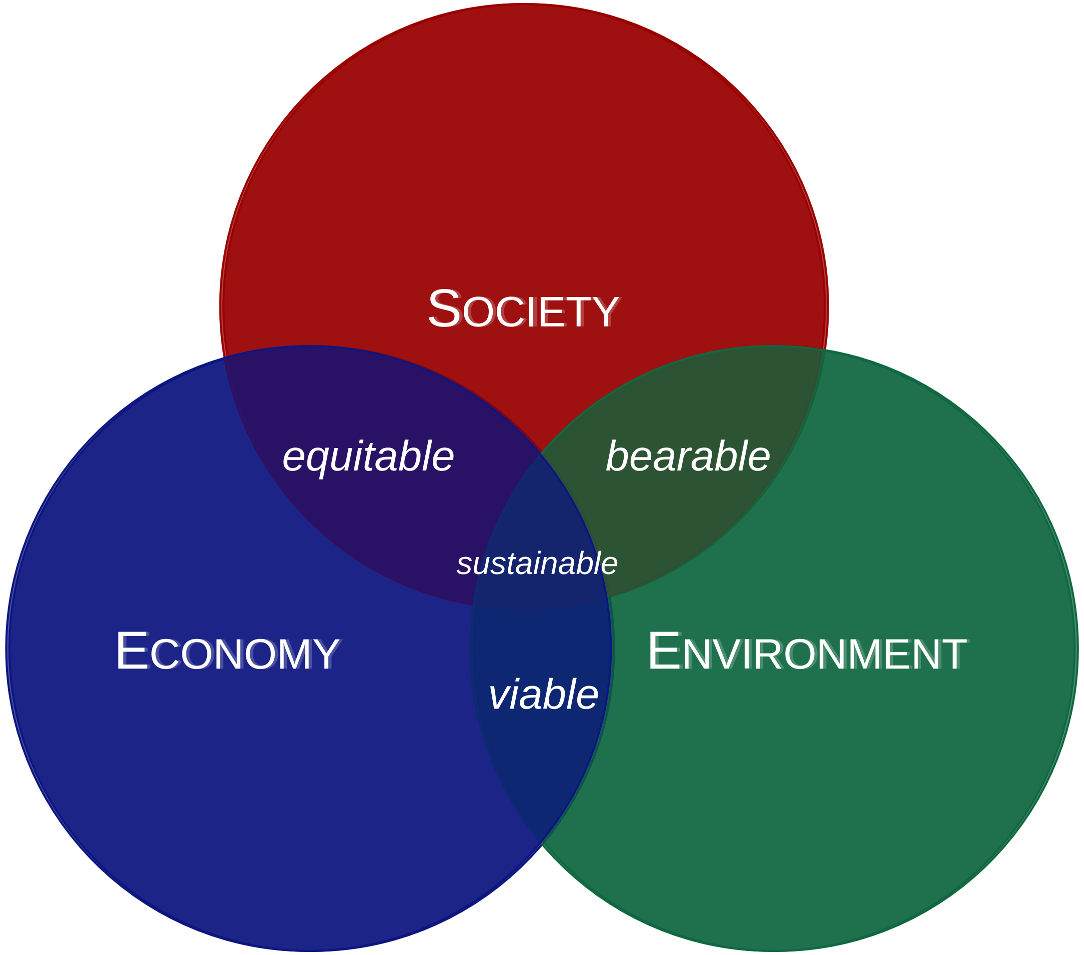
A framework to measure sustainability

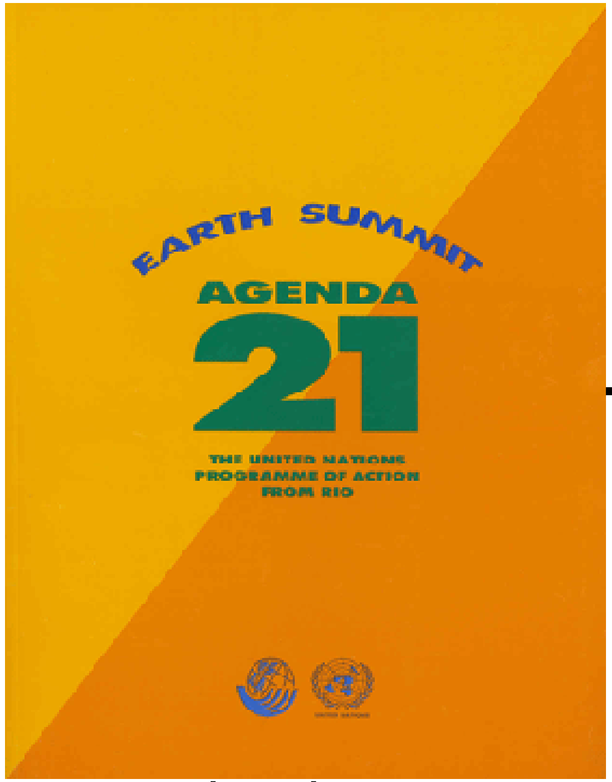
Quantitative Sustainability

David Lusseau

The Three Pillars



How do we translate it for public & private sectors?



non-binding action plan

1992-2000

no timeline, indicators, nor targets

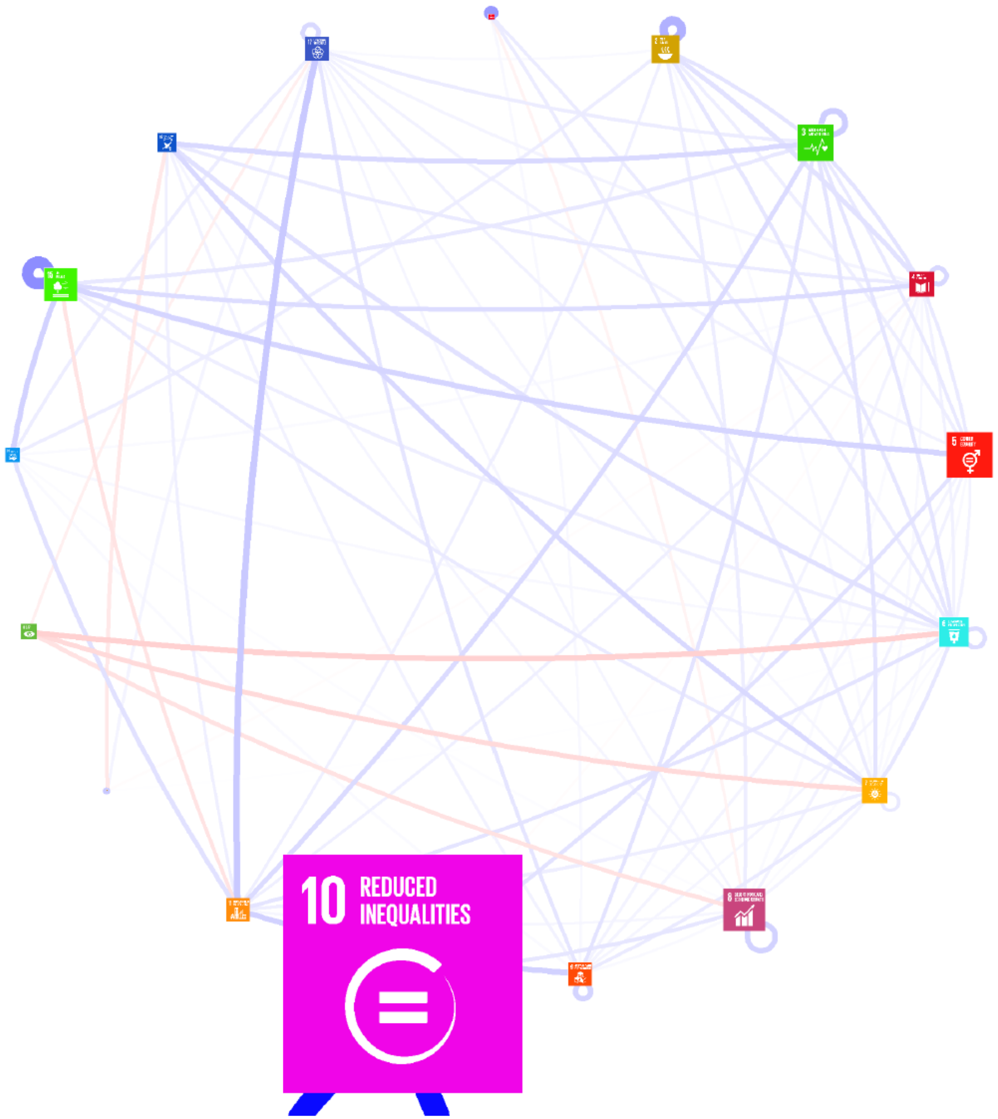
2000-2015

2015-2030

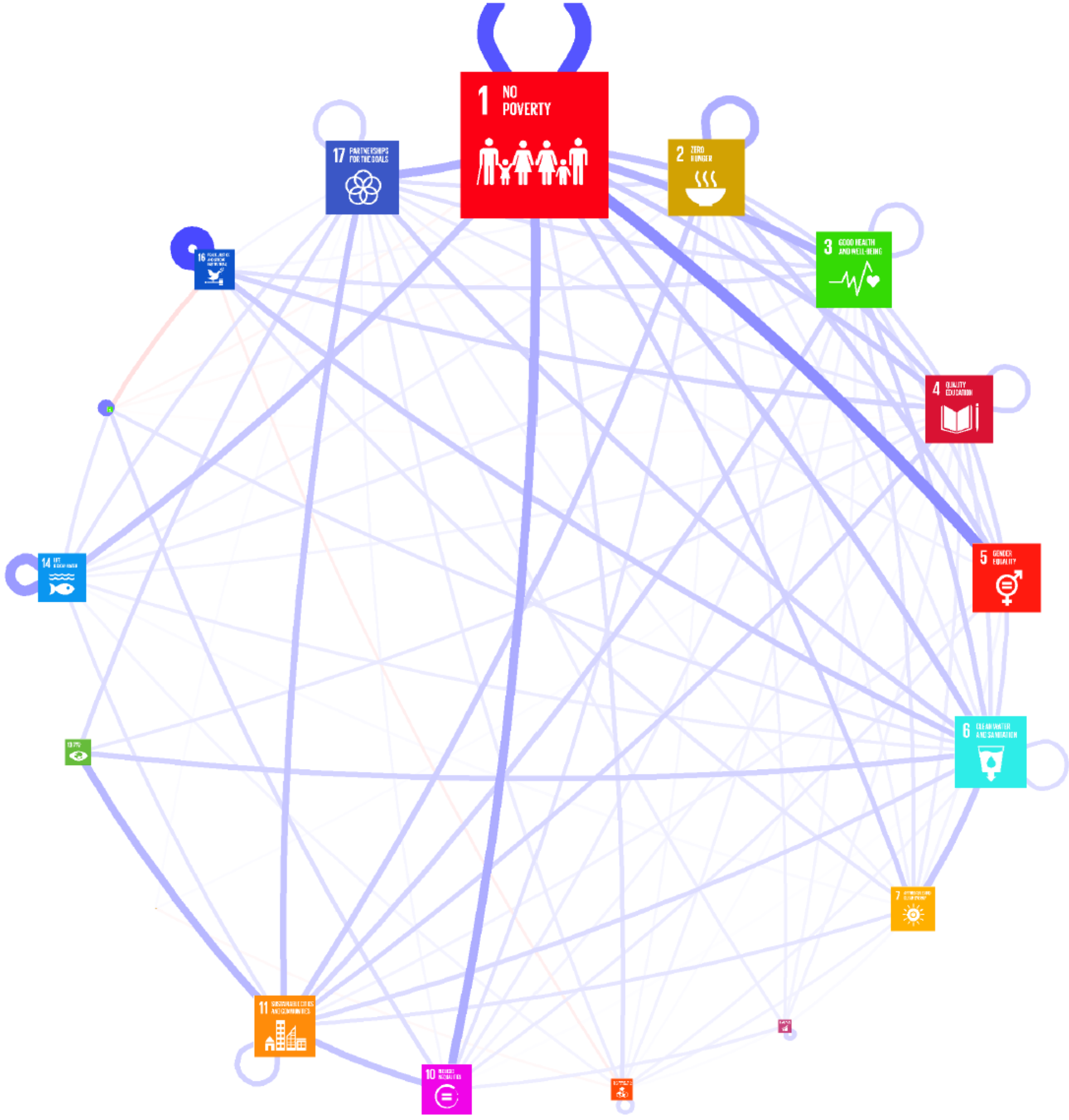
Capturing the key dimensions of the problem

The network of SDG interactions

High-income countries

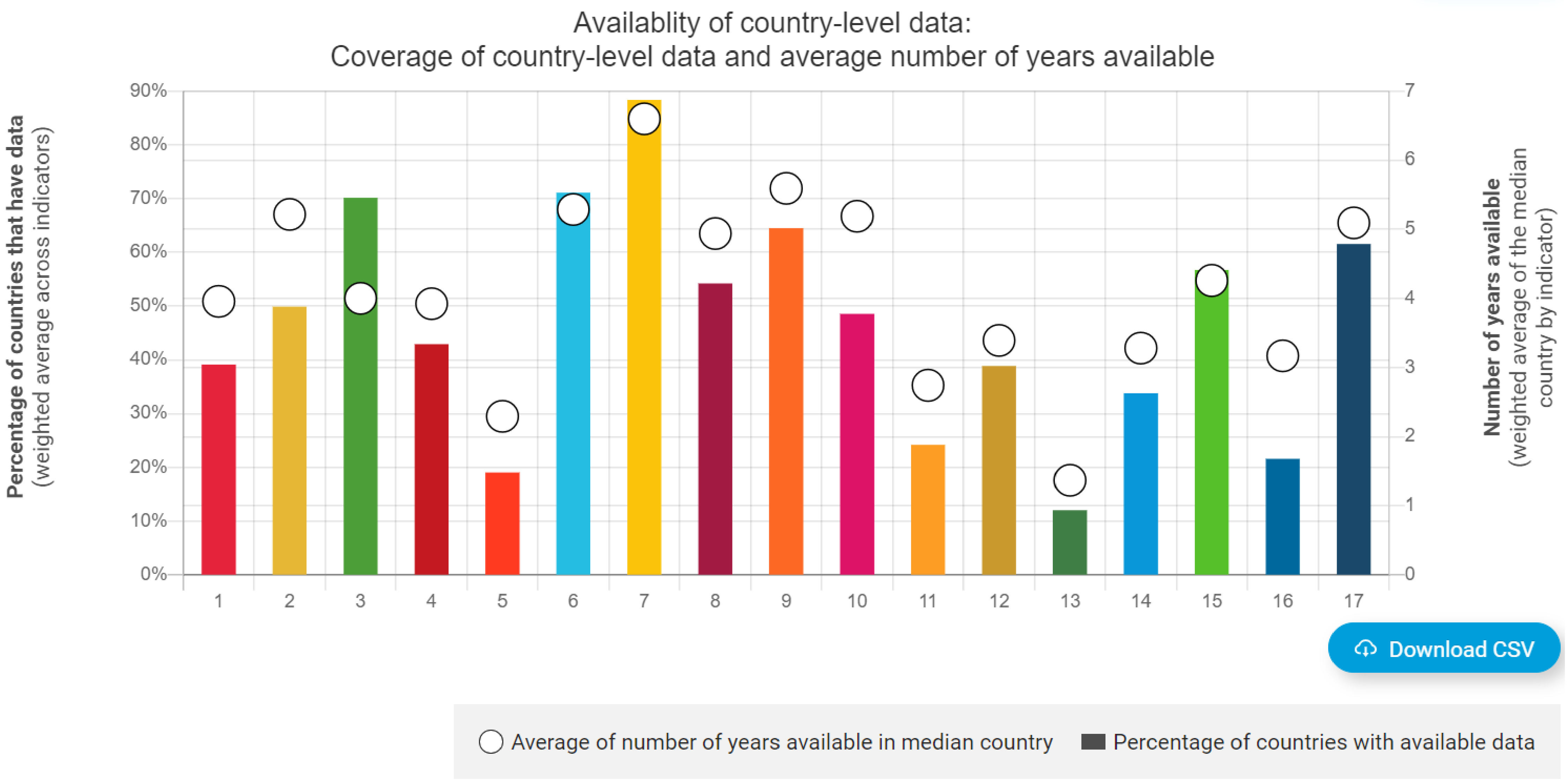


Low-income countries



Lusseau & Mancini 2019 Nature Sustainability

Data availability



https://unstats.un.org/sdgs/dataportal/analytics/

Conclusions

- We need S.M.A.R.T. objectives & targets
  - (Specific, Measurable, Achievable, Relevant & Time-Bound)

- They need to capture the three dimensions of sustainability

- Data remains sparse 30 years on

- Globally we still confuse ambitions and objectives

What is sustainability?

Quantitative Sustainability

David Lusseau

Worldviews







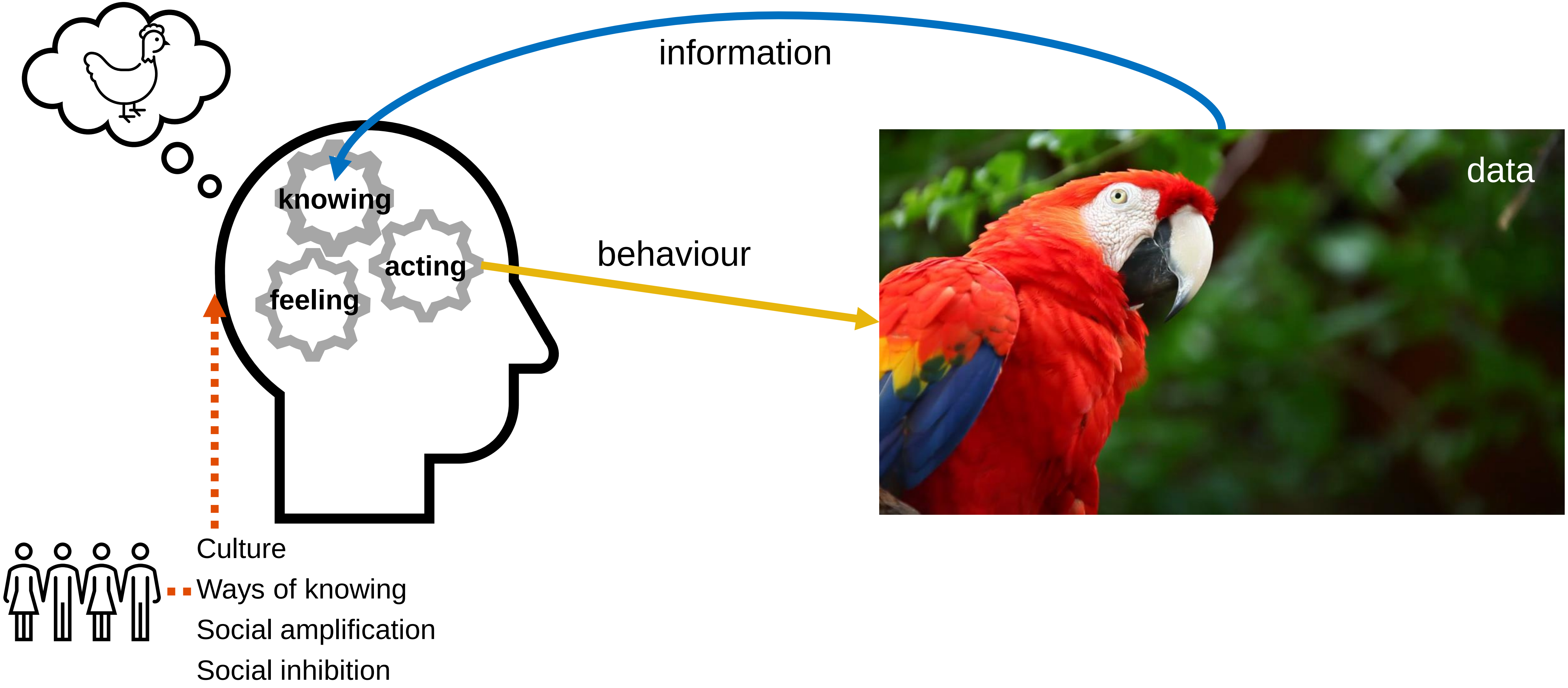








Worldviews – foundations – a model of the world

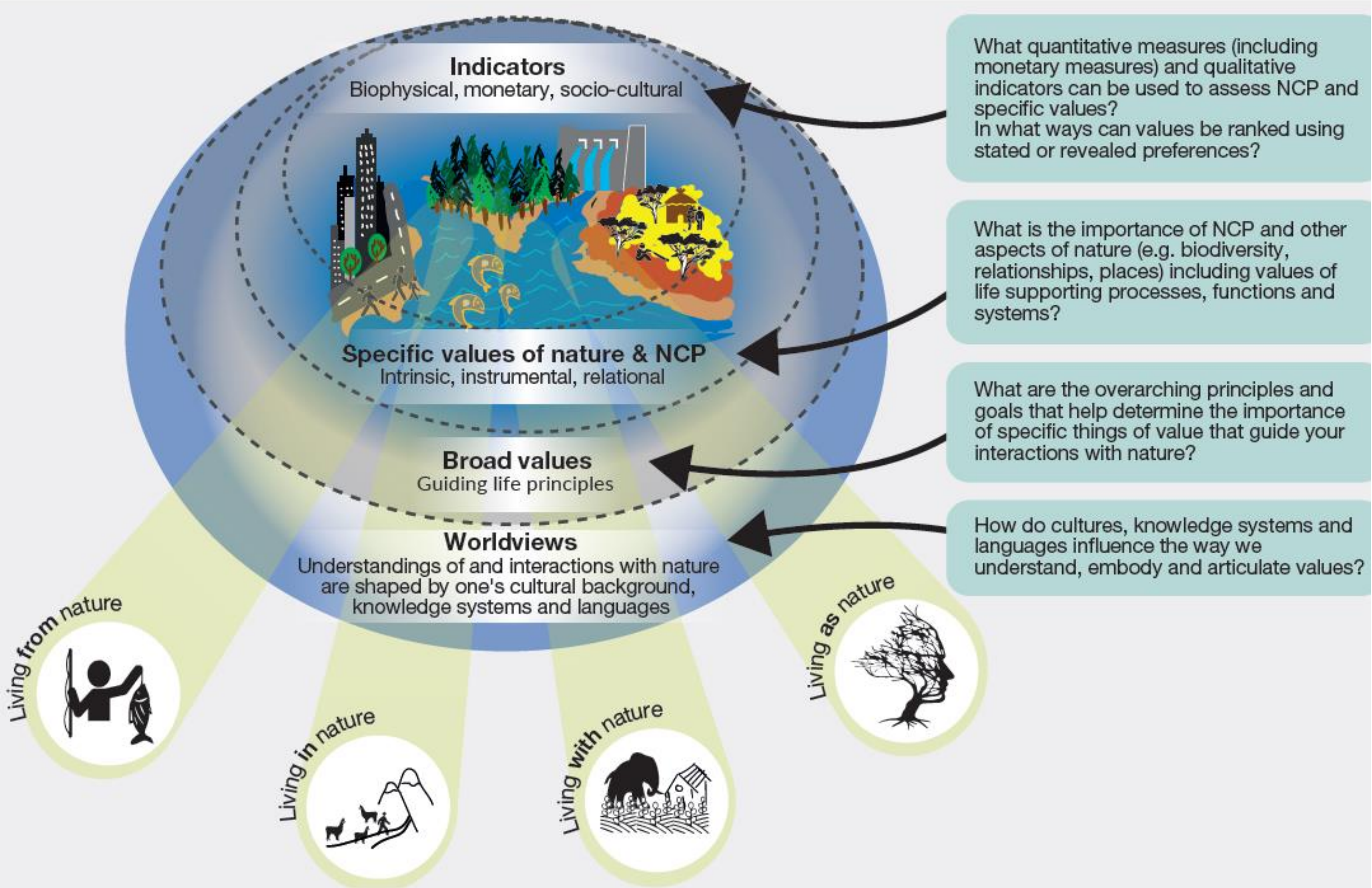


Sustainability is a difficult notion to express across worldviews

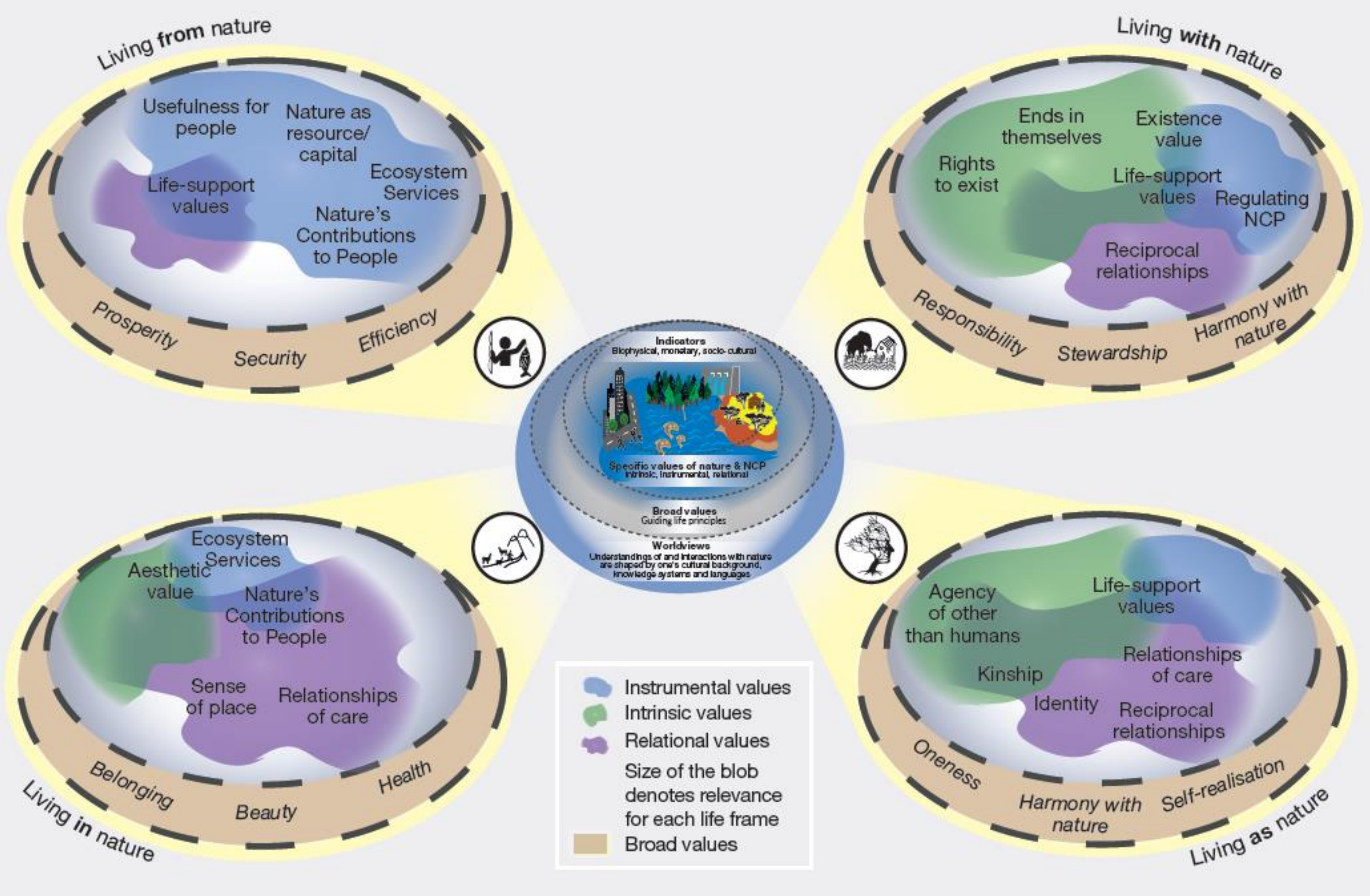
We are special

We are not special

Worldviews affect values



Pascual et al. 2023 Nature



Living from nature
Usefulness for people
Nature as resource/ capital
Life-support values
Ecosystem Services
Nature's Contributions to People
Prosperity
Security
Efficiency
Living with nature
Ends in themselves
Existence value
Rights to exist
Life-support values
Regulating NCP
Reciprocal relationships
Responsibility
Stewardship
Harmony with nature
Indicators
Biophysical, monetary, socio-cultural
Specific values of nature & NCP
Intrinsic, instrumental, relational
Broad values
Guiding life principles
Worldviews
Understandings of and interactions with nature are shaped by one's cultural background, knowledge systems and languages
Ecosystem Services
Aesthetic value
Nature's Contributions to People
Sense of place
Relationships of care
Belonging
Beauty
Health
Living in nature
Agency of other than humans
Life-support values
Relationships of care
Kinship
Identity
Reciprocal relationships
Oneness
Harmony with nature
Self-realisation
Living as nature
Instrumental values
Intrinsic values
Relational values
Size of the blob denotes relevance for each life frame
Broad values

Global consensus definition of sustainability

- "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

What is sustainability?

- It is a diverse concept – all have an intrinsic view of this notion but those views differ slightly
- How we understand sustainability depends on our worldviews about the relationship between people and nature
- The challenge: there is not one optimal definition

How can we coordinate globally such a varied concept?

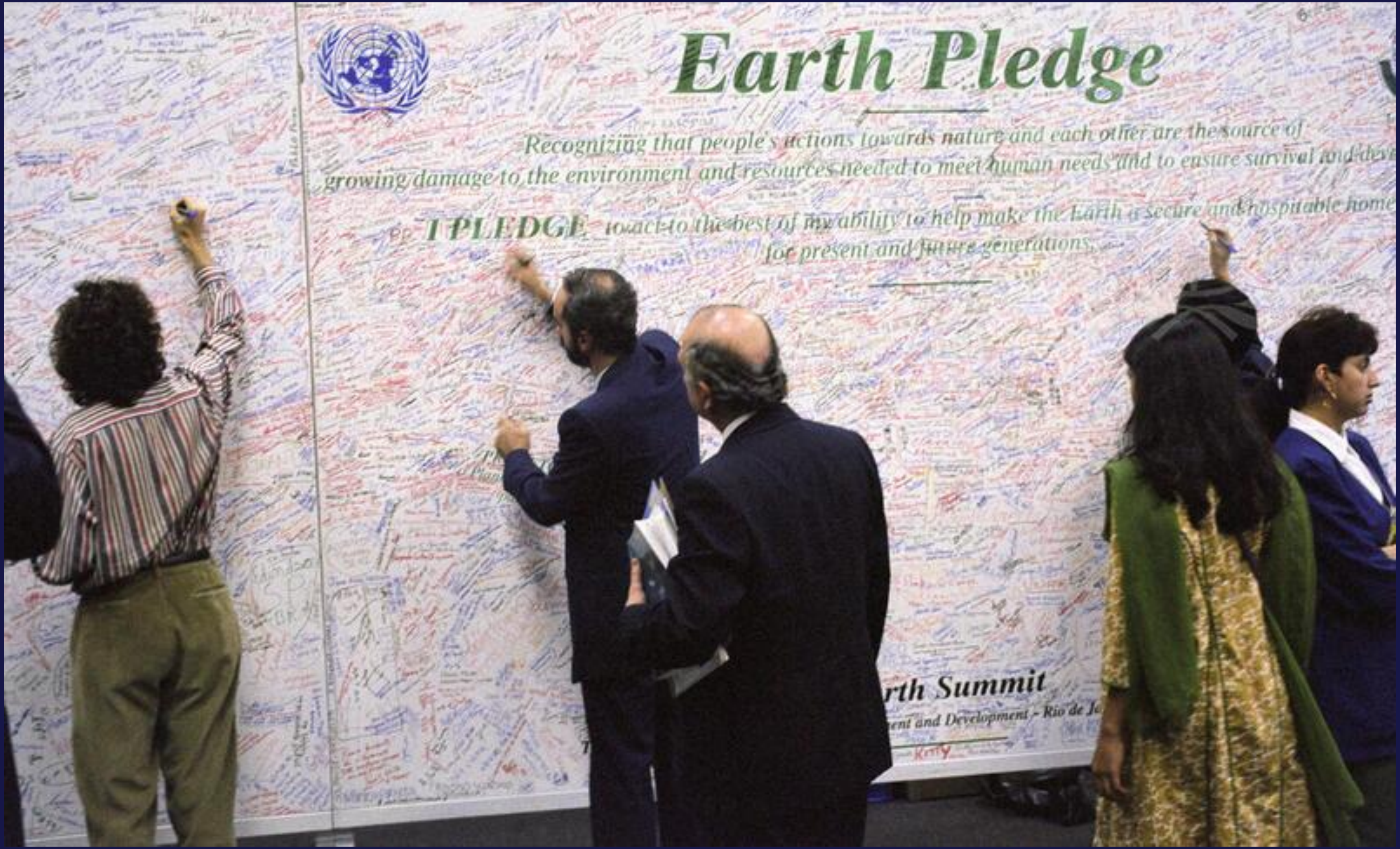
Quantitative Sustainability

David Lusseau

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....”

Reaching consensus



UN Photo 1992

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

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.

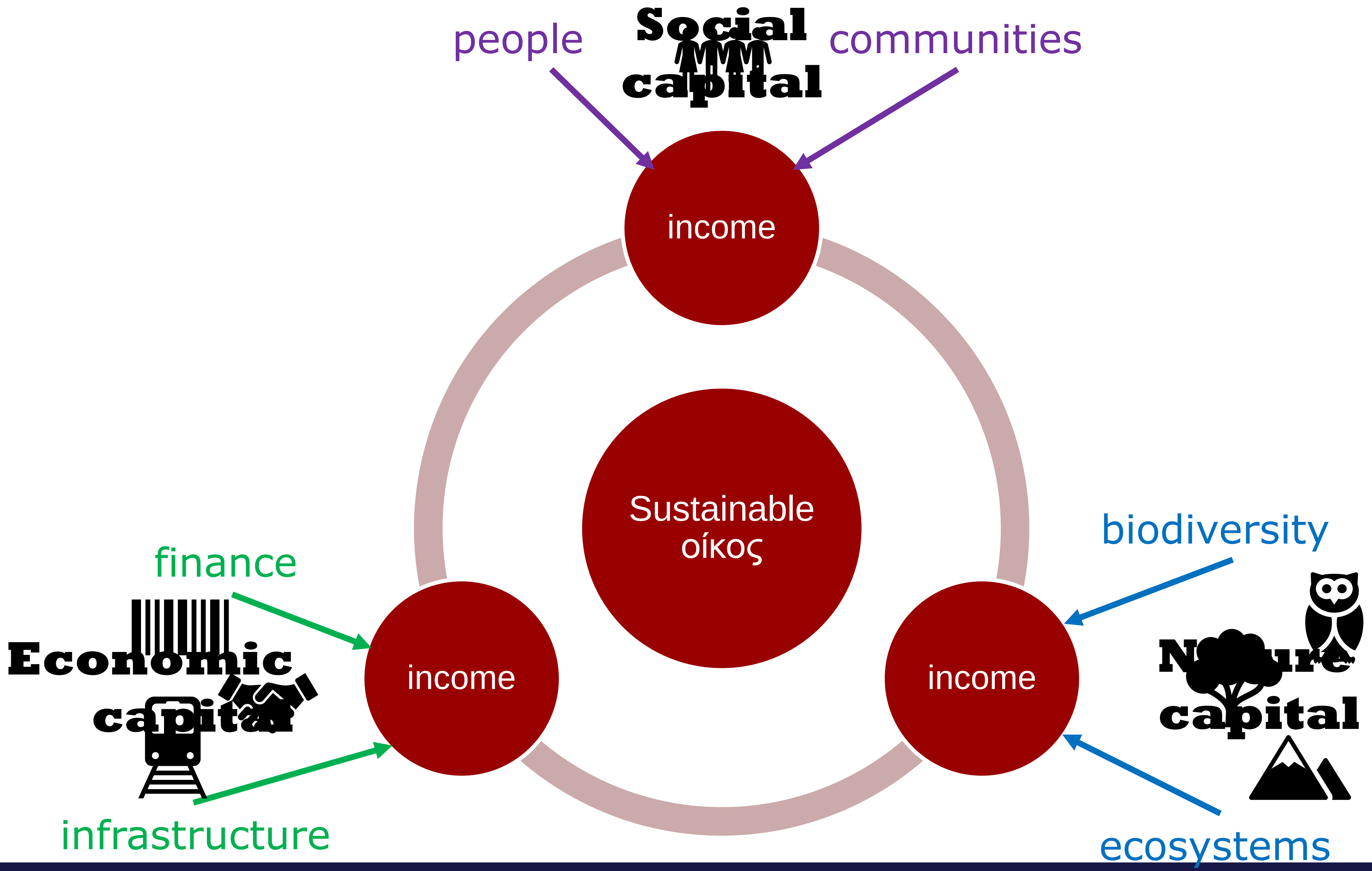
- **Article 25** - Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family.

What is at the origin of nowadays SDGs?

