The sustainability challenge
- and the role of technology

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The sustainability challenge

- Environmental sustainability and the eco-efficiency challenge that faces us
- Assessing eco-efficiency
- The role of technology
- Relative and absolute sustainability
- An absolute sustainability perspective on technology

?

What characterizes a sustainable product?

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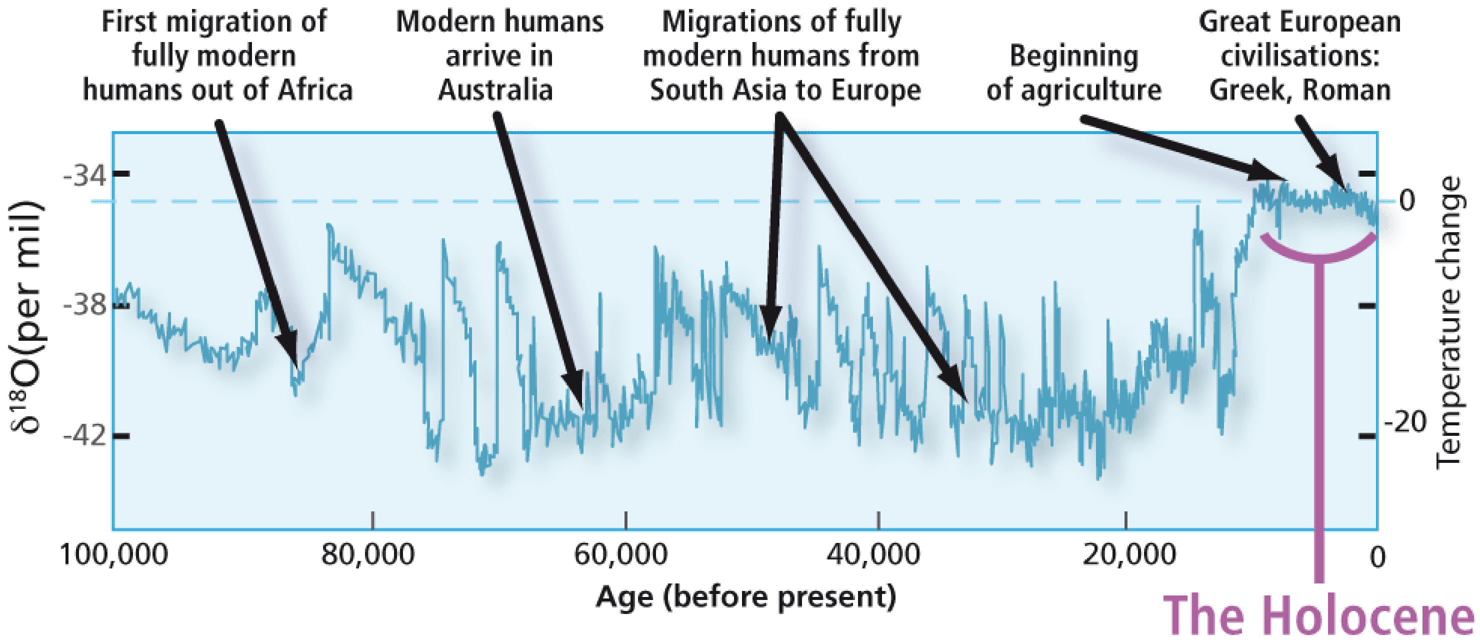
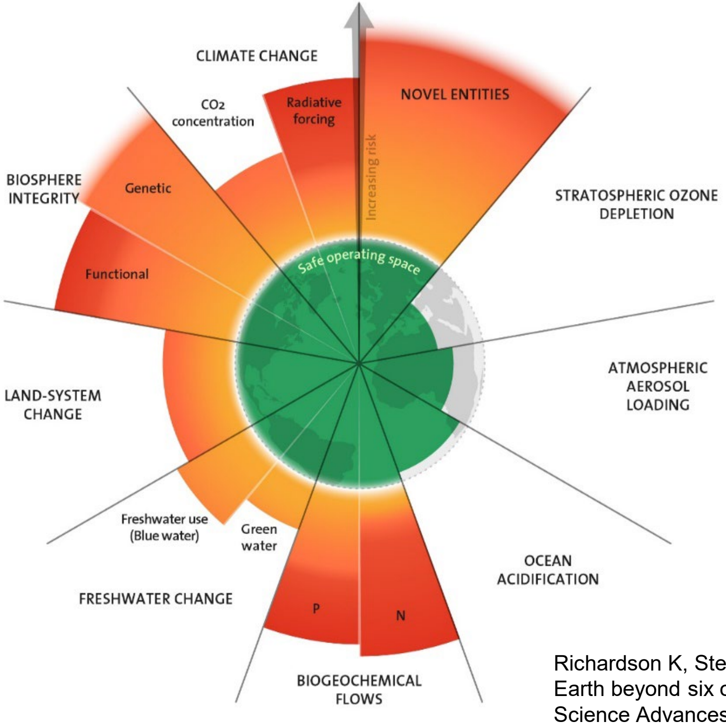
The sustainability challenge

