boundaries & Determine Safe Operating Space**
   - Use the **Planetary Boundaries framework** (Steffen et al., 2015) or LCIA (Life Cycle Impact Assessment) models.
   - Example: climate boundary (CO_2 limit), nitrogen boundary (total N fixation).
2. **Allocate the Safe Operating Space to Different Activities**
   - Distribute the global boundary among countries, sectors, companies, or products using ethical or practical allocation principles.
3. **Calculate the Impact Profile Using LCA**
   - Perform a complete **life cycle assessment** of the product or activity (including raw materials, production, use, disposal).
4. **Compare Impact vs. Allocated Space**
   - If the life-cycle impacts stay below the allocated space → **sustainable**.
   - If they exceed it → **unsustainable**.

4. Identifying the Boundaries

The "Where is the boundary?" slide refers to **ILCD-recommended characterization models** (Hauschild et al., 2013).

These models define how to measure environmental pressures (e.g., CO_2-equivalent, eutrophication potential, toxicity) in consistent, comparable ways across impact categories.

This step ensures that the boundaries chosen are **scientifically robust** and align with existing **Life Cycle Impact Assessment (LCIA)** methods.



5. Planetary Boundaries and LCIA

Key references:

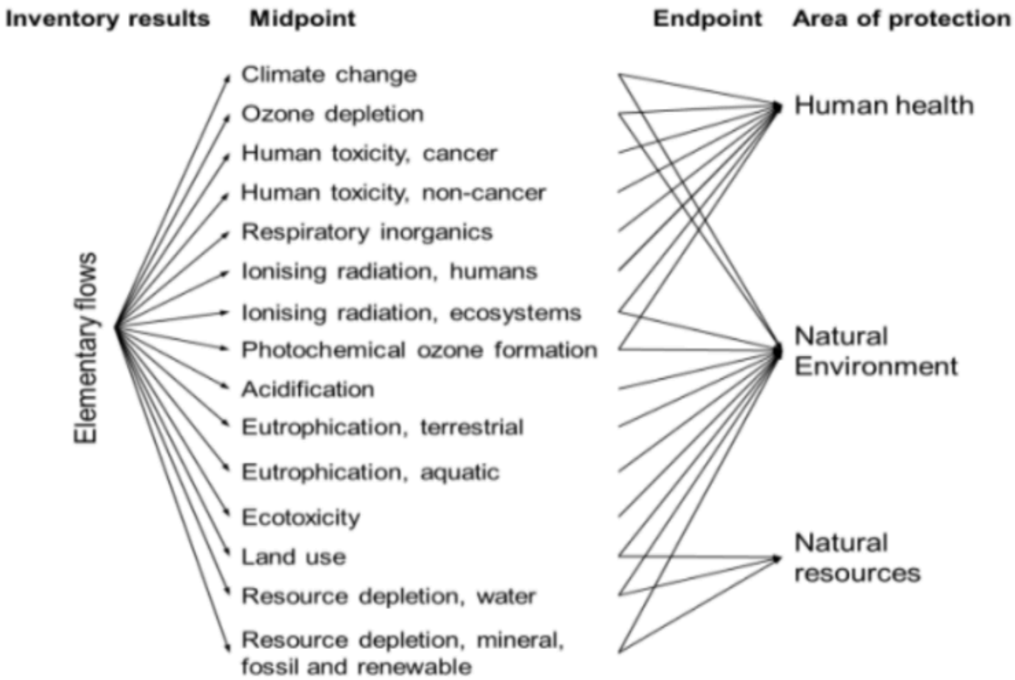
- **Ryberg et al. (2016):** Discusses challenges in integrating Planetary Boundaries into LCA.
- **Hauschild et al. (2013):** Defines best practices for characterization modeling in LCA.

Main challenge:

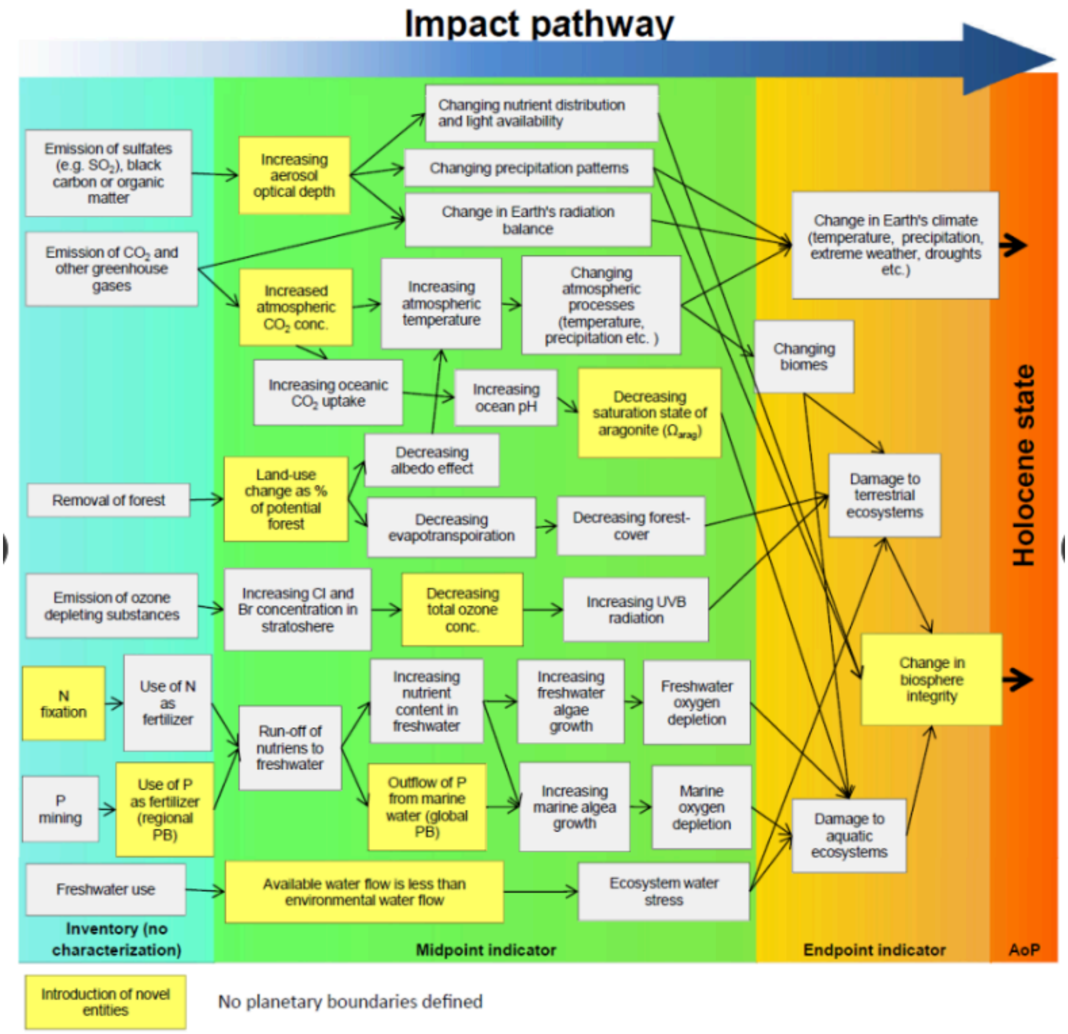
PBs are defined at a **global scale**, while LCAs typically operate at a **product or company level**.

Bridging this gap requires:

- Clear boundary translation (global → local, company → product).
- Ethical principles for how much "environmental space" each actor can use.



Inventory results
Midpoint
Endpoint
Area of protection
Elementary flows
Climate change
Ozone depletion
Human toxicity, cancer
Human toxicity, non-cancer
Respiratory inorganics
Ionising radiation, humans
Ionising radiation, ecosystems
Photochemical ozone formation
Acidification
Eutrophication, terrestrial
Eutrophication, aquatic
Ecotoxicity
Land use
Resource depletion, water
Resource depletion, mineral, fossil and renewable
Human health
Natural Environment
Natural resources



Impact pathway
Emission of sulfates (e.g. SO_2), black carbon or organic matter
Emission of CO_2 and other greenhouse gases
Removal of forest
Emission of ozone depleting substances
N fixation
Use of N as fertilizer
P mining
Use of P as fertilizer (regional PB)
Freshwater use
Increasing aerosol optical depth
Changing nutrient distribution and light availability
Changing precipitation patterns
Change in Earth's radiation balance
Increased atmospheric CO_2 conc.
Increasing atmospheric temperature
Changing atmospheric processes (temperature, precipitation etc.)
Increasing oceanic CO_2 uptake
Increasing ocean pH
Decreasing saturation state of aragonite (Ω_{arag})
Decreasing albedo effect
Land-use change as % of potential forest
Decreasing evapotranspoiration
Decreasing forest-cover
Increasing Cl and Br concentration in stratoshere
Decreasing total ozone conc.
Increasing UVB radiation
Run-off of nutriens to freshwater
Increasing nutrient content in freshwater
Increasing freshwater algae growth
Freshwater oxygen depletion
Outflow of P from marine water (global PB)
Increasing marine algea growth
Marine oxygen depletion
Available water flow is less than environmental water flow
Ecosystem water stress
Change in Earth's climate (temperature, precipitation, extreme weather, droughts etc.)
Changing biomes
Damage to terrestrial ecosystems
Change in biosphere integrity
Damage to aquatic ecosystems
Holocene state
Inventory (no characterization)
Midpoint indicator
Endpoint indicator
AoP
Introduction of novel entities
No planetary boundaries defined

6. Allocating the Safe Operating Space

The allocation step is critical and conceptually complex.

Different principles exist to decide how the **global safe space** is divided among actors.

Allocating the Safe Operating Space

Name	Description	Ethical Norm (Tentative)
Equal per capita (EPC)	Each person (or actor) gets the same share of the safe operating space, regardless of wealth or responsibility.	**Egalitarian**
Capability to reduce (CR)	Shares are smaller for those with greater financial/technological capacity — i.e., richer regions get less allowance.	**Prioritarian**
Historical debt (HD)	Shares are smaller for regions with higher past cumulative environmental impacts.	**Prioritarian**
Grandfathering (GF)	Shares are proportional to each actor's environmental impact in a reference year — everyone reduces by the same fraction.	**Inegalitarian**
Economic value added (EVA)	Shares are proportional to economic output — those who contribute more to GDP get a larger share.	**Utilitarian**
Cost efficiency (CE)	Shares are inversely proportional to the cost of reducing emissions — allocate reductions where they're cheapest to achieve.	**Utilitarian**
Final consumption expenditure (FCE)	Shares are proportional to total consumer spending — those who consume more get a larger share.	**Utilitarian**

Interpretation

- **Egalitarian (EPC)** → fairness by equality (each human equal right).
- **Prioritarian (CR, HD)** → fairness by responsibility and capacity; the rich or historically polluting must do more.
- **Utilitarian (EVA, CE, FCE)** → maximize efficiency or welfare given limited space.
- **Inegalitarian (GF)** → preserves the status quo — easiest politically, least fair ethically.

Performing AESA

- Identify biophysical boundaries and determine safe operating spaces
    - PBs or LCIA
- Allocate the safe operating space to different activities
- Calculate the impact profile of the activity using LCA
- Compare impact and allocated space

Key Studies and Principles:

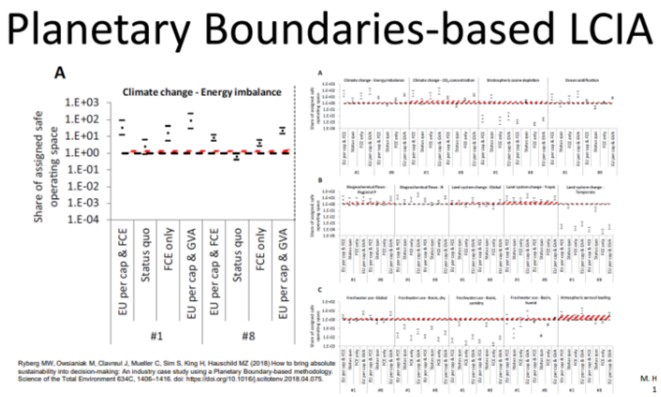
1. **Hjalsted et al. (2021):**
    - Explores **ethical allocation principles** to operationalize PBs at individual and industrial levels.
    - Allocation can be based on:
        - Population (equal per capita rights)
        - Economic output (contribution to GDP)
        - Historical responsibility (polluter-pays principle)
        - Capability (ability to reduce emissions)
2. **Bjørn et al. (2020):**
    - Reviews all **life-cycle–based methods** for AESA.
    - Summarizes advantages, limitations, and ongoing challenges for implementing PB-based assessments in real-world cases.
3. **Ryberg et al. (2018):**
    - **Demonstrates a case study where PB-based LCA is applied to industry.**
    - Shows how to bring absolute sustainability into **decision-making** by comparing product-level impacts to allocated global limits.

7. Planetary Boundaries-Based LCIA

This is the **operational version** of AESA:

- Integrates PB thresholds directly into LCIA models.
- Each environmental impact category (climate, eutrophication, land use, etc.) is compared to a **reference limit** derived from planetary boundaries.
- The outcome shows **which processes exceed their safe share.**

In simple terms, this approach transforms LCA results from “relative” numbers (kg CO_2) into “absolute” sustainability statements (e.g., “this product uses 3× more than its fair share of the climate boundary”).



Graph A – Climate Change (Energy Imbalance)

Y-axis: Share of the assigned *safe operating space* used by laundry washing (log scale).

Red dashed line (= 1) → sustainability threshold.

Values above 1 mean *unsustainable* (exceeding allocated share); below 1 means *within limits*.

X-axis: Allocation principles tested for two scenarios:

- **#1:** Current conditions (baseline).
- **#8:** Future scenario with eco-efficiency improvements (cleaner energy, better detergents, etc.).

Allocation methods:

- **EU per capita + FCE** – per person and consumption-based
- **Status quo** – current emissions
- **EU per capita + GVA** – per person and GDP-based

- Under *most allocation principles*, laundry washing exceeds the assigned safe space (above red line).
- Even with eco-efficiency improvements (#8), only some scenarios fall below 1 — meaning still not fully sustainable.
- **Choice of allocation principle changes the conclusion**:
  - Using **per capita** or **FCE** (egalitarian/utilitarian) → larger fair share → potentially sustainable.
  - Using **status quo** or **GVA (economic-based)** → smaller fair share → unsustainable.

Graph B and C (Full figure in paper)

They show the same comparison across multiple Planetary Boundary categories:

- **B:** Biogeochemical flows (nitrogen & phosphorus)
- **C:** Freshwater use

Across all PBs, **results vary widely**:

- For some impact types (e.g., phosphorus), all scenarios exceed limits.
- For others (e.g., freshwater), some allocation rules permit sustainability.

Interpretation

This study demonstrates **why allocation ethics matter** in AESA:

- Different “fairness” principles → different sustainability verdicts.
- A product may appear *green* or *unsustainable* purely due to the chosen distribution logic.

- Therefore, transparency in allocation choice is essential for credibility.

Main Points

- **AESA = LCA + Planetary Boundaries.**
- It allows **quantitative evaluation** of whether an activity is absolutely sustainable.
- **Four steps:** define boundaries → allocate → calculate impacts → compare.
- **Allocation** is the most challenging and ethically sensitive part.
- AESA covers **all environmental impact categories**, not just climate.
- The goal is to make sustainability **measurable in absolute terms**, enabling industries and policymakers to check if they operate *within planetary limits.*

Lecture	Focus	Key Idea
1 – From Relative to Absolute Sustainability	IPAT equation, eco-efficiency	We must move beyond "more sustainable than before."
2 – Planetary Boundaries and Absolute Sustainability	PB framework, Holocene stability	Sustainability means staying within Earth's safe operating space.
3 – AESA	Implementation via LCA	How to measure and test absolute sustainability quantitatively.

Heide, Hauschild & Ryberg (2023) – *"Reflecting the importance of human needs fulfilment in absolute sustainability assessments: Development of a sharing principle."*

Goal of the study:

To create a *new sharing principle* for AESA — one that connects a product's environmental impact to its *contribution to human well-being* (rather than only to its economic value).

This new method is called the **Fulfilment of Human Needs (FHN) principle**.

Problem being solved:

When calculating if a product is *absolutely sustainable*, we must decide how to **allocate the global "safe operating space" (SoSOS)** — the environmental capacity allowed by planetary boundaries — to individual products or sectors.

Current allocation rules (like per capita or economic value) fail to reflect *how important the product is to fulfilling basic human needs*.

Innovation:

The FHN principle operationalizes the ethical theory of **sufficientarianism** — ensuring that everyone gets "enough" to live decently within planetary limits.

2. Context

Absolute Environmental Sustainability Assessment (AESA)

- AESA evaluates whether a product or activity stays within its *fair share* of the global safe operating space.
- It builds on Life Cycle Assessment (LCA) and the Planetary Boundaries framework.
- The SoSOS (Share of Safe Operating Space) represents how much of the global limit is assigned to a specific product, company, or sector.

Why a New Sharing Principle Was Needed

- Most AESAs use **economic-based allocation** (e.g., *final consumption expenditure*, FCE).
- Problem: **money ≠ welfare**. Wealthier societies spend proportionally less on essentials like food (Engel's Law), meaning the FCE method undervalues basic needs.
- For instance, in Denmark only ~6% of household spending is on food, while a healthy sustainable diet should claim ~10% of the safe operating space (EAT-Lancet Commission).

The FHN principle instead bases allocation on **how essential the product or service is to fulfilling human needs**, not its market price.

3. Theoretical Foundation

The FHN principle combines three ethical distribution theories:

Ethical Principle	Meaning	How it's applied
Egalitarianism	Equal rights per person	Everyone receives an equal base share of the safe space (per capita).
Sufficientarianism	Everyone should have "enough" to meet basic needs	Priority to products that meet essential needs like nutrition, health, housing.
Utilitarianism	Maximize total welfare	Used for differentiating subcategories (e.g., within transport or health).

This hybrid approach better reflects human well-being rather than economic wealth.

4. Methodology

Planetary Boundaries Considered

The FHN method was tested for four PBs:

1. **Climate Change**
2. **Land-System Change**
3. **Freshwater Use**
4. **Nitrogen Cycling**

Two-Step Approach

Because not all boundaries behave the same way, they used different methods per PB type:

1. Climate Change

- Based on **sustainable consumption patterns** in countries closest to environmental and social sustainability (e.g., Costa Rica, Sri Lanka, Albania).
- These countries were identified using criteria:
  - Human Development Index (HDI) > 0.7
  - Ecological footprint < 3 global ha/capita
  - Carbon footprint < 5 t CO_2e/capita/year
- Average household and government spending in these countries was analyzed across **19 consumption categories** (food, housing, transport, health, etc.).
- The EAT-Lancet Commission's values for sustainable diets (9.6% of global GHG budget to food) were used as the baseline.

2. Land, Water, and Nitrogen

- Used a **status quo (SQ)** approach: share of impact based on current emissions in the most sustainable countries (to reflect sector differences).
- Data were obtained via **EXIOBASE** input–output models and **ILCD** impact categories (e.g., water depletion, land use, eutrophication).

5. Operationalization – How the FHN Principle Works

Step 1: Identify Essential Needs

Divide total consumption into categories (e.g., food, housing, health).

Step 2: Assign Safe Operating Space

Use global PB thresholds (e.g., 52 Gt CO_2-eq/year for 2020) divided by global population and then by category shares from sustainable consumption patterns.

Step 3: Downscale to Product Level

Translate from sector to product using function-based or expenditure-based scaling:

- **Functional approach** for essentials with measurable outcomes (e.g., nutrients from food, clothing mass, distance traveled).
- **Economic approach** (FCE) only when functionality can't be easily measured.

Step 4: Calculate the Sustainability Ratio

Sustainability Ratio=Actual Impact (LCA)Assigned Share of SoSOS\text{Sustainability Ratio} = \frac{\text{Actual Impact (LCA)}}{\text{Assigned Share of SoSOS}}

Sustainability Ratio=Assigned Share of SoSOSActual Impact (LCA)

If the ratio < 1 → product is *absolutely sustainable*.

6. Case Studies

Case 1 – Peanuts (Food Item)

- Tested for 100 g of peanuts against four PBs.
- Actual CO_2 impact = 0.23 kg CO_2e/100 g.
- Assigned SoSOS (climate) = 0.42 kg CO_2e/100 g → Ratio = 0.56 (<1).

  → **Absolutely sustainable for climate change**.

  Also sustainable for land use, water, and nitrogen due to low impacts.

Case 2 – Cotton T-Shirt (Textile Product)

- LCA showed 5.43 kg CO_2e per t-shirt.
- Assigned SoSOS = 7.5 kg CO_2e (sustainable consumption baseline).

  → Sustainable for **climate** but **unsustainable** for land, nitrogen, and water use (up to 300× over safe share).
- Reducing clothing consumption from **10.9 kg → 4 kg/year** per person would make t-shirts sustainable for climate but still not for water or land.

7. Main Findings

Category	Result
Peanuts	Sustainable for all PBs – fulfills essential nutritional needs efficiently.
T-Shirt	Sustainable only for climate (if consumption reduced); unsustainable for other PBs.
Interpretation	Products serving *basic needs* receive a larger share of safe space; non-essentials must drastically improve or reduce production.

8. Methodological Contributions

- First operationalization of **sufficientarianism** in AESA.
- Introduces **importance of need fulfilment** as a variable in environmental allocation.
- Highlights that **behavioral change** (reduced consumption) is as crucial as technological improvement.
- Shows feasibility of integrating **social well-being** into **Planetary Boundaries-based LCA**.

9. Limitations and Challenges

- Limited data availability for "most sustainable" countries.
- Difficulty defining when someone has "enough" of a product.
- Hard to apply to complex **B2B products** (intermediate goods).
- Does not yet include *regionalized PBs* (important for water and land).
- Using Indonesia as a reference for "sustainable" impacts is an approximation.
- Method still proof-of-concept — needs refinement before industrial use.

10. Implications for Companies

- Companies can use FHN-based AESA to prioritize **essential and high-need products**.
- Demonstrates that **reducing demand** (e.g., fast fashion, overconsumption) is as important as improving efficiency.
- Encourages firms to align production portfolios with **human well-being** and **planetary limits**, not profit alone.
- To claim "absolute sustainability," firms should test their products using **multiple sharing principles** and report uncertainty ranges.

11. Key Takeaways

Concept	Meaning / Contribution
AESA	Framework for assessing absolute sustainability relative to planetary limits.
FHN Principle	Allocates environmental capacity based on the importance of fulfilling basic human needs.
Sufficientarianism	Ethical focus on "enough for everyone."

Concept	Meaning / Contribution
SoSOS	Share of Safe Operating Space assigned to a product or sector.
Findings	Essential goods (like food) get a larger sustainable share; luxury or excess goods receive smaller or insufficient shares.
Main message	Sustainability must account for *what* we produce and *why* — not just *how efficiently*.

12. Summary Sentence

> Heide, Hauschild, and Ryberg (2023) propose the Fulfilment of Human Needs (FHN) principle — a novel method to distribute the Earth's limited environmental space based on human necessity rather than economic value. It offers a more socially grounded way to assess whether products are absolutely sustainable within the Planetary Boundaries framework.

Examples of Other Absolute Sustainability Metrics

Main idea:

This lecture explores other frameworks that **quantify sustainability in absolute, science-based terms**, outside the Planetary Boundaries-based Life Cycle Assessment (LCA) system.

These include:

- **The Ecological Footprint and Earth Overshoot Day**
- **The Science-Based Targets initiative (SBTi)**

The purpose is to show how absolute sustainability can be measured, communicated, and implemented in real-world contexts — from **countries** and **companies** to **individual products**.

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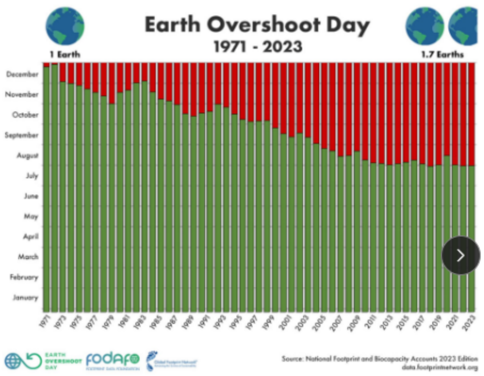


2. Ecological Footprint

Definition

The **Ecological Footprint (EF)** measures how much biologically productive land and water area is required to:

- Produce the resources a population consumes, and
- Absorb the wastes it generates (especially CO_2).

It is expressed in **global hectares (gha)** per person.

Core Concept

It compares:

- **Biocapacity** → the planet's ability to regenerate resources,
- **Footprint** → humanity's demand for those resources.

When demand exceeds biocapacity, we are in **ecological overshoot**.

Earth Overshoot Day

Earth Overshoot Day marks the date when humanity's resource consumption for the year exceeds the Earth's capacity to regenerate those resources in that year.

Examples (from the lecture):

Year	Earth Overshoot Day
2015	7 August
2016	9 August
2017	5 August
2018	1 August
2019	3 August

Year	Earth Overshoot Day
2020	16 August *(pandemic year – temporary improvement)*
2021	3 August
2022	1 August
2023	2 August

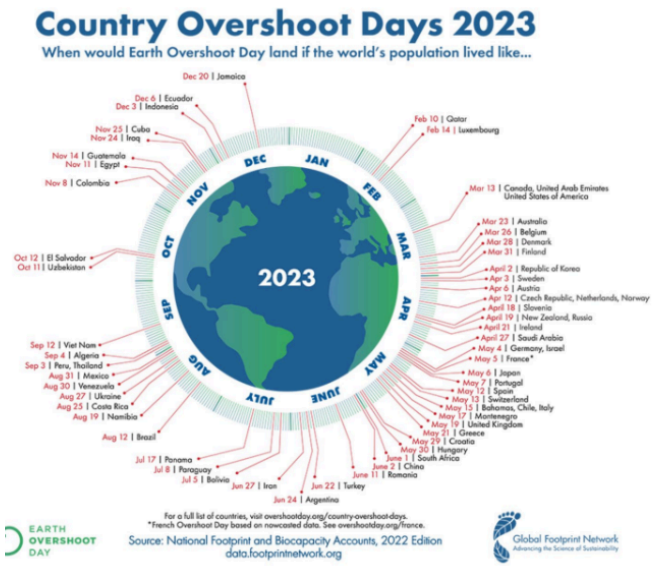
Interpretation:

Each year, Earth Overshoot Day occurs earlier — except in 2020, when COVID-19 reduced emissions and resource use.

Currently, humanity consumes roughly **1.7 Earths** worth of resources annually.

Relation to Absolute Sustainability

- EF represents a **global-scale absolute metric** — it directly compares human use with the planet's regenerative capacity.
- It has a **life-cycle logic**, since it includes both production and consumption impacts.
- It focuses on **land use and CO_2 emissions**, linking back to Planetary Boundaries for **land-system change** and **climate**.



3. The Science-Based Targets Initiative (SBTi)

Background

- Founded in **2015** by CDP, UN Global Compact, WRI, and WWF.
- Purpose: Help companies set **science-based GHG reduction targets** aligned with the **Paris Agreement** (limit global warming to well below 2°C, ideally 1.5°C).

Official site:

https://sciencebasedtargets.org

Philosophy

SBTi is an example of an **absolute sustainability metric** applied at the **corporate level**.

It translates the global climate boundary (carbon budget) into specific, measurable emission reduction targets for individual companies.

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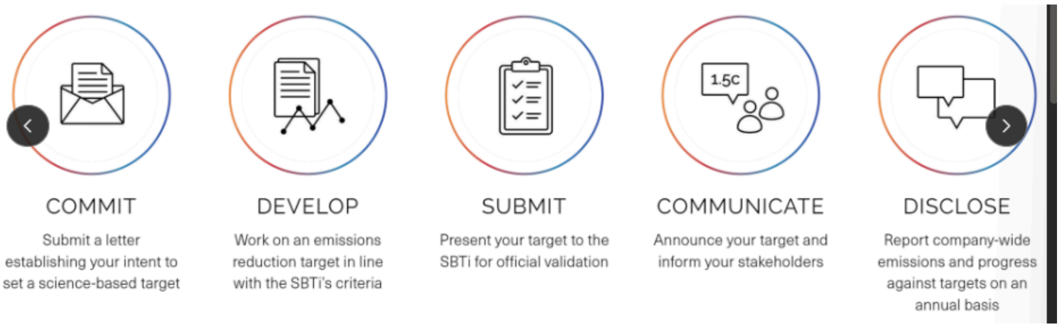
4. The Five Steps of SBTi

While Hauschild's slide references them visually, they correspond to the standard SBTi process:

1. **Commit:**
   - Company signs up and commits publicly to setting science-based targets.
2. **Develop:**
   - Calculate the company's emissions baseline and model reduction pathways (using sectoral tools).
3. **Submit:**
   - Targets are sent to SBTi for validation.
4. **Communicate:**
   - Approved targets are made public and shared on the SBTi platform.
5. **Disclose and Reduce:**
   - Companies report progress annually and are re-assessed periodically.

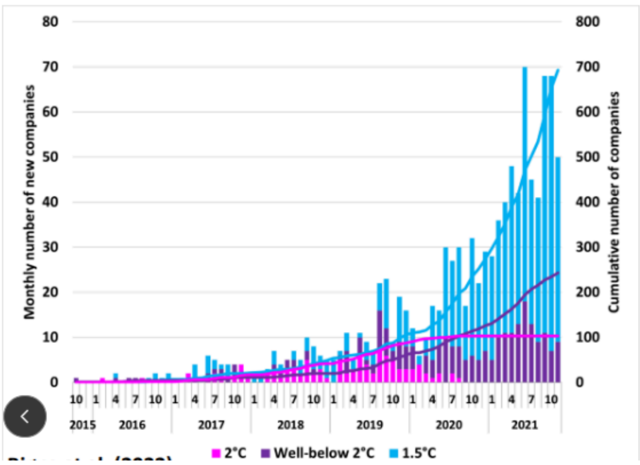


5. Rapid Growth of SBTi

Hauschild references **Bjørn et al. (2022)** showing the **exponential rise in participation**.

As of **April 2023**, thousands of companies have joined the initiative — from small firms to multinational corporations.

This growth reflects a major shift in corporate sustainability from **voluntary efficiency reporting** to **science-based accountability**.

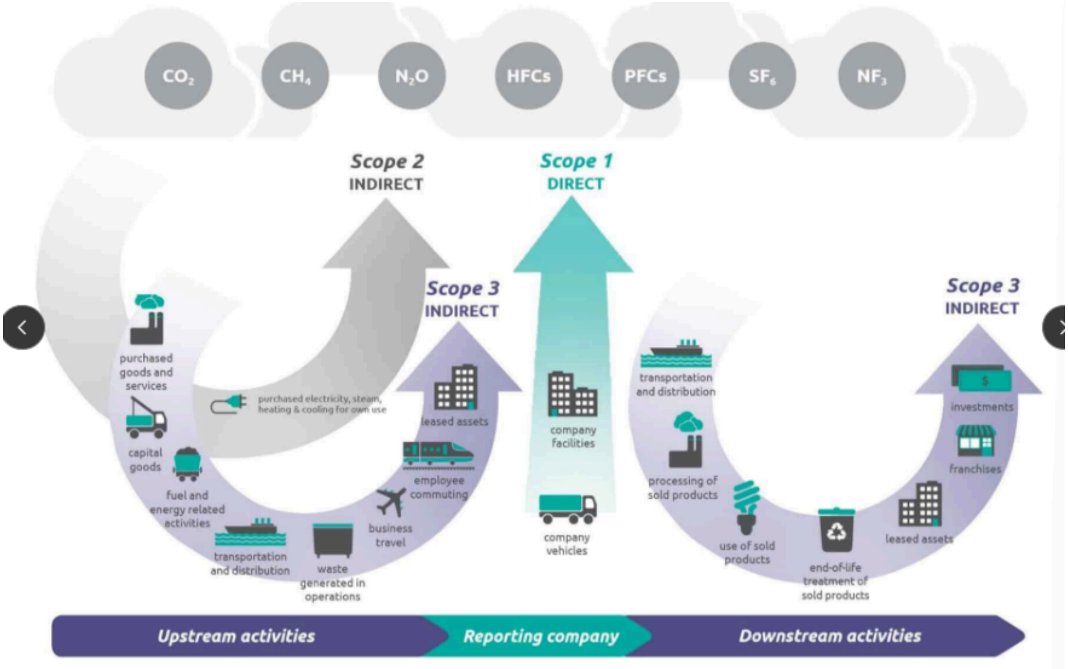


6. The Three Scopes of Emissions

SBTi (like the GHG Protocol) distinguishes between three emission scopes:

Scope	Definition	Examples
1 – Direct	Emissions from owned or controlled sources.	Company vehicles, onsite fuel combustion.
2 – Indirect (Energy)	Emissions from purchased electricity, heat, or steam.	Office electricity, industrial power use.
3 – Value Chain	All other indirect emissions upstream and downstream.	Supplier emissions, product use, logistics, waste.

For many companies, **Scope 3** accounts for more than 80% of total emissions — making it critical for achieving genuine climate neutrality.



7. Setting Science-Based Targets

Targets must be **"science-based"**, meaning consistent with IPCC scenarios for limiting global warming.

Typical SBTi Requirements

- Targets aligned with **1.5°C or well-below 2°C** pathways.
- **Sectoral approaches:** Specific reduction models per industry (e.g., cement, transport, energy).
- **Absolute contraction approach (grandfathering):** Every company reduces by the same proportion relative to its baseline.

Quantitative rules:

- Include at least **95% of Scope 1 & 2** emissions.
- Include **≥67% of Scope 3** emissions if they represent >40% of total.
- Must cover both **short-term** (5–10 years) and **long-term** (2050 or earlier).
- Require **≥4.2% annual linear reduction** (short term).
- **90% total reduction** by 2050 for net-zero alignment.

8. Two Example Companies

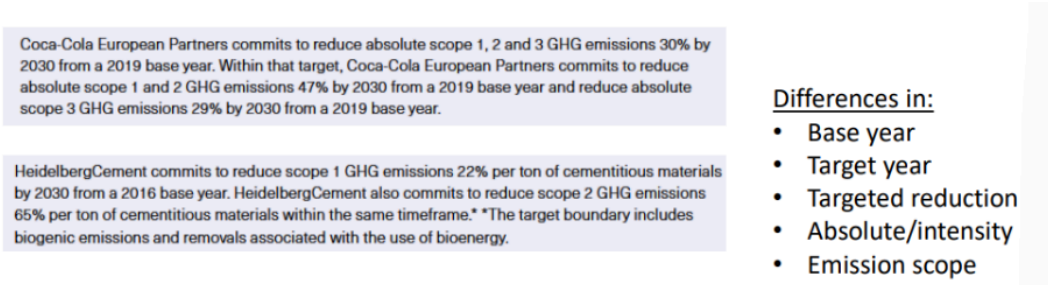
Hauschild's slides (linked to SBTi's public database) show how targets differ by:

- **Base year** (the year from which reductions are measured).
- **Target year** (usually 2030 or 2050).
- **Type of reduction** (absolute vs intensity-based).
- **Emission scope covered.**

Example contrasts:

- *Company A*: Absolute target of 42% reduction by 2030, covering all scopes.
- *Company B*: Intensity target (e.g., CO_2 per ton of product) — less strict, but still valid if aligned with science.

Database: https://sciencebasedtargets.org/companies-taking-action



Absolute Sustainability Metrics

All the frameworks presented share three key features:

1. **They relate performance to absolute environmental limits.**
    - E.g., carbon budgets or planetary regeneration capacity.
2. **They quantify how much improvement is needed** to reach or stay within these limits.
3. **They shift focus from "efficiency" to "effectiveness":**
    - Relative metrics ask: *Is it better?*
    - Absolute metrics ask: *Is it good enough?*

Main Examples Covered

Metric	Scale	Focus	Type	Key Concept
Ecological Footprint	Global, national	Land & CO_2	Accounting metric	Compares human demand vs Earth's regeneration rate (Overshoot Day).
SBTi	Company level	GHG emissions	Corporate target system	Aligns business targets with Paris Agreement (1.5°C).

10. Conceptual Integration with Previous Lectures

Lecture	Theme	Progression
1 – From Relative to Absolute Sustainability	Why eco-efficiency is not enough.	Establishes need for absolute benchmarks.
2 – Planetary Boundaries	Defines the physical limits.	Provides the scientific basis.
3 – AESA (Absolute Environmental Sustainability Assessment)	How to measure impacts relative to the boundaries.	Operational method using LCA.
4 – Other Metrics (EF, SBTi)	Real-world examples.	Shows how these ideas are already applied at national and corporate scales.

11. Key Takeaway

> Absolute sustainability metrics — whether ecological footprints, science-based corporate targets, or LCA-based AESA — all aim to answer one fundamental question:
>
> **Are we operating within the planet's safe limits?**

They transform sustainability from a comparative statement ("greener than before") into a **quantitative boundary condition** ("within the Earth's carrying capacity").

Absolute Sustainability and Planetary Boundaries – Integrated Summary

1. The Core Question

> How can human activities, industries, and products meet human needs while keeping total environmental pressure within the planet's biophysical limits?

That's the essence of **Absolute Environmental Sustainability (AES)**.

It shifts the conversation from "better" to **"enough."**

2. From Relative to Absolute Sustainability (Lecture 1 & Hauschild 2022)

Concept	Meaning	Implication
Relative sustainability	Comparison between alternatives ("better than before")	Common in eco-efficiency and traditional LCA; good for optimization but not for planetary safety.
Absolute sustainability	Comparison with *biophysical limits* ("within Earth's capacity")	Introduces a *reference point* based on environmental boundaries (e.g., climate, biodiversity).

The IPAT Equation

$I = P \times A \times T$

Where:

- **I** = Environmental impact
- **P** = Population
- **A** = Affluence (GDP per person)
- **T** = Technology factor (impact per GDP)

→ To halve impact by 2030 while P↑ and A↑, **T must improve by ~3×**.

Eco-efficiency (1/T) must therefore grow *exponentially*.

The Limitation of Relative Metrics

Efficiency gains often trigger the **rebound effect**:

- Cheaper, more efficient products → more consumption → total impact ↑

  Example: lighting energy efficiency ↑100× since 1800 → total light use ↑ even faster.

Conclusion:

We need *eco-effectiveness* (operating within limits), not just eco-efficiency.

---

3. Planetary Boundaries Framework (Lecture 2 & Steffen et al., 2015)

Purpose

Define the *safe operating space* for humanity — conditions under which Earth's systems remain stable (Holocene-like).

The Nine Planetary Boundaries

Earth System Process	Control Variable	Status (2015)	Status (2023)	Boundary Type
1. Climate change	CO_2 conc. < 350 ppm	**Transgressed**	✓	Core
2. Biosphere integrity	Extinction rate, biodiversity	**Transgressed**	✓	Core
3. Land-system change	Forest cover > 75%	**Transgressed**	✓	Structural
4. Biogeochemical flows	N, P cycles	**Transgressed**	✓	Structural
5. Freshwater use	Withdrawals < 4000 km^3/yr	Within	✓ (Transgressed regionally)	Regional
6. Ocean acidification	Mean surface pH	Within	-	Global
7. Stratospheric ozone	O_3 conc. > 276 DU	Safe	Safe (recovered)	Global
8. Aerosols	PM concentration	Unquantified	Unquantified	Regional
9. Novel entities	Chemical pollution	Unquantified	✓	Global

6 of 9 boundaries exceeded (2023).

Core Boundaries

- **Climate change**
- **Biosphere integrity**

→ If either fails, others destabilize — they're "planetary life-support systems."

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4. The Holocene to Anthropocene Shift

- **Holocene (past 12,000 years)**: stable climate enabling agriculture, civilization.
- **Anthropocene**: human-driven instability (climate, land, nitrogen, species).

  → Sustainability = *staying within Holocene conditions.*

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5. Life Cycle Thinking & Eco-Efficiency (Hauschild 2022 + Lectures 1–3)

Life Cycle Assessment (LCA)

Quantifies environmental impacts from cradle to grave:

- Scope 1: Direct emissions (owned operations)
- Scope 2: Purchased energy
- Scope 3: Entire value chain

Eco-Efficiency Equation

Eco-efficiency=Delivered FunctionEnvironmental Impact=1T\text{Eco-efficiency} = \frac{\text{Delivered Function}}{\text{Environmental Impact}} = \frac{1}{T}

Eco-efficiency=Environmental ImpactDelivered Function=T1

Measured through **LCA**, capturing global, regional, and local impacts.

But LCA alone gives *relative* results. To achieve *absolute* assessment, LCA must be combined with PBs → **AESA.**

6. AESA: Absolute Environmental Sustainability Assessment (Lecture 3)

Step	Description	Methods / References
1. **Identify biophysical boundaries**	Use PBs or LCIA indicators to define safe operating limits.	Hauschild et al. 2013; Ryberg et al. 2016
2. **Allocate the safe operating space (SoSOS)**	Divide global limits among actors (countries, sectors, products).	Hjalsted et al. 2020; Bjørn et al. 2020
3. **Calculate impact via LCA**	Quantify full life-cycle impact of product/activity.	ISO 14040/44
4. **Compare impact vs. allocation**	Impact < Allocation → sustainable.	Ryberg et al. 2018

Allocation Approaches

Principle	Logic	Examples
Grandfathering	Equal % reduction from current levels.	Science Based Targets (SBTi)
Per capita	Equal rights per person.	Nykvist et al. (2013)
Economic (FCE)	Based on market value contribution.	Current practice
Ethical / Needs-based	Based on necessity & welfare contribution.	Heide et al. (2023)

AESA = LCA + PBs

It translates relative results into *absolute performance indicators*.

7. Operationalization: Planetary Boundaries-Based LCIA

- Converts PB thresholds into **characterization factors** within LCIA.
- Enables assessing whether a company/product *exceeds its fair share* of the global limits.
- Tested in industrial case studies (e.g., European laundry washing → Ryberg et al., 2018).

8. Allocation and Ethics (Hjalsted et al., 2020; Heide et al., 2023)

Challenge:

Global safe space must be shared fairly.

Evolution of Sharing Principles

Principle	Ethical Foundation	Strengths	Limitations
Grandfathering	Equal % reduction	Simple, pragmatic	Rewards heavy emitters
Per capita	Egalitarianism	Equal right to pollute	Ignores differences in need
GDP-based	Utilitarianism	Reflects productivity	Favours rich economies
FHN (Heide et al. 2023)	Sufficientarianism	Links to human well-being	Complex, data-intensive

9. The Fulfilment of Human Needs (FHN) Principle (Heide et al., 2023)

Goal

Distribute planetary safe space according to *how essential a product/service is* to fulfilling basic human needs.

Methodology

1. Identify basic needs → nutrition, health, housing, mobility, education, etc.
2. Use sustainable reference countries (HDI > 0.7, ecological footprint < 3 gha).
3. Determine SoSOS per need category using global PB thresholds.
4. Assign product shares → via functional or expenditure-based scaling.

Case Studies

Product	Result (CO_2)	Other PBs
Peanuts (food)	0.56 < 1 → sustainable	Sustainable for all PBs
T-shirt (textile)	Sustainable only for climate	Unsustainable for land, water, nitrogen

Interpretation:

Essential goods = larger safe share.

Luxury goods = smaller or negative safe share.

Behavioral change (consumption reduction) is crucial.

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10. Other Absolute Sustainability Metrics (Lecture 4)

Metric	Scale	Basis	Key Idea
Ecological Footprint (EF)	Global/National	Land, CO_2, biocapacity	Measures overshoot of resource demand vs Earth's capacity.
Earth Overshoot Day	Global	Calendar marker	When annual resource use exceeds yearly regeneration.
Science-Based Targets initiative (SBTi)	Company	GHG budgets aligned with 1.5 °C	Converts planetary carbon budget into corporate targets.

SBTi Framework

Aspect	Standard
Reduction path	1.5 °C / < 2 °C (Paris Agreement)
Coverage	≥95% of Scope 1 & 2; ≥67% of Scope 3
Time horizon	5–10 yrs (short) + 2050 (long)
Annual contraction	≥ 4.2%
Target type	Absolute or intensity-based
Verification	Public database + annual reporting

Outcome:

SBTi translates *planetary limits into corporate governance* — making climate accountability measurable.

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11. Conceptual Chain of Evolution

Stage	Framework / Tool	Focus	Outcome
1970s	**Limits to Growth**	Finite Earth systems	Introduces absolute constraints
1987	**Brundtland Report**	Needs & intergenerational equity	Defines sustainability normatively
1997	**Triple Bottom Line**	People–Planet–Profit	Corporate integration
2009–2015	**Planetary Boundaries**	Earth system thresholds	Defines safe operating space
2013–2020	**AESA**	LCA + PB integration	Quantifies absolute sustainability
2023	**FHN Principle**	Human needs fulfilment	Links sustainability with well-being

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12. Synthesis: From Efficiency → Sufficiency → Effectiveness

Approach	Question	Metric Type	Philosophy
Efficiency	"Are we using less?"	Relative	Eco-efficiency, IPAT
Sufficiency	"Do we have enough?"	Ethical	Human needs fulfilment
Effectiveness	"Are we within limits?"	Absolute	AESA, PBs, SBTi

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13. Integrated Takeaways

- **Planetary Boundaries** define the *scientific guardrails* of sustainability.
- **AESA** operationalizes them through LCA — connecting products to planetary limits.
- **Allocation principles** translate global space into local responsibility.
- **FHN principle** ensures sustainability respects *human well-being and fairness*.
- **Corporate tools (SBTi, EF)** bring absolute metrics into governance and policy.
- The true challenge: *systemic sufficiency* — aligning technology, consumption, and ethics with the safe operating space.

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14. Key Equations & Indicators

Equation	Meaning
I=P×A×TI = P \times A \times TI=P×A×T	IPAT: quantifies impact drivers
Eco-efficiency=ServiceImpact=1T\text{Eco-efficiency} = \frac{\text{Service}}{\text{Impact}} = \frac{1}{T}Eco-efficiency=ImpactService=T1	Measures technological performance
Sustainability Ratio=Actual ImpactAllocated SoSOS\text{Sustainability Ratio} = \frac{\text{Actual Impact}}{\text{Allocated SoSOS}}Sustainability Ratio=Allocated SoSOSActual Impact	< 1 → Sustainable
Annual Reduction=4.2%\text{Annual Reduction} = 4.2\%Annual Reduction=4.2%	Minimum SBTi trajectory
Earth Overshoot Day	Earth's BiocapacityHuman Demand=Days per year\frac{\text{Earth's Biocapacity}}{\text{Human Demand}} = \text{Days per year}Human DemandEarth's Biocapacity=Days per year

---

15. Final Summary

> Absolute Sustainability = Meeting present and future human needs within the safe operating space of Earth's systems.

To achieve it, we must:

- Combine **scientific limits (PBs)** with **social ethics (needs, equity)**.
- Transition from **efficiency gains** to **systemic sufficiency**.
- Embed **planetary boundaries** into design, manufacturing, and policy via **AESA, SBTi, and EF.**

The future of sustainability assessment lies in **integrating planetary science, industrial ecology, and human-centered ethics** — ensuring that what we produce and consume is not only *better* but *enough*.

7. Social - and Health Dimensions

Date	@October 21, 2025
Status	Done

Studies before teaching session:

Follow the sequence of activities as described below:

7.1 - Social aspects

Watch the video lecture Sustainability tools for Society II by Karyn Morrissey.

Read the section 3.3 in the article Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment.

If you have further interest in social life cycle assessment, you might be get further inside reading this paper

Implementing the guidelines for social life cycle assessment:past, present, and future

7.2 - Health assessment - tools and indicators

7.2.1 - The Global Burden of Disease (GBD)

Watch the video lecture Introduction to the Global Burden of Disease (GBD).

Practice the GBD with the Exercise: Exploring the Global Burden of Disease Visualization.**7.2.2 - Health assessment: Gasoline versus electric vehicles and bikes**

Download and open the Spreadsheet template: Carbon footprint and health impact of cars and bikes that compares the carbon footprint and health impacts of gasoline vehicles, electric vehicles and bikes.

Watch the video lecture **Health assessment - Gasoline vs electric vehicles vs bike** and study/fill in the excel template while watching.

The beauty of using comprehensive databases is that once we have done the carbon footprint, we have the impacts on health and ecosystems "for free" (just expand the columns by clicking on the "+" signs on the top margin of the hidden columns).

Fill the ochre/brown highlighted empty cells as you watch the video lecture (see detailed instructions in cells D76 to D84 of the "selected processes" tab for more info - we have updated data of health benefits of biking per km).**7.2.3-4 - Impacts of product on health overview**

Watch the video lecture Consumption, products and health - Exposome and health impacts**.**

If you are interested (optional), you can also watch the short video lecture Global Trade - Part A - Using LCA to Explore how our Consumption Impacts Global Health, which addresses the question: How many deaths are we inducing in Asia via our consumption of products produced there?

Teaching session:

7.3 - Exercise: Health benefit of physical exercise

Reopen your Spreadsheet template: Carbon footprint and health impact of cars and bikes from above to fill the information related to physical exercise:

Complement the cells K68 and K69 on this tab, by finding under tab physical exercise data the corresponding gain in physical activity for a person with moderate activity that does average biking.

Hint: you can look on cell K70 to help you, and a negative number of min lost is a benefit!

Then go to the carbon footprint calculator, and select in A125 the process of selected processes that corresponds to biking average.

In F125 of that tab select the number of km driven per V-km.

Interpret results on human health as displayed in columns L and M and on the graph in the range AF15 to AM75.

7.4 - Self-assessment

Open the self-assessment and answer the different questions.

When you have completed and submitted the self-assessment, you can download the solution spreadsheet about carbon -and health footprint of cars. You should use the solutions to review your own results.

–

7.5 - Using the health assessment

You can choose to use the carbon footprint file you have created/adapted from the morning coffee example.

You can expand the health columns by clicking on the "+" signs on the top margin of the hidden columns and you can directly interpret results and graphs, plus think of potential additional impacts on a product or service users.