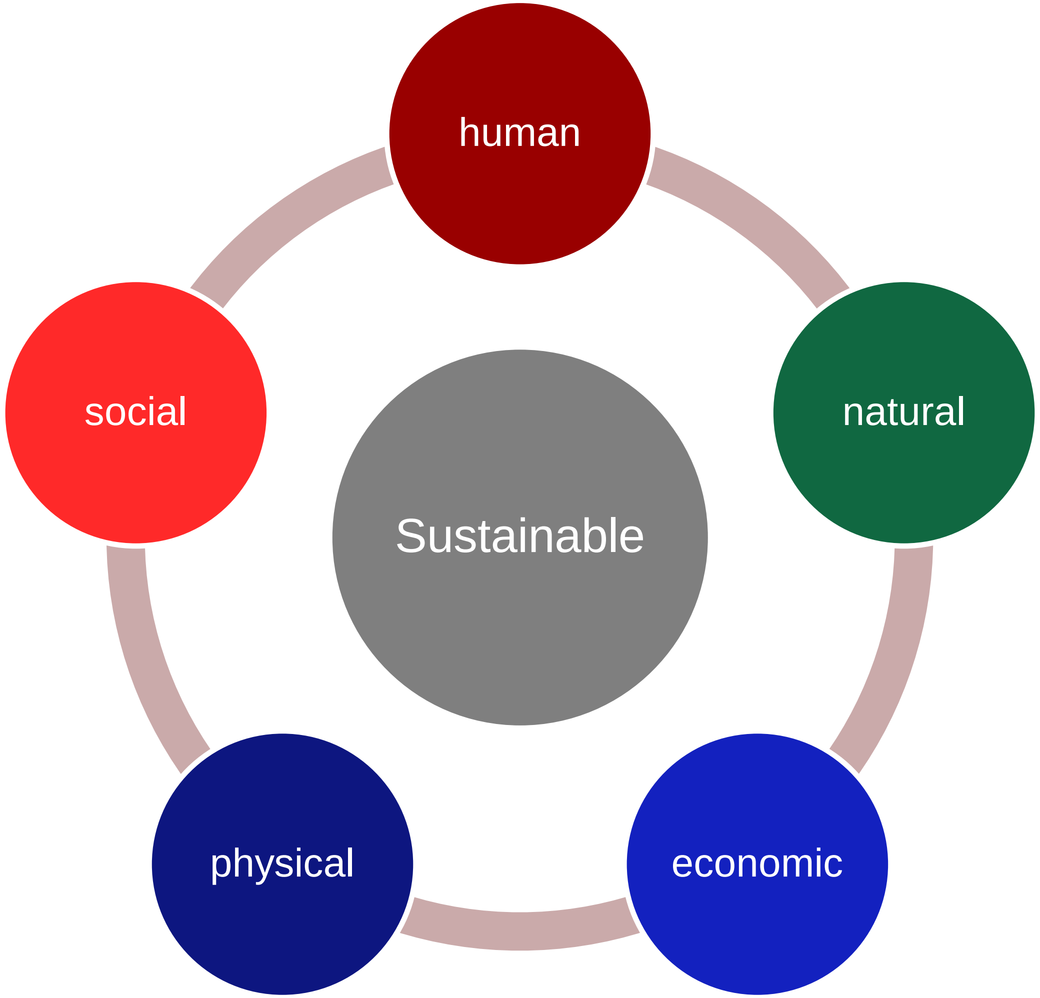
- The modern *sustainability* concept emerged from interactions between economic development & environmentalism

- Consensus II: 1992 Rio Declaration
  - Reconcile Stockholm declaration with economic development & UDHR
  - needed for global security
  - needed to adhere to Universal Human Rights

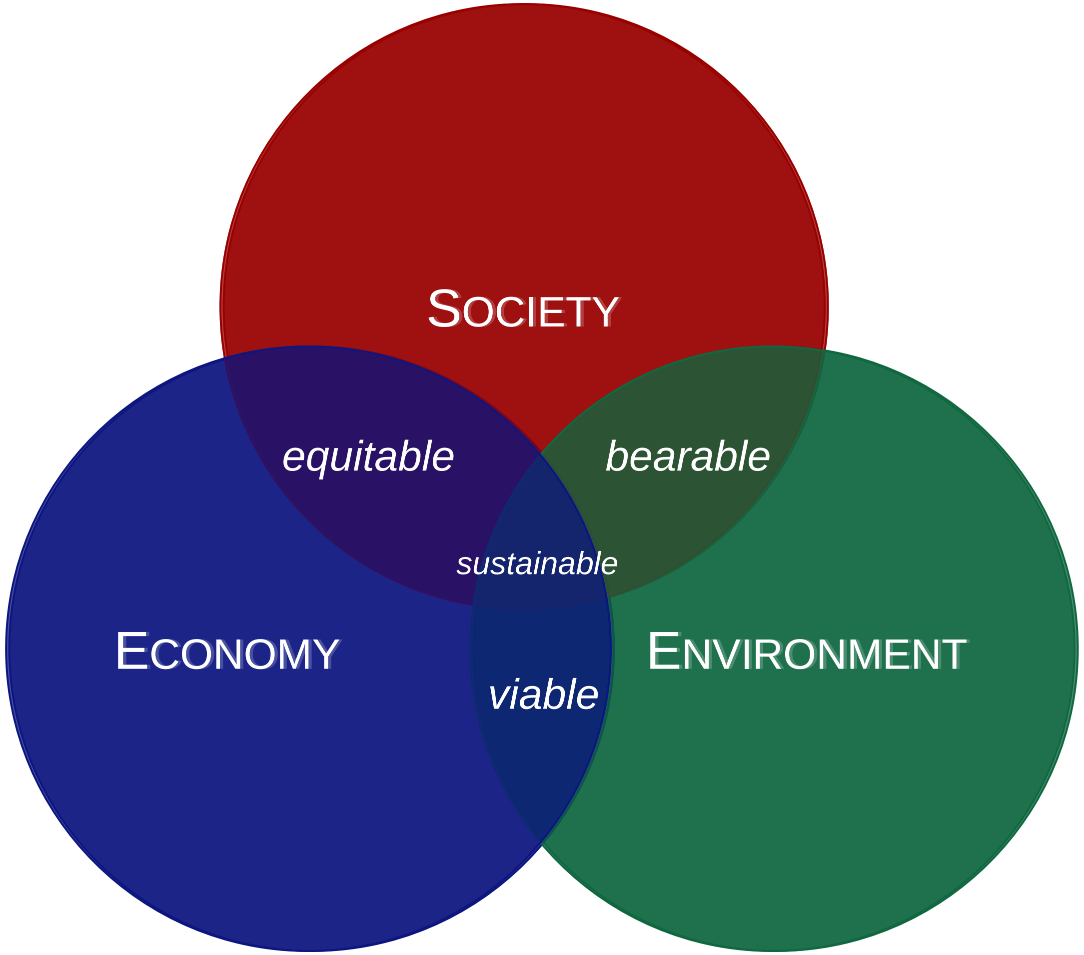
Implementing Rio 1992: Socioecological perspective



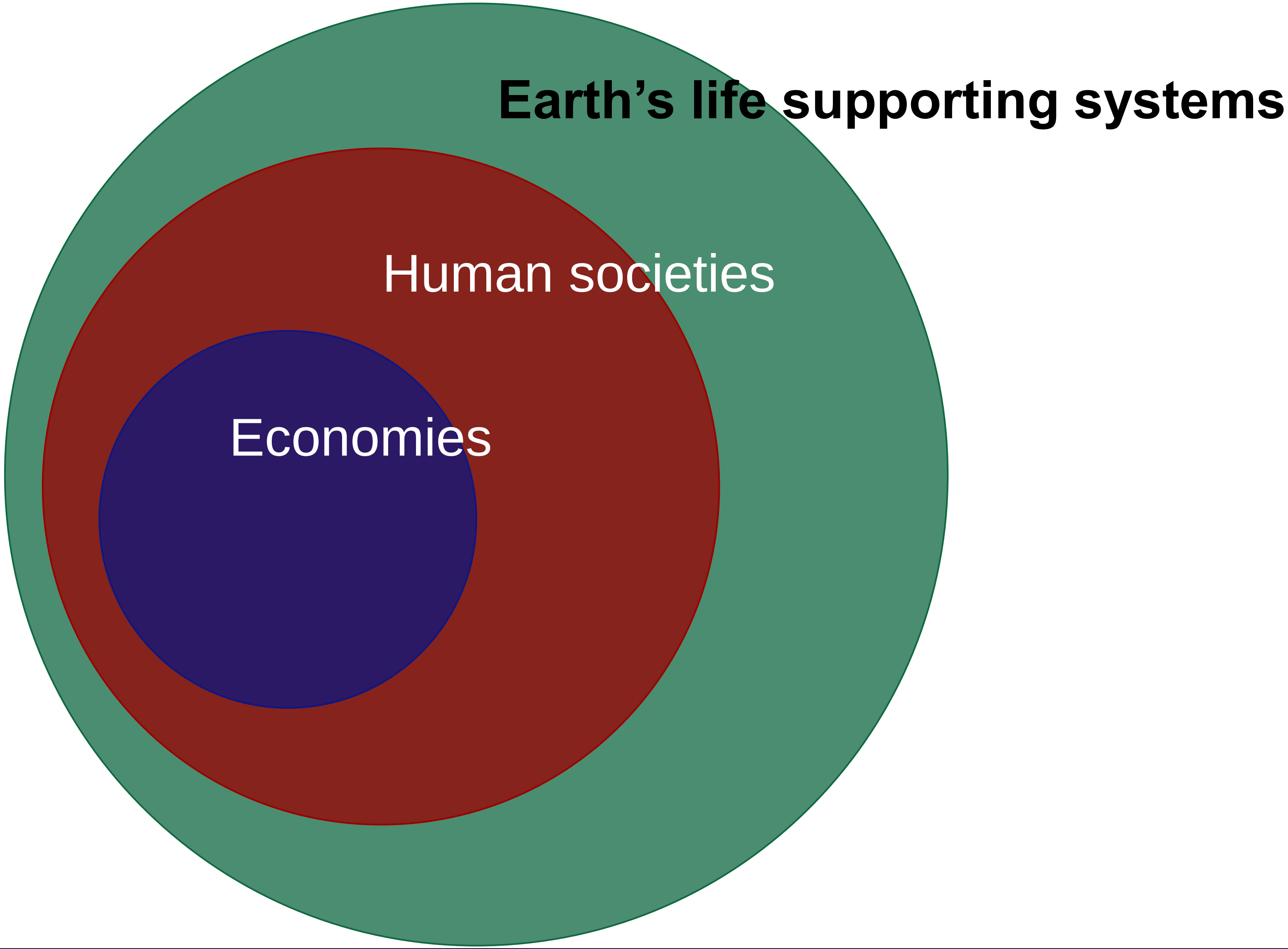
Alternative formulation



Alternative formulation



Alternative formulation



Operational definition

- We have a consensus definition
- We have a framework in which human-nature relations can be operationalized across worldviews to meet this definition
- Consensus-building takes a long time

Stig Irving Olsen, Associate Professor

Quantitative Sustainability: Conceptual frameworks

Learning outcomes of video

- Describe the conceptual causal relationship of environmental impacts
- Describe the importance of technology development in relation to other actions toward a more sustainable future

The sustainability challenge

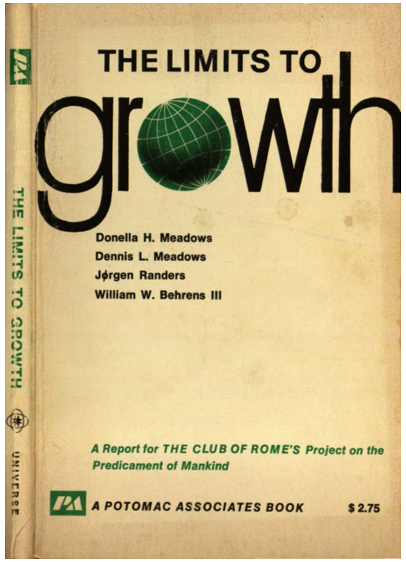
$$I = P \cdot A \cdot T = Pop \cdot \frac{GDP}{person} \cdot \frac{I}{GDP}$$

- 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.

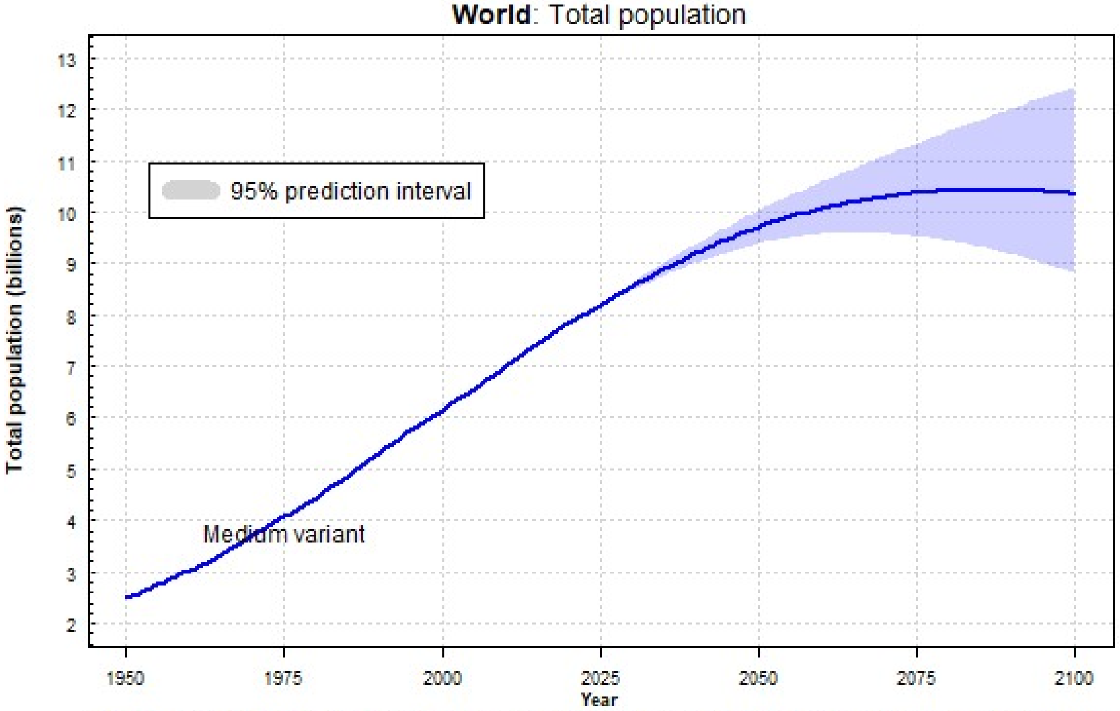
Commoner B (1972) The environmental cost of economic growth. In Ridker RG (ed.) Population, Resources and the Environment, pp. 339- 63. U.S. Government Printing Office, Washington, DC.

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



The global population is increasing

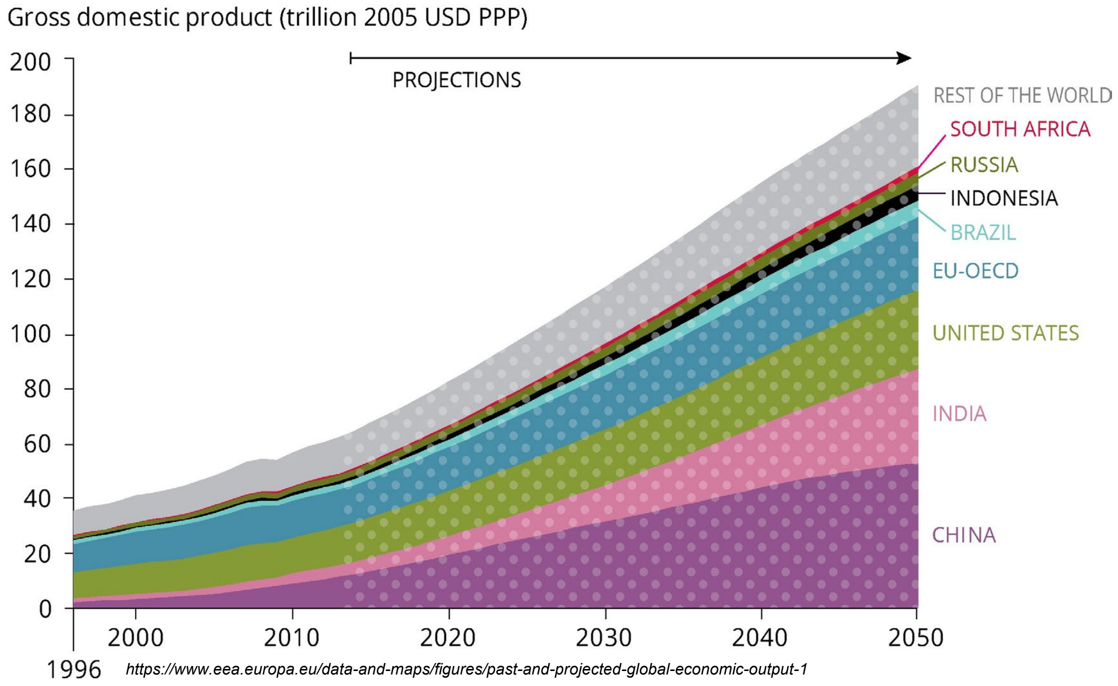
$$I = Pop \cdot \frac{GDP}{person} \cdot \frac{I}{GDP}$$



United Nations, DESA, Population Division. *World Population Prospects 2022*. http://population.un.org/wpp/

The affluence is increasing

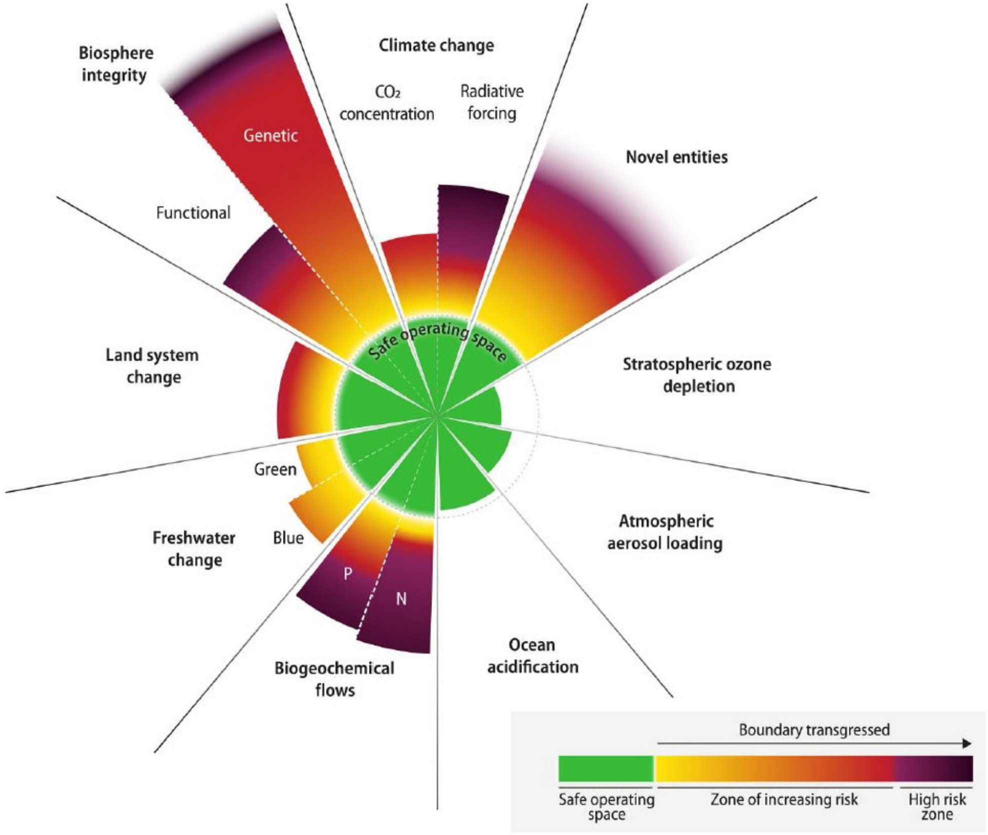
$$I = Pop \cdot \frac{GDP}{person} \cdot \frac{I}{GDP}$$



https://www.eea.europa.eu/data-and-maps/figures/past-and-projected-global-economic-output-1

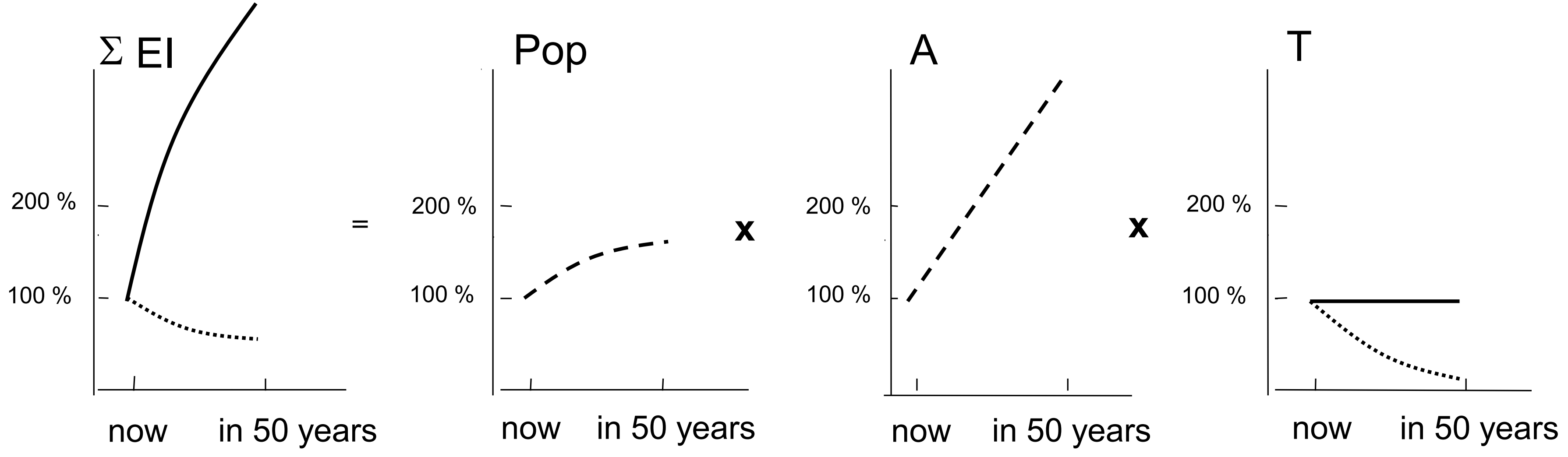
The environmental impacts should be reduced

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



Richardson et al., Sci. Adv. ***9****, eadh2458 (2023)*

How much should the technology factor be reduced?



P · A = the total human demand/consumption will grow by at least a factor of 4-5 in 50 years

Σ EI = the total human impact on the environment will grow accordingly, if the technology factor remains unchanged

T ($\frac{I}{GDP}$) should be reduced by a factor 4 to 20 to achieve environmental sustainability

Need to address the consumption/demand

- Rebound effect
- Increasing human demands

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

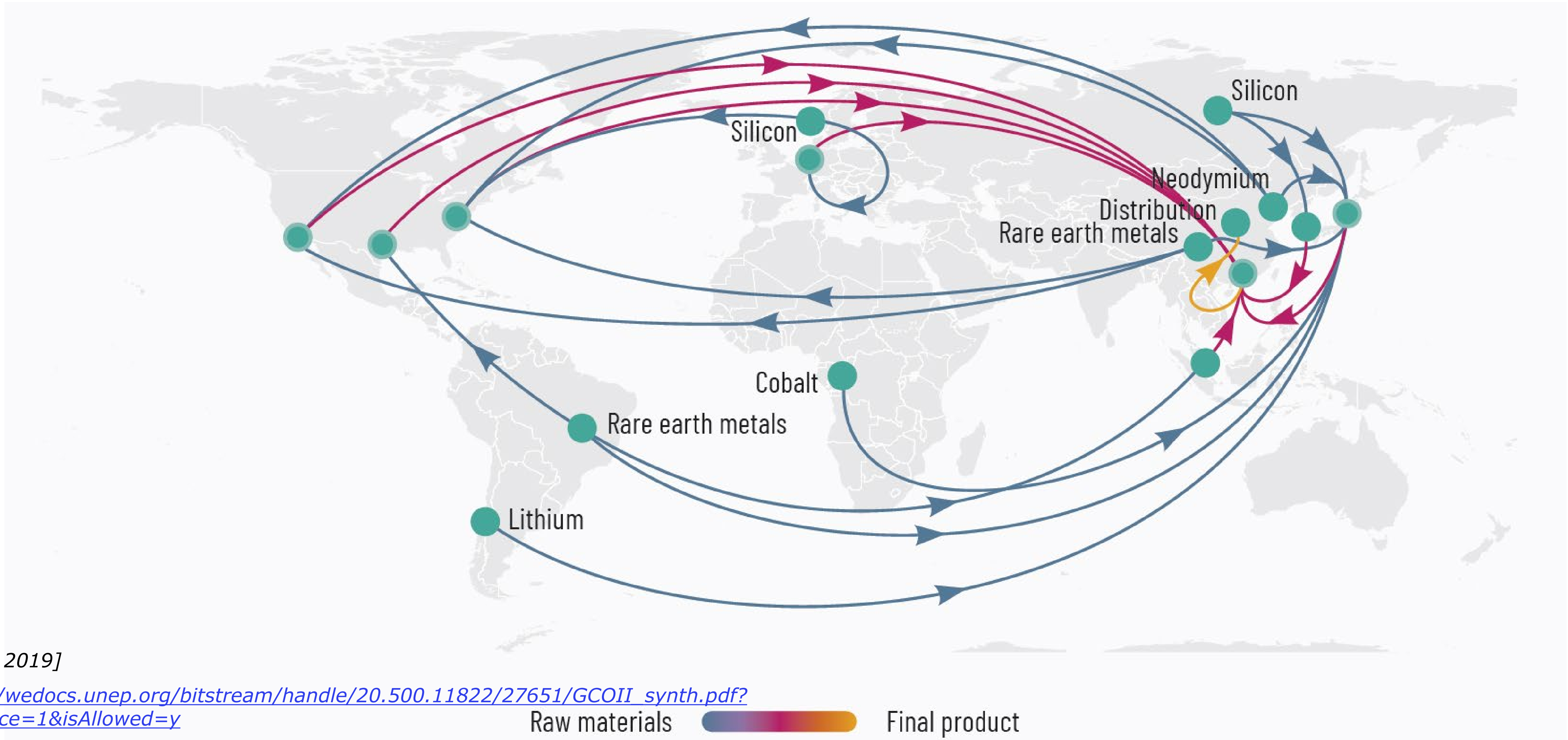
Stig Irving Olsen, Associate Professor

Quantitative Sustainability: The assessment framework

Learning outcomes of video

- Illustrate the generic life cycle of products and systems
- Explain the fundamentals of LCA
- Identify indicators for life cycle sustainability assessment
- Formulate a simplified assessment approach

Value chain is the life cycle - from cradle to grave



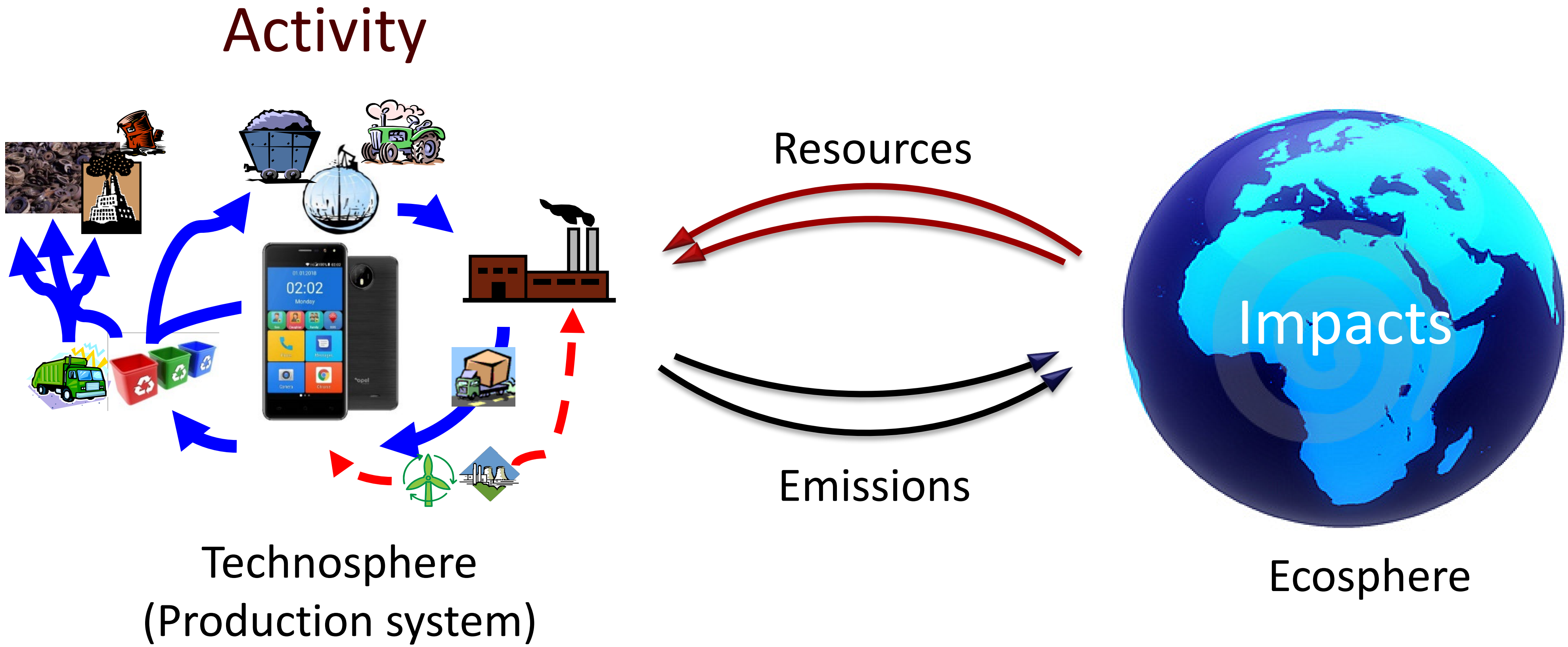
[UNEP, 2019]

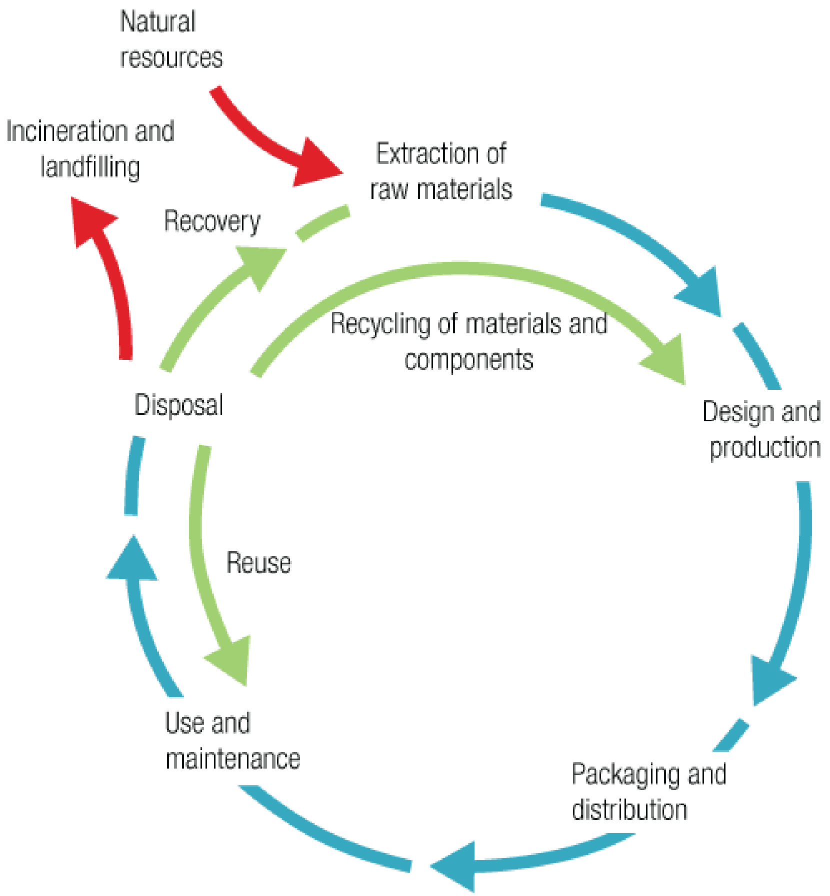
https://wedocs.unep.org/bitstream/handle/20.500.11822/27651/GCOII_synth.pdf?sequence=1&isAllowed=y

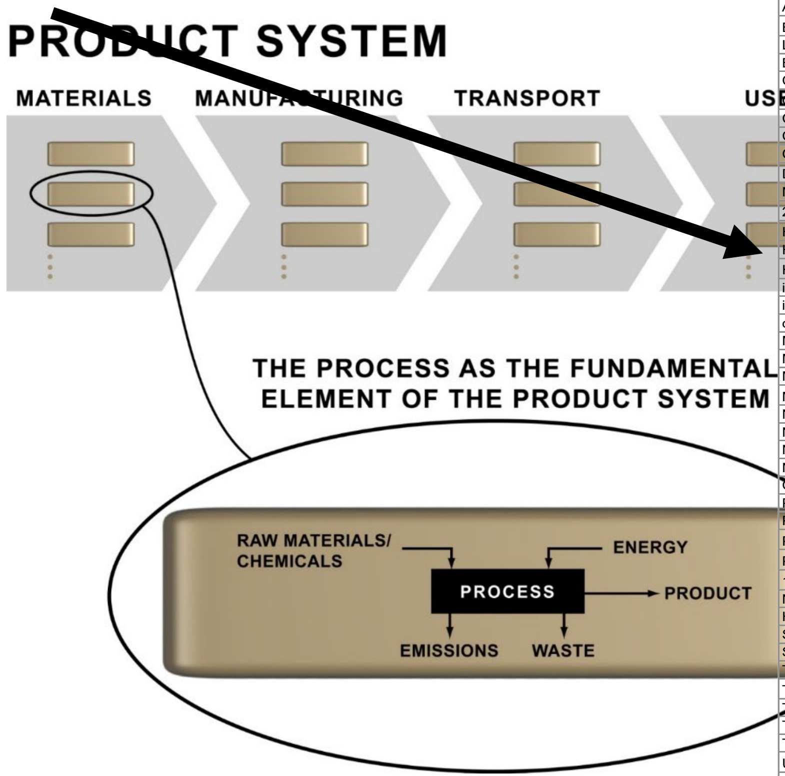

01.01.2018
02:02
Monday
Messages
Camera
Chrome
opel

What is LCA?

How we understand the life cycle - from cradle to grave





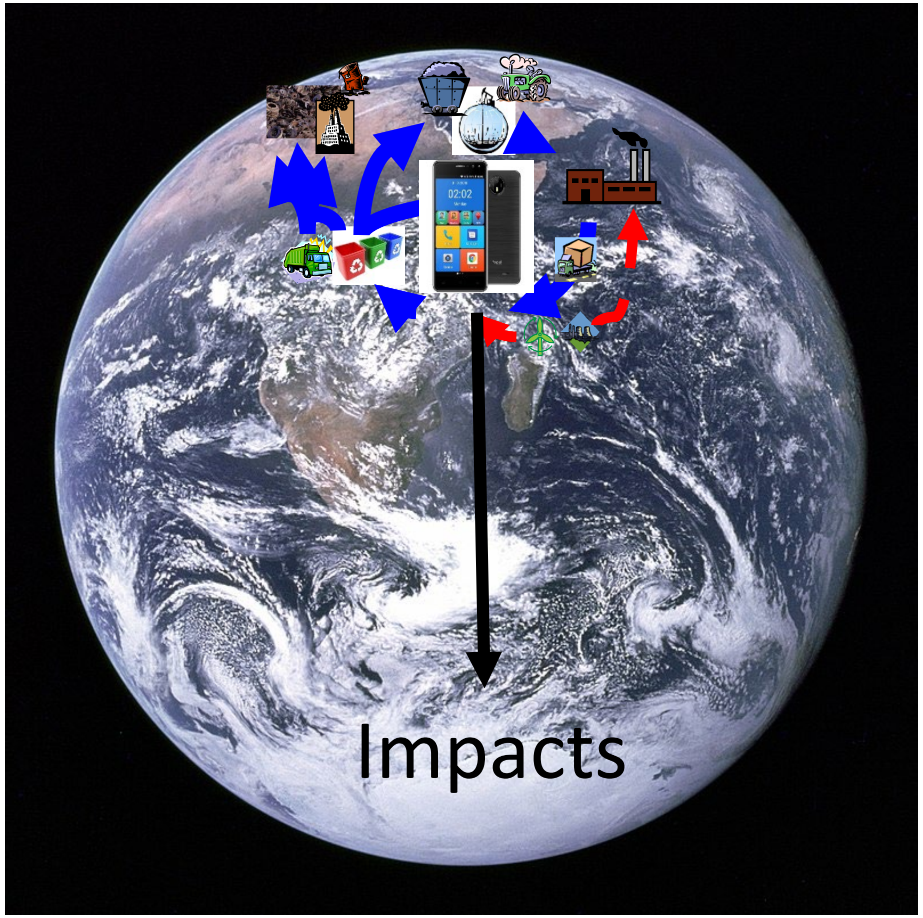


		Emission	Emission
	CAS.no.	to air	to w ater
Substance		g	g
2-hydroxy-ethanacrylate	816-61-0	0,0348	
4,4-methylenebis cyclohexylamine	1761-71-2	5,9E-02	
Ammonia	7664-81-7	3,7E-05	4,2E-05
Arsenic (As)	7440-38-2	2,0E-06	
Benzene	71-43-2 (cur	5,0E-02	
Lead (Pb)	7439-92-1	8,5E-06	
Butoxyethanol	111-76-2	6,6E-01	
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, pow er 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	

What is 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



A fundamental feature of LCA is the focus on service

+ washing

& transport

Vs

Same function

X 30

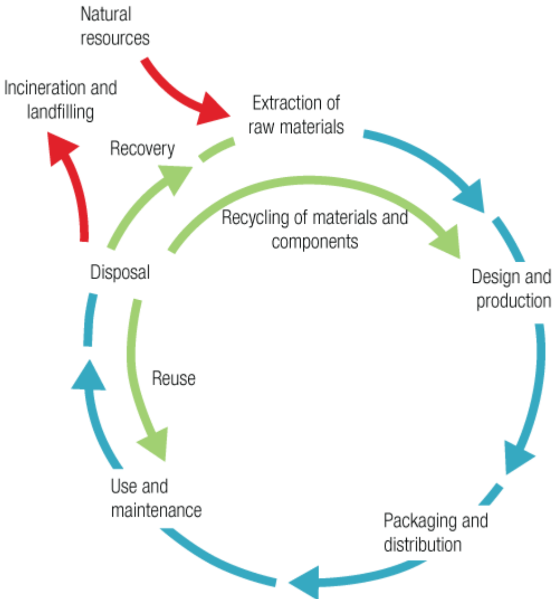
LCA is for comparisons

Is better than

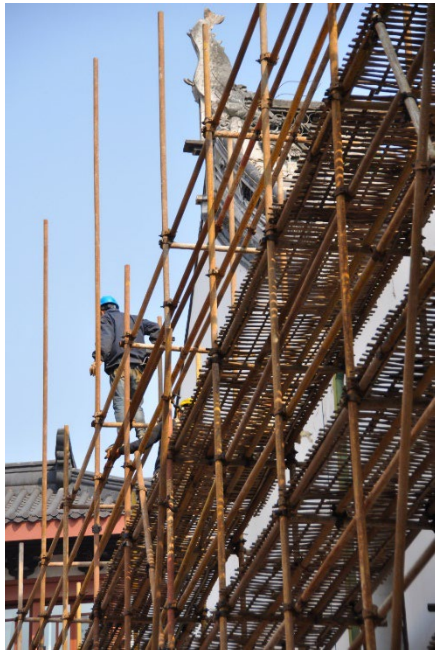
But is it OK for the environment?