Keeping the planet in the holocene

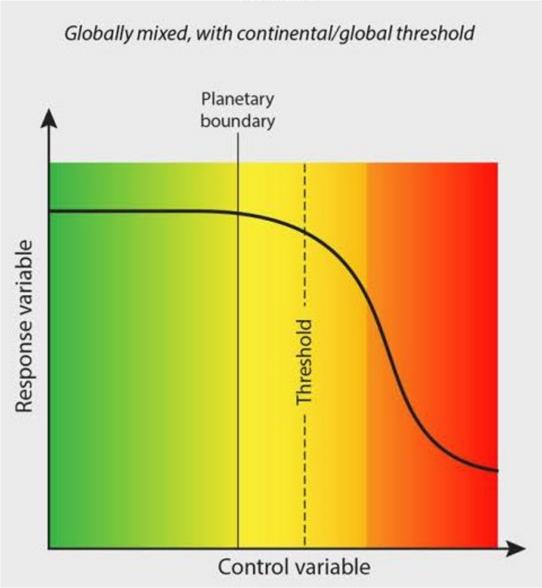


International Geosphere Biosphere Programme (2015)
http://www.igbp.net/globalchange/anthropocene.4.1b8ae20512db692f2a680009238.html (accessed 06 04 2015)

Planetary boundaries



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



Steffen W, Richardson K, Rockström J et al. (2015) Planetary boundaries: Guiding human development on a changing planet. Science 347(6223), 736-746

The sustainability challenge

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

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.

- *I* is the environmental impact
- *P* is the **population**
- A is the **Affluence**, the material standard of living
- T is the **Technology factor**, the environmental intensity of the technology

…… how do we measure the affluence?

Median income families around the world

Cuba

Japan

Kuwait

Mali

The sustainability challenge

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

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.

- *I* is the environmental impact
- *P or POP* is the **population**
- *A* is the **Affluence**, the material standard of living, represented by $\frac{GDP}{person}$
- *T* is the **Technology factor,** the environmental impact per created value $\frac{I}{GDP}$

The sustainability challenge

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

- The global population may level off around 10 billion
- Material standard of living will grow strongly in newly industrialised countries (Asia, South America)
- The environmental impact already exceeds sustainable levels in many areas
- So what is the challenge?