🌍 SOCIAL LIFE CYCLE ASSESSMENT (S-LCA)

1. Context and Purpose

Social Life Cycle Assessment expands the logic of traditional Environmental LCA (E-LCA) and Life Cycle Costing (LCC) into the **social dimension of sustainability**.

The key idea: every product or service affects **people** throughout its life cycle — workers, consumers, communities — and these effects can be measured and improved.

S-LCA doesn't ask *"Should we produce this?"* but rather *"Given that we produce it, what are the social and socio-economic consequences across its value chain?"*

It complements E-LCA (environmental flows) and LCC (economic flows) to form **Life Cycle Sustainability Assessment (LCSA)**.

- Companies have a central role in the transition towards more sustainable economic systems
- Various tools are available to support sustainability assessments
  - little information on how suitable they are for companylevel assessments and how companies can use them in real-life applications.
- Furthermore, sustainability is not only about minimizing the environmental impact of goods and services
  - but also, about enhancing the social and economic well-being of the people who use them.
- This lecture set will introduce students to a set of tools that they can use to assess a set of sustainability tools for use within their academic & future careers
  - that cover the three pillars of sustainability – environmental, economic and social

Deep-dive on the social impacts of EVs

- Develop a conceptual S-LCIA across the lifecycle of EVs
- Quantitatively assess the health impacts of EVs using DALY's

2. Objects and Scope

Object of study:

- Products or services (not whole organizations).
- Analysis covers the *full life cycle*: raw material extraction → manufacturing → distribution/use → end-of-life (reuse, recycling, disposal).

Goal and scope definition (same logic as E-LCA):

- Define the **functional unit (FU)** – the quantified service provided (e.g. "1 vehicle-km by a mid-size BEV").
- Establish **system boundaries** – which life-cycle stages and stakeholders are included.
- Identify **impact categories** – e.g., workers' rights, community health, consumer safety.
- Specify **data sources** – social indicators, databases, case studies.

Key stakeholders usually considered:

1. **Workers** – conditions, wages, safety, rights.
2. **Local communities** – health, access to resources, cultural impacts.
3. **Consumers/users** – product safety, accessibility, data privacy.
4. **Society** – broader effects like employment creation, corruption, governance.
5. **Value chain actors** – suppliers, SMEs, distributors, recyclers.

Tool	Purpose	How It Works	Typical Applications
Multi-Criteria Decision Analysis (MCDA)	Supports decision-making when multiple, often conflicting sustainability criteria must be balanced (environmental, social, economic).	Uses weighting and scoring systems (e.g., AHP, TOPSIS, PROMETHEE) to compare options based on stakeholder preferences and performance indicators.	Selecting best technology, material, or policy alternative; prioritizing sustainability actions.

Tool	Purpose	How It Works	Typical Applications
Material Flow Analysis (MFA)	Tracks the flow of materials, energy, or waste through a defined system to identify inefficiencies and resource hotspots.	Quantifies input, stock, and output of materials across system boundaries using mass balance principles.	Waste management planning, circular economy design, industrial ecology, resource efficiency analysis.
Life Cycle Cost Assessment (LCCA)	Evaluates the total economic cost of a product, process, or service over its entire life cycle.	Aggregates costs (investment, operation, maintenance, disposal) discounted over time to a present value.	Infrastructure projects, building design, product cost optimization, comparing long-term investment options.
Input–Output Models (I/O Models)	Captures the interdependence of industries and sectors to assess environmental or social impacts through economic linkages.	Uses national or multi-regional economic tables to trace flows of goods, services, and emissions between sectors.	Assessing global supply-chain impacts (e.g., carbon, employment, pollution embodied in trade).
Sustainability Indicators and Indices	Provide measurable metrics to evaluate and communicate sustainability performance.	Combine multiple variables into normalized or composite indicators (e.g., Human Development Index, Ecological Footprint).	Policy monitoring, corporate sustainability reporting, comparing regional or sectoral sustainability.
Cost–Benefit Analysis (CBA)	Compares the total expected costs and benefits of a project or policy to determine net social value.	Monetizes all impacts (including externalities) to calculate Net Present Value (NPV) or Benefit–Cost Ratio (BCR).	Environmental policies, infrastructure investments, public health interventions.
Optimisation Methods	Identify the best solution that meets specific objectives (e.g., minimize emissions, cost, or maximize efficiency) under given constraints.	Mathematical or computational models (linear programming, genetic algorithms, Pareto optimization) simulate trade-offs and select optimal configurations.	Supply chain design, energy systems modeling, resource allocation, sustainability planning.

Social Life Cycle Assessment (S-LCA)

Definition:

A methodology developed to evaluate the *social and socio-economic* impacts — both **positive** and **negative** — associated with a product or organization throughout its life cycle, from raw material extraction to disposal.

🔷 Context (link to Module 5)

- **Life Cycle Costing (LCC)** quantifies total financial costs (capital, operation, maintenance, residual value).
- **S-LCA**, by contrast, focuses on **human well-being**, **working conditions**, and **social equity** across the same life-cycle stages.

🔷 Main Objectives of S-LCA

1. **Assess social impacts** such as:
    - Employment and labor rights
    - Health and safety at work
    - Gender equality and non-discrimination
    - Community well-being and access to resources
    - Consumer safety and transparency
2. **Identify hotspots** where social risks or benefits are concentrated.
3. **Support decision-making** toward socially responsible design and supply chains.

🔷 Core Features

Aspect	Description
Area of protection	Human well-being
Stakeholders	Workers, local communities, consumers, society, value-chain actors, and (since 2020) children
Assessment scope	Life-cycle perspective: extraction → production → use → disposal
Approaches	1. *Reference Scale* (qualitative risk/performance rating) 2. *Impact Pathway* (quantitative cause–effect models, often in DALYs)
Data sources	Surveys, company records, databases (e.g., SHDB, PSILCA)
Standard reference	**UNEP (2020)** *Guidelines for Social Life Cycle Assessment of Products and Organizations*

🔷 Why It Matters

- Integrates **people** into the sustainability equation ("People, Planet, Profit").
- Helps companies address **Social SDGs** (e.g., SDG 3, 5, 8, 10, 12, 16).
- Enables **Life Cycle Sustainability Assessment (LCSA)** when combined with LCA and LCC.

⚙️ Process in S-LCA

- **Objects:**

  S-LCA can be applied to **products** (e.g., an electric car, a t-shirt, a medical device) or **services** (e.g., healthcare, transportation).

- **Scope:**

  Always **life-cycle based**, meaning it considers *all stages* — extraction of raw materials, manufacturing, distribution, use, and end-of-life (reuse, recycling, disposal).

This full life-cycle view ensures that social risks aren't simply shifted from one stage or country to another.

👥 Social and Socio-Economic Aspects

S-LCA assesses how activities along the value chain **affect people (stakeholders)** both:

- **Directly:**

  e.g., worker health and safety, fair wages, labor rights.

- **Indirectly:**

  e.g., community well-being, cultural heritage, supply-chain employment, consumer safety.

Stakeholders include **workers, local communities, consumers, society, value-chain actors, and children** (per UNEP 2020 update).

🚫 S-LCA Does *Not* Decide Whether a Product Should Exist

Unlike ethical or political assessments, S-LCA **does not judge** whether a product *should* be produced.

Instead, it provides **information on how production and use affect people**, guiding **improvements** rather than moral conclusions.

For instance, it can identify poor labor conditions in cobalt mining but doesn't dictate that EVs should be banned — only that sourcing practices should improve.

🔁 Similarities with LCCA

S-LCA and Life Cycle Cost Assessment share structural and data similarities:

Commonality	Explanation
Life-cycle logic	Both trace flows through all product stages.
Data intensity	Both require detailed information across supply chains (materials, processes, locations).
System boundaries	Must be defined consistently to avoid double counting or missing effects.
Goal	Support better design and decision-making — one from a social lens, the other from an economic one.

Hence the comment: *"Not least its data requirements!"* — because social data (like wage levels, safety statistics, gender ratios) can be as complex and difficult to collect as financial or environmental data.

S-LCA & Impact Assessment

Purpose

The **social impact assessment** phase quantifies, interprets, and evaluates the **magnitude and significance** of social impacts throughout a product's life cycle.

It connects *activities* (e.g., factory labor conditions, community interactions) to their *social outcomes* (e.g., well-being, health, equity).

Two Complementary Approaches

Approach	Focus	Nature	Example output
Reference Scale (Type I)	Evaluates **social performance** or **risk** level for each process or region.	Qualitative or semi-quantitative	"High risk of child labor in cobalt mining sector (DRC)"
Impact Assessment (Type II)	Evaluates **consequential impacts** by modelling the **cause–effect chain** between an activity and its social outcome.	Quantitative (when possible)	"X number of occupational injuries per functional unit → Y DALYs lost"

The two can be combined: the reference scale identifies *where* risks occur, while the impact pathway quantifies *how much* harm or benefit results.

🔄 Impact Pathway Approaches

Main Goal

To link **causes (social stressors)** → **mechanisms** → **effects (social outcomes)**

For example: *Excessive working hours → fatigue → increased accident risk → health burden in DALYs.*

How It Works

1. **Identify social stressors:** unsafe working conditions, low wages, discrimination, etc.
2. **Trace the mechanism:** how this stressor affects people's well-being or health.
3. **Characterize the impact:** quantify effects on the selected indicator (e.g., number of injuries, lost life years).
4. **Aggregate results:** across the life cycle and stakeholder groups.

This is called an **impact pathway**, and it can be modeled:

- **Qualitatively:** describing links between stressors and outcomes in narrative or categorical form.
- **Quantitatively:** using epidemiological data, social statistics, or dose-response models.

Common Indicators

- **Human health:** measured in **DALYs (Disability-Adjusted Life Years)** — combining years of life lost (YLL) and years lived with disability (YLD).
- **Socio-economic well-being:** employment creation, fair income, social inclusion.
- **Community impacts:** access to resources, displacement, education levels.

Example:

> Cause: Poor occupational safety in battery manufacturing
>
> **Effect Pathway:** Chemical exposure → chronic illness → reduced life expectancy
>
> **Quantification:** Convert illness incidence × disability weight × duration → DALYs per functional unit (e.g., 1 EV battery)

In summary

- **Reference Scale** → tells us *where* social problems are (screening).
- **Impact Pathway** → tells us *how severe* they are and *whom* they affect.

  Together, they make S-LCA a bridge between **qualitative social realities** and **quantitative sustainability metrics**.

3. Two Assessment Frameworks

A. Reference Scale Approach (Performance/Risk-based)

This is **descriptive or semi-quantitative**. It rates how good or bad the social performance is for each indicator at each life-cycle stage.

Typical indicators (from UNEP Guidelines or databases like SHDB/PSILCA):

- Risk of child/forced labor
- Health & safety incidents
- Gender wage gap
- Working hours, fair wage gap
- Community complaints or conflicts
- Access to social security, training
- Consumer safety and data privacy

How it works:

1. Build an inventory of social data (country, sector, facility, etc.).
2. Use predefined scales to rate risks or performance (e.g., "very low" → "very high").
3. Weight and aggregate into social hotspots.

Output: a heatmap of *where in the life cycle* the social risks are concentrated.

Databases like **Social Hotspots Database (SHDB)** or **PSILCA** help quantify risks using country/sector averages (e.g., "high risk of forced labor in cobalt mining, DRC").

Strength: broad screening even with little site data.

Limitation: no causal modeling — doesn't quantify impacts like DALYs.

B. Impact Pathway Approach (Cause-Effect-based, S-LCIA)

This mirrors the logic of environmental LCIA models — it traces **cause–effect chains** linking social stressors to measurable human outcomes.

Steps:

1. Identify **social stressors** (e.g., overtime hours, exposure to hazards).
2. Define **mechanisms** linking the stressor to an outcome (e.g., fatigue → accidents).
3. Quantify **midpoint indicators** (e.g., number of non-fatal injuries).
4. Convert midpoints to **endpoint impacts** — usually measured in **DALYs** (Disability-Adjusted Life Years).

DALY basics:

- DALY = Years of Life Lost (YLL) + Years Lived with Disability (YLD).
- Combines mortality and morbidity into one number.
- 1 DALY = one lost year of "healthy life".

Example conversion:

`Injury cases × disability weight × duration = DALYs`

Midpoint categories could include:

- Workplace accidents
- Working hours & stress
- Mental health issues
- Discrimination or harassment incidents
- Community displacement or violence

Endpoint category: *Human health (DALYs)*.

Strength: quantitative, comparable across systems (aligns with E-LCA).

Limitation: needs detailed epidemiological and social data.

---

4. Data and Methodological Tools

Databases

- **Social Hotspots Database (SHDB)** — sector & country level indicators (ILO, UN sources).
- **PSILCA (Product Social Impact Life Cycle Assessment)** — detailed datasets linking Ecoinvent sectors with 100+ social indicators.

  Both integrate into software like **SimaPro** or **openLCA**.

Indicators examples

- **Health & safety:** injury rate, fatality rate, OHS training hours.
- **Labor rights:** freedom of association, collective bargaining coverage.
- **Fair wage:** ratio of actual wage to living wage.
- **Discrimination:** gender pay gap, employment of minorities.
- **Community:** number of grievances, land-use conflicts.
- **Society:** corruption perception, social security coverage.

---

5. Typical Workflow

1. **Goal and Scope Definition**

   Define FU, boundaries, stakeholders, purpose.

2. **Social Life Cycle Inventory (S-LCI)**

   Collect social data per stage and actor. Combine site-specific info with SHDB/PSILCA data.

3. **Impact Assessment (S-LCIA)**

   - *Reference scale*: classify risk level (e.g., 1–5).
   - *Impact pathway*: compute midpoint and endpoint effects (e.g., DALYs).

4. **Interpretation**

Identify social hotspots; evaluate uncertainties; compare scenarios; formulate improvement strategies.

6. Example — Electric Vehicle (EV) Case

- Think about the lifecycle stages of an EV
  - Stage 1: Resource extraction and processing
  - Stage 2: Manufacturing
  - Stage 3: Distribution and operation
  - Stage 4: Waste and disposal
- For each stage develop a basic impact assessment S-LCIA

Functional unit: 1 vehicle-kilometre delivered by a mid-size BEV (battery electric vehicle) over 150,000 km.

Life-cycle stages:

1. **Raw materials & extraction:** mining of lithium, cobalt, nickel, copper.
2. **Manufacturing:** battery cell and pack production, vehicle assembly.
3. **Distribution & operation:** logistics, dealerships, maintenance, charging.
4. **End-of-life:** reuse, recycling, disposal of batteries.

Stakeholders & Key Risks:

- **Workers:** child labor and unsafe conditions in artisanal cobalt mining (DRC).
- **Communities:** air and water pollution around mines, displacement.
- **Consumers:** product safety and battery-fire risk.
- **Society:** job transitions from ICE manufacturing to EV supply chains.

Reference Scale Output Example:

Life-cycle stage	Indicator	Risk level	Evidence source
Cobalt mining (DRC)	Child labor	Very high	SHDB sector data
Battery manufacturing (China)	Overtime	High	PSILCA
Charging operation (EU)	Consumer safety	Low	National stats

Impact Pathway Example (Injury → DALY):

- *Stressor:* Hazardous work in cobalt mining.
- *Mechanism:* Poor OHS → higher accident frequency.
- *Midpoint:* 15 injuries / 1,000 worker-years.
- *Endpoint:* 15 × disability weight (0.05) × 0.1 year = **0.075 DALYs** per 1,000 worker-years.
  → Normalize by production volume to get DALY/FU.

Interpretation:

Mining dominates social burden; improvements could include:

- Supplier audits and traceable supply chains.
- OHS training and protective gear provision.
- Shifting to certified or recycled cobalt.
- Worker welfare programs and community development funds.

7. Challenges and Ongoing Developments

- **Data gaps:** Many social indicators lack reliable, site-level data.
- **Causality:** Hard to model complex cause–effect chains for social outcomes.
- **Aggregation:** Ethical and cultural variability in weighting social categories.
- **Double counting:** Overlaps between categories (e.g., health impacts counted both as “workers” and “community”).
- **Standardization:** UNEP Guidelines (2009, updated 2020) aim to harmonize methods.

Emerging trends include:

- Quantifying **human well-being** and **social value creation**, not just risk.
- Integrating **agent-based modeling** or **multi-criteria decision analysis (MCDA)**.

- Linking S-LCA with **SDG (Sustainable Development Goal)** indicators.

8. Comparing the Three Pillars

Dimension	Tool	Typical Unit	Data Type	Outcome
Environmental	LCA	kg CO_2-eq, kg SO_2-eq	Physical flows	Environmental impact
Economic	LCC	€ per FU	Monetary	Cost efficiency
Social	S-LCA	qualitative risk / DALYs	Socio-economic indicators	Human well-being

When combined → **Life Cycle Sustainability Assessment (LCSA)** = LCA + LCC + S-LCA.

9. Take-away

Social LCA transforms ethical narratives into structured, data-based analysis. It doesn't moralize production — it *illuminates consequences*, revealing where social harm hides behind the supply chain.

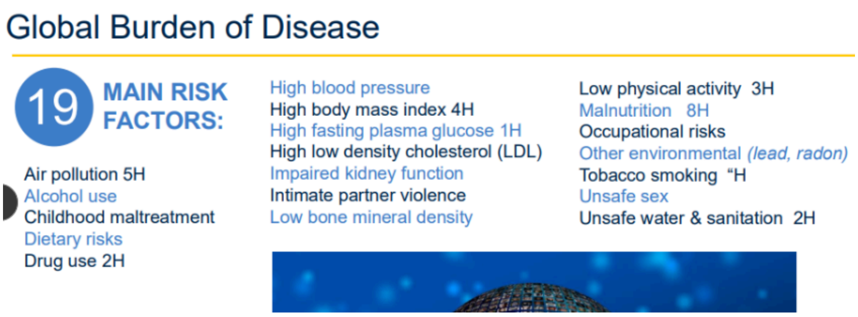
In the same way that CO_2 footprints reshaped climate policy, social footprints could reshape global labor practices — if we treat them with the same scientific discipline.

Excellent — this new lecture ("Social Aspects & Health," by Olivier Jolliet) expands your previous S-LCA slides into a quantitative health framework. Here's a detailed synthesis connecting all its sections so you can use it for notes or reports.

Global Burden of Disease (GBD) Framework

- Define metrics for characterizing impacts on human health and related burden of disease accounting for both mortality and morbidity
- Interpret data and graphs to identify and compare main risk factors on human and environmental health impact

Purpose: Quantify population health loss by combining **mortality (death)** and **morbidity (disease/disability)** into one comparable unit: the **DALY – Disability-Adjusted Life Year**.

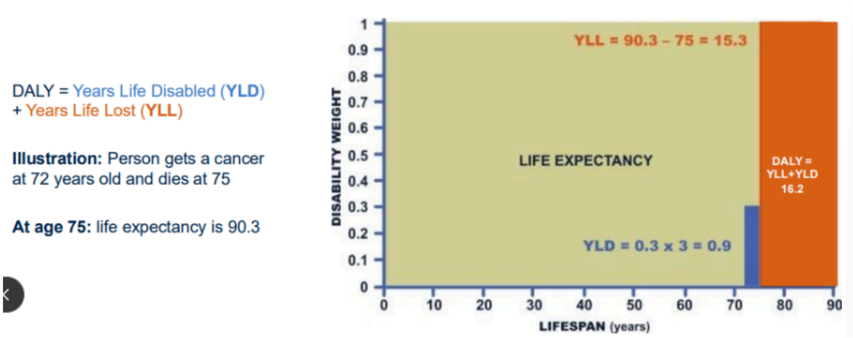


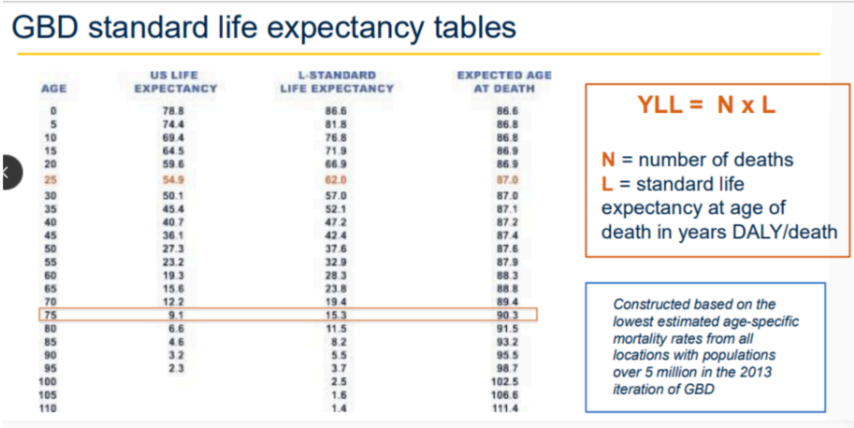
The burden of disease can be thought of as a measurement of the gap between current health status and an ideal situation where everyone live into old age (e.g. the average Japanese woman), free of disease and disability. - Disability Adjusted Life Years"

1 DALY = 1 year of healthy life lost.

Formulae:

- **DALY = YLL + YLD**
  - **YLL = N × L**, where *N* = deaths and *L* = remaining life expectancy.
  - **YLD = I × DW × L**, where *I* = incidence, *DW* = disability weight (0 = perfect health, 1 = death), and *L* = duration.





GBD standard life expectancy tables

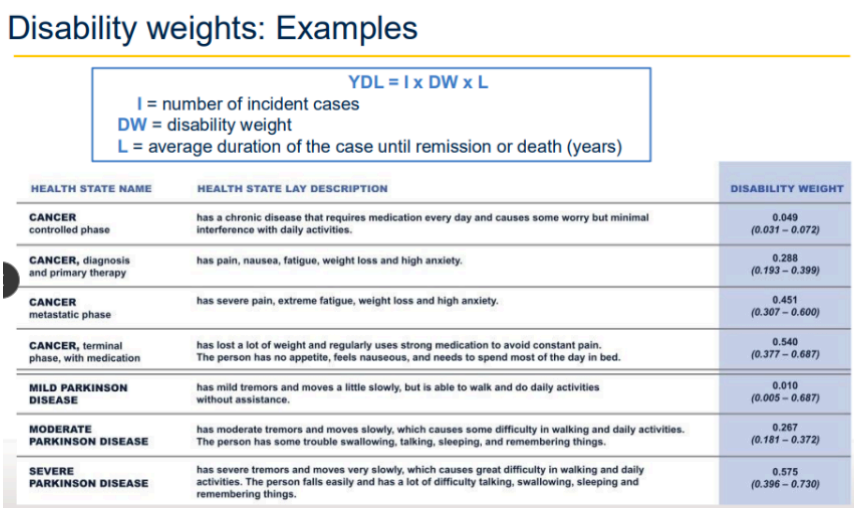
AGE	US LIFE EXPECTANCY	L-STANDARD LIFE EXPECTANCY	EXPECTED AGE AT DEATH
0	78.8	86.6	86.6
5	74.4	81.8	86.8
10	69.4	76.8	86.8
15	64.5	71.9	86.9
20	59.6	66.9	86.9
25	54.9	62.0	87.0
30	50.1	57.0	87.0
35	45.4	52.1	87.1
40	40.7	47.2	87.2
45	36.1	42.4	87.4
50	27.3	37.6	87.6
55	23.2	32.9	87.9
60	19.3	28.3	88.3
65	15.6	23.8	88.8
70	12.2	19.4	89.4
75	9.1	15.3	90.3
80	6.6	11.5	91.5
85	4.6	8.2	93.2
90	3.2	5.5	95.5
95	2.3	3.7	98.7
100		2.5	102.5
105		1.6	106.6
110		1.4	111.4

YLL = N x L

N = number of deaths
L = standard life expectancy at age of death in years DALY/death

Constructed based on the lowest estimated age-specific mortality rates from all locations with populations over 5 million in the 2013 iteration of GBD

GBD defines "ideal" life expectancy using the lowest recorded age-specific mortality rates (e.g., Japanese women ≈ 90 years).



Disability weights: Examples

YDL = I x DW x L
I = number of incident cases
DW = disability weight
L = average duration of the case until remission or death (years)

HEALTH STATE NAME	HEALTH STATE LAY DESCRIPTION	DISABILITY WEIGHT
CANCER controlled phase	has a chronic disease that requires medication every day and causes some worry but minimal interference with daily activities.	0.049 *(0.031 – 0.072)*
CANCER, diagnosis and primary therapy	has pain, nausea, fatigue, weight loss and high anxiety.	0.288 *(0.193 – 0.399)*
CANCER metastatic phase	has severe pain, extreme fatigue, weight loss and high anxiety.	0.451 *(0.307 – 0.600)*
CANCER, terminal phase, with medication	has lost a lot of weight and regularly uses strong medication to avoid constant pain. The person has no appetite, feels nauseous, and needs to spend most of the day in bed.	0.540 *(0.377 – 0.687)*
MILD PARKINSON DISEASE	has mild tremors and moves a little slowly, but is able to walk and do daily activities without assistance.	0.010 *(0.005 – 0.687)*
MODERATE PARKINSON DISEASE	has moderate tremors and moves slowly, which causes some difficulty in walking and daily activities. The person has some trouble swallowing, talking, sleeping, and remembering things.	0.267 *(0.181 – 0.372)*
SEVERE PARKINSON DISEASE	has severe tremors and moves very slowly, which causes great difficulty in walking and daily activities. The person falls easily and has a lot of difficulty talking, swallowing, sleeping and remembering things.	0.575 *(0.396 – 0.730)*

To measure the **severity of a health condition** on a scale from **0 to 1**, where:

- **0** = perfect health (no loss of well-being)
- **1** = equivalent to death (complete loss of health)

Each health condition is assigned a **disability weight (DW)** based on its impact on daily functioning and quality of life.

Symbol	Meaning
I	Number of incident cases
DW	Disability weight (severity of condition)
L	Average duration of the condition (in years) until remission or death

Imagine 100 workers develop a chronic illness from toxic exposure:

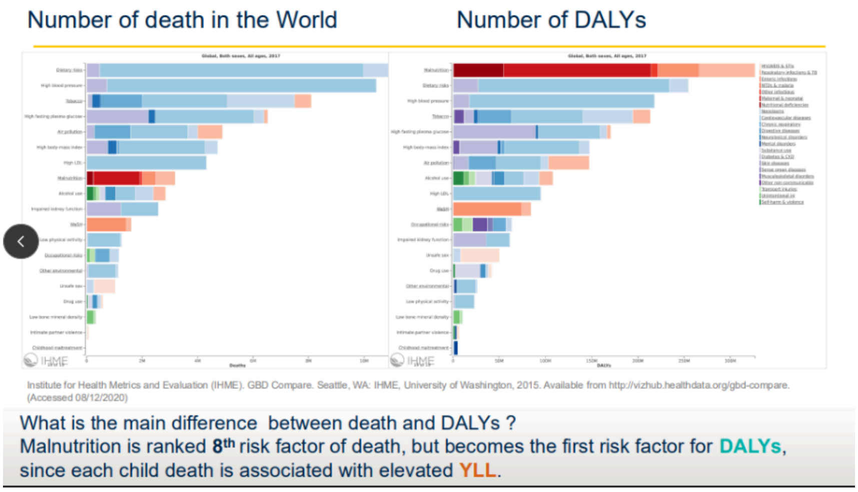
- I=100I = 100I=100 cases
- DW=0.3DW = 0.3DW=0.3
- L=10L = 10L=10 years

$YLD = 100 \times 0.3 \times 10 = 300 \text{ years of healthy life lost}$

This means **300 DALYs** lost due to morbidity (if no deaths occur).

Insight: DALYs measure the *gap* between actual health and this ideal state.

Key risk factors (2019 ranking sample):



DALYs are the more comprehensive measure of health impacts — used in Global Burden of Disease studies and in S-LCA when linking social impacts to human well-being.

~Air pollution, tobacco, dietary risks, malnutrition, high BMI, high blood pressure, high fasting glucose, unsafe water/sanitation, occupational risks, alcohol, drug use, low physical activity, unsafe sex, etc.

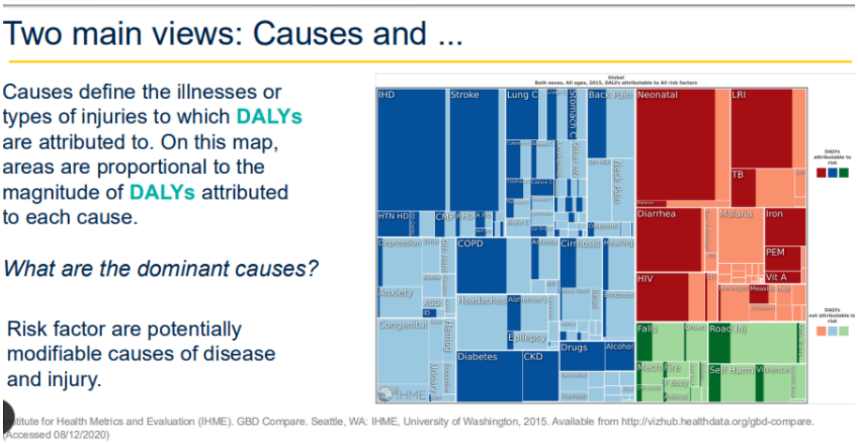
Note: *Malnutrition* ranks lower in deaths but highest in DALYs because it affects children with very high YLL.

Interpretation:

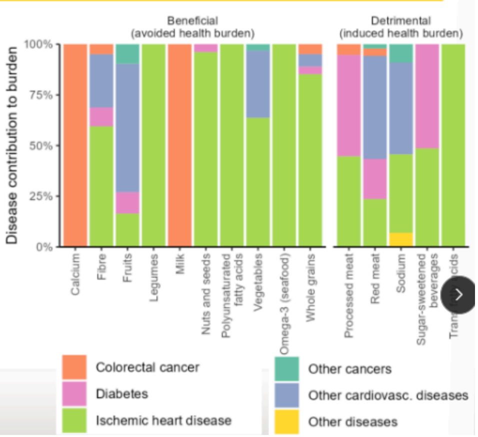
- "Causes" → diseases or injuries (e.g., cancer, ischemic heart disease).
- "Risk factors" → modifiable precursors (e.g., diet, smoking).

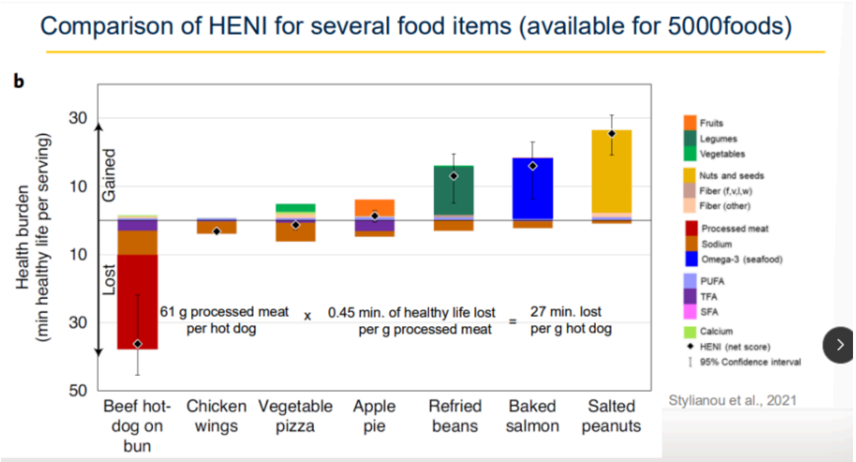
  GBD allows comparing both views globally.

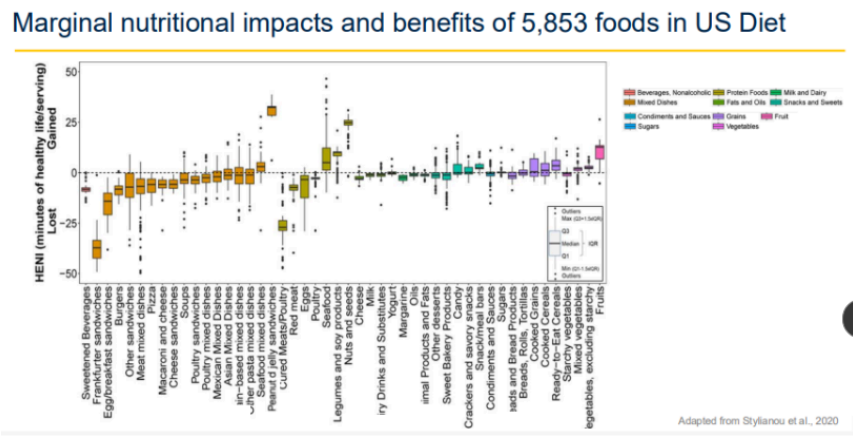
Main take-away: DALYs give a fuller picture than deaths alone — crucial for LCA's *human health* damage category.



Nutritional risk factor, Denmark average	Impact per g of risk component
	µDALY/g
calcium	-10.56
omega 3 Fatty acids in seafood	-9.33
nuts	-2.38
fibre	-1.48
pufa	-0.788
whole grains	-0.271
additional Factor Of Fiber In WholeGrains	-0.138
legumes	-0.171
additional Factor Of Fiber In Legumes	-0.722
fruits	-0.114
additional Factor Of Fiber In Fruits	-0.265
vegetables	-0.043
additional Factor Of Fiber In Veg	-0.435
milk	-0.0146
sugar Sweetened Beverages	0.0230
red meat	0.322
processed meat	0.375
additional Factor Of Sodium In ProcMeats	5.60
transfat	9.82
sodium_total	10.70







🩺 Two Main Views in Health Impact Analysis

1. Causes

- Represent the **diseases or injuries** that directly lead to lost healthy life years (DALYs).
- Examples: ischemic heart disease (IHD), stroke, lung cancer, diarrhoea, malaria, HIV/AIDS, depression.
- Each *cause* can have multiple underlying risk factors.
- The treemap in the slide shows each box sized by the total **DALYs** attributable to that disease — larger boxes = greater global health burden.

Dominant causes globally:

- Cardiovascular diseases (IHD, stroke)
- Neonatal and infectious diseases (malaria, TB, diarrhoea, neonatal disorders)
- Chronic diseases (COPD, diabetes, cirrhosis)
- Mental and neurological disorders (depression, anxiety, substance abuse)

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2. Risk Factors

- Represent the **modifiable contributors** that increase the likelihood of disease or injury.
- They are *upstream* causes — the levers we can target with prevention or policy.

Examples:

- **Behavioral:** smoking, alcohol use, diet, low physical activity
- **Metabolic:** high blood pressure, obesity, high glucose, high cholesterol
- **Environmental:** air pollution, unsafe water, occupational risks

These risk factors interact with causes.

For example:

> “High blood pressure” (risk factor) → increases likelihood of “stroke” or “heart disease” (cause).

⚙️ Why This Distinction Matters

- **Causes** tell us *what diseases* people suffer and die from.
- **Risk factors** tell us *why* those diseases occur and *where prevention is possible*.
- Understanding both is crucial for **policy prioritization**, **public health strategy**, and **social impact assessment** in S-LCA.

💡 Connection to S-LCA

In **Impact Pathway S-LCIA**, this dual view mirrors how we:

- Identify **causes** → specific social or health outcomes (e.g., workplace injury).
- Identify **risk factors** → social conditions that increase their likelihood (e.g., lack of protective equipment, long hours, unsafe materials).

Thus, **risk factors are modifiable levers**, just as **stakeholder conditions** are intervention points in S-LCA.

In summary:

Perspective	Focus	Example	Purpose
Causes	Diseases or injuries producing DALYs	Stroke, cancer, HIV	Quantify burden of illness
Risk Factors	Modifiable behaviors or exposures leading to disease	Smoking, malnutrition, unsafe water	Identify prevention targets

Summary

- DALYs – Disability Adjusted Life Years offer a more comprehensive metrics than death to account for both mortality and morbidity
- It measures the gap between current health status and an ideal reference situation of living a long and healthy life
- The Global Burden of Disease project provides worldwide comparison of health status, causes for death and risk factors for 153 countries
- The website is an amazing source of information, you can mine, relevant to many questions related to human health

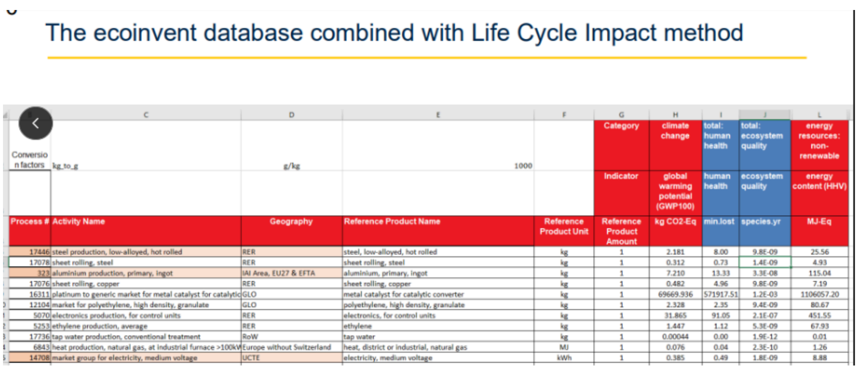
🚗 2. Quantitative Health Assessment via Life Cycle Thinking

Case: Gasoline vs Electric Vehicle vs Bike

Goal → Compare **human health** and **ecosystem** impacts for transportation options.

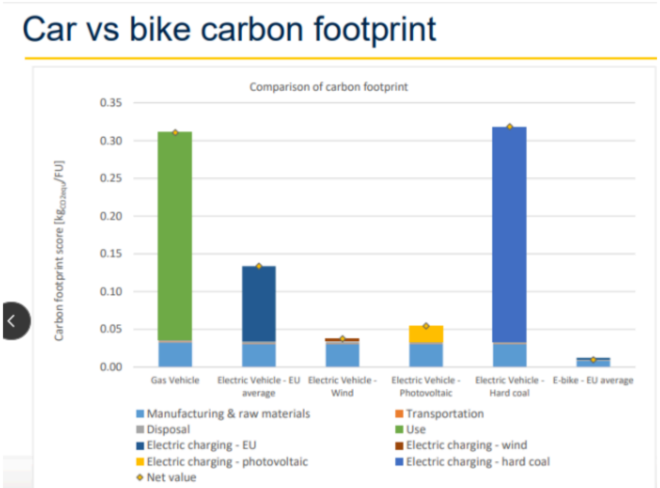
Method:

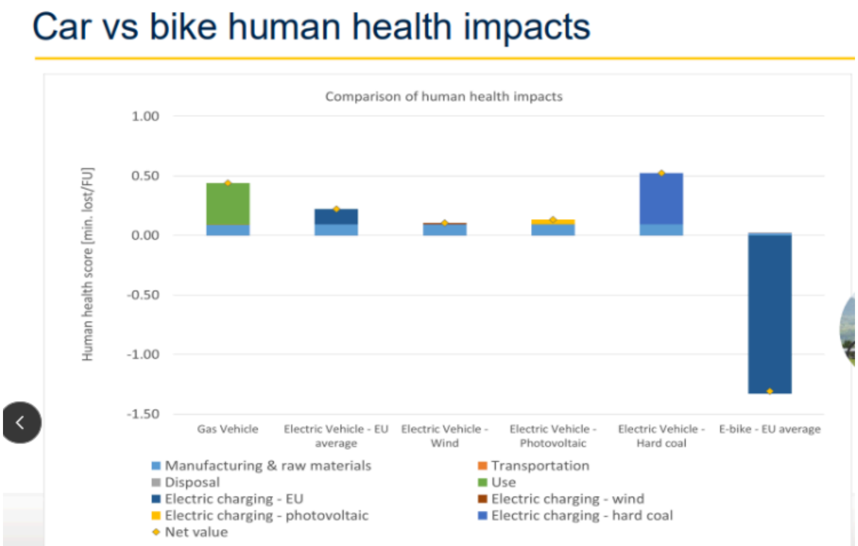
Combine *ecoinvent* life-cycle inventory with *Impact World+* or *ReCiPe* impact models. Impacts are expressed in **DALY / functional unit** (e.g., passenger-km).

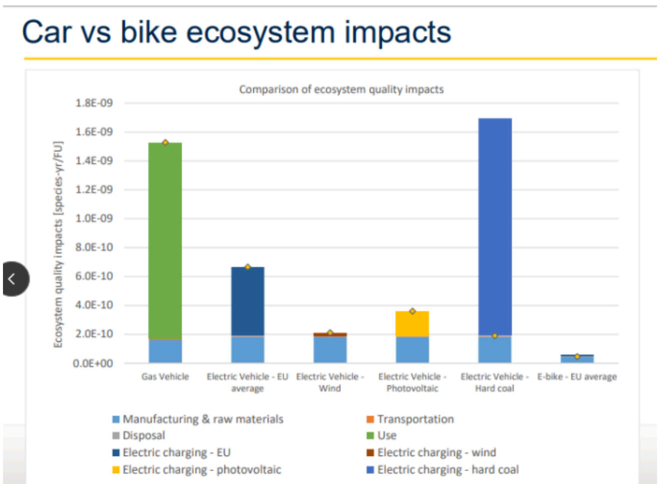


The ecoinvent database combined with Life Cycle Impact method

Conversion factors	kg_to_g	g/kg	1000		Category	climate change	total: human health	total: ecosystem quality	energy resources: non-renewable
					Indicator	global warming potential (GWP100)	human health	ecosystem quality	energy content (HHV)
Process #	Activity Name	Geography	Reference Product Name	Reference Product Unit	Reference Product Amount	kg CO2-Eq	min.lost	species.yr	MJ-Eq
17446	steel production, low-alloyed, hot rolled	RER	steel, low-alloyed, hot rolled	kg	1	2.181	8.00	9.8E-09	25.56
17078	sheet rolling, steel	RER	sheet rolling, steel	kg	1	0.312	0.73	1.4E-09	4.93
323	aluminium production, primary, ingot	IAI Area, EU27 & EFTA	aluminium, primary, ingot	kg	1	7.210	13.33	3.3E-08	115.04
17076	sheet rolling, copper	RER	sheet rolling, copper	kg	1	0.482	4.96	9.8E-09	7.19
16311	platinum to generic market for metal catalyst for catalytic	GLO	metal catalyst for catalytic converter	kg	1	69669.936	571917.51	1.2E-03	1106057.20
12104	market for polyethylene, high density, granulate	GLO	polyethylene, high density, granulate	kg	1	2.328	2.35	9.4E-09	80.67
5070	electronics production, for control units	RER	electronics, for control units	kg	1	31.865	91.05	2.1E-07	451.55
5253	ethylene production, average	RER	ethylene	kg	1	1.447	1.12	5.3E-09	67.93
17736	tap water production, conventional treatment	RoW	tap water	kg	1	0.00044	0.00	1.9E-12	0.01
6843	heat production, natural gas, at industrial furnace >100kW	Europe without Switzerland	heat, district or industrial, natural gas	MJ	1	0.076	0.04	2.3E-10	1.26
14708	market group for electricity, medium voltage	UCTE	electricity, medium voltage	kWh	1	0.385	0.49	1.8E-09	8.88







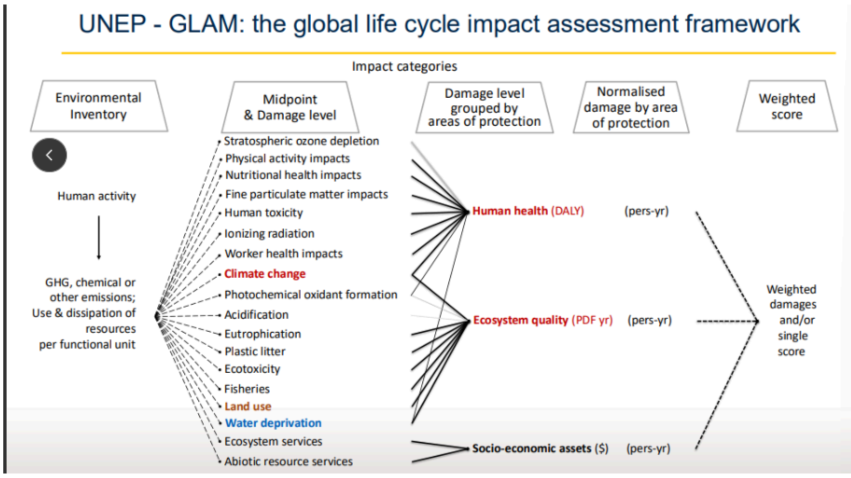
Observed trends:

- **Gasoline car:** dominant emissions during use phase (combustion → $PM_{2.5}$, NO_x).
- **EV (EU mix):** lower use-phase emissions; higher manufacturing burden (battery).
- **EV (renewables):** large health benefit vs fossil charging.
- **Bike/E-bike:** minimal life-cycle health burden; positive health gains via physical activity.

Impact categories (grouped by "areas of protection"):

1. **Human health (DALY pers-yr)** — climate change, particulate matter, ionizing radiation, human toxicity, nutrition, physical activity, worker health.
2. **Ecosystem quality (species·yr)** — acidification, eutrophication, ecotoxicity, land use.
3. **Socio-economic assets ($ pers-yr)** — material resource losses, property damage.

Weighted damage assessment: Combines midpoints → endpoints → single score; UNEP's GLAM (Global Life-Cycle Impact Assessment Method) provides normalization and weighting.



UNEP-GLAM: Global LCIA Framework

1. Environmental Inventory

- **Starting point:** The **inputs and outputs** from human activity, quantified per *functional unit* (FU).

  Examples:

  - Greenhouse gases (GHG)
  - Pollutant emissions (NOx, SO_2, $PM_{2.5}$, heavy metals)
  - Resource use (land, water, energy)
  - Dissipation of materials (e.g., microplastics)

These are the measurable flows from the **life cycle inventory (LCI)** stage.

---

2. Midpoint & Damage Level (Impact Categories)

Impacts are first modeled at **midpoints**, which are specific environmental mechanisms affected by human activity — the "in-between" level before final damages occur.

Examples of **midpoint categories**:

- Stratospheric ozone depletion
- Climate change
- Fine particulate matter ($PM_{2.5}$) impacts
- Human toxicity
- Acidification, eutrophication
- Water deprivation
- Land use, ecosystem services
- Worker health and nutritional impacts

At this stage, each emission or resource flow is translated into a **potential impact**, e.g., kg CO_2 → climate change potential.

---

3. Damage Level — Areas of Protection (AoPs)

The midpoints are aggregated into three overarching "**Areas of Protection**" that represent what society ultimately wants to safeguard:

Area of Protection	Measured in	Meaning
Human health	**DALY (Disability-Adjusted Life Years)**	Years of healthy life lost due to disease, pollution, or occupational risks.
Ecosystem quality	**PDF·yr (Potentially Disappeared Fraction of species × years)**	Biodiversity loss and ecosystem damage.
Socio-economic assets	**$ per person-year**	Material and economic damages (e.g., property loss, resource depletion).

These convert different impact types into comparable units at the "damage" (endpoint) level.

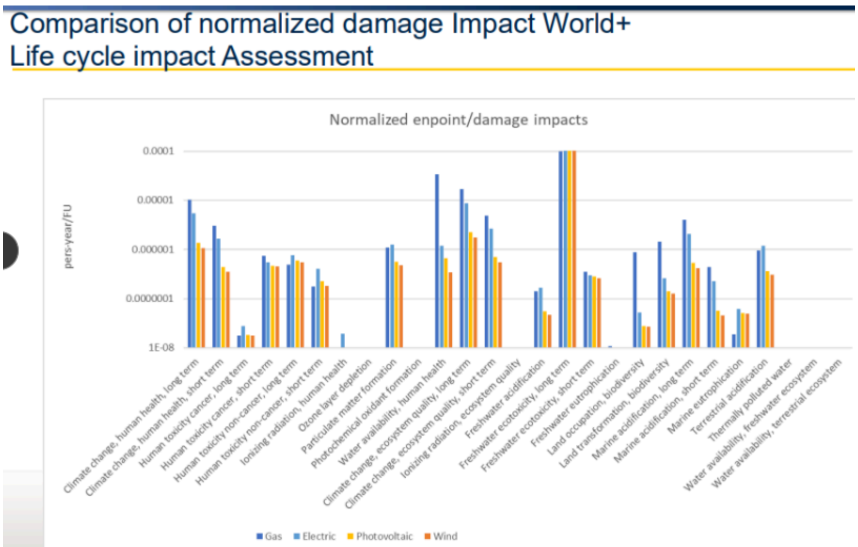
4. Normalisation

- Expresses each damage type relative to a reference (e.g., average per-capita annual impact in a region or globally).
- Allows comparison of the *relative importance* of different categories (e.g., climate vs toxicity vs land use).

5. Weighting & Aggregation

- Assigns importance factors (weights) to each area of protection based on policy, expert, or stakeholder input.
- Produces:
    - **Weighted damages** (per area of protection), or
    - A **single score** that reflects total sustainability performance per functional unit.

- GLAM harmonizes impact categories for **environmental, social, and economic** dimensions of **Life Cycle Sustainability Assessment (LCSA)**.
- Human health (DALY) bridges environmental LCA and **Social LCA** — both use the same health-based unit, allowing integrated assessment.
- The approach helps translate complex inventories into **policy-relevant metrics** such as "minutes of healthy life lost," "species lost per year," or "economic cost per person."



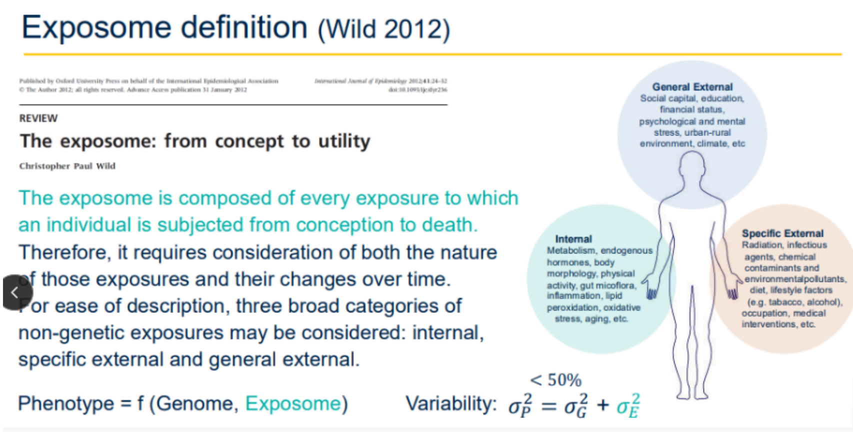
🧬 Consumption, products and health - Exposome and health impacts

- Identify the multiple exposures an individual is exposed to
- Define the exposome and a vision towards its operationalization
- Compare the impact magnitude of various exposure to consumer products, foods, pollution and climate change, occupational exposure, noise and physical exercise
- Discuss trade-offs and synergies between reduction in human health impacts and other environmental impacts

Definition (Wild 2012):

The *exposome* = the sum of all exposures (chemical, physical, social, behavioral, biological) an individual experiences from conception to death.