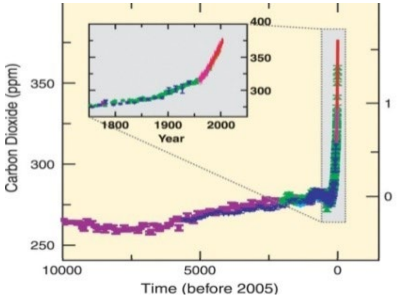
(Absolute perspective)

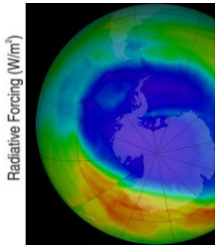
LCA helps avoiding problem shifting



- life cycle from cradle to grave
- All relevant environmental imapcts
- working environment
- resource consumption (biotic and abiotic)







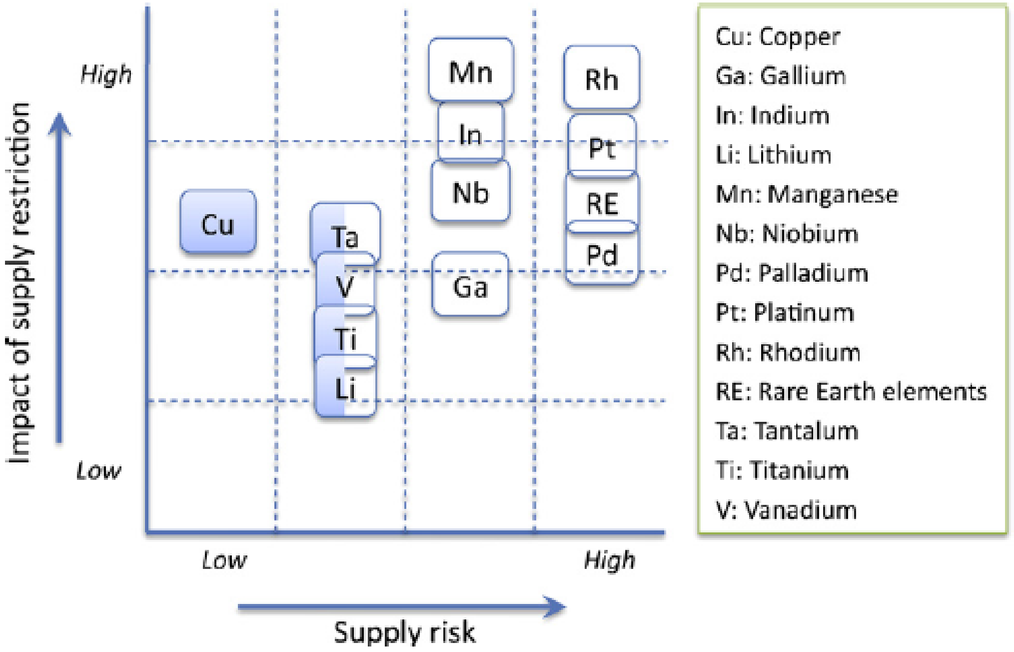
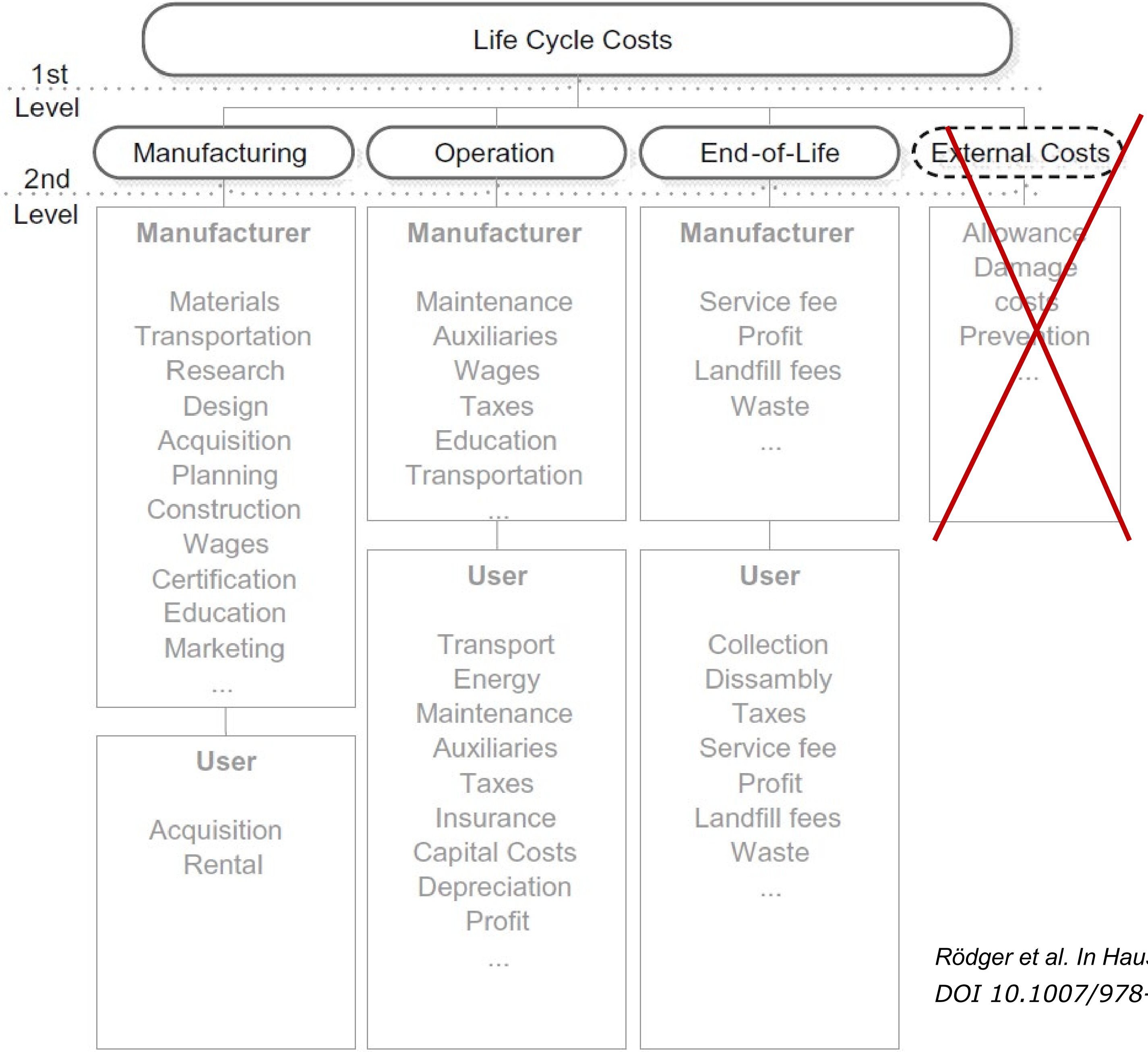


Fig. 2.3. Criticality grid for 11 materials.

Life Cycle Sustainability Assessment (LCSA)

Life Cycle Assessment	Life Cycle Costing	Social Life Cycle Assessment
LCA	LCC	SLCA

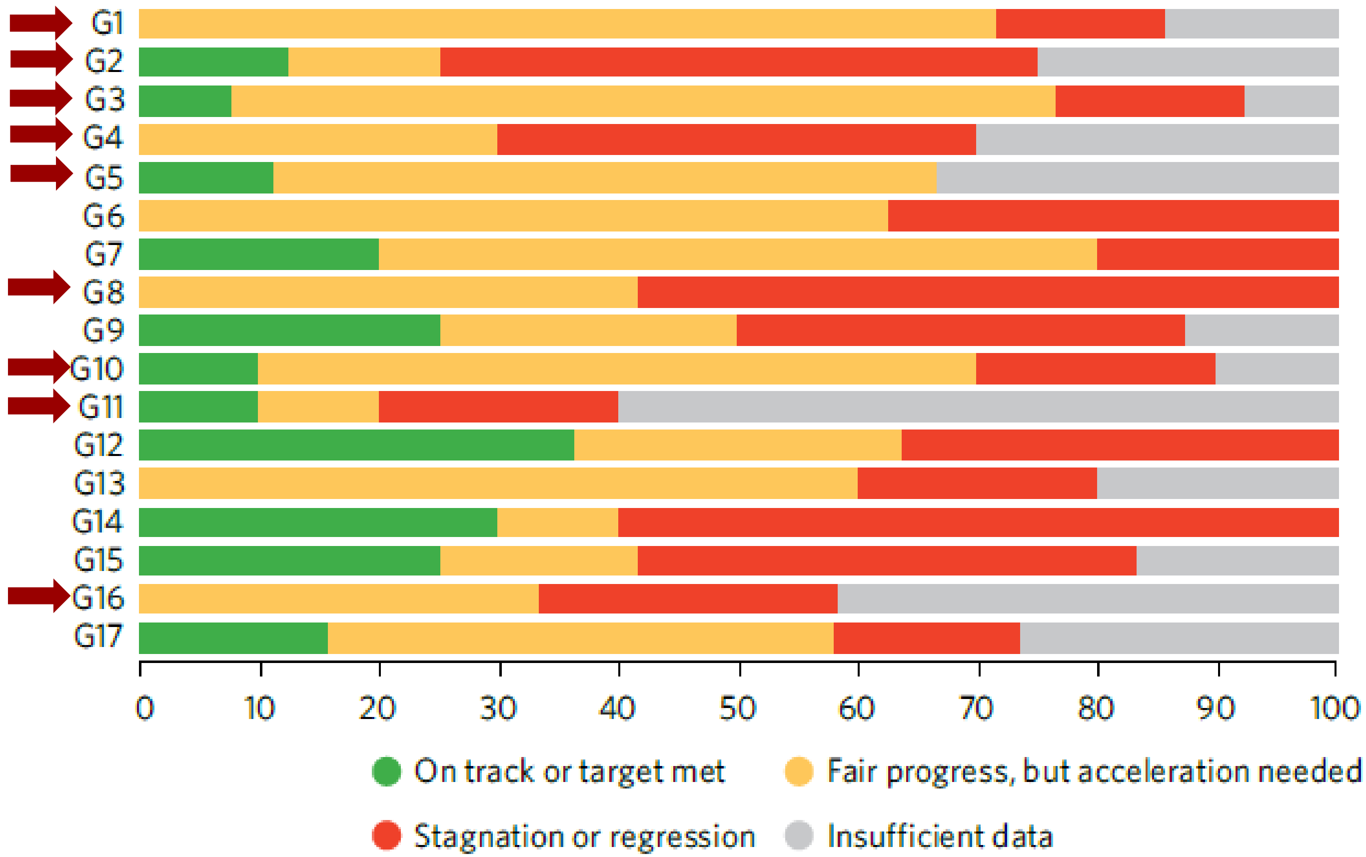
LCA + LCC + SLCA = LCSA



Rödger et al. In Hauschild et al (Eds) Life cycle Assessment, 2018
DOI 10.1007/978-3-319-56475-3_15

DTU

The social side



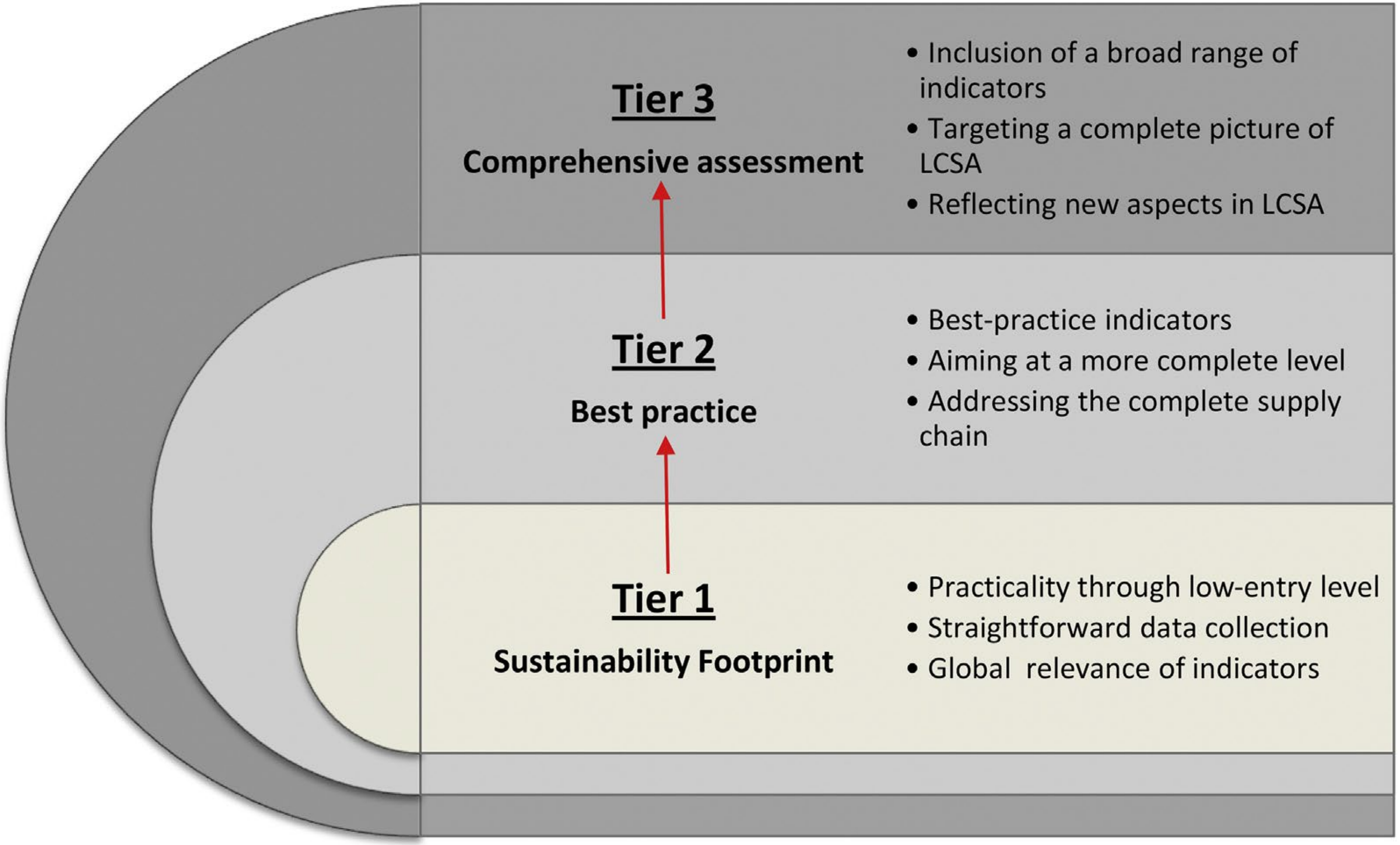
https://unstats.un.org/sdgs/report/2023/progress-midpoint/

Stakeholder categories	Worker	Local community	Value chain actors (not including consumers)	Consumer	Society	Children
Subcategories	1. Freedom of association and collective barganing 2. Child labor 3. Fair salary 4. Working hours 5. Forced labor 6. Equal opportu-nities/discri-mination 7. Health and safety 8. Social bene-fits/social security 9. Employment relationship 10. Sexual harassment 11. Smallholders including farmers	1. Access to material resources 2. Access to immaterial resources 3. Delocalization and migration 4. Cultural heri-tage 5. Safe and healthy living conditions 6. Respect of indigenous rights 7. Community engagement 8. Local employ-ment 9. Secure living conditions	1. Fair compe-tition 2. Promoting social res-ponsibility 3. Supplier rela-tionships 4. Respect of intellectual property rights 5. Wealth distri-bution	1. Health and safety 2. Feedback mechanism 3. Consumer privacy 4. Transparency 5. End-of-life responsibility	1. Public com-mitments to sustainability issues 2. Contribution to economic development 3. Prevention and mitigation of armed conflicts 4. Technology development 5. Corruption 6. Ethical treatment of animals 7. Poverty alle-viation	1. Education provided in the local commu-nity 2. Health issues for children as consumers 3. Children concerns regarding marketing practices

UNEP, 2020. Guidelines for Social Life

Cycle Assessment of Products and Organizations 2020. Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (eds.). United Nations Environment Programme (UNEP).

Stepwise Life Cycle Sustainability Assessment



Neugebauer et al, Journal of Cleaner Production 102 (2015)
http://dx.doi.org/10.1016/j.jclepro.2015.04.053

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.

Quantitative Sustainability framework

	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

Summary

- 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

DTU

Associate professor Stig Irving Olsen

Defining the object of assessment

Learning objectives of this video

- Describe the central properties of a product or system
- Define the object of assessment - the functional unit

The use context sets the background for defining our product or system

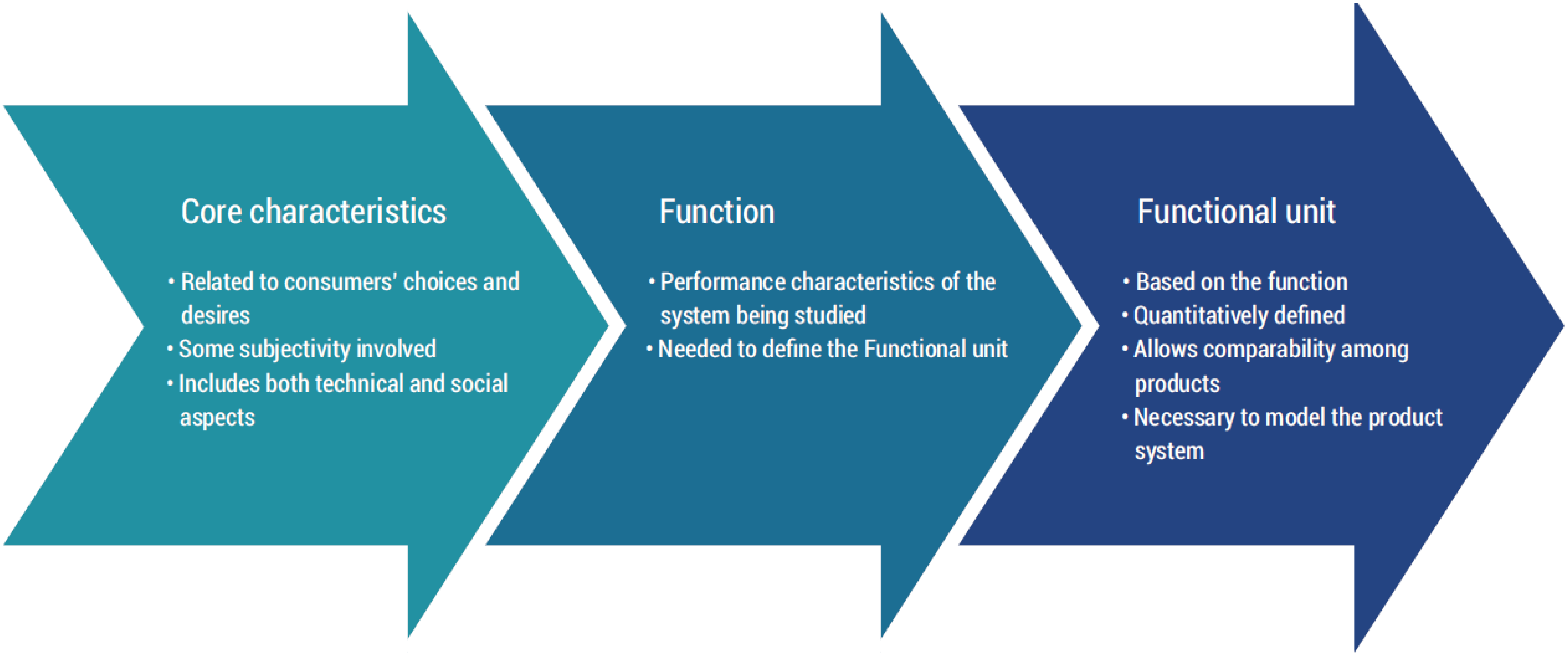
- ***"What should the product be used for?"***
- ***"What does the product do?"***
- ***"... For whom?"***
- ***"... How long?"*** and ***"... how often?"***
- ***"... Where in the world?"***
- → ***Which value contribution does the product deliver to the user***.

List the obligatory and positioning properties of the product or system you are assessing

- Obligatory properties:
  - Decisive for the customers perceiving the products as a product
  - Potential legal requirements
  - Helps define the product

- Positioning properties
  - Makes the product attractive to the customer and position the product in relation to comparable products

Defining the object of assessment is key to comparative studies



UNEP, 2020. Guidelines for Social LifeCycle Assessment of Products and Organizations 2020.Benoît Norris, C., et al (eds.). United Nations Environment Programme (UNEP) (15) (PDF) Guidelines for Social Life Cycle Assessment of Products and Organizations 2020.

Available from: https://wedocs.unep.org/handle/20.500.11822/34554;jsessionid=550D7CE83D0AEDDC5362FC7FA33DA7AA

Defining the functional unit – quantification of service/function/ use context - is essential

- The functional unit is the object for the analysis:

- Expresses the service the product/system deliver in quantitative and qualitative terms
  - Quantity (weight, volume, area, use frequency………)
  - Duration of the service

- Central qualitities or properties

- Essential in order to ensure equivalence between the compared services/systems

Example of definition of functional unit

$$\underbrace{\text{Complete coverage}}_{\text{What?}}\ \underbrace{\text{of 1 m}^2}_{\text{How much?}}\ \underbrace{\text{primed outdoor wall}}_{\text{What?}}\ \underbrace{\text{for 10 years}}_{\text{For how long/ how many times?}}\ \underbrace{\text{in Germany}}_{\text{Where?}}$$

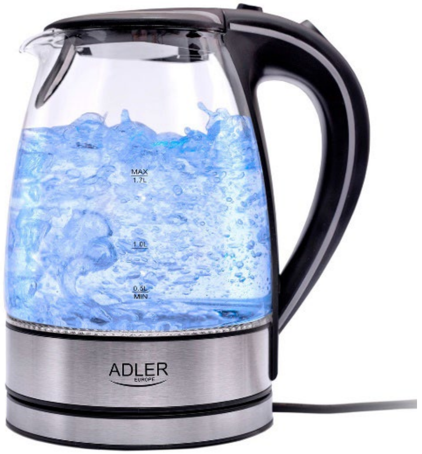
$$\underbrace{\text{in a uniform color at 99.9 \% opacity}}_{\text{How well?}}$$

MZ Hauschild, RK Rosenbaum, SI Olsen: Life Cycle Assessment, Theory and Practice

DOI 10.1007/978-3-319-56475-3

Exercise: Describe the functional unit

- Of a water boiler



- Of a lawn mower

Examples of functional units

- Water boiler:
  - Heat 1 liter of water to the boiling point three times a day for a year in Denmark

What How much How well How many times How long Where

Carbon footprint

In person teaching

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

In person teaching session – format & learning objectives

- Plenum lecture (OJ-60B): Understand why and how to make a carbon footprint (10’)

- Group interpretation (All): Interpret the car case study results (10’)
  and follow-up on main learning shared Vevox

- OJ: Introduce input data for the morning coffee exercise. (5’)
  shortly present the morning coffee wirksheet

- Groups using the on-line platform:
  Perform the carbon footprint of a morning cup of coffee (25’)

- In groups: Discuss results and their meaning- (10’)
  In TAs facilitated room discussion: Share feedbacks and highlights (5’)

- Assess your understanding of a carbon footprint: Self-assessment (10’)

in Module 8, you will be able to apply the carbon footprint approach to your case study!

Determining the carbon footprint of human activity

Why and how

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

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

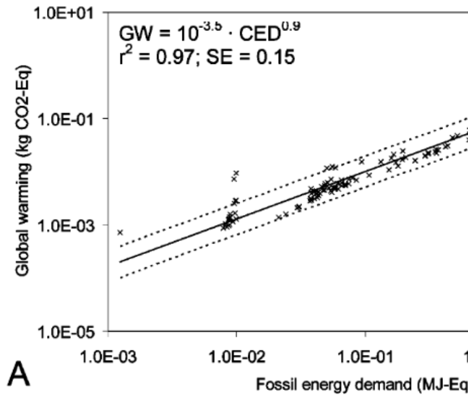
- Because it is useful: It helps identify hotspots in production process and compare products & scenarios per unit of consumption/function

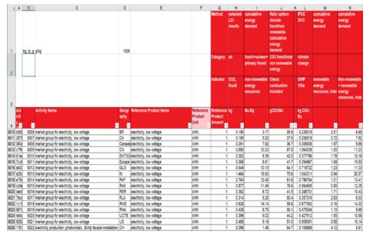
- Because we have a lot of data available to quantify the GHG emission for more than 20,000 processes

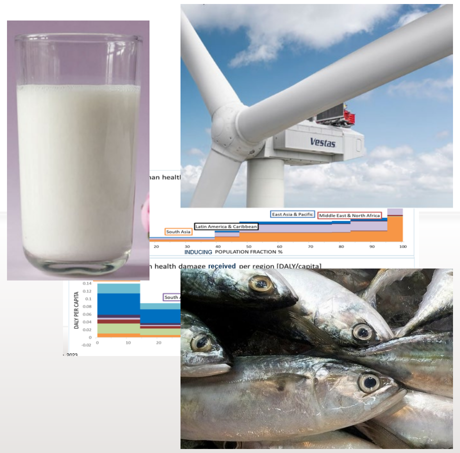
- Because it is relatively simple: every engineers and everybody able to do multiplication and additions can do it

- 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.







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}

How to perform a carbon footprint

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

Case study: Gasoline vs electric vehicle

How to perform a carbon footprint

Collect the
product input data
You!

Column E
e.g. 1040 kg_{steel}/V x 1/150,000km
6.2 kg/100 V-km x 1

Transform them per
functional unit
FU= 1 V-km You

Column F
0.0069 kg_{steel}/V-km
0.062 kg_{gas}/V-km

x
x

Find GHG emission
factors per unit input:
 # in database

Column A→ H
2.2 kg_{CO2eq}/kg_{steel}
4.45 kg_{CO2eq}/kg_{gas}

=
=

Multiply F x H
to get the carbon
footprint per FU

Column I
0.015 kg_{CO2eq}/FU
0.275 kg_{CO2eq}/FU

Process #	Transportation by Gas Vehicle Functional unit (FU)= 1 vehicle km Life Cycle stage (150,000 km lifespan)	Quantity original unit	Unit	Quantity per FU	Process #	Carbon footprint [kgCO2equ/unit]	Carbon footprint [CO2equ./FU]
	Manufacturing (Materials + Processing)	per vehicle over lifespan		per FU			
17299	steel, low-alloyed, hot rolled	1040	kg	6.93E-03	17299	2.18	1.51E-02
16619	sheet rolling, steel	780	kg	5.20E-03	16619	0.31	1.62E-03
458	aluminium, primary, ingot	55	kg	3.67E-04	458	7.21	2.64E-03
16616	Copper & other metals (Zn, Ni, Pb)	38	kg	2.53E-04	16616	0.48	1.22E-04
12456	platinum	1.70E-03	kg	1.13E-08	12456	69669.94	7.90E-04
14632	polyethylene, polypropylene & PVC	175	kg	1.17E-03	14632	2.33	2.72E-03
17718	synthetic rubber	46	kg	3.07E-04	17718	2.97	9.10E-04
7943	glas	32	kg	2.13E-04	7943	1.06	2.25E-04
7364	electronics, for control units	6.1	kg	4.07E-05	7364	31.86	1.30E-03
7587	ethylene, paints, fluids	30	kg	2.00E-04	7587	1.45	2.89E-04
17773	tap water	3400	kg	2.27E-02	17773	0.00	9.87E-06
9148	heat, district or industrial, natural gas	2400	MJ	1.60E-02	9148	0.08	1.21E-03
7235	electricity, medium voltage	2250	kWh	1.50E-02	7235	0.38	5.77E-03
	Transportation	per vehicle		per FU			
18124	transport, freight train	556.50	metric ton*km	3.71E-03	18124	0.05	1.70E-04
18241	transport, freight, lorry 16-32 metric ton	59.10	metric ton*km	3.94E-04	18241	0.19	7.52E-05
18438	transport, freight, sea, container ship	11376.81	metric ton*km	7.58E-02	18438	0.01	7.71E-04
	Use phase	per V-km		per FU			
14137	Supply chain petrol, low-sulfur	0.0619	kg	6.19E-02	14137	1.02	6.30E-02
100001	Direct combustion	0.0619	kg petrol	6.19E-02	100001	3.43	2.12E-01
	Disposal	per vehicle over lifespan		per FU			
19923	plastic mixture incineration	221.00	kg	1.47E-03	19923	2.35	3.46E-03
19515	Glass to landfill	283.00	kg	1.89E-03	19515	0.01	1.07E-05
7235	Avoided electricity plastic incineration	221.00	kWh	-0.00435	7235	0.38	-1.67E-03

Sum up → **0.311**

The ecoinvent database

12772_Cut-off Cumulative LCIA v3.8_selected short1b

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		kg_to_g	g/kg	1000			Method	selected LCI results	cumulative energy demand	Ratio carbon dioxide fossil/non renewable cumulative energy demand		IPCC 2013	cumulative energy demand	cumulative energy demand
2							Category	air	fossil+nuclear+ primary forest	CO2 fossil/total non renewable energy		climate change		
3							Indicator	CO2, fossil	non-renewable energy resources	Check combustion included		GWP 100a	renewable energy resources, total	Non-renewable + renewable energy resources, total
4	Activity U...		Activity Name	Geography	Reference Product Name	Reference Product Unit	Reference Product Amount	kg	MJ-Eq	gCO2/MJ		kg CO2-Eq		
6010	b068	6006	market group for electricity, low voltage	BR	electricity, low voltage	kWh	1	0.190	3.17	59.9		0.239016	3.51	6.69
6011	2878	6007	market group for electricity, low voltage	CA	electricity, low voltage	kWh	1	0.195	5.20	37.5		0.206518	2.72	7.92
6012	060e	6008	market group for electricity, low voltage	Canada	electricity, low voltage	kWh	1	0.291	7.92	36.7		0.306936	1.97	9.89
6013	c7f9	6009	market group for electricity, low voltage	CN	electricity, low voltage	kWh	1	0.890	10.23	87.0		1.064039	1.00	11.23
6014	61ea	6010	market group for electricity, low voltage	ENTSO	electricity, low voltage	kWh	1	0.352	8.39	42.0		0.377786	1.78	10.16
6015	7ccb	6011	market group for electricity, low voltage	Europe	electricity, low voltage	kWh	1	0.368	8.81	41.7		0.394867	1.68	10.50
6016	ab00	6012	market group for electricity, low voltage	GLO	electricity, low voltage	kWh	1	0.648	10.10	64.1		0.718722	1.23	11.33
6017	e26c	6013	market group for electricity, low voltage	IN	electricity, low voltage	kWh	1	1.484	19.63	75.6		1.543311	0.94	20.57
6018	e75e	6014	market group for electricity, low voltage	RAF	electricity, low voltage	kWh	1	0.764	12.40	61.6		0.796764	1.01	13.41
6019	cc6e	6015	market group for electricity, low voltage	RAS	electricity, low voltage	kWh	1	0.877	11.45	76.6		0.984805	0.90	12.35
6020	deb8	6016	market group for electricity, low voltage	RER	electricity, low voltage	kWh	1	0.362	8.72	41.5		0.388731	1.71	10.43
6021	7bcc	6017	market group for electricity, low voltage	RLA	electricity, low voltage	kWh	1	0.314	5.20	60.4		0.357316	2.83	8.03
6022	1c19	6018	market group for electricity, low voltage	RME	electricity, low voltage	kWh	1	0.828	14.14	58.6		0.877363	0.16	14.30
6023	667c	6019	market group for electricity, low voltage	RNA	electricity, low voltage	kWh	1	0.438	8.75	50.1		0.475546	1.15	9.89
6024	4bbc	6020	market group for electricity, low voltage	UCTE	electricity, low voltage	kWh	1	0.399	9.02	44.2		0.427512	1.55	10.56
6025	9292	6021	market group for electricity, low voltage	US	electricity, low voltage	kWh	1	0.469	9.19	51.0		0.509351	0.95	10.14
6026	1761	6022	electricity production, photovoltaic, 3kWp facade installation,	CH	electricity, low voltage	kWh	1	0.096	1.49	64.7		0.109668	4.12	5.61

Scenario comparison and interpretation

Interpretation Principles

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

DTU

Interpretation question for each scenario

Which are the largest contribution to the environmental impact in terms of production phase, in terms of pollutant?

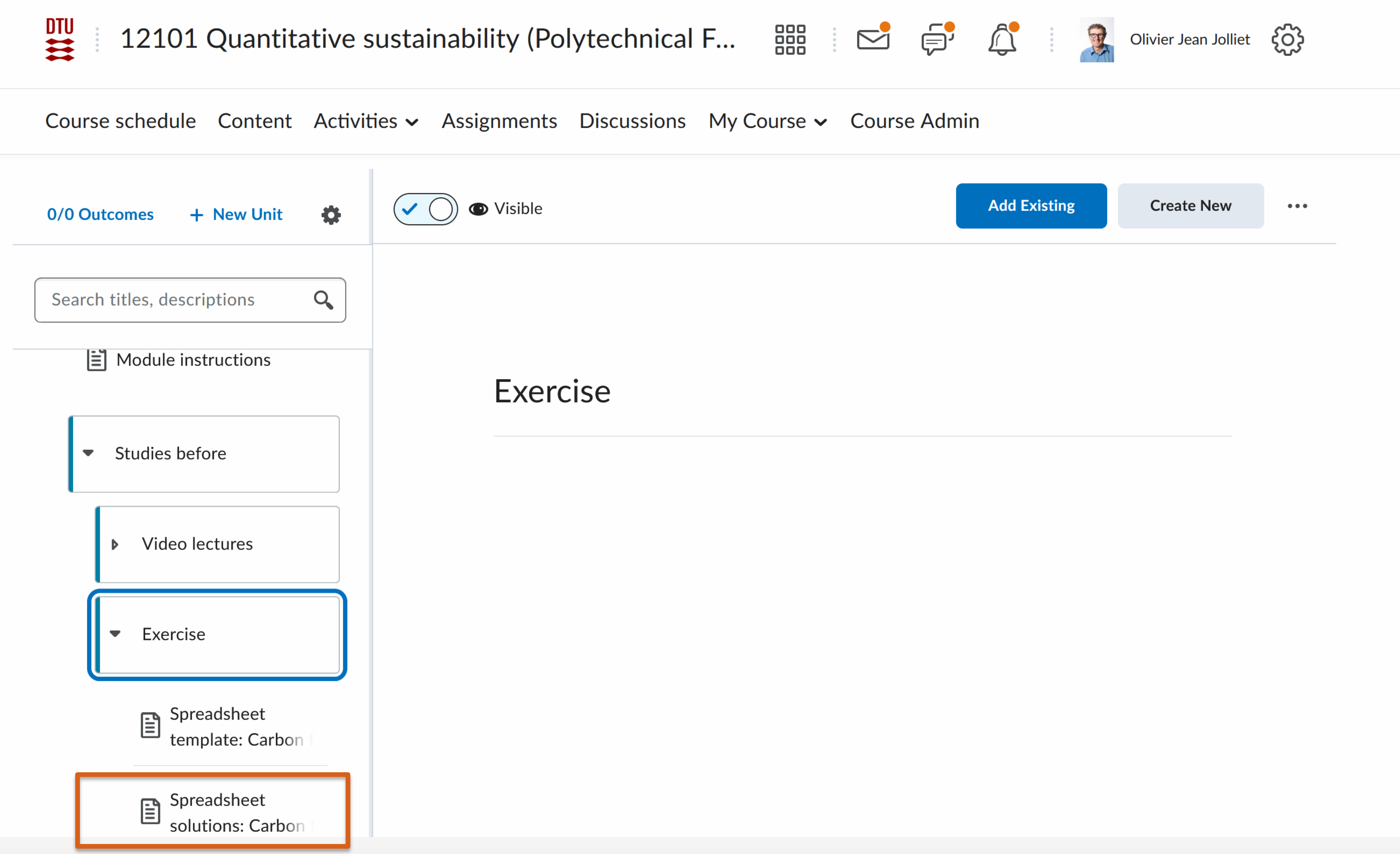
- The grouping of processes can be arbitrary and depends on how the system is modeled.
- Also consider large sets of individual processes that each appear to have small impacts but lead to substantial impacts when summed

Which life cycle stage has the highest potential to reduce impacts (also depending on feasibility)

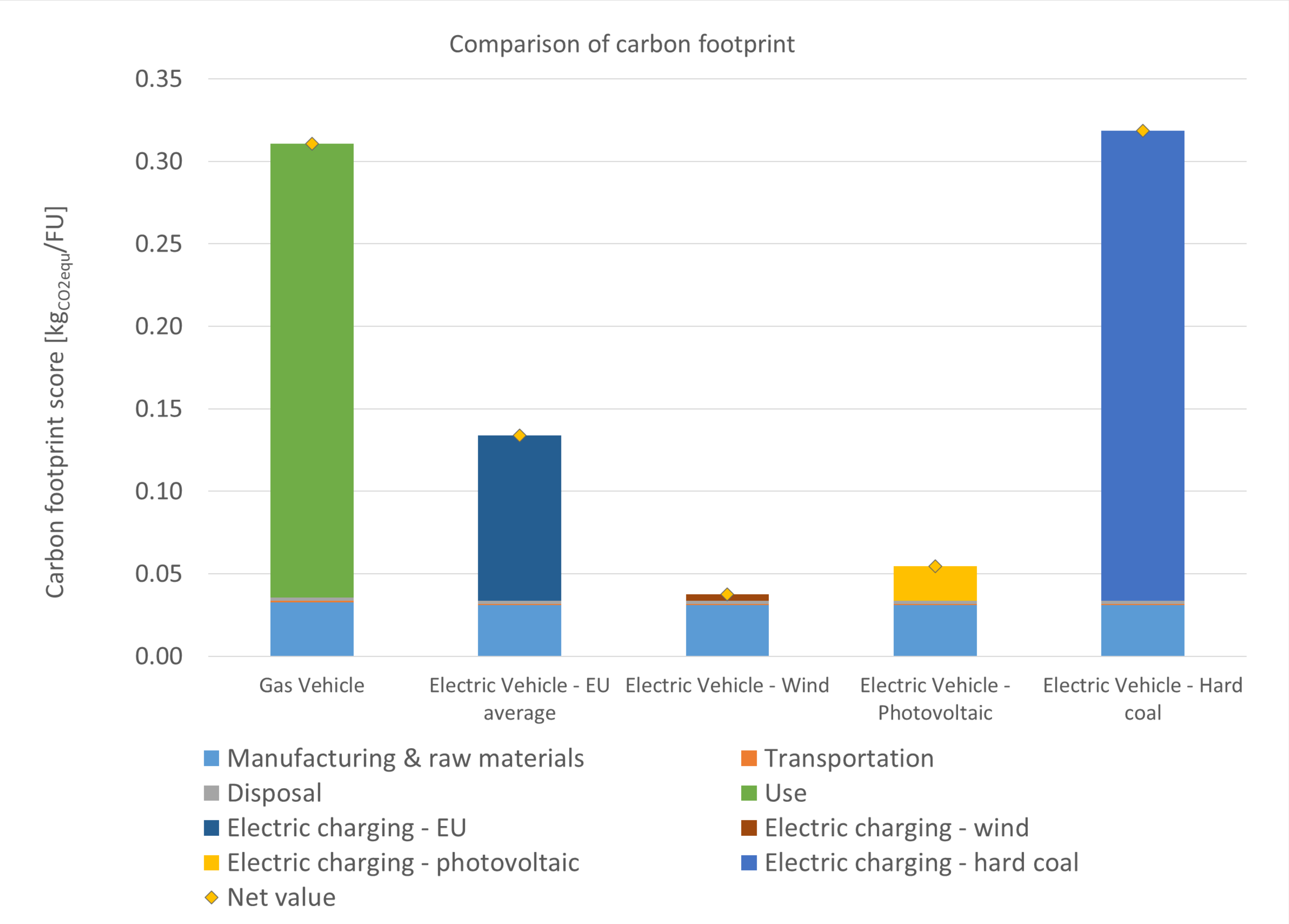
- In some win-win cases, both impacts and costs can be reduced at the same time.
- Even a limited low-cost intervention can be extremely efficient in reducing impacts.
- **If some results are surprising:** WHY? What are the underlying parameter components and stages responsible for it?