Climate change 2020-2030

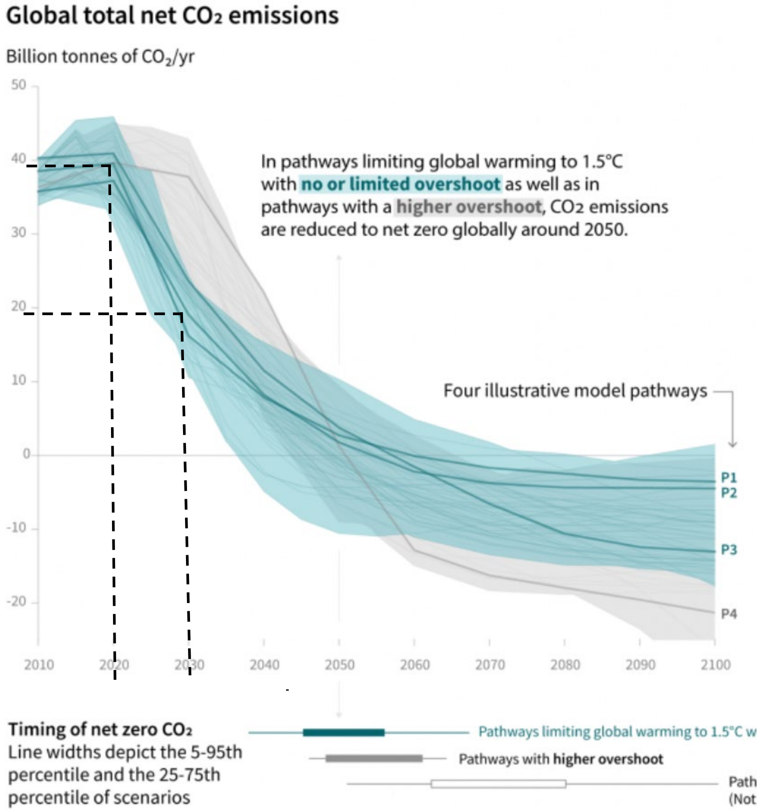
$$I = P \cdot A \cdot T$$

$$T = \frac{I}{P \cdot A}$$

Climate change 2020-2030

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

$$T = \frac{0.5}{P \cdot A}$$

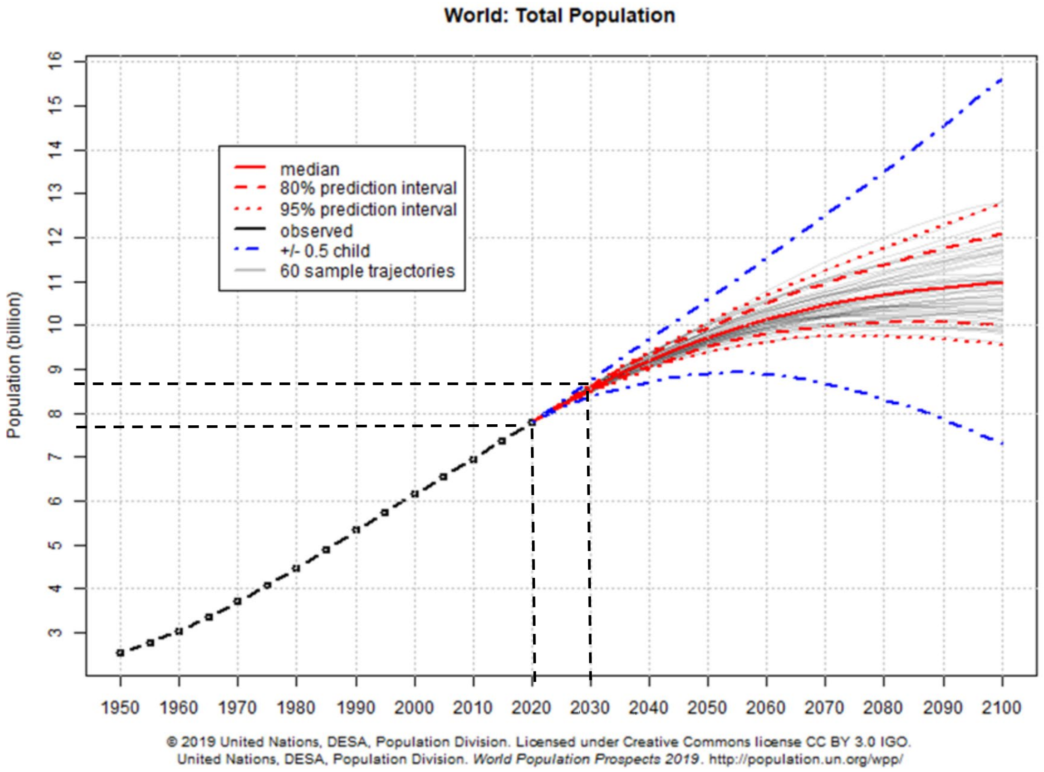


IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24, doi:10.1017/9781009157940.001.

Climate change 2020-2030

$$I = {\color{red}P} \cdot A \cdot T$$

$$T = \frac{0.5}{{\color{red}1.1} \cdot A}$$



Climate change 2020-2030

$$I = P \cdot \color{red}{A} \cdot T$$

$$T = \frac{0.5}{1.1 \cdot \color{red}{1.3}}$$

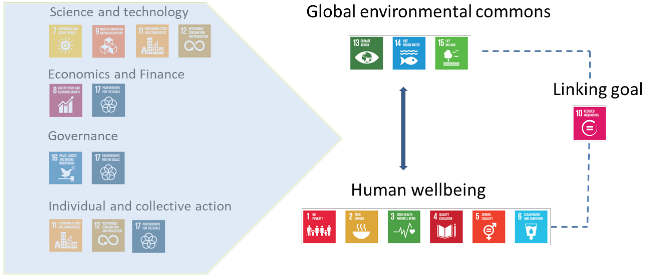
Year	GDP/person (USD)	Decade increase
1960	458	
1970	812	1,8
1980	2550	3,2
1990	4303	1,7
2000	5590	1,3
2010	9621	1,7
2021	12262	1,3

World Bank 2022

Eco-efficiency

Eco-efficiency can be defined as the ratio between the functional output and the environmental impacts caused by an activity

$$\textit{Eco-efficiency} = \frac{\textit{Delivered service}}{\textit{Environmental impact}}$$