Phenotype = f (genome, exposome) → human health results from both genetics and environment.



Three exposure categories:

1. **Internal:** metabolism, hormones, microbiome, inflammation, aging.
2. **Specific external:** diet, pollutants, chemicals, infections, radiation, occupation.
3. **General external:** socioeconomic status, education, urban form, stress, climate.

Inclusion of various impacts on human health

Table of contents

- Climate change
- Fine particulate impacts
- Nutrition impacts
- Physical exercise
- Chemicals in products

Vision:

Quantify personal exposure history → personalized health footprints:

"Tell me where and how you lived, ate, and worked — and I'll tell you your health profile."

---

4. Major Environmental Health Drivers

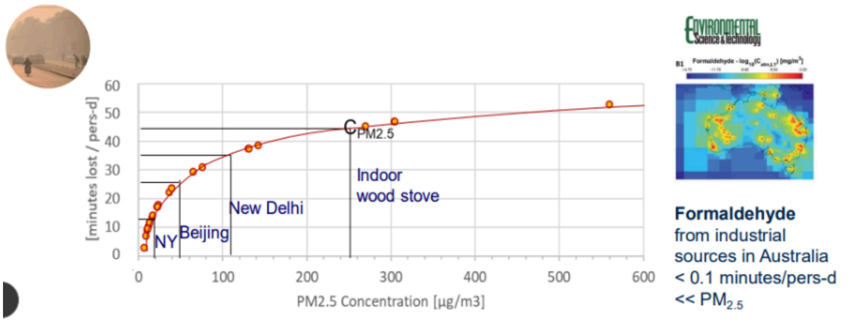
A. Air pollution ($PM_{2.5}$)

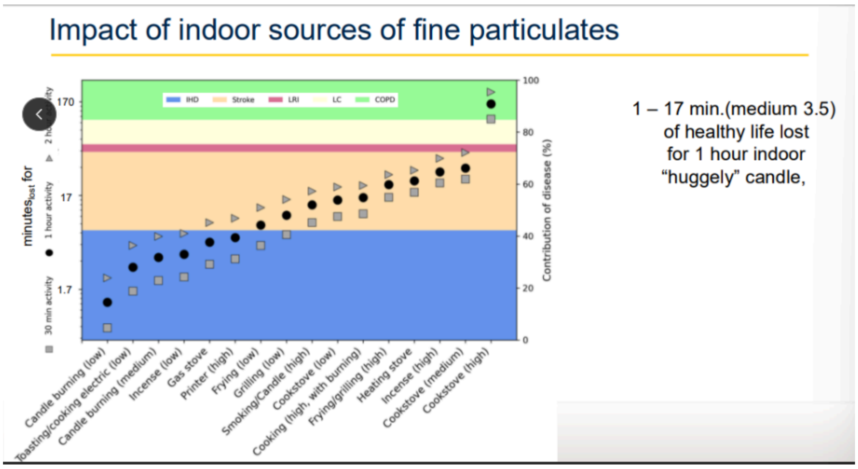
- 6.5 mil deaths per year, 65% in Asia, largely cardiovascular disease
- ~6.5 million deaths / year worldwide (≈ 17 800 per day).
- Dominated by cardiovascular and respiratory diseases.
- Indoor sources (e.g., wood stoves, candles) can yield minutes of life lost per hour of exposure.

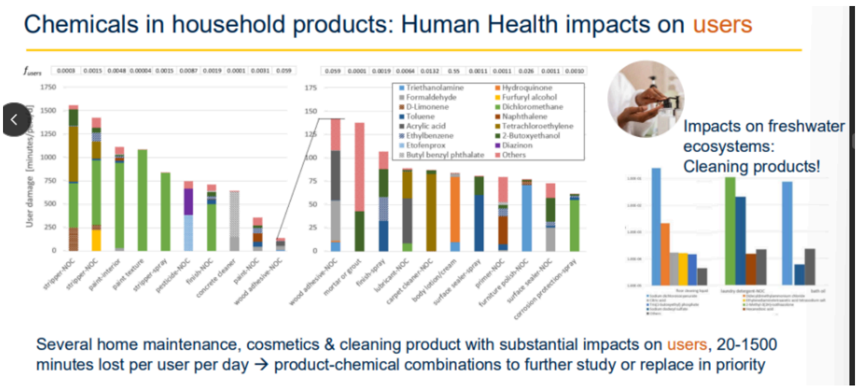
B. Chemical exposure (consumer products)

USEtox model estimates **DALY / kg chemical in product** for user and environmental routes.

Cleaning and cosmetic products can cause **20 – 1500 min of healthy life lost per user per day** in extreme cases — targets for substitution.





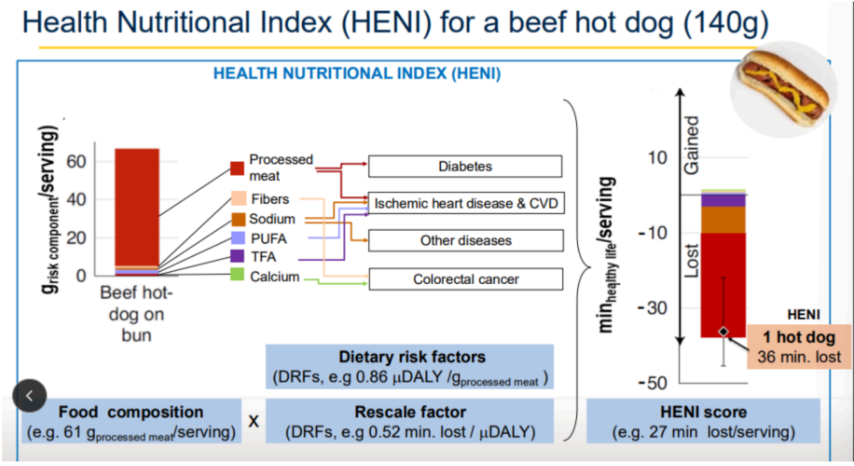


C. Nutrition → HENI (Health Nutritional Index)

Stylianou et al. (2021 Nature Food) quantified minutes of life lost/gained for 5800 foods.

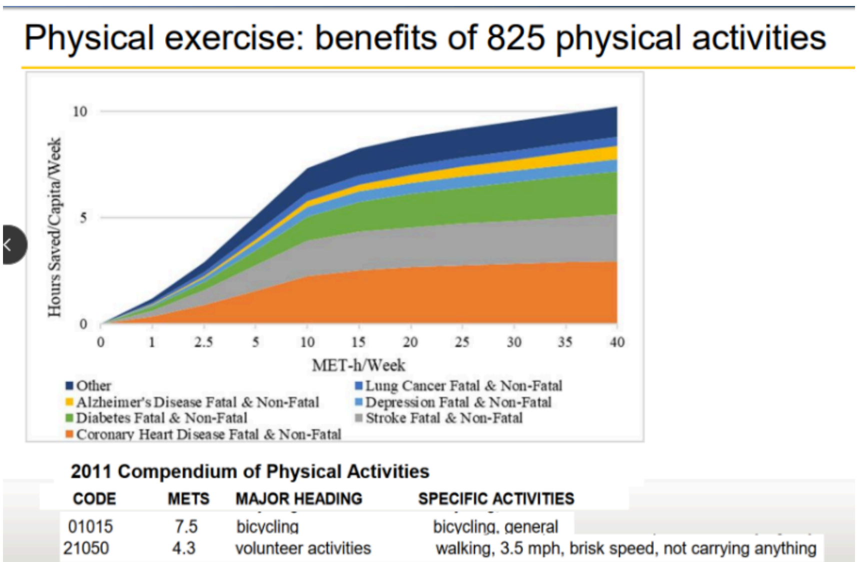
Example: **Beef hot dog (140 g) ≈ 36 min lost/serving** (processed meat → CVD, cancer).

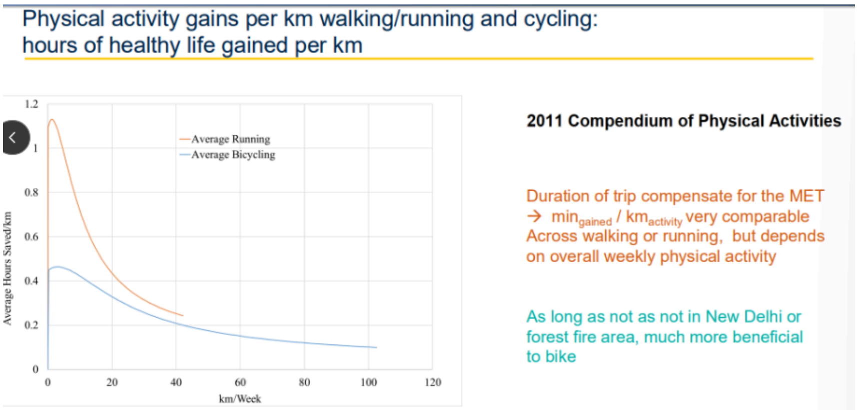
Positive foods (nuts, legumes, fruits) yield life minutes gained.



D. Physical Activity

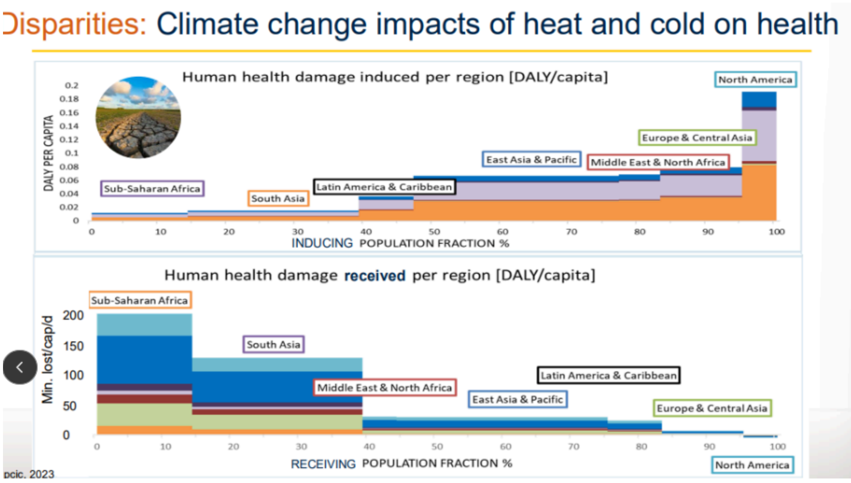
Roughly **hours of healthy life gained per km walked/cycled** – comparable between walking/running; gains persist unless air quality is extremely poor (e.g., Delhi smog).

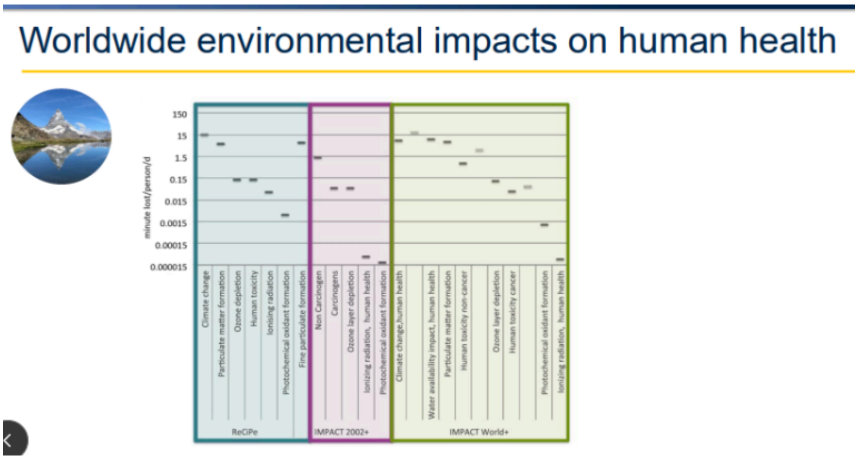




E. Climate change

Heat and cold stress already cause millions of DALYs; impacts distributed unequally (Rupčić 2023).



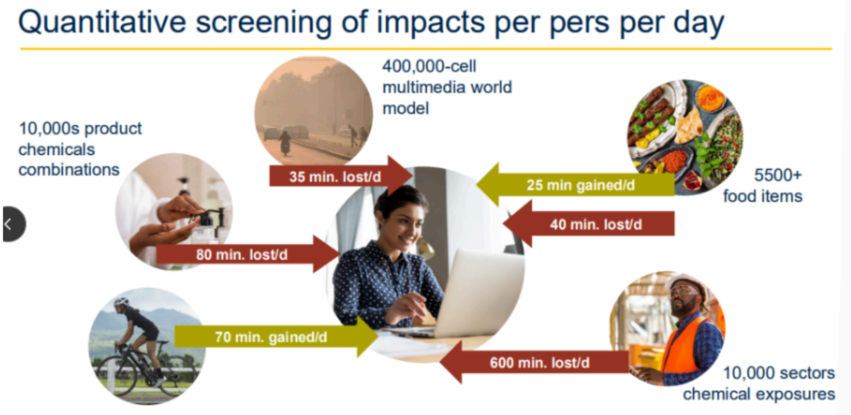


🔄 5. Quantitative Screening — "Minutes of Healthy Life Lost or Gained per Day"

Indicative global averages (Jolliet 2020–2023):

- ≈ **+25 min/d** from physical activity
- ≈ **−35 min/d** from diet
- ≈ **−40 min/d** from chemical exposure
- ≈ **−80 min/d** from air pollution
- Net ≈ hundreds of minutes/day traded across behaviors and environments.

This holistic accounting merges LCA with epidemiology to express all health pressures on a single scale: minutes or DALYs per person-day.



Global Trade & Health

- Connect LCA with economic models to characterize impacts due to global trade
- Explore how those who induce pollution are decoupled from those impacted by that pollution
- Interpret graphs to determine magnitude of imbalance in inducing vs. consuming regions

Problem: Consumption in one region drives emissions — and thus DALYs — elsewhere.

Method: Environmentally Extended Multi-Regional Input-Output model + pollution transport & exposure modules ("M^3" project).

Workflow:

1. Production system → emissions → fate/transport → population exposure → dose-response → DALYs.
2. Link to economic flows (USD) → assign impacts to final consumers.

Findings:

- PM-related deaths heavily concentrated in Asia but largely *induced* by consumption in Europe & North America.
- Example: ~46 000 PM-related deaths linked to Western consumption.
- Control tech (99 – 99.9 % removal efficiency) is effective but costly → ethical trade-offs.

Ethical question:

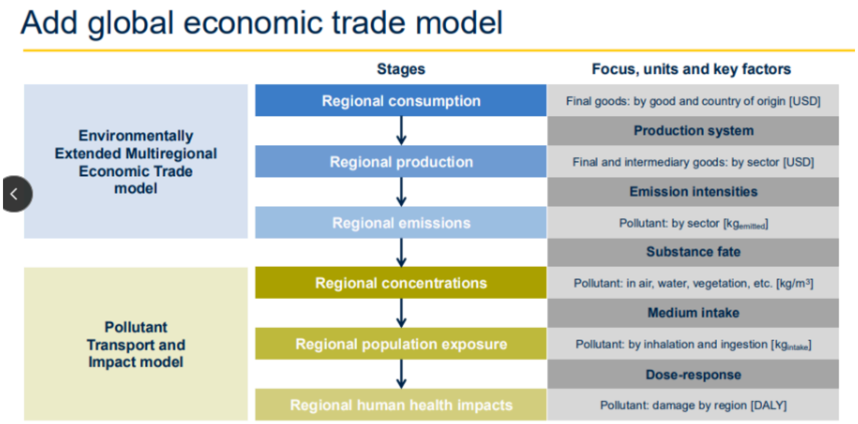
"To what extent are consumers responsible for health damages occurring abroad?"

In a globalized economy, Western and high-income consumers are partly responsible for particulate-matter-related deaths in Asia, since a significant portion of regional air pollution stems from manufacturing goods exported to meet global demand. Multi-regional input–output studies show that roughly one-quarter of Asia's PM-related premature deaths are linked to exports for consumption in Europe and North America. This means that while the emissions occur locally, the drivers are transboundary economic activities. Through life-cycle and trade perspectives, responsibility extends beyond producers to the consumers, companies, and policies that sustain such supply chains. Consequently, the health burden of production—measured in DALYs—is an externalized cost of our consumption. Ethical accountability therefore requires cleaner production standards, transparent supply chains, and sustainable consumption choices that recognize the shared human impact of global trade.

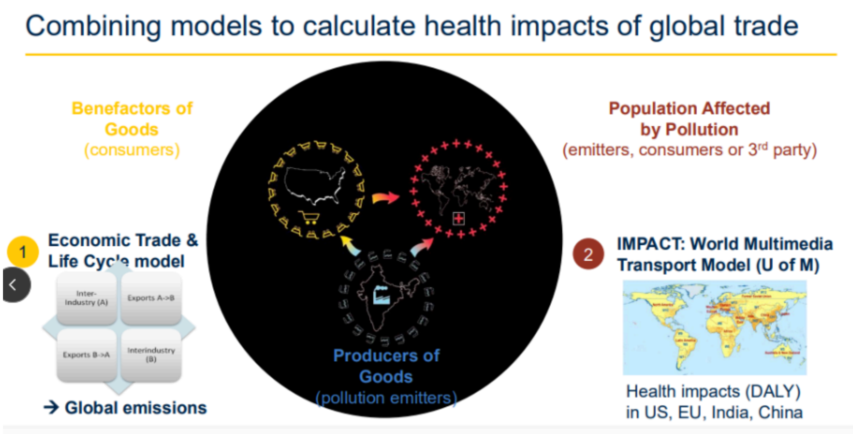
Where are the impacts associated with ALL global trade?

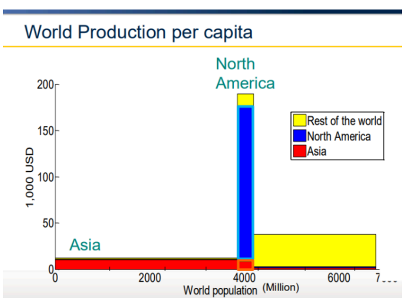
The health and environmental impacts of global trade are overwhelmingly **produced and experienced in Asia**,**induced by consumption in high-income regions**, and**mediated through international supply chains**.

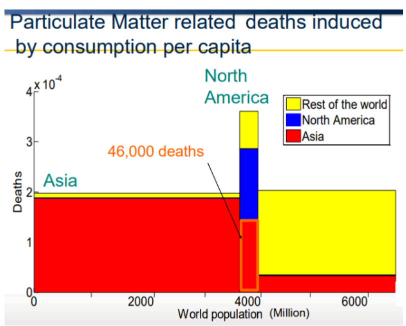
Global trade therefore redistributes economic value northward and health damage southward — a pattern that life cycle assessment tools make visible.



Region	Role in Global Trade	Main Situation	Resulting Health Impact (DALYs or deaths)
Asia (especially China, India, Southeast Asia)	*World's manufacturing hub – exports electronics, textiles, metals, etc.*	High industrial emissions, dense populations, weaker emission control	**Highest PM-related mortality and DALYs**, many induced by exports
Europe & North America	*Major consumers and importers*	Outsource pollution-intensive production overseas; relatively strict local air-quality laws	**Lower direct impacts**, but indirectly responsible for deaths abroad
Africa & Latin America	*Resource and agricultural exporters*	Mining, deforestation, and fuel extraction create local pollution and health damage	**Moderate–high local exposure**, low consumption benefit
Rest of the World	Mixed import/export balance	Often downstream in value chains	Varied, but smaller shares of induced DALYs







⚖️ 7. Key Integrative Insights

- **DALY** is the universal unit bridging epidemiology and life-cycle models.

- **GBD** provides global baselines for mortality + morbidity.
- **S-LCA + GBD + Exposome + Trade LCA** = quantitative social sustainability.
- **Health gains/losses** can now be compared across behaviors, products, and policies — from diet and transport to chemicals and global trade.

Would you like me to turn this into a *two-page visual cheat-sheet* (summary boxes + formulas + diagrams for DALY, exposome, EV vs bike, etc.)? It would fit neatly for your **Quantitative Sustainability Module 7** revision.

Implementing the Guidelines for Social Life Cycle Assessment: Past, Present, and Future," *Int. J. Life Cycle Assessment*, Tokede & Traverso, 2020)

🌍 1. Context and Purpose

The paper critically reviews the **UNEP/SETAC 2009 Guidelines for Social Life Cycle Assessment (S-LCA)** and the **2013 Methodological Sheets**, analysing 58 case studies published between 2009–2019.

Main goal → evaluate **how well the Guidelines are being implemented** and how future versions could address their weaknesses.

S-LCA's goal remains:

> "to promote the improvement of social conditions for all stakeholders and the socio-economic performance of a product throughout its life cycle."

⚙️ 2. Overview of the Guidelines

UNEP/SETAC (2009): the first standardized reference for assessing *positive and negative social impacts* from extraction → disposal.

Two impact modeling families were defined:

Type	Description	Example
Type I	*Performance/reference-scale* evaluation — compares qualitative scores or risks (e.g., 1–5)	SHDB, PSILCA risk screening
Type II	*Impact pathway / cause-effect* modeling — attempts quantitative links between social stressors and outcomes	DALY conversions, job creation models

The 2013 Methodological Sheets expanded to 31 **subcategories** (workers, consumers, local community, society, value-chain actors).

By 2020 revision → increased to **38 subcategories**, added **"children"** as stakeholder group, and explicitly included **positive impacts**.

🧩 3. Key Methodological Challenges Identified

1. **Data scarcity**
   - Most studies rely on generic, sector-country databases (SHDB, PSILCA).
   - Lack of site-specific or temporal data limits reliability.
2. **Limited coverage**
   - Only **47% of all subcategories** were actually implemented in the 58 case studies.
   - Top 3 indicators studied: worker *health & safety (81%)*, *working hours (76%)*, *fair salary (73%)*.
   - Least covered: consumer *privacy (22%)*, *feedback & transparency (24%)*, *end-of-life responsibility (19%)*.
3. **Unequal stakeholder focus**
   - 68% addressed *workers*;
   - 25% *consumers*;
   - 46% *local communities*;
   - 44% *society*;
   - 34% *value chain actors*.

     → Consumers and value-chain actors are the **most neglected**.
4. **Lack of contextualisation**
   - Indicators often treated as universal, though social realities vary widely (e.g., gender ratios, cultural labor norms).

- Without local calibration, high “risk” scores may misrepresent real conditions.

5. **Unclear definition of “well-being”**
   - “Human well-being” is the main *area of protection (AoP)*, but poorly defined.
   - Authors call for including both **objective well-being (economic/material)** and **subjective well-being (psychological/social)**.
6. **Theoretical fragmentation**
   - 11+ competing theories underpin S-LCA: stakeholder theory, systems theory, capability theory, network theory, etc.
   - No unified framework to link these or describe causality.
7. **Functional unit inconsistency**
   - S-LCA borrowed “functional unit” from environmental LCA, but often applied inconsistently.
   - Only **one study** justified a subjective FU (“quality of life”).
   - Units vary: mass, area, time, money, or whole company.
   - The link between *social utility* and FU remains unclear.

🧮 4. Main Findings from the Mapping Review (2009–2019)

- **58 case studies** across 35 countries — 60% in G20; Africa and Oceania nearly absent.
- **64%** of studies followed the Guidelines; **36%** used alternative frameworks.
- Post-2017 trend: **growing number of non-Guidelines approaches**, especially *impact-based* and *context-oriented* (e.g., Roundtable for Product Social Metrics, WBCSD 2016).
- Indicators still dominated by worker-related categories; consumer and society impacts lag behind.
- Functional unit choice shows correlation with E-LCA units (mass, energy, area) but lacks social justification.

🧠 5. Proposed Directions for the Future S-LCA Guidelines

The authors propose **four main improvements** for the 2020+ revisions:

1. **Expand stakeholder coverage**

   → More emphasis on *consumers* and *value-chain actors*, often underrepresented and marginalized.
2. **Localise indicators**

   → Indicators shouldn’t be homogenised across sectors; their relevance must be *context-specific* and *justified*.
3. **Develop a stronger theoretical foundation**

   → Integrate social, organisational, and governance theories into a coherent, flexible framework.

   → Encourage transdisciplinarity (social sciences, psychology, humanities).
4. **Clarify and justify functional units**

   → Define *social utility* as a measurable or perceivable function (e.g., “1 year of employment for 100 workers,” “1 educational service delivered”).

   → Move beyond purely physical FUs.

🗣️ 6. Other Notable Observations

- **Participation gap:** few studies used *participatory stakeholder engagement*; yet participatory approaches are essential to capture real perceptions and avoid misinterpretations.
- **Positive impacts:** rarely reported; need systematic inclusion (e.g., job satisfaction, education, empowerment).
- **Technological opportunity:** authors suggest *machine learning and data science* to help gather and process social data from multiple sources.
- **Integration into rating systems:** S-LCA could complement sustainability certifications (e.g., BREEAM, LEED) which focus on “use phase” rather than “production phase”.

🔭 7. The Big Picture

Challenge	2020+ Solution
Incomplete data coverage	Link S-LCA to dynamic databases and participatory data collection
Weak context specificity	Require explicit justification of indicator relevance

Challenge	2020+ Solution
Poor theoretical grounding	Establish flexible meta-framework integrating stakeholder, systems, and capability theories
Narrow stakeholder scope	Add children, consumers, value-chain actors; include positive impacts
Confusing functional unit use	Define "social utility" and provide examples per sector
Limited accessibility	Simplify communication for non-experts and policy use

🧭 8. Core Takeaway

S-LCA is still **methodologically young**.

Its evolution depends on bridging **quantitative rigor** (DALYs, cause-effect) and **qualitative insight** (context, meaning, participation).

The 2020 revision of the UNEP/SETAC Guidelines — and the upcoming ISO standard — are steering it toward this balance: from a checklist of indicators to a theory-driven, context-aware system for improving **human well-being across value chains**.

Would you like me to make a **diagram or matrix** summarizing the comparison between *Type I vs Type II*, *2009 vs 2020 Guidelines*, and *main gaps + proposed improvements* for your DTU "Quantitative Sustainability" notes? It would visually tie together this paper and your lecture slides.

UNEP 2020 "Guidelines for Social Life Cycle Assessment of Products and Organizations

🌍 1. Purpose and Scope of the 2020 S-LCA Guidelines

The 2020 update expands the earlier **2009 UNEP/SETAC Guidelines** to cover not just *products* but also *organizations*.

It provides a consistent methodological framework to **identify, measure, and improve social and socio-economic impacts across life cycles**.

Main aims:

- Integrate S-LCA within the Life Cycle Sustainability Assessment (LCSA) triangle → **Environmental LCA + Life Cycle Costing (LCC) + S-LCA**.
- Make S-LCA applicable to both **companies** and **product systems**.
- Include **positive impacts**, **context sensitivity**, and **stakeholder participation**.

⚙️ 2. Conceptual Foundations

2.1. Definition

> "S-LCA is a compilation and evaluation of the social and socio-economic aspects and the positive and negative impacts of products and organizations along their life cycle."

2.2. Object and Area of Protection (AoP)

Area of Protection: *Human well-being.*

S-LCA focuses on impacts that affect human well-being, encompassing:

- **Living conditions** (income, health, housing)
- **Human rights and dignity**
- **Capabilities and freedoms**
- **Cultural and social cohesion**

👥 3. Stakeholder Groups and Sub-Categories

The 2020 Guidelines refine the stakeholder model to **6 groups** and **38 subcategories**, integrating both *positive* and *negative* indicators.

Stakeholder	Example sub-categories (selected)
Workers	Health & safety, fair salary, working hours, child/forced labour, freedom of association, discrimination, social benefits
Consumers	Health & safety, privacy, feedback, transparency, end-of-life responsibility
Local community	Access to resources, community engagement, cultural heritage, safe living conditions
Society	Corruption, public commitment to sustainability, local employment, technology development
Value chain actors	Fair competition, promoting social responsibility, supplier relationships

Stakeholder	Example sub-categories (selected)
Children *(new 2020 addition)*	Child labour, access to education, protection from exploitation

→ 2009 version had 5 stakeholder groups and 31 sub-categories; 2020 adds **children** and several new issues like **migrant workers**, **human trafficking**, and **digital privacy**.

🧩 4. Types of Assessment Approaches

Type I — *Performance or Reference Scale*

- Evaluates risk or social performance levels (e.g., "very low" to "very high").
- Often based on databases such as **SHDB** or **PSILCA**.
- Used for **screening and hotspot identification**.

Type II — *Impact Pathway (Cause–Effect)*

- Quantifies cause–effect links between activities and outcomes.
- Uses **impact pathways**, often with indicators in **DALYs** (Disability-Adjusted Life Years).
- Connects social stressors (e.g., accidents, low wages) → human health or well-being losses.

The Guidelines encourage combining both: *screening* via Type I → *quantification* via Type II.

🧮 5. Methodological Phases (mirrors Environmental LCA)

1. **Goal and Scope Definition**
    - Purpose, system boundaries, stakeholders, and functional unit (FU) or equivalent.
    - For organizations → can define "organisational functional unit" (e.g., per employee, per service delivered).
2. **Social Life Cycle Inventory (S-LCI)**
    - Compilation of social data along the value chain.
    - Mix of **quantitative**, **qualitative**, and **semi-quantitative** indicators.
    - Encourages **multi-source triangulation**: surveys, databases, and secondary statistics.
3. **Social Life Cycle Impact Assessment (S-LCIA)**
    - *Reference Scale* (qualitative) or *Impact Pathway* (quantitative).
    - Must identify *midpoints* (e.g., "number of accidents") and *endpoints* (e.g., "DALYs").
    - Introduces new guidance for *positive impact assessment.*
4. **Interpretation**
    - Integrate results, identify improvement opportunities, consider uncertainty and stakeholder feedback.

🔍 6. Major 2020 Innovations

Innovation	Description
Inclusion of Organizations	Framework now supports assessment at company or institutional level.
Positive Impacts	Explicit methodology for capturing beneficial effects (training, empowerment, inclusion).
Children as Stakeholders	New group addressing child rights and educational opportunities.
Context Sensitivity	Requires justification of indicator relevance for each local setting.
Functional Unit Clarity	Emphasises defining FU as *social function* (e.g., "1 person-year of safe work").
Guidance on Data Quality	Introduces data-quality indicators (DQIs) for social metrics.
Ethical Safeguards	Principles for privacy, consent, and fair representation in social data collection.

🧠 7. Integrating S-LCA into Sustainability Decision-Making

- The Guidelines position S-LCA as part of **Life Cycle Sustainability Assessment (LCSA)**:
  LCSA = E-LCA (planet) + LCC (profit) + S-LCA (people).
- Calls for **cross-comparison** through normalization (e.g., DALYs, QALYs, well-being indices).
- Links to **UN SDGs**: S-LCA indicators can directly report progress on Goals 1–8, 10, 12, 16.

🧭 8. Challenges Acknowledged in 2020

1. **Data limitations** → heavy reliance on secondary/global averages.
2. **Lack of standard cause–effect models** (unlike environmental LCA).
3. **Double counting risk** between stakeholder groups.
4. **Ethical & cultural variability** — social acceptability differs by region.
5. **Difficulty capturing positive social value.**
6. **Communication** — translating complex results into actionable insights.

🌐 9. Future Directions Highlighted

- Development of **standardized quantitative impact pathways** (e.g., worker health → DALY).
- Expansion of **digital and crowdsourced data** (real-time social indicators).
- Integration with **organizational sustainability reporting (GRI, SDGs, ISO 26000)**.
- Closer alignment with **Environmental LCA (ISO 14040/44)** and emerging **ISO S-LCA standard**.
- Move toward **hybrid S-LCA** — combining reference-scale screening and quantitative modeling.

📘 10. Comparison Summary — 2009 vs 2020

Aspect	2009 Guidelines	2020 Guidelines
Scope	Products only	Products **and organizations**
Stakeholder groups	5	6 (added children)
Sub-categories	31	38
Positive impacts	Not explicit	Explicitly integrated
Functional unit	Poorly defined	Clarified; can include social functions
Assessment types	Reference scale	Reference + Impact pathway
Data quality guidance	Minimal	Introduced DQI framework
Context sensitivity	Weak	Required
Theory base	Stakeholder model	Broader integration (capability theory, systems thinking)
Integration with LCSA	Mentioned	Fully embedded

🧭 11. Core Takeaway

The **2020 UNEP S-LCA Guidelines** represent a shift from a descriptive, qualitative checklist to a **flexible, systemic, and potentially quantitative** tool.

Their central insight: *"social sustainability" is measurable only when contextualized — not universalized.*

Future S-LCA must integrate human data (subjective well-being, empowerment) with life-cycle models, grounding sustainability in lived human experience rather than abstract averages.

Life Cycle Thinking Tools: LCA, LCC, and S-LCA," from *Life Cycle Sustainability Assessment for Decision-Making*, 2020

🌱 1. Life Cycle Thinking & LCSA Framework

Life Cycle Thinking (LCT) expands beyond single-issue assessment. It views every product, process, or service as a system of flows — *inputs → transformations → outputs* — across all stages: extraction, production, use, and disposal.

Life Cycle Sustainability Assessment (LCSA) integrates three core tools:

1. **LCA** – Environmental dimension ("planet")
2. **LCC** – Economic dimension ("profit")
3. **S-LCA** – Social dimension ("people")

They share the same structural phases (Goal & Scope → Inventory → Impact Assessment → Interpretation) but differ in **units, impact categories, and data types.**

🌍 2. Life Cycle Assessment (LCA)

Definition (ISO 14040/44):

A compilation and evaluation of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle.

Phases:

1. **Goal & Scope Definition**
   - Define the *functional unit (FU)* (quantitative measure of the system's function).
   - Set *system boundaries* (processes included/excluded).
   - Identify assumptions, impact categories, and data quality requirements.
2. **Life Cycle Inventory (LCI)**
   - Collect data on *energy, materials, emissions, and wastes* per unit process.
   - Validate and allocate flows between co-products or recycling loops (ISO 14049 gives guidance).
3. **Life Cycle Impact Assessment (LCIA)**
   - **Classification:** Assign emissions/flows to impact categories (e.g., climate change, eutrophication, toxicity).
   - **Characterization:** Quantify contributions (e.g., CO_2 × GWP = kg CO_2-eq).
   - **Normalization (optional):** Compare results against reference values.
   - **Weighting (optional):** Aggregate to a single score based on relative importance.
4. **Interpretation**
   - Identify hotspots, check completeness/sensitivity/consistency, and propose improvements.

Applications: product design, process optimization, eco-labeling, policy-making, and sustainable procurement.

💰 3. Life Cycle Costing (LCC)

Purpose: Evaluate all *economic costs* incurred throughout a product's entire life cycle — from design and production to use and disposal.

Types:

- **Conventional LCC:** internal costs only.
- **Environmental LCC:** costs across all value-chain actors (suppliers, users, recyclers).
- **Societal LCC:** includes externalities borne by society (healthcare, taxes, etc.).

Phases:

1. **Goal & Scope Definition**
   - Define purpose (e.g., compare design options).
   - Define system units, assumptions, time horizon, and discount rate.
2. **Inventory**
   - Gather data on *investment, operation, maintenance, and end-of-life* costs.
   - Validate for completeness and accuracy.
3. **Calculation of LCC Results**
   - Use discounting to compare future and present costs.
   - Conduct sensitivity and risk analyses.
4. **Interpretation**
   - Identify major cost drivers and uncertainties.
   - Recommend cost-effective sustainable options.

Core principle:

(LCC = C_{design} + C_{production} + C_{operation} + C_{maintenance} + C_{disposal})

→ shifts focus from short-term purchase price to long-term sustainability.

👥 4. Social Life Cycle Assessment (S-LCA)

Definition (UNEP/SETAC, 2009):

A technique to assess *social and socio-economic* aspects of products and potential positive or negative impacts throughout the life cycle — focusing on human well-being and social behavior.

4.1. Structure and Phases

1. **Goal & Scope Definition**
    - Define purpose, boundaries, and stakeholders (workers, local communities, consumers, society, value-chain actors).
    - Specify *functional unit* (sometimes difficult — could be a service unit, person-year, or product).
    - Determine which impact categories and indicators will be assessed.
2. **Social Life Cycle Inventory (S-LCI)**
    - Collect *primary data* (interviews, surveys, participatory workshops) and *secondary data* (databases like SHDB, PSILCA).
    - Ensure quality: validity, completeness, representativeness, and documentation.
3. **Social Life Cycle Impact Assessment (S-LCIA)**
    - **Two approaches:**
        - **Performance/Reference Point:** qualitative scoring (low–high risk).
        - **Impact Pathway:** quantitative cause-effect modeling (DALYs, well-being indices).
    - Indicators can be *quantitative* (e.g., injury rates) or *qualitative* (e.g., perception of safety).
4. **Interpretation**
    - Identify social hotspots, data gaps, and improvement opportunities.
    - Evaluate engagement level of stakeholders.

4.2. Key Stakeholder Groups (UNEP/SETAC, 2009)

Stakeholder	Example subcategories
Workers	Child/forced labor, fair wage, safety, discrimination
Local community	Health, access to resources, cultural heritage
Consumers	Product safety, transparency, privacy
Society	Governance, technology development, corruption
Value chain actors	Fair competition, supplier relations

🔬 5. Methodological Parallels Across LCA–LCC–S-LCA

Phase	LCA	LCC	S-LCA
Goal & Scope	Define FU, boundaries	Define cost structure & time	Define FU, stakeholders
Inventory	Material/energy/emissions	Costs & financial flows	Social indicators
Impact Assessment	Midpoints → endpoints	Discounted cost analysis	Reference scale / DALY
Interpretation	Hotspots, sensitivity	Sensitivity, uncertainties	Stakeholder validation

→ Common structure allows **integrated LCSA** modeling.

🧮 6. Integration & Decision-Making

LCA, LCC, and S-LCA can be combined with **multi-criteria decision analysis (MCDA)** methods — such as **Analytic Hierarchy Process (AHP)** or **TOPSIS** — to aid trade-off analysis among environmental, economic, and social indicators.

Examples:

- **Biofuel supply chains** (Halog & Manik, 2011): integrated LCA–LCC–S-LCA for sustainability.
- **Buildings and materials**: weighting social indicators (health, comfort) with AHP.
- **Raw materials sourcing**: linking S-LCA with risk assessment and economic models.

🧭 7. Challenges and Future Work

1. **Functional Unit in S-LCA:** Hard to standardize; social utility not easily quantifiable.
2. **Data quality:** Especially for social data — needs participatory, contextual collection.
3. **Harmonization:** Methods differ widely; UNEP 2020 update aims for standardization.
4. **Positive impacts:** S-LCA now seeks to capture beneficial effects (education, training, equality).
5. **Integration:** Coupling LCA, LCC, and S-LCA remains complex but critical for policy relevance.

📘 8. Takeaway: The Triad of Sustainability Assessment

Tool	Main focus	Core unit	Example metric
LCA	Environmental	kg CO_2-eq	GWP, eutrophication, toxicity
LCC	Economic	€	Net present cost
S-LCA	Social	qualitative or DALY	Worker safety, well-being

Together, they operationalize the **Triple Bottom Line (People–Planet–Profit)** using shared life-cycle logic.

Each tool examines a different "currency" of sustainability: emissions, money, and human welfare.

Would you like me to make a **concise summary table or mind-map diagram** linking these three (LCA–LCC–S-LCA) into one visual for your Notion page or DTU report? It could include the methods, outputs, and integration points in LCSA.

BMJ systematic review and meta-analysis by **Poole et al. (2017)** titled *"Coffee consumption and health: umbrella review of meta-analyses of multiple health outcomes.*

☕ **Coffee and Health — Poole et al., BMJ 2017**

Reference: Poole R, Kennedy OJ, Roderick P, Fallowfield JA, Hayes PC, Parkes J. *BMJ* 2017;359:j5024.

Study type: Umbrella review of 201 meta-analyses of observational and interventional studies on coffee consumption and 67 health outcomes.

🔍 1. Aim & Design

To evaluate **the associations between coffee consumption and multiple health outcomes**, including all-cause mortality, cardiovascular disease (CVD), cancers, metabolic, neurological, and liver conditions.

- **Data sources:** PubMed, Embase, Cochrane up to July 2017.
- **Inclusion:** Meta-analyses of observational (cohort, case-control) and interventional studies on coffee or caffeine.
- **Quality assessment:** AMSTAR and GRADE frameworks.

📊 2. Main Results (Quantitative Summary)

Overall mortality:

- Compared to non-drinkers, **3–4 cups/day** associated with:
  - **17% lower all-cause mortality** (RR ≈ 0.83, 95% CI 0.79–0.88)
  - **19% lower cardiovascular mortality** (RR ≈ 0.81)
  - **18% lower cancer mortality** (RR ≈ 0.82)

Highest benefit range: ~3–4 cups/day (diminishing returns beyond 6+ cups).

Cardiometabolic outcomes:

- ↓ Type 2 diabetes risk (~30% lower).
- ↓ Metabolic syndrome.
- ↓ Ischemic heart disease, stroke, and heart failure risk.

Liver outcomes:

- Strongest protective effects observed.
  - ↓ Liver cirrhosis (~65–70% lower risk)
  - ↓ Hepatocellular carcinoma (≈40% lower risk)

Neurological outcomes:

- ↓ Parkinson's disease and Alzheimer's risk.
- No clear link for multiple sclerosis or epilepsy.

Cancer:

- Generally neutral or protective (notably for endometrial, prostate, melanoma, and liver cancer).
- Slight ↑ risk for **lung cancer** (likely due to smoking confounding).

Pregnancy outcomes:

- ↑ Risk with high intake:

- Low birth weight
- Preterm birth
- Pregnancy loss

🧠 3. Mechanisms (proposed)

- **Antioxidant & anti-inflammatory compounds:** chlorogenic acids, polyphenols.
- **Improved insulin sensitivity & glucose metabolism.**
- **Reduced liver fat and fibrosis progression.**
- **Enhanced endothelial function & lipid metabolism.**
- **Caffeine effects:** adenosine receptor antagonism → neuroprotection, increased alertness.

⚖️ 4. Interpretation

- **Net effect:** Coffee consumption (up to 3–4 cups/day) *more likely to benefit than harm* most adult populations.
- **Exceptions:** Pregnant women and individuals at risk of fractures (postmenopausal women).
- **Causality caveat:** Evidence mostly observational → residual confounding (especially smoking, diet, socioeconomic status).

Authors' conclusion:

> "Coffee drinking appears safe within usual levels of intake and more likely to benefit health than harm."

📉 5. Limitations

- Predominantly **observational data** (can't confirm causation).
- **Publication bias** toward positive studies.
- **Variability** in coffee type, brewing method, cup size, and caffeine content.
- Many meta-analyses overlap → same cohorts reused.

🌍 6. Sustainability & Public Health Implications

- Coffee as part of sustainable diets aligns with **planetary health** principles when sourced ethically.
- Potential **social trade-offs:** coffee cultivation tied to labor conditions, land use, and income disparities — links directly to **S-LCA** topics.
- **Life cycle perspective:** Health benefit to consumers must be weighed against production-stage social/environmental burdens.

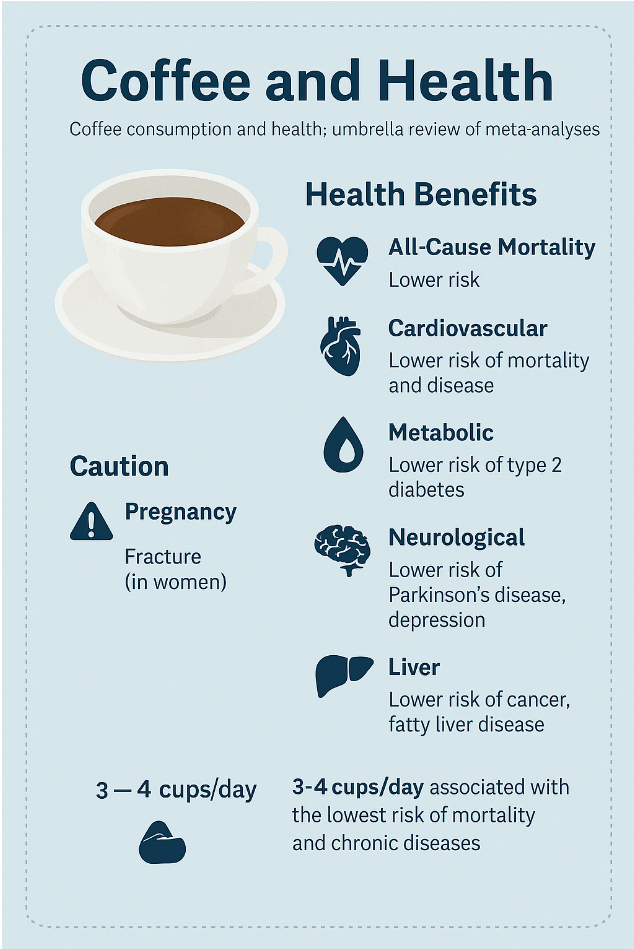
🧭 7. Key Numbers for Notes

Outcome	Optimum intake	Risk ratio vs non-drinkers	Evidence strength
All-cause mortality	3–4 cups/day	0.83	High
CVD mortality	3–4 cups/day	0.81	High
Type 2 diabetes	3–4 cups/day	0.70	High
Liver cirrhosis	≥2 cups/day	0.30	Moderate–high
Liver cancer	3–4 cups/day	0.60	High
Pregnancy complications	>3 cups/day	↑ risk	High

☕ TL;DR for your Notion

> Moderate coffee consumption (3–4 cups/day) is associated with the lowest risk of mortality and many chronic diseases, especially liver and cardiovascular.
>
> High intake may be harmful in **pregnancy** and possibly for **bone health**.
>
> Health benefits likely derive from a complex mix of **bioactive compounds** rather than caffeine alone.

Would you like me to extend this into a **one-page infographic summary** (showing benefits by system: cardiovascular, metabolic, neurological, liver, etc.) for your sustainability or health portfolio?



1. Determine the change in mortality & disease risk per cup of coffee

Here are risk Data from Poole et al., 2017, BMJ. Extract from the abstract:

Beneficial association

There was evidence of a non-linear association between consumption and some outcomes, with summary estimates indicating largest relative risk reduction at intakes of three to four cups a day (3.5 on average) versus none, including all cause mortality (relative risk 0.83, 95% confidence interval 0.79 to 0.88), ..., and cardiovascular disease (0.85, 0.80 to 0.90). High versus low consumption was associated with an 18% lower risk of incident cancer (0.82, 0.74 to 0.89).

1. Based on these data calculate the average percentage risk reduction per cup of coffee per person per day and its 95th confidence interval for
   a) all cause mortality:
   b) cardiovascular disease:
   c) cancer:

Outcome (contrast)	RR at ~3–4 cups/day vs none	Avg. % reduction **per cup**	95% CI (per cup)
All-cause mortality	0.83 (0.79–0.88)	**(1-0.83) / 3.5 = 4.86%**	3.43% – 6.00%
Cardiovascular **mortality**	0.81 (0.72–0.90)	**5.43%**	2.86% – 8.00%
Cardiovascular **disease**	0.85 (0.80–0.90)	**4.29%**	2.86% – 5.71%
Cancer incidence (high vs low)	0.82 (0.74–0.89)	**5.14%**	3.14% – 7.43%

Harmful associations

Harmful association were largely nullified by adequate adjustment for smoking, except in pregnancy, where high versus low/no consumption was associated with low birth weight (odds ratio 1.31, 95% confidence interval 1.03 to 1.67), preterm birth in the first (1.22, 1.00 to 1.49) and second (1.12, 1.02 to 1.22) trimester, and pregnancy loss (1.46, 1.06 to 1.99).

1d. Give an advice about coffee consumption during pregnancy:

Coffee should be **limited or avoided during pregnancy**.

Evidence shows that high coffee intake is linked to a higher risk of **low birth weight**, **preterm birth**, and **pregnancy loss**. These effects happen because caffeine crosses the placenta, and the fetus cannot metabolize it efficiently, even moderate amounts can accumulate.

2. Get from the GBD the background rate

Google GBD compare and enter the GBD (you might have to register now).