Never let it go until you understand the rational for a difference or a surprising results. Either you made a mistake … or you will learn something!

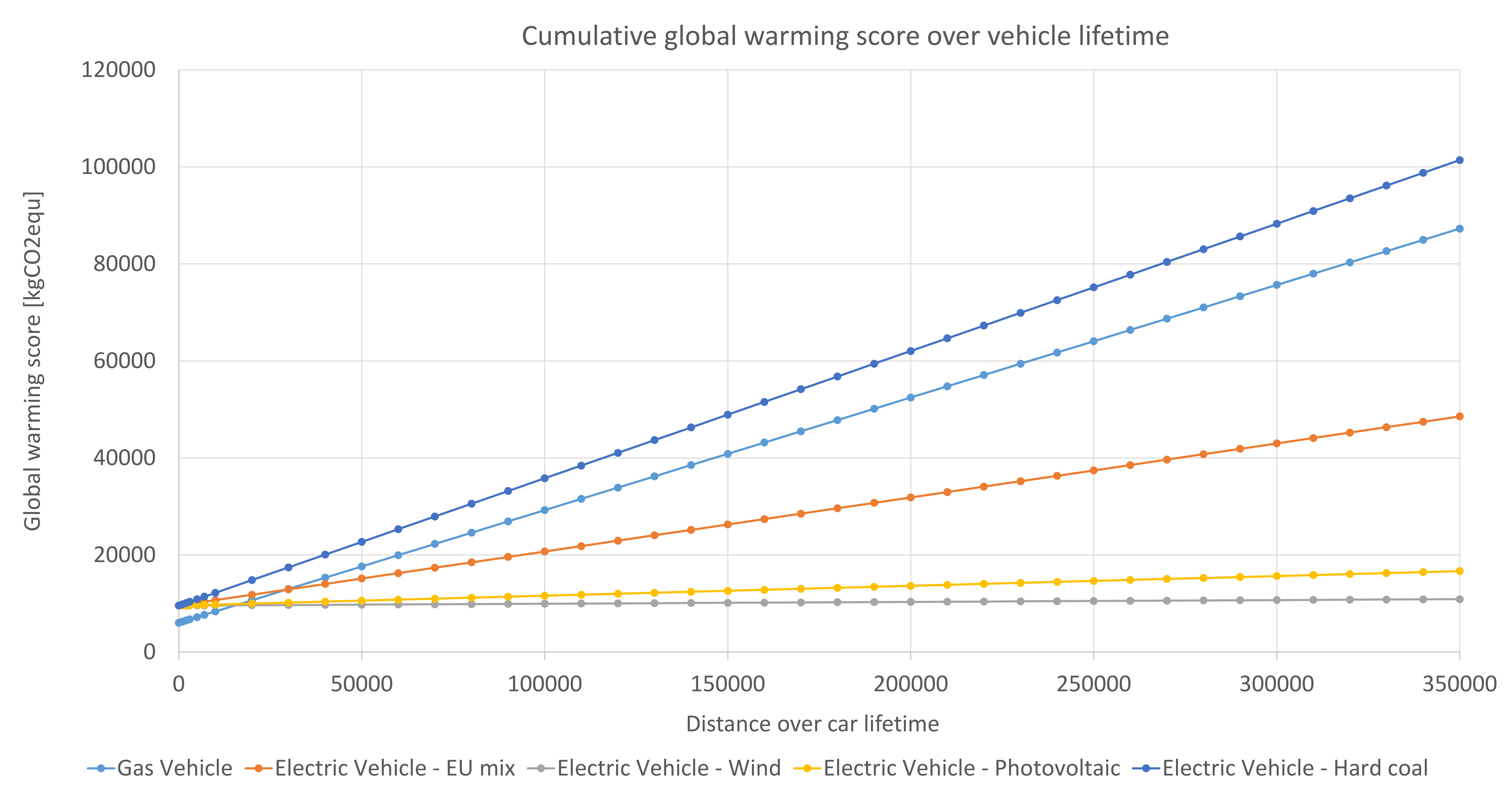
Download the car solutions



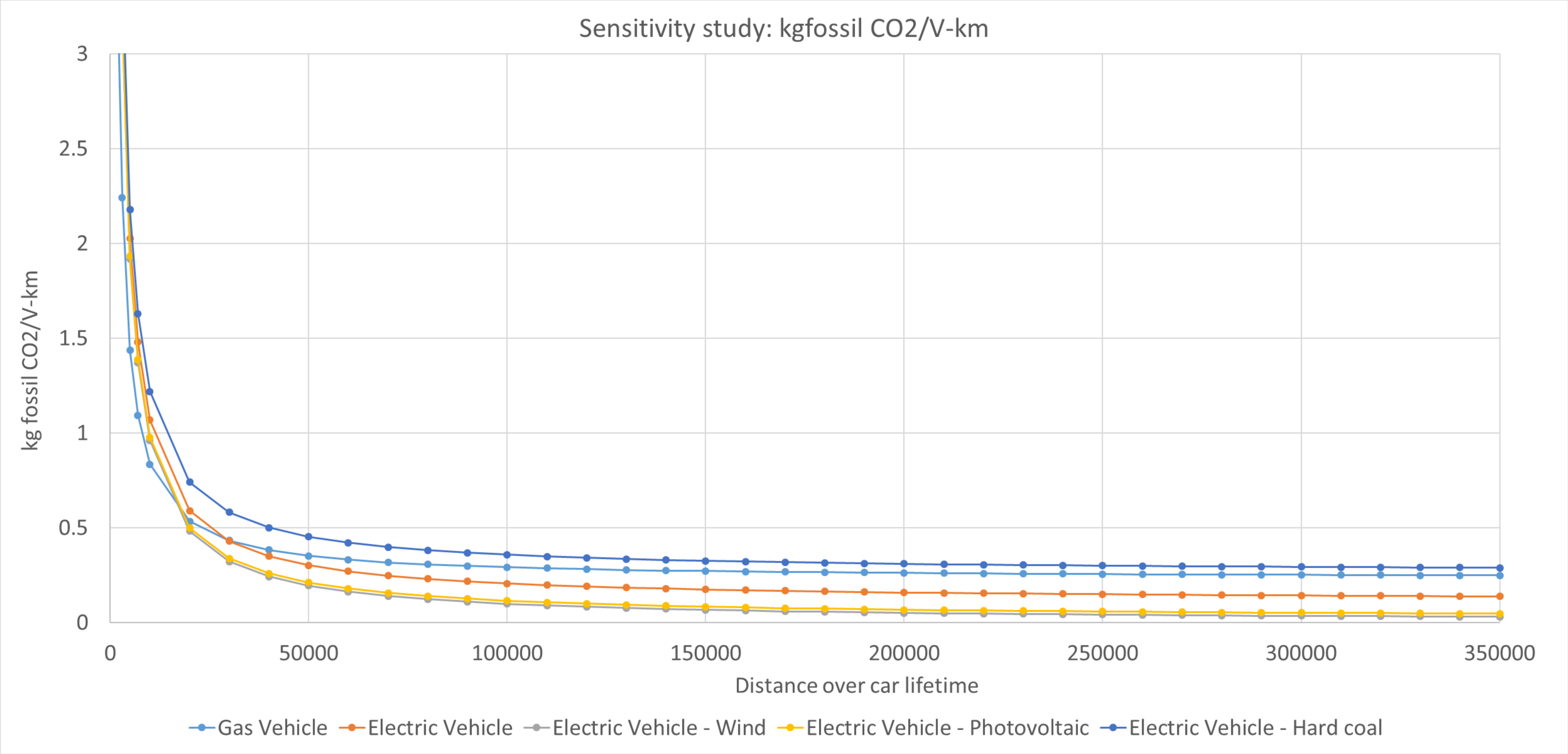
Carbon footprint: gasoline vs electric vehicle



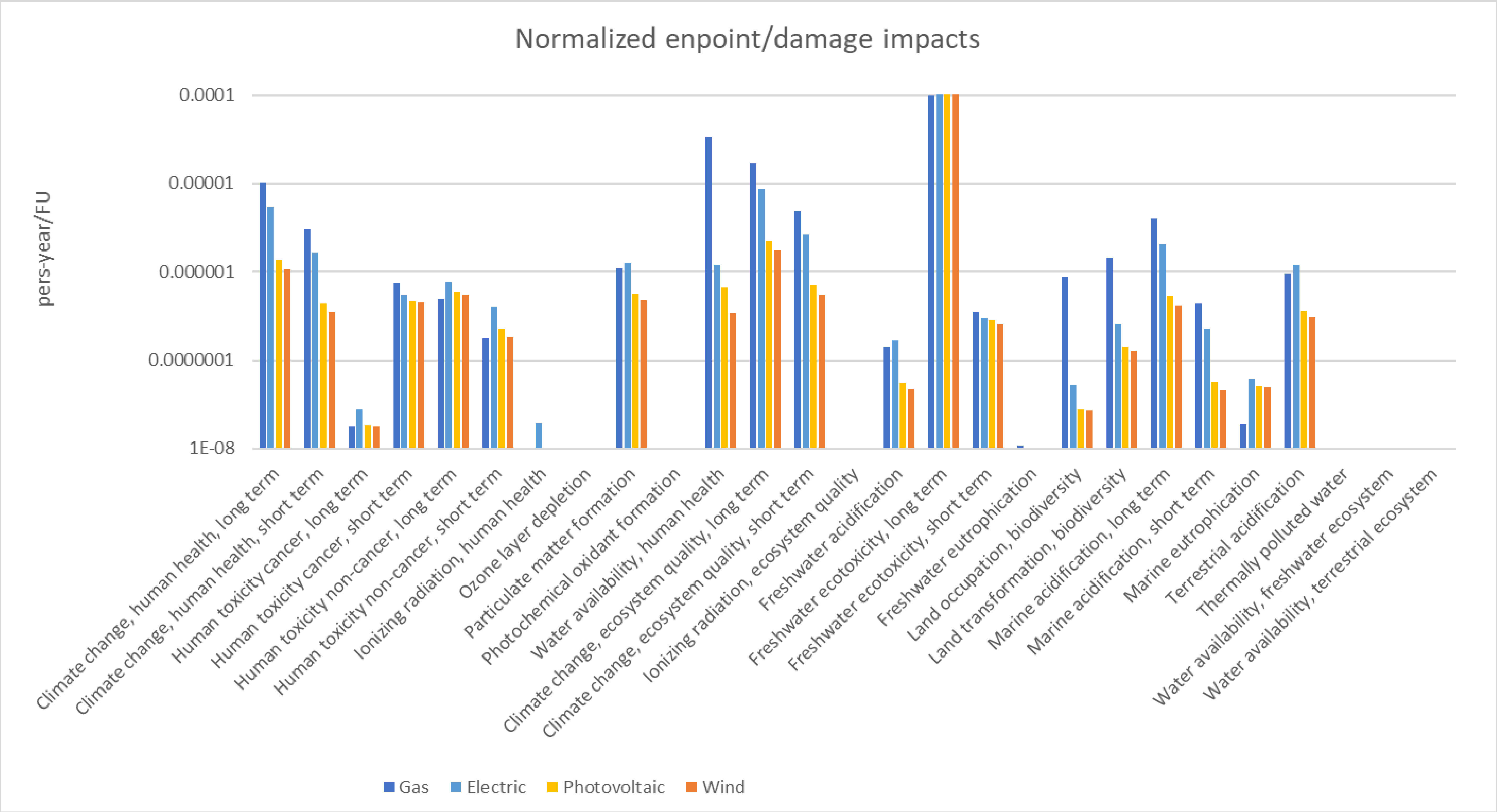
Sensitivity study: cumulative carbon footprint as a function of vehicle lifetime



Sensitivity study: carbon footprint per FU as a function of vehicle lifetime



Comparison of normalized damage Impact World+ Life cycle impact Assessment



Carbon footprint practice

Morning coffee – important for case study and exam

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

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Coffee carbon footprint exercise

Carbon footprint of a cup of coffee - input data and footprint analysis of baseline scenario.

First download the carbon footprint template "Spreadsheet template - Carbon footprint of coffee (vSep2025b).xlsx" you are going to study.

A morning coffee might be essential for many people. But, **what are the most important inputs contributing to the carbon footprint of a cup of roasted coffee?**

You want to calculate the carbon footprint 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 coffee green beans.

Coffee needs to be roasted which requires 2.63 MJ of heat from natural gas and 0.11 kWh DK electricity **per kg coffee**.

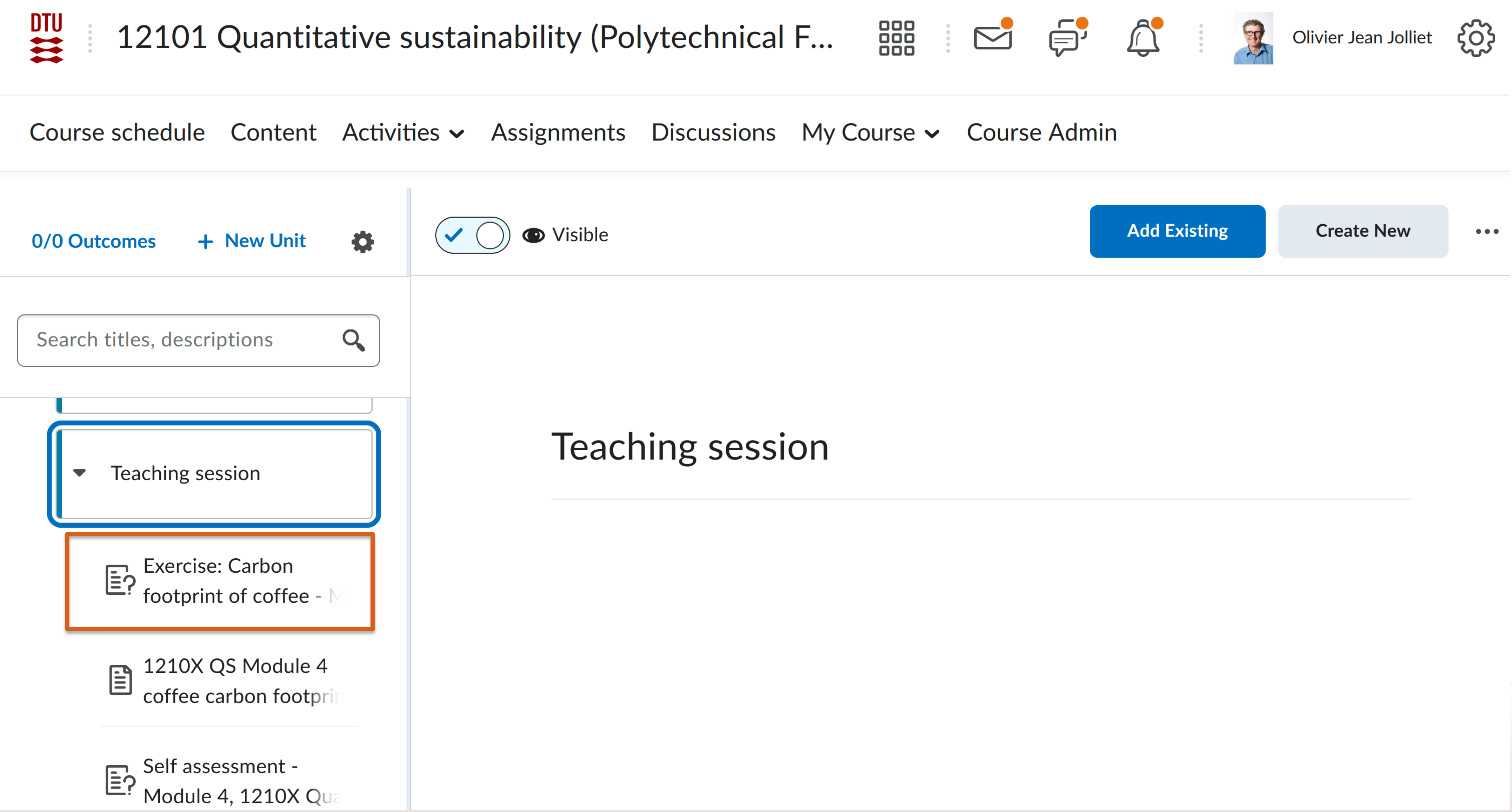
The coffee maker has a lifespan of 10 years and is used by 2 persons getting 2 cups every day of the year

Hot water heating requires **0.12 kWh per liter water** and **0.028 kWh per cup** for the coffee machine stand-by.

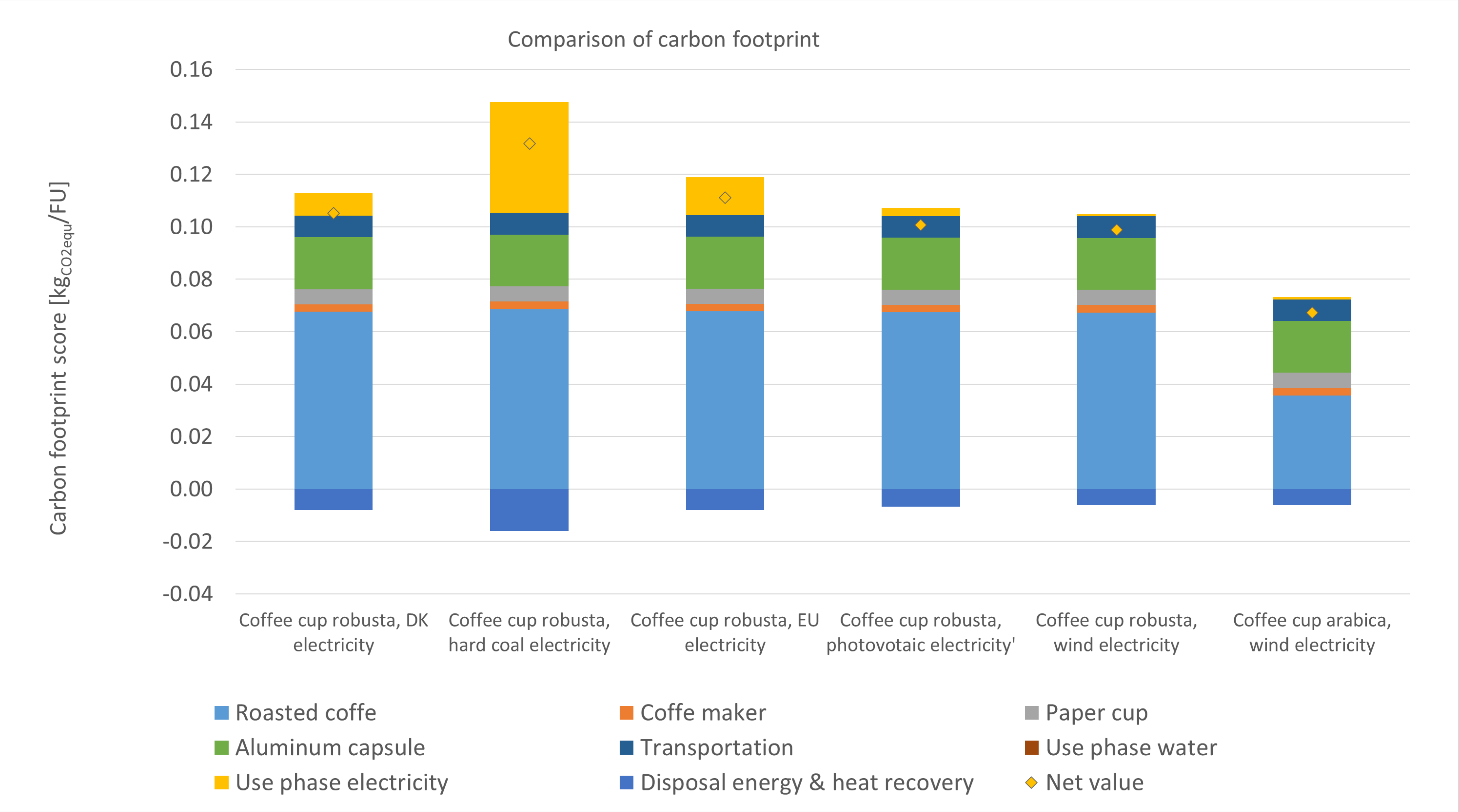
Coffee is transported over 3500 km by truck and 4500 km by sea freight.

At its end of life, paper packaging and the coffee maker are incinerated with energy recovery.

Go on module 4, teaching session



Carbon footprint comparison



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 CO_2 and energy balance of a cup of roasted coffee.

You want to calculate the energy and CO_2 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 CO_2

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

Introduction to environmental indicators

Carbon footprint

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

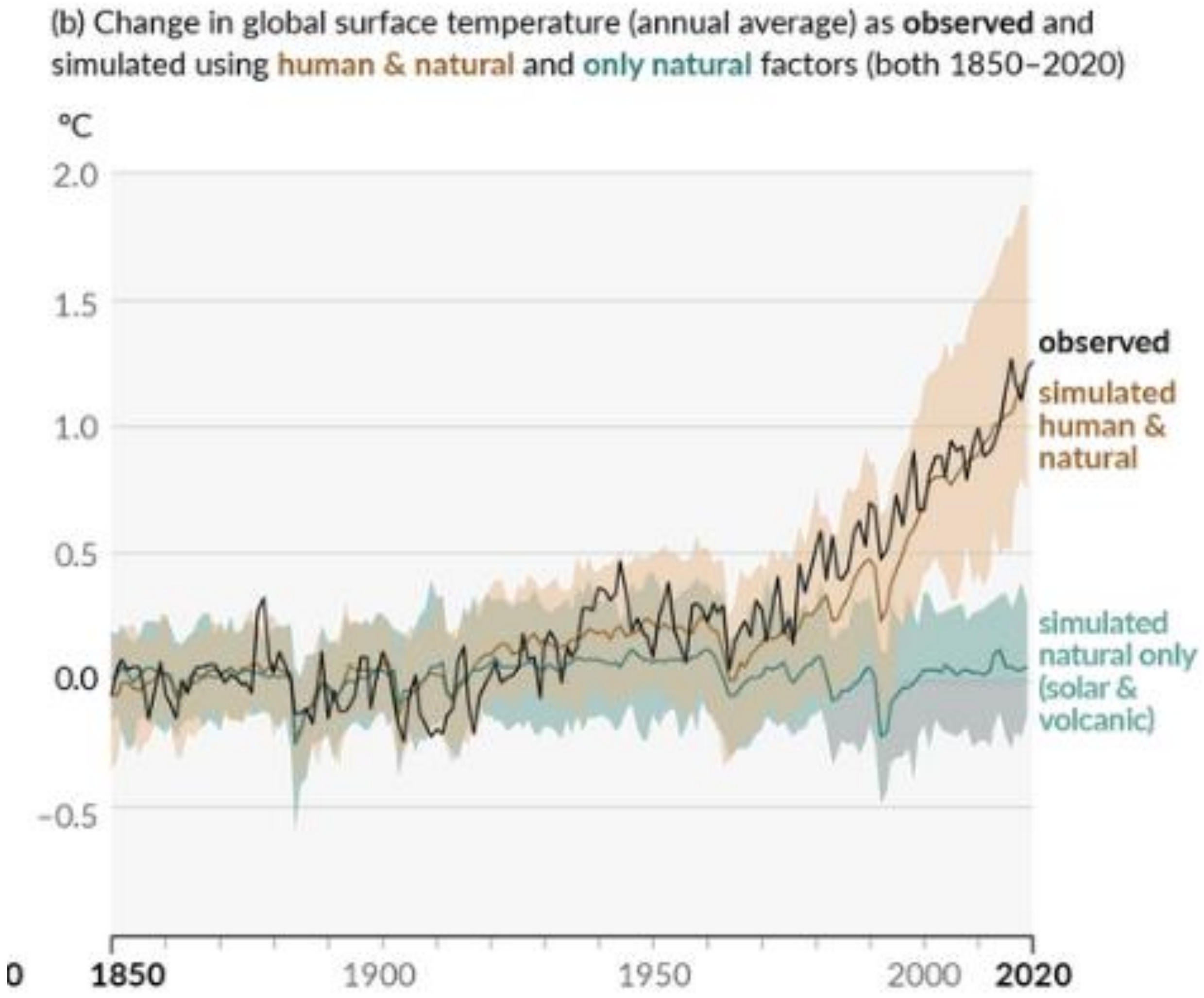
DTU

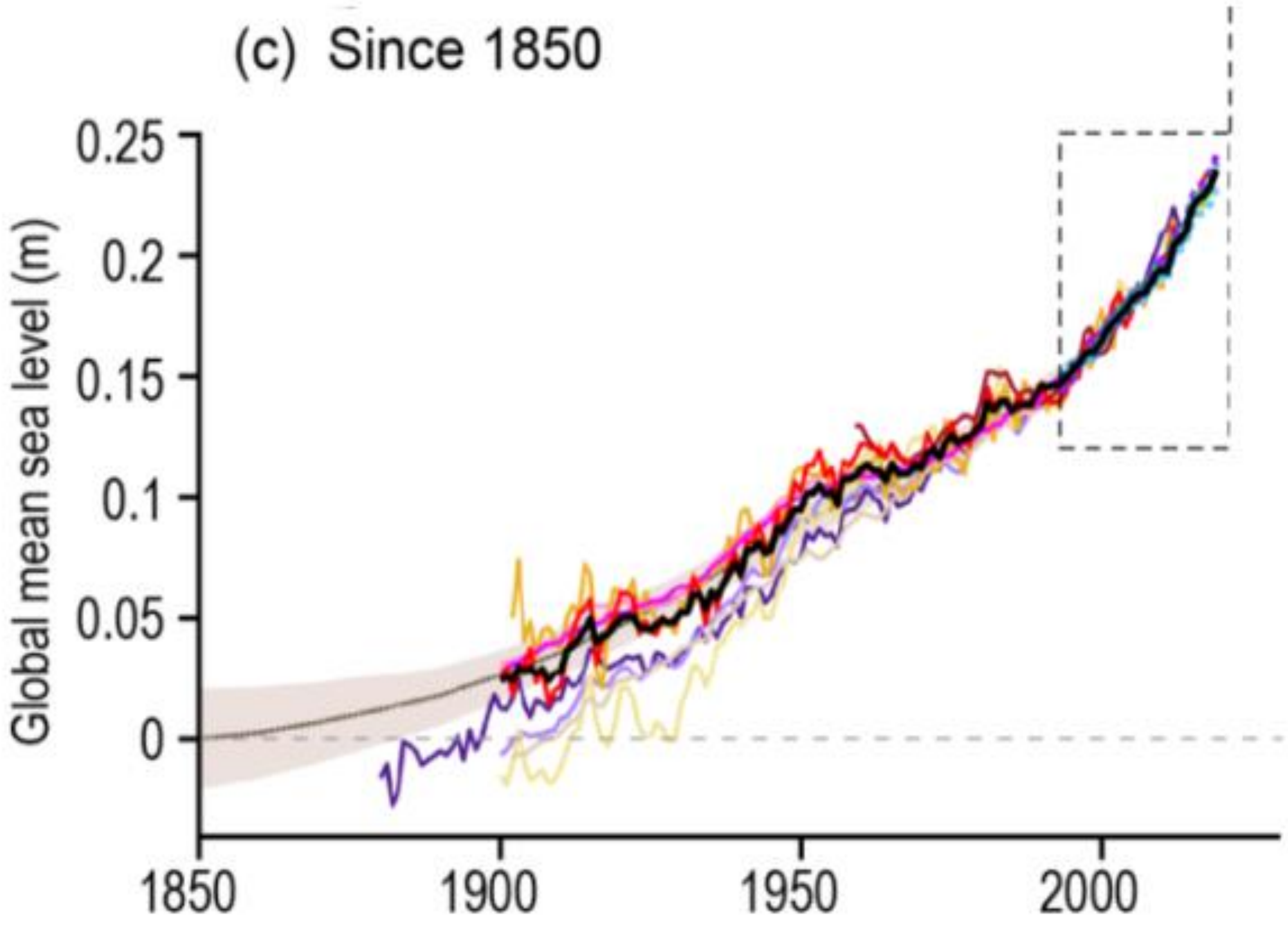
Learning objectives

- Apply a causal framework to relate human activity to climate change indicators
- Calculate carbon footprint to determine how different substances can be aggregated based on impact
- Position the carbon footprint vs other indicators

Global warming – Diagnostic and causes

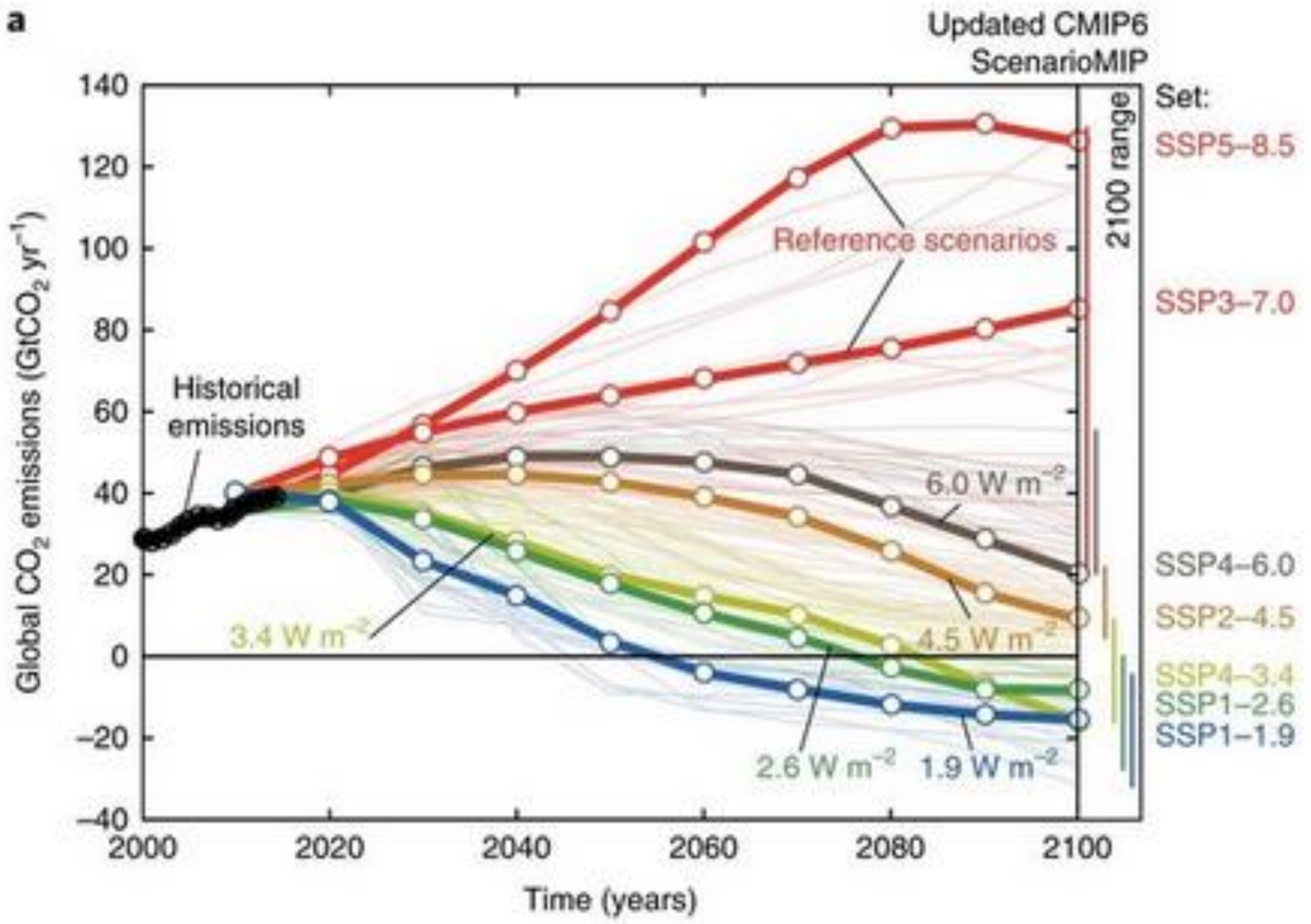
Global warming relative to 1850-1900 (°C)

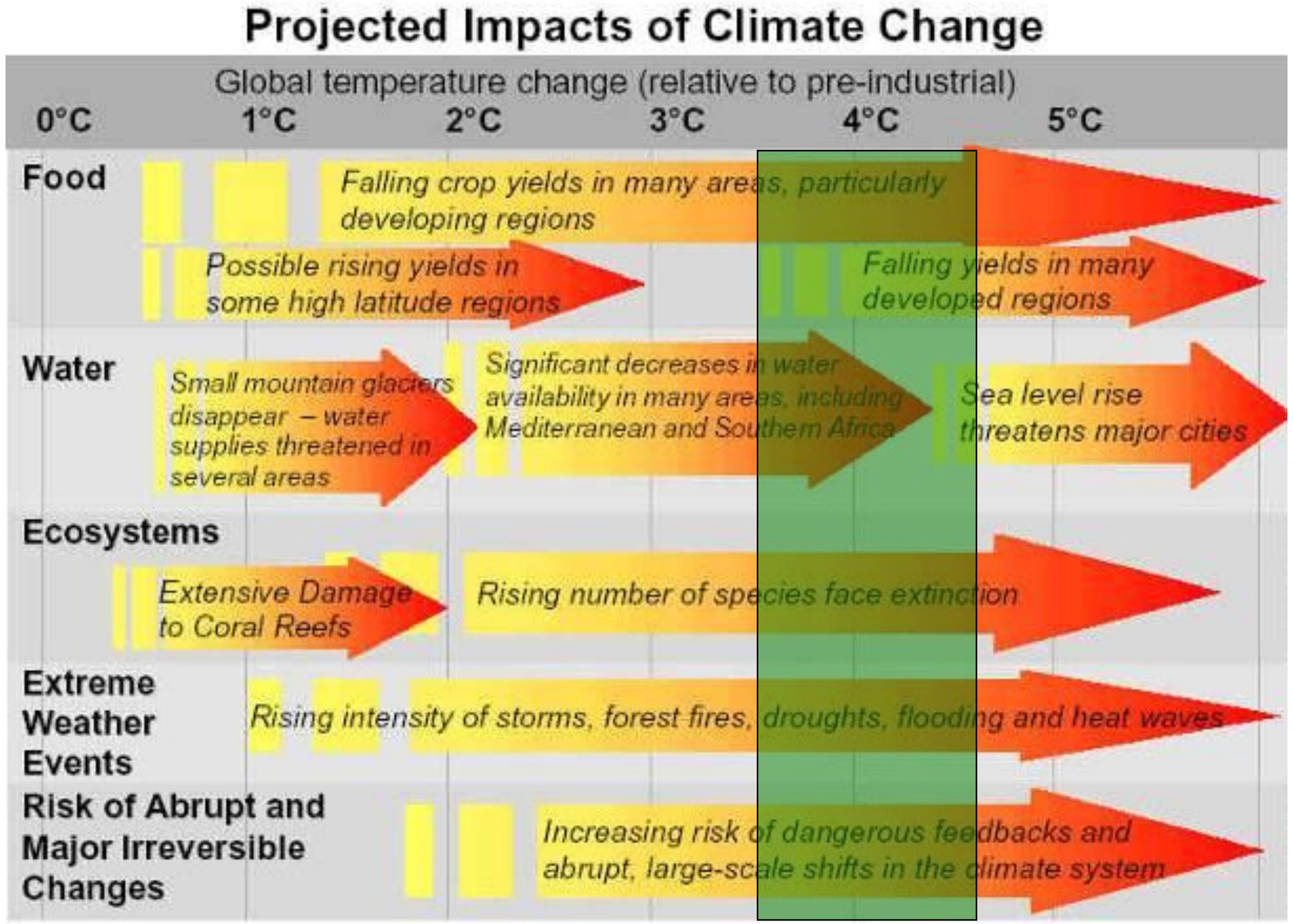




(IPCC, October 2019, SPECIAL REPORT: GLOBAL WARMING OF 1.5 ºC Summary for Policymakers")

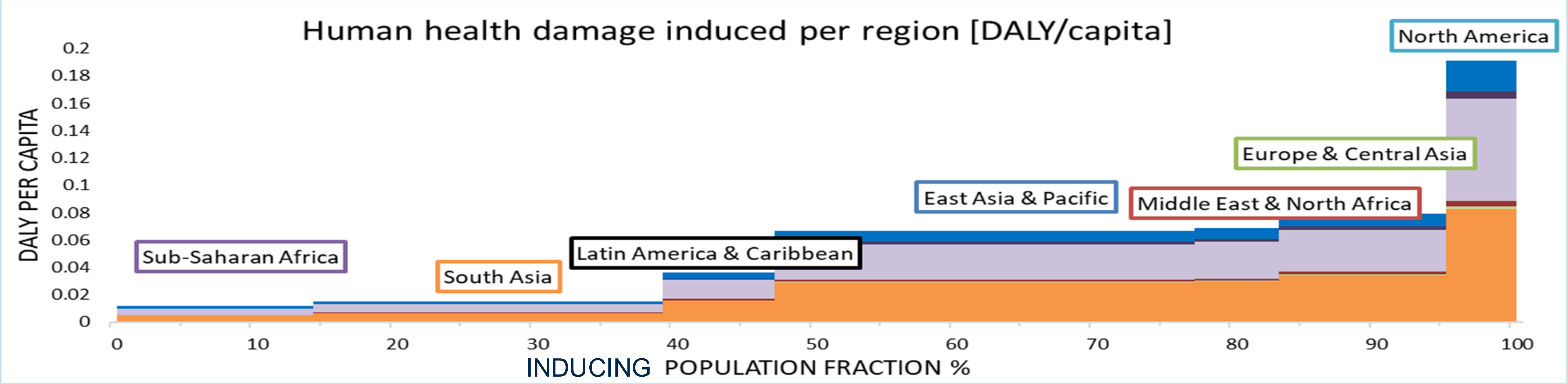
The emissions projections and related impacts