Improved eco-efficiency means creating more with less

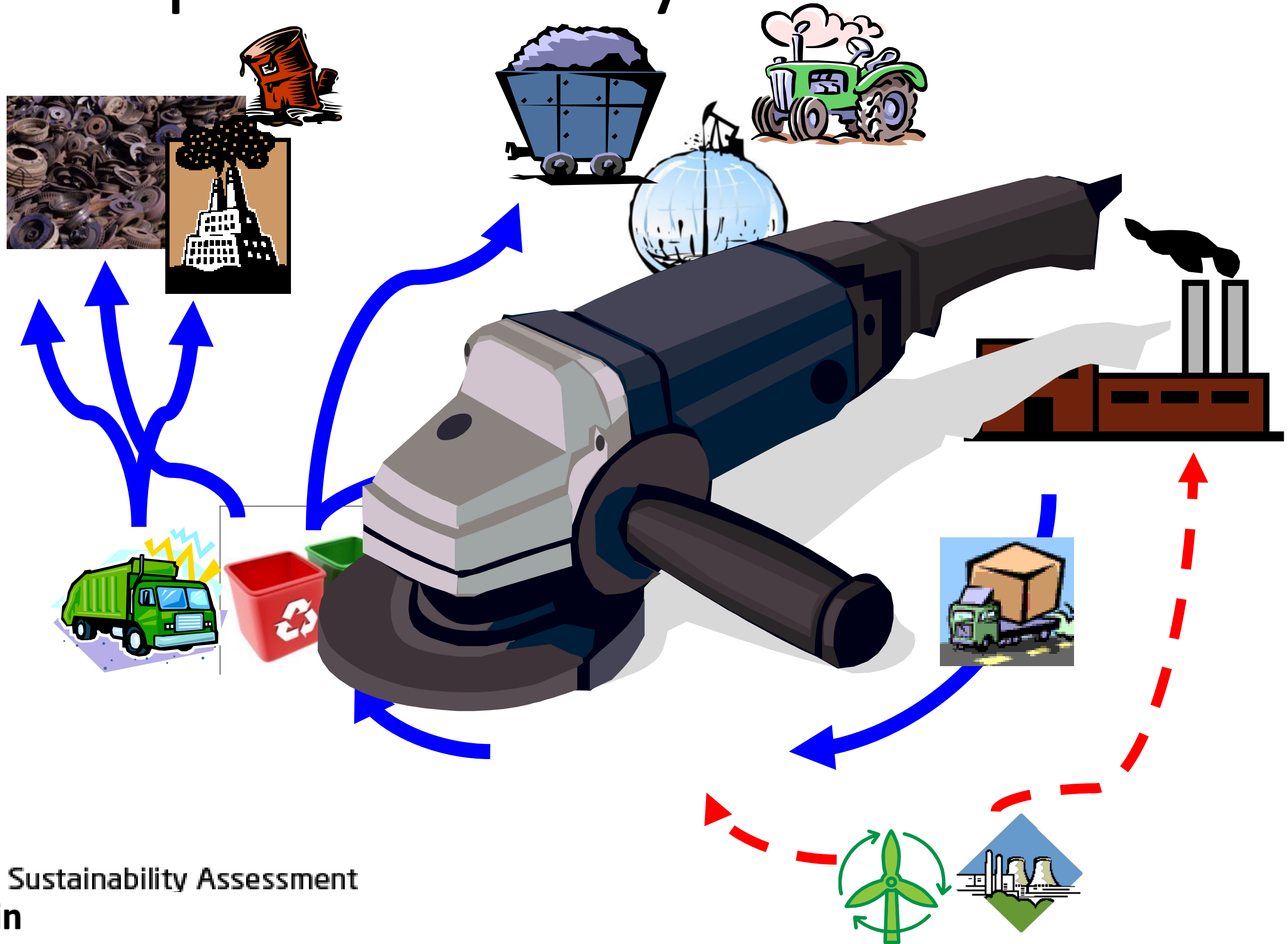
Eco-efficiency

Eco-efficiency can be defined as the ratio between the functional output and the environmental impacts caused by an activity

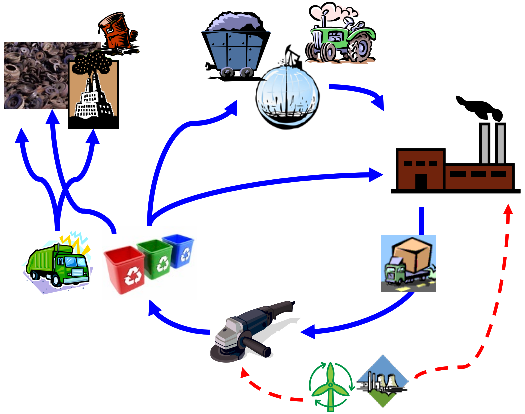
$$\textit{Eco-efficiency} = \frac{\textit{Delivered service}}{\textit{Environmental impact}} = 1/T$$

Eco-efficiency is the reciprocal of the technology factor in the IPAT equation, but how is it measured?

The product life cycle



Quantifying eco-efficiency

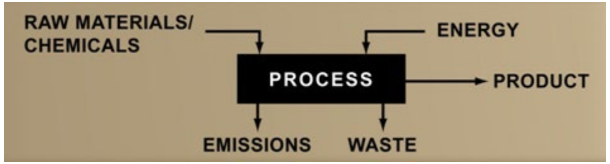


For eco-efficiency, a systems perspective is needed;

- Adapting a life cycle perspective to avoid problem-shifting
- Considering all relevant types of impacts
- Addressing trade-offs between impacts (and sustainability dimensions)

Environmental impacts

Throughout the life cycle processes exchange substances and materials with the surroundings



- Resources and materials go in
- Products, emissions and waste go out

All these exchanges have the potential to impact on the environment and contribute to the environmental problems that we know

We have to study the environmental impacts throughout the life cycle

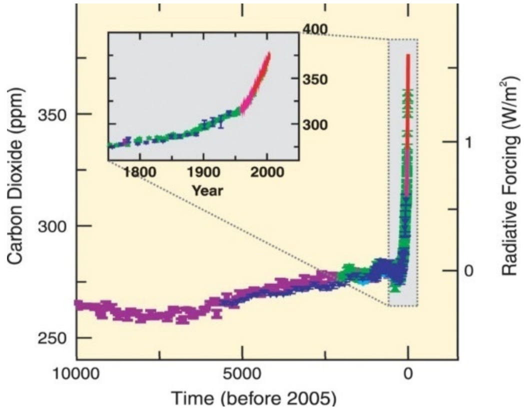
Environmental impacts

From the ***global***

- Greenhouse effect and climate change
- Degradation of stratospheric ozone
- Depletion of non-renewable resources

… over the ***regional***

- Acidification
- Enrichment with nutrients
- Toxicity to ecosystems and humans
- Photochemical and particle air pollution



Environmental impacts

… to the ***local***

- Clearing of land, loss of soil and habitats
- Depletion of water resources

The environmental impacts can be calculated for each exchange and expressed for the whole life cycle of the product

A common metric for all environmental impacts is the ***Person equivalent, PE***:

How large is the impact from the product compared to the ***annual environmental impact from an average person***?