Click on the 9th icon

Select Denmark, DALYs, All, Both, Rate

Select for the cause a) all causes put your mouse on the last data for 2023 and write down the rate of DALY/100000 and its confidence interval for

a) All causes: 30931,63 DALYs per 100,000 (27623.35 - 34868,42)

Also do it for selecting as causes

b) B.2 Cardiovascular disease: 3932.5 DALYs per 100,000 (3567.72 - 4228.77)

c) B.1 Neoplasm (=cancer): 6558.61 DALYs per 100.000 (6159.43 - 6843.2)

3. Convert the background rates from DALY/100000 to min. / pers / day

If you have a burden rate of 5000 DALY/100000, this will correspond to 0.05 DALY/pers/. As DALYs are years, this also corresponds to 0.05 days lost/pers/day

Considering we have 24 × 60 = 1440 minutes in a day, the burden rate will correspond to 0.05 days lost/pers/day x 1440 =

1. **Calculate the burden rates and their confidence interval in min./pers./day for**

   minutes/person/day = (DALY per 100,000 ÷ 100,000) × 1,440

   a. **All causes** – **30,931.63 per 100,000** → (30,931.63 / 100,000) × 1,440 = **445.42 min/person/day**

   95% CI: (27,623.35 → **397.78** min) – (34,868.42 → **502.11** min)

   b. **B.2 Cardiovascular disease – 3,932.50 /100,000 → 56.63 min/person/day**

   95% CI: (3,567.72 → **51.38** min) – (4,228.77 → **60.89** min)

   c. B.1 Neoplasm (cancer) – 6,558.61 /100,000 → 94.44 min/person/day

   95% CI: (6,159.43 → **88.70** min) – (6,843.20 → **98.54** min)

4. Calculate the min. gained per cup of coffee

Multiply the percentage risk reduction per cup of coffee per person per day from 1) by the burden rate from 3) to obtain the minutes gained per cup of coffee for a) b) and c). Also obtain a confidence interval by using the low-low values of 1 & 3 and the highhigh values from 1-3.

minutes gained per cup = (percent reduction per cup ÷ 100) × (burden minutes/person/day)

- All causes: **445.42** min/day (CI **397.78–502.11**)
- CVD: **56.63** min/day (CI **51.38–60.89**)
- Cancer: **94.44** min/day (CI **88.70–98.54**)

And per-cup risk reductions (linearized at 3–4 cups/day):

- All-cause mortality: **4.86%** (CI **3.43–6.00**)
- Cardiovascular disease: **4.29%** (CI **2.86–5.71**)
- Cancer (neoplasms): **5.14%** (CI **3.14–7.43**)

a) **All causes**

445 ALL CAUSES MIN/PERS/DAY X 4.9% REDUCTION IN ALL CAUSES PER (CUP OF COFEE(PERS/DAY))

Point: 0.0486 × 445.42 = **21.65 min/cup/day**

CI (low–low, high–high):

- Low: 0.0343 × 397.78 = **13.64 min**
- High: 0.0600 × 502.11 = **30.13 min**

b) **B.2 Cardiovascular disease**

Point: 0.0429 × 56.63 = **2.43 min/cup/day**

CI: 0.0286 × 51.38 = **1.47 min** → 0.0571 × 60.89 = **3.48 min**

c) **B.1 Neoplasm (cancer)**

Point: 0.0514 × 94.44 = **4.85 min/cup/day**

CI: 0.0314 × 88.70 = **2.79 min** → 0.0743 × 98.54 = **7.32 min**

8. Resource Management, Scarcity and Criticality

Date	@October 28, 2025
Status	Done

In this week we are going to exemplify resource management concepts with simple fisheries management examples.

We are going to cover how we might exploit (extract) resources sustainably (so that the resource can be used by future generations as well), focusing on renewable resources. Once we cover this concept we will look at the wider footprint of the exploitation, including biodiversity costs.

Studies before teaching session:

Watch the three video lectures:

Video lecture 1: Fundamental concepts

Video lecture 2: The tragedy of the commons

Video lecture 3: Finding sustainable trade-offs in resource management

Watch nobel lecture:

Watch Ostrom's Nobel Lecture

Read articles:

- Graedel et al 2015 on material criticality
- The Ecology Encyclopedia entry on Maximum Sustainable Yield

Self assessment:

Complete the self-assessment.

Teaching session:

I will provide you with a foundation on the concept of biodiversity. I will then recap key concepts from the material above and we will have a Question & Answer session on this.

We will then go through an exercise together: the exercise.

I will use R to go through the exercise and will post R code in this module to replicate the in class walkthrough after the session. The exercise can be done with many tools (even excel) and we will walk through multiple implementation in class. If you want to start using R, there are plenty of resources to help, including this free book.

https://www.pnas.org/doi/full/10.1073/pnas.1500415112

🌍 Core theme: Resource management

You'll be looking at how renewable resources — like fish stocks — can be extracted without collapsing the system. The big question is:

> How much can we take now without preventing future generations from doing the same?

The course uses **fisheries** as an example because they're a near-perfect microcosm of the sustainability problem: common resources, uncertain regeneration rates, and competing economic incentives.

⚖️ Video 1 – Fundamental Concepts

This covers the basic vocabulary and models:

- **Renewable vs non-renewable resources** — fish vs fossil fuels.
- **Stock and flow** — stock = what exists, flow = what we extract.
- **Carrying capacity (K)** — the population level the environment can support long-term.
- **Regeneration rate** — how fast the resource replenishes itself.
- **Sustainable yield** — extraction rate ≤ regeneration rate.

You'll likely encounter the **logistic growth model** for populations:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right)$$

where (N) is population, (r) is growth rate, (K) is carrying capacity.

⚠️ Video 2 – The Tragedy of the Commons

This is the classic parable: when a resource is shared and access is free, individuals have incentives to overuse it — even though collective overuse harms everyone.

In fisheries, this means each fisher maximizes personal catch, driving stocks down and eventually destroying the industry.

You'll discuss possible **governance mechanisms**:

- Quotas (limit catches)
- Territorial rights
- Community management
- Taxes or tradable permits

🔄 Video 3 – Sustainable Trade-offs

Here, the focus shifts from "don't overfish" to "how do we decide what's fair, efficient, and ecologically safe?"

Expect to see trade-off curves between:

- **Economic profit**
- **Ecological integrity**
- **Social equity**

The idea is to find a *sustainable equilibrium* — not maximizing one metric, but balancing all three.

🧠 Elinor Ostrom's Nobel Lecture

Ostrom challenges the assumption that only governments or markets can prevent overexploitation. She shows how **local communities** often develop sophisticated, self-enforcing rules for managing common resources — fisheries, forests, irrigation systems — when:

- There's clear boundary definition (who can use it)
- Transparent monitoring
- Graduated sanctions for rule-breakers
- Strong communication and trust networks

Her framework is optimistic: collective action *can* work, if designed well.

🔬 Articles

Graedel et al. (2015) – introduces *material criticality*: even if something isn't scarce, it can be "critical" if society depends on it and supply is fragile (like rare earth metals for electronics).

Ecology Encyclopedia: Maximum Sustainable Yield (MSY) – defines the maximum long-term average catch that can be taken without depleting the resource. MSY often corresponds to harvesting at half the carrying capacity (N = K/2 in logistic models).

🧩 Exercise

You'll simulate or calculate how fish stocks respond to different harvest rates. In R or Excel, this often involves:

1. Starting from a population (N_t)
2. Calculating growth (rN_t(1 - N_t/K))
3. Subtracting harvest (H_t)
4. Repeating over time to see whether (N_t) stabilizes or collapses

You'll likely visualize outcomes under different management strategies — unrestricted fishing, quotas, or cooperative regulation — to see which sustain the stock.

🌱 Big picture

You're moving from **biological limits** (how much nature can regenerate) → **social limits** (how people coordinate to respect that). It's the essence of sustainable development: science meets governance.

Resource Management — Complete Overview

1. What is resource management?

It’s the study of how we use natural resources—renewable and non-renewable—without exhausting them, balancing human benefit with long-term ecological stability.

---

2. **Types of resources**

Renewable resources can regenerate through natural processes fast enough to sustain exploitation (soil, plants, animals, water, wind).

Non-renewable resources cannot regenerate on human time scales (minerals, oil, gas).

A simple test:

Can the resource harness Earth systems to make more of itself within the timeframe of my use?

If not → non-renewable.

If yes → renewable.

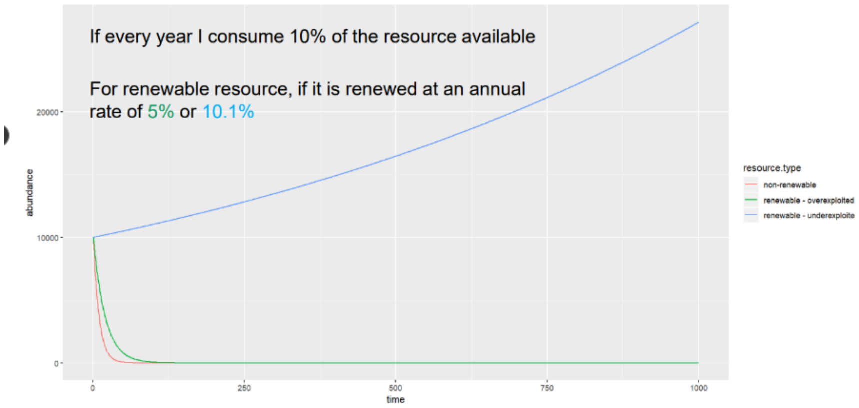
---

3. **Exploitation types**

We can:

- **Extract** resources directly (consumptive use)
- **Use products** generated by resources (non-consumptive use)

The key question: *Does our use impair the resource’s ability to renew itself?* If yes, even non-consumptive use becomes effectively consumptive.



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4. **Use patterns**

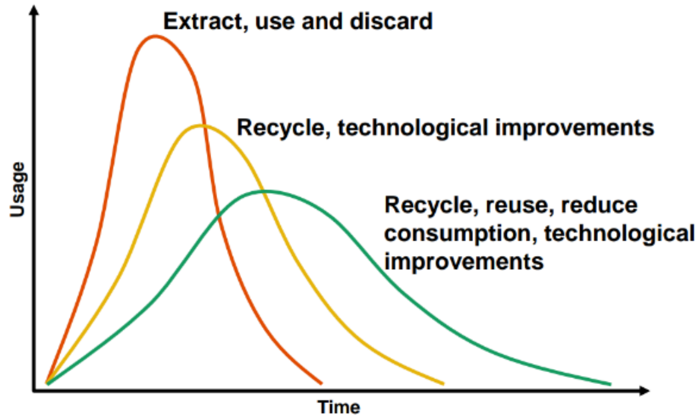
Non-renewable use pattern: extract → use → discard.

Improved patterns: recycle, reuse, reduce consumption, adopt new technology.

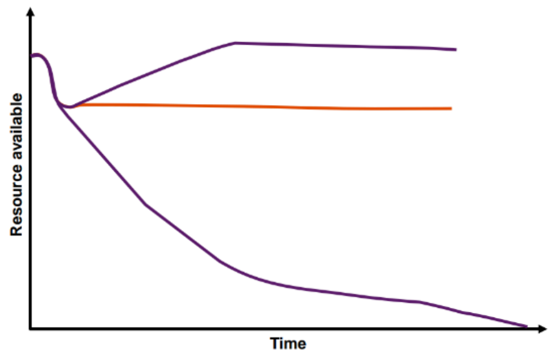
Typically follows a curve: adoption → demand peak → transition or abandonment.

Renewable use pattern: can be sustained if extraction ≤ regeneration; otherwise follows the same boom-and-bust pattern.

Adoption → demand peak → transition/abandonment



Adoption → demand peak → transition/abandonment
Adoption → demand peak → sustained



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5. **Sustainability of exploitation**

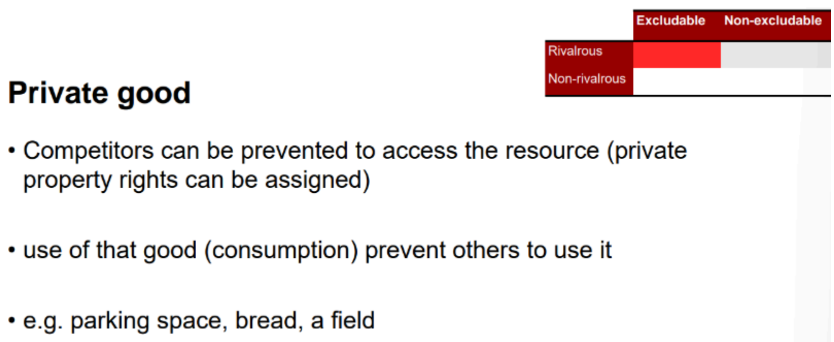
Governance feasibility depends on:

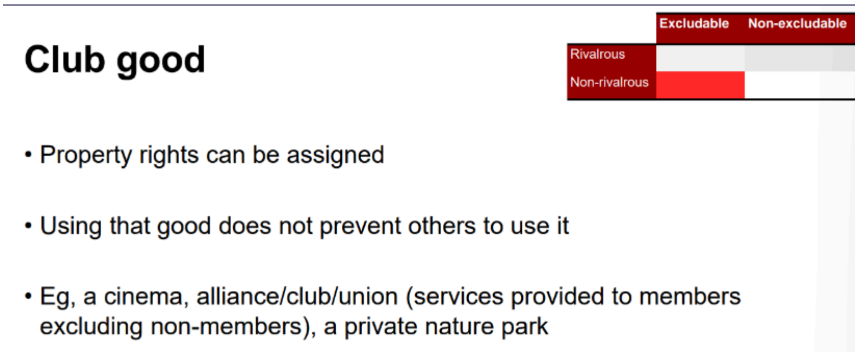
1. Whether one user's extraction reduces another's opportunity.
2. Whether users can be *excluded* from accessing the resource.

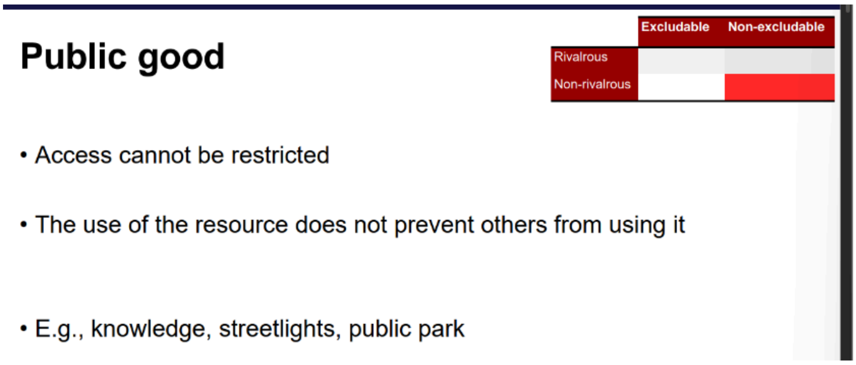
---

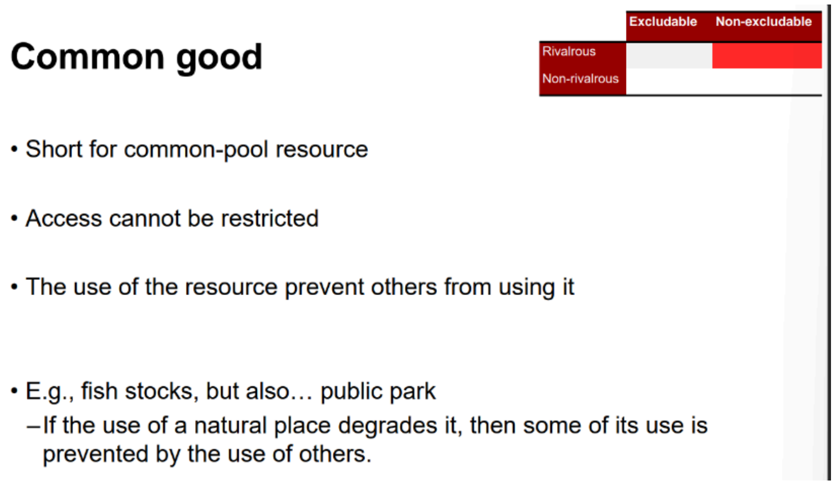
6. **Four resource types (based on excludability × rivalry)**

	Excludable	Non-excludable
Rivalrous	Private good (e.g. bread, parking space)	Common good (fish stocks, public parks that degrade with use)
Non-rivalrous	Club good (cinema, membership services, private park)	Public good (knowledge, streetlights, air quality)









7. **The ocean problem**

Primary production (e.g., fish spawning) isn't fixed in one place; we can't build fences around most marine resources. That makes exclusion and regulation inherently difficult.

8. **Ecosystem services**

Natural systems deliver:

- **Provisioning** (food, water, materials)
- **Regulating** (climate control, pollination)
- **Supporting** (nutrient cycles)
- **Cultural** (recreation, heritage)

Degrading *common resources* harms everyone's ability to benefit from these services.

9. **Tragedy of the Commons (ToC)**

Example: multiple countries share a fish stock. If one adds more vessels, it gains short-term benefits, but total stock collapses, harming all.

Without regulation (since exclusion isn't possible), the *rational choice* is to defect—leading to resource collapse.

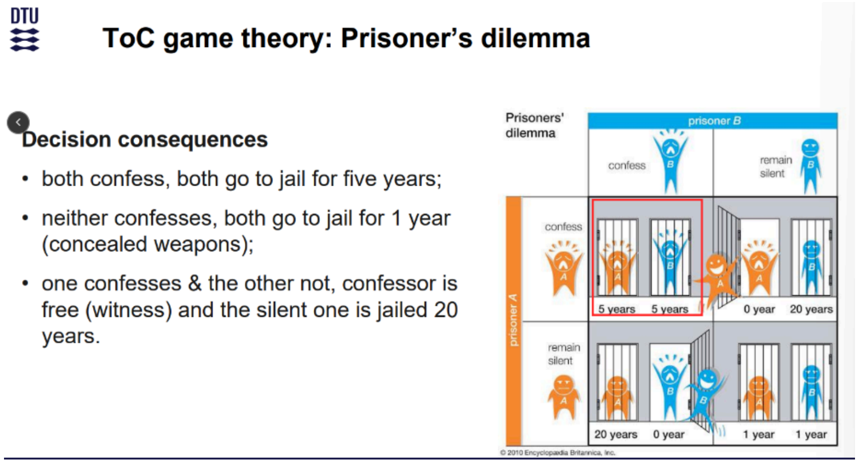
This is modeled by the **Prisoner's Dilemma**:

- Both cooperate → low penalty (1 year)
- Both defect → moderate penalty (5 years)
- One defects → huge asymmetry (free / 20 years)

Nash equilibrium: no player can improve their payoff by changing strategy alone.

In ToC, equilibrium = both defect → overexploitation.

- several countries can exploit a fish stock, if a country has more fishing effort than allotted (e.g., more vessels) the stock can be overexploited
- The benefits of extra vessels are received by the one country increasing its fleet, but the costs are shared among all countries
- Without interventions – recall exclusion interventions are not possible – it will always be beneficial to defect
- Leads to a race to the bottom and resource collapse



Nash equilibrium:
no player can improve his payoff by changing his strategy from his equilibrium strategy to another strategy provided his opponent keeps his equilibrium strategy

10. **Possible fixes**

- **Assign property rights** → convert common to private/club goods (e.g., quotas).
- **Common policies** (e.g., EU fisheries) → attempt collective club governance.

  Still imperfect: common goods remain hard to sustain globally.

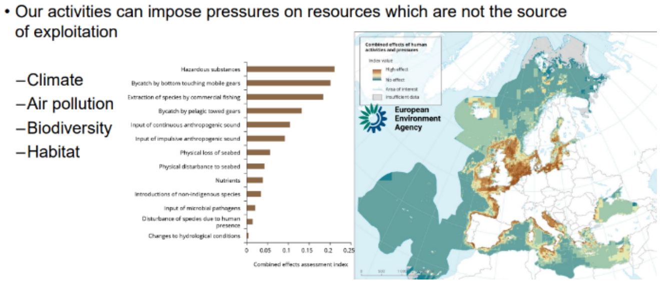
11. **Summary of core concepts**

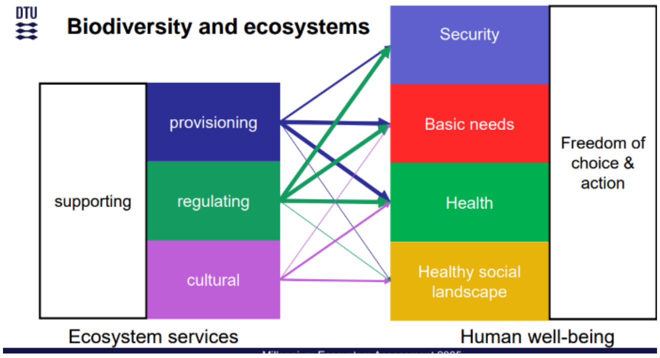
- Renewable natural resources lead to different exploitation patterns because they need not become exhausted.
- Our means and abilities to govern resource exploitation depends on whether people can be excluded from its exploitation and whether resource use by some diminish resource use opportunities for others
- Common goods are complex to govern, unfortunately most regulating and cultural ecosystem services are common goods

12. **Indirect use and pressures**

Human activities affect resources we don't exploit directly via:

- Climate change
- Air and water pollution
- Habitat degradation
- Biodiversity loss





13. **Biodiversity and human well-being**

Ecosystem services underpin **freedom, security, basic needs, health, and social stability** (Millennium Ecosystem Assessment, 2005).

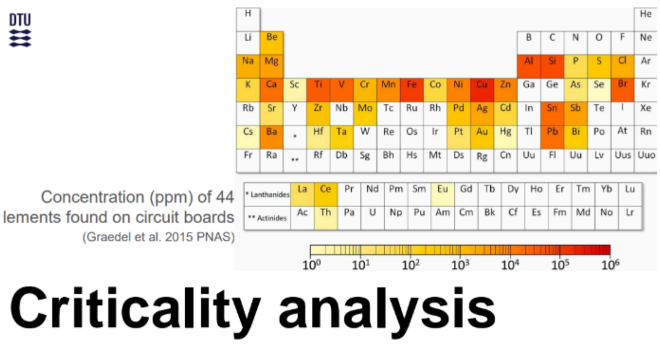
Loss of biodiversity directly reduces quality of life.

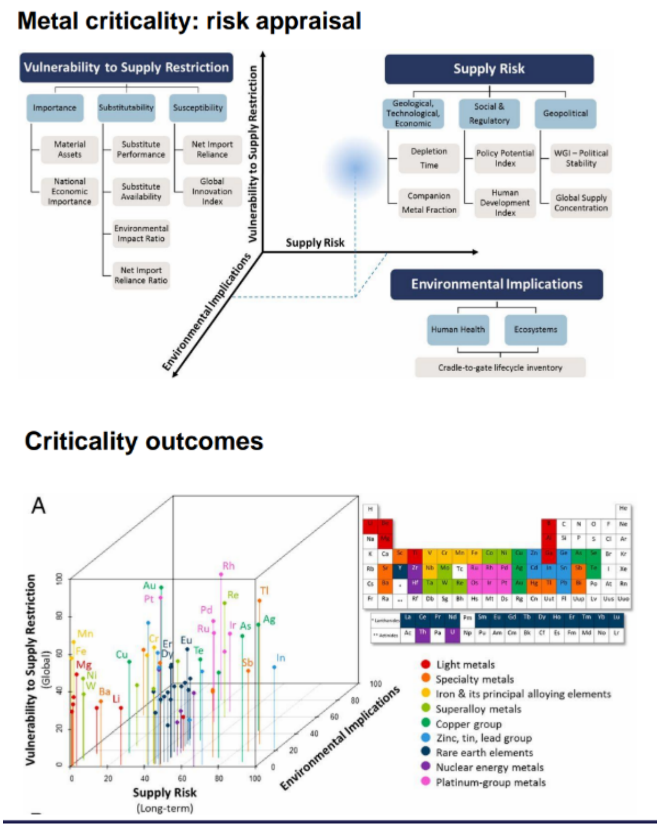
Applications

14. **Criticality analysis (Graedel et al., 2015)**

Even non-renewable materials differ in *criticality*—a measure of supply risk × economic importance × environmental impact.

Example: circuit boards use 44 elements in ppm concentrations; many have high criticality due to geopolitical or environmental constraints.





15. **Fisheries model: Maximum Sustainable Yield (MSY)**

Population model for a renewable resource (biomass B):

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$$

- (r): intrinsic growth rate
- (K): carrying capacity
- (C_t): catch

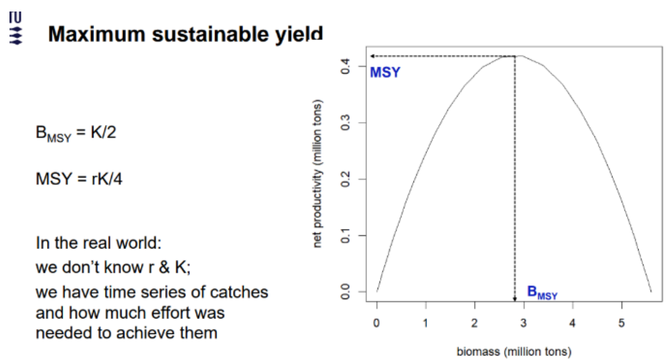
Growth follows a logistic curve: fastest at **half carrying capacity** ((B = K/2)).

From this,

$$B_{MSY} = \frac{K}{2}, \quad MSY = \frac{rK}{4}$$

MSY = maximum long-term average catch sustainable indefinitely.

In practice, we don't know r and K, so fisheries use *catch* and *effort* time-series data.



16. **Catch per Unit Effort (CPUE) and the Schaefer model**

$$C_t = qE_tB_t \quad \Rightarrow \quad \frac{C_t}{E_t} = qB_t = CPUE_t$$

where q = catchability coefficient, E = effort.

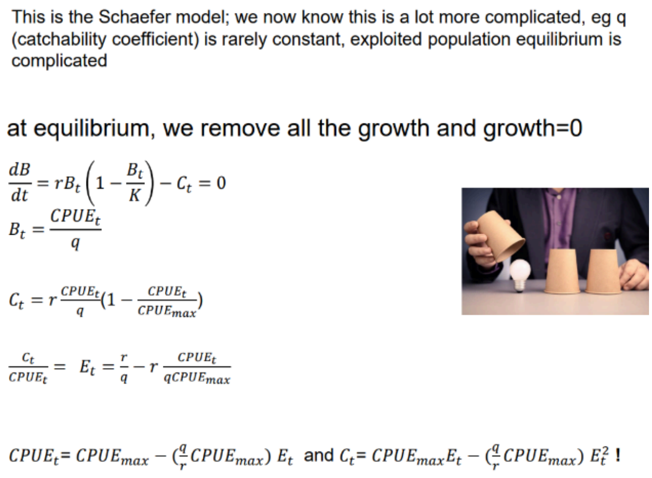
CPUE tracks abundance; if it falls, stock declines.

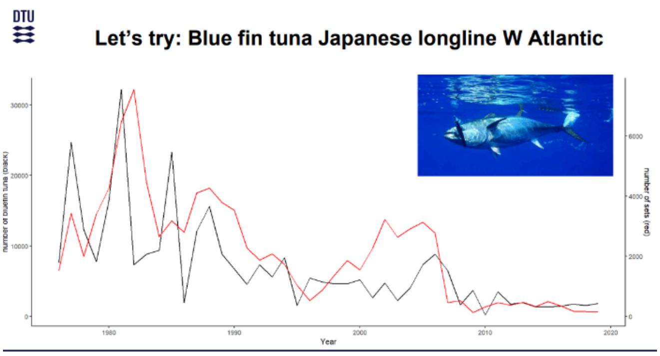
At equilibrium:

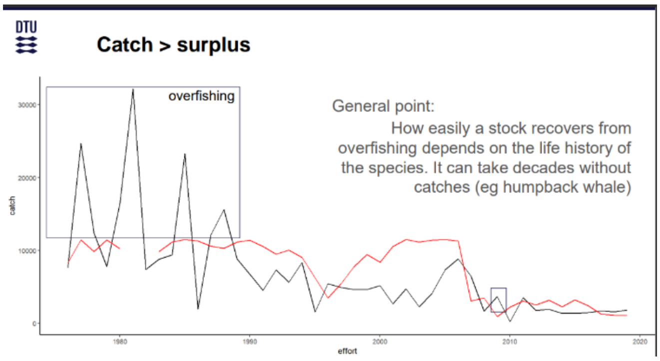
$\frac{dB}{dt} = rB(1 - \frac{B}{K}) - C = 0$

leading to quadratic relationships among C, E, and CPUE.

Graphically, sustainable yield rises with effort, peaks at MSY, then declines.







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17. **Real-world examples**

- Bluefin tuna in the Western Atlantic: effort exceeded sustainable levels ("excess effort") → catch > surplus → stock collapse. Recovery may take decades (e.g., humpback whales).

---

18. **Beyond MSY: bioeconomic and biodiversity trade-offs**

Sustainability involves three intersecting dimensions:

1. **Bioeconomics** – efficiency, profit, supply/demand, fuel use (carbon footprint).

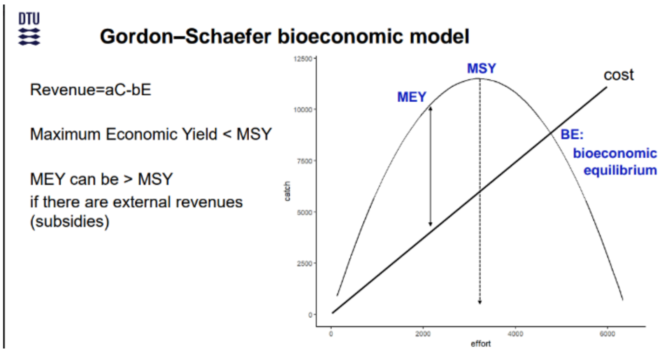
   Modeled with the **Gordon–Schaefer bioeconomic model**.

   - Profit = Revenue – Cost

- **Bioeconomic equilibrium (BE)** = where profit = 0.
- **Maximum Economic Yield (MEY) < MSY (typically), unless subsidized.**
- MEY occurs at lower effort → higher profit per unit effort.

2. **Biodiversity footprint** – bycatch and habitat degradation.

   Fishing methods have associated probabilities of catching non-target or endangered species.
3. **Multi-criteria optimization** – find effort yielding acceptable profit, biodiversity impact, and catch.



19. **Biodiversity costs and bycatch**

Potential Biological Removal (PBR) quantifies acceptable bycatch:

$PBR = N_{min} \times R''_{MSY} \times F_r$

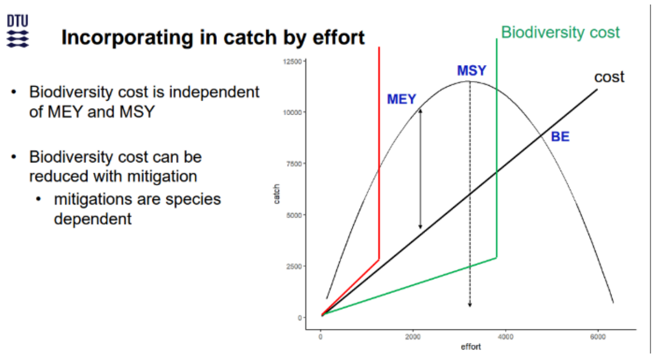
where:

- (N_{min}) = minimum population estimate
- (R''_{MSY}) = maximum net growth rate
- (F_r) = recovery factor (0–1, species-specific)

Biodiversity cost acts as an independent constraint:

it's not optimized for profit or yield but to maintain ecological targets.

Mitigation (gear modification, closures, etc.) reduces these costs.



revenue = f(cost)

cost = f(effort)

Sustainability search

- Am I overexploiting the stock & how much can I fish before I do so (MSY)
- Is staying at or below MSY profitable? And if so, how much should I fish to maximise economic yield? (MEY)
- Can I meet my food security target (floor) with this fishing effort and if not, what are the consequences of trying to meet it?
- Can I meet my biodiversity target (ceiling) with this fishing effort and if not, what are the consequences of trying to meet it?
- What fishing effort does not over-exploit my fish stock, maximise my economic yield, and meet my food security and biodiversity targets?

20. **Integrated catch-effort model with biodiversity cost**

Visual integration:

- **MSY curve:** maximum biological yield.
- **MEY point:** economic optimum (profit max).
- **Biodiversity cost line:** ecological constraint.

  Sustainable management lies where these three intersect.

---

21. Gillnetting exercise

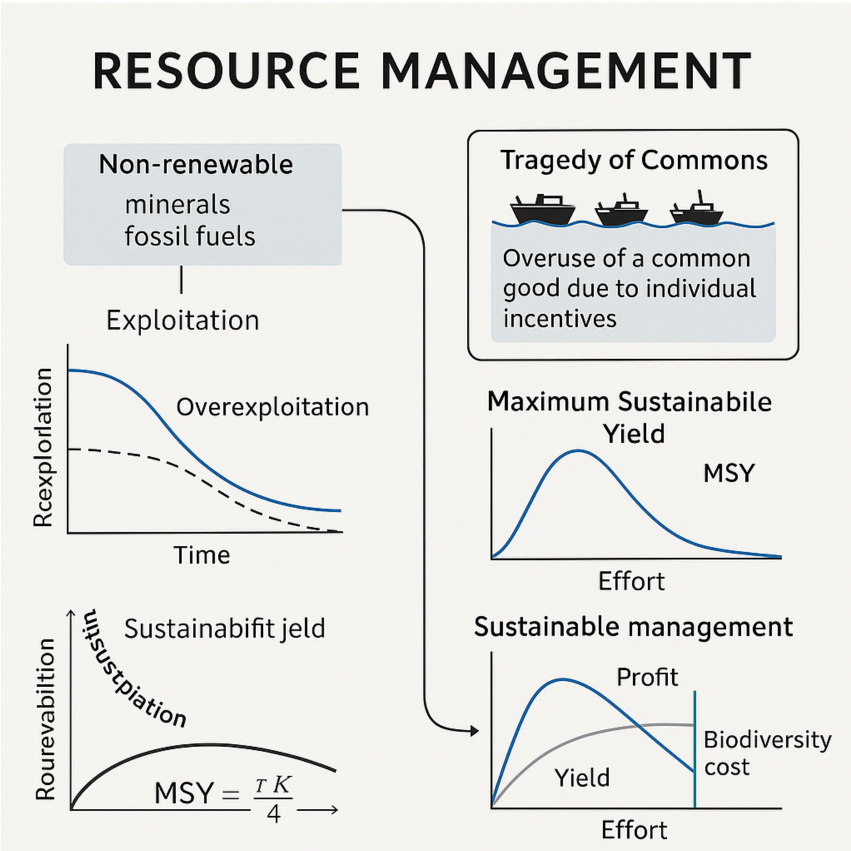
Students simulate fishing under different efforts using Excel/R/Python to visualize:

- Biomass over time
- Yield vs effort
- Profit vs effort
- Biodiversity trade-off

Goal: identify the sustainable zone balancing ecology + economy + biodiversity.

Grand summary

1. **Resources**: renewable vs non-renewable; consumptive vs non-consumptive use.
2. **Governance**: depends on excludability and rivalry.
3. **Common goods** (like oceans) are hardest to manage—cause of the *Tragedy of the Commons*.
4. **MSY** gives the biological sustainability threshold.
5. **MEY** adds economic optimization.
6. **Biodiversity cost** imposes ecological constraints.
7. **Sustainable management** = trade-off among yield, profit, and ecological integrity.
8. **Broader perspective**: everything is interconnected—our energy, consumption, and technology choices ripple through ecosystems.



🌍 Resource Management — Fundamental Concepts

1. What is resource management?

It's the science (and art) of balancing **human extraction** of natural resources with the **planet's regenerative capacity**.

The aim is to exploit resources in a way that maintains long-term availability—avoiding depletion or collapse.

---

2. **Natural resources**

A resource can be classified by asking:

> Can it harness Earth's systems to make more of itself within the timeframe relevant to human use?

- **Non-renewable resources**: cannot regenerate quickly enough.

  Examples: minerals, oil, natural gas.

- **Renewable resources**: can regenerate naturally within human time scales.

  Examples: soil, plants, animals, water, wind.

---

3. **Exploitation types**

We can interact with resources in two broad ways:

- **Consumptive use:** direct extraction or consumption that reduces the quantity available.

  e.g. cutting trees for timber, catching fish, burning fuel.

- **Non-consumptive use:** uses that do not directly diminish the resource stock (at least ideally).

  e.g. tourism, recreation, wind energy.

However, even non-consumptive activities can become *effectively consumptive* if they damage the resource's capacity to renew (like ecotourism that harms coral reefs).

---

4. **Non-renewable resource use pattern**

Typical trajectory:

Adoption → Demand peak → Transition/Abandonment

Over time, usage first increases with technological adoption, peaks as extraction becomes harder or expensive, and eventually declines when substitutes emerge or reserves run out.

Possible mitigation patterns:

- Recycling and reuse
- Technological improvements
- Reduction of consumption

These strategies delay depletion but can't make the resource truly renewable.

---

5. **Renewable resource use pattern**

Two possible paths:

1. **Unsustainable use:** adoption → demand peak → decline/abandonment

   (resource exploited faster than it regenerates → collapse).

2. **Sustainable use:** adoption → demand peak → sustained equilibrium

   (harvest = renewal rate).

This sustainability requires regulation and feedback monitoring.

---

6. **Sustainability of exploitation**

Our ability to manage resources depends on two criteria:

1. **Rivalry:** does one person's use reduce another's opportunity?
2. **Excludability:** can access be restricted?

When both are true, management is relatively easy (private goods).

When both are false, governance becomes complex (public or common goods).

---

7. **Resource types — the 2×2 matrix**

Type	Excludable?	Rivalrous?	Examples
Private goods	✅ Yes	✅ Yes	Bread, land, parking space
Club goods	✅ Yes	❌ No	Cinema, gym membership, private park
Common goods (common-pool resources)	❌ No	✅ Yes	Fish stocks, forests, groundwater
Public goods	❌ No	❌ No	Knowledge, streetlights, public parks

8. **Private goods**

- Ownership and exclusion possible (property rights).
- One's consumption prevents another's use.
- Market mechanisms can efficiently allocate them.

9. **Club goods**

- Membership limits access (excludable), but sharing doesn't necessarily reduce use.
- Examples: Netflix subscriptions, professional associations, private natural reserves.

10. **Public goods**

- Non-excludable and non-rivalrous.
- Everyone can benefit without reducing others' access.
- Examples: clean air, national defense, open knowledge.
- Problem: *free-riding*—no incentive for individuals to pay for maintenance.

11. **Common goods (Common-pool resources)**

- Anyone can access them (non-excludable), but overuse reduces availability (rivalrous).
- Classic example: fisheries, forests, or even overcrowded public parks.

  If a natural site degrades with use, its "common" nature creates self-limiting quality—each user's enjoyment diminishes with crowding or damage.

These are the most difficult to govern: they lead directly to the **tragedy of the commons** unless cooperation or regulation is established.

12. **Conclusions**

- **Renewable resources** have fundamentally different exploitation dynamics—they *can* persist indefinitely, *if managed properly*.
- The sustainability of exploitation depends on:
  - The degree of **rivalry** (does one user's consumption affect others?)
  - The degree of **excludability** (can access be controlled?)
- **Common goods** present the hardest challenge: access is open, and use by some limits use by others.

In short, **sustainability is as much a social problem as an ecological one.**

💡 Conceptual synthesis

Non-renewable resources → *finite and exhaustible.*

Renewable resources → *potentially infinite but fragile.*

Effective management → *requires balancing ecological regeneration, technological efficiency, and equitable governance.*

Resource Management — The Tragedy of the Commons

1. Introduction

The lecture explores what happens when **shared (common) resources** are used by multiple independent actors without effective regulation.

It connects **ecological processes**, **human decision-making**, and **economic behavior**, showing how individual incentives often conflict with collective sustainability.

2. **Diversity in natural resource use**

Not all resource use is direct extraction. Human societies depend on a wide range of **ecosystem services**, some tangible and some indirect.

3. **Indirect use of resources**

Our activities can stress resources we *don't* exploit directly. These *indirect pressures* include:

- **Climate impacts** (e.g., emissions from energy use altering global temperature)
- **Air pollution** (acid rain damaging forests)
- **Biodiversity loss** (habitat destruction, invasive species)
- **Habitat alteration** (urbanization, deforestation)

This means sustainability cannot focus solely on the resource we exploit; it must include the *whole ecological network* it interacts with.

4. **Biodiversity and ecosystems**

Ecosystem services (Millennium Ecosystem Assessment, 2005):

- **Supporting:** nutrient cycling, soil formation, primary production.
- **Provisioning:** food, water, fuel, raw materials.
- **Regulating:** climate control, pollination, waste treatment.
- **Cultural:** recreation, aesthetics, education, heritage.

All these together sustain **human well-being** through:

- Security
- Health
- Basic needs
- Freedom of choice and action
- A healthy social landscape

Ecosystem degradation undermines all of these benefits.

5. **Regulating and Cultural Services as Common Goods**

When **common resources degrade**, others lose access to their benefits — even if they weren't the ones exploiting them.

Example: one country's overfishing, or one factory's emissions, can reduce everyone's benefit from oceans or air quality.

These are typically *non-excludable* (no one can be prevented from using them) and *rivalrous* (use by some reduces quality for others).

6. **The Tragedy of the Commons (ToC)**

A classic problem in resource economics and ecology:

Scenario:

Multiple actors share a renewable resource (e.g., a fish stock).

If one actor increases effort (e.g., adds more fishing vessels), they gain extra short-term benefit.

However, the *cost* of depletion is distributed among *all* users.

Key insight:

Without coordination or enforcement (since exclusion is impossible), it's *always* rational for each actor to maximize their own exploitation — leading to **overuse and collapse**.

Result:

A "race to the bottom" in which everyone ends up worse off.

This is the ecological version of the *Prisoner's Dilemma.*

7. **Game theory: the Prisoner's Dilemma**

Setup:

Two prisoners must decide independently whether to confess.

- Both stay silent → 1 year each (best collective outcome)
- One confesses → goes free, the other gets 20 years (temptation to defect)

- Both confess → 5 years each (worse for both)

Lesson:

Each individual's *rational strategy* (confess / defect) leads to a worse collective outcome.

In resource management, this mirrors overexploitation: each fisher's "rational" decision to catch more results in total depletion.

8. **Nash equilibrium**

A **Nash equilibrium** occurs when no player can improve their payoff by changing strategy alone, assuming the other keeps theirs constant.

In the Tragedy of the Commons, the Nash equilibrium = *everyone defects*.

This makes the system stable but unsustainable — a paradoxical trap of rational self-interest.

9. **Possible solutions**

1. **Assign property rights**
   - Transform common goods into **private** or **club goods**.
   - Example: fishing quotas or tradable permits.
   - Enables exclusion and accountability, reducing overexploitation.
2. **"Common policies" (European approach)**
   - Regional or national agreements convert open-access resources into *shared but regulated* pools (a kind of club good).
   - Still difficult to enforce and vulnerable to non-compliance.
3. **Ostrom's solution: polycentric governance**
   - Elinor Ostrom's Nobel-winning insight: sustainable management often succeeds when communities self-organize.
   - **Polycentric systems** = multiple overlapping governance levels (local, national, global) cooperating, not a single authority.
   - Works when users have clear boundaries, collective monitoring, sanctions for defectors, and trust.

10. **Conclusions**

- **Common goods** are the hardest to manage — and most ecosystem services (like air quality, biodiversity, and climate regulation) belong to this category.
- Traditional market or state control alone often fails; **cooperation, communication, and shared governance** are essential.
- Sustainability depends on changing the *incentive structure* so that individual rationality aligns with collective well-being.

💡 **Conceptual takeaway**

The tragedy of the commons shows that:

- Environmental collapse is not just an ecological failure — it's a *coordination failure*.
- Rational actors pursuing short-term gain destroy the collective resource base.
- Solutions require **institutional design** (rules, rights, and relationships) as much as **scientific knowledge** about the ecosystem.

Resource Management — Finding Sustainable Trade-offs

1. **Purpose**

This lecture moves from the *qualitative logic* of resource use (renewable vs non-renewable, governance) to a *quantitative, model-based* understanding.

The central aim: **how to find the balance between economic profit, ecological stability, and biodiversity protection.**

2. **Fishing as a case study**

Fisheries are used as a model for renewable resource management because:

- Populations grow and regenerate (biological dynamics).
- Humans extract biomass (economic pressure).
- Both are influenced by ecological limits and market forces.

3. **Population model of a renewable resource**

Basic logistic growth with harvesting:

$$
B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t
$$

Where:

- (B_t) = biomass at time t
- (r) = intrinsic growth rate
- (K) = carrying capacity (maximum sustainable biomass)
- (C_t) = catches (human extraction)

If $(C_t = 0)$, population approaches (K).

If (C_t) is large, population declines — possibly to collapse.

---

4. **Example parameters**

For North Atlantic cod:

- $(K = 5.6 \times 10^6)$ tons
- $(r = 0.3)$
- Starting biomass $(B_0 = 1)$ ton

Without fishing, biomass grows logistically toward (K).

The instantaneous growth rate is $(rB_t(1 - B_t/K))$.

---

5. **Yield (harvest) dynamics**

The *annual yield* or catch depends on biomass and growth rate.

Initially, yield increases with effort; past a certain point, extraction outpaces regeneration, and the population collapses.

---

6. **Maximum Sustainable Yield (MSY)**

The theoretical maximum harvest that can be maintained indefinitely:

$$
B_{MSY} = \frac{K}{2}, \qquad MSY = \frac{rK}{4}
$$

At $(B = K/2)$, growth rate $(rB(1 - B/K))$ peaks.

In reality, (r) and (K) are unknown, so managers rely on **time-series data** of catch and effort.

If harvest > MSY → overfishing → collapse.

If harvest < MSY → underuse → lost economic potential.

---

7. **Dynamics around MSY**

When effort fluctuates near MSY, populations oscillate — recovery takes decades once depleted.

Ecosystem complexity (predation, environment) makes MSY estimates uncertain, so it's treated as a **precautionary limit, not a target.**

---

8. **Catch-per-unit-effort (CPUE) — Schaefer model**

$C_t = qE_tB_t$

$\frac{C_t}{E_t} = qB_t = CPUE_t$

Where:

- (E_t) = effort (boats, fuel, hours)
- (q)= catchability coefficient (efficiency of effort)

CPUE serves as a proxy for biomass.

If CPUE declines, stock abundance is decreasing.

However, (q) is rarely constant — technology, behavior, and environment complicate the relationship.

---

9. **Beyond biology: introducing economics and ecology**

The lecture warns against treating sustainability as *single-dimensional*.

Real management involves **three intertwined layers**:

1. **Bioeconomics** – efficiency, fuel use, profit margins, market price.
   Higher effort = higher cost and CO_2 emissions.
2. **Biodiversity footprint** – bycatch, habitat degradation, collateral mortality.
3. **Multi-criteria optimization** – finding effort that yields good profit, acceptable biodiversity impact, and sufficient catch.

---

10. **The Gordon–Schaefer Bioeconomic Model**

A fusion of biology and economics.

- **Revenue** = (aC - bE)
  (income from catch minus cost of effort)
- **Bioeconomic Equilibrium (BE)**: where cost = revenue → no profit.
- **Maximum Economic Yield (MEY)**: effort that maximizes profit (where marginal revenue = marginal cost).
  → MEY usually occurs at *lower effort* than MSY (healthier stock, less fuel).
- If external subsidies exist, MEY may exceed MSY — *perverse incentives*.

Hierarchy:

$\text{Effort}MEY < \text{Effort}MSY < \text{Effort}_{OpenAccess}$

---

11. **Biodiversity impact — bycatch**

Every fishing technique has a bycatch probability — unintended catch of non-target, often endangered species.

To constrain this, managers apply the **Potential Biological Removal (PBR)** formula:

$PBR = N_{min} \times R''_{MSY} \times F_r$

Where:

- (N_{min}): minimum estimated population size
- (R''_{MSY}): species' maximum growth rate
- (F_r) :recovery factor (safety buffer)

This defines a *cap* on permissible bycatch, independent of profit or yield.

---

12. **Integrating the trade-offs**

When plotted together:

- **MSY curve** → biological sustainability limit
- **MEY point** → economic optimum (profit max)
- **Biodiversity constraint** → ecological safeguard

The intersection of these defines the **sustainable operating space.**

Mitigation (gear changes, seasonal bans, spatial closures) can shift biodiversity costs downward, expanding the feasible sustainability zone — but every mitigation is species-specific.

---

13. **Key takeaway**

Resource management isn't about maximizing yield — it's about **balancing competing objectives** under uncertainty:

- Biological: ensure regeneration.
- Economic: sustain livelihoods and profit.
- Ecological: preserve biodiversity and ecosystem services.

The **sustainable trade-off** occurs where *efficiency, equity, and ecology* coexist — not where one dominates.

🧭 **Synthesis across all lectures**

Stage	Focus	Core idea
Concepts	What are resources? How do rivalry/excludability define management needs?	Common goods (like fish stocks) are hardest to manage.

Stage	Focus	Core idea
Tragedy of the Commons	Why do open resources collapse?	Individual rationality → collective ruin; fix through property rights or cooperative governance (Ostrom).
Trade-offs	How to quantify sustainable use?	MSY, MEY, biodiversity constraints — biological, economic, ecological harmony.

RESOURCE MANAGEMENT — COMPLETE SUMMARY

1. What is Resource Management?

Resource management is about balancing **human use** of natural resources with their **regeneration**.

It asks: *How can we extract benefits today without destroying future availability?*

The central problem: **human demand grows exponentially**, but ecosystems regenerate **logistically** (with limits).

2. Natural Resources

Type	Definition	Examples
Renewable	Can harness Earth systems to replenish within human timeframes	Soil, plants, animals, water, wind
Non-renewable	Cannot regenerate quickly enough for sustainable exploitation	Oil, gas, minerals

Test:

Can the resource make more of itself within your timescale of use?

If yes → renewable.

If no → non-renewable.

3. Exploitation Types

- **Consumptive use:** extraction/consumption that reduces stock (fishing, logging, mining).
- **Non-consumptive use:** doesn't reduce stock directly (tourism, renewable energy).
  However, if it damages renewability (e.g., coral reef tourism → bleaching), it becomes effectively consumptive.

4. Resource Use Patterns

Non-renewable pattern:

Adoption → demand peak → decline (transition or abandonment).

Possible improvements: **recycle, reuse, reduce consumption, innovate**.

Renewable pattern:

Can be **sustained** if extraction ≤ regeneration.

Unsustainable if exploitation > regeneration → collapse.

5. Governance and Sustainability

Our ability to manage a resource depends on:

1. Whether one actor's extraction reduces another's opportunity (rivalry).
2. Whether users can be excluded from accessing it (excludability).

Together, these define the **resource type matrix**:

	Excludable	**Non-excludable**
Rivalrous	Private goods (bread, parking)	Common goods (fish stocks, forests)
Non-rivalrous	Club goods (cinema, membership)	Public goods (air, knowledge)

- **Private goods:** easy to manage (ownership).
- **Common goods:** most difficult (no exclusion, high rivalry).