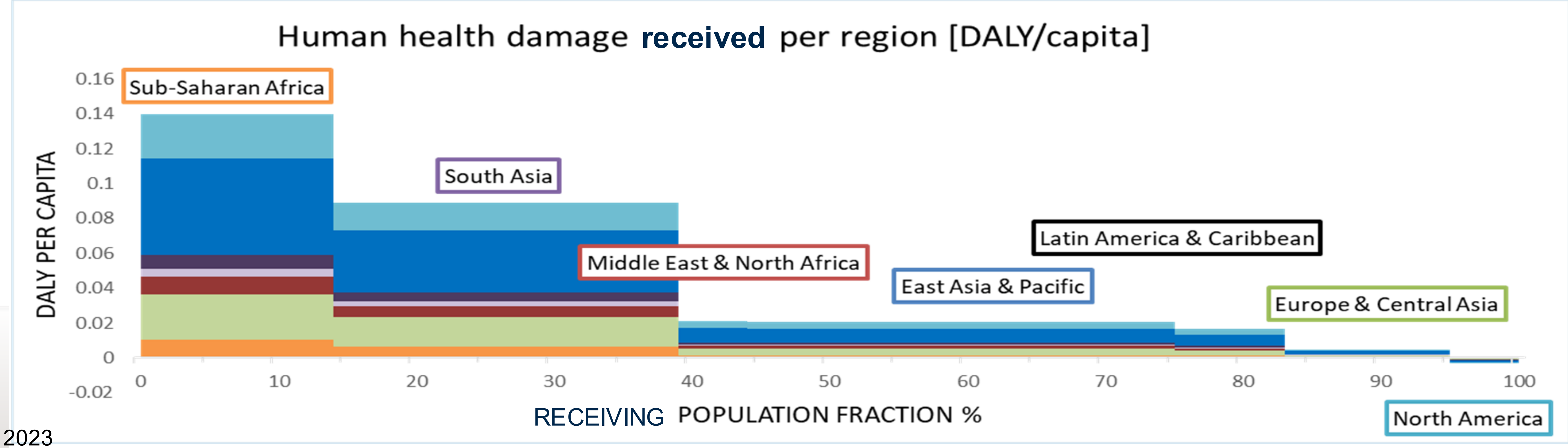




Likely range of 'business as usual' by 2100

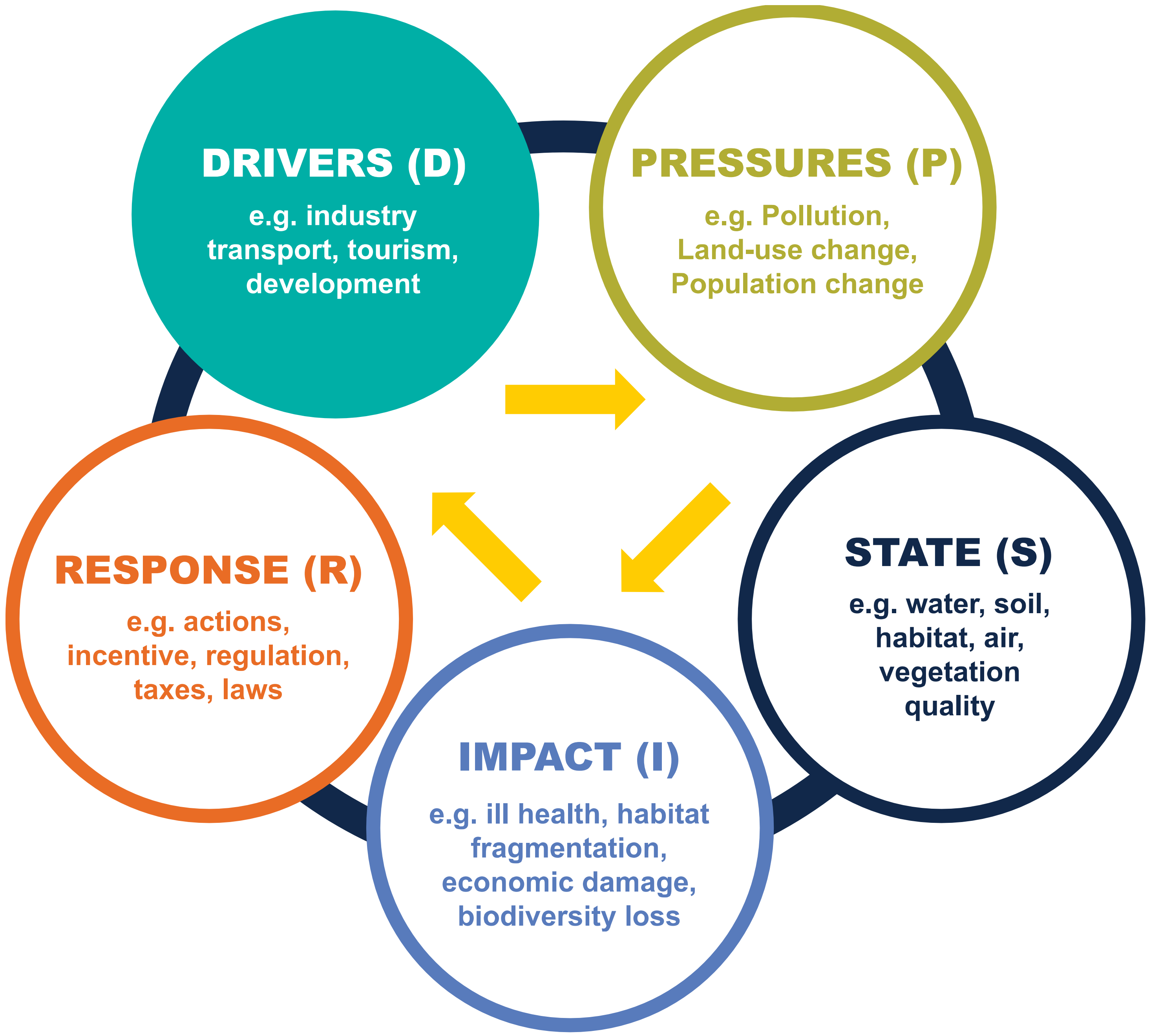
Disparities: Climate change impacts of heat and cold on health





Rupcic, 2023

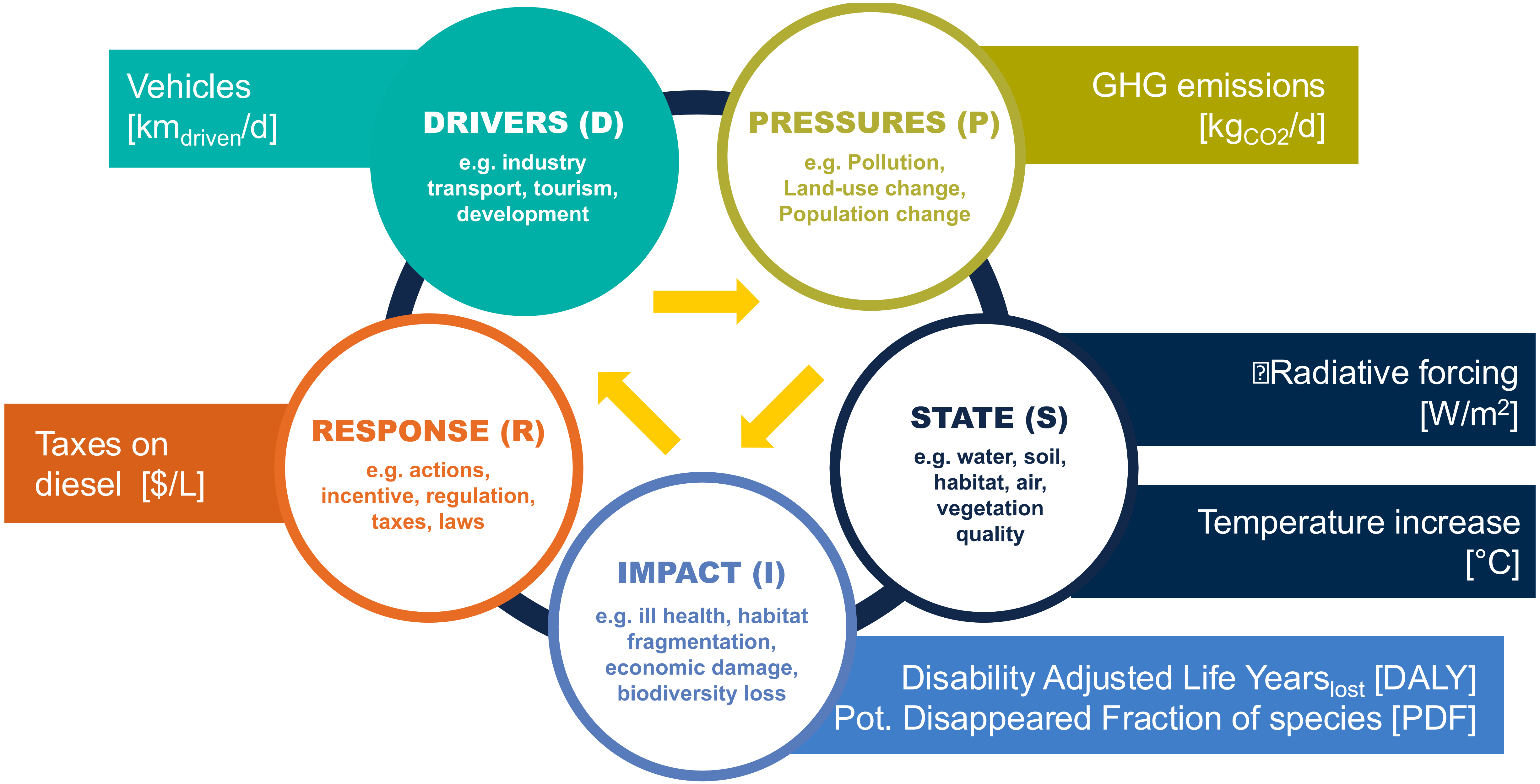
The DPSIR model: to categorize and causally link indicators



The DPSIR model: applied to climate change impact of transportation

11 SUSTAINABLE CITIES AND COMMUNITIES

13 CLIMATE ACTION



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Perfluorocarbons (PFC-14)	7380 kg_{CO2e}/kg_{PFC}
Sulphur Hexafluoride (SF_6)	24300 kg_{CO2e}/kg_{SF6}

Average DK carbon footprint per capita

Substance		Unit kg_i	Emissions kg_i/pers/y	GWP100 kg_{CO2e}/kg_i	GW score kg_{CO2e}/pers/d
Carbon dioxide	fossil	kg CO_2	8000*	1	
Methane	biogenic	kg CH_4	46.1		
Methane	fossil	kg CH_4	4.7		
Nitrous Oxide*		kg N_2O	3.2		
HFCs, PFCs,SF6					80
TOTAL kg_{CO2e}/pers/y					**xxxxx**
TOTAL kg$_{CO2e}$/pers/d					**xxx**

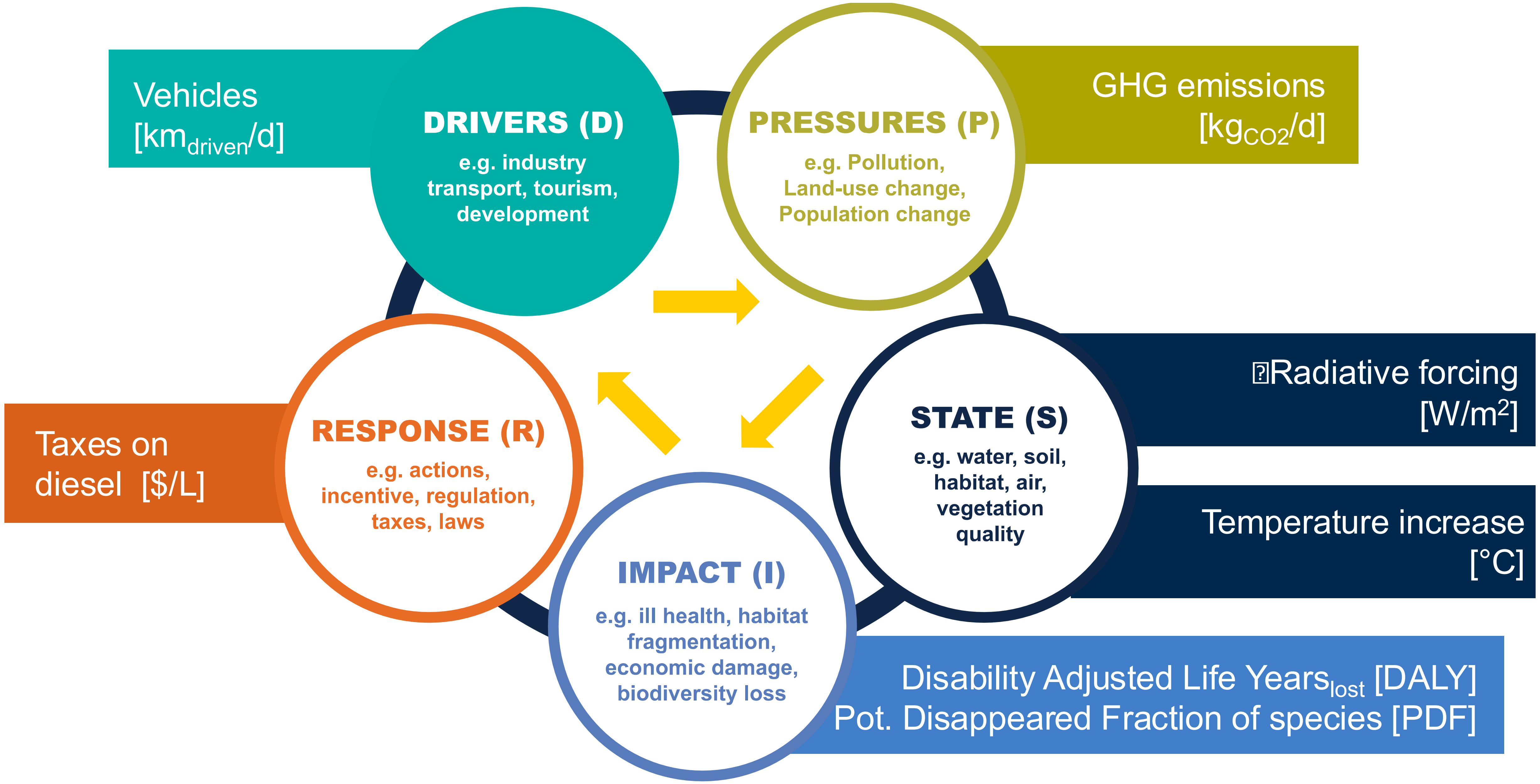
*consumption based emissions

Average US carbon footprint per capita

Substance		Unit kg_i	Emissions kg_i/pers/y	GWP100 kg_{CO2e}/kg_i	GW score kg_{CO2e}/pers/d
Carbon dioxide	fossil	kg CO_2	8000*	1	8000
Methane	biogenic	kg CH_4	46.1	27.0	1250
Methane	fossil	kg CH_4	4.7	29.8	140
Nitrous Oxide*		kg N_2O	3.2	273	870
HFCs, PFCs,SF6					80
TOTAL kg_{CO2e}/pers/y					**10340**
TOTAL kg$_{CO2e}$/pers/d					**28.3**

*consumption based emissions

At which level of the cause effect chain is the carbon footprint?



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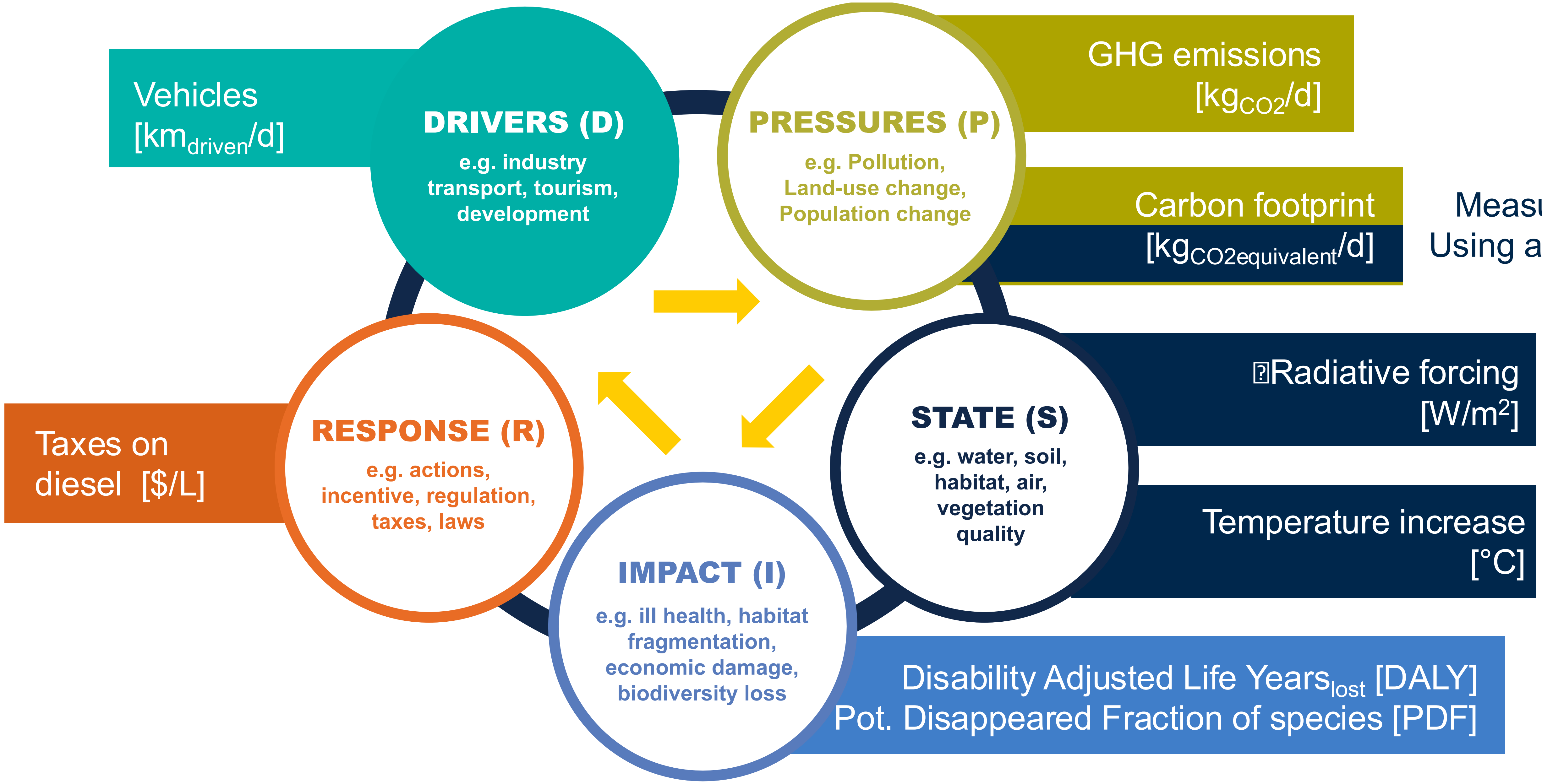
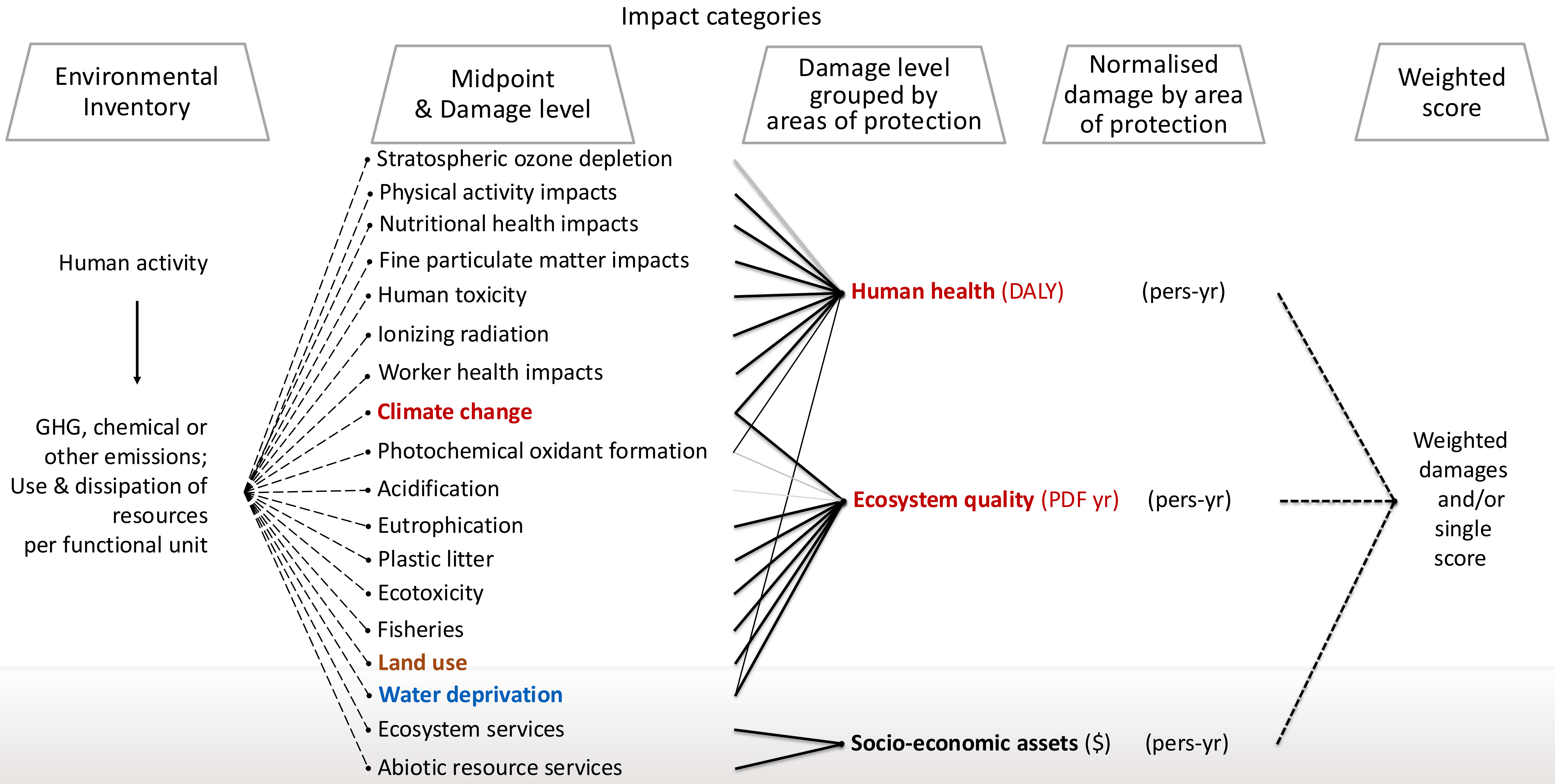


Measures a pressure
Using a state indicator!

UNEP - GLAM: the global life cycle impact assessment framework



Primary energy and carbon footprint

Gasoline vs electric vehicles

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

Learning Objectives

- Define a process to establish a carbon footprint
- Define primary, final and useful energy
- Compare aggregated primary energy and CO2 for various materials and processes
- Perform the carbon footprint of a gasoline versus an electric car
- Interpret results, comparing scenario performances and identifying hot spots

Case study: Gasoline vs electric vehicle

Building the energy balance and carbon footprint

1. *Functional unit (FU):* Identify the functional basis for comparing the different scenarios. Footprints are calculated per functional unit (FU representative of what service you want, not a ratio)

2. *Collect composition and consumption data:* collect the inputs to product manufacturing and its consumption during operation and calculate each input/FU (what you need to provide the service, in e.g. kg_{input}/FU, kWh/FU)

3. *Find resource consumption and GHG emission factors per unit input:* Find in databases for each input the $MJ_{\text{non renewable primary energy}}$ and GHG emission in $kg_{\text{CO2 equivalent}}$ per unit input

4. *Calculate energy balance and carbon footprint per FU:* Multiply 2 and 3 to obtain the contribution of each input to the energy and carbon footprint ($MJ_{\text{non renewable primary energy}}$ /FU, $kg_{\text{CO2 equivalent}}$ /FU)

5. *Total footprint and interpretation:* Sum up the footprint of each input to calculate the total energy and carbon footprint of the considered service or product

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2 *Collect composition and consumption data:* collect the inputs to product manufacturing and its consumption during operation and calculate each input/FU
(what you need to provide the service, in e.g. kg_{input}/FU, kWh/FU)

What is a suitable functional unit to compare these vehicles?

What are the main inputs data to collect for each vehicles?

Energy and CO_2 balance gasoline: calculate each input/FU

	1	2							
Vehicle lifespan (km/vehicle)	150000			Non renewable primary energy			Carbon footprint		
Transportation by Gas Vehicle FU= 1 vehicle km	Quantity original unit	Quantity per FU	Unit	Energy/Unit [MJ/Unit]	Energy per FU [MJ/FU]	fraction energy	CO2equ/Unit [kg/unit]	CO2equ./FU	fraction carbon
Manufacturing (Materials + Processing)	per vehicle over lifespan	per FU							
steel, low-alloyed, hot rolled	1040		kg		0.00E+00	0.0%		0.00E+00	0.0%
sheet rolling, steel	780	5.20E-03	kg	4.96	2.58E-02	8.9%	0.32	1.66E-03	9.8%
aluminium, primary, ingot	55	3.67E-04	kg	218.90	8.03E-02	27.7%	20.97	7.69E-03	45.4%
Copper & other metals (Zn, Ni, Pb)	38	2.53E-04	kg	74.58	1.89E-02	6.5%	5.86	1.49E-03	8.8%
platinum	1.70E-03	1.13E-08	kg	1095329	1.24E-02	4.3%	69212	7.84E-04	4.6%
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tap water	3400	2.27E-02	kg	0.01	1.19E-04	0.0%	0.00	7.55E-06	0.0%
heat, district or industrial, natural gas	2400		MJ		0.00E+00	0.0%		0.00E+00	0.0%
electricity, medium voltage	2250		kWh		0.00E+00	0.0%		0.00E+00	0.0%
Transportation	per vehicle	per FU							
transport, freight train	556.50		t-km	0.70	0.000	0.00%	0.04	0.00E+00	0.0%
transport, freight, lorry 16-32 metric ton	59.10		t-km		0.000	0.00%		0.00E+00	0.0%
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Supply chain petrol, low-sulfur	0.0619		kg		0.000	0.0%		0.00E+00	0.0%
Direct combustion	0.0619		kg	0.00	0.000	0.0%	3.11	0.00E+00	0.0%
Disposal	per vehicle over lifespan	per FU							
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Total		per FU							
Total	-		-		**0.290**	100.0%		**0.017**	100.0%
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							DALY/kgCO2e	DALY/FU	

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Primary energy definition

Primary energy is defined as the energy contained in the energy carriers at the point of extraction from the environment, including the upstream energy usage for extraction, preparation, and distribution.

The **final energy is the energy** purchased by the consumer and delivered to him.

The **useful energy** is the portion of final energy which is actually available after final conversion to the consumer for the respective use.

Energy: definitions

	Primary energy = including extraction and preparation	**Final energy** = bought	**Useful energy** = used
Gas	1.25 MJ prim	1 MJ final	0.95 MJ useful
Electricity	3.4 MJ prim	1 MJ final	1 MJ useful
	12.1 MJ prim	1 kWh final = 3.6 MJ final	1 kWh useful

Extraction and preparation

Efficiency

Non-renewable primary energy and CO_2 aggregated inventory flows

		Non-renewable primary energy (MJ per unit)	CO_2 (kg per unit)	gCO_2/MJ ratio
Energy Carriers	1 kWh electricity (Europe)	8.8	0.49	47
	1 kWh electricity (USA)	12.1	0.71	59
	1 kWh electricity (Japan)	11.5	0.53	46
	1 kWh electricity (Switzerland)	7.9	0.11	13
	1 kWh electricity (China)	10.4	0.98	94
	1L gasoline (no combustion)	42.9	0.49	11
	1L gasoline (with combustion)	42.9	2.88	65
	1 kg light oil (42.7 MJ final)	56.8	3.71	65
Transport	1,000 km kg transport 16-32 ton Lorry	2.6	0.15	58
	1 pers • km by train (Intercity)	0.98	0.06	58
	1 pers • km by plane (Intercontinental)	3.28	0.19	60
	1 pers • km by car	3.0	0.17	57

Non-renewable primary energy and CO_2 Aggregated inventory flows

		Non-renewable primary energy (MJ per unit)	CO_2 (kg per unit)	gCO_2/MJ ratio
Materials	1 m^3 concrete	1,381	257	186
	1 m^3 water	5.55	0.30	54
	1 kg steel, low alloy	27.4	1.63	59
	1 kg copper	31.2	1.86	60
	1 kg primary aluminium	160.4	9.55	59
	1 kg recycled aluminium	22.4	1.32	60
	1 kg gold	269,000	16,500	61
	1 kg paper newsprint	24.3	1.22	50
	1 kg glass	11.5	0.63	55
	1 kg polyethylene HDPEs	76.4	1.56	20
Material processing	1 kg plastic film extrusion	9.25	0.50	54
	1 kg injection moulding	27.1	1.24	46
End of life	1 kg landfilled steel	0.197	0.00657	33
	1 kg landfilled aluminium	0.521	0.02010	39
	1 kg incinerated municipal solid waste	0.43	0.50	1,161
	1 kg incinerated polyethylene	0.22	2.99	13,606

Energy and CO_2 balance: light bulb example

1

2a

2b

The ecoinvent database
12772_Cut-off Cumulative LCIA v3.8_selected short1b

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		kg_to_g	g/kg	1000			Method	selected LCI results	cumulative energy demand	Ratio carbon dioxide fossil/non renewable cumulative energy demand		IPCC 2013	cumulative energy demand	cumulative energy demand
2							Category	air	fossil+nuclear+ primary forest	CO2 fossil/total non renewable energy		climate change		
3							Indicator	CO2, fossil	non-renewable energy resources	Check combustion included		GWP 100a	renewable energy resources, total	Non-renewable + renewable energy resources, total
4	Activity U…		Activity Name	Geography	Reference Product Name	Reference Product Unit	Reference Product Amount	kg	MJ-Eq	gCO2/MJ		kg CO2-Eq		
6010	b068	6006	market group for electricity, low voltage	BR	electricity, low voltage	kWh	1	0.190	3.17	59.9		0.239016	3.51	6.69
6011	2878	6007	market group for electricity, low voltage	CA	electricity, low voltage	kWh	1	0.195	5.20	37.5		0.206518	2.72	7.92
6012	060e	6008	market group for electricity, low voltage	Canada	electricity, low voltage	kWh	1	0.291	7.92	36.7		0.306936	1.97	9.89
6013	c7f9	6009	market group for electricity, low voltage	CN	electricity, low voltage	kWh	1	0.890	10.23	87.0		1.064039	1.00	11.23
6014	61ea	6010	market group for electricity, low voltage	ENTSO	electricity, low voltage	kWh	1	0.352	8.39	42.0		0.377786	1.78	10.16
6015	7ccb	6011	market group for electricity, low voltage	Europe	electricity, low voltage	kWh	1	0.368	8.81	41.7		0.394867	1.68	10.50
6016	ab00	6012	market group for electricity, low voltage	GLO	electricity, low voltage	kWh	1	0.648	10.10	64.1		0.718722	1.23	11.33
6017	e26d	6013	market group for electricity, low voltage	IN	electricity, low voltage	kWh	1	1.484	19.63	75.6		1.543311	0.94	20.57
6018	e75e	6014	market group for electricity, low voltage	RAF	electricity, low voltage	kWh	1	0.764	12.40	61.6		0.796764	1.01	13.41
6019	cc6e	6015	market group for electricity, low voltage	RAS	electricity, low voltage	kWh	1	0.877	11.45	76.6		0.984805	0.90	12.35
6020	deb8	6016	market group for electricity, low voltage	RER	electricity, low voltage	kWh	1	0.362	8.72	41.5		0.388731	1.71	10.43
6021	7bcd	6017	market group for electricity, low voltage	RLA	electricity, low voltage	kWh	1	0.314	5.20	60.4		0.357316	2.83	8.03
6022	1c19	6018	market group for electricity, low voltage	RME	electricity, low voltage	kWh	1	0.828	14.14	58.6		0.877363	0.16	14.30
6023	667d	6019	market group for electricity, low voltage	RNA	electricity, low voltage	kWh	1	0.438	8.75	50.1		0.475546	1.15	9.89
6024	4bbd	6020	market group for electricity, low voltage	UCTE	electricity, low voltage	kWh	1	0.399	9.02	44.2		0.427512	1.55	10.56
6025	9292	6021	market group for electricity, low voltage	US	electricity, low voltage	kWh	1	0.469	9.19	51.0		0.509351	0.95	10.14
6026	1761	6022	electricity production, photovoltaic, 3kWp facade installation,	CH	electricity, low voltage	kWh	1	0.096	1.49	64.7		0.109668	4.12	5.61

Use of ecoinvent: tips for good use – be careful

ELECTRICITY:
select the mix corresponding to each scenario

Medium voltage for industrial use, **Low voltage** for household use

TRANSPORT:
beware the load rate

(includes 40% empty trips for trucks)

Data in energy sector available in three forms:

a) Energy data **per fuel unit quantity**,
e.g. per kg oil or liter gasoline: without combustion,

b) Energy **per MJ final (bought)** energy: **"burned" = with combustion**
Use the net calorific values to convert back to fuel quantities
(kg oil, m^3 gas or liter gasoline)

c) Energy **per MJ useful (delivered)** energy: **"heat" = with combustion**

Be sure to include end-of-life process & only use fossil CO_2, not biogenic CO_2. Avoid to use heavy metal uptake by crops.

Energy and CO_2 balance gasoline: calculate footprint/input

3 3

Vehicle lifespan (km/vehicle)	150000			Non renewable primary energy			Carbon footprint		
Transportation by Gas Vehicle FU= 1 vehicle km	Quantity original unit	Quantity per FU	Unit	Energy/Unit [MJ/Unit]	Energy per FU [MJ/FU]	fraction energy	CO2equ/Unit [kg/unit]	CO2equ./FU	fraction carbon
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steel, low-alloyed, hot rolled	1040		kg		0.00E+00	0.0%		0.00E+00	0.0%
sheet rolling, steel	780	5.20E-03	kg	4.96	2.58E-02	8.9%	0.32	1.66E-03	9.8%
aluminium, primary, ingot	55	3.67E-04	kg	218.90	8.03E-02	27.7%	20.97	7.69E-03	45.4%
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platinum	1.70E-03	1.13E-08	kg	1095329	1.24E-02	4.3%	69212	7.84E-04	4.6%
polyethylene, polypropylene & PVC	175	1.17E-03	kg	79.36	9.26E-02	32.0%	2.32	2.70E-03	15.9%
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heat, district or industrial, natural gas	2400		MJ		0.00E+00	0.0%		0.00E+00	0.0%
electricity, medium voltage	2250		kWh		0.00E+00	0.0%		0.00E+00	0.0%
Transportation	per vehicle	per FU							
transport, freight train	556.50		t-km	0.70	0.000	0.00%	0.04	0.00E+00	0.0%
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							8.30E-07 DALY/kgCO2e	1.41E-08 DALY/FU	

Scenario comparison and interpretation

Interpretation Principles

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

DTU

Learning Objectives

- Evaluate results, draw conclusions, explain the limitations of the study, and make recommendations, based on the results of the preceding inventory and impact assessment phases
- Identify the critical points in the life cycle (e.g., where much of the impact occurs)
- Assess the quality and robustness of results using a series of checks (e.g., quality control, sensitivity analysis, and uncertainty analysis)

Results Interpretation: look from different angles!



Each level:
after input flows, pollutants inventory, after characterisation and carbon footprint impact evaluation;

Interpret results from multiple angles, for:

Each LCA stage (raw material, manufacturing, transportation, use, disposal), concentrating on those which generate the largest impact and on those which offer the best impact reduction potential;

Each component contribution for a multi-component product.

Each pollutant and processes, analysing their respective contribution to each midpoint impact category.

Each midpoint impact category, analysing their respective contribution to each damage or weighted final score per scenario

Interpretation question for each scenario

Which are the largest contribution to the environmental impact in terms of production phase, in terms of pollutant?

- The grouping of processes can be arbitrary and depends on how the system is modeled.
- Also consider large sets of individual processes that each appear to have small impacts but lead to substantial impacts when summed

Which life cycle stage has the highest potential to reduce impacts (also depending on feasibility)

- In some win-win cases, both impacts and costs can be reduced at the same time.
- Even a limited low-cost intervention can be extremely efficient in reducing impacts.

Interpretation questions across scenarios: why? Why? WHY?

- Are the differences between scenarios significant, relevant?
  For which impact category?
- Are differences/conclusions correct and robust: *check check check*
- What is the cause for difference in term of process, inventory flow?
- What are the key parameters affecting the environmental impact?
  (sensitivity studies)
- **If some results are surprising:** WHY? What are the underlying parameter components and stages responsible for it?

Never let it go until you understand the rational for a difference or a surprising results.
Either you made a mistake … or you will learn something!