The Person equivalent

Impact category	Annual impact level per person in , 2010 (person.year)	
	Europe	**The world**
Climate change	**9.2 ton CO_2-eq**	**8.1 ton CO_2-eq**
Ozone depletion	0.022 kg CFC-11-eq	0.041 kg CFC-11-eq
Photochemical ozone formation	32 kg NMVOC-eq	57 kg NMVOC-eq
Terrestrial acidification	$7.4 \cdot 10^2$ mole H+ eq	$7.8 \cdot 10^2$ mole H+ eq
Terrestrial eutrophication	$5.5 \cdot 10^2$ mole N eq	$3.5 \cdot 10^2$ mole N eq
Freshwater eutrophication	1.49 kg P eq	0.62 kg P eq
Marine eutrophication	17 kg N eq	9.4 kg N eq
Freshwater ecotoxicity	$8.7 \cdot 10^3$ [PAF].m^3.day	$6.7 \cdot 10^2$ [PAF].m^3.day
Land use, soil quality	11 tons eroded soil	9 tons eroded soil
Land use, biodiversity loss	$7.5 \cdot 10^3$ m^2.year	$6.2 \cdot 10^3$ m^2.year
Water depletion	256 m^3	395 m^3

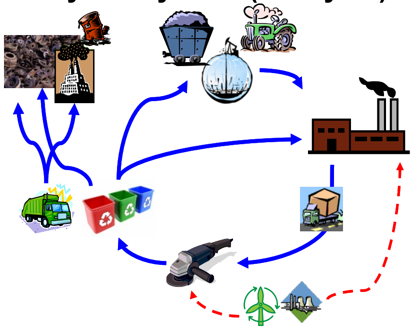
Laurent A, Olsen SI, Hauschild MZ (2011) Normalization in EDIP97 and EDIP2003: updated European inventory for 2004 and guidance towards a consistent use in practice. Int J Life Cycle Assess 16, 401-409
Benini L, Mancini L, Sala S, Manfredi S, Schau EM, Pant R (2014) Normalisation method and data for Environmental Footprints. Report EUR 26842 EN. Joint Research Centre. Institute for Environment and Sustainability. European Commission.
Bjørn A, Hauschild M (2015) Introducing carrying capacity based normalization in LCA: framework and development of midpoint level references. Int J Life Cycle Assess 20(7), 1005-1018, 2015

Environmental Life Cycle Assessment (LCA)