6. Oceans — The Management Nightmare

Marine resources are hard to enclose.

Fish move, and jurisdictional boundaries are fluid.

→ A perfect setup for the **Tragedy of the Commons**.

⚠️ THE TRAGEDY OF THE COMMONS (ToC)

---

7. Indirect and Direct Resource Use

Human activity affects both exploited and *non-exploited* resources through:

- Climate change
- Air pollution
- Habitat degradation
- Biodiversity loss

We often exploit indirectly by disrupting systems that support others.

---

8. Ecosystem Services and Human Well-being

Type of service	Example
Supporting	Nutrient cycling, soil formation
Provisioning	Food, water, timber
Regulating	Climate control, pollination
Cultural	Recreation, heritage, aesthetics

All underpin **health, security, and social stability**.

Degrading common resources reduces everyone's ability to benefit — even non-users.

---

9. Tragedy of the Commons — The Mechanism

Scenario:

Several countries fish a shared stock.

One adds more vessels → higher individual profit.

The cost of depletion is shared across all → overexploitation inevitable.

Without exclusion mechanisms, it's *rational to defect*.

→ "Race to the bottom" → resource collapse.

---

10. Game Theory Analogy: The Prisoner's Dilemma

Players' choice	Outcome
Both cooperate	Light sentence (1 year)
Both defect	Moderate sentence (5 years each)
One defects	Defector goes free, other gets 20 years

Everyone acting in self-interest produces the worst collective outcome.

This mirrors overfishing and unsustainable consumption.

---

11. Nash Equilibrium

A stable outcome where no player can improve their situation by changing alone.

In ToC, **everyone defects** → equilibrium is stable but *disastrous* for the resource.

---

12. Fixing the Commons

1. **Assign property rights:**
    - Turn common → private/club goods (e.g., fishing quotas, tradable permits).
2. **Common policy approach:**
    - Regional/national agreements (e.g., EU fisheries).

3. **Ostrom's polycentric governance:**
    - Multiple layers of institutions (local → global).
    - Works when users define clear boundaries, monitor each other, and enforce sanctions.
    - Cooperation, trust, and community control sustain commons better than top-down rules.

FINDING SUSTAINABLE TRADE-OFFS

13. Modeling Renewable Resource Dynamics

Population model:

$B_{t+1} = B_t + rB_t(1 - \frac{B_t}{K}) - C_t$

- (B_t): biomass
- (r): intrinsic growth rate
- (K): carrying capacity
- (C_t): catches

Growth is fastest at **B = K/2**.

Too much catch → negative growth → collapse.

14. Maximum Sustainable Yield (MSY)

$B_{MSY} = \frac{K}{2}, \quad MSY = \frac{rK}{4}$

- **MSY** = highest catch sustainable long-term.
- Overfishing (> MSY) → collapse; underfishing (< MSY) → inefficiency.

In practice: we estimate r and K using **catch + effort data**.

15. Catch Per Unit Effort (CPUE) — Schaefer Model

$C_t = qE_tB_t \quad \Rightarrow \quad \frac{C_t}{E_t} = qB_t = CPUE_t$

- (E_t): effort (boats, time, fuel).
- (q): catchability coefficient.
- CPUE approximates abundance — declining CPUE = declining stock.

16. Bioeconomic Trade-offs

Three layers of analysis:

1. **Biological:** MSY (how much can we take sustainably).
2. **Economic:** profit vs effort (costs, fuel, prices).
3. **Ecological:** biodiversity costs (bycatch, habitat impact).

Goal: find the "sweet spot" balancing all three.

17. The Gordon–Schaefer Bioeconomic Model

- **Revenue = aC – bE**
- **Cost** rises with effort.
- **Profit** = Revenue – Cost.

Key outcomes:

- **Bioeconomic equilibrium (BE):** no profit (cost = revenue).
- **Maximum Economic Yield (MEY):** profit-maximizing effort.
- **MEY < MSY** (fewer boats, higher stock, less CO_2).
- **Subsidies** can perversely push MEY > MSY.

Effort hierarchy:

$E_{MEY} < E_{MSY} < E_{OpenAccess}$

18. Biodiversity Impacts

Fishing and extraction cause **bycatch** — unintended mortality of non-target species.

To limit this:

$PBR = N_{min} \times R''_{MSY} \times F_r$

- (N_{min}): minimum population
- (R''_{MSY}): max net growth rate
- (F_r): recovery factor (safety buffer)

This defines *independent biodiversity limits*, separate from economic or yield considerations.

19. Integrated Trade-offs

When plotted together:

- **MSY curve:** biological limit.
- **MEY point:** economic optimum.
- **Biodiversity constraint:** ecological safeguard.

The sustainable operating point lies **below all three**, satisfying:

$Profit > 0, \quad Catch < MSY, \quad Impact < PBR$

Mitigation measures (gear modification, temporal closures, habitat protection) can reduce biodiversity cost and expand sustainable range.

20. Final Integration: 3 Pillars of Sustainability

Pillar	Metric	Example in fisheries
Environmental	MSY / ecological footprint	Avoid overfishing
Economic	MEY / net profit	Optimize efficiency
Social	Equity / governance	Polycentric, fair access

Sustainable management = intersection of these three.

🧭 GRAND TAKEAWAY

1. **Concepts:** Define the resource and understand the role of rivalry/excludability.
2. **Commons:** Recognize that unregulated shared access → collapse.
3. **Trade-offs:** Quantify sustainability via MSY, MEY, and biodiversity constraints.

True sustainability ≠ maximum yield.

It's a balanced compromise between ecology, economy, and equity.

Would you like me to turn this super summary into a **PDF revision sheet** — clean layout, equations boxed, and section headers color-coded (perfect for printing or Notion upload)?

Self-assessment - Module about resource management, 1210X, Quantitative methods to assess sustainability

Question 1

If a resource exploitation extracts (yields) less of that resource than MSY (maximum sustainable yield); is that resource exploitation sustainable?

> Not necessarily. while the yield is below MSY, it may relates to an economic yield which is too small to sustain the exploiter economically or to afford fair wages to employees. It is also possible that the resource exploitation causes biodiversity degradation, affecting resources (eg species) that are not the target resource of the exploitation. the yield may be below MSY, but the yield impact on biodiversity may be greater than a commonly agreed acceptable threshold.

MSY is the **maximum long-term average yield** that a population can produce without depleting itself.
It corresponds (in theory) to harvesting when the stock is at **half of carrying capacity (K/2)**.
So:

- Harvest < MSY → the stock should regenerate faster than it's being removed.
- Harvest = MSY → population stays roughly constant (in a perfect model).
- Harvest > MSY → population declines → collapse risk.

In that simple **biological sense**, yes — harvesting less than MSY *should* be sustainable.

Why "less than MSY" can still be unsustainable

Several real-world factors break the simplicity of that model:

- **Uncertainty in parameters:** we rarely know *r* (growth rate) or *K* (carrying capacity) precisely. Even small errors can shift true MSY drastically.
→ what looks "below MSY" could actually exceed it.
- **Ecosystem effects:** MSY focuses on *one species*. But removing prey or predator species can destabilize the whole food web.
→ so the harvest might be "biologically sustainable" for that species, but not *ecologically sustainable*.
- **Bycatch and habitat damage:** even if the target stock regenerates, the fishing method might harm non-target species or habitats.
→ that violates **biodiversity sustainability**.
- **Economic and social unsustainability:** sometimes, operating below MSY means effort is too low to be economically viable, or access is inequitable.

Question 2

Which of these resource is not a renewable resource?

Lithium

Question 3

What is the problem with common goods?

Their access cannot be restricted and the use of the resource prevent others from using it.

Question 4

Can you sustain the exploitation of a non-renewable resource?

iT depends, it is a matter of recyclability.

Question 5

Why are common goods easy to overexploit?

The benefits of taking more than your share of a common good are all received by the one user overexploiting, and the costs (consequences) of this overexploitation are shared among all users of the resource. So the user taking more than its share always receive more net benefits than other users.

Because **they are non-excludable and rivalrous.**
Explanation:

- *Non-excludable* → no one can be prevented from using the resource.
- *Rivalrous* → one person's use reduces what's available for others.

This means everyone has an incentive to take as much as possible before others do — a dynamic known as the **Tragedy of the Commons** — leading to overexploitation and potential collapse (e.g., overfishing, groundwater depletion).

Question 6

What is the difference between Maximum Sustainable Yield (MSY) and Maximum Economic Yield (MEY)?

MSY only relate to the resource extraction: it is the maximum amount of a renewable resource you can extract theoretically without jeopardising the sustainability of the resource exploitation (ie without overexploiting it). MEY is the maximum economic gain an exploiter can make from extracting a renewable resource, it accounts for the amount of resource extracted and the price at which it can be sold as well as the total cost of extracting that amount of resource. MEY is typically achieved at a resource yield which is smaller than MSY.

Concept	Meaning	Goal	Effort Level
MSY (Maximum Sustainable Yield)	The largest biological yield (harvest) that can be sustained indefinitely without depleting the resource.	**Biological sustainability.**	Higher effort — maximizes catch, not profit.
MEY (Maximum Economic Yield)	The level of harvest effort that gives the highest *economic profit* (revenue − cost).	**Economic efficiency.**	Lower effort — maximizes profit, not catch.

In short:

> MSY = maximum biological catch.
> MEY = *maximum profit (economic yield).*

Typically,
$Effort_{MEY} < Effort_{MSY}$
so MEY is both more profitable **and** more sustainable for the ecosystem.

10. Circular Economy

Date	@November 11, 2025
Status	Done

In this module you will:

Studies before:

- Be introduced to Circular Economy (CE) and CE Strategies
- Be presented with the CE readiness approach and the ready2LOOP tool
- Explore a variety of best cases illustrating the concepts introduced

Teaching session:

- Recap the main concepts previously presented
- Structured discussion on the topics of Circular Economy, CE Strategy and CE readiness
- Exercise to address CE Strategy(ies) in your case study

Follow the sequence of activities as described below:

Studies before teaching session:

Watch video lectures:

Video lecture: What is the problem?

Video lecture: The promise of circularity

Video lecture: Deploying circular economy strategies

Video lecture: Circular economy readiness

Read the article Making the transition to a Circular Economy within manufacturing companies: the development and implementation of a self-assessment readiness tool.

This article describes the development process of the ready2LOOP tool, including the mapping of the aspects that indicate CE readiness of product manufactures.

Read the article Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation.

This article describes the development of the Circularity Strategy Scanner.

Teaching session:

Recap of the main concepts previously presented.

Structured discussion on the topics of Circular Economy, CE Strategy and CE readiness.

- Facilitated by a Menti exercise
- Clarifications and questions

Exercise to address CE Strategy(ies) in your case study.

- Check the exercise guideline:
- Reflect about which and how CE Strategies are connected to your case study
- Identify the necessary assumptions to allow the implementation of one or more CE Strategies
- Identify how these assumptions can influence the quantified sustainability of your case study

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LECTURE 1 – WHAT'S THE PROBLEM?

Slides 1–2:

Introduction to the series — four lectures:

1. What's the problem? 2. The promise of circularity 3. Deploying CE strategies 4. CE Readiness.

   Sets the frame: unsustainable "take–make–dispose" model.

Slides 3–5:

Cites *Meadows et al., 1972* and the *DTU Centre for Absolute Sustainability*:

Human-centered growth overshoots planetary limits — urgent systemic change is required.

Slide 6 ("WorldChanging"):

Linear-economy failure metrics:

- 44.7 Mt of e-waste/year
- only 20 % properly recycled
- $11.5 billion of recoverable materials lost
- ore gold ≈ 5 g/t vs PCBs ≈ 575 g/t — we discard far richer "urban mines."

Slides 7–8:

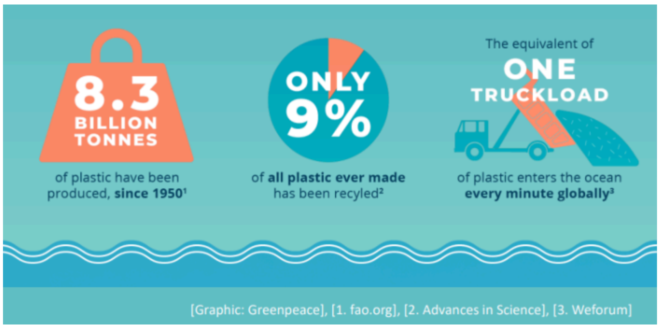
Graphics from the Ellen MacArthur Foundation showing the *Linear Economy Flow*: resources → production → use → waste.

The takeaway: linearity destroys both material value and ecosystem stability.

Slides 9–13 ("Plastics as a proxy"):

Plastics embody our uncircularity: short life, massive rebound effects, marine pollution, microplastics in food chains.

Illustrates the resource–waste disconnection.



Slides 14–16:

Reinforces that sustainability crises are design-made — therefore design-solvable.

Call to action: "We designed these problems; we must design the solutions."

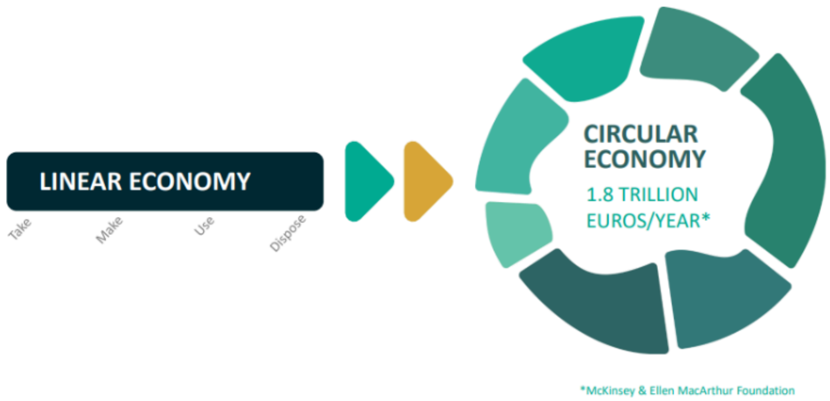
LECTURE 2 – THE PROMISE OF CIRCULARITY

Slides 18–21:

Circular Economy is Europe's fastest-growing business-strategy domain.

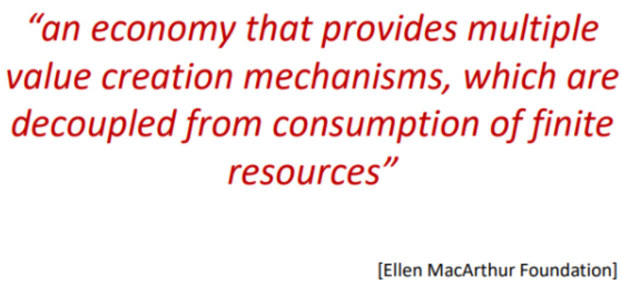
Goals: *close material loops*, *decouple value from resource input*, and *apply systemic thinking.*

Economic potential: ≈ €1.8 trillion per year (McKinsey + EMF).



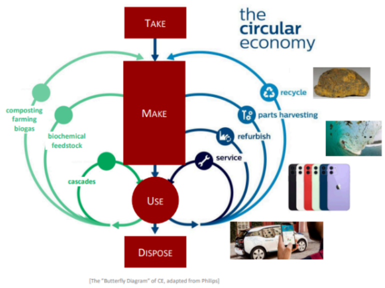
Slide 22 (Definition):

A circular economy *creates multiple value-creation mechanisms decoupled from finite-resource consumption.*



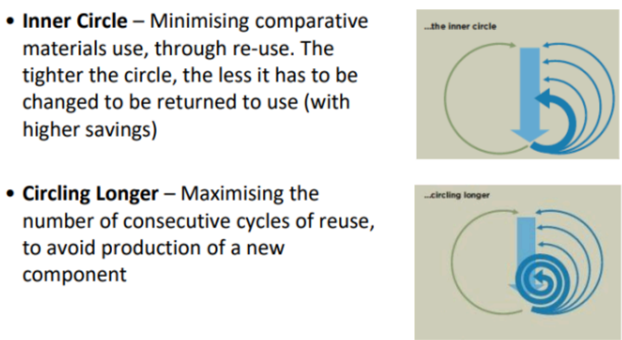
Slide 23 (Butterfly Diagram):

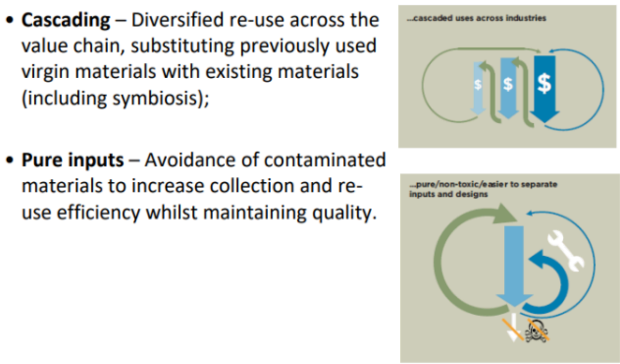
Illustrates biological and technical cycles — reuse, repair, remanufacture, recycling, cascading, composting — replacing "take–make–dispose."

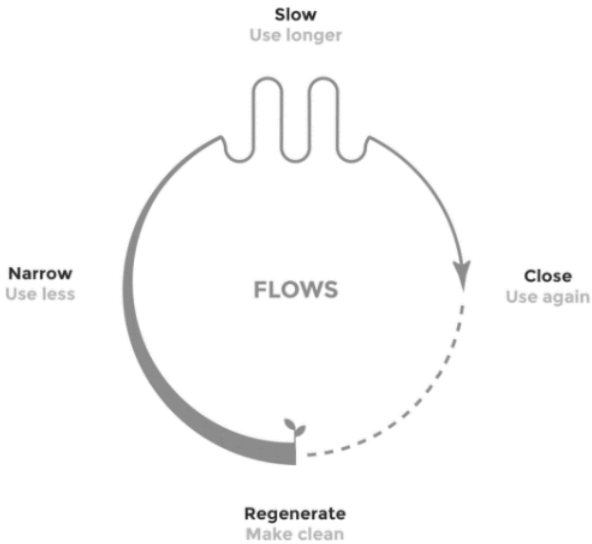


Slides 24–25 (Value Creation Mechanisms):

- *Inner circles:* tight loops (reuse, repair) save most resources.
- *Circling longer:* extend product life via multiple use cycles.
- *Cascading:* use outputs of one system as inputs for another.
- *Pure inputs:* non-toxic, separable materials to enable high-quality reuse.







1. Narrow – "Use less"

Goal: Reduce the total amount of resources and energy entering the system.

How:

- Design products that require fewer materials (lightweight design, material efficiency).
- Increase production efficiency — fewer inputs, less waste.
- Extend functionality per unit of resource (e.g., multifunctional designs, shared assets).

Example: A company redesigns packaging to use 60% less plastic while maintaining strength — narrowing the flow of raw material.

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2. Slow – "Use longer"

Goal: Extend the lifespan of products to delay the need for new ones.

How:

- Design for durability, modularity, and repairability.
- Encourage maintenance, refurbishment, resale, and leasing models.
- Support consumer behavior that favors longevity over replacement.

Example: Patagonia's repair program or Fairphone's modular phone — both enable longer use and slower turnover of goods.

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3. Close – "Use again"

Goal: Keep materials circulating by closing the loop — reintroducing them into production rather than letting them become waste.

How:

- Implement reuse, remanufacturing, recycling, or take-back systems.
- Design with pure, separable materials to allow high-quality recovery.
- Create product–service systems where ownership remains with the producer.

Example: A manufacturer recollects used products, disassembles them, and reuses the components in new units — keeping materials within the loop.

4. Regenerate – "Make clean"

Goal: Restore and enhance natural and industrial systems rather than just minimizing damage.

How:

- Use renewable energy, bio-based materials, and restorative processes.
- Support ecosystems through composting, soil regeneration, and water purification.
- Design waste streams that become nutrients for other systems ("industrial symbiosis").

Example: Agricultural systems using compostable packaging that becomes fertilizer — the flow is not only closed but *restorative*.

In short:

Narrow reduces flow, **Slow** delays flow, **Close** loops flow, and **Regenerate** cleans and renews the flow.

Together, they shift us from an extractive linear model to a regenerative circular system.

Slides 26–44:

Repetition of diagrams reinforcing value-loop logic and emphasizing the economic and environmental promise of circularity.

LECTURE 3 – DEPLOYING CIRCULAR STRATEGIES

Slides 46–47:

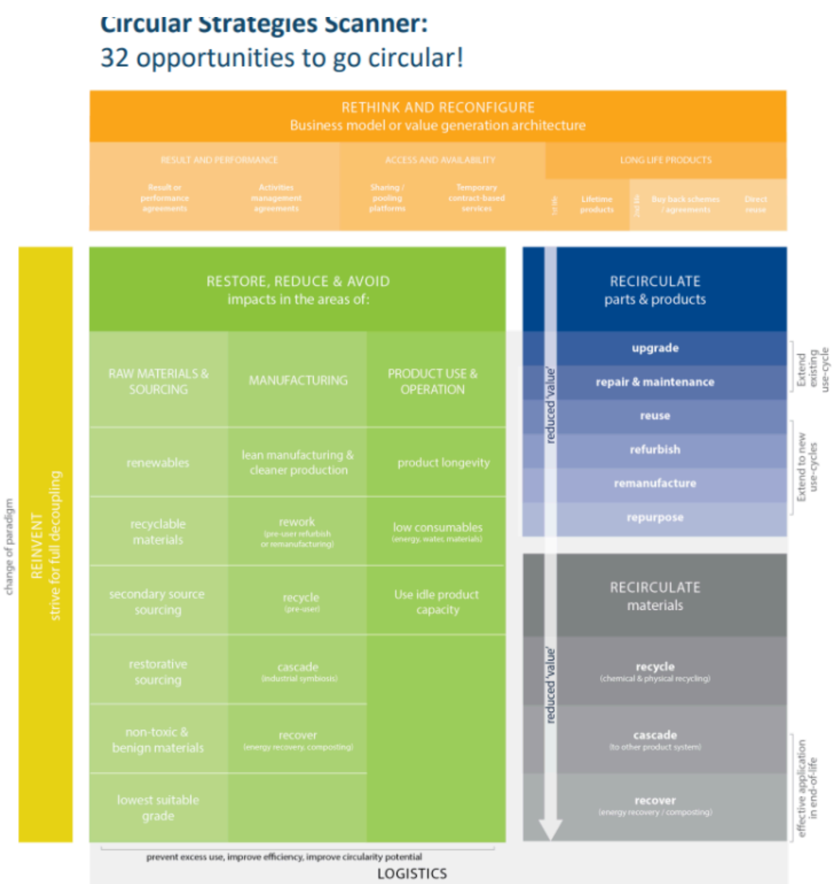
Transition to implementation: how to "go circular."

Slide 48–49 (Circular Strategies Scanner):

Based on Blomsma et al. (2019): 32 strategies grouped along the product life cycle — design, production, use, end-of-life.

Slides 50–53:

Case visuals: *CPH Village* (shipping-container housing) and *Steelcase "Think" chair* — demonstrate design for reuse, modularity, and material recovery.



Slide 54:

Reference to *www.circitnord.com* — DTU and Nordic partners' circular-economy workbooks (guides for companies and students).

LECTURE 4 – CIRCULAR READINESS

Slides 62–63:

Opens with www.ready2loop.org — collaboration platform assessing CE maturity and readiness across 800 companies, 16 sectors, 38 countries.

Emphasis: cooperation across *entire value chains*.

Slides 64–66 (8 Dimensions for CE Transition):

Framework: Strategy & Business Model, Product & Service Innovation, Manufacturing & Value Chain, Technology & Data, Use & Maintenance, Take-Back & EoL Strategies, Policy & Market, Organisation.

Technology & Data

Technology & Data

Readiness of 'Technology & Data' measures your capabilities for the creation of value, through enhanced data management and sharing of the provided solutions.

Use, Support & Maintenance

Use, Support & Maintenance

Readiness of 'Use, Support & Maintenance' measures the capabilities need to provide enhanced maintenance and repair services, aiming at an extended value creation from the provided solutions.

Takeback & End-of-Life Strategies

Takeback & End-of-Life Strategies

Readiness of 'Takeback and End-of-Life Strategies' measures the capabilities that will ensure maximised value of end-of-life products.

Policy & Market

Policy & Market

Readiness of 'Policy & Market' measures the external readiness of the legislative frameworks and markets for the development and provision of circular solutions.

Organisation

Slides 67–81 (Examples per dimension):

- *Mobike* – bike sharing (business model).
- *RePack* – reusable e-commerce packaging (service innovation).
- *Carlsberg Green Fibre Bottle* – bio-based packaging (manufacturing).
- *WasteIQ* – smart waste management (data analytics).
- *Konecranes* – predictive maintenance (Use & Maintenance).
- *Refurb* – repair and resell model (Take-Back).
- *Copenhagen Village* – affordable housing as a service (Policy & Market).
- *Bose* – internal sustainability maturity model (Organisation).

Slides 82–84:

Reiterate systemic approach: material providers → repair services — all must collaborate.

Circularity now seen as a route to *net-zero carbon*.

SUMMARY – BRINGING IT ALL TOGETHER

Slides 85–87:

Checklist for practice:

• Identify your circularity pattern (narrowing, slowing, closing, regenerating).

• Select relevant strategies from the 32 Scanner.

• Assess readiness via ready2loop.org.

• Use circitnord.com for tools and case guides.

Final message: circular design is both a technical and cultural transformation — a systemic shift from *ownership* to *stewardship* of materials.

TechNova, a global electronics company, is planning the next generation of its popular consumer laptop, the TechNova Pro 15. Historically, TechNova has followed a linear business model: raw materials are extracted, components are manufactured, the laptop is assembled, sold, and after a few years, discarded or minimally recycled. TechNova's design team has noted that some components, particularly the battery and printed circuit boards (PCBs) assemblies, are difficult to separate for recycling. Consumers rarely perform repairs themselves, which means most devices end up being discarded. This approach has resulted in significant resource consumption, e-waste generation, and missed opportunities for material recovery.

In response to increasing regulatory pressure, environmental concerns, and consumer demand for sustainable products, TechNova aims to transition towards a circular model. The goal is to reduce environmental impacts and conserve natural resources.

Key Information

Product lifetime: 3–5 years in the current linear model.

Main materials: aluminium chassis, lithium-ion battery, PCBs, plastics, and small amounts of rare-earth metals.

Current functional unit: The laptop must provide a computing platform capable of performing standard office and multimedia tasks for an individual user, typically used 5 days a week, 8 hours per day, by a professional or student over 4 years.

Current reference flow: 1 fully assembled laptop delivered to the customer.

Current system boundary: Cradle-to-grave, from raw material extraction through manufacturing, distribution, use, and end-of-life disposal

1. Consider what type of circularity pattern(s) might best be suited for TechNova to follow: narrowing, slowing, closing, regenerating?
   Main focus = *Slow + Close*, supported by *Narrow* and *Regenerate* principles.
2. Identify which of the 32 circular strategies TechNova could/should follow. Reflect on the reasoning. The CE Strategy Scanner can aid you!
   reinvent, upgrade, repair & mantenance
3. Identify if there would be changes to the system boundaries, functional unit, and reference flow if the CE Strategy(ies) is/are implemented. If so, what would they be?
   System boundries - Currently *cradle-to-grave* → would become *cradle-to-cradle*
   Functional unit - lifetime extends
   Reference flow - The flow thus includes *reverse logistics* and *remanufacturing output*.
4. Can you apply Circular Economy concepts in your own projects? Would employing CE strategy(ies) reflect in an improved sustainability performance (environmental, economic, and social dimensio

11. Energy Systems and Transition/Decarbonization

Date	@November 18, 2025
Status	Done

This module will focus on the impact of electricity production on the world emissions by reviewing the life cycle assessment (LCA) emissions reported by the United Nations (UN) on electricity producing technologies in the report Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources (2022).

These emissions should be considered as reference levels and one can determine the resulting emission from a country or a region by the electricity producing technology mix and the energy consumption of the county or region. A method for estimating the resulting global emission is proposed and the excel sheet "Planetary CO2 boundary - Electricity Technology Mix" is provided to apply the method. The Global Warming Potential (gCO2e/kWh) estimated by the electricity technology mix is compared to the planetary boundary as specified by the UN global warming scenario of a 1.5 or 2.0 degree global temperature increase by end of 2100.

Finally Decarbonization strategies of changes to the electricity technology mix of the world and Denmark scaled to global production are evaluated and discussed. You are encouraged to propose your own decarbonizing strategies and investigate if the planetary boundary of Global Warming Potential is violated.

Studies before teaching session:

Watch the video lectures below:

Video lecture 1 : Decarbonizing energy systems

Video lecture 2 : Wind energy as example

Video lecture 3 : Exercise planetary boundary of Global Warming Potential due to electricity mix

Download the excel file Planetary CO2 boundary - Electricity Technology Mix.

Reading instruction:

Read Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources from page 6-30

Read The Closing Window - Climate crisis calls for rapid transformation of societies from page XVI to XX.The supplementary literature is the World Energy Outlook 2023.

Decarbonizing energy systems

1. Know the technologies

Describe the main electricity generation technologies used globally (coal, gas, wind, solar, hydro, nuclear, biomass, etc.).

2. Know where CO_2 comes from

Explain how electricity-producing units create CO_2 (fuel combustion, materials, manufacturing, etc.).

3. Know different country mixes

Describe how the electricity mix differs around the world (e.g., Denmark = wind-heavy, France = nuclear-heavy, China = coal-heavy).

4. Estimate emissions per kWh

Calculate the CO_2e of producing 1 kWh using weighted averages of emission factors.

5. Discuss future CO_2 emissions

Discuss how emissions may change in the future and propose strategies to decarbonize (phase out coal, expand renewables, etc.).

6. Discuss needed technologies

Identify extra technologies needed for a clean system (storage, CCS, nuclear, interconnectors, demand response, etc.).

7. Analyse a country scenario

Analyse electricity emissions for a specific country and compare them to UN scenarios for 1.5°/2.0° warming.

8. Evaluate planetary boundary violation

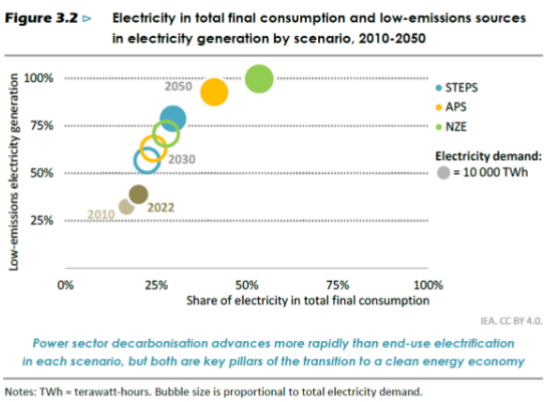
Check if the electricity mix breaks or respects the planetary CO_2 boundary.

> You must understand electricity technologies, know where their CO_2 comes from, estimate emissions, analyse national/global scenarios, and judge whether a future electricity mix respects the 1.5 °C planetary boundary.

Electricity is becoming a bigger part of the total energy system because everything is being electrified (transport, heating, industry).

Therefore: **clean electricity matters more than ever.**

Electricity fraction of energy consumption



Source: IEA Energy Outlook 2023

Electricity-producing technologies

Fuel-based

- Coal
- Gas
- Biomass
- Nuclear

  CO_2 mainly comes from **burning fuels**, except nuclear.

Renewables

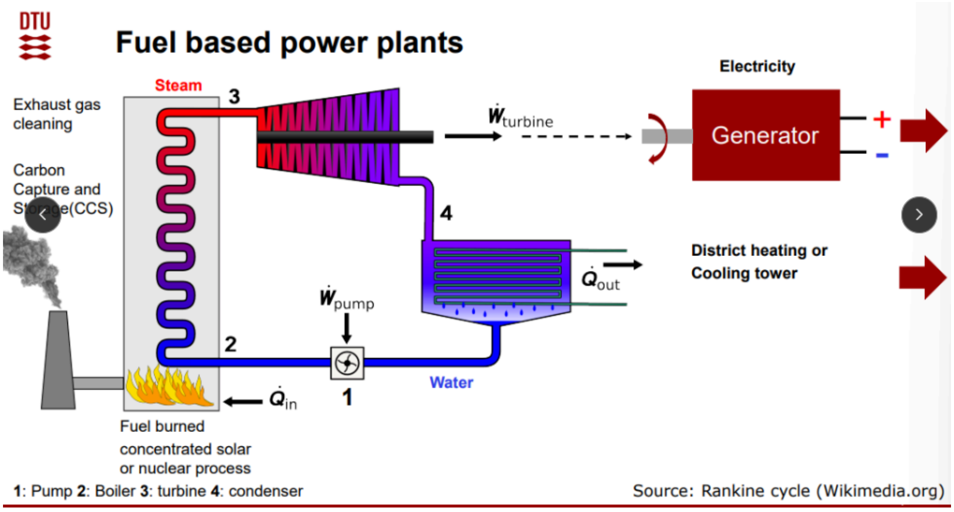
- Wind
- Solar PV
- Hydro
- Geothermal / Tidal

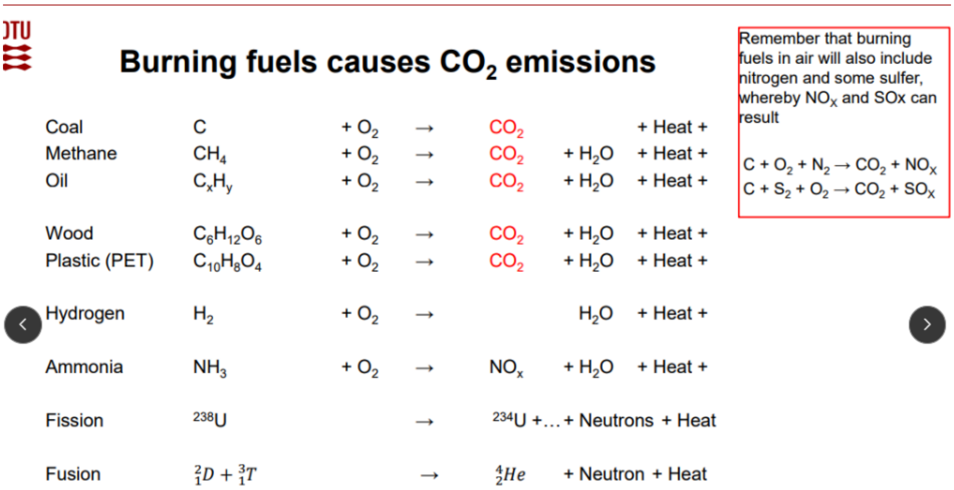
  CO_2 comes from **materials**, not operation.

Burn carbon → produce CO_2 + heat.

Coal, gas, oil, biomass → all release CO_2 when burned.

All fossil fuels = **chemical carbon emissions**.

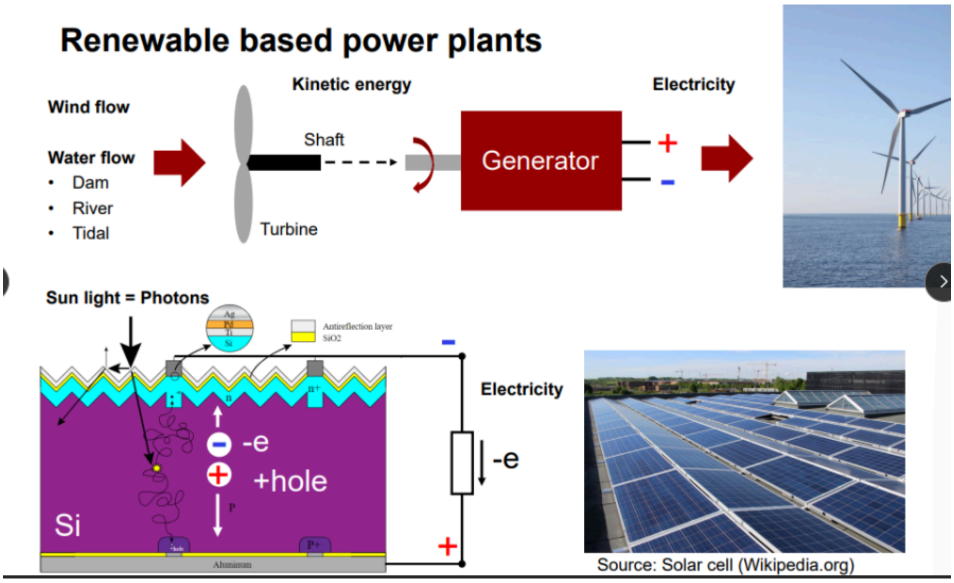




Renewables generate electricity using **natural energy flows**:

- Wind kinetic energy
- Water flow
- Sunlight exciting electrons in PV cells

No combustion, so **very low operational CO_2**.



Building energy plants requires materials:

- Steel, cement, copper, silicon → high CO_2 footprints
- Mining + industrial chemistry = big emissions

  These matter especially for renewables.

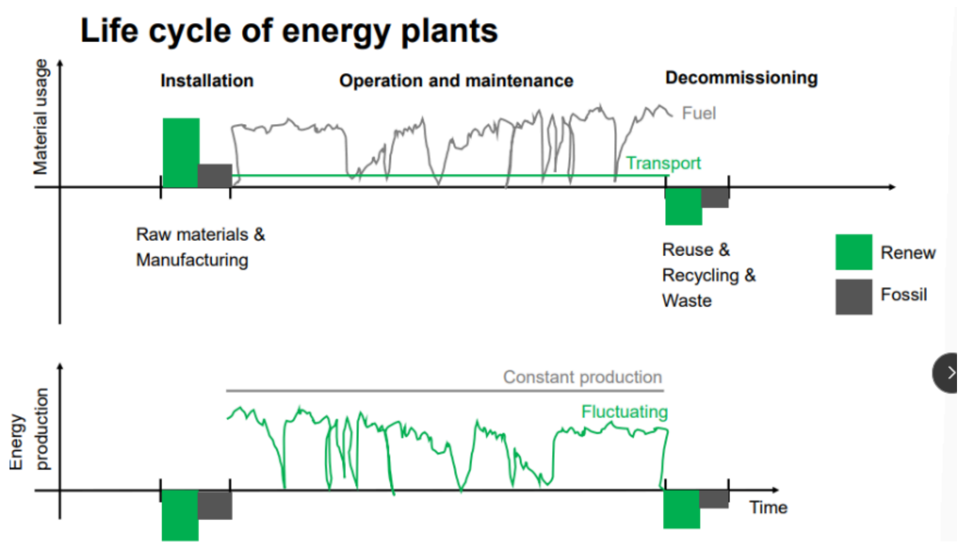
Material manufacturing causes CO_2 emissions

Materials	Chemical process	Impact
Mining Iron ore and making metal	$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$	1.9 ton CO_2e /ton$_{Fe}$
Remelting recycled steel (NLMK Dansteel)	Fe + heat/electricity + → Fe	0.7 ton CO_2e /ton$_{Fe}$
Refining Iron ore using hydrogen ("Green steel")	$Fe_2O_3 + 3\,H_2 \rightarrow 2\,Fe + 3\,H_2O$	? (Demo at Salzgitter)
Concrete (turning limestone to CaO)	$CaCO_3$ + Heat → $CaO + CO_2$	0.1- 0.2 ton CO_2e /ton$_{Concrete}$
Green cement (Aalborg Portland)	As above but use minerals and heating with less CO_2 foot-print	30 % lower than cement ~ 0.6 ton CO_2e /ton$_{Cement}$
Making sand into silicon for PV wafers Making Copper ore into copper for wires	$SiO_2 + 2\,C \rightarrow Si + 2\,CO$ $2\,Cu_2S + 3\,O_2 \rightarrow 2\,Cu_2O + 2\,SO_2$ $2\,Cu_2O + Cu_2S \rightarrow 6\,Cu + 2\,SO_2$	5-16 ton CO_2e /ton$_{Copper}$ 3-4 ton CO_2e /ton$_{Copper}$ SO_2 causes acid rain

4 phases:

1. Materials
2. Installation
3. Operation
4. Decommissioning + recycling

Total emissions = everything across the life cycle.

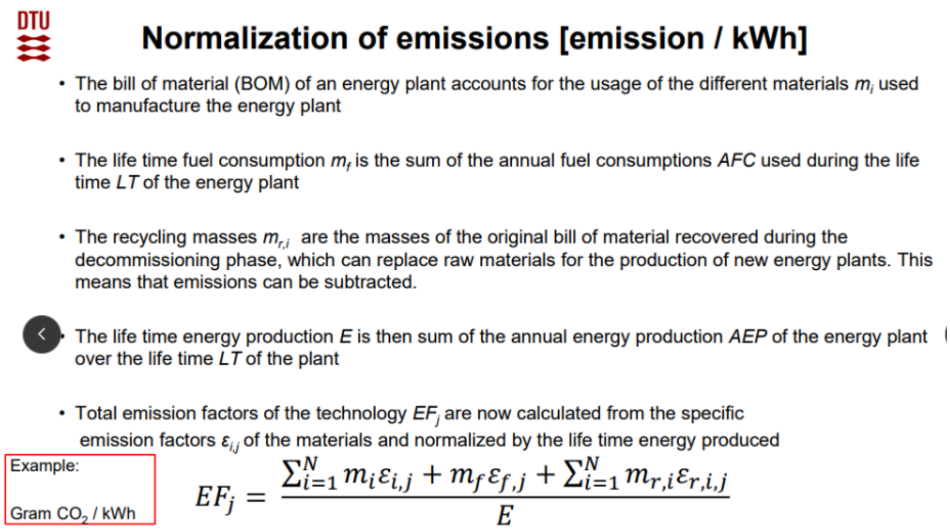


The core formula:

$EF = \frac{\text{materials+fuel use−recycling credit}}{\text{lifetime energy produced}}$

Lifetime energy is huge for wind & hydro → **very low g CO_2/kWh**.

Lifetime energy is low for coal → **extremely high g CO_2/kWh**.

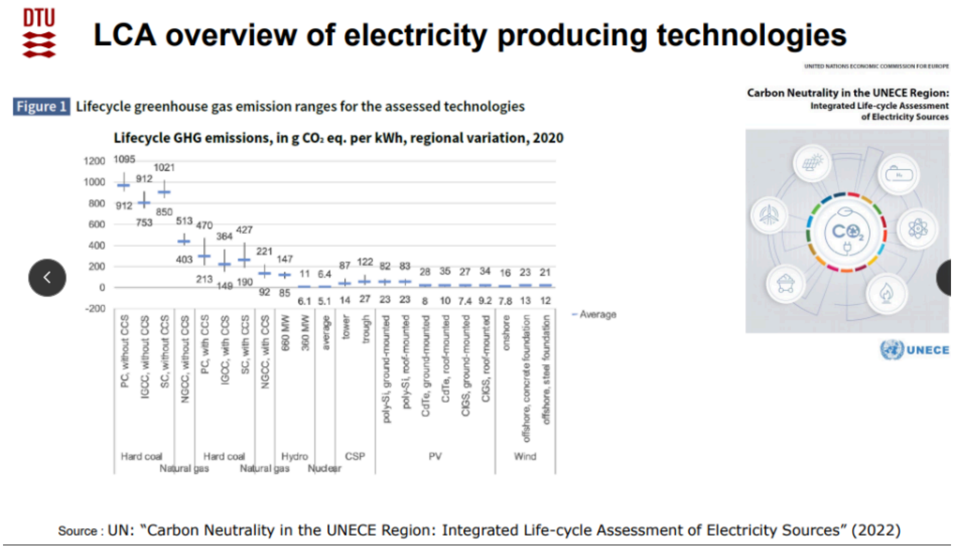


The UN report shows:

- **Coal:** ~1023 g CO_2/kWh
- **Gas:** ~434 g
- **Solar PV:** ~37 g
- **Wind:** ~12 g
- **Nuclear:** ~5 g

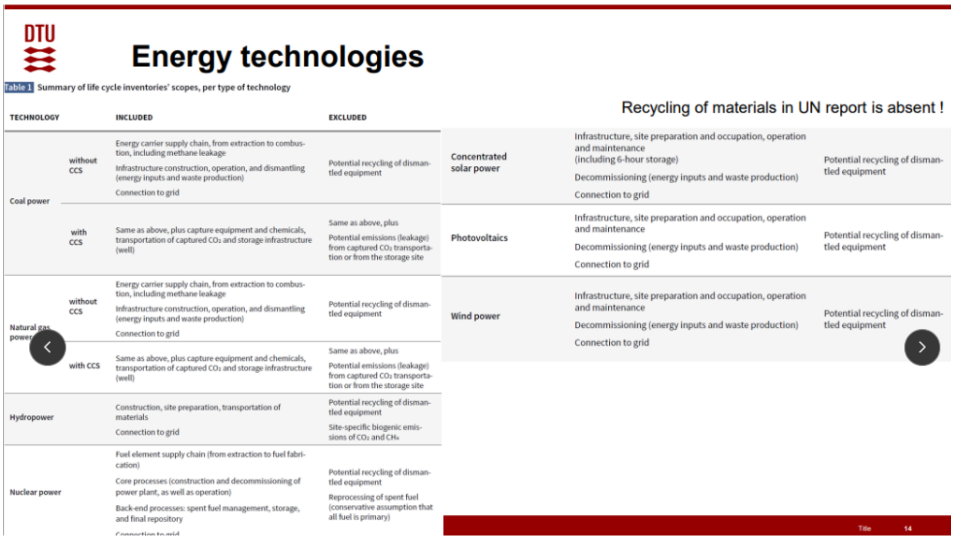
Coal → wind is almost **200× difference**.

This is why the world's electricity mix matters so much.



Coal, gas = high emissions.
Wind, solar, nuclear = extremely low.

The LCA diagrams show where emissions come from for each.



TECHNOLOGY		INCLUDED	EXCLUDED
Coal power	without CCS	Energy carrier supply chain, from extraction to combustion, including methane leakage; Infrastructure construction, operation, and dismantling (energy inputs and waste production); Connection to grid	Potential recycling of dismantled equipment
	with CCS	Same as above, plus capture equipment and chemicals, transportation of captured CO_2 and storage infrastructure (well)	Same as above, plus; Potential emissions (leakage) from captured CO_2 transportation or from the storage site
Natural gas power	without CCS	Energy carrier supply chain, from extraction to combustion, including methane leakage; Infrastructure construction, operation, and dismantling (energy inputs and waste production); Connection to grid	Potential recycling of dismantled equipment
	with CCS	Same as above, plus capture equipment and chemicals, transportation of captured CO_2 and storage infrastructure (well)	Same as above, plus; Potential emissions (leakage) from captured CO_2 transportation or from the storage site
Hydropower		Construction, site preparation, transportation of materials; Connection to grid	Potential recycling of dismantled equipment; Site-specific biogenic emissions of CO_2 and CH_4
Nuclear power		Fuel element supply chain (from extraction to fuel fabrication); Core processes (construction and decommissioning of power plant, as well as operation); Back-end processes: spent fuel management, storage, and final repository; Connection to grid	Potential recycling of dismantled equipment; Reprocessing of spent fuel (conservative assumption that all fuel is primary)
Concentrated solar power		Infrastructure, site preparation and occupation, operation and maintenance (including 6-hour storage); Decommissioning (energy inputs and waste production); Connection to grid	Potential recycling of dismantled equipment
Photovoltaics		Infrastructure, site preparation and occupation, operation and maintenance; Decommissioning (energy inputs and waste production); Connection to grid	Potential recycling of dismantled equipment
Wind power		Infrastructure, site preparation and occupation, operation and maintenance; Decommissioning (energy inputs and waste production); Connection to grid	Potential recycling of dismantled equipment

The table lists the **main environmental impact categories** used in Life Cycle Assessment (LCA).

These categories describe different types of environmental harm — not just CO_2.

Below is what each category *means* in simple, operational terms.

1. Climate change — kg CO_2 eq.

What it measures:

Total greenhouse gas effect, converted to CO_2-equivalent, over 100 years (GWP100).

Why it matters:

This is the category you use for the **planetary boundary / 1.5 °C calculations**.

---

2. Freshwater eutrophication — kg P eq.

What it measures:

How much phosphorus-like nutrient pollution reaches freshwater.

Too much → algae blooms → dead lakes.

Main drivers:

Agriculture, wastewater, some manufacturing processes.

3. Ionising radiation — kBq ^{235}U eq.

What it measures:

Potential human radiation exposure compared to radiation from uranium-235.

Relevant for:

Nuclear energy (obviously), but also some industrial processes.

4. Human toxicity — CTUh

(Comparative Toxic Units for humans)

What it measures:

Potential health impacts (disease cases) due to chemical emissions during the life cycle of the technology.

Examples:

Heavy metals, solvents, by-products from manufacturing.

5. Land use — "points"

From the LANCA model.

What it measures:

How using land affects:

1. Erosion resistance
2. Mechanical filtration
3. Physicochemical filtration
4. Groundwater recharge
5. Biotic production (ecosystem productivity)

Used for:

Wind farms (land footprint), hydro reservoirs, solar farms, mining.

6. Water resource depletion — m^3

What it measures:

How much freshwater is consumed or depleted.

Important for:

Hydro, nuclear cooling, PV manufacturing (cleaning & processing).

7. Mineral, fossil and renewable resource depletion — kg Sb eq.

(antimony equivalent)

What it measures:

Scarcity of minerals/metals — how much the technology contributes to depletion.

Key drivers:

Copper, silicon, rare earth metals in wind turbines, PV, batteries.

Among all the categories above, the one that **dominates differences between electricity technologies** is:

Climate change (CO_2e)

This is why the whole module focuses on it for planetary boundaries.

The other categories matter but vary far less between technologies.