Energy and CO_2 balance gasoline: calculate total and interpret

5 5

Vehicle lifespan (km/vehicle)	150000			Non renewable primary energy			Carbon footprint		
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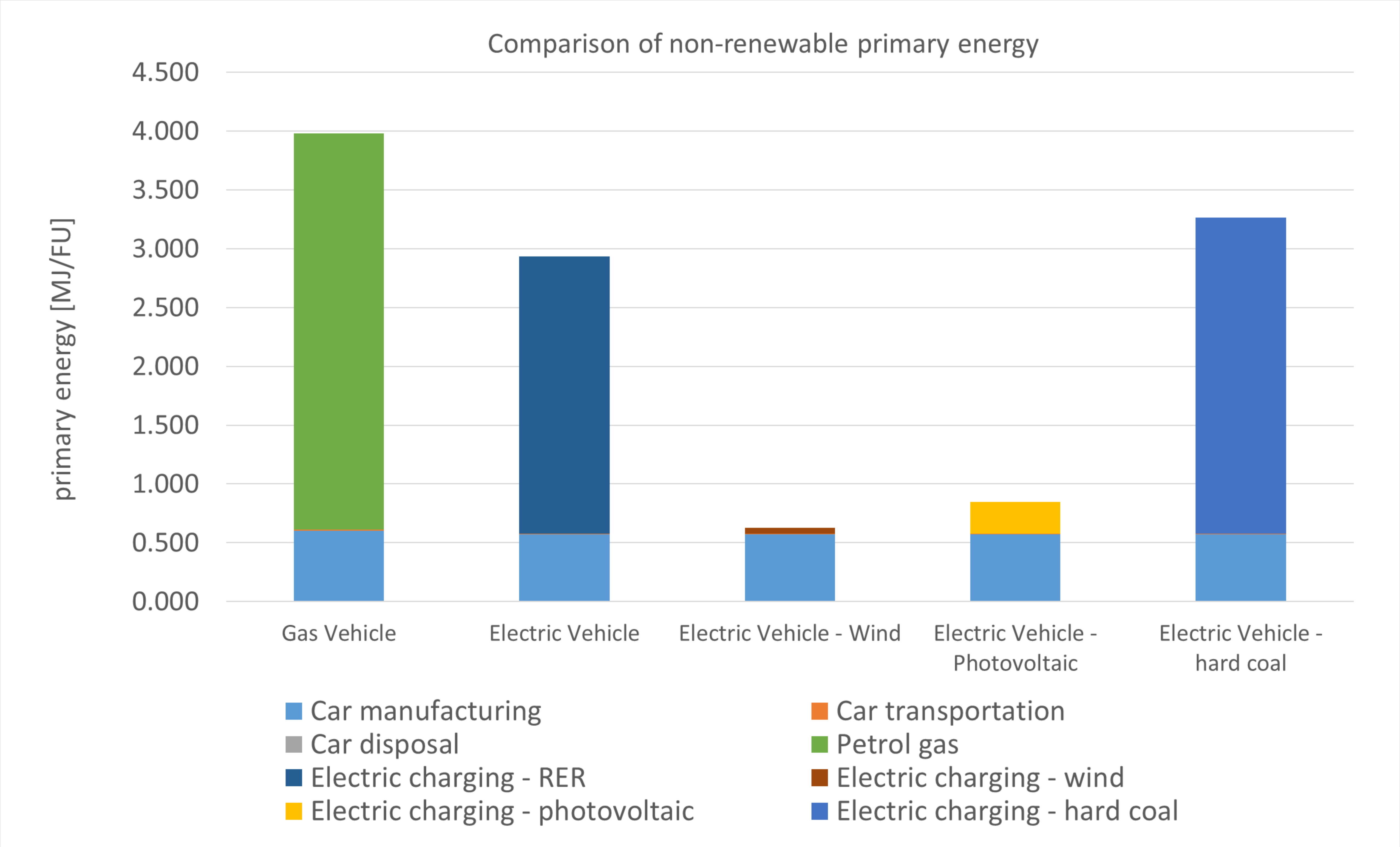
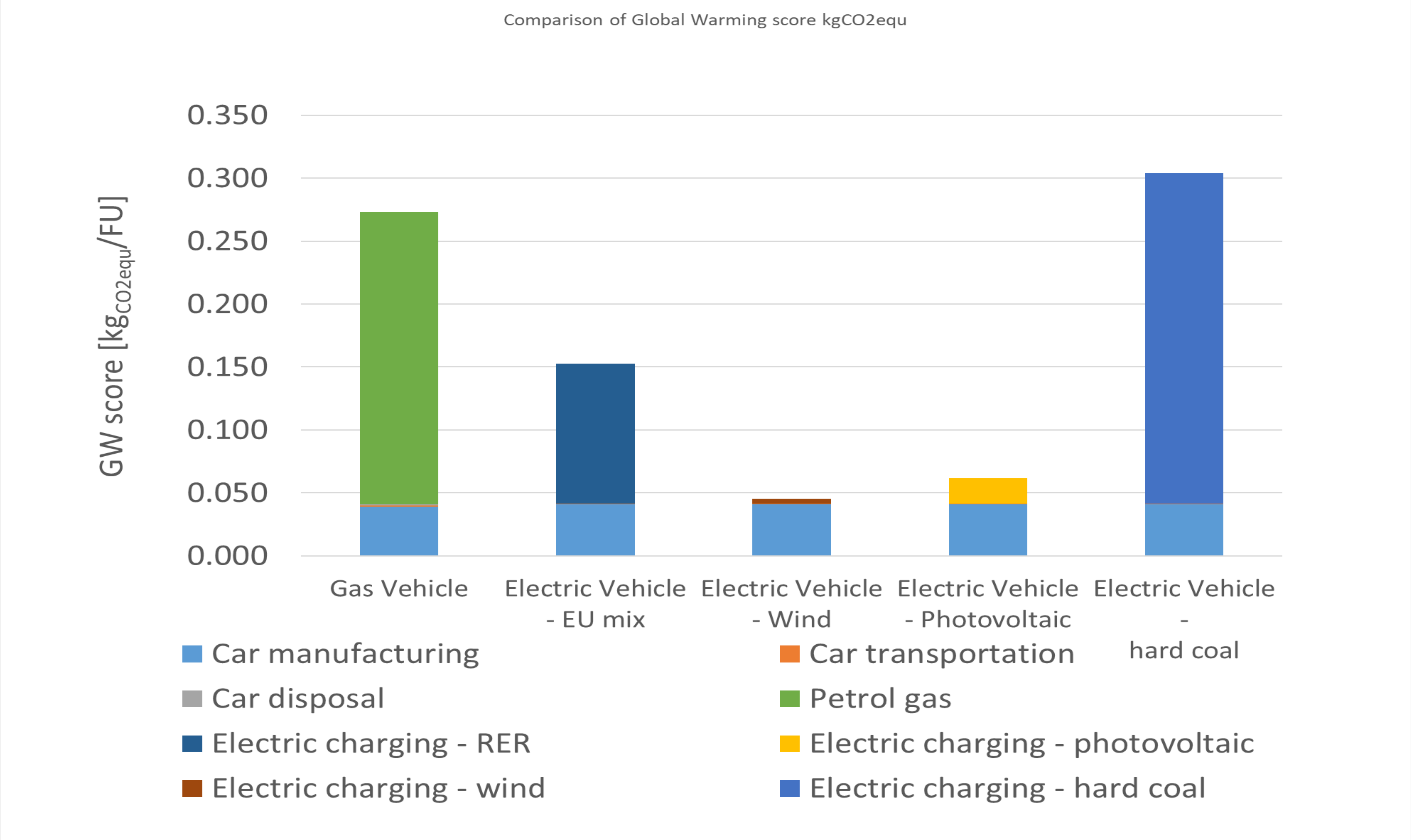
5 5

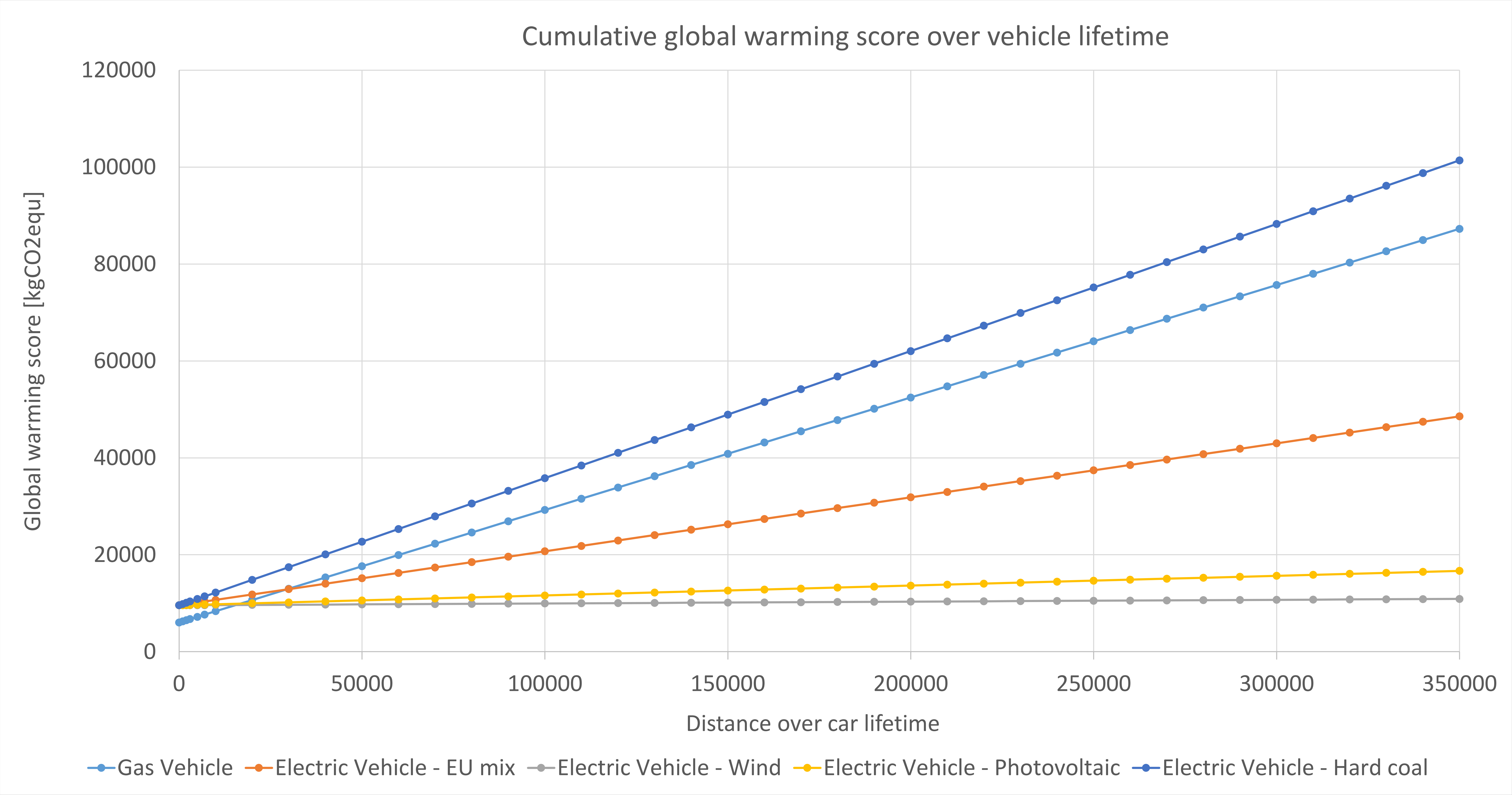
Energy balance: gasoline vs electric vehicle



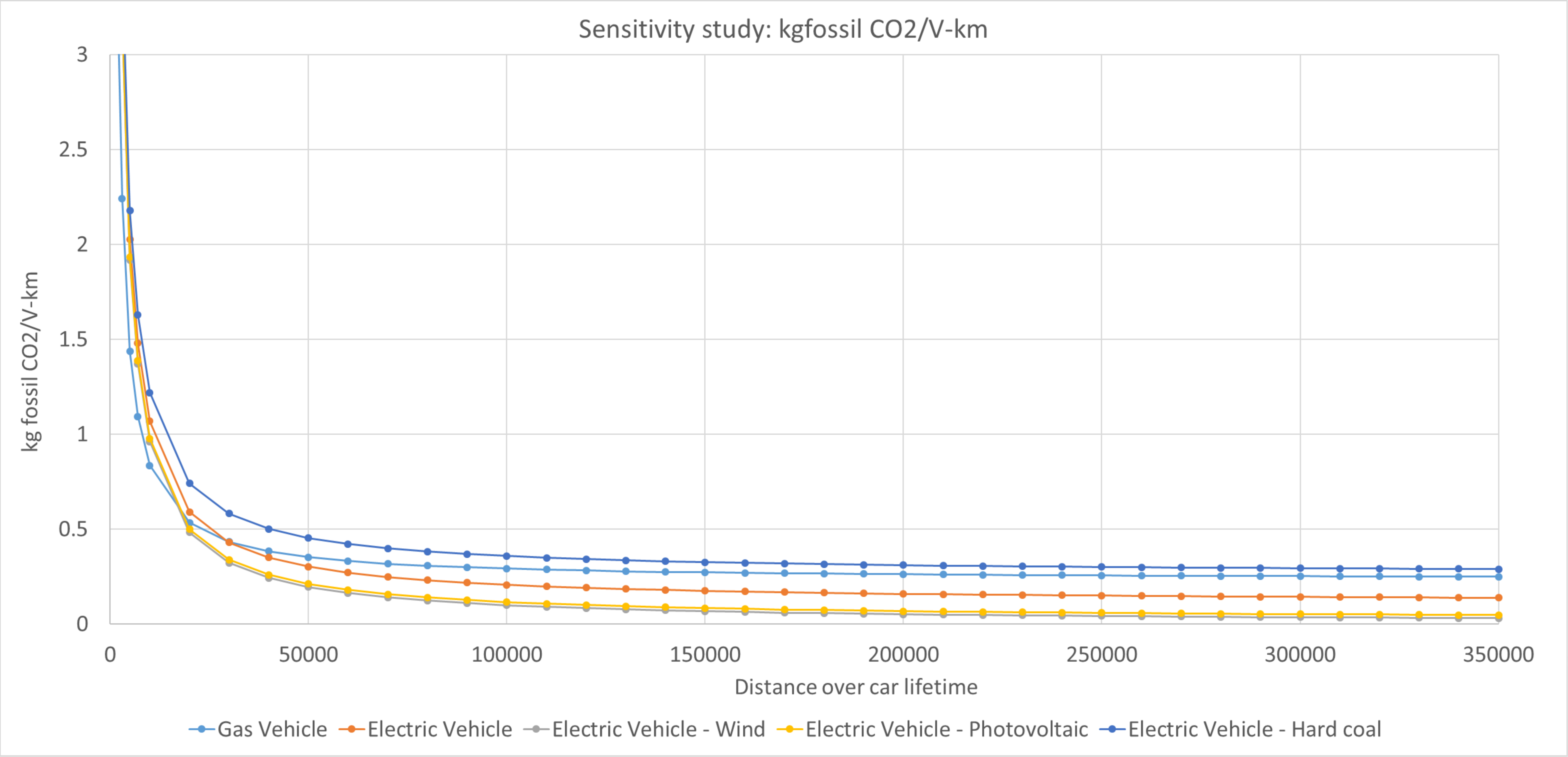
Carbon footprint: gasoline vs electric vehicle



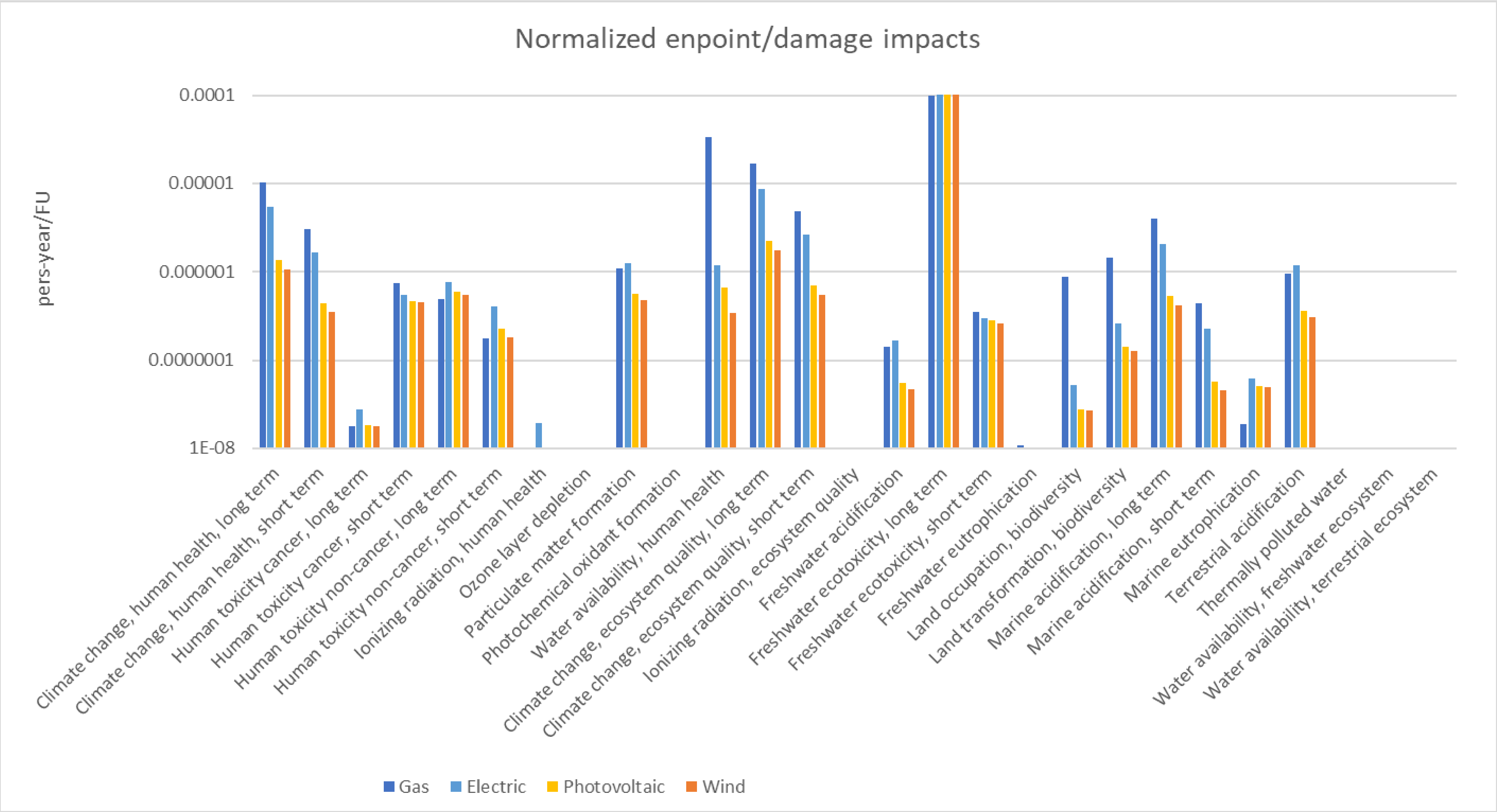
Sensitivity study: cumulative carbon footprint as a function of vehicle lifetime



Sensitivity study: carbon footprint per FU as a function of vehicle lifetime



Comparison of normalized damage Impact World+ Life cycle impact Assessment



Exercise and case study

Morning cofee

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

Your morning coffee

A morning coffee might be essential for many people. But what are the most important inputs contributing to the CO_2 and energy balance of a cup of roasted coffee.

You want to calculate the energy and CO_2 balance of a cup of roasted coffee. To have a cup of coffee (1 cup is 1 dl = 0.1 liters), you need 10 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 CO_2

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

Building the energy balance and carbon footprint: apply to your case study adapting the car comparison template

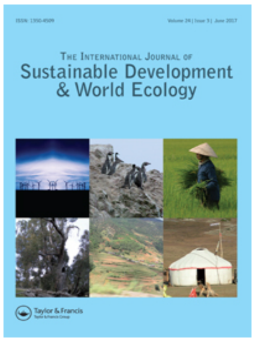
1. *Functional unit (FU):* Identify the functional basis for comparing the different scenarios. Footprints are calculated per functional unit (FU representative of what service you want, not a ratio)

2. *Collect composition and consumption data:* collect the inputs to product manufacturing and its consumption during operation and calculate each input/FU (what you need to provide the service, in e.g. kg_{input}/FU, kWh/FU)

3. *Find resource consumption and GHG emission factors per unit input:* Find in databases for each input the $MJ_{non\ renewable\ primary\ energy}$ and GHG emission in $kg_{CO2\ equivalent}$ per unit input

4. *Calculate energy balance and carbon footprint per FU:* Multiply 2 and 3 to obtain the contribution of each input to the energy and carbon footprint ($MJ_{non\ renewable\ primary\ energy}$ /FU, $kg_{CO2\ equivalent}$ /FU)

5. *Total footprint and interpretation:* Sum up the footprint of each input to calculate the total energy and carbon footprint of the considered service or product



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Sustainability assessment tools – their comprehensiveness and utilisation in company-level sustainability assessments in Finland

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ABSTRACT

Companies have a central role in the transition towards more sustainable economic systems, as they are one of the major sources of environmental impacts, economic activity and social development. Various tools are available to support sustainability assessments, but there is little information on how suitable they are for company-level assessments and how companies use them in real-life applications. The article examines some of the commonly used tools and the utilisation of these tools in Finnish companies. A sample of seven tools was compiled: multi-criteria decision analysis (MCDA), material flow analysis, life cycle assessment (LCA), input–output models, sustainability indicators and indices, cost–benefit analysis (CBA) and optimisation methods. MCDA, LCA, CBA and optimisation methods were found to be successful with respect to many of the criteria used in the evaluation, but none of them was comprehensive. The assessment indicates that MCDA has the greatest potential to be successfully applied to support sustainability assessment, but solely applying MCDA is not suggested, since MCDA needs input from other tools and methods, in order to have reliable impact assessments. Finnish companies regularly employ sustainability criteria and indices, and a few construction companies had applied LCA, but utilisation of other tools was rare. The findings indicate that the tools frequently discussed in research are not actually used by companies. Expert-driven sustainability trials and user-friendly, simplified tools could be a solution to issues of accessibility in real-world applications.

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Companies; comprehensiveness; sustainability assessment tools; sustainability reporting; decision analysis

1. Introduction

Many of our planet's limits have been exceeded through actions such as growing use of material resources, which harm the environment and human health (Rockström et al. 2009; SOER 2015; Steffen et al. 2015). This has raised concerns about the sustainability of current economic systems. The discussion of sustainability has its origins in the Brundtland Commission's definition of sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987). The UN conference on the environment and development held in Rio de Janeiro in 1992 formally adopted the concept of sustainable development, and the term has been used in scientific and political discussions ever since. Furthermore, the number of research articles focusing on sustainable development from a methodological and a conceptual perspective has been increasing in recent decades (Bond et al. 2012; Singh et al. 2012).

Work on the theme of sustainable development is characterised by the presence of extensive multidisciplinary definitions, which are occasionally contradictory (Bolis et al. 2014). Some definitions focus on environmental issues, while broader definitions encompass ethical and social values as well (Bolis et al. 2014). Here we consider sustainable development as a broad concept covering environmental, economic and social pillars. In a company context, this means, for example, that a company should create prosperity and generate work possibilities at the same time (Global Reporting Initiative 2013). Companies have a central role in the transition towards more sustainable economic systems, as they are one of the major sources of environmental impacts, economic activity and social development. Furthermore, companies are among the main consumers of natural resources. Developing eco-friendly designs and sustainability-oriented innovations can bring a company new business opportunities (Klewitz & Hansen 2014). On the other hand, sustainable development can cause challenges for the economic success of a company. For instance, the sustainability of biofuel companies has been questioned greatly because of unexpected negative environmental impacts and also the harm caused to food security (Liew et al. 2014).

Companies invest considerable time and resources in informing their stakeholders about their impacts on sustainability, by, for instance, releasing sustainability

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reports or reporting their sustainability impacts via the Internet (Häkkinen et al. 2013). Sustainability reports may play a key role in how seriously a company takes sustainability into account (Silvestre et al. 2015). These reports describe the company's impact on sustainable development (e.g. emissions related to climate change and employment figures) (Global Reporting Initiative 2013). Reporting is a way of communicating with stakeholders, but there is little correlation between the performance of environmental disclosure in reports and economic variables (da Rosa et al. 2013). Another issue is that information on how sustainable strategies are developed in practice is not available (Egels-Zandén & Rosén 2015).

To increase their role in supporting sustainable development, companies need to detect the sources of their main impacts and assess how their operations influence sustainable development. To bring structure to sustainable development assessments, various tools can be utilised (e.g. Singh et al. 2012; Myllyviita et al. 2014). Sustainable development has been one of the most highly recognised topics in the field of research devoted to methodological development and operational research (e.g. Mustajoki et al. 2011; Myllyviita et al. 2013). There are several structured methods and less formal tools available, and the number is likely to increase (Gasparatos 2010; Poveda & Lipsett 2011). Consequently, definition and classification of tools is a complex matter. These tools serve as an 'attempt to understand a system and offer information in a format that can assist the decision making process' (Gasparatos et al. 2008).

Several reviews of sustainability assessment tools are available in the literature, but the scope and the purposes of these reviews are highly varied. Hörisch et al. (2015) tested the impact of implementing sustainability management tools on key dimensions of corporate environmental performance. Their analyses indicate that different tools are effective for different purposes. One limitation of their research is its focus solely on large companies. Ferreira et al. (2013) reviewed decision support tools used in the building refurbishment sector and concluded that, as the decision-making process is usually time-consuming, it is important to make the process faster and more effective. Hence, a successful tool should be fairly simple and straightforward to use. Additionally, Sharifi and Murayama (2013) revealed that the sustainability assessment tools embedded within the broader planning framework are successful with regard to applicability. Myllyviita et al. (2011) reviewed decision support tools used to encourage sustainable use of forest resources. In their review, the case studies utilising hybrid approaches (i.e. simultaneous use of qualitative and quantitative tools) showed more active participation of stakeholders than those case studies in which only a single tool was applied. Lozano (2012) provided an analysis of 16 of the most widely used sustainability assessment tools and determined that 'each initiative has advantages with respect to scope and focus for the sustainability dimensions and the company system's elements, but it has certain disadvantages when it comes to dealing with the complexity and broadness of sustainability'.

Even though there has been active methodological and conceptual discussion of sustainable development, fewer studies have been done on the utilisation of tools at the company level (e.g. da Rosa et al. 2013; Egels-Zandén & Rosén 2015). In some cases, the results of the sustainability assessments have led to major changes in the ways the company operates. For instance, the carbon footprint of cola cans and bottles has been assessed since the 1960s, and the findings have greatly influenced how a company packs its products. One major problem is that small and medium-sized enterprises (SMEs) lack the resources, time and methodological expertise required (Crals & Vereeck 2005; Häkkinen et al. 2013; Judl et al. 2015), although some SMEs have done extensive work connected to sustainability-orientated innovations (Klewitz & Hansen 2014). As SMEs represent more than 80% of companies operating in Europe, they have been identified as significant contributors to sustainable development (Biondi et al. 2002). The best available knowledge and lessons learned should be presented in an understandable format for company uses to advance companies' role in implementing sustainable development in practice.

SMEs have an important role in Finland: they are a source of national competitiveness (Akola & Havupalo 2013). Altogether 98% of Finnish enterprises were classified as SMEs in 2009 (Akola & Havupalo 2013). Finland and Finnish enterprises use a significant amount of natural resources, and the national carbon footprint has remained high despite efforts aimed at resource-efficiency (Putkuri et al. 2013). On a governmental level, Finland is committed to promoting sustainable economic growth and the sustainable use of its natural resources; this is seen in, for example, the Government programme and the Government strategy to promote the cleantech business (Finnish Government 2014; Ministry of Employment and the Economy 2014). Finland has agreed on several sustainable development targets. These targets include reduction of greenhouse gas emissions of at least 80% by 2050 from 1990 levels (Ministry of the Environment 2014) and recycling or materially recovering 70% of non-hazardous construction and demolition waste by 2020 (European union 2016). Therefore, it is interesting to see how companies in a seemingly committed country such as Finland measure and assess their sustainability in practice.

There is an enormous amount of research focusing on sustainability assessment tools, but only a few of the studies have addressed actual utilisation of these tools at the company level. This is an important topic, as companies are major players in the transition towards sustainable economic systems. Our overall target was to compare the utilisation of sustainability assessment tools between research articles and the company level. The first aim was to assess the success of seven sustainability assessment tools. This sample of seven tools was compiled on the basis of a review of research articles. The specified success criteria (previously defined by Myllyviita et al. (2014) were used in the assessment of these tools. Our second aim was to gain insight into the utilisation of these tools in company-level sustainability assessments. To do this, we carefully reviewed sustainability reports and web pages of 127 Finnish companies. Companies from four sectors (energy, hotels and restaurants, mining and construction) were included. From this analysis, we describe the success of the seven sustainability assessment tools and discuss their benefits and limitations. Furthermore, we illustrate the current state of the utilisation of these tools at the company level sustainability assessments. Finally, proceeding from our extensive surveys, we describe means to advance the utilisation of these tools and ways to support sustainability assessments of companies.

2. Material and methods

There are three parts to the body of this paper: (1) an evaluation of the sustainability assessment tools commonly used in research articles; (2) a review of the utilisation of these tools in Finnish companies; and (3) a comparative assessment in which we evaluate whether Finnish companies apply these tools (see Figure 1).

2.1. Tools to assess sustainability – a review

A sample of tools used to assess the sustainability of companies in research articles was selected using Web of Knowledge database. The search keys were: sustainability, economic and systems. These search keys were considered to point to a wide range of studies wherein various sustainability assessment tools were used. On the basis of the search, a sample consisting of 50 articles' abstracts was studied, and the tools used in the articles to study sustainability were included in our assessments. As a result of the article review, a sample of seven tools was obtained, which are as follows: multi-criteria decision analysis (MCDA), material flow analysis (MFA), life cycle assessments (including environmental, economic, social and sustainability aspects) (LCAs), input–output (IO) models, sustainability indicators and indices, cost–benefit analysis (CBA) and optimisation methods.

2.1.1. Multi-criteria decision analysis

MCDA is a group of diverse methods that help decision-makers to identify and select preferred alternatives, when faced with a complex decision problem characterised by multiple objectives (Belton & Stewart 2002). MCDA is, typically, based on preference measurement: that is, the decision-maker is able to state whether they prefer an option A or B and also determine the strength of his/her preferences. In a discrete choice set up, there is a limited amount of alternatives to be considered, whereas in a continuous set up the number of alternatives can be infinite. MCDA is a commonly used method in sustainability assessments, because of its ability to deal with conflicting and incommensurable aspects such as environmental, economic and social dimensions (Merad et al. 2013; Myllyviita et al. 2013).

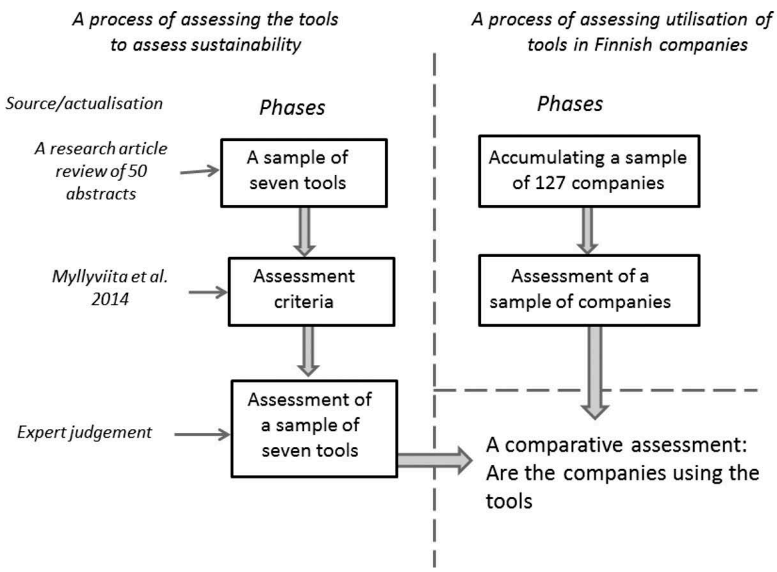

Figure 1. A flowchart for evaluation used in this paper. The process included a systematic evaluation of sustainability assessment tools commonly used for academic research purposes. We also reviewed the web pages and sustainability reports of Finnish companies to assess how these tools are used in practice.

2.1.2. Material flow analysis

MFA (and a subtype of it, substance flow analysis) refers to the analysis of the throughput of process chains comprising extraction or harvest, chemical transformation, manufacturing, consumption, recycling, and disposal of materials (Bringezu & Moriguchi 2002). The MFA process is based on physical units quantifying the inputs and outputs of materials or substances related to those processes. The system analysed may be geographical (e.g. a nation) or functional (e.g. a sector). The principle underlying the economy-wide MFA approach involves a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment and dependent on a constant throughput of materials and energy (Hinterberger et al. 2003).

2.1.3. Life cycle assessment and other life cycle methods

LCA is a method assessing the environmental impacts of a product or a service from the cradle to the grave. Guidelines for conducting an environmental LCA are given in the standard by International Organisation for Standardisation (ISO) 14040:2006 (ISO 2006). While LCA has some similarities with MFA, the latter is based on assessing a single material or substance, whereas LCA considers several impacts and materials. Various impacts, such as climate change, acidification and toxic emissions, can be included in the LCA. Life cycle costing (LCC) is an approach that assesses the total cost of an asset over its life cycle, including initial capital costs, maintenance costs, operating costs and the asset's residual value at the end of its life (Sesana & Salvalai 2013). Social LCA (SLCA) is developed towards evaluating social impacts, such as employment, workplace health and equity (Benoît 2009; Macombe et al. 2013). This approach is based on the same principles as LCA, but the methods are not well-established yet. So far, SLCA has only been applied for a limited number of cases, but the topic is greatly discussed in the field of LCA (Benoît 2009; Jeswani et al. 2010; Macombe et al. 2013). Life cycle sustainability assessment (LCSA) integrates environmental, economic and social aspects simultaneously, but so far, this topic has remained at a conceptual level (Hoogmartens et al. 2014).

2.1.4. Input–output models

The IO model is a quantitative method that describes the interdependencies between different branches of the economy. The model is based on analyses originally developed by Leontief (1936). The environmentally extended IO (EEIO) analysis is a method for evaluating the linkages between economic consumption activities and environmental impacts. This is an extensively utilised method for assessing the consumption-based drivers of environmental impacts (e.g. Koskela et al. 2011; Kitzes 2013).

2.1.5. Sustainability indicators and indices

The efforts to develop sustainability indicators and indices have increased since the beginning of the 1990s (Rinne et al. 2013). Some of the most commonly used sustainability indicators are connected to gross domestic product and greenhouse gas emissions, for example. The aim behind the indicators and indices is to simplify, quantify, analyse and communicate complicated information to support policymaking and public communication (Singh et al. 2012). Much conceptual and empirical research exists on criteria for sustainability and development of sustainability indicators, while fewer studies focus on the utilisation of sustainability indicators (Rinne et al. 2013).

2.1.6. Cost–benefit analysis

CBA is a method that estimates the equivalent monetary value of the benefits and costs of a project. Based on CBA, it is possible to state whether the project is worth pursuing. The basis of CBA is on economic metrics. However, the concept of sustainable development can be included into CBA. This would, however, require some changes in CBA, such as including, for example, the Social Discount Rate (Sáez & Requena 2007) and monetary valuation of the ecosystem services (Pearce et al. 2006). While also including non-priced external effects in money terms into a standard CBA, this can be referred to as an 'extended' CBA (Brouwer & van Ek 2004). These improvements notwithstanding, valuation of ecosystem services has been highly criticised (see, e.g., Kumar & Kumar 2008 for details), since assigning a monetary value to nature and natural resources has been deemed questionable.

2.1.7. Optimisation methods

Optimisation methods are used to seek an optimal alternative among a potentially infinite number of alternatives. Optimisation methods are a versatile group of methods, ranging from the simplest linear programming to more complex multi-objective optimisation methods. Optimisation methods have been applied in several fields, such as forestry (Diaz-Balteiro & Romero 2008) and the building sector (Evins 2013). Despite the fact that optimisation methods have, typically, been expert-driven tools, integrating stakeholders has been considered to be a necessary part of a process (Maness & Farrell 2004).

2.2. The assessment criteria for the tools

The tools commonly used in research articles to assess sustainability were evaluated. We utilised specific

Table 1. Criteria for assessing tools previously developed by Myllyviita et al. (2014).

Dimension 1: Transparency
-it is clear what is the decision problem and criteria -negative aspects mentioned -justification or reasoning of other decision-makers is presented -analyses and results are clearly stated (from the viewpoint of possible participants)
Dimension 2: Flexibility
-participants can change decision criteria and alternatives -iteration between the phases -new ideas included
Dimension 3: Consensus building
-multiple participants -awareness and acceptance of worldviews -participants engaged from an early stage -conflicts acknowledged
Dimension 4. Operability
-decision criteria are measurable -decision alternatives are compared -trade-offs between decision criteria acknowledged -implementation orientation (yields action plan) -uncertainties analysed

assessment criteria, since it is important to have a unified evaluation framework that treats all tools equally (see Table 1). As there are no widely accepted criteria for this type of assessment, we applied previously developed criteria based on democracy and planning theories, along with participatory planning work by Myllyviita et al. (2014). The criteria were originally developed for use in the natural resources planning process. Our purpose of using these assessment criteria in our study was the detection of a transparent and flexible decision support tool. True underlying decision problems are a precondition also for successful sustainability assessments. In addition, characteristics such as operability are called for. More detailed descriptions of the dimensions and assessment criteria can be found in Myllyviita et al. (2014).

The assessment criteria are grouped under the following four dimensions: transparency, flexibility, consensus-building and operability (see Table 1). Each dimension includes three to five criteria. The definitions of the original criteria were modified slightly, since the criteria were originally developed to assess case studies, whereas the aim for this paper is to evaluate tools.

Dimension 1: Transparency was assessed with four criteria, which aimed to address, if possible, whether participants involved in a process are able to understand the purpose and reasoning behind a tool. Also, a tool should be able to inform about possible negative impacts associated with the decision problem. In addition, a tool should also present the justifications of other decision-makers.

Dimension 2: Flexibility was assessed with three criteria, which aim to assess if a tool has the possibilities to be modified based on participants' wishes. A tool should enable a selection of decision criteria and a modification of the decision alternatives, as well. The possibilities to iterate the process should be a part of a flexible tool.

Dimension 3: Consensus building was assessed using five criteria. With these criteria, the tool's possibilities to address different perceptions related to the decision problem and, thus, increase the probability to reach a consensus are assessed. To reach a mutual understanding, participants should be engaged at an early stage. A successful tool should allow an acknowledgement of possible conflicts and different worldviews.

Dimension 4: Operability was assessed with five criteria that aim to assess whether a tool has possibilities to be efficiently applied to support decision-making. An action plan can be generated if a tool is capable to produce a clear conclusion, that is, define if a certain alternative is better than others. If the generated results are more ambiguous, generating an action plan is more challenging. To increase the operability, the decision criteria should be measurable. Possible trade-offs between them should be acknowledged, since without trade-off consideration some benefits may be maximised at the expense of others. Since uncertainty is, in most cases, significant in sustainable decision-making, a tool should include an uncertainty assessment.

We developed a simple scoring system for the purposes of this paper. Interpretations of the assessment criteria are not absolute (i.e. including new ideas is always attainable, but would require more effort and modifications); therefore, we applied the following scoring system. In the assessment system, '+' indicates that a tool has some possibilities to address the criterion and '++' indicates that this aspect is regularly implemented by the tool. 'O' stands for criterion fulfilment that could not be determined. Finally, '–' implies that a tool has no chance of meeting the criterion. The assessments of all tools were completed by the three authors. The evaluation was completed in a joint meeting, where each tool was assessed with respect to each criterion. In these assessments, we focused on assessing the tools, as they are described in the standards, instruction materials and well-accepted research. First, each author expressed his/her own perceptions and arguments. In the case of a disagreement, a more profound discussion was taking place. Finally, an agreement was reached. Using three expert opinions, instead of one, more reliable results were achieved. Nevertheless, the assessment is influenced by the expertise of the authors; therefore, a different group of evaluators could possibly generate a slightly different kind of results. For instance, iteration is mentioned in the standards for LCA (ISO 2006); therefore, it is safe to say that iteration is a part of LCA. However, the interpretation of some assessment criteria is more subjective. It is not unambiguously possible, for example, to determine whether the 'analyses and results [are] clearly stated'. In this case, some interpretation was required.