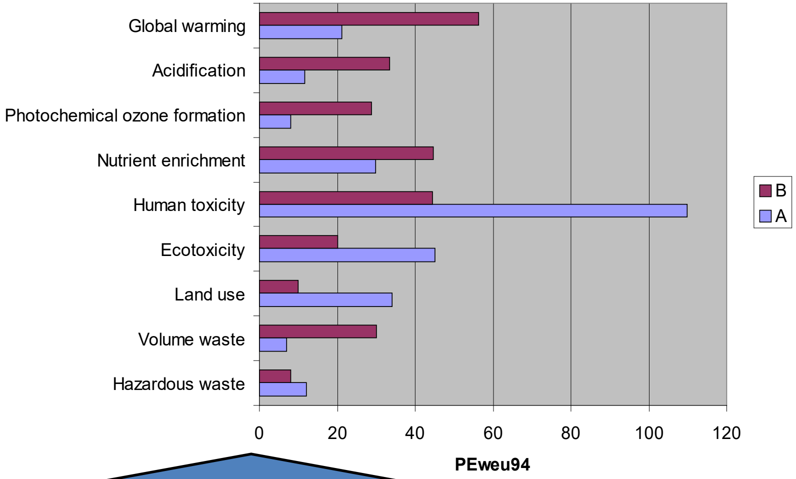
Inventory of environmental exchanges

Substance	CAS.no.	Emission to air g	Emission to water g
2-hydroxy-ethanacrylate	816-61-0	0,0348	
4,4-methylenebis cyclohexylamine	1761-71-2	5,9E-02	
Ammonia	7664-81-7	3,7E-05	4,2E-05
Arsenic (As)	7440-38-2	2,0E-06	
Benzene	71-43-2 (cur	5,0E-02	
Lead (Pb)	7439-92-1	8,5E-06	
Butoxyethanol	111-76-2	6,6E-01	
Carbondioxide	124-38-9	2,6E+02	
Carbonmonoxide (CO)	630-08-0	1,9E-01	
Cadmium (Cd)	7440-46-9	2,2E-07	
Chlorine (Cl2)	7782-50-5	4,6E-04	
Chromium (Cr VI)	7440-47-3	5,3E-06	
Dicyclohexane methane	86-73-6	5,1E-02	
Nitrous oxide(N2O)	10024-97-2	1,7E-02	
2,4-Dinitrotoluene	121-14-2	9,5E-02	
HMDI	5124-30-1	7,5E-02	
Hydro carbons (electricity, stationary combustic	-	1,7E+00	
Hydrogen ions (H+)	-		1,0E-03
i-butanol	78-83-1	3,5E-02	
i-propanol	67-63-0	9,2E-01	
copper (Cu)	7740-50-8	1,8E-05	
Mercury(Hg)	7439-97-6	2,7E-06	
Methane	74-82-8	5,0E-03	
Methyl i-butyl ketone	108-10-1	5,7E-02	
Monoethyl amine	75-04-7		7,9E-06
Nickel (Ni)	7440-02-0	1,1E-05	
Nitrogen oxide (NOx)	10102-44-0	1,1E+00	
NMVOC, diesel engine (exhaust)	-	3,9E-02	
NMVOC, power plants (stationary combustion)	-	3,9E-03	
Ozone (O3)	10028-15-6	1,8E-03	
PAH	ikke specifik	2,4E-08	
Phenol	108-95-2		1,3E-05
Phosgene	75-44-5	1,4E-01	
Polyeter polyol	ikke specifik	1,6E-01	
1,2-propylenoxide	75-56-9	8,2E-02	
Nitric acid	7782-77-6 (c	8,5E-02	
Hydrochloric acid	7647-01-0 (c	1,9E-02	
Selenium (Se)	7782-49-2	2,6E-05	
Sulphur dioxide(SO2)	7446-09-5	1,3E+00	
Toluene	108-88-3	4,8E-02	
Toluene-2,4-diamine	95-80-7	7,9E-02	
Toluene diisocyanat (TDI)	26471-62-5	1,6E-01	
Total-N	-		2,6E-05
Triethylamine	121-44-8	1,6E-01	
Unspecified aldehydes	-	7,5E-04	
Uspecified organic compounds	-	1,5E-03	
Vanadium	7440-62-2	1,8E-04	
VOC, diesel engine (exhaust)	-	6,4E-05	
VOC, stationary combustion (coal fired)	-	4,0E-05	
VOC, stationary combustion (natural gas fired)	-	2,2E-03	
VOC, stationary combustion (oil fired)	-	1,4E-04	
Xylene	1330-20-7	1,4E-01	
Zinc (Zn)	7440-66-6	8,9E-05	

Analysed system (life cycle)



Environmental profile of solutions



Quantifying eco-efficiency

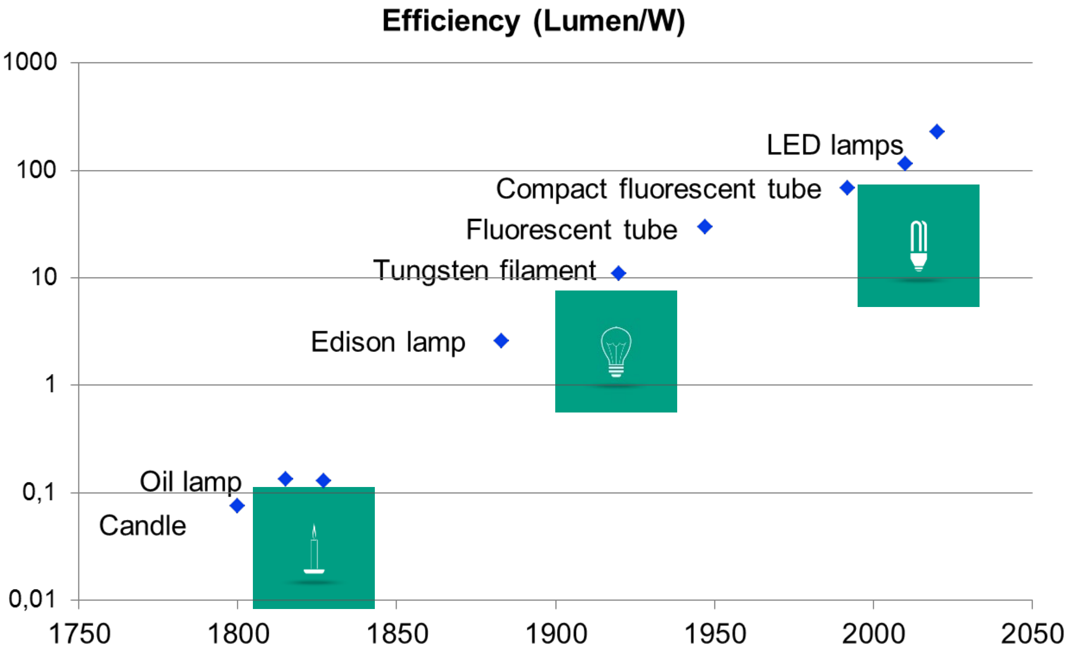
- LCA fixes the delivered service by focusing on a functional unit
- LCA quantifies environmental impacts per delivered service, looking at the whole life cycle and all relevant environmental impacts

→ **LCA is the tool to quantify eco-efficiency**

Factor 3 improvements in 2030?