Impacts

Table 3 **Selected environmental indicators for Life Cycle Impact Assessment**

CATEGORY	UNIT	REFERENCE	DESCRIPTION
Climate change	kg CO_2 eq.	IPCC (2013)	Radiative forcing as global warming potential, integrated over 100 years (GWP100), based on IPCC baseline model.
Freshwater eutrophication	kg P eq.	EUTREND, Struijs, Beusen [16]	Expression of the degree to which the emitted nutrients reach the freshwater end compartment. As the limiting nutrient in freshwater aquatic ecosystems, a surplus of phosphorus will lead to eutrophication.
Ionising radiation	kBq ^{235}U eq	Frischknecht, Braunschweig [17]	Human exposure efficiency relative to ^{235}U radiation. The original model is Dreicer, Tort [18] and follows the linear no-threshold paradigm to account for low dose radiation (details in Box 5).
Human toxicity	CTUh (comparative toxic units)	USEtox 2.1. model Rosenbaum, Bachmann [19]	The characterization factor for human toxicity impacts (human toxicity potential) is expressed in comparative toxic units (CTUh), the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue. Unit: [CTUh per kg emitted] = [disease cases per kg emitted]1

Impacts (continued)

CATEGORY	UNIT	REFERENCE	DESCRIPTION
Land use	points	LANCA model, Bos, Horn [20]	The LANCA model provides five indicators for assessing the impacts due to the use of soil: 1. erosion resistance; 2. mechanical filtration; 3. physicochemical filtration; 4. groundwater regeneration and 5. biotic production.
Water resource depletion	m^3	Swiss Ecoscarcity Frischknecht, Steiner [21]	Water use related to local consumption of water. Note: only air emissions are accounted for. *In this method, all flows have an identical characterisation factor of 42.95 m^3/m^3 – we therefore choose to account for these flows uncharacterised, i.e. 1 m^3/m^3.*
Mineral, fossil and renewable resource depletion	kg Sb eq.	Van Oers, De Koning [22]	Scarcity of resource in relation to that of antimony. Scarcity is calculated as « reserve base ».

Climate change: 1023 g CO_2/kWh

Highest of all technologies by a huge margin.

Other impacts:

- Very high **freshwater eutrophication**
- High **carcinogenic effects**
- High **ionising radiation** (yes, surprisingly higher than wind/solar because of mining activities)
- Very high **water use**
- Very high **minerals + metals** demand

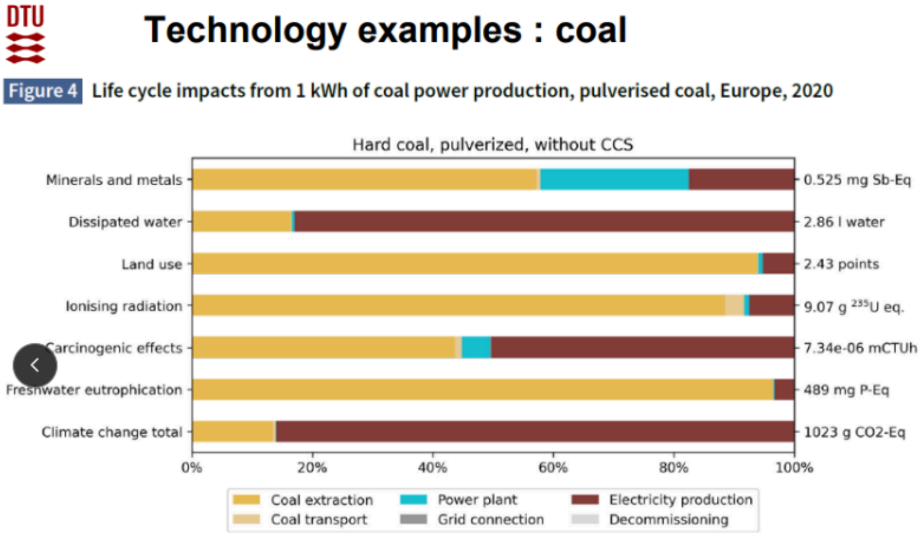
Where impacts come from:

Mostly **combustion** + coal extraction + power plant operation.

Interpretation:

Coal wrecks basically every LCA category.

This is why decarbonization = kill coal first.



Climate change: 434 g CO_2/kWh

Roughly half of coal, but still huge.

Other impacts:

- Still notable water use
- Moderate land use
- Similar ionising radiation levels as coal
- Lower toxicity and eutrophication than coal

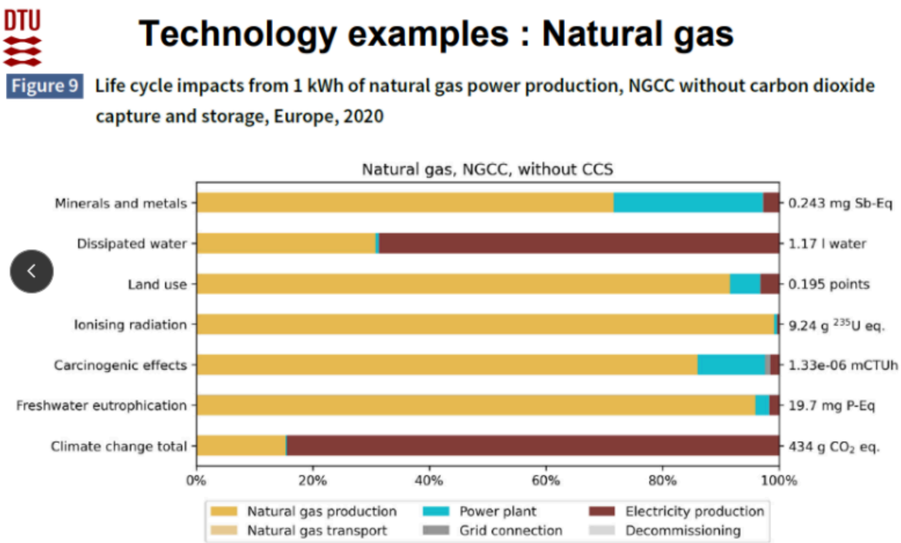
Where impacts come from:

Fuel extraction + combustion + pipeline infrastructure.

Interpretation:

Better than coal, still not compatible with 1.5°C without CCS.

Gas reduction is step 2 after phasing out coal.



Climate change: 5.13 g CO_2/kWh

Insanely low. Close to wind.

Other impacts:

- High ionising radiation (obviously)

- Moderate water use (cooling)
- Moderate minerals & land use
- Very low eutrophication & toxicity

BUT: the radiation value is **still small** environmentally — orders of magnitude smaller compared to fossil CO_2 damage.

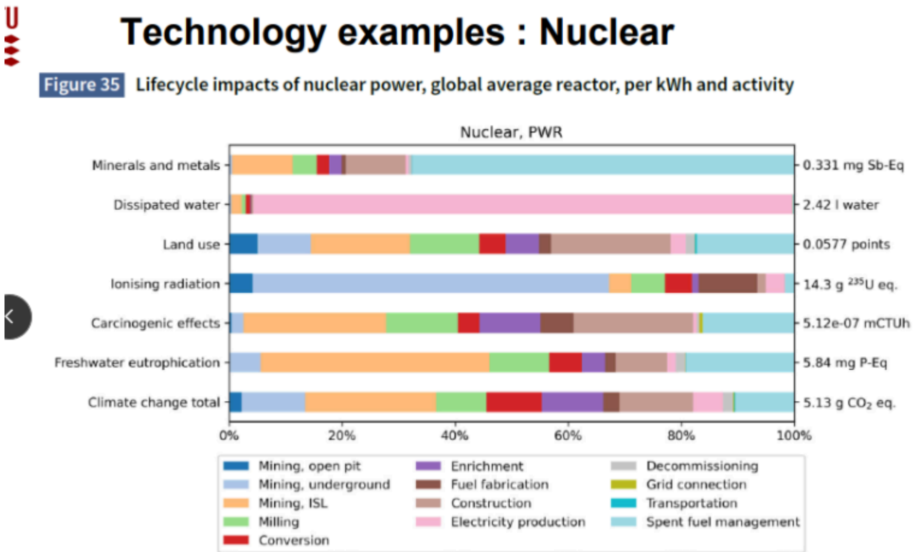
Where impacts come from:

Mining → enrichment → construction → spent fuel.

Interpretation:

If you want fast decarbonization, nuclear mathematically works extremely well.

Low CO_2, stable, high output.



Climate change: 36.7 g CO_2/kWh

Very low compared to fossil fuels.

Other impacts:

- Very high **minerals & metals** demand
- High **land use**
- Moderate eutrophication
- Moderate dissipated water
- Moderate ionising radiation (from materials production)

Where impacts come from:

- Silicon purification
- Module manufacturing
- Metal use
- Inverters
- Construction

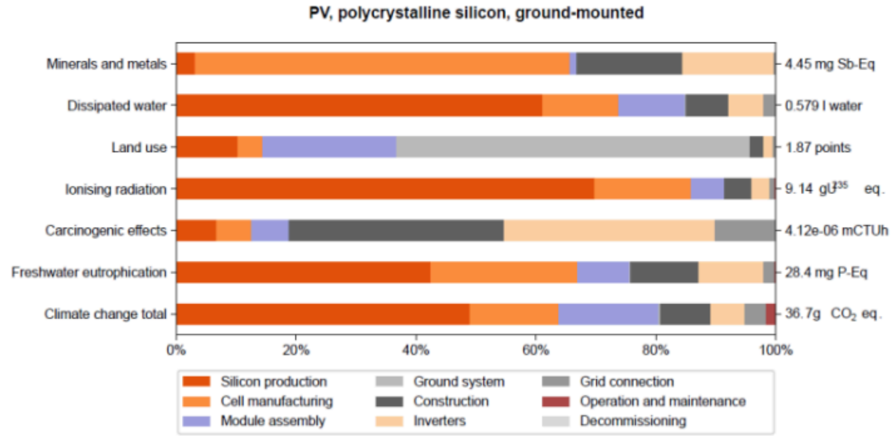
Interpretation:

Great for climate.

Material-intense but improves as manufacturing becomes greener.

Technology examples : Solar PV

Figure 25 Life cycle impacts from 1 kWh of poly-Si, ground-mounted, photovoltaic power production, Europe, 2020



Climate change: 12.4 g CO_2/kWh

Among the lowest of any technology.

Other impacts:

- Very low land use (surprisingly; the area can still be used for agriculture)
- Very low water use
- Very low toxicity
- Very low eutrophication
- Low minerals/metals compared to solar

Where impacts come from:

- Tower (steel)
- Blades
- Foundations
- Transportation
- Installation

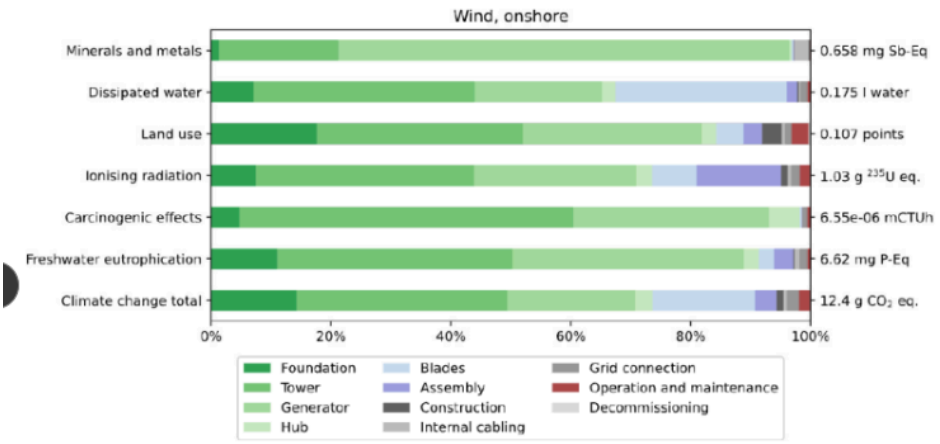
Interpretation:

Wind is the **cleanest large-scale solution** for electricity production.

This is why every climate scenario ramps up wind massively.

Technology examples : Onshore wind

Figure 12 Life cycle impacts from 1 kWh of onshore wind power production, Europe, 2020



These are the values you must remember:

Tech	CO_2 (g/kWh)	Notes
Coal	**1023**	catastrophic for climate
Gas	**434**	still dirty
Nuclear	**5**	extremely low-carbon
Solar PV	**36.7**	low carbon, high materials
Wind	**12.4**	lowest + easiest to scale

Two key insights from the professor:

- **Climate change category shows differences of ~200× between technologies**
- Other categories differ much less (10–20×)

This is why **climate impact dominates decarbonization strategy**.

Coal → 1023 g

Gas → 434 g

Solar → 37 g

Wind → 12 g

Nuclear → 5 g

Everything else is commentary.

DTU

LCA impact summary based on main technologies

Technology and LCA impact	Climate change total [g CO_2 / kWh]	Freshwater eutrophication [mg P-Eq/kWh]	Carcinogenic effects [mCTUh/kWh]	Ionizing radiation [g ^{235}U Eq/kWh]	Land use [points/kWh]	Dissipated water [Liter/kWh]	Minerals and metals [mg Sb-Eq / kWh]	Source
coal	1023	489	7,34E-06	9,07	2,43	2,86	0,525	Fig 4
Natural gas	434	19,7	1,33E-06	9,24	0,195	1,17	0,243	Fig 9
Nuclear	5,13	5,84	5,12E-07	14,3	0,0577	2,42	0,331	Fig 35
Solar PV	36,7	28,4	4,12E-06	9,14	1,87	0,579	4,45	Fig 25
Onshore wind	12,4	6,62	6,55E-06	1,03	0,107	0,175	0,658	Fig 12
Source :	Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources, UN (2022)							

- **Largest difference between technologies seen for climate change (CO_2e emission) ~ a factor of 200**
  Smaller difference for other impacts such as Ionizing radiation (~ 14) and Dissipated water (~ 16)
- **Table 13 and 14 on the next slides provide the full overview of the technology impacts**

PER KWH		CLIMATE CHANGE [g CO₂ eq.]	FRESHWATER EUTROPHICATION [mg P eq.]	CARCINOGENIC EFFECTS [µCTUh]	IONISING RADIATION [g ²³⁵U eq.]	LAND USE [points]	DISSIPATED WATER [l]	MINERALS AND METALS [µg Sb eq.]
Hard coal	PC, without CCS	1000	490	7.3	9.1	2.4	2.9	520
Hard coal	IGCC, without CCS	850	420	6.4	7.5	2.1	1.7	590
Hard coal	SC, without CCS	950	460	6.9	8.2	2.3	2.6	500
Natural gas	NGCC, without CCS	430	20	1.3	9.2	0.2	1.2	240
Hard coal	PC, with CCS	370	690	10	13	3.4	5.1	780
Hard coal	IGCC, with CCS	280	570	8.6	10	2.8	2.7	690
Hard coal	SC, with CCS	330	640	9.7	12	3.2	4.6	740
Natural gas	NGCC, with CCS	130	24	1.7	11	0.24	2.00	310
Hydro	660 MW	150	13	2.6	12	2.5	0.37	610
Hydro	360 MW	11	1.3	0.35	0.84	0.21	0.039	61
Nuclear	average	5.1	5.8	0.51	14	0.058	2.4	330
CSP	tower	22	11	2.1	4.5	3.6	0.18	340
CSP	trough	42	14	6.3	6.1	3.5	0.34	650
PV	poly-Si, ground-mounted	37	28	4.1	9.1	1.9	0.58	4500
PV	poly-Si, roof-mounted	37	39	1.6	9.8	0.86	0.63	7200
PV	CdTe, ground-mounted	12	8.8	3.4	1.9	1.4	0.13	1500
PV	CdTe, roof-mounted	15	14	1.1	1.9	0.15	0.16	2600
PV	CIGS, ground-mounted	11	8.8	3.4	1.8	1.3	0.13	1700
PV	CIGS, roof-mounted	14	14	1.1	1.8	0.15	0.16	2800
Wind	onshore	12	6.7	6.6	1.0	0.11	0.18	680
Wind	offshore, concrete foundation	14	7.0	5.5	1.2	0.11	0.16	980
Wind	offshore, steel foundation	13	6.8	7	1.2	0.099	0.16	990

Full LCIA results

Table 14 is summarizing the resulting emission per kWh electricity produces in Europe

PER KWH		CLIMATE CHANGE BIOGENIC	CLIMATE CHANGE FOSSIL	CLIMATE CHANGE LAND USE AND LAND USE CHANGE	CLIMATE CHANGE TOTAL	FRESHWATER AND TERRESTRIAL ACIDIFICATION	FRESHWATER ECOTOXICITY	FRESHWATER EUTROPHICATION	MARINE EUTROPHICATION
		[kg CO_2-Eq]	[kg CO_2-Eq]	[kg CO_2-Eq]	[kg CO_2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]
Hard coal	PC, without CCS	6.87E-05	1.02E+00	1.67E-04	**1.02E+00**	1.73E-03	4.72E-01	4.89E-04	5.14E-04
Hard coal	IGCC, without CCS	5.38E-05	8.49E-01	1.40E-04	**8.49E-01**	1.05E-03	3.46E-01	4.24E-04	4.18E-04
Hard coal	SC, without CCS	6.45E-05	9.53E-01	1.56E-04	**9.53E-01**	1.63E-03	4.33E-01	4.58E-04	4.82E-04
Natural gas	NGCC, without CCS	7.78E-05	4.34E-01	8.21E-05	**4.34E-01**	3.26E-04	1.16E-01	1.97E-05	4.96E-05
Hard coal	PC, with CCS	1.06E-04	3.68E-01	2.47E-04	**3.69E-01**	1.80E-03	8.26E-01	6.90E-04	7.29E-04
Hard coal	IGCC, with CCS	7.23E-05	2.79E-01	1.89E-04	**2.79E-01**	1.35E-03	4.94E-01	5.71E-04	5.36E-04
Hard coal	SC, with CCS	9.90E-05	3.33E-01	2.34E-04	**3.33E-01**	2.25E-03	7.51E-01	6.37E-04	6.92E-04
Natural gas	NGCC, with CCS	9.39E-05	1.28E-01	9.93E-05	**1.28E-01**	6.07E-04	2.34E-01	2.40E-05	7.42E-05
Hydro	660 MW	5.32E-05	1.47E-01	1.09E-04	**1.47E-01**	4.15E-04	3.97E-01	1.26E-05	9.54E-05
Hydro	360 MW	1.80E-05	1.07E-02	9.21E-06	**1.07E-02**	4.45E-05	2.73E-02	1.33E-06	1.23E-05
Nuclear	average	2.56E-05	5.24E-03	2.26E-05	**5.29E-03**	4.28E-05	2.70E-02	6.45E-06	8.20E-05
CSP	tower	3.02E-05	2.16E-02	3.36E-05	**2.17E-02**	9.24E-05	3.65E-02	1.11E-05	2.21E-05
CSP	trough	4.57E-05	4.19E-02	5.60E-05	**4.20E-02**	1.51E-04	1.10E-01	1.38E-05	2.88E-05
PV	poly-Si, ground-mounted	3.43E-04	3.62E-02	1.51E-04	**3.67E-02**	3.01E-04	7.91E-02	2.84E-05	[illegible]
PV	poly-Si, roof-mounted	3.34E-04	3.67E-02	1.69E-04	**3.72E-02**	3.34E-04	6.99E-02	3.93E-05	[illegible]
PV	CdTe, ground-mounted	8.86E-05	1.18E-02	2.54E-05	**1.19E-02**	6.27E-05	5.59E-02	8.75E-06	[illegible]
PV	CdTe, roof-mounted	5.59E-05	1.45E-02	4.38E-05	**1.46E-02**	8.82E-05	3.96E-02	1.42E-05	1.54E-05
PV	CIGS, ground-mounted	8.58E-05	1.13E-02	2.52E-05	**1.14E-02**	6.11E-05	5.58E-02	8.76E-06	1.25E-05
PV	CIGS, roof-mounted	5.47E-05	1.40E-02	4.33E-05	**1.41E-02**	8.64E-05	4.02E-02	1.42E-05	1.52E-05
Wind	onshore	1.87E-05	1.24E-02	1.99E-05	**1.24E-02**	5.28E-05	7.48E-02	6.67E-06	1.39E-05
Wind	offshore, concrete foundation	1.74E-05	1.42E-02	2.58E-05	**1.42E-02**	1.00E-04	6.62E-02	6.98E-06	2.84E-05
Wind	offshore, steel foundation	1.87E-05	1.33E-02	2.46E-05	**1.33E-02**	9.45E-05	7.94E-02	6.84E-06	2.69E-05

TERRESTRIAL EUTROPHICATION	CARCINOGENIC EFFECTS	IONISING RADIATION	NON-CARCINOGENIC EFFECTS	OZONE LAYER DEPLETION	PHOTOCHEMICAL OZONE CREATION	RESPIRATORY EFFECTS, INORGANICS	DISSIPATED WATER	FOSSILS	LAND USE	MINERALS AND METALS
[mol N-Eq]	[CTUh]	[kg U235-Eq]	[CTUh]	[kg CFC-11.]	[kg NMVOC-.]	[disease i.]	[m³ water-.]	[megajoule]	[points]	[kg Sb-Eq]
4.97E-03	7.34E-09	8.74E-03	1.14E-07	1.04E-08	1.25E-03	2.51E-08	1.23E-01	1.41E+01	2.43E+00	5.25E-07
4.00E-03	6.43E-09	7.47E-03	9.57E-08	8.74E-09	9.78E-04	1.36E-08	7.23E-02	1.21E+01	2.06E+00	5.89E-07
4.69E-03	6.90E-09	8.19E-03	1.06E-07	9.76E-09	1.16E-03	2.36E-08	1.12E-01	1.32E+01	2.28E+00	5.00E-07
7.49E-04	1.33E-09	9.24E-03	7.49E-09	6.66E-08	2.25E-04	1.33E-09	5.02E-02	7.86E+00	1.95E-01	2.43E-07
6.82E-03	1.04E-08	1.32E-02	1.66E-07	1.57E-08	1.68E-03	2.93E-08	2.18E-01	2.00E+01	3.45E+00	7.83E-07
5.10E-03	8.62E-09	1.01E-02	1.30E-07	1.18E-08	1.25E-03	1.72E-08	1.16E-01	1.63E+01	2.77E+00	6.85E-07
8.93E-03	9.66E-09	1.23E-02	1.53E-07	1.49E-08	1.55E-03	3.13E-08	1.98E-01	1.84E+01	3.18E+00	[illegible]
1.87E-03	1.67E-09	1.11E-02	1.30E-08	7.81E-08	2.70E-04	3.14E-09	8.59E-02	9.26E+00	2.40E-01	[illegible]
1.04E-03	2.56E-09	1.16E-02	2.17E-08	3.40E-08	3.85E-04	9.45E-09	1.58E-02	2.24E+00	2.45E+00	6.06E-07
1.43E-04	3.54E-10	8.40E-04	1.39E-09	2.37E-09	4.30E-05	8.07E-10	1.66E-03	1.63E-01	2.11E-01	6.06E-08
9.70E-05	5.51E-10	1.43E-02	5.50E-09	4.62E-10	2.65E-05	2.21E-09	1.31E-01	1.64E+01	6.25E-02	3.33E-07
2.46E-04	2.09E-09	4.46E-03	2.61E-09	2.69E-09	7.54E-05	8.82E-10	7.60E-03	3.91E-01	3.62E+00	3.36E-07
3.61E-04	6.25E-09	6.12E-03	4.61E-09	5.61E-09	1.05E-04	1.86E-09	1.47E-02	6.88E-01	3.54E+00	6.45E-07
4.48E-04	4.12E-09	9.14E-03	7.83E-09	6.97E-09	1.30E-04	2.21E-09	2.49E-02	6.43E-01	1.87E+00	4.45E-06
5.10E-04	1.63E-09	9.76E-03	1.38E-08	7.18E-09	1.43E-04	2.31E-09	2.72E-02	6.64E-01	4.43E-01	7.21E-06
1.39E-04	3.44E-09	1.86E-03	3.67E-09	1.03E-09	4.16E-05	6.40E-10	5.63E-03	1.83E-01	1.39E+00	1.53E-06
1.73E-04	1.14E-09	1.89E-03	7.46E-09	9.49E-10	4.86E-05	7.68E-10	7.05E-03	2.20E-01	1.48E-01	2.64E-06
1.36E-04	3.39E-09	1.75E-03	3.77E-09	9.91E-10	4.08E-05	6.20E-10	5.64E-03	1.75E-01	1.35E+00	1.66E-06
1.71E-04	1.14E-09	1.79E-03	7.59E-09	9.10E-10	4.79E-05	7.48E-10	7.08E-03	2.12E-01	1.47E-01	2.81E-06
1.26E-04	6.56E-09	1.03E-03	2.98E-09	6.71E-10	4.63E-05	7.06E-10	7.52E-03	1.75E-01	1.08E-01	6.75E-07
2.93E-04	5.52E-09	1.19E-03	3.17E-09	1.24E-09	8.99E-05	6.57E-10	6.74E-03	1.97E-01	1.11E-01	9.77E-07
2.76E-04	7.00E-09	1.19E-03	3.41E-09	1.18E-09	8.44E-05	6.19E-10	6.67E-03	1.90E-01	9.94E-02	9.93E-07

If you know:

- **The mix of technologies** (coal %, gas %, solar %, wind %, nuclear %...)
- **The total global electricity production**

...then you can compute the **total CO_2 emitted** by global electricity production.

This is what you later compare with the **1.5 °C planetary boundary**.

Installed capacity (GW)

Left graph:

- Fossil ≈ 4500 GW
- Nuclear ≈ 415 GW
- Renewables ≈ 2700 GW

But note: **capacity is not equal to actual electricity produced**.

Solar/wind produce fewer hours per year → lower actual output.

Global electricity production (TWh)

Right graph shows **actual electricity generated** in 2019:

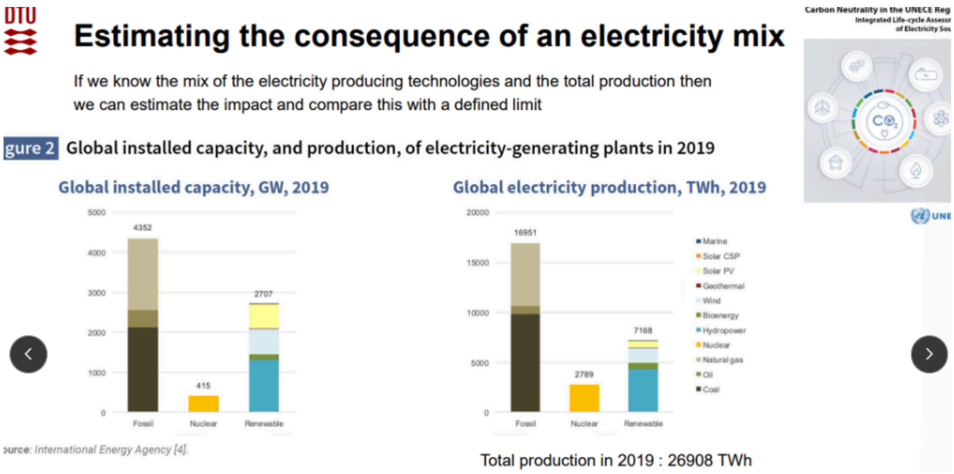
- **Fossil:** 16951 TWh
- **Nuclear:** 2798 TWh
- **Renewables:** 7160 TWh

  (hydro + wind + solar + bioenergy)

TOTAL PRODUCTION IN 2019 = 26,908 TWh

This number is later used to compute:

$E_m = EF_{\text{avg}} \cdot E$

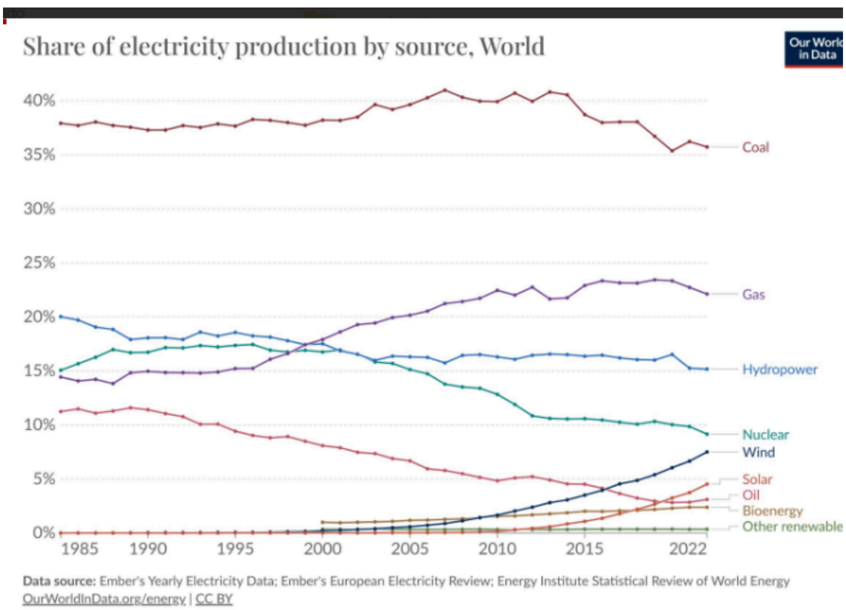


This graph shows how the world's electricity mix changed between 1985–2023:

- **Coal**: decreased slowly from ~40% to ~36%. Still dominant.
- **Gas**: increased from ~15% to ~23%.
- **Hydropower**: slightly declining.
- **Nuclear**: declining slowly.
- **Wind**: rising fast (now ~7%).
- **Solar**: rising extremely fast (from 0 to ~5%).
- **Oil**: almost disappeared.

Interpretation:

Despite growth in solar/wind, **coal and gas still dominate global electricity** → this is why global CO_2 emissions remain huge.



You need the world's total electricity production and technology shares so you can calculate how much CO_2 electricity emits — and check if this violates the planetary boundary.

This slide walks you through the **exact calculation** of global CO_2 emissions from electricity in 2019 **using only 4 technologies**:

- Coal
- Gas
- Nuclear

- Hydro

These are the biggest contributors, so the example shows the contrast between fossil vs non-fossil.

1. Electricity production in 2019

From earlier slides:

- Coal: **9500 TWh**
- Gas: **6500 TWh**
- Nuclear: **2800 TWh**
- Hydro: **4000 TWh**

Convert TWh → kWh by multiplying by 10910^9109.

2. Emission factors (kg CO_2/kWh)

From UN LCA report:

- Coal → **1.02**
- Gas → **0.434**
- Nuclear → **0.00529**
- Hydro → **0.0107**

Coal and gas = dirty.

Nuclear and hydro = almost negligible.

3. Multiply production × emission factor

Coal $9,500 TWh \rightarrow 9.7 Gt\ CO_2$

Gas $6,500 TWh \rightarrow 2.8 Gt\ CO_2$

Nuclear $2,800 TWh \rightarrow 0.02 Gt\ CO_2$

Hydro $4,000 TWh \rightarrow 0.04 Gt\ CO_2$

---

4. Key Insight (the professor's point)

👉 Coal alone emits 9.7 Gt CO_2

👉 Gas adds another 2.8 Gt

→ Coal + gas = 12.5 Gt CO_2

Now compare:

Global emissions total = 53 Gt CO_2e/year

So:

- Coal alone = **18%** of all global emissions
- Coal + gas = **24%** of all global emissions

That's why electricity is the #1 target for decarbonization.

Nuclear + hydro = **only ~0.6% of coal's emissions**

Insanely small.

---

5. Giga-ton reminder box

$1 \text{ Gt} = 10^{12} \text{ kg} 1 Gt = 1012 kg$

(You just multiply TWh → kWh → kg → Gt.)

---

6. UN Emission Gap Report (2022)

The report gives the **allowed future emissions** for:

- **1.5 °C warming**

- **1.8 °C**
- **2.0 °C**

The graph shows the **pathways**:

Blue = 1.5 °C

Yellow = 2.0 °C

Red = world's current policies

Grey = business as usual

Spoiler: current policies → exceeds everything.

---

7. Current global emissions

≈ 53 Gt CO_2e/year

Your earlier electricity calculation (12.5 Gt) is compared against this.

That's why the professor keeps showing:

> "Electricity alone takes up a gigantic fraction of the global carbon budget."

---

8. What this slide wants you to understand

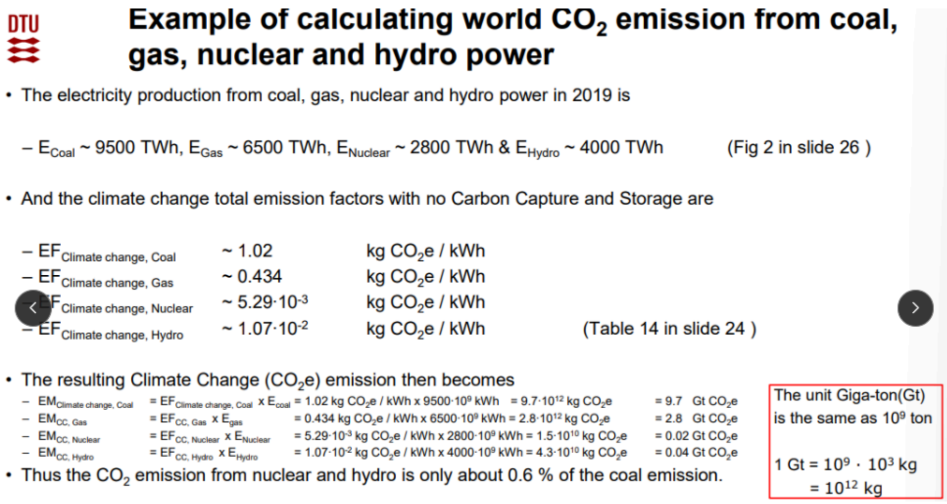
- You now know how to **calculate total electricity emissions**.
- You now know the **global allowed pathways** for 1.5 °C.
- You can now check:

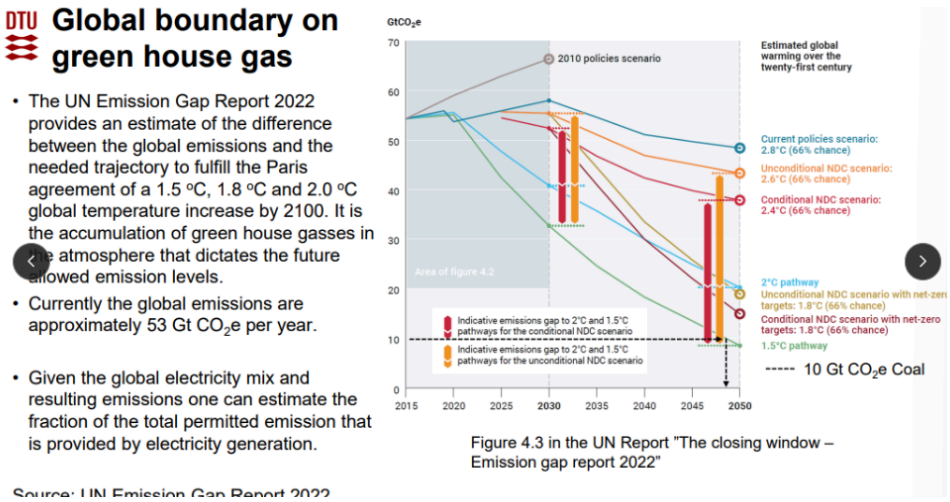
  Does the world's current electricity mix violate or respect the 1.5 °C boundary?

  (Answer: it violates.)

This is the core exercise of the module.

Coal: 9.7 Gt
Gas: 2.8 Gt
Electricity total: 12.5 Gt
World total: 53 Gt
1.5 °C allows: ~33 Gt
Electricity alone is enough to blow the climate budget unless coal/gas collapse.





This slide shows how different countries' CO_2 emissions have evolved over time and what their **climate targets (NDCs)** imply for the future.

But the professor is using the slide to emphasize ONE shocking comparison:

*👉 Coal + gas electricity emissions alone = 12.5 Gt CO_2e

= roughly the ENTIRE annual emissions of China**

China's current total emissions: ~12–13 Gt CO_2/year.

Your electricity calculation:

- Coal = 9.7 Gt
- Gas = 2.8 Gt
- **Total = 12.5 Gt**

So the world's electricity emissions are literally comparable to the CO_2 footprint of the largest emitter on Earth.

This is why the slide highlights China.

Why this matters

It's a way to **visualize the scale**:

- The world's fossil electricity system = same damage as an entire China.
- Fixing electricity → eliminates a "China-sized" block of global emissions.

This reinforces the earlier message:

Decarbonizing electricity is the single most impactful climate move.

What the tiny graphs show

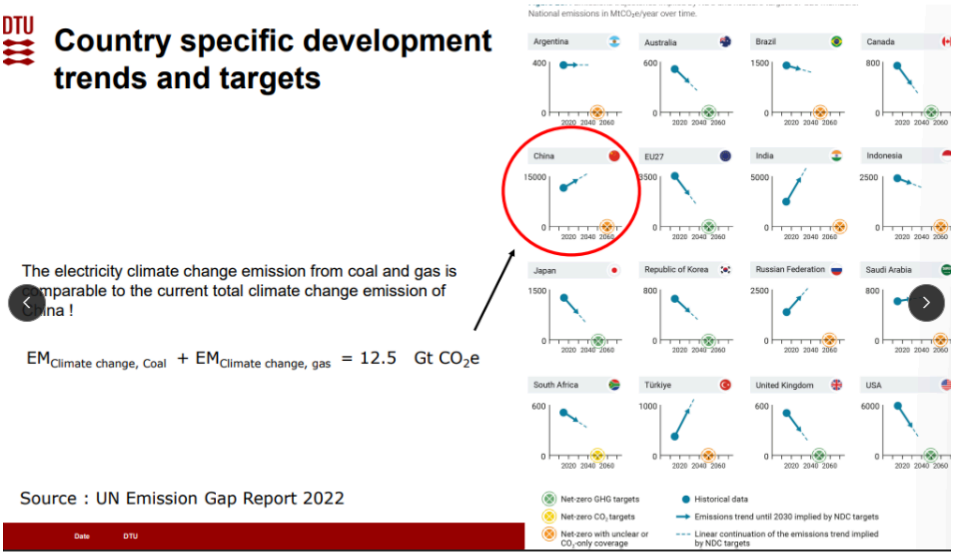
Each mini-plot (Argentina, Australia, Brazil, Canada, China, EU27, India, etc.) shows:

1. **Historical emissions**
2. **Projected emissions under current policies**
3. **NDC targets** (Nationally Determined Contributions)
4. Whether the country has:
   - Net-zero commitments
   - Insufficient reduction
   - Increasing trend
   - Declining trend

But again, the instructor's intent is NOT for you to memorize these.

The goal is to show that **China is massive**, and your electricity calculation reaches *the same scale*.

Coal + gas electricity emissions are so gigantic (12.5 Gt) that they equal the total annual emissions of China — highlighting how crucial electricity decarbonization is.



If the world wants to stay under 1.5 °C:

👉 **Electricity (coal + gas) consumes ~38% of the ENTIRE emissions budget**

👉 Even if EVERYTHING ELSE stopped emitting, electricity alone would push us toward the limit.

If coal and gas stay as they are, the 1.5 °C limit will be violated around ~2045.

The electricity system MUST decarbonize first — otherwise the climate target becomes mathematically impossible.

Coal already uses 18% of the global emissions budget; coal + gas use 24% — and under the 1.5°C budget, they swallow 38%, making decarbonizing electricity absolutely essential.

Comparison of electricity climate change emission to total global climate change emission limit

- The Coal climate change emission was found to be $EM_{CC,Coal}$ = 9.7 Gt CO_2e in 2019
- The global emission limit was around $EM_{CC,\ Global}$ = 53 Gt CO_2e (Fig ES.3 on slide 27)

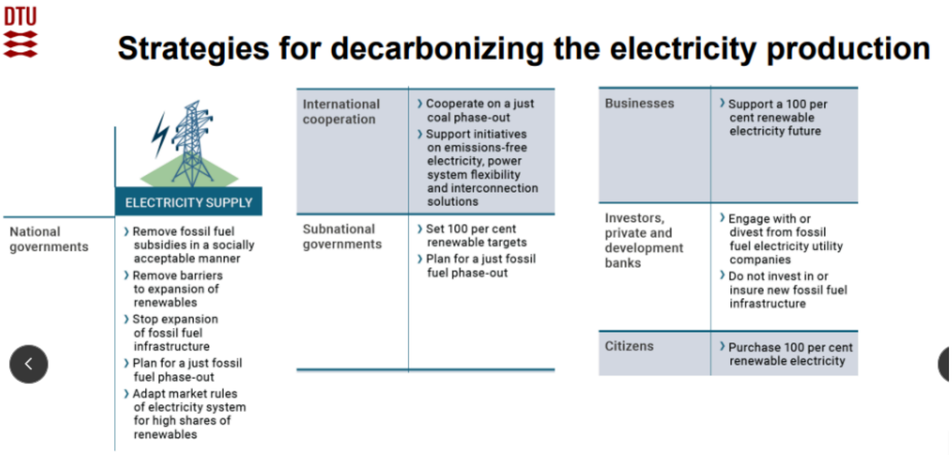
Thus the fraction of the planetary limit from the electricity production based on coal is

$$f_{Coal} = \frac{EM_{CC,Coal}}{EM_{CC,Global}} = \frac{9.7\ Gt\ CO_2e}{53\ Gt\ CO_2e} = 18\ \%$$

And if the emission from electricity production from natural gas is also included then one gets

$$f_{Coal+Gas} = \frac{EM_{CC,Coal} + EM_{CC,Gas}}{EM_{CC,Global}} = \frac{9.7\ Gt\ CO_2e + 2.8\ Gt\ CO_2e}{53\ Gt\ CO_2e} = 24\ \%$$

If the 2030 climate emission target of 1.5 °C is used $EM_{CC,\ Global}$ = 33 Gt CO_2e then $f_{coal\ +\ gas}$ = 38 %, which shows that the electricity production has a large impact on the climate change emissions. Unchanged coal and gas will violate limit around 2045.



Conclusion

- The United National report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources " (2022) provides a baseline reference on the emission expected from the technologies of the electricity mix of countries and regions.
- The electricity mix of different countries and regions can be found from statistical sources (Hannah Ritchie and Pablo Rosado (2020) - "Electricity Mix" Published online at OurWorldInData.org.)
- Impacts from the electricity mix can then be estimated using the reference values and compared to the UN emission gap report in order to understand how close the planetary climate change emission is to the planetary boundary.

The student of the course is encouraged to examine possible decarbonization strategies in the exercise in the following lectures.

Decarbonizing energy systems

How sustainable is Wind Energy?

Wind is good, but not magically perfect.

Issues:

– Material production uses non-green energy

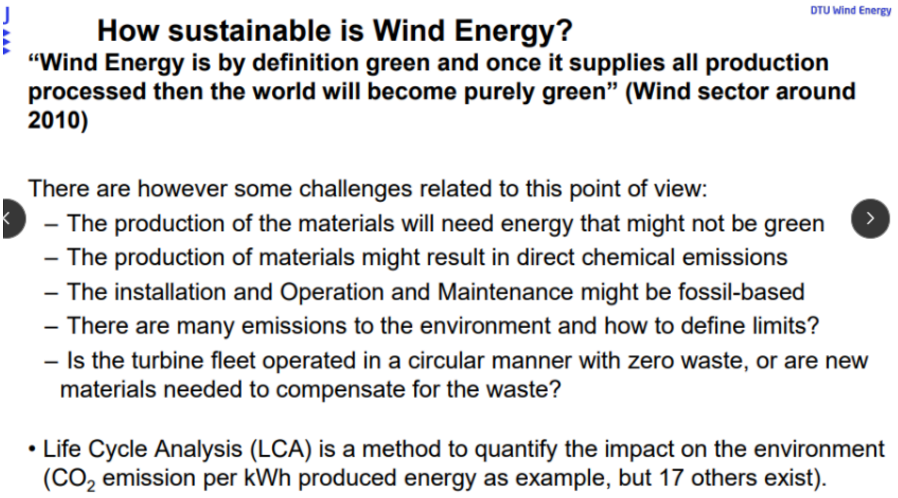
– Chemical emissions from materials

– Installation & O&M may be fossil-based

– Many types of environmental impacts

– Circularity of wind turbines is not yet perfect

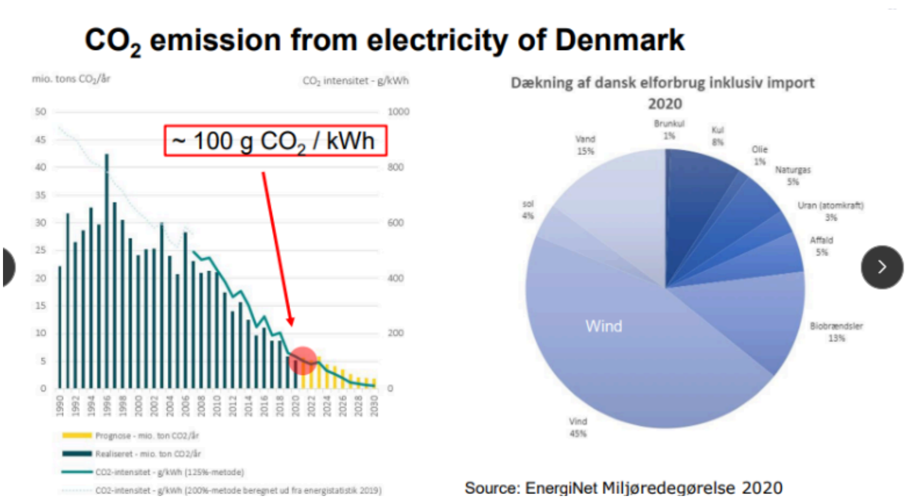
→ LCA is needed to quantify real impacts.



CO_2 emission from electricity of Denmark

Denmark's electricity sits around **~100 g CO_2/kWh**, thanks to a very high wind share.

Shows how wind dramatically lowered national CO_2 intensity.

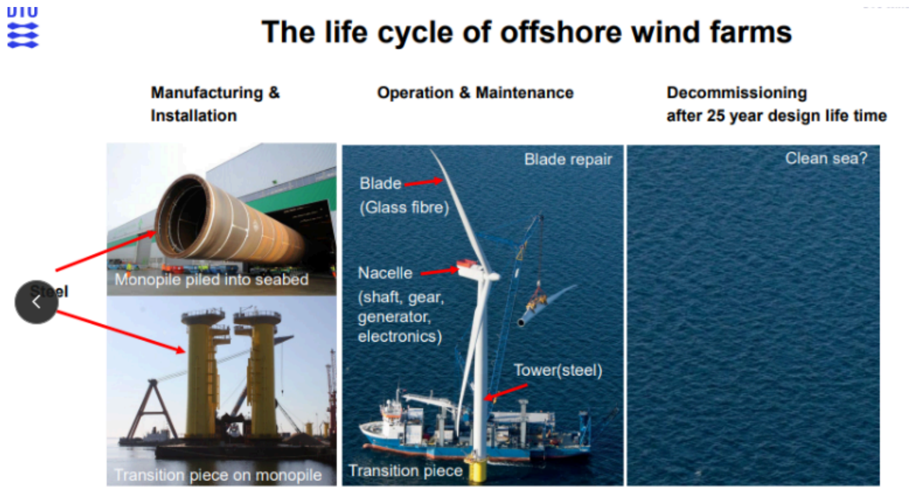


The life cycle of offshore wind farms

Three phases:

Manufacturing & Installation → Operation & Maintenance → Decommissioning (after ~25 years).

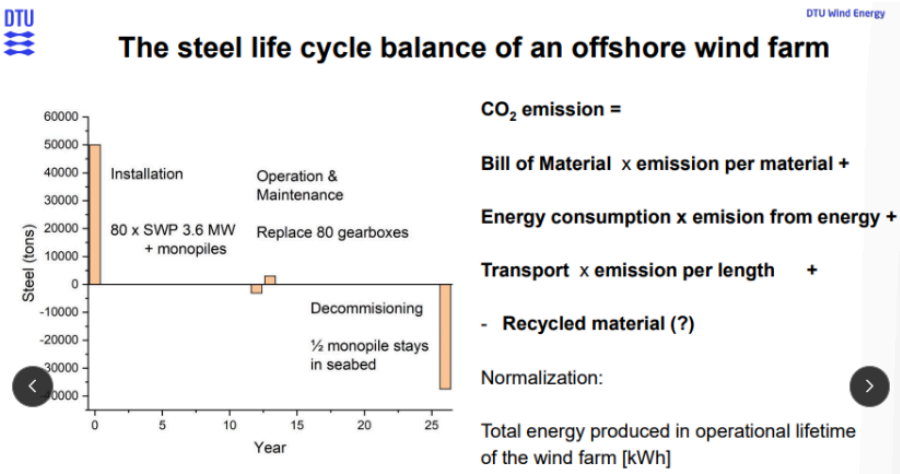
Shows components: monopile, tower, nacelle, blades.



The steel life cycle balance of an offshore wind farm

CO_2 = materials + energy + transport − recycling, normalized by total lifetime energy production.

Shows steel usage over time and its contribution to emissions.



Manufacturing of iron: From mine ore to metal

Explains blast-furnace production of iron with coal at 2000 °C.

Results: **~1.9 t CO_2 per tonne of iron**, plus ~6.8 MWh energy use.

→ Steel is a major CO_2 hotspot in wind turbines.

Blast furnace operating at 2000 °C

$$Fe_2O_3 + 3CO \rightarrow 2Fe(L) + 3CO_2$$

$$C + O_2 \rightarrow 2CO$$

$$2Fe_2O_3 + 3C \rightarrow 4Fe(L) + 3CO_2$$

Burn iron mineral with coal → **Liquid iron + CO_2**

$E = 6.8\ MWh/ton_{Fe}$ **$m_{CO2} = 1.9$ ton CO_2 eq/ton$_{Fe}$**

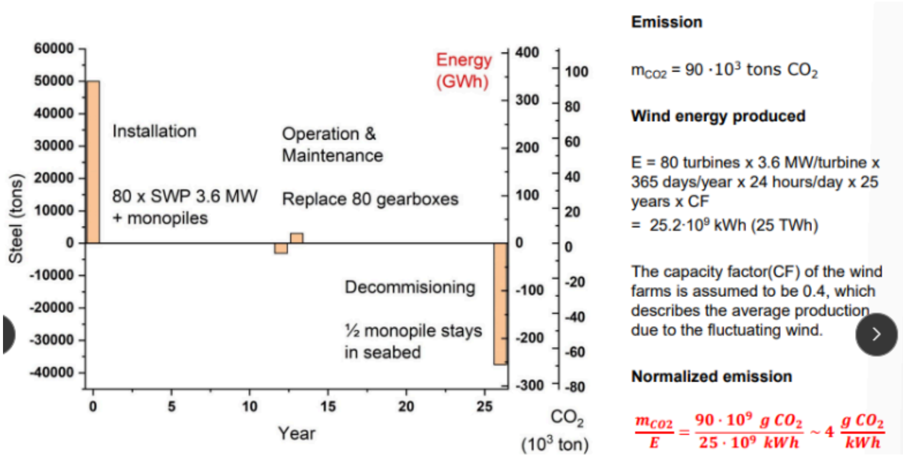
Energy usage and CO_2 emissions due to steel balance

Example farm:

– ~90,000 t CO_2 from steel

– ~25.2 TWh generated over lifetime

Normalized steel contribution: **≈ 4 g CO_2/kWh**.