2.3. The review of company-level sustainability assessment

Our review of the companies in Finland was accomplished by studying web pages and sustainability reports of the companies. In this review, the aim was to detect utilisation of the seven tools (again, MCDA, LCA, MFA, IO models, sustainability indicators and indices, CBA and optimisation). Altogether 39 energy companies, 20 hotels and restaurants, 20 mines and 48 construction enterprises were included in a review. The companies were selected on the basis of the scale of their total revenue, and the four sectors included were chosen for their importance for sustainable development. Many of the companies reviewed are multinational, and, thus, their performance in Finland also reflects the situation in their other countries of operation. Web-pages and sustainability reports of these companies were carefully studied. First an assistant studied the reports, and did his preliminary analyses. To ensure validity, a senior researcher reviewed the preliminary analyses. If the web pages or sustainability reports of a company showed evidence of the utilisation of a specific tool, a positive observation was recorded (see Table 3, in the 'Results and discussion' section). After reading all the reports and web pages, the percentages of positive observations were calculated. Also, a review on how the companies addressed sustainability (i.e. an assessment on which the dimensions of sustainability were highlighted in their sustainability reports and web pages) was actualised. The percentage of positive observations was also calculated.

3. Results and discussion

Using the Web of Knowledge database for our study, we compiled the sample of seven tools that are commonly used in research articles to support sustainability assessments (see Subsection 2.1 for details). Using predetermined assessment criteria (Myllyviita et al. 2014), we evaluated these tools. Furthermore, we reviewed the sustainability reports and web pages of Finnish companies, as described above, to gain insights into how often these tools are applied in company-level sustainability assessments.

3.1. The assessment of commonly used tools to assess sustainability of economic systems

As a result of the research article review, a sample of seven tools, MCDA, MFA, LCAs, IO models, sustainability indicators and indices, CBA and optimisation methods, was obtained. The seven tools commonly used to assess the sustainability of economic systems in the reviewed journal articles were evaluated with respect to assessment criteria developed by Myllyviita et al. (2014), as explained earlier. Based on three expert judgements, none of these tools was successful with respect to all criteria (Table 2). Nevertheless, MCDA,

Table 2. The results of assessment of the sample of seven commonly used tools to assess sustainability (in the assessment system, '+' indicates that a tool has some potential to address the criterion and '++' denotes this aspect being regularly implemented by a tool, whereas '–' indicates that a tool has no capability to meet the criterion and 'O' stands for criterion fulfilment that could not be determined).

Criteria for assessing tools	MCDA	MFA	LCA	IO-model	Sustainability indicators and indices	CBA	Optimisation
Dimension 1: Transparency							
-it is clear what is the decision problem and criteria	++	–	+	+	–	++	++
-negative aspects mentioned	+	–	++	+*	+	++	+
- justification or reasoning of other decision-makers is presented	+	–	–	–	–	–	–
- analyses and results are clearly stated (from the viewpoint of possible participants)	+	+	+	+	+	++	+
Dimension 2: Flexibility							
-participants can change decision criteria and alternatives	++	–	+	–	–	+	+
-iteration between the phases	++	–	++	–	–	+	+
-new ideas included	++	–	+	–	–	+	+
Dimension 3: Consensus building							
-multiple participants	++	–	+	–	–	+	+
-awareness and acceptance of worldviews	+	–	–	–	–	–	–
-participants engaged from an early stage	+	–	+	–	–	–	–
-conflicts acknowledged	+	–	–	–	–	–	–
Dimension 4. Operability							
-decision criteria are measurable	++	++	++	++	+	++	++
-decision alternatives are compared	++	–	++	+	0	++	++
-trade-offs between decision criteria acknowledged	++	–	+	–	–	+	+
-implementation orientation (yields action plan)	++	+	++	+	+	++	++
-uncertainties analysed	+	+	+	+	–	+	+

* Iif EEIO is applied.

LCAs, CBA and optimisation methods regularly implement many of the assessment criteria. On the other hand, MFA and sustainability indicators and indices were considered to be relatively limited in their capacity to address sustainable development.

MCDA was considered to be a transparent tool (Table 2). When applying MCDA, it is crucial that the decision problem and the criteria are clearly stated, that is, problem structuring is an essential part of the process (Belton & Stewart 2002). Since the target in MCDA is on maximising the utility (or to find the decision alternative with the highest utility or value), the negative aspects associated are often less processed. The justification and reasoning applied by other decision-makers are not presented in MCDA applications (or in any other tool assessed in this paper) unless more in-depth discussions take place (e.g. Mustajoki et al. 2011). Based on weights (which define the importance of decision criteria), participants are able to gain some insights of other participants' preferences (e.g. Belton & Stewart 2002). A typical result of MCDA application is a decision alternative with a highest utility (or in the case of sustainability – the most sustainable); however, it may not be easy for participants to detect how the superior decision alternative has been determined, unless time and resources are allocated for describing the process to the participants (e.g. Mustajoki et al. 2011). Flexibility is one of the benefits of using MCDA, since MCDA allows a modification of the decision criteria and alternatives (e.g. Myllyviita et al. 2013). Iteration and including new ideas into a process are possible, even in a standard MCDA application (Belton & Stewart 2002). Consensus building is moderately well considered in MCDA, since multiple participants are typically engaged (Belton & Stewart 2002). MCDA has some potential to engage participants from an early stage (to structure the decision problem, for example). Conflicts can be acknowledged, since it is possible to incorporate various stakeholder groups into an assessment (Mustajoki et al. 2011). MCDA is successful in terms of operability, since various decision criteria are transformed as measurable and the comparison of decision alternatives is a very basic element of MCDA. An uncertainty assessment in MCDA is not typically actualised in a very sophisticated manner.

MFA appears to be less successful, compared to MCDA (Table 2). This is justified by the fact that the aim of MFA is merely to quantify material flows and stocks in a well-defined system, whereas sustainable development is a far more complex issue. Nevertheless, MFA can transform sustainable development assessment results as comprehensive, comparable and verifiable by (1) providing systematic information and indicators for the assessment; (2) identifying critical pathways, links and key substances; and (3) allowing the dynamic interaction between the material flow and social, economic and environmental processes (Huang et al. 2012). One advanced application of MFA is a connection of MFA with national economics accounts and, thus, enabling the IO models of the economic structures, causing material flows (Koskela et al. 2013).

LCAs appeared to be moderately successful tools to assess the sustainability of economic systems (Table 2). LCA was evaluated to be a moderately transparent method. Nevertheless, the justification and reasoning of other decision-makers are not detectable. Clarity of LCA-generated results and the process itself was not considered to be transparent as the ones generated with MCDA, since LCA is a more engineer-orientated tool and less focus is given to problem structuring (Häkkinen et al. 2013). Nevertheless, goal and scope definition is considered to be a fundamental part of LCA (ISO 2006). LCA is moderately flexible, since iteration is included (ISO 2006). The starting point in LCA is a set of impact categories (e.g. climate change and ecotoxicity), and a relevant set of decision criteria is selected from these. Including new ideas into LCA is not as straightforward as in MCDA, since there may not be suitable characterisation factors (i.e. determinants for the harmfulness of considered emissions) for less established impact categories. LCA has some potential to increase consensus, but tools for conflict management and the acceptance of worldviews are not given within LCA. Operability of LCA is high, since the LCA results are easy to implement: based on a comparative environmental LCA, it is possible to determine the most environmentally friendly alternative. However, it is possible that there are trade-offs between impact categories, that is, the most environmentally friendly alternative cannot be determined without the defining importance of impact categories (Myllyviita et al. 2013). The operability of LCA is moderate, since decision criteria are measurable. Also, uncertainty or sensitivity analysis is customary. However, the sensitivity assessment generally focuses on input parameters, but the uncertainty in LCA may be connected to the system boundaries as well (Mattila et al. 2012).

The IO model was considered to be a less transparent tool than MCDA and LCA, since in IO models, the focus is on the interdependencies between different branches of the economy. Therefore, the IO models are typically utilised at a higher level of decision-making, for example, regional (Liping & Bin 2010), national (Mattila et al. 2013) and global (Wiedmann et al. 2011). IO models can be used in company-level decision-making by generating a hybrid-LCA. In hybrid applications, a standard LCA is compiled, based on data on material and energy consumption, and an economic IO model is used to account for processes for which direct data are not available (e.g. Deng et al. 2011). The flexibility of IO models is lower compared to MCDA and LCA, since decision criteria and alternatives are not easily modified. IO models do not include tools for consensus building, but the operability of the tool is relatively high, because decision criteria are measurable and a comparison of alternatives is attainable. Also, an action plan can be generated, but as discussed earlier, these action plans are typically related to higher-level decision-making. Also, an uncertainty analysis can be conducted, but as in LCA and MCDA, uncertainty assessment is not very advanced in IO modelling.

Unlike the other tools assessed in this paper, sustainability criteria and indices are not methods, but merely tools to structure and communicate information about key issues, and their trends are considered to be relevant for sustainable development (Rametsteiner et al. 2011). Sustainability reports, for example, include a number of sustainability indicators and indices (such as climate-change-related emissions and employment figures) (Global Reporting Initiative 2013). Still, sustainability criteria and indices can bring some new ideas into processes, but they do not have the capabilities to bring consensus as such. Sustainability criteria can also provide some insights into conflicts and different worldviews.

CBA was considered to be a transparent method, since it is understandable, even for laymen. Analyses are clearly stated, as all aspects are expressed in monetary units. However, the decision-makers' justifications are not considered in CBA. CBA is not very flexible, for example, the inclusion of environmental or social aspects of sustainability is not possible as such. However, for instance, ecosystem services can be transformed into monetary units using monetary valuation methods (Pearce et al. 2006). The consensus building of CBA is not advanced, since the focus is only on economics. On the other hand, operability is advanced, since all decision criteria are measurable, and the action plan is generated (i.e. the aim is to reveal whether the plan is reasonable in economic terms). CBA is a potential method for sustainability assessments, as it is simple and comprehensive, but as a sole tool, it is not adequate, since it lacks the means to address other dimensions of sustainability, besides economics. CBA can be adapted to utilise metrics that are different from money, such as employment (Taylor 2001). Therefore, the utilisation of CBA for complex sustainability assessments is attainable (Gasparatos et al. 2008).

Optimisation methods were considered to be transparent, since the decision problem is, typically, clearly stated, that is, there is an aim to define the optimal alternative, including, for instance, some constraints (see, e.g., Evins 2013). Optimisation methods are flexible, since the modification of decision criteria and alternatives is advanced. The consensus building of optimisation methods is moderately low, since tools for engaging participants are not included. The major benefit of using optimisation is operability. This is because of the highly quantitative nature of optimisation methods.

3.2. The tools applied by Finnish companies

The review (Table 3) revealed that the tools available for sustainability assessments are seldom applied by the companies in these four sectors (i.e. energy, hotels and restaurants, mining and construction), at least based on publicly available sources. Sustainability criteria and indices were utilised, moderately, often. However, they are not considered to be methods, but merely tools that can be applied to describe past sustainability trends. In fact, LCA was the only structured method that was applied occasionally (Table 3), but only in the construction sector. In the construction sector, the life cycle perspective is especially important, since the lifespan of buildings can be up to 100 years. Therefore, assessing not only the impacts of the construction phase, but also the whole lifespan of a house (e.g. energy consumption and rebuilding) is important.

Sustainable development was verbally addressed in some manner by most of the companies examined (on their web pages or in their sustainability reports), and these companies gave some information about their role in sustainable development (see Table 4). Different dimensions of sustainability (environmental, social and economic) aspects were, in most cases, addressed. Most of the reviewed companies had compiled a sustainability report (Table 4). Since compiling a sustainability report is a major investment of time and resources, in most cases, only the largest companies will compile a sustainability report. As some of the included energy companies were moderately small, sustainability reports were not often compiled.

Table 3. Percentages of companies applying the various tools to assess sustainability (only sustainability criteria and indices were regularly applied, though companies in the construction sector had applied LCA also) with, in all, 39 energy companies, 20 hotels and restaurants, 20 mines and 48 construction companies were reviewed.

	Sector			
Tool	Construction	Mining	Hotels and restaurants	Energy
Life cycle assessment	17%	0%	0%	0%
Material flow analysis	0%	0%	0%	0%
Input–output models	0%	0%	0%	0%
Multi-criteria decision analysis	0%	0%	0%	0%
Sustainability criteria and indices	63%	50%	60%	69%
Cost–benefit analysis	0%	0%	0%	0%
Optimisation methods	0%	0%	0%	0%

Table 4. The percentage of companies addressing sustainable development and various aspects of sustainability in their sustainability reports or on their web pages (39 energy, 20 hotel and restaurant, 20 mining and 48 construction companies were reviewed).

	Sector			
	Construction	Mining	Hotels and restaurants	Energy
Sustainable development mentioned	60%	65%	60%	90%
Environmental aspects mentioned	63%	70%	65%	87%
Economic aspects mentioned	50%	55%	35%	69%
Social aspects mentioned	63%	70%	65%	80%
Sustainability reports present	63%	55%	50%	10%

In the sectors of construction, mining and hotels and restaurants, sustainability reporting was more common (Table 4).

3.3. Utilisation of tools to support sustainability assessments

The number of publications on sustainability assessment has been increasing over the last decades (Bond et al. 2012). In these publications (see references in Bond et al. 2012), various tools (e.g. LCA, MCDA and CBA) are used to support sustainability assessments. However, we discovered in our study that quite often these tools are not utilised on a company level. It is possible that companies do regularly utilise some of the tools assessed in this paper, but this is not reported. However, if the sustainability assessments are not reported (on company webpages or sustainability reports), the information in these assessments is not usable in decision-making outside companies. Thus, the potential contribution to the transformation to more sustainable companies may remain low. Therefore, it is important that sustainability assessments are reported in a transparent manner.

Based on the results of this paper, it appears that MCDA has the greatest potential to be successfully applied to support sustainability assessments (Table 2). However, it should be acknowledged that, solely, using MCDA to support sustainability assessments is not suggested, since MCDA, in many cases, needs input from other tools and methods, such as LCA (e.g. Elghali et al. 2007), CBA (Brouwer & van Ek 2004) and sustainability indicators (Mendoza & Martins 2006). Furthermore, several other tools seemed promising, but as discussed in the earlier sections, they would require some modifications, such as tools to integrate social aspects and tools to integrate stakeholders, for example. In most cases, the simultaneous use of different methods is beneficial (Myllyviita et al. 2011, 2014). Additionally, there are other tools not included this paper that could be successful, as well (e.g. risk assessment, monetary valuation methods, exergy analysis and several qualitative tools).

A relevant question here is how the tools can be used to assess wider systems than single companies and expand the perspective to the sustainability assessment of economic systems. Deepening the LCA approach by, for example, integrating social and economic dimensions of sustainable development may be beneficial (Jeswani et al. 2010). One option could be to create a toolbox that combines the procedural parts of criteria and indicators and the environmental impact assessment, supplemented with calculation algorithms of LCA and CBA (Buytaert et al. 2011). However, several methodological challenges remain, yet to be solved before these tools can be successfully integrated (Hoogmartens et al. 2014). Special focus should also be given to how these tools are applied, since the facilitator and the way in which the participants are engaged can be more influential than the tool itself (Myllyviita et al. 2014). It is also important to remember that the concept of sustainable development is highly ambiguous and that, in consequence, there are no widely accepted criteria addressing what constitutes a successful sustainability assessment tool. Therefore, the assessments compiled in this paper (especially in Table 2) are not exhaustive either.

3.4. Suggestions for future research: company-oriented sustainability trials

The results presented in this paper (in Table 4, in particular) show that sustainability is in companies' interest, as most of the companies mentioned sustainable development on their web pages. Furthermore, many of the companies had published a sustainability report. Also, successful tools to support the assessment of sustainable development are available (see Table 2). Nevertheless, application of these tools is not very commonplace in Finnish companies (as shown in Table 3). As earlier research has revealed, companies lack information and access to tools (see Häkkinen et al. 2013).

More importance should be given to bridging the gap between researchers who have knowledge of the tools and company managers who need support in their utilisation. One option for further development of the tools discussed in this paper is to create easy-to-use Web-based versions of these tools. There are several tools that can be downloaded without charge or be used on the Web (e.g. openLCA and the MCDA methods applied by SuperDecisions). There is, at least to our knowledge, no research on utilisation of these Web-based versions of the tools. Also, the reliability of these versions can be questioned. Nevertheless, these tools can yield some insights for company managers and at least provide learning experiences.

It is apparent that there is methodological expertise available to support sustainability assessments of companies and also that the companies are interested in sustainable development. Interviewing company managers could provide valuable information on their needs related to the assessment of sustainability. Also, semi-structured interviews could provide valuable information on the reasons why companies are not currently using many of the sustainability assessment tools addressed in this paper. Evidently, more information surrounding this topic is needed. In addition, the cooperation between experts and companies should be developed further. For instance, Judl et al. (2015) actualised a series of streamlined LCAs for SMEs. In their experience, the key issues in a product life cycle could be identified within 10–40 hours of research work, with only 8 hours of company involvement. Sustainability assessment trials of this sort, with the aim of generating an action plan that is feasible for an actual company, could be fruitful for both company-level decision-making and methodologically oriented research. In particular, SMEs would be suitable for such trials, as they do not have the resources and abilities to prepare the assessments without expertise.

3.5. Conclusions

Sustainable development and tools to support it have been extensively studied, but far fewer studies have investigated the actual company-level utilisation of these tools. The aim of our study was to address this central and timely issue. In summary, we systematically evaluated a sample of tools commonly used in research articles and found that none of the tools reviewed was comprehensive with respect to the assessment criteria. To meet the needs of sustainable development, some modifications to the tools are needed. Previous studies have shown that simultaneous use of several tools has substantial benefits. For example, MCDA requires input from other tools and methods, in order for reliable quantitative impact assessments to result. In our review of the web pages and sustainability reports of 39 energy companies, 20 hotels and restaurants, 20 mines and 48 construction companies for determining the state of utilisation, we found that Finnish companies seldom use any of the tools reviewed. Of the tools considered, sustainability indicators and indices were regularly applied, and only a few companies (in the construction sector) had used LCA. There is, evidently, a gap between research and companies, since the tools that are so often discussed in research articles are not used at the company level. It is apparent that, to bridge this gap, companies need more support with the utilisation of tools. One solution could be small-scale sustainability trials conducted by sustainability experts (e.g. members of research institutes or consultation companies specialising in relevant topics). Within these sustainability trials, companies could find ways to minimise their negative impacts on the environment and simultaneously gain potential economic benefits, without excessive investment of resources in sustainability assessment.

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12105-6 ▪ Quantitative Methods to assess sustainability ▪ Module 5

Economic dimensions

George Manthos
Quantitative Sustainability Assessment (QSA)
DTU Sustain

Outline

- Life Cycle Costing (*45 min*)
  - ➢ Definitions and Perspectives (*20 min*)
  - ➢ Go beyond the exercise (*10 min*)
  - ➢ Advantages, disadvantages, and perspectives (*15 min*)

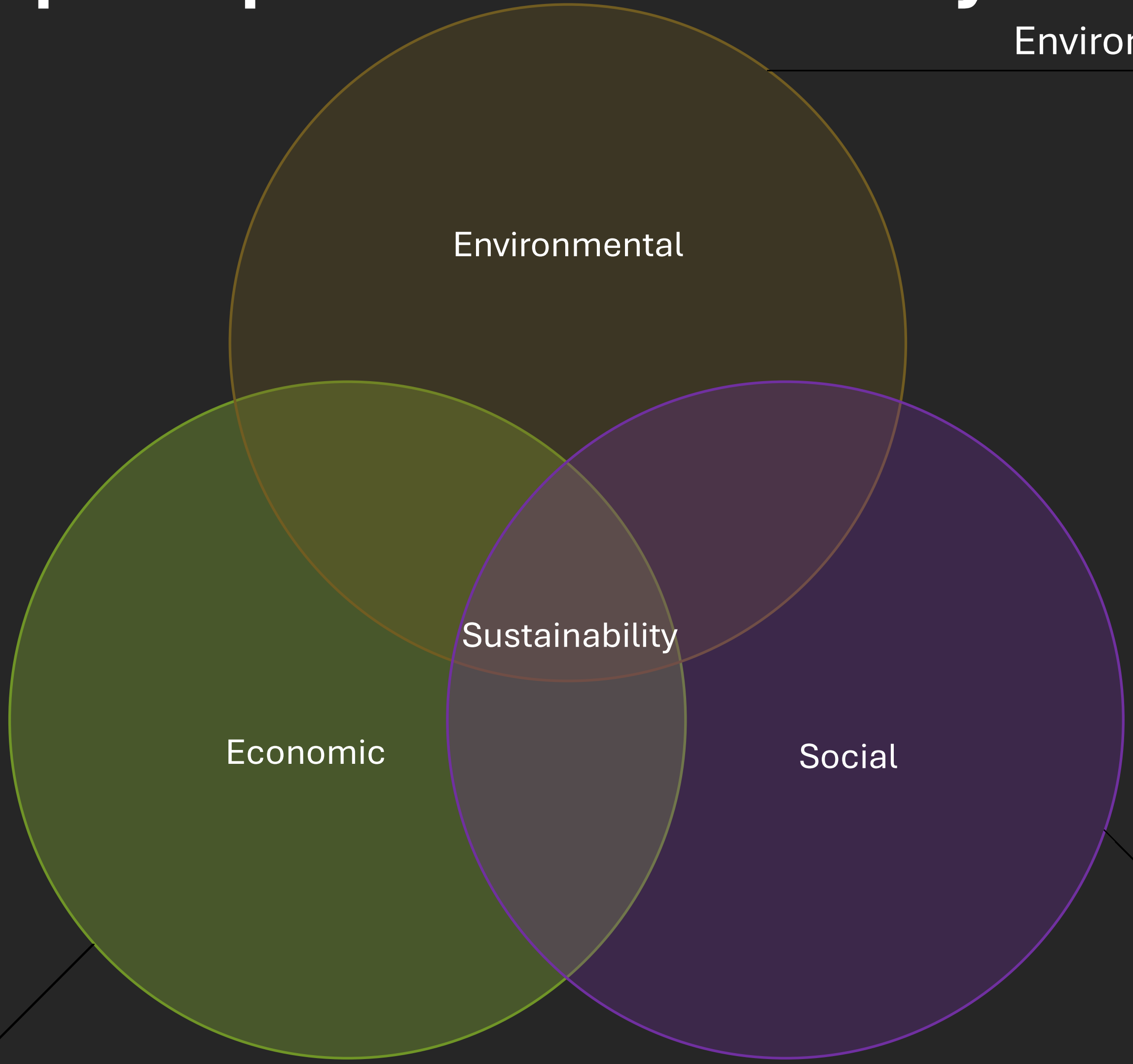
- Break

- Hands-on exercise, use the TAs for guidance (*45 min*)
  - ➢ Life-cycle cost of coffee
    - FU, stages, and assumptions (*10 min*)
    - Hands-on example, and try to find data on the web for:
    - Electricity price for consumers in Denmark
    - Prices of coffee machines (and life span)
    - Price of coffee

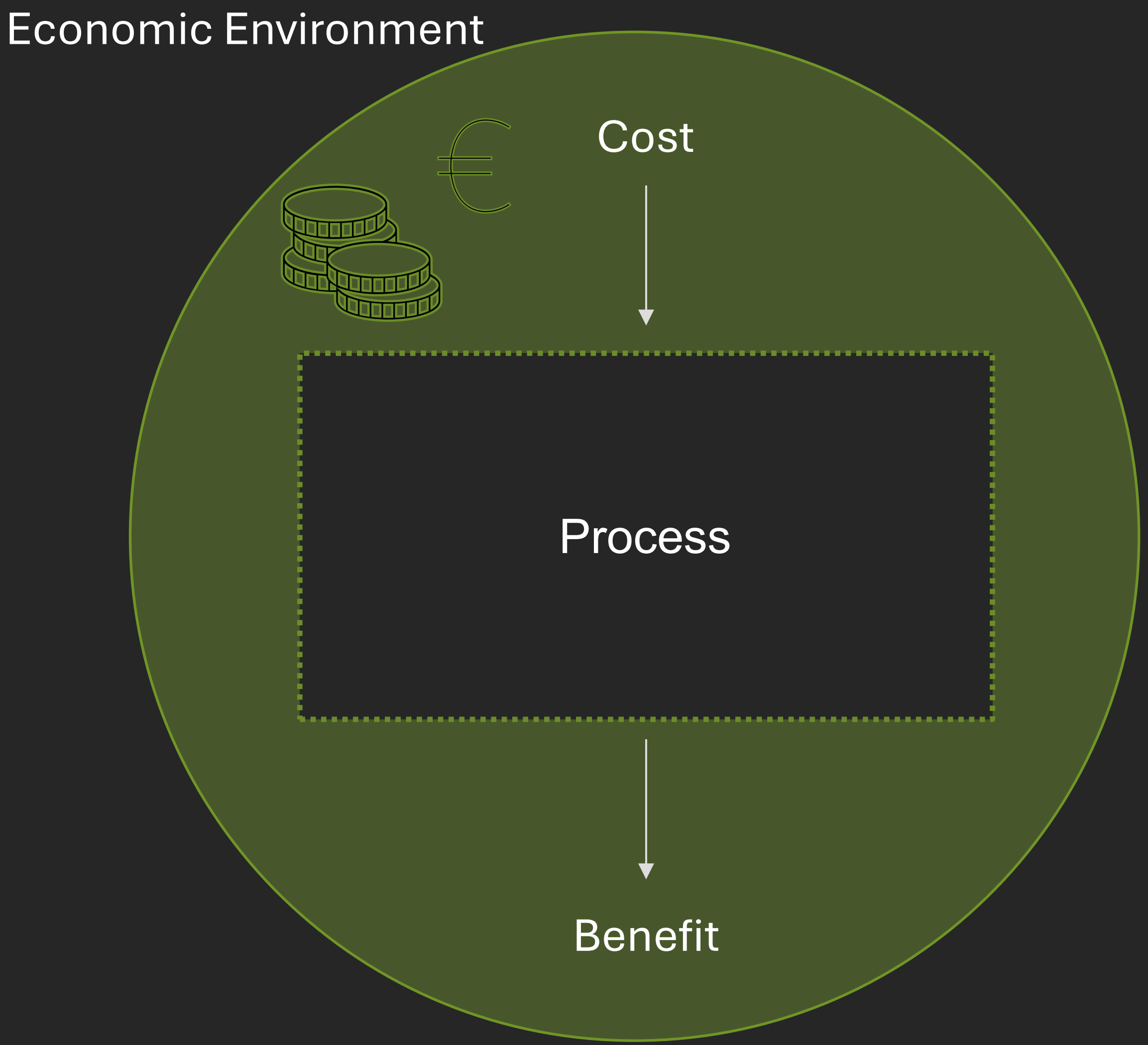
Learning objectives - Questions

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

Basic principles of Sustainability

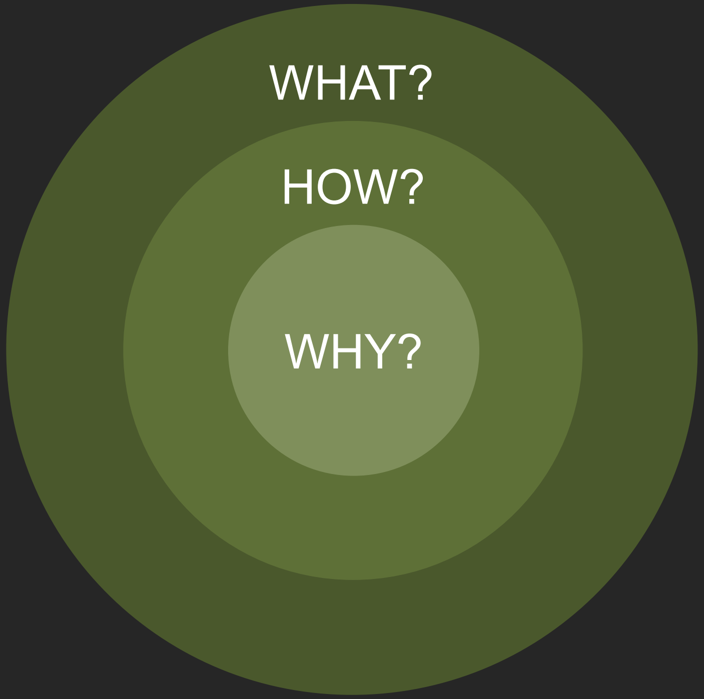


Life Cycle Costing (LCC)



- 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, how, why…



- ***<u>What</u>* 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.

- ***<u>How</u>* 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.

- ***<u>Why</u>* we want to achieve it?**

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

LCC – 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)

Is it really worth it?

Join the Vevox session

Go to **vevox.app**

Enter the session ID: **193-312-294**

Or scan the QR code

What are the implications of the LCC?

Pricing	0%
Social issues and policy making	0%
Decision making	0%
Energy optimization	0%
Performance management	0%
Mass and energy balance estimation	0%
Estimation of prospective potentials	0%

What are the implications of the LCC?

RESULTS SLIDE

Implications of LCC

Pricing

When we know LCC we can ensure an appropriate price for the product

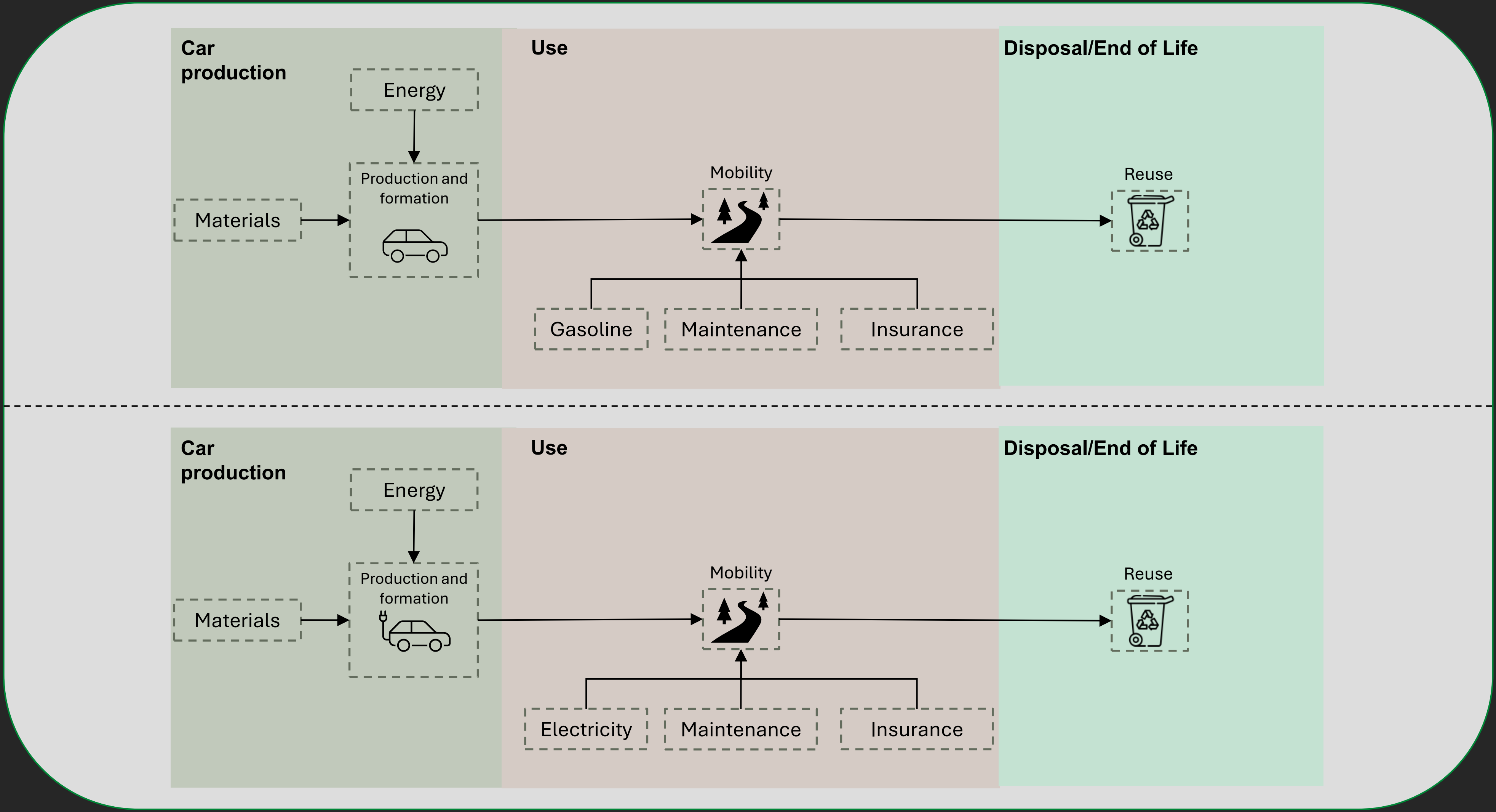
Performance Management

Highlights the consequences of releasing a product to the market
Identify areas at which the cost reduction would be more effective

Decision-making

Premises for decision-making regarding product introduction, continuation, etc.

Exercise – Gasoline VS Electric Vehicle



LCC – Simple Formula

Capital cost + Lifetime operating cost + Lifetime maintenance cost + Disposal costs - Residual value

=

LCC

LCC – Simple Formula

Capital cost

Capital cost refers to one-time expenses incurred on the purchase of assets

Lifetime operating cost

The total expenses incurred to operate and maintain an asset over its entire useful life.

Lifetime maintenance cost

The total expenses associated with maintaining an asset over its entire useful life.

Disposal costs

The total expenses associated with properly getting rid of an asset at the end of its useful life.

Residual value

The estimated worth of an asset at the end of its useful life

Depreciation

$$\textit{Annual depreciation} = \frac{\text{Capital cost} - \text{Residual value}}{\textit{Useful lifetime}}$$

Reflecting how much value is lost over time

Exercise 1: Gasoline VS Electric Vehicle (10 min)

- Match each cost component from the car case study to its corresponding LCC category. Repeat this process for all three scenarios

- Think critically about why each cost belongs where it does.

- Then respond to the following questions

Capital cost + Lifetime operating cost + Lifetime maintenance cost + Disposal costs − Residual value

To which category does the 'tire change' belong?

To which category does the 'tire change' belong?

maintanance
lifetime
maintanence
time maintenance
+13.5 more responses
maintenance&disposal
mantenite
operating costs
free palestine maint
lifetime maintenance
another response
car
lccc
disposal
lmc
maintenance costs
maintenance
lcc
ltmc
free palestine
maintenance cost
life maintenance
maintainance cost
maintenence
maintenance :)
maintenancen

RESULTS SLIDE

To which category do 'electricity' and 'petrol' belong?

40 Join at: **vevox.app** ID: **193-312-294** Showing Results

To which category do 'electricity' and 'petrol' belong?

operational
variable cost
free israel
operational cost
operate
opex
oc
operation
operating
loc
operating cost
operating costs
use
free palestine
οπερασιοναλ
lifetime operational
operation cost
op
capital costs

RESULTS SLIDE

Is the 'Insurance' is capital or operating cost?

Capital cost

0%

Operating Cost

0%

Is the 'Insurance' in capital or operating cost?

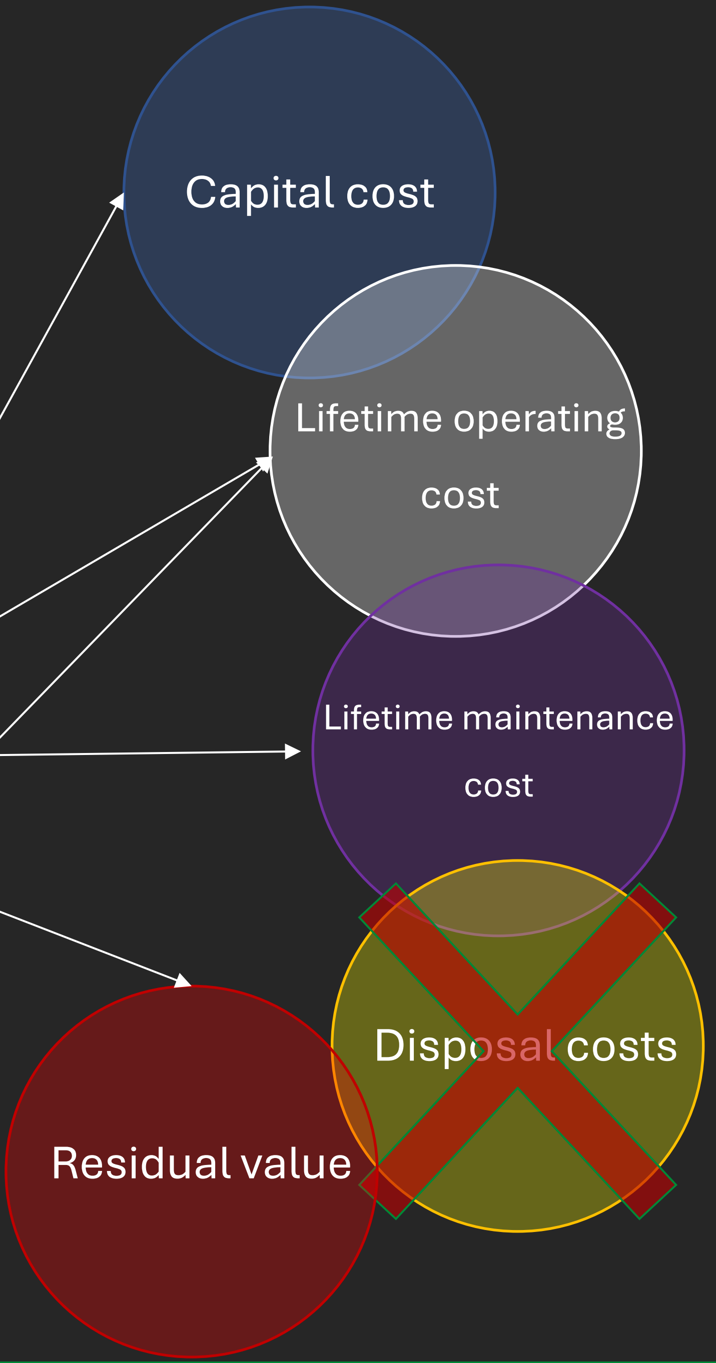
Capital cost 5.26%

Operating Cost 94.74%

RESULTS SLIDE

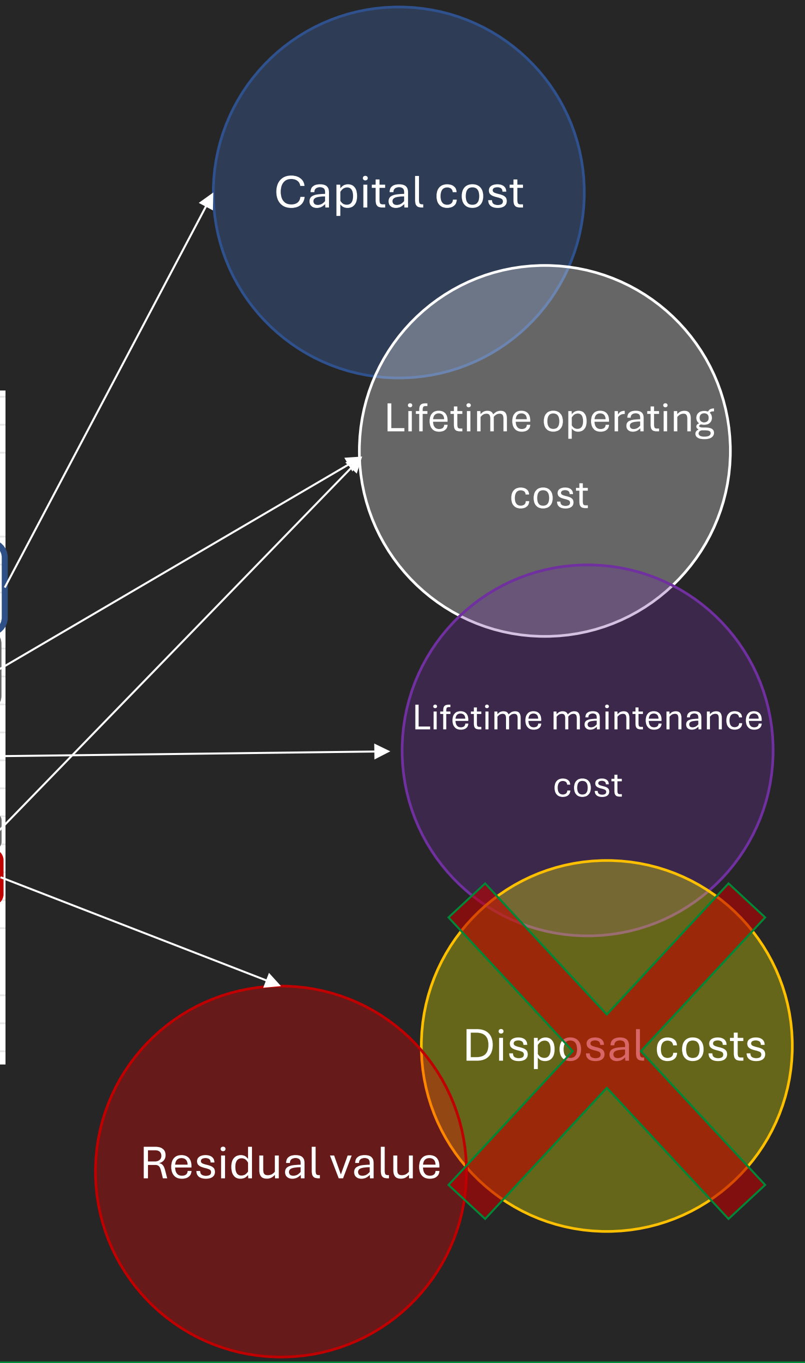
Gasoline Vehicle

Vehicle lifetime before resale	10						
Vehicle lifespan (km/vehicle)	150000				Costs		
Transportation by Gas Vehicle FU= 1 vehicle km		Quantity original unit	Quantity per FU	Unit	price/Unit [Euro/Unit]	Cost per FU [Euro/V-km]	fraction costs
Life Cycle stage (150,000 km lifespan)							
Purchase	Cost relevant distance	per vehicle over lifespan	per FU				
1 vehicle incl. Taxes	150000	1	6,67E-06	p	40000,00	2,67E-01	54,3%
Tax on vehicle at purchase	150000	1	6,67E-06	p		0,00E+00	0,0%
Fixed annual costs	km/yr	per year	per FU				
Insurance per year	15000	1	6,67E-05	p	500,00	0,033	6,8%
Registration taxes per year	15000	1	6,67E-05	p	200,00	0,013	2,7%
Variabl cost maintenance	km until change		per FU				
maintenance per 10000km	10000	1	1,00E-04	p	750,00	0,075	15,3%
Tires change every 20000 km	20000	4	2,00E-04	p	150,00	0,030	6,1%
Variable cost Fuel - Use phase	liter	per V-km	per FU				
Supply chain petrol, low-sulfur	1	0,0450	4,50E-02	L	2,05	0,092	18,8%
Resale value - end of life		per vehicle over lifespan	per FU				
1 vehicle	150000	-1,00	-6,67E-06	p	3000,00	-2,00E-02	-4,1%
Total			per FU				
Total		-		-		**0,491**	100,0%
							104,1%



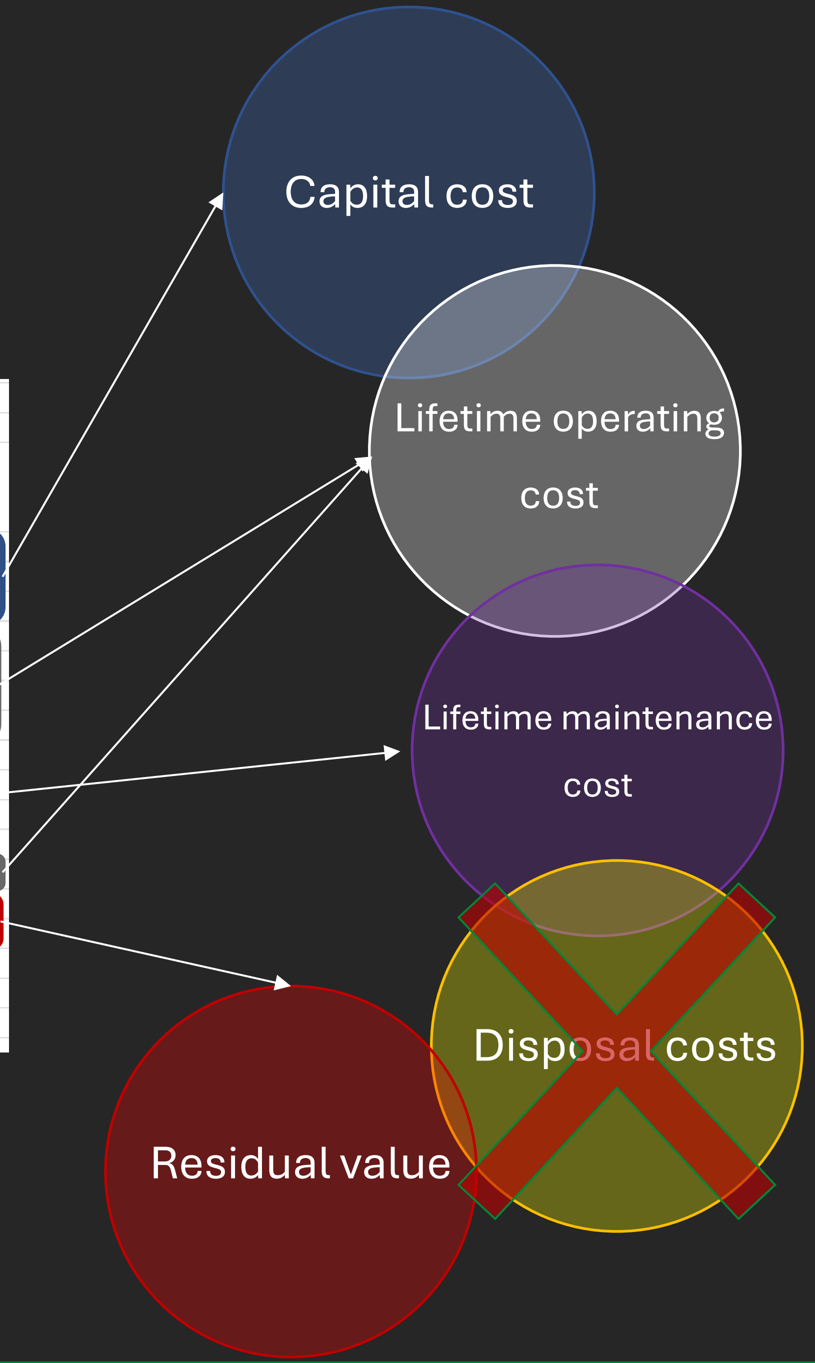
Electric Vehicle

Vehicle lifetime before resale	10						
Vehicle lifespan (km/vehicle)	225000				Costs		
Transportation by Electric Vehicle FU= 1 vehicle km Life Cycle stage (x km lifespan)		Quantity original unit	Quantity per FU	Unit	price/Unit [Euro/Unit]	Cost per FU [Euro/V-km]	fraction costs
Purchase	Cost relevant distance	per vehicle over lifespan	per FU				
1 vehicle	225000	1	4,44E-06	p	60000,00	2,67E-01	68,6%
Tax on vehicle at purchase	225000	1	4,44E-06	p		0,00E+00	0,0%
Fixed annual costs		annual purchase	per FU				
Insurance per year	22500	1,00	4,44E-05	p	700,00	0,031	8,0%
Taxes for immatriculation per year	22500	1,00	4,44E-05	p	100,00	0,004	1,1%
Variable cost maintenance			per FU				
maintenance per 10000km	10000	1,00	1,00E-04	p	300,00	0,030	7,7%
Tires change every 20000 km	20000	4,00	2,00E-04	p	150,00	0,030	7,7%
Variable cost Fuel - Use phase		per V-km	per FU				
electricity	1	0,2	2,00E-01	kWh	0,2	0,040	10,3%
Resale value - end of life		per vehicle over lifespan	per FU				
1 vehicle	225000	-1,00	-4,44E-06	p	3000,00	-1,33E-02	-3,4%
Total			per FU				
Total		-		-		**0,389**	100,0%
							103,4%

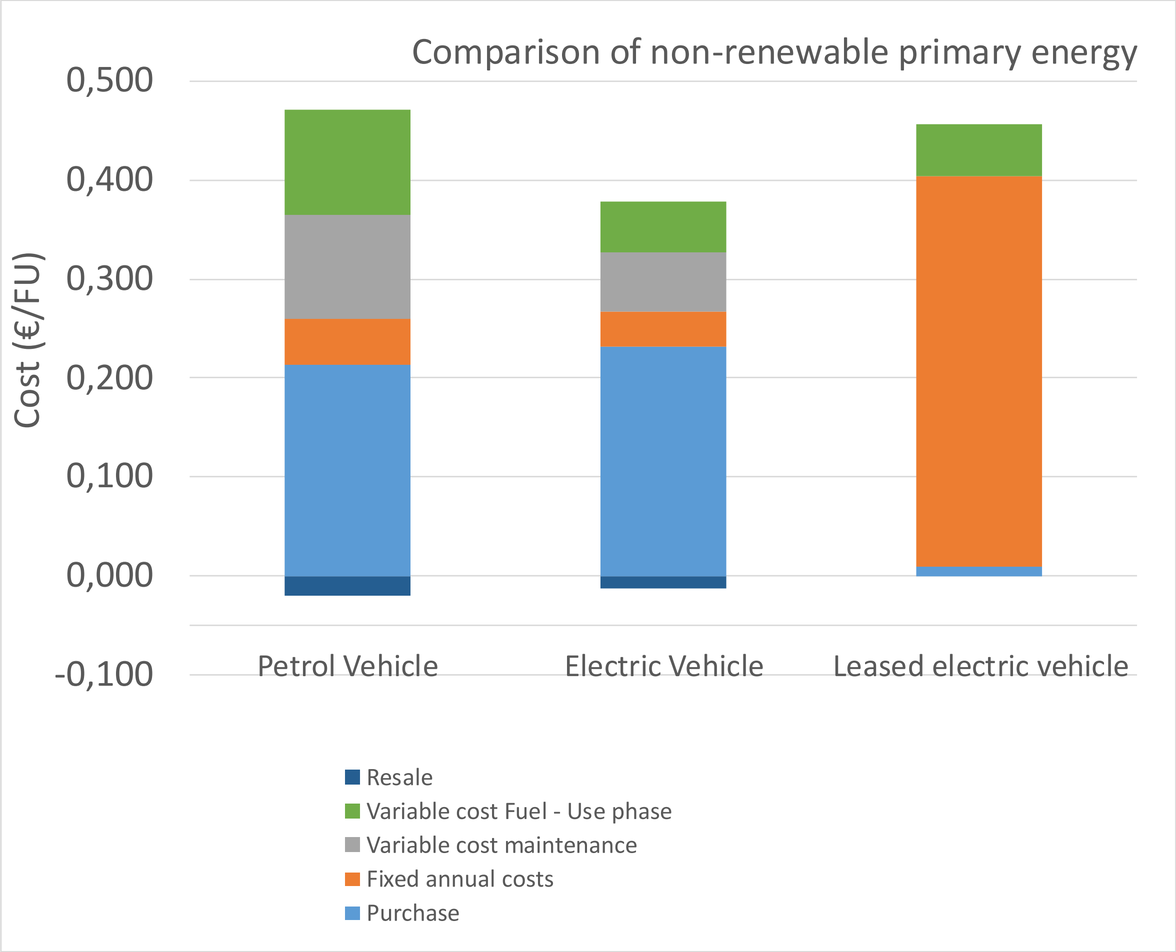


Electric Vehicle – Leasing

Vehicle lifetime before resale	10						
Vehicle lifespan (km/vehicle)	225000				Costs		
Transportation by leased Electric Vehicle FU= 1 vehicle km Life Cycle stage (x km lifespan)		Quantity original unit	Quantity per FU	Unit	price/Unit [Euro/Unit]	Cost per FU [Euro/V-km]	fraction costs
Purchase	Cost relevant distance	per vehicle over lifespan	per FU				
1 vehicle (3 times new leasing)	225000	1	4,44E-06	p	2000,00	8,89E-03	1,9%
Tax on vehicle at purchase	225000	1	4,44E-06	p	0,00	0,00E+00	0,0%
Fixed annual costs		annual purchase	per FU				
Insurance per year	22500	1,00	4,44E-05	p	0,00	0,000	0,0%
Taxes for immatriculation per year	22500	1,00	4,44E-05	p	100,00	0,004	1,0%
Leasing 3x3+1 years	22500	1,00	4,44E-05	p	8800,00	0,391	85,7%
Variable cost maintenance			per FU				
maintenance per 10000km	10000	1,00	1,00E-04	p	0,00	0,000	0,0%
Tires change every 20000 km	20000	4,00	2,00E-04	p	0,00	0,000	0,0%
Variable cost Fuel - Use phase		per V-km	per FU				
electricity	1	0,26	2,60E-01	L	0,20	0,052	11,4%
Resale value - end of life		per vehicle over lifespan	per FU				
1 vehicle	225000	-1,00	-4,44E-06	p		0,00E+00	0,0%
Total			per FU				
Total		-		-		**0,456**	100,0%



Comparative results



Advantages of LCC

Improve forecasting
Applying Life Cycle Costing (LCC) enables a more accurate estimation of the total cost associated with a procurement.

Improved awareness
Enhance management's understanding of the cost drivers and the resources required for the procurement.

Performance trade-off against cost
The LCC technique not only focuses on cost but also takes into account other factors such as the quality of goods and the level of service provided.

Disadvantages of LCC

Time consuming
LCC can become extended or more complex due to rapid changes in technology.

Costly
The longer the project's lifetime, the higher the operating costs incurred over time.

Technology
Technology always change day to day (uncertain estimation)

Economic feasibility and Scaling effects

- *Reduction of "per unit" fixed cost*
  - ➢ *Increased production lead 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*

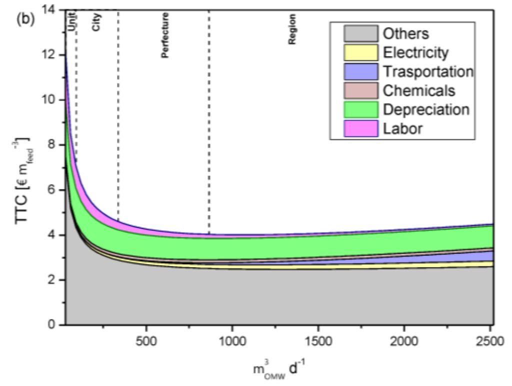
BUT… What is the connection?

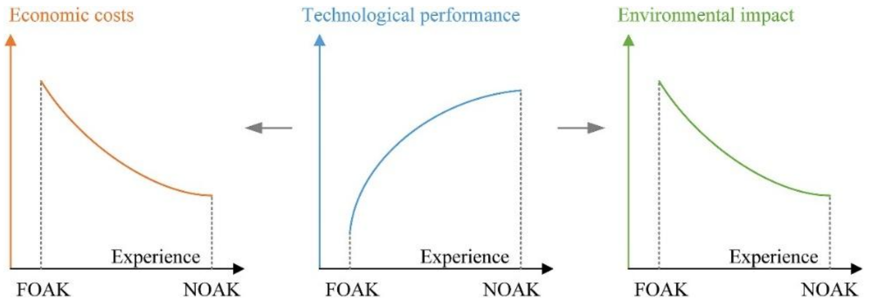
$$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n$$

C_t = *Cost in scale t*

S_t = *Capacity in scale t*

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





Briefly...

- *LCC can help determine whether the revenue generated by a product is <u>sufficient</u> to cover the costs incurred throughout its life cycle.*
- *It <u>reveals</u> opportunities for cost reduction and minimization, thereby creating scope for profit maximization over the asset's lifetime.*
- *It <u>identifies</u> the cost involved at different stages of the life cycle and <u>examines</u> its effect in pricing and decision-making.*

BREAK

Hands-on exercise – Coffee maker

- Big question no. 1 (*Vevox app*):

Can you define the Functional Unit?

- Big question no. 2 (*Vevox app*):

Can you define the Life Cycle stages?

In which one we are working on?

- Big question no. 3 (*Vevox app*):

Can you define the assumptions?

- Big question no. 4 (35 min):

Can you fill the missing boxes on the Excel sheet?

Reflect on the graph!!

Which scenario is "more" feasible?

Can you define the FU?

Join at: **vevox.app**

ID: **193-312-294**

Preparing Results

Can you define the FU?

"Being able to fill one cup with hot good quality coffee in under a minute with a limited energy consumption, waste and noise production in an average european household."

One cup coffee in

1 cup of coffee (1 dl)

Coffee maker

Cup of coffee

One cup of coffee

One cup of coffe in denmark

1 dl = 1 cup

1 cup of coffee

1 cup of coffee

time to make a single cup of coffee

1 cup of coffee

Cofee maker

1 cup of coffee

* 1 cup of coffee of 1 dl.
* Using 11.5g of coffee
* In Denmark

+4 more messages

RESULTS SLIDE

Can you define the assumptions?

Can you define the assumptions?

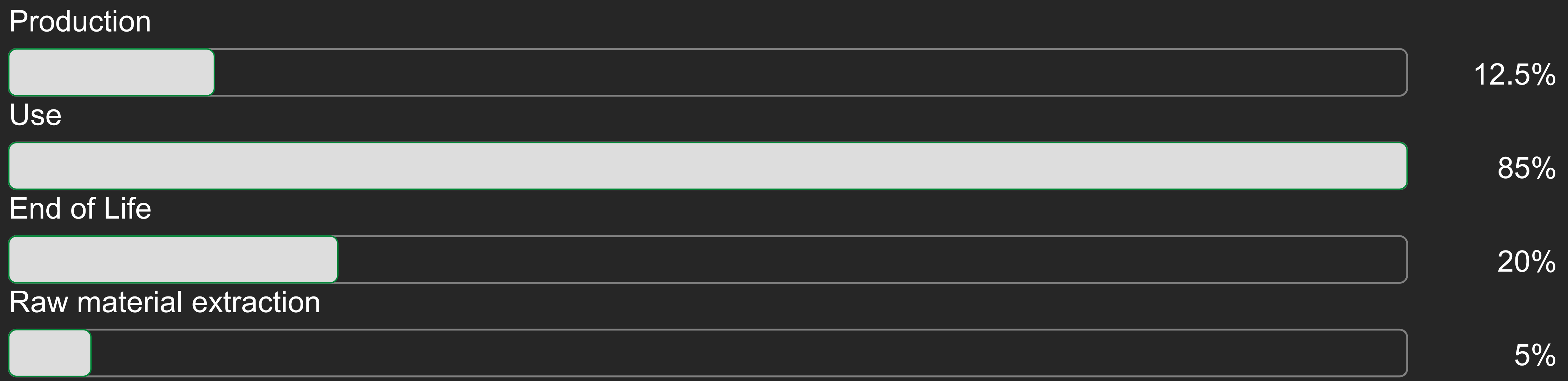
Life time of the coffee machine, the number of cups of coffee made	No maintenance	Electricity, Maintenance	Life span
Life span	The coffee machine's manufacturing is out of the scope.	Nr of cups	No maintenance
Electricity mix	Amount of water used before chalk cleaning is needed	The assumptions are that the coffee machine can interchangably use any	No maintenance
how many times used and quantity of coffee made	Single use cup Singe use capsule 2,31 kr kWh	used only it has no value	+5 more messages

RESULTS SLIDE

In which Life Cycle Stage we are working on?

Production	0%
Use	0%
End of Life	0%
Raw material extraction	0%

In which Life Cycle Stage we are working on?

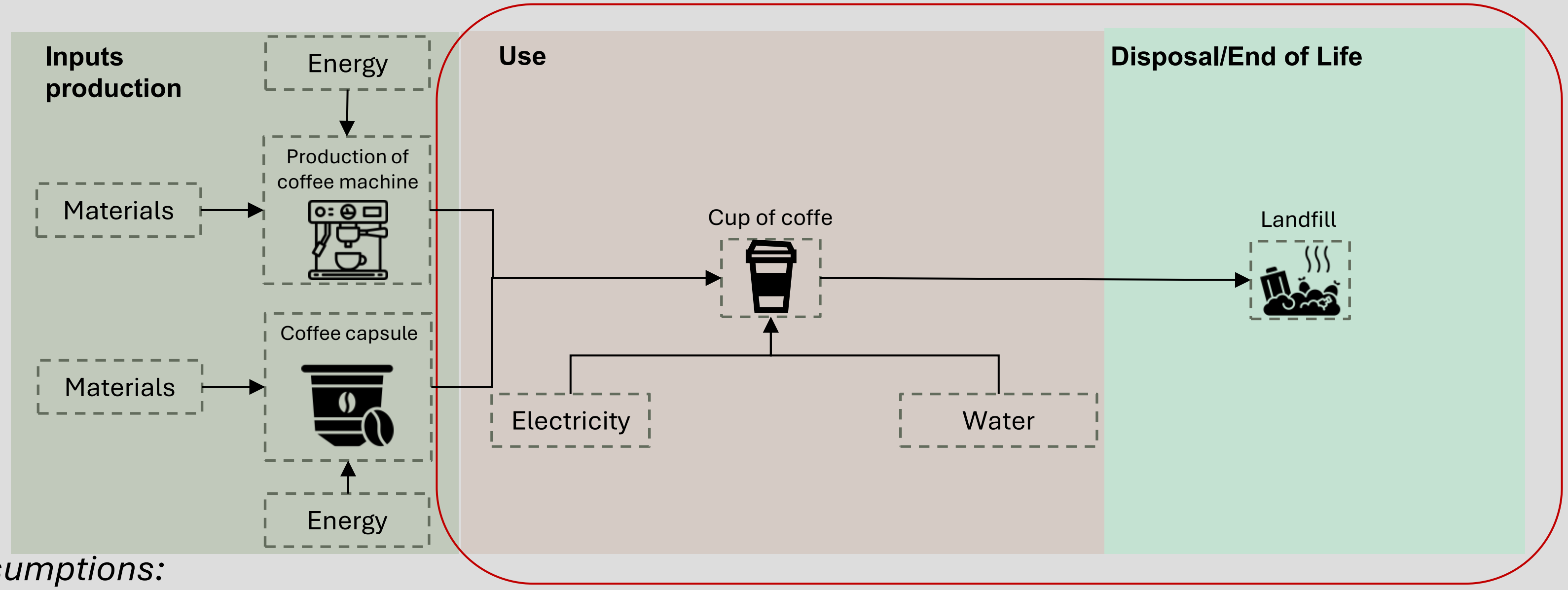


RESULTS SLIDE

Hands-on exercise – Coffee maker

- *The production of one standard cup of coffee using a domestic automatic espresso machine*

- LCC stages

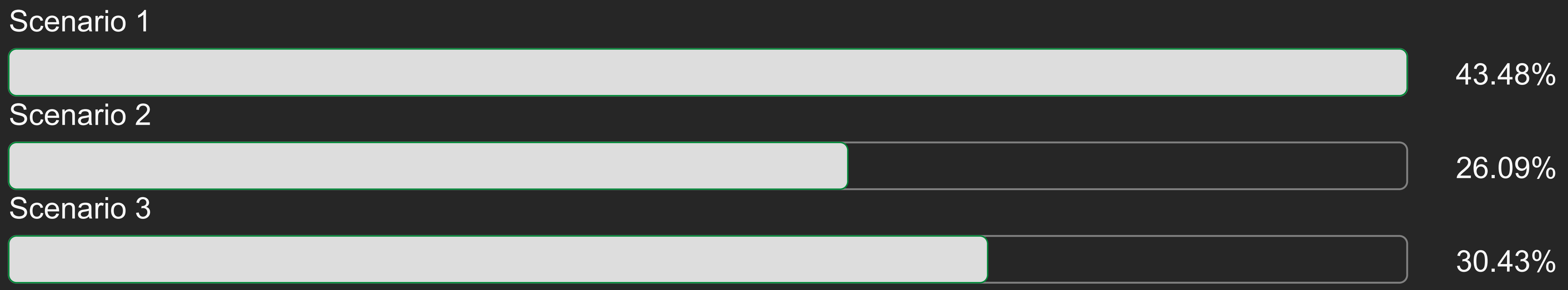


- *Assumptions:*
  - *No milk or sugar added*
  - *Doesn't include cleaning and maintenance impacts proportionally allocated per cup*

Which scenario is "more" feasible?

Scenario 1	0%
Scenario 2	0%
Scenario 3	0%

Which scenario is "more" feasible?



RESULTS SLIDE

Thank you!

You never give me your money; you only give me your funny paper

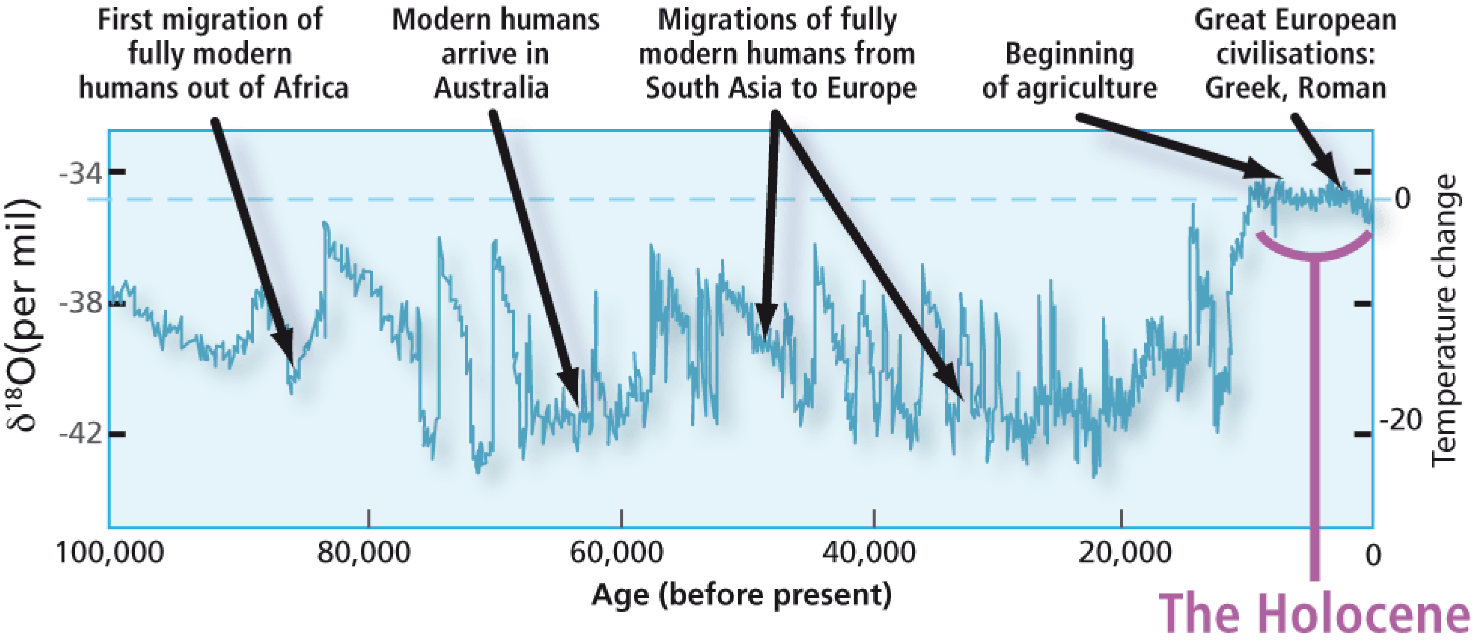
Paul McCartney, 1969

Planetary boundaries and absolute sustainability

Michael Hauschild
Technical University of Denmark
mzha@dtu.dk

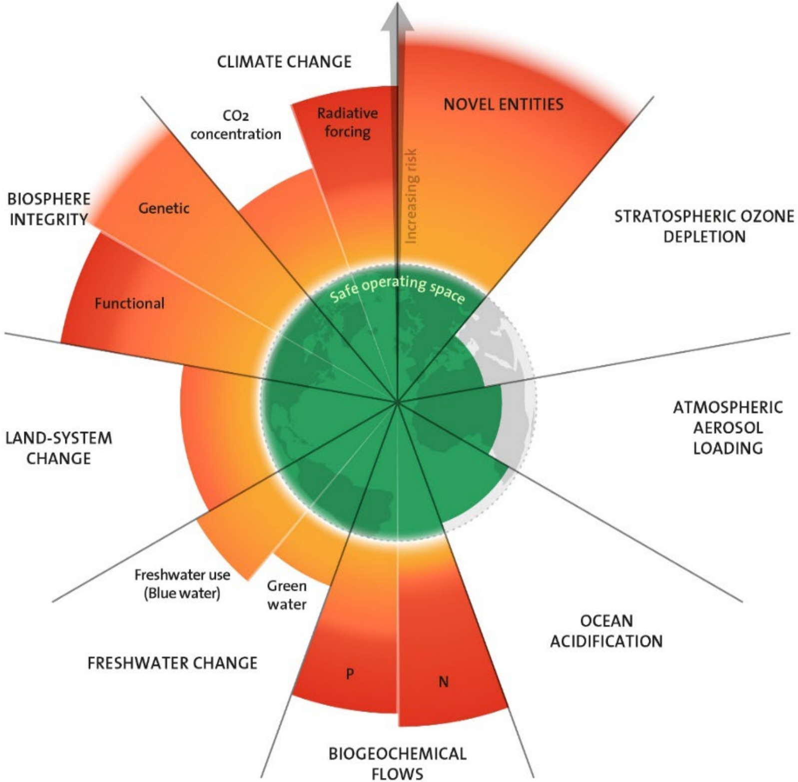
The sustainability challenge

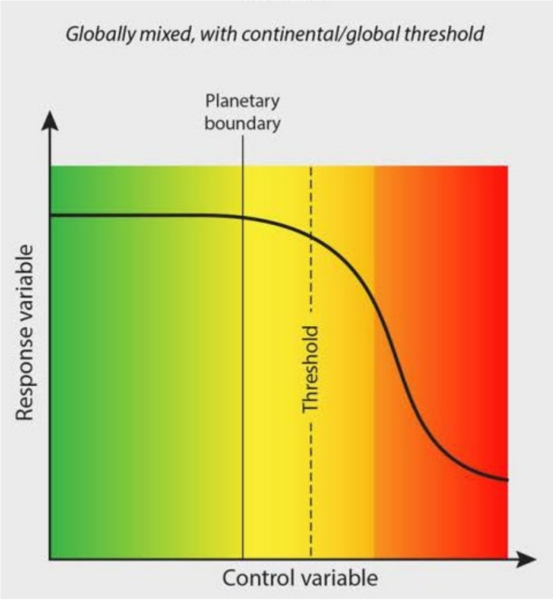
Keeping the planet in the holocene



International Geosphere Biosphere Programme
http://www.igbp.net/globalchange/anthropocene.4.1b8ae20512db692f2a680009238.html

Planetary boundaries



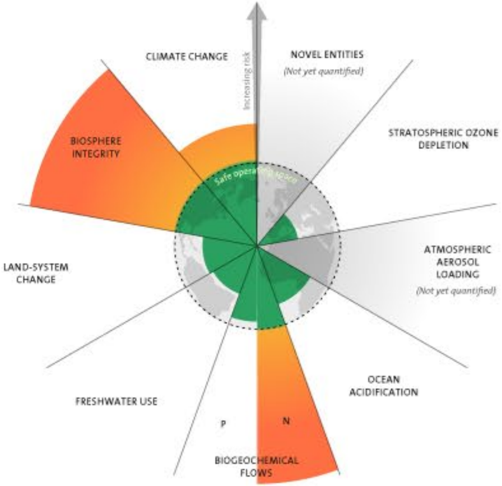


Steffen W, Richardson K, Rockström J et al. (2015) Planetary boundaries: Guiding human development on a changing planet. Science 347(6223), 736-746

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

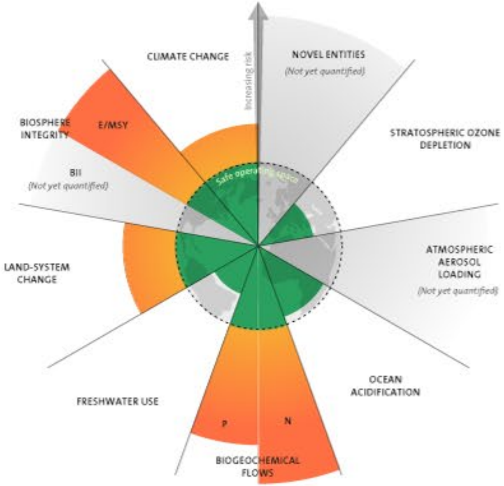
Planetary boundaries

2009



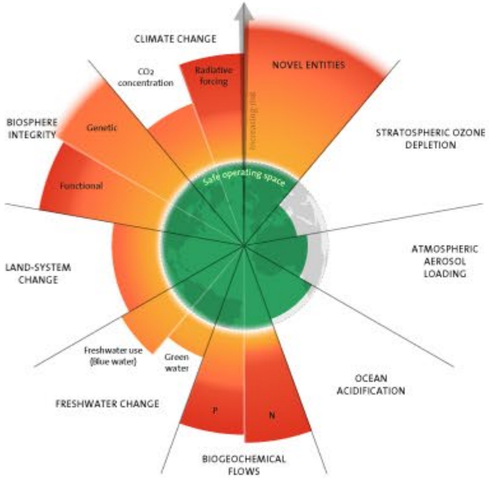
3 boundaries crossed

2015



4 boundaries crossed

2023



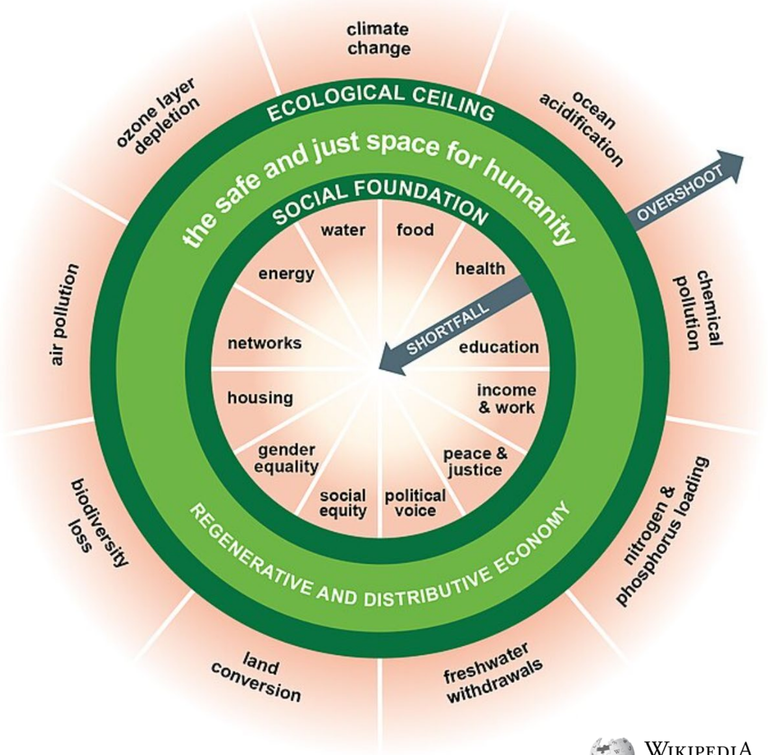
6 boundaries crossed

Absolute sustainability

Meeting the needs of present and future generations ***within the biophysical boundaries*** *of our climate and ecosystems – within the safe operating space*

Absolute boundaries for social sustainability?

- Social science and natural science
- What is for negotiation?



Wikipedia The Free Encyclopedia

Summarizing

- **Planetary boundaries** are limits for our pressure on earth system processes that **ensure climate stability**
- They cover **many types of environmental impact** but at the core are climate change and biosphere integrity
- Absolute sustainability is **meeting the needs** of present and future generations while **respecting the Planet's biophysical boundaries**

AESA for assessing absolute environmental sustainability

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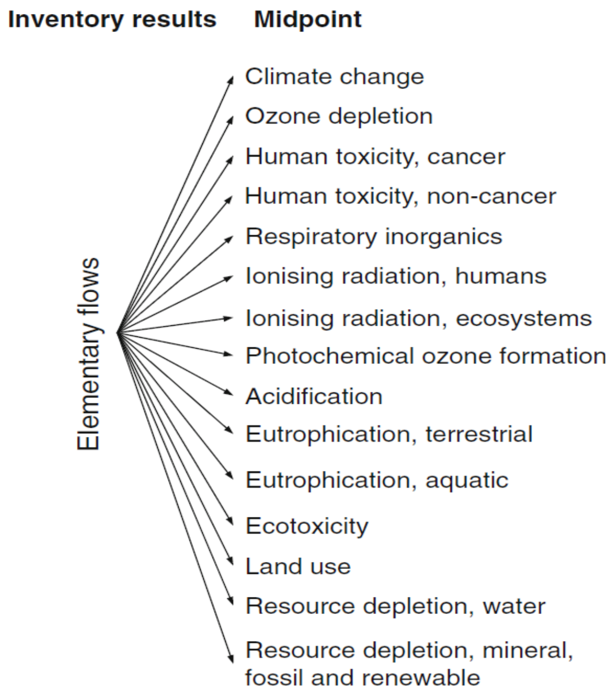