Developments in efficiency

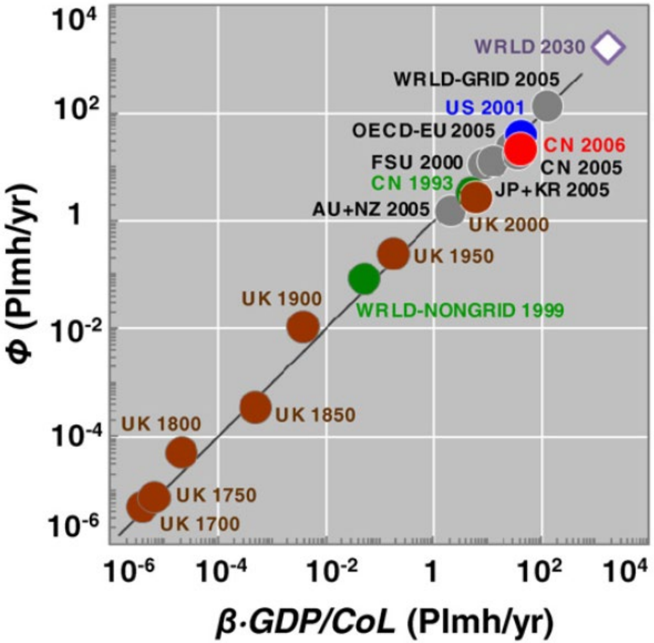
The example of lighting technology



Franceschini , S (2015) Eco-innovation dynamics and sustainability – new perspectives in innovation studies illuminated through the case of lighting and its energy consumption. PhD thesis DTU Management Engineering, Technical University of Denmark, Lyngby

Development in consumption

Consumption of light



Ability to purchase light

"Over the past three centuries, and even now, the world spends about **0.72%** of its GDP on light and **0.54%** of its GDP on the consumption of energy associated with light"

Tsao JY, Saunders HD, Creighton JR, Coltrin ME, Simmons JA (2010) Solid-state lighting: an energy-economics perspective. J. Phys.D: Appl. Phys. 43, 354001 (17p)

The rebound effect

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

- Consumption (Affluence) and efficiency (Technology factor) are not always independent
- In some cases an increase in efficiency can drive an increase in consumption meaning that $A \cdot T$ remains constant or even grows, leading to higher impact

?

Do you know examples of rebound effects where improvements in eco-efficiency are partially or fully neutralized by increased use of the product?

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Relative and absolute sustainability

LCA supports **relative assessments of environmental sustainability** (*"more sustainable than…"*)?

- Same or higher functionality with less environmental impact

Absolute sustainability (*"sustain-able"*)?

- Where is the boundary beyond which the activity becomes unsustainable?
- What is sustainable in absolute terms?

Sustainable?

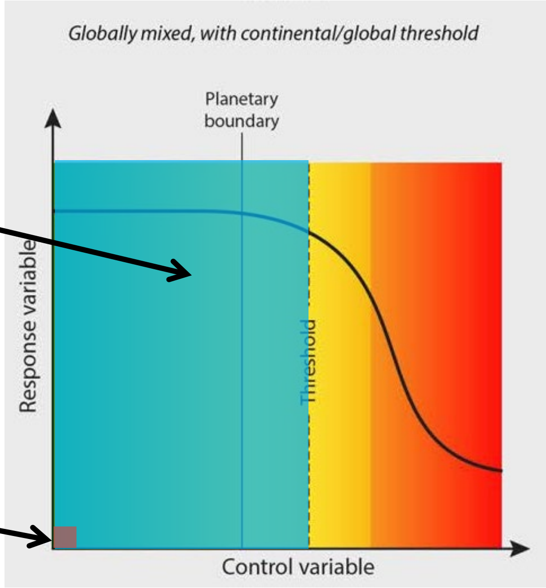
Greenwashing
calls for
absolute metrics
in the sustainability
assessment
of products

A sustainable level of impact

- Respect environmental limits
- Assign"pollution space" to our activities

Total pollution space

Pollution space assigned to technology, product, company, individual, country, …



Steffen W, Richardson K, Rockström J et al. (2015) Planetary boundaries: Guiding human development on a changing planet. Science 347(6223), 736-746

Sustainable per capita impacts

Impact category	Current impact	Sustainable impact
Climate change	8.1 ton CO_2-eq	0.98 ton CO_2-eq
Ozone depletion	0.041 kg CFC-11-eq	0.078 kg CFC-11-eq
Photochemical ozone formation	57 kg NMVOC-eq	2.5 kg NMVOC-eq
Terrestrial acidification	$7.8 \cdot 10^2$ mol H+ eq	$1.4 \cdot 10^3$ mol H+ eq
Terrestrial eutrophication	$3.5 \cdot 10^2$ mol N eq	$1.8 \cdot 10^3$ mol N eq
Freshwater eutrophication	0.62 kg P eq	0.46 kg P eq
Marine eutrophication	9.4 kg N eq	31 kg N eq
Freshwater ecotoxicity	$6.7 \cdot 10^2$ [PAF].m^3.dagy	$1.0 \cdot 10^4$ [PAF].m^3.day
Land use, soil quality	9 tons eroded soil	1.2 tons eroded soil
Water depletion	395 m^3	490 m^3

Laurent A, Olsen SI, Hauschild MZ (2011) Normalization in EDIP97 and EDIP2003: updated European inventory for 2004 and guidance towards a consistent use in practice. Int J Life Cycle Assess 16, 401-409
Bjørn A, Hauschild M (2015) Introducing carrying capacity based normalization in LCA: framework and development of midpoint level references. Int J Life Cycle Assess, 20(7), 1005-1018.