Onshore turbine emission from LCA studies of Vestas

20 years of LCAs show stable emission levels.

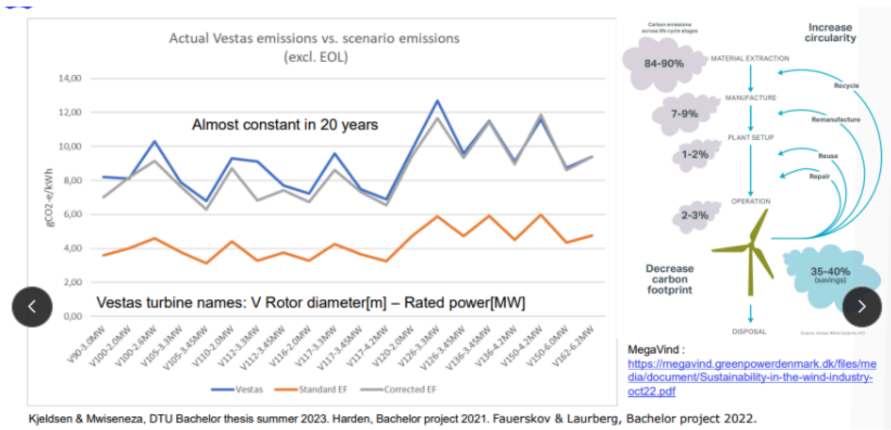
Breakdown:

– Materials = 84–90%

– Transport = 7–9%

– O&M = 2–3%

Circularity improvements could reduce emissions ~35–40%



UN ranking of electricity producing technologies

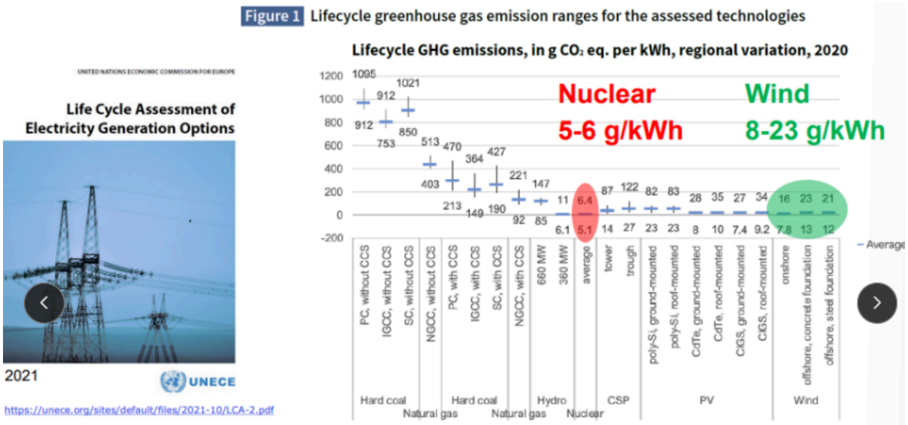
UN LCA comparison:

– **Wind = 8–23 g CO_2/kWh**

– **Nuclear = 5–6 g CO_2/kWh**

Both extremely low.

Coal >1000 g, gas ~400 g, solar ~40 g.

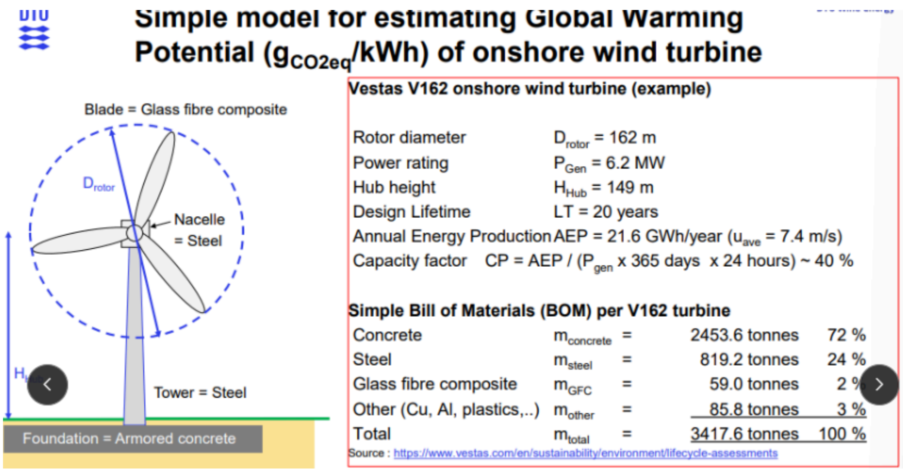


Simple model for estimating Global Warming Potential (gCO_2eq/kWh) of onshore wind turbine

Example: Vestas V162 (6.2 MW).

Specs: Drotor = 162 m, Hub height = 149 m, AEP = 21.6 GWh/year, CF ~40%, lifetime 20 years.

Bill of materials: 72% concrete, 24% steel, 2% glass fibre, 3% other.



Simple model for estimating Global Warming Potential

Uses emission factors:

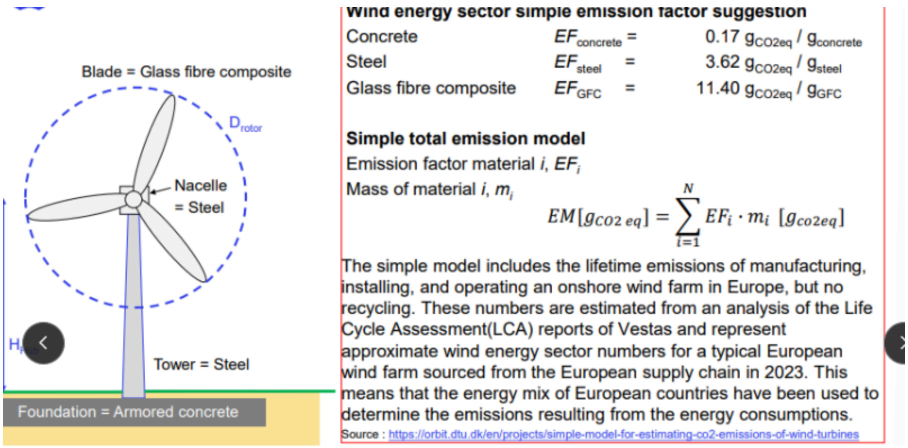
– Concrete: 0.17 g/g

– Steel: 3.62 g/g

– Glass fibre: 11.4 g/g

Equation: Σ(EF × mass).

Covers manufacturing, installation, operation (no recycling).



Simple model for estimating Global Warming Potential (table)

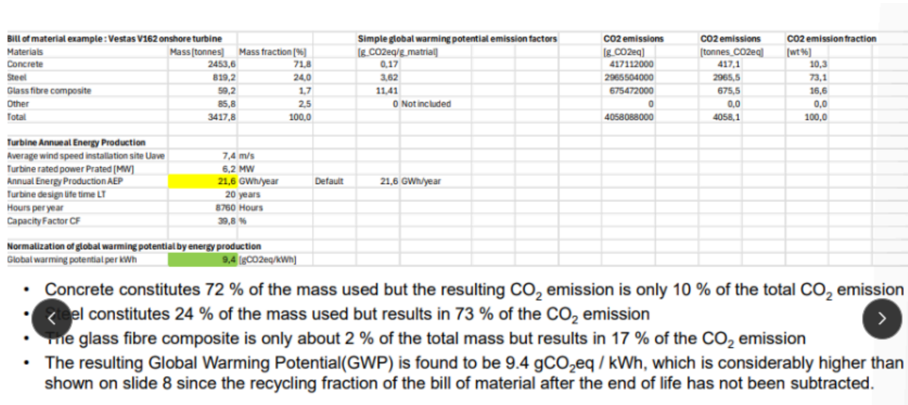
Results:

– Concrete = 10% of CO_2

– Steel = 73%

– Glass fibre = 17%

Final GWP = **9.4 g CO_2/kWh** (higher because recycling not included).



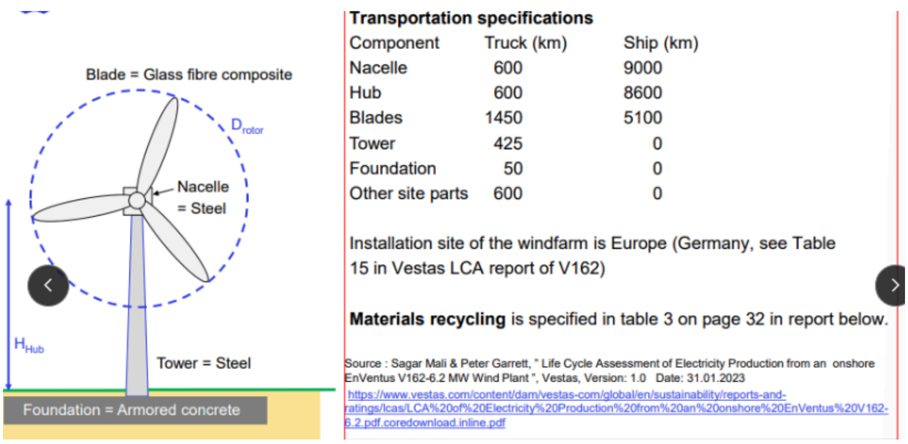
Bill of material example : Vestas V162 onshore turbine				Simple global warming potential emission factors		CO2 emissions	CO2 emissions	CO2 emission fraction
Materials	Mass [tonnes]	Mass fraction [%]		[g_CO2eq/g_matrial]		[g_CO2eq]	[tonnes_CO2eq]	[wt%]
Concrete	2453,6	71,8		0,17		417112000	417,1	10,3
Steel	819,2	24,0		3,62		2965504000	2965,5	73,1
Glass fibre composite	59,2	1,7		11,41		675472000	675,5	16,6
Other	85,8	2,5		0	Not included	0	0,0	0,0
Total	3417,8	100,0				4058088000	4058,1	100,0
Turbine Annueal Energy Production								
Average wind speed installation site Uave	7,4	m/s						
Turbine rated power Prated [MW]	6,2	MW						
Annual Energy Production AEP	21,6	GWh/year	Default	21,6	GWh/year			
Turbine design life time LT	20	years						
Hours per year	8760	Hours						
Capacity Factor CF	39,8	%						
Normalization of global warming potential by energy production								
Global warming potential per kWh	9,4	[gCO2eq/kWh]						

- Concrete constitutes 72 % of the mass used but the resulting CO_2 emission is only 10 % of the total CO_2 emission
- Steel constitutes 24 % of the mass used but results in 73 % of the CO_2 emission
- The glass fibre composite is only about 2 % of the total mass but results in 17 % of the CO_2 emission
- The resulting Global Warming Potential(GWP) is found to be 9.4 gCO_2eq / kWh, which is considerably higher than shown on slide 8 since the recycling fraction of the bill of material after the end of life has not been subtracted.

Transport assumptions in simple GWP model

Lists truck and ship km for nacelle, blades, hub, tower etc.

Based on the official Vestas LCA report.



Simple model for estimating Levelized Cost of Energy of onshore wind turbine electricity production

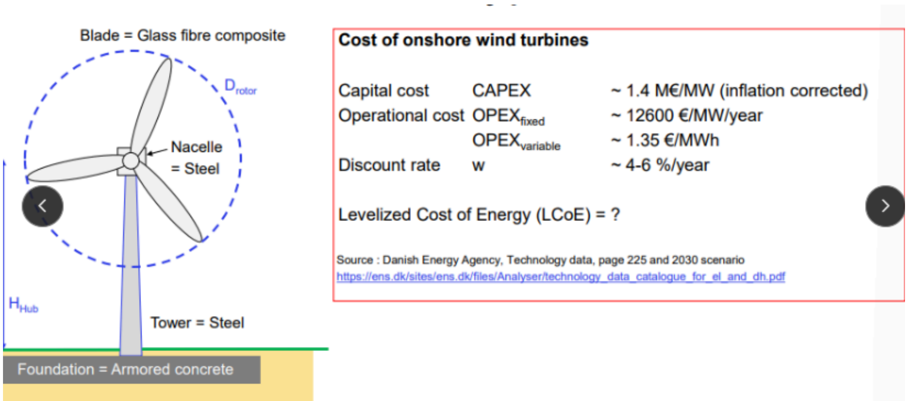
Input values:

– CAPEX ~1.4 M€/MW

– OPEX fixed: 12,600 €/MW/year

– OPEX variable: 1.35 €/MWh

– Discount rate: 4–6%

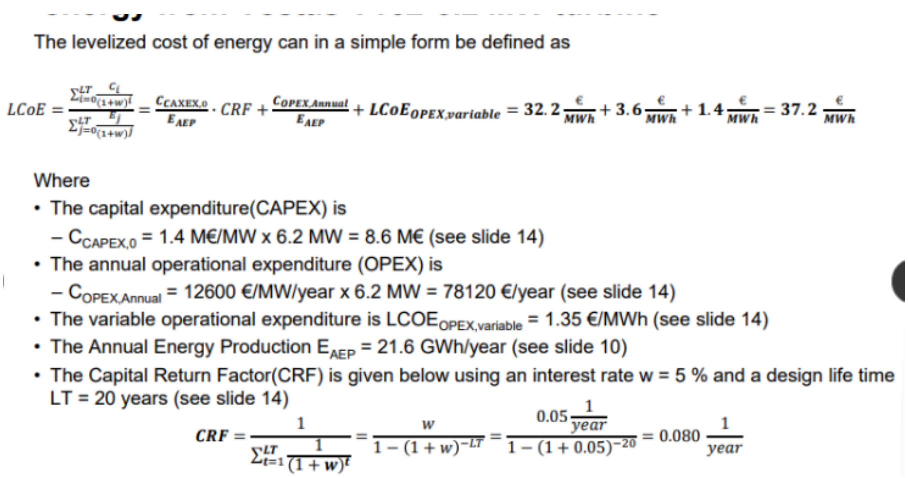


Levelized Cost of Energy estimate of onshore wind energy from Vestas V162-6.2 MW turbine

Using CAPEX 8.6M€, OPEX 78k€/year, AEP 21.6 GWh/year.

Result:

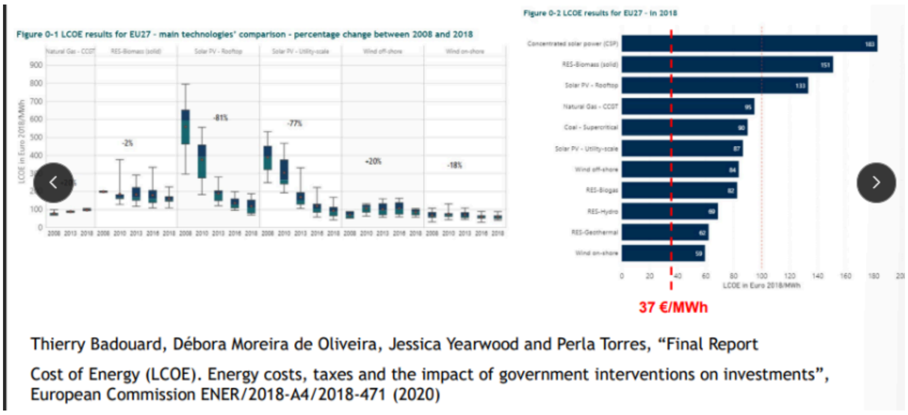
LCoE ≈ 33 €/MWh → extremely competitive.



LCoE levels of electricity sources of Europe

Shows European comparison.

Onshore wind is among the **cheapest sources** (~37 €/MWh), far below fossil fuels.

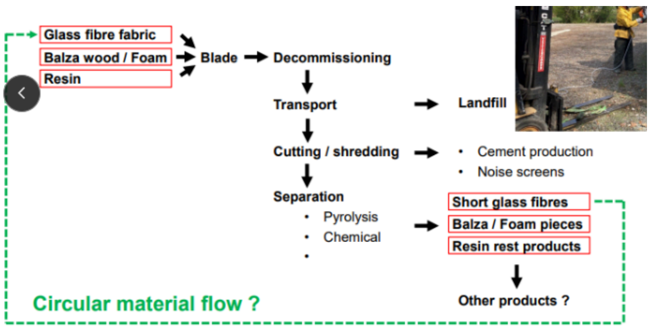


Circularity of wind turbine blades

Describes the difficulty of recycling blades (glass fibre + resin).

Current options: shredding, pyrolysis, cement kilns, noise barriers, chemical separation.

Circularity still limited.



Great news on turbine blade recycling in 2023

DecomBlades + 3B Fibreglass created full blade-to-blade recycling:

Cut → shred → grind → pyrolysis → remelt fibres.

Recycled fibres match the mechanical quality of new fibres.

Conclusion

Main points:

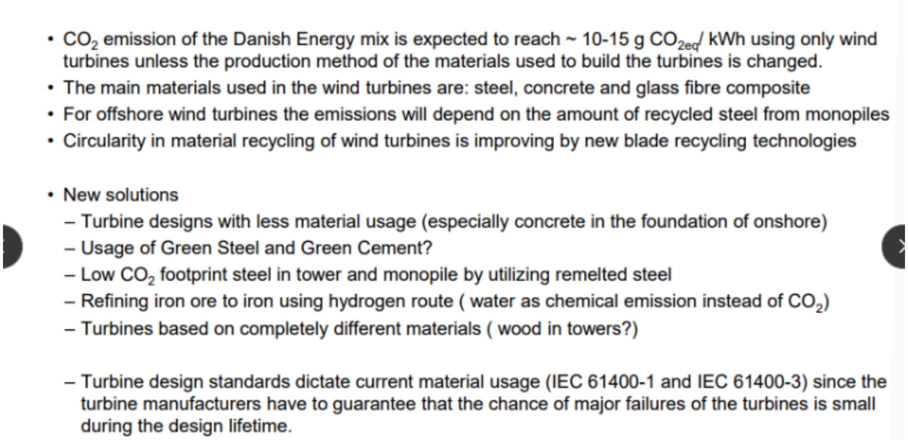
– Danish energy mix could reach **10–15 g CO_2/kWh** with wind alone if materials become greener.

– Steel, concrete, and glass fibre dominate emissions.

– Offshore results depend strongly on monopile steel recycling.

– Circularity is rapidly improving.

– Future improvements: green steel, green cement, new materials (even wood towers).



Violation of planetary boundary of Global Warming Potential due to electricity mix

Violation of planetary boundary of Global
Warming Potential due to electricity mix

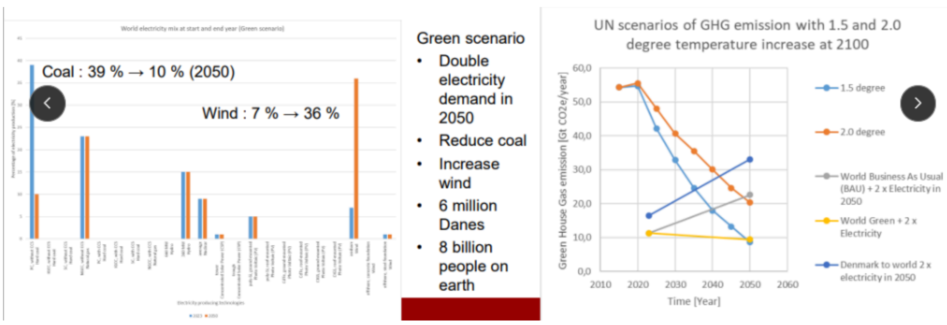
Agenda

Outlines the exact pipeline you're expected to master:

- Types of electricity technologies
- Where emissions come from (LCA logic)
- How to compute **g CO_2/kWh**
- How to scale that to **global emissions**
- How to compare the result with **climate targets / planetary limits**

This structure is basically the exam roadmap.

Violation of planetary boundary of Global Warming Potential due to electricity mix



Translation: Electricity is a major source of CO_2. Depending on how dirty the mix is, it can **push humanity beyond the safe climate boundary**.

1. **Your task** is to compute how much CO_2 the world emits from electricity, based on the **technology mix** (coal, gas, wind, solar, etc.).
2. You then compare that total CO_2 to the **planetary boundary for 1.5 °C** warming (the blue curve).
3. You must **propose a 2050 electricity mix** (like the "green scenario") and check if that future mix still **violates or respects** the climate boundary.
4. The "green scenario" assumes:

- **Electricity demand doubles by 2050**
- **Coal drops from 39% → 10%**
- **Wind increases from 7% → 36%**

5. Then you also take a **country example (e.g., Denmark)** and scale it up to the world to see if it fits inside the 1.5 °C pathway.
6. The right-hand graph shows the **target emissions curves** for 1.5° and 2.0° — these curves tell you if your scenario is safe or violating the boundary.

You compute CO_2 from electricity mixes → compare to the 1.5 °C emission limit → propose a 2050 mix → check if it keeps the world inside the safe climate boundary.

you must be able to do in the "GWP violation" exercise:

1. Calculate CO_2e from an electricity mix

Given a mix of coal, gas, wind, solar, nuclear, etc., compute the **total CO_2e emissions** of that electricity production.

2. Compare those emissions to the 1.5 °C planetary boundary

Use the UN 1.5 °C emissions pathway to check whether the world stays **inside** or **violates** the climate boundary.

3. Propose a 2050 electricity mix and test if it's safe

Build a hypothetical 2050 mix (coal down, renewables up, electricity demand doubled) and see if this future mix still **crosses** the planetary limit.

4. Scale a country example to the world

Take the electricity consumption/emissions of one country (e.g., Denmark), scale it to a world with 8 billion people, and check if **everyone living like that** would violate the 1.5 °C boundary.

You must compute CO_2e from electricity mixes, compare them to the 1.5 °C limit, design a 2050 mix, and scale national scenarios to see if the planet can handle everyone consuming electricity like that.

Overall goal

States clearly:

> "Given an electricity mix, compute CO_2e/kWh, compute global emissions, compare with climate targets."

Translation:

You must be able to take **% coal, % gas, % nuclear, % renewables** → and convert it into **total climate impact**.

Electricity = many technologies

Reminds you that "electricity" is not a single homogeneous thing.

Different technologies → radically different climate profiles.

This is the foundation of everything that comes later.

A simple way to estimate the Global Warming Potential (and other impacts) of the electricity mix of the world is to use the emission factors EF_i provided by the UN report "UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE : "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)" and then determine the weighted average emission factor $EF_{average}$ of the electricity produced by the mix of the technologies with a fraction given as f_i:

$$EF_{average} = \sum_{i=1}^{N} EF_i \cdot f_i$$

Where i is the index of the N different electricity technologies each with a fraction f_i of the electricity mix. Thus the sum over all the fractions f_i must give 1.

The emission of the world E_m is now determined by multiplying the average Emision Factor $EF_{average}$ with the global electricity consumption E:

$$E_m = EF_{average} \cdot E$$

1. Each electricity technology has an emission factor

Coal, gas, wind, solar, nuclear, etc.

These are the $\mathbf{EF_i}$ values (g CO_2/kWh or kg CO_2/kWh).

2. Each technology has a fraction in the mix

Coal maybe 39%, wind 7%, etc.

These are the $\mathbf{f_i}$ values.

All fractions must sum to **1** (100%).

3. Compute the weighted average emission factor

$EF_{\text{average}} = \sum_{i=1}^{N} EF_i \cdot f_i$

This gives the **average CO_2 per kWh** of the entire world's electricity.

4. Multiply by global electricity consumption

If the world consumes **E** (in kWh or TWh), then total emissions are:

$E_m = EF_{\text{average}} \cdot E$

This gives global emissions in **Gt CO_2e per year**.

Take each technology's CO_2 intensity × its share in the mix → sum → multiply by total world electricity → you get the world's total CO_2 emissions from electricity.

Scaling a country electricity production to global impact

The Impact of a country can be writen by the "I = PAT" equation as

$$I_{country} = P_{country} \cdot A \cdot T$$

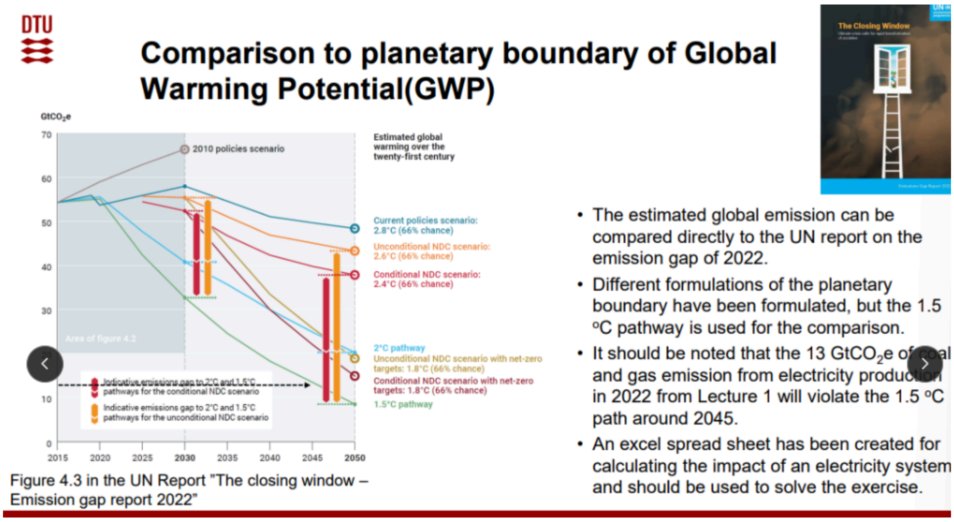
Where

- $I_{country}$ is the impact of the country in terms of CO_2 emission in Gt CO_{2e}/year
- $P_{country}$ in the population of the country in the unit of [persons]
- A is the affluence in terms of energy consumption per citizen per year [kWh/ person / year]
- T is the emission of the technology mix in the unit of [g CO_{2e} / kWh]

This country impact can be scaled to the global impact I_{Global} by multiplying with the ratio of citizens on Earth and in the country

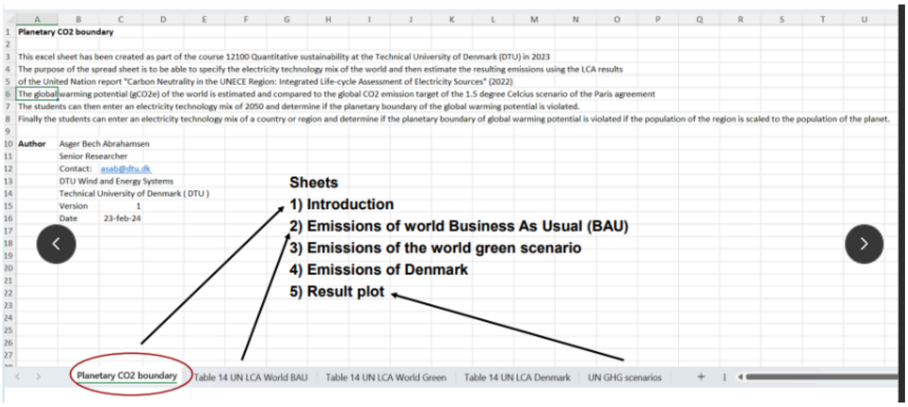
$$I_{Global} = I_{country} \frac{P_{Global}}{P_{country}}$$

where P_{global} is the global population in the units of [persons].

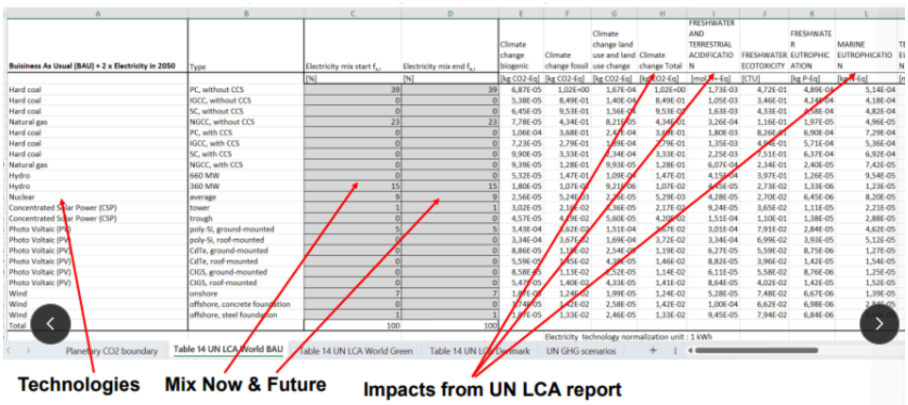


Wind Energy as example

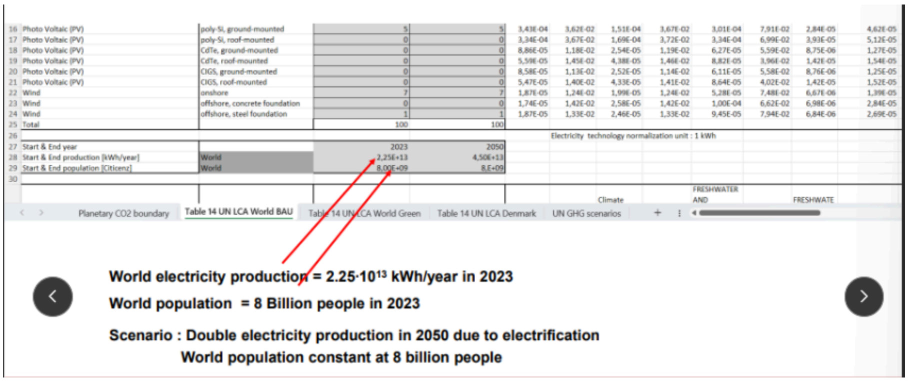
Overview of PlaneraryCO2boundary tool



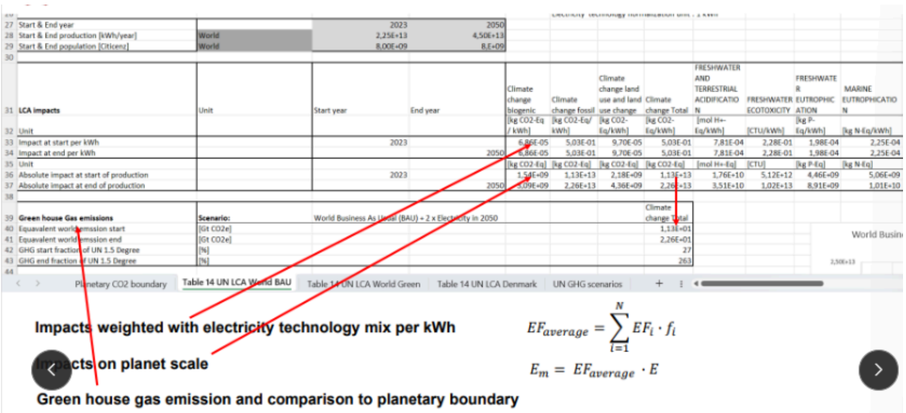
Emission input from UN report on LCA of electricity producing technologies



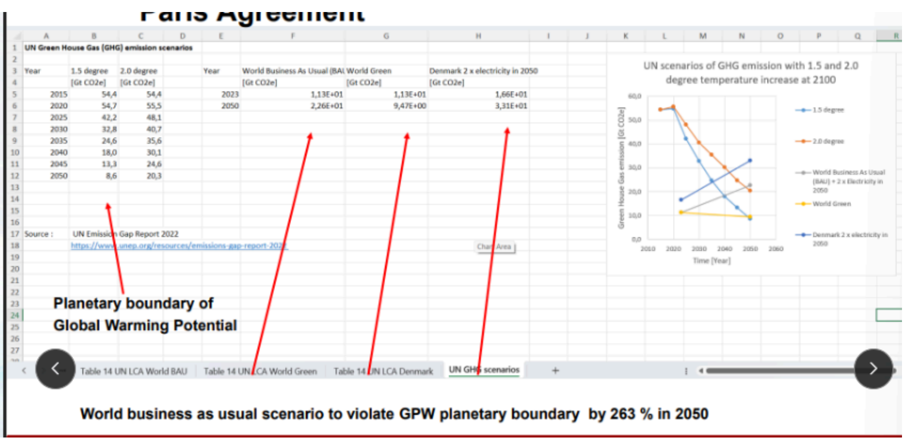
Specification of present and future year, energy production and population



Resulting impacts



Comparison to planetary boundary given by the Paris Agreemen



Scenario : World green mix coal ↓ and onshore wind ↑

World Green	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$	Climate change biogenic
		[%]	[%]	[kg CO2-Eq]
Hard coal	PC, without CCS	39	10	6,87E-05
Hard coal	IGCC, without CCS	0	0	5,38E-05
Hard coal	SC, without CCS	0	0	6,45E-05
Natural gas	NGCC, without CCS	23	23	7,78E-05
Hard coal	PC, with CCS	0	0	1,06E-04
Hard coal	IGCC, with CCS	0	0	7,23E-05
Hard coal	SC, with CCS	0	0	9,90E-05
Natural gas	NGCC, with CCS	0	0	9,39E-05
Hydro	660 MW	0	0	5,32E-05
Hydro	360 MW	15	15	1,80E-05
Nuclear	average	9	9	2,56E-05
Concentrated Solar Power (CSP)	tower	1	1	3,02E-05
Concentrated Solar Power (CSP)	trough	0	0	4,57E-05
Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04
Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04
Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05
Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05
Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05
Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05
Wind	onshore	7	36	1,87E-05
Wind	offshore, concrete foundation	0	0	1,74E-05
Wind	offshore, steel foundation	1	1	1,87E-05
Total		100	100	

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Scenario : World Green double production in 2050 and same population

Start & End year		2023	2050				
Start & End production [kWh/year]	World	2,25E+13	4,50E+13				
Start & End population [Citicenz]	World	8,00E+09	8,E+09				
LCA impacts	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	[kg CO2-Eq/kWh]	[kg CO2-Eq/kWh]
Impact at start per kWh		2023		6,86E-05	5,03E-01	9,70E-05	5,03E-01
Impact at end per kWh			2050	5,41E-05	2,11E-01	5,43E-05	2,11E-01
Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]
Absolute impact at start of production		2023		1,54E+09	1,13E+13	2,18E+09	1,13E+13
Absolute impact at end of production			2050	2,44E+09	9,47E+12	2,44E+09	9,47E+12
Green house Gas emissions	**Scenario:**	World Green					Climate change Total
Equavalent world emssion start	[Gt CO2e]						1,13E+01
Equavalent world emssion end	[Gt CO2e]						9,47E+00
GHG start fraction of UN 1.5 Degree	[%]						27
GHG end fraction of UN 1.5 Degree	[%]						110

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

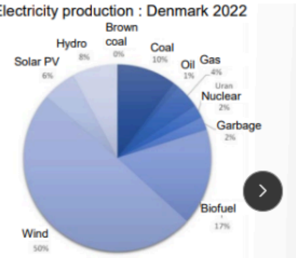
World Green scenario to violate GPW planetary boundary by 110 % in 2050

Region scaled to planet emission : Denmark

Denmark scaled to world	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$
		[%]	[%]
Hard coal	PC, without CCS	30,0	30,0
Hard coal	IGCC, without CCS	0,0	0,0
Hard coal	SC, without CCS	0,0	0,0
Natural gas	NGCC, without CCS	4,0	4,0
Hard coal	PC, with CCS	0,0	0,0
Hard coal	IGCC, with CCS	0,0	0,0
Hard coal	SC, with CCS	0,0	0,0
Natural gas	NGCC, with CCS	0,0	0,0
Hydro	660 MW	8,0	8,0
Hydro	360 MW	0,0	0,0
Nuclear	average	2,0	2,0
Concentrated Solar Power (CSP)	tower	0,0	0,0
Concentrated Solar Power (CSP)	trough	0,0	0,0
Photo Voltaic (PV)	poly-Si, ground-mounted	6,0	6,0
Photo Voltaic (PV)	poly-Si, roof-mounted	0,0	0,0
Photo Voltaic (PV)	CdTe, ground-mounted	0,0	0,0
Photo Voltaic (PV)	CdTe, roof-mounted	0,0	0,0
Photo Voltaic (PV)	CIGS, ground-mounted	0,0	0,0
Photo Voltaic (PV)	CIGS, roof-mounted	0,0	0,0
Wind	onshore	27,5	27,5
Wind	offshore, concrete foundation	0,0	0,0
Wind	offshore, steel foundation	22,5	22,5
Total		100,0	100,0

Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

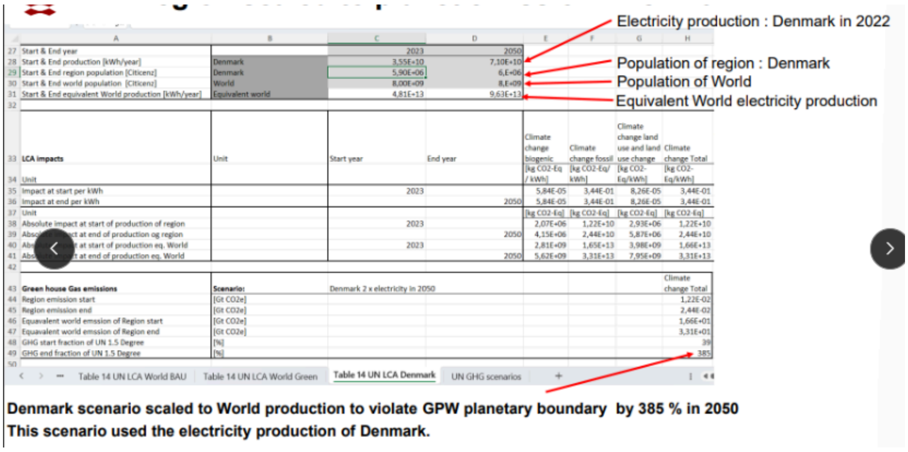
Electricity production : Denmark 2022



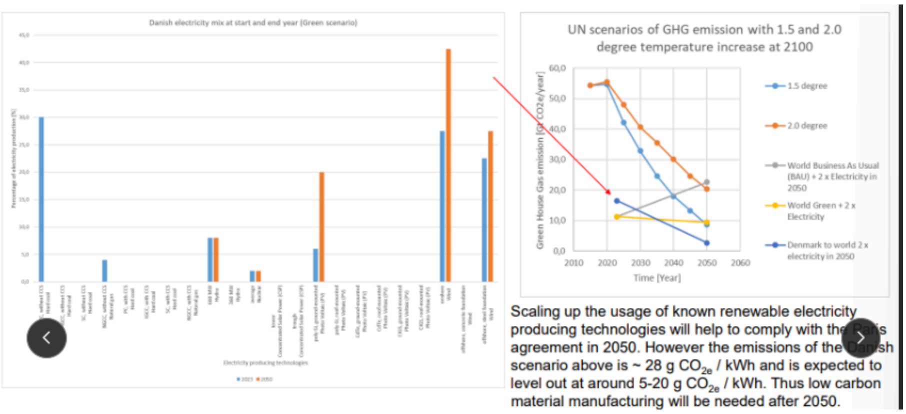
Source: Energi.net "Miljø redegørelse 2022

Denmark scenario is to keep the technology mix and double production in 2050

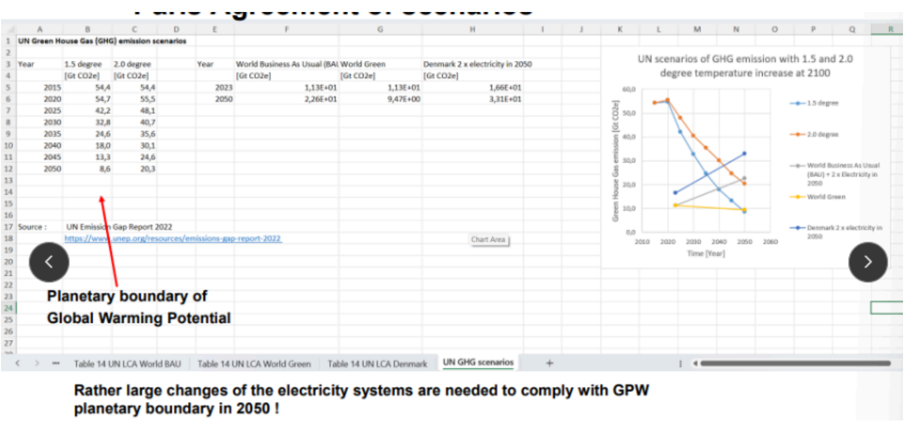
Region scaled to planet emission : Denmark



Result example of green Denmark scaled to planet impact



Comparison to planetary boundary given by the Paris Agreement of scenarios



Exercise for all student

Exercise for all students

- Select the World Green scenario and change the technology mix to what you believe is the best strategy for the green transition. Does it comply with the planetary boundary of the global warming potential?

- Select a region (Europe, ..) or country of interest and find the electricity technology mix. Enter this into the sheet "Table 14 UN LCA Denmark". Find the electricity production of the region or country and also the population and enter this in the tool. Will this country violate the planetary boundary for global warming potential if the electricity production is doubled in 2050? And how do you suggest changing the technology mix in order to comply with the planetary boundary of GWP?

Learning objectives of decarbonizing the energy system — Summary

This slide tells you *exactly* what you're expected to know and be able to do after this module:

1. Know the technologies

You must describe the major electricity-producing technologies worldwide (coal, gas, nuclear, wind, solar, hydro, biomass, etc.).

2. Know where CO_2 comes from

You must explain how electricity units emit CO_2 — mainly from fuel combustion or from materials/manufacturing for renewables.

3. Know country differences

You must recognize and describe how electricity mixes differ between countries (e.g., France = nuclear, Denmark = wind, China = coal-heavy).

4. Calculate CO_2 per kWh

You must be able to compute the CO_2 intensity of an electricity mix using weighted averages of emission factors.

5. Discuss future emissions + decarbonization

You must discuss how emissions could evolve in the future and which strategies (renewables, CCS, nuclear, flexibility, grids) can lower emissions.

6. Discuss additional required technologies

You must identify extra system technologies: grid expansion, energy storage, demand response, sector coupling, etc.

7. Analyse a country vs UN scenarios

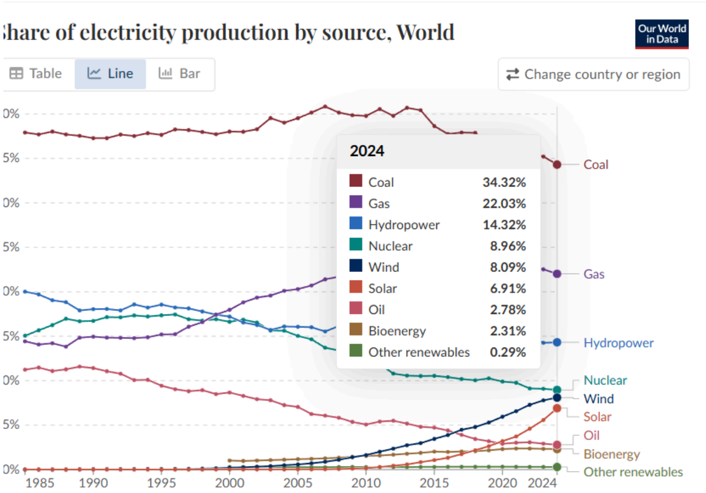
You must analyse a country's CO_2 emissions and compare them with UN climate pathways (1.5°C / 2.0°C).

8. Decide if the planetary boundary is violated

You must evaluate whether a given electricity mix is compatible with — or violates — the CO_2 limit required to stay within the planetary boundary (1.5°C).

Essence in one sentence:

You must understand electricity technologies, calculate their CO_2, compare mixes to global climate limits, and judge whether a system is inside or outside the 1.5°C boundary.



EXERCISE - HAND CALCULATION 75% COAL WITHOUT CCS + 25% ONSHORE WIND

DTU

Example of calculating world CO_2 emission from coal, gas, nuclear and hydro power

- The electricity production from coal, gas, nuclear and hydro power in 2019 is
  - E_{Coal} ~ 9500 TWh, E_{Gas} ~ 6500 TWh, $E_{Nuclear}$ ~ 2800 TWh & E_{Hydro} ~ 4000 TWh (Fig 2 in slide 26)
- And the climate change total emission factors with no Carbon Capture and Storage are
  - $EF_{Climate\ change,\ Coal}$ ~ 1.02 kg CO_2e / kWh
  - $EF_{Climate\ change,\ Gas}$ ~ 0.434 kg CO_2e / kWh
  - $EF_{Climate\ change,\ Nuclear}$ ~ $5.29 \cdot 10^{-3}$ kg CO_2e / kWh
  - $EF_{Climate\ change,\ Hydro}$ ~ $1.07 \cdot 10^{-2}$ kg CO_2e / kWh (Table 14 in slide 24)
- The resulting Climate Change (CO_2e) emission then becomes
  - $EM_{Climate\ change,\ Coal} = EF_{Climate\ change,\ Coal} \times E_{coal}$ = 1.02 kg CO_2e / kWh x $9500 \cdot 10^9$ kWh = $9.7 \cdot 10^{12}$ kg CO_2e = 9.7 Gt CO_2e
  - $EM_{CC,\ Gas} = EF_{CC,\ Gas} \times E_{gas}$ = 0.434 kg CO_2e / kWh x $6500 \cdot 10^9$ kWh = $2.8 \cdot 10^{12}$ kg CO_2e = 2.8 Gt CO_2e
  - $EM_{CC,\ Nuclear} = EF_{CC,\ Nuclear} \times E_{Nuclear}$ = $5.29 \cdot 10^{-3}$ kg CO_2e / kWh x $2800 \cdot 10^9$ kWh = $1.5 \cdot 10^{10}$ kg CO_2e = 0.02 Gt CO_2e
  - $EM_{CC,\ Hydro} = EF_{CC,\ Hydro} \times E_{Hydro}$ = $1.07 \cdot 10^{-2}$ kg CO_2e / kWh x $4000 \cdot 10^9$ kWh = $4.3 \cdot 10^{10}$ kg CO_2e = 0.04 Gt CO_2e
- Thus the CO_2 emission from nuclear and hydro is only about 0.6 % of the coal emission.

The unit Giga-ton(Gt) is the same as 10^9 ton

$1\ \text{Gt} = 10^9 \cdot 10^3\ \text{kg}$
$= 10^{12}\ \text{kg}$

1. Values you should use (GIVEN)

Emission factors (climate change total, NO CCS):

- Coal (hard coal, pulverized, without CCS):
  $EF_{\text{coal}} = 1.02 \text{ kg CO}_2\text{e/kWh}$ ($\approx$ $1020 \text{ g CO}_2\text{e/kWh}$)
- Onshore wind:
  $EF_{\text{wind}} = 0.0124 \text{ kg CO}_2\text{e/kWh}$ ($\approx$ $12.4 \text{ g CO}_2\text{e/kWh}$)

World electricity production (from the lecture/exercise):

- 2024:
  $TWhE_{2024} = 26908 \text{ TWh}$
- 2050 scenario (2× electricity):
  $TWhE_{2050} = 2 \times 26908 = 53816 \text{ TWh}$

Remember:
$1\ TWh = 109\ kWh$

2. Formula for the mix emission factor - Weighted average emission factor

Fractions: (GIVEN)
$f_{\text{coal}} = 0.75, \quad f_{\text{wind}} = 0.25$
Weighted average emission factor:
$EF_{mix} = \sum EFi \cdot fi$
$EF_{\text{mix}} = f_{\text{coal}}\, EF_{\text{coal}} + f_{\text{wind}}\, EF_{\text{wind}}$
Plug in numbers:

$$\begin{aligned} EF_{\text{mix}} &= 0.75 \cdot 1.02 + 0.25 \cdot 0.0124 \\ &= 0.765 + 0.0031 \\ &\approx 0.7681 \text{ kg CO}_2\text{e/kWh} \end{aligned}$$

So your mix has:
$EF_{\text{mix}} \approx 0.768 \text{ kg CO}_2\text{e/kWh} = 768 \text{ g CO}_2\text{e/kWh}$

3. Total world emissions for this mix (2024)

Step 1 – Convert electricity to kWh

For **2050 with 2× electricity**:

$$\begin{aligned} E_{2050} &= 53816 \text{ TWh} \\ &= 53816 \times 10^9 \text{ kWh} \\ &= 5.3816 \times 10^{13} \text{ kWh} \end{aligned}$$

Step 2 – Multiply by EF_mix

$$\begin{aligned} EM_{\text{world,2050}} &= EF_{\text{mix}} \cdot E_{2050} \\ &= 0.7681 \frac{\text{kg}}{\text{kWh}} \times 2.6908 \times 10^{13} \text{ kWh} \\ &\approx 2.07 \times 10^{13} \text{ kg CO}_2\text{e} \end{aligned}$$

Step 3 – Convert kg → Gt

$\text{Gt} = 10^{12} \text{ kg}$
$EM_{\text{mix,2024}} \approx \frac{2.07 \times 10^{13}}{10^{12}} \approx 20.7 \text{ Gt CO}_2\text{e/year}$

4. FINAL (RESUMO)

Emission from coal (75%):
$EM_{\text{coal}} = EF_{\text{coal}} \cdot (f_{\text{coal}} \cdot E_{\text{world}})$
$= 1.02 \cdot (0.75 \cdot 2.6908 \times 10^{13})$
$= 2.059 \times 10^{13} \text{ kg CO}_2\text{e} = 20.6 \text{kg CO}_2\text{e}$

Emission from wind (25%):

$EM_{\text{wind}} = EF_{\text{wind}} \cdot (f_{\text{wind}} \cdot E_{\text{world}})$
$= 0.0124 \cdot (0.25 \cdot 2.6908 \times 10^{13})$
$= 8.35 \times 10^{10} \text{ kg CO}_2\text{e} = 0.0835 \text{ Gt CO}_2\text{e}$

Total world CO_2:

$EM_{\text{total}} = 20.6 + 0.0835 \approx 20.7 \text{ Gt CO}_2\text{e}$

(Optional) Same mix with *current* electricity (2024)

Just change EEE:
$E_{2024} = 26908 \times 10^9 = 2.6908 \times 10^{13} \text{ kWh}$
$EM_{\text{world,2024}} = 0.7681 \times 2.6908 \times 10^{13} \approx 2.07 \times 10^{13} \text{ kg} \approx 20.7 \text{ Gt CO}_2\text{e/year}$

Compare with the 1.5 °C boundary (if they ask)

Typical 1.5 °C **global emissions allowance** often used in the slides:

- 2030 target: $\approx 33 \text{ Gt CO}_2\text{e/year} \approx 33 GtCO_2e/year$

Your 2050 scenario: **41.3 Gt**.
Fraction of the budget:
$\frac{41.3}{33} \approx 1.25 \Rightarrow 125\%$
So: **75% coal + 25% wind with 2× electricity demand clearly violates the 1.5 °C boundary.**

Buisiness As Usual (BAU) + 2 x Electricity in 2050	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
		[%]	[%]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]
Hard coal	PC, without CCS	36	75	6,87E-05	1,02E+00	1,67E-04	1,02E+00
Hard coal	IGCC, without CCS	0	0	5,38E-05	8,49E-01	1,40E-04	8,49E-01
Hard coal	SC, without CCS	0	0	6,45E-05	9,53E-01	1,56E-04	9,53E-01
Natural gas	NGCC, without CCS	25	0	7,78E-05	4,34E-01	8,21E-05	4,34E-01
Hard coal	PC, with CCS	0	0	1,06E-04	3,68E-01	2,47E-04	3,69E-01
Hard coal	IGCC, with CCS	0	0	7,23E-05	2,79E-01	1,89E-04	2,79E-01
Hard coal	SC, with CCS	0	0	9,90E-05	3,33E-01	2,34E-04	3,33E-01
Natural gas	NGCC, with CCS	0	0	9,39E-05	1,28E-01	9,93E-05	1,28E-01
Hydro	660 MW	0	0	5,32E-05	1,47E-01	1,09E-04	1,47E-01
Hydro	360 MW	14	0	1,80E-05	1,07E-02	9,21E-06	1,07E-02
Nuclear	average	8	0	2,56E-05	5,24E-03	2,26E-05	5,29E-03
Concentrated Solar Power (CSP)	tower	1	0	3,02E-05	2,16E-02	3,36E-05	2,17E-02
Concentrated Solar Power (CSP)	trough	0	0	4,57E-05	4,19E-02	5,60E-05	4,20E-02
Photo Voltaic (PV)	poly-Si, ground-mounted	7	0	3,43E-04	3,62E-02	1,51E-04	3,67E-02
Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	3,67E-02	1,69E-04	3,72E-02
Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	1,18E-02	2,54E-05	1,19E-02
Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	1,45E-02	4,38E-05	1,46E-02
Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	1,13E-02	2,52E-05	1,14E-02
Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	1,40E-02	4,33E-05	1,41E-02
Wind	onshore	8	25	1,87E-05	1,24E-02	1,99E-05	1,24E-02
Wind	offshore, concrete foundation	0	0	1,74E-05	1,42E-02	2,58E-05	1,42E-02
Wind	offshore, steel foundation	1	0	1,87E-05	1,33E-02	2,46E-05	1,33E-02
Total		100	100				
					Electricity technology normalization unit :		
Start & End year		2024	2050				
Start & End production [kWh/year]	World	2,25E+13	4,50E+13				
Start & End population [Citicenz]	World	8,00E+09	8,E+09				

LCA impacts	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	CO2-Eq/kWh]	[kg CO2-Eq/kWh]
Impact at start per kWh		2024		7,47E-05	4,81E-01	9,65E-05	4,82E-01
Impact at end per kWh			2050	5,62E-05	7,68E-01	1,30E-04	7,68E-01
Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]
Absolute impact at start of production		2024		1,68E+09	1,08E+13	2,17E+09	1,08E+13
Absolute impact at end of production			2050	2,53E+09	3,46E+13	5,86E+09	3,46E+13

Green house Gas emissions	Scenario:	World Business As Usual (BAU) + 2 x Electricity in 2050					Climate change Total
Equavalent world emssion start	[Gt CO2e]						1,08E+01
Equavalent world emssion end	[Gt CO2e]						3,46E+01
GHG start fraction of UN 1.5 Degree	[%]						26
GHG end fraction of UN 1.5 Degree	[%]						402

12: Sustainable Transition

Date	@November 25, 2025
Status	Done

Studies before teaching session:

Watch video lectures:

Video lecture: Sustainability transitions

Video lecture: Pathways and interventions, Systemic sustainabilty transitions

Teaching session:

We will walk through the exercises together: Exercise: Sustainability transitions - system dynamics.

1. We will do the first one together.
2. You will move to the 2nd one on your own.
3. We debrief exercise 2.

After teaching sessions:

1. Short videos where I walk you through the browser-based software and I walk you through the first exercise in details are available for reviewing.

Sustainability transitions

Quantitative Sustainability framework contain many different indicators

This slide shows how sustainability is inherently multi-indicator and multi-stage.

Environmental, economic, social, resource, circularity, and transition indicators all map onto different life-cycle stages (extraction, manufacturing, use, disposal).

It highlights that a single sustainability analysis merges many dimensions, and that different modules of the course correspond to different indicator categories.

Results must be interpreted and evaluated

When interpreting outcomes, you must check:

• Which assumptions are the most sensitive or uncertain.

• Which data points are most uncertain and whether they can be improved.

• What parts of the life-cycle were excluded and how much that might distort results.

• Whether all sustainability dimensions were addressed or if omissions can be defended.

Interpretation is not passive; it requires critical assessment of data quality, scope and gaps.

(Flowchart slide)

This slide (adapted from Hauschild et al.) shows a formal decision-logic for interpreting LCA/LCSA output:

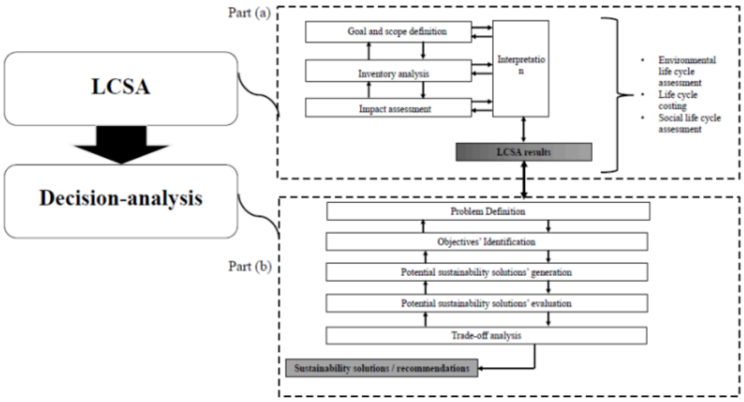
• First assess whether a dataset is influential.

• If uncertainty is high, determine whether representativeness or accuracy can be improved.

• If precision is insufficient, revise the study goal or revisit the modelling.

• If acceptable, conclusions can be formulated.

It standardizes how to judge whether results are robust enough to support decisions.



*Sustainability **2018**, 10, 3863; doi:10.3390/su10113863*

Results must be interpreted and evaluated

When interpreting results, two things matter above all: **assumptions/uncertainties** and **completeness**.

Assumptions and uncertainties

You need to examine:

• Which assumptions in your model are the most sensitive or uncertain.

• Which datasets carry the highest uncertainty, and whether you can strengthen or update them.

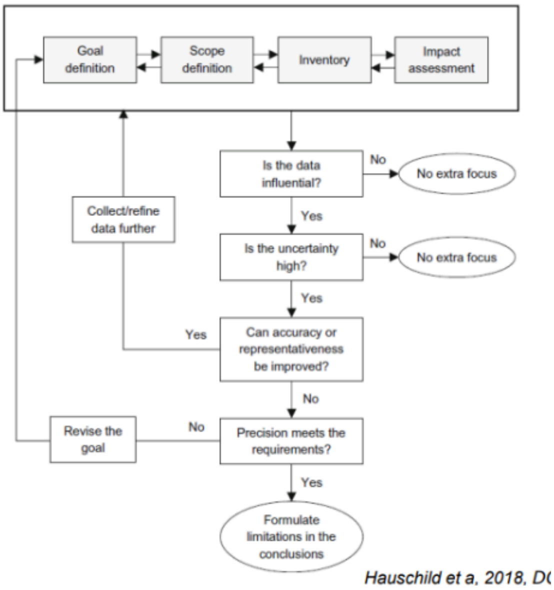
Completeness

You must assess:

• Which life-cycle stages were excluded and how much that could influence the outcome.

• Whether all relevant sustainability dimensions and aspects were considered — and, if not, whether you can justify the omissions.

	Life Cycle Stage					
Sustainability Impact area	Extraction of raw materials	Manufacturing stage	Use stage	Disposal stage	Measured by:	Covered in module
Resources					Use of biotic and abiotic resources	4, DAVLU
					Circular economy indicators	8, TMcA
Environment					Climate change, Carbon footprint	3, OJOLL
					Absolute boundaries	7, MZHA
Economic					Life Cycle Costs	5, KAMORR
Social/Health					Socioeconomic impacts	6, KAMORR, OJOLL
					Health impacts	
Transition					Interpretation System dynamics	9, ASAB 10, DAVLU, SIOL



Ecolabels provide visual decision support – EPDs provide more in depth information

Ecolabels (e.g., Nordic Swan, EU Ecolabel) are quick, visual, consumer-friendly tools that summarise sustainability performance.

EPDs (Environmental Product Declarations) offer detailed, quantitative, phase-specific environmental impacts (upstream, core, downstream).

The message: **visual labels support fast decisions**, while **EPDs support technical, in-depth evaluation**.

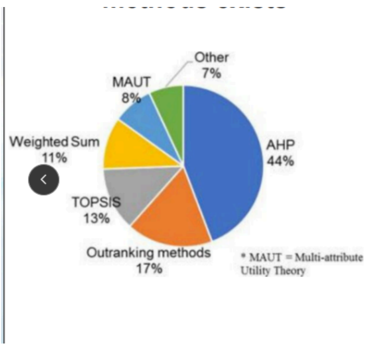
Many different Multi criteria decision analysis methods exists

This slide compares a range of MCDA methods such as AHP, TOPSIS, MAUT, ELECTRE, PROMETHEE, weighted sum, etc.

It shows differences in:

- Their ability to handle trade-offs.
- The strength of sustainability ranking.
- Whether qualitative data can be included.
- Whether methods support direct comparisons of alternatives.

There's no one-size-fits-all: the "best" method depends on the decision context.



	Compensatory (weak sustainability) or potentially non-compensatory (strong sustainability)	Potential to generate aggregated score(s)	Potential to use for single product studies (without need for comparisons)	… inputs as such (without transformation to semi-quantitative inputs)
SAW	weak	yes	yes	no
AHP	weak	yes	yes	yes
MAVT/MAUT	weak	yes	yes	no
TOPSIS	weak	yes	no	yes
ELECTRE	potentially strong	yes	no	no
PROMETHEE	potentially strong	yes	no	no
VIKOR	weak	yes	no	no
MODM	weak	no	no	yes
DEA	potentially strong	yes	no	no
LCS Dashboard	potentially strong	yes	yes	no
SEEBalance	potentially strong	yes	yes	no
PEF normalization and weighting	weak	yes	yes	no
Distance to target weighting	weak	yes	yes	no
Monetary weighting	weak	yes	yes	yes

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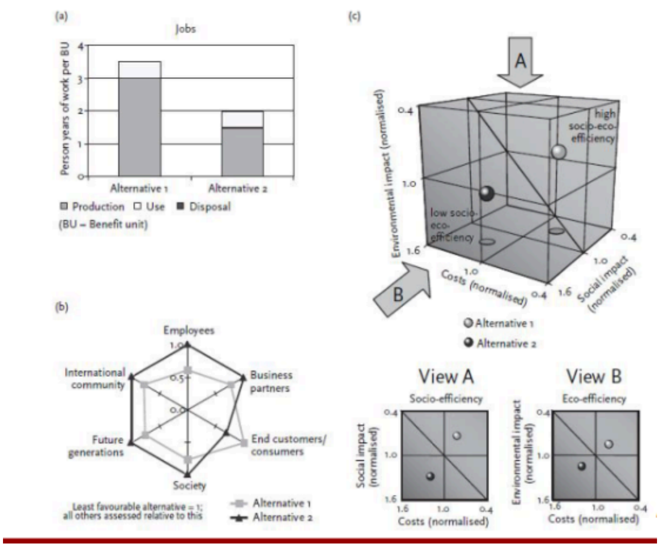
Visualizations can provide overview

This slide shows examples of diagrams (bar charts, 3D cubes, two-axis plots) to demonstrate that visualization helps make multidimensional sustainability indicators digestible.

These visuals allow quick identification of differences between alternatives across environmental, economic, and social dimensions.

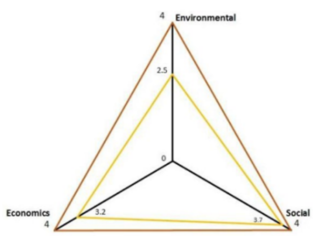


Three sided triangle still requires aggregation within each dimension

The sustainability triangle (environment–economy–social) simplifies the comparison but hides internal complexity.

Each vertex still represents multiple aggregated indicators.

Conclusion: the triangle is intuitive but insufficient for deeper evaluation.

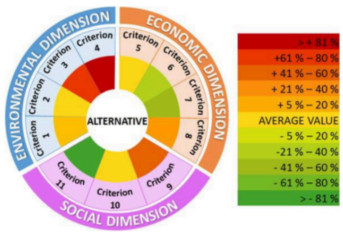


Sustainability crowns compare several indicators within each dimension

The “crown” visualization compares multiple criteria inside the environmental, economic, and social pillars.

Color coding compresses performance into a gradient, supporting nuanced comparison without losing multidimensional structure.

More informative than the triangle because it exposes internal variation.

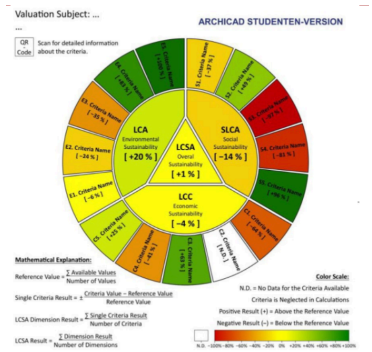


LCSA wheel fulfils all comparison criteria

The LCSA wheel integrates LCA, SLCA and LCC into a single clear visual.

It shows deviations from reference values, making the multidimensional comparison explicit and balanced.

This visualization meets all comparison criteria: clarity, integrability, transparency and multidimensionality.



Summary

Key conclusions:

• Visualizations = strong for overview and communication.

• MCDA = strong for structured guidance in decision problems.

• Interpretation must assess assumptions, uncertainties, and completeness.

• Choice of decision-support depends on study goal/scope and the data available.

Pathways and interventions

1. What sustainability transitions actually are

What does sustainability transition mean?

- Systemic interventions to
  - Sustain acceptable outcomes on the three dimensions of sustainability
  - Change the system currently in unacceptable state
- Applies to all scales:
  - Manufacturing system
  - Resource exploitation system
  - Socioecological system

Sustainability transitions refer to **systemic changes** designed to:

1. Restore or maintain acceptable levels of environmental, social, and economic outcomes.
2. Shift systems that are currently in an *undesirable* state toward a *desirable* one.

These transitions apply at any scale:

• Manufacturing systems

• Resource extraction systems

• Entire socio-ecological systems

Transitions are not linear improvements — they require understanding **system structure, feedbacks, thresholds, and resilience**.

---

2. System perspectives: understanding what a "system" includes

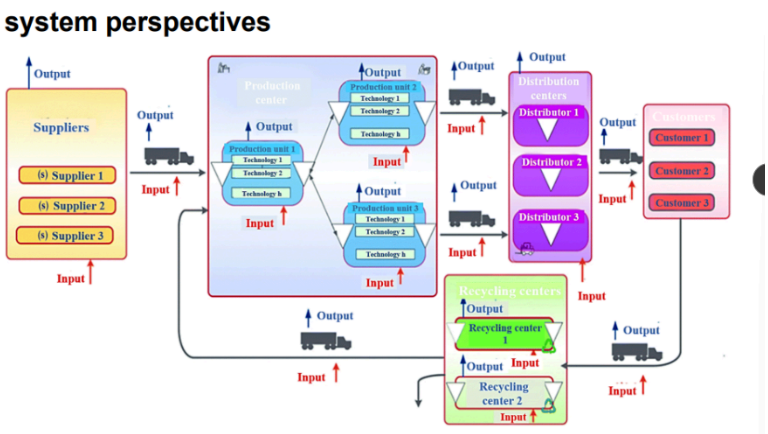
2.1 Technical / industrial systems

The diagram (p.19) shows a full supply chain:

• Suppliers → production centers → distribution → customers → recycling loops.

Each node has its own **inputs, outputs, technologies**, and feedbacks.

Understanding such a map is crucial because interventions in one part of the system (e.g., supplier efficiency) cascade downstream.



2.2 Socio-ecological systems (SES)

Slide with tourists–operators–wildlife–governance (p.20):

SES contains humans + nature + institutions.

Dynamics include:

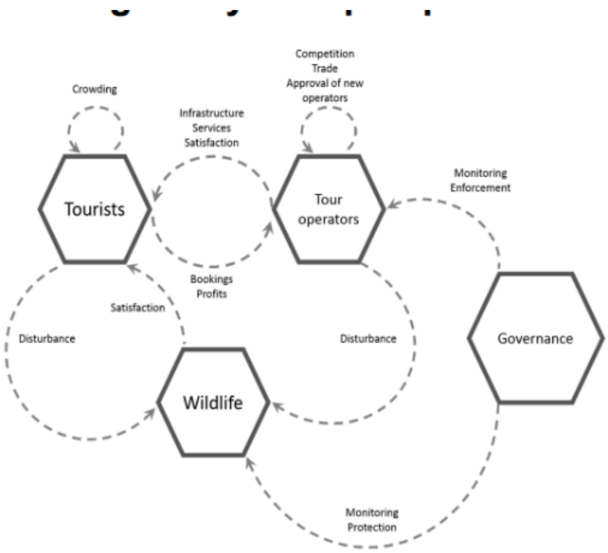
• Tourist behavior (demand, crowding)

• Wildlife sensitivity (disturbance, protection)

• Operator incentives (profit, competition)

• Governance (rules, monitoring, sanctions)

This shows why sustainability depends on **interactions**, not isolated elements.



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3. System dynamics → multi-state systems

Systems are rarely stable in one single "equilibrium."

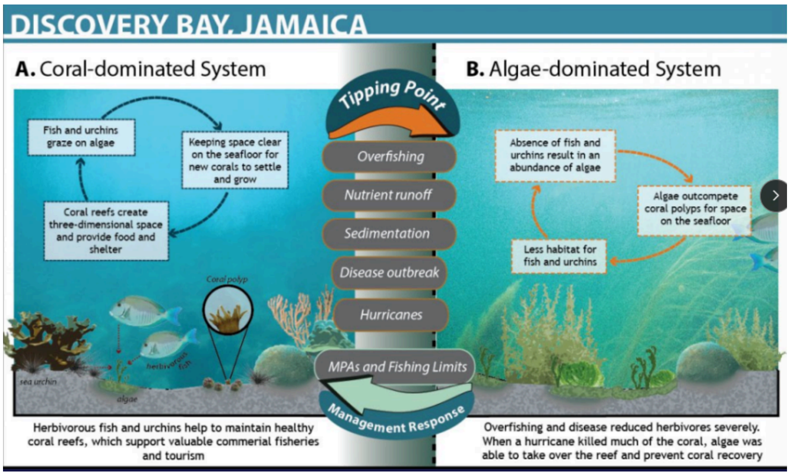
They behave like landscapes with multiple valleys (states). A system can:

• Sit in a stable valley (“attractor”)

• Be pushed into another valley after shocks

• Transition gradually or abruptly

This is why sustainability transitions can be sudden or irreversible.



4. Tipping points & regime shifts (critical concept)

Slide: **Discovery Bay Jamaica — coral vs algae dominated system**

Illustrates a classic tipping point:

Coral state → algae state

Drivers include:

• Overfishing

• Nutrient runoff

• Sedimentation

• Disease

• Hurricanes

Once corals collapse, the system **does not simply recover** when pressure is removed.

This is due to **hysteresis**.

5. Hysteresis

Hysteresis = system state depends on **history**, not only current conditions.

Example: coral reefs

• You may need *much stronger interventions* to push the system *back* to coral-dominance than the interventions that caused the collapse.

Implications:

• Sustainability transitions require understanding that **recovery ≠ reversal**.

• “Undoing” damage is often harder.

6. Discontinuities in state shift

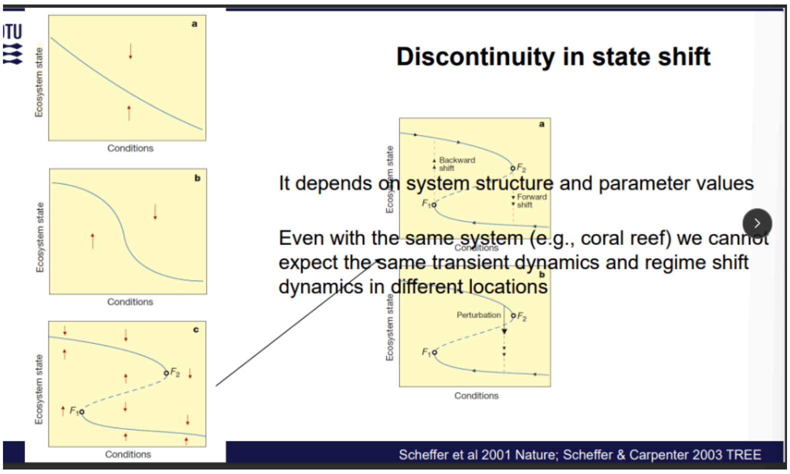
From Scheffer et al. (p.24):

Even if conditions move smoothly, system response can jump abruptly.

Key insights:

• Same type of system (e.g., coral reef) behaves differently depending on **parameter values**, **local feedbacks**, **initial conditions**.

• You cannot copy-paste solutions across locations.



7. Early warning signals

As a system approaches a tipping point:

1. **Loss of resilience**

   The system recovers more slowly from disturbances.

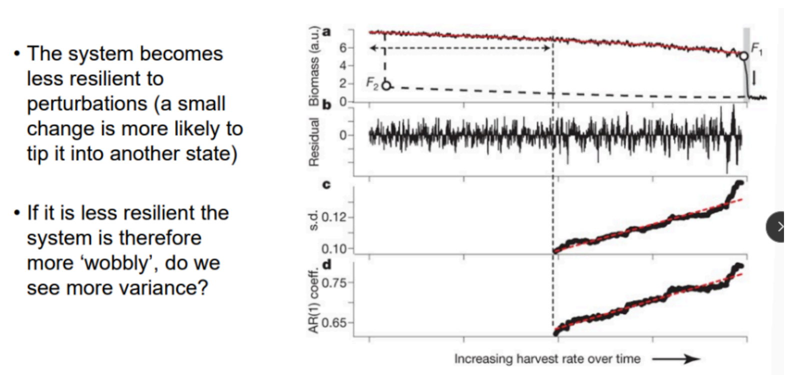
2. **Increased variance**

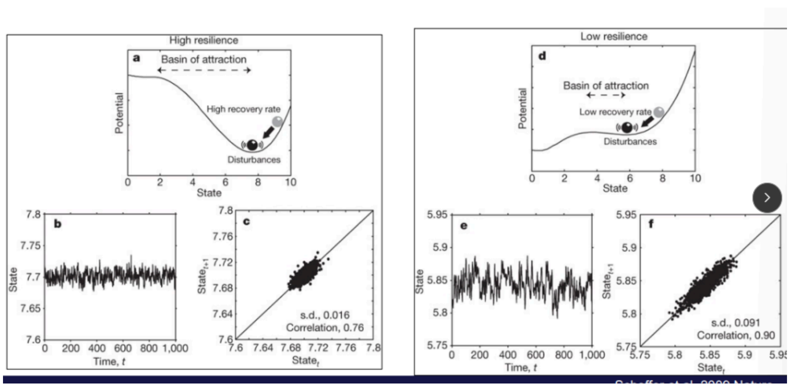
   The system becomes “wobbly.”

3. **Rising autocorrelation (AR1)**

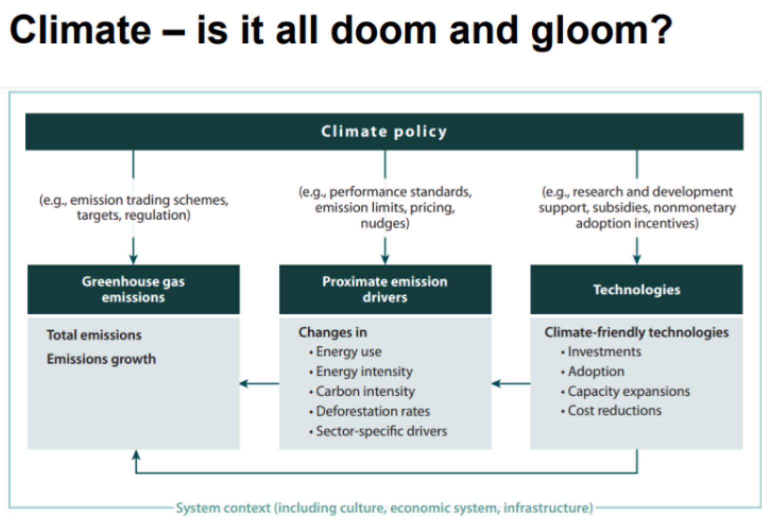
   The system’s current state becomes more dependent on its previous state — classic early-warning metric.

These metrics allow forecasting possible regime shifts.





8. Interventions — how to shift systems



Three categories:

8.1 Economic interventions

(Carrot and stick)

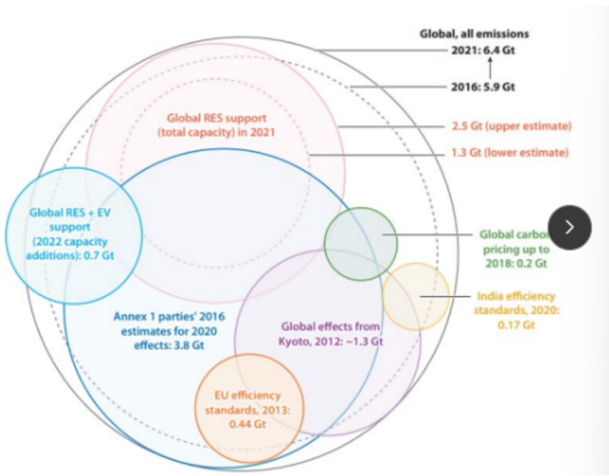
• Pricing

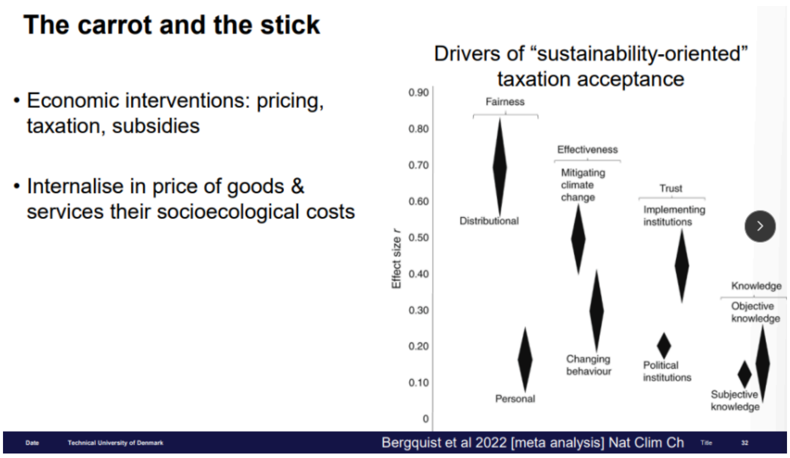
• Taxes

• Subsidies

Aim: internalize socio-ecological costs into market signals.

Key point: acceptance of sustainability taxes depends on values, fairness perception, and trust (Bergquist et al. 2022).





Value creation

- There is public demand for 'more sustainable' goods & services
- A market creating opportunities (value creation)
- n.b. data showing the sustainable 'value' of goods & services is therefore valuable

8.2 Behavioural interventions

- Habit change

• Information signals

• Social norms

• Nudging

Nudging example:

• UK plastic bag levy → ~80% reduction in bag usage

• Increasing the fee years later was needed to "re-shock" the system

• Behavioural effects decay over time → nudges must evolve

8.3 Governance interventions

Systems are shaped by rules, institutions, and enforcement.

Governance tools include:

• Regulations

• Co-management structures

• Cap-and-trade mechanisms

• Hybrid governance (public-private partnerships)

Governance influences:

• Responsibility distribution

• Compliance

• Monitoring

• Incentives for sustainable behaviour

---

9. Climate policy: is it all doom?

From Hoppe et al. 2023:

The most impactful intervention to date is **policy support for renewable energy deployment**.

Renewables rise not because markets "naturally" chose them, but because of **policy**.

---

10. Value creation & sustainable markets

There is real consumer demand for more sustainable goods.

This creates:

• Business opportunities

• Incentives to innovate

• Strategic importance of communicating "sustainable value"

Data on sustainability performance becomes economically valuable because it shapes consumer and regulatory decisions.

---

11. Nudging — deeper details

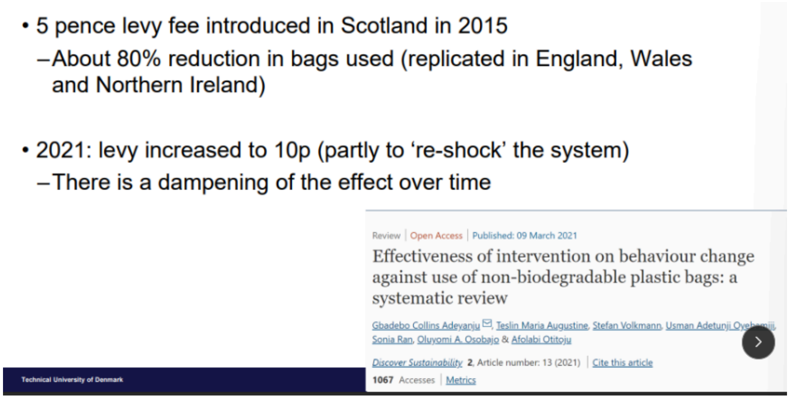
Nudging meta-analysis (p.36):

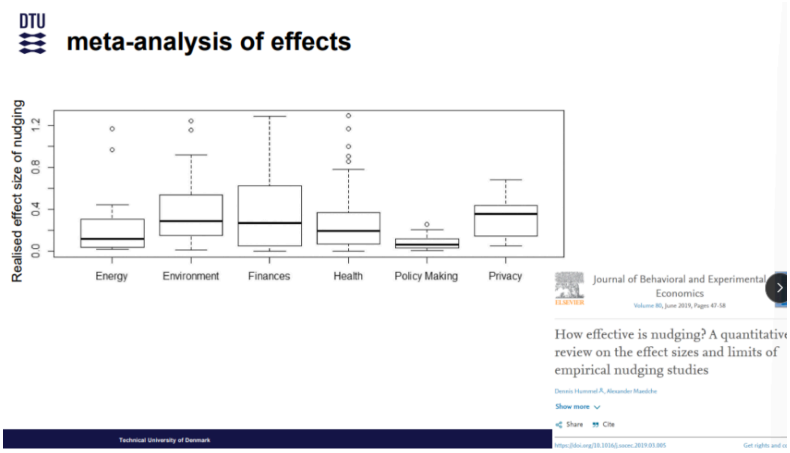
• Nudges generally work, but effect sizes vary

• Many nudges lose impact over time

• Effectiveness depends heavily on context, design, and cognitive load

Nudging is a **support tool**, not a standalone transition pathway.





12. Methods → How we study transitions

12.1 From SES map to system dynamics

We aim to understand:

- System state
- Transient dynamics
- Drivers of change
- Potential tipping points

12.2 Deterministic system dynamics

Based on ergodic theory:

- ODEs or PDEs describing feedbacks and flows

• Causal loop diagrams

• Bayesian Belief Networks

Used when structure is well understood.

12.3 Stochastic modelling

Necessary when:

• System behaviour is uncertain

• Interactions are too complex

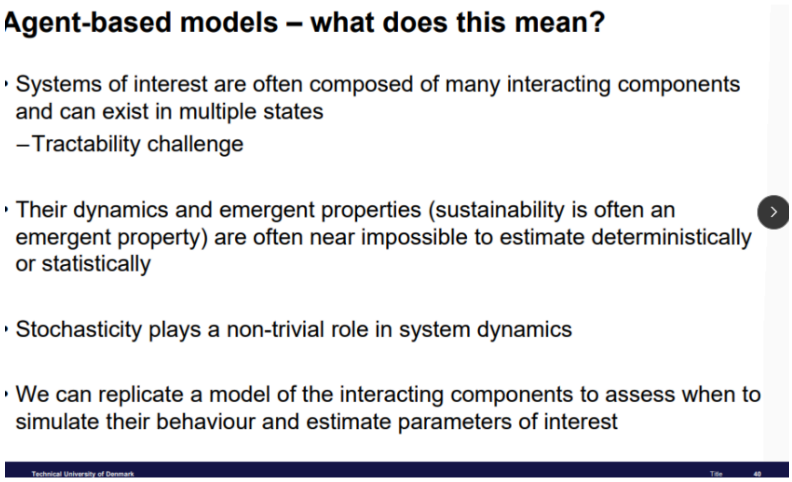
• Emergence cannot be predicted analytically

Tools:

• Agent-based models (ABM)

• Multi-agent simulations

These allow exploration of “what-if” policy and behavioural scenarios.



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13. Agent-Based Models (ABM)

ABM simulates individuals (agents) interacting under rules.

Useful for sustainability because:

• Systems have many interacting parts

• Behaviour is emergent (not predictable from averages)

• Stochasticity matters

• Feedbacks create non-linear outcomes

ABM can evaluate how policies, behaviours, or governance structures change collective outcomes.

---

14. Case Study: Wildlife Tourism SES (very detailed section in slides)

14.1 Operators

Operators move in space → wildlife encounters depend on distribution.

Key mechanics:

• Correlated random walks

• Encounter probability

• Time spent with animals ~ Weibull distribution

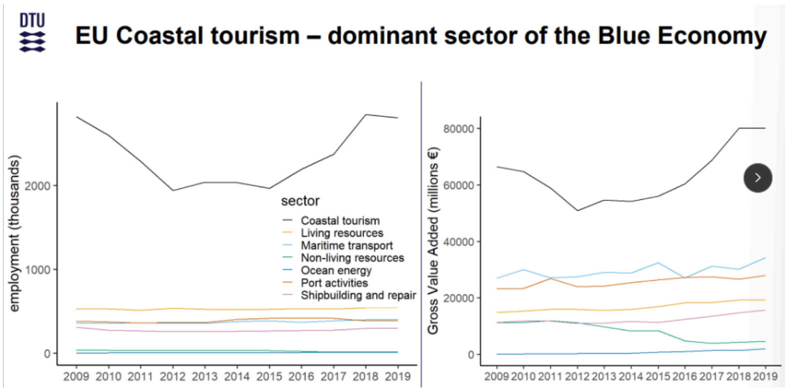
• Quotas allocated yearly

• Behavioural phenotypes: optimist, pessimist, trustful, envious

• Ratings depend on tourist satisfaction

Enforcement example:

- "Tradeable Wildlife Allowances"
- Defection → fine of 1000 units
- Prices depend on supply/demand
- Reinforcement learning through profit history
- Retirement after 3 years of zero profit



14.2 Tourists

Large population (1M sampled daily) with:

- Income classes (high/mid/low) influencing willingness to pay
- Specialist vs generalist scenarios
- Seasonal demand
- Satisfaction depends on wildlife encounter quality

Tourist behaviour influences system sustainability.

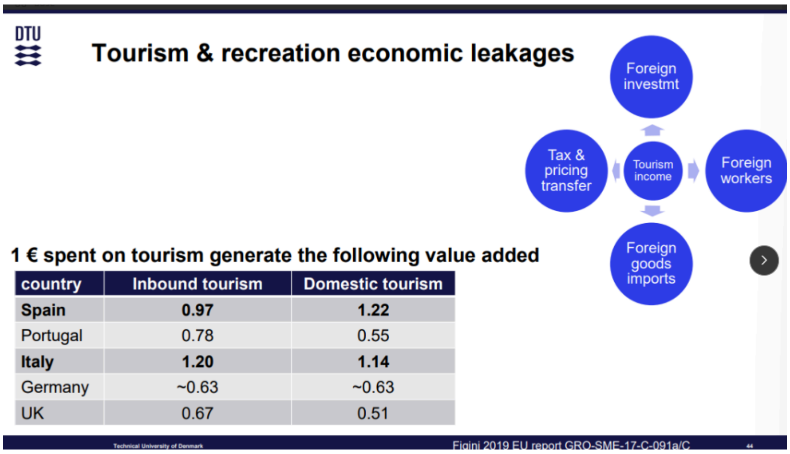
Tourism & Recreation Biodiversity Footprint

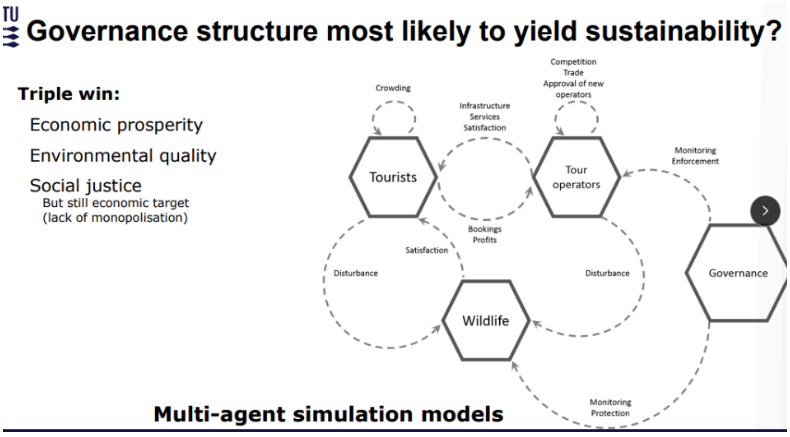
Threats	all	marine
Habitat modification	6,491	1,569
Disturbance	4,291	1,097
Both	**8,836**	1,757
Total species assessed	147,517	17,081
Proportion of assessed	6%	10%

14.3 Company lifespan & monopolisation

Simulations show:

- High monopolisation → lower sustainability
- Turnover patterns depend on demand and governance
- Sustainable governance reduces monopolistic risk





15. Governance models

Evaluated structures include:

• Free market

• Regulations

• Hybrid models (e.g., cap-and-trade, co-management)

Criteria considered:

• Responsibility allocation

• Monitoring

• Uncertainty

• Behavioural compliance

• Economic competition

Result: **Hybrid public–private governance** creates the widest "sustainable space."

Tour operator component

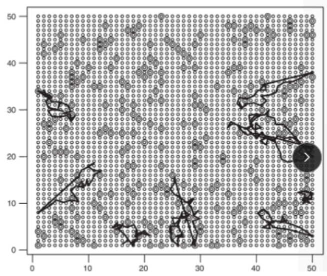
- At each tour, correlated random walk in the 'study area'
- Discrete grid: encounter overlap wildlife/operator
- Encounter duration: Weibull distribution

- Each year, operators are assigned a sustainable quota (delivered or not depending on management scheme)

- Each operator run one tour per day run if enough bookings are obtained

- Encounter dependent on $p_{encounter}$, duration dependent on max_y (/365 days). Decision: cooperate and adhere to maximum encounter duration or not
  - Phenotypes: optimist, pessimist, trustful or envious

- Rating dependent on tourist satisfaction



Tour operator component

- Tradeable Wildlife Allowance – TWA: When a tour operator at the end of the day has spent all the time they were allowed with the animals, they will try to buy some extra TWA from tour operators that did not spend much of their allowed time.

- If a defecting tour operator is detected, 1000 money units are subtracted from their profits
  - A ticket is about 30 units).

- At the end of the year
  - the tour operators also decide on investments for the next year.
    - infrastructure or services
  - Update ticket price – function of demand:supply ratio.
  - If profits= for 3 years the operator retires.
  - New tour operators can start every year or every 6 years (scenarios)

Tourists component

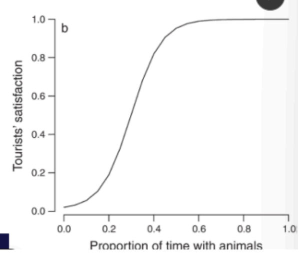
- A tourist population (1,000,000) is sampled every day and visitors try to book tours

- Scenario: specialists, generalists, mixed

- 3 income groups influencing willingness to pay
  - High income (10% of the total population) N(60,1.30)
  - Middle income N(45,3.5)
  - Low income N(30,1.5)

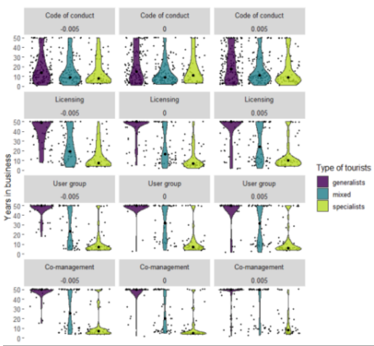
- Satisfaction dependent on time spent with animals

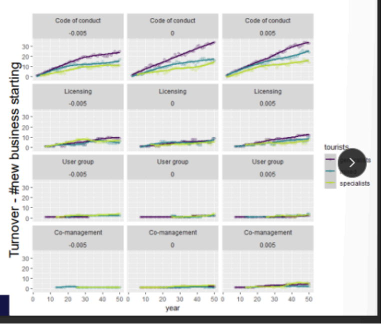
- Seasonal and annual trends in daily numbers

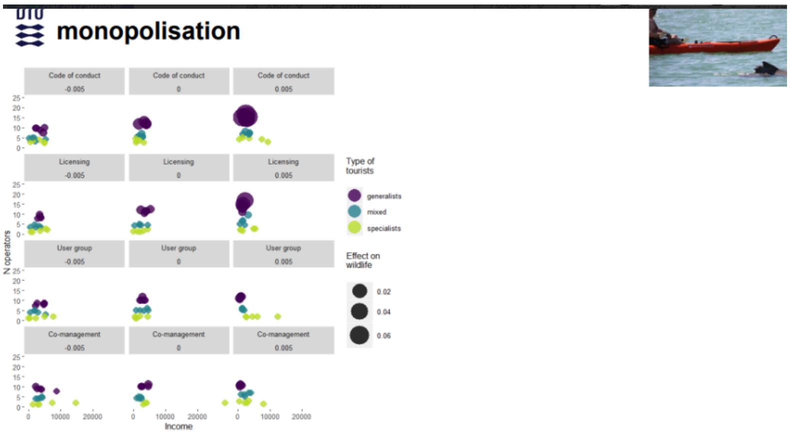


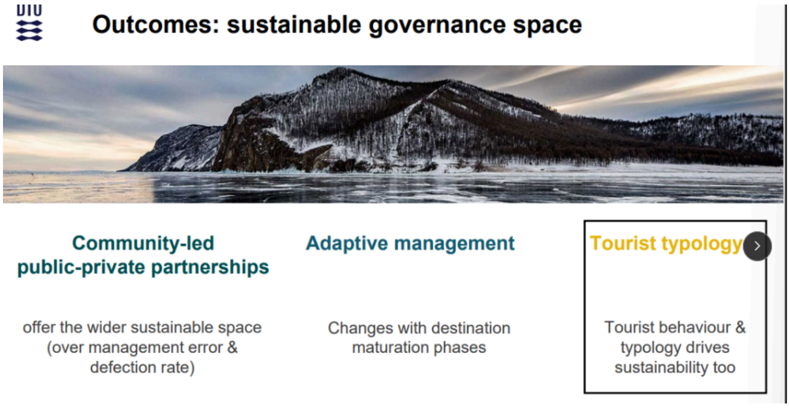
Technical University of Denmark

Companies lifespan









16. Final outcomes

Community-led public-private partnerships + adaptive management deliver:

• Economic prosperity

• Social fairness

• Environmental quality

BUT:

Sustainability is **context-dependent**:

• The same intervention does not guarantee the same result in another system.

• Parameter values, history, feedbacks, behaviour → everything matters.

17. Final summary

- Systemic interventions can reshape how societies use the planet.

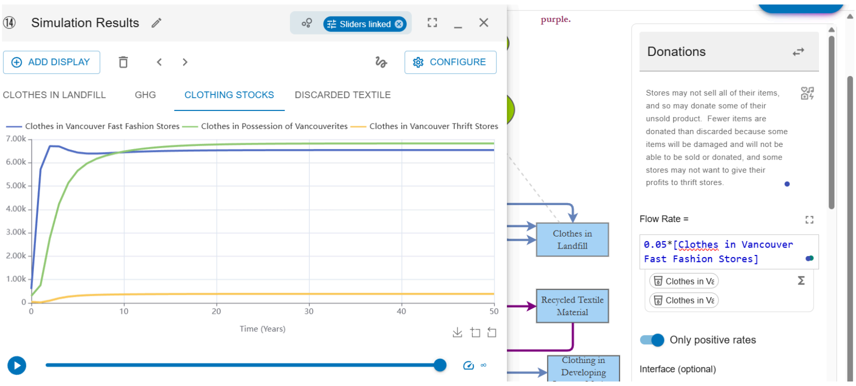
• Mathematical tools (dynamic systems, ABM, early-warning theory) allow us to understand state-change mechanisms.

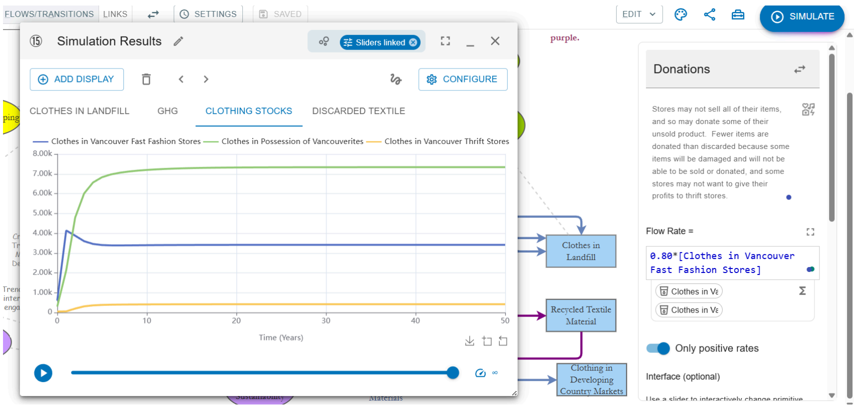
• Sustainability transitions *are possible*, but only when matched to system structure, history, and behavioural realities.

Donations

When you select the 'donations' flow link, you can see that it is a fixed proportion of clothes from fashion stores (starting at 0.05; hence 5%). What happens to GHG and the number of clothes in possession of Vancouverites (inhabitants of Vancouver btw) over the long-term as you increase this proportion?

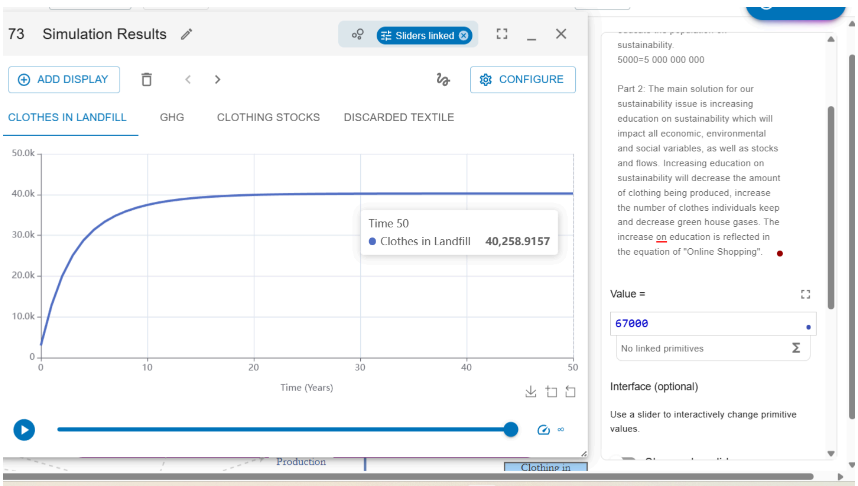
Your graph shows it perfectly: the green curve climbs and stabilizes at a higher level when you increase donations. Why? Because donations inject an additional stream of garments into personal wardrobes without requiring new purchases. You get an accumulation effect—people simply end up with more clothes circulating in the system.





Education on sustainability

The default value for Education on sustainability is 5000. Find using the optimiser the value that will minimise the amount of clothes in the landfill. Search for values between 0 and 1,000,000 using a maximum of 1000 iteration with a step reduction factor of 0.01.



Your model has been set to the optimal solution.

Primitive	Optimum	Range
Goal Primitive		
[Clothes in Landfill]	39493.0444537403	--
Changed Primitives		
[Education on Sustainability]	66666.66749999992	66666.56749999992 - 66666.76749999993

What is the shape of the relationship between the value for Education on sustainability and "clothes in the landfill"? (you can check this out from the results page of your optimisation). Do you have a feel for why this might be

Your model has been set to the optimal solution.

Primitive	Optimum	Range
Goal Primitive		
[Clothes in Landfill]	688873.416040536	--
Changed Primitives		
[Education on Sustainability]	1	0.9 - Infinity