Consumer perspective

- A personal impact budget:
  - How large a part of my environmental space is occupied by this product or activity?
  - Is it worth that much to me if my consumption must stay within the sustainability boundaries?
  - Sustainable impact budget, a personal environmental sustainability space

The Science Based Targets Initiative (SBTi)

- SBTi established in 2015

SCIENCE BASED TARGETS
DRIVING AMBITIOUS CORPORATE CLIMATE ACTION

CDP DRIVING SUSTAINABLE ECONOMIES

UN GLOBAL COMPACT

WWF

WORLD RESOURCES INSTITUTE

- *"…**in line with what the latest climate science** says is necessary to meet the goals of the Paris Agreement—to limit global warming to **well-below 2°C** above pre-industrial levels and pursue efforts to limit warming to **1.5°C**."*

https://sciencebasedtargets.org/

Rapidly growing

As of January 4 2026:

https://sciencebasedtargets.org/

Five steps

COMMIT

Submit a letter establishing your intent to set a science-based target

DEVELOP

Work on an emissions reduction target in line with the SBTi's criteria

SUBMIT

Present your target to the SBTi for official validation

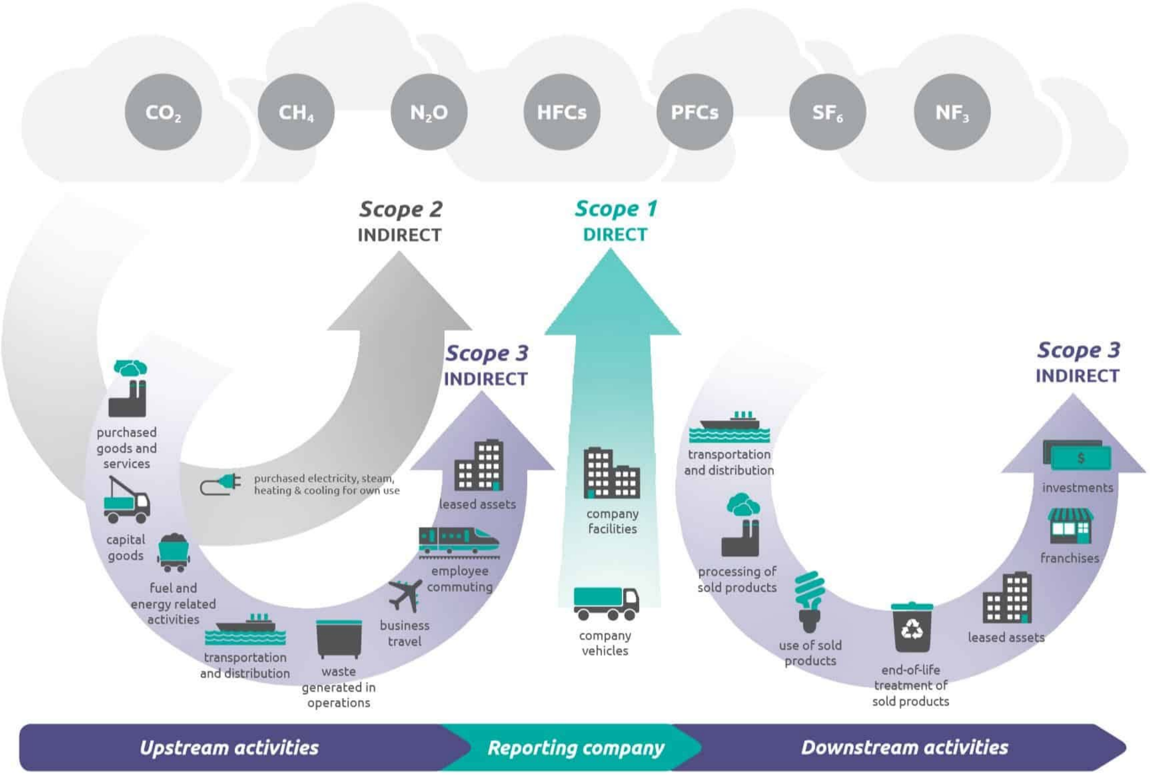
COMMUNICATE

Announce your target and inform your stakeholders

DISCLOSE

Report company-wide emissions and progress against targets on an annual basis

The three scopes



The sustainable product?

- How large are the environmental impacts of the product?
- How does it compare to
  - The share of my sustainable space that I wish to spend on it (*consumer perspective*)?
  - The space that we can allow for it in our portfolio (*company perspective*)?

    … considering the growth in our market volume (rebound effect)?
  - The space that we can allow this product or technology to occupy out of our total space (*command and control economy societal perspective*)

… and then there are the social and economical sustainability dimensions

Sustainability – according to the UN global goals

Summarizing

- Eco-efficiency assessments require a **life cycle perspective**
- Sustainability requires strong improvements in eco-efficiency
- Eco-efficiency is necessary but not sufficient
- Industry's current focus on eco-efficiency must be combined with an absolute frame to ensure that solutions are also eco-effective
- Remaining space up to the boundary is a scarce resource that we need to share
- **Absolute sustainability**
  - guides everyday consumer decisions
  - offers an essential long-term perspective for strategic decisions
- *Full sustainability assessment must* ***address all relevant SDGs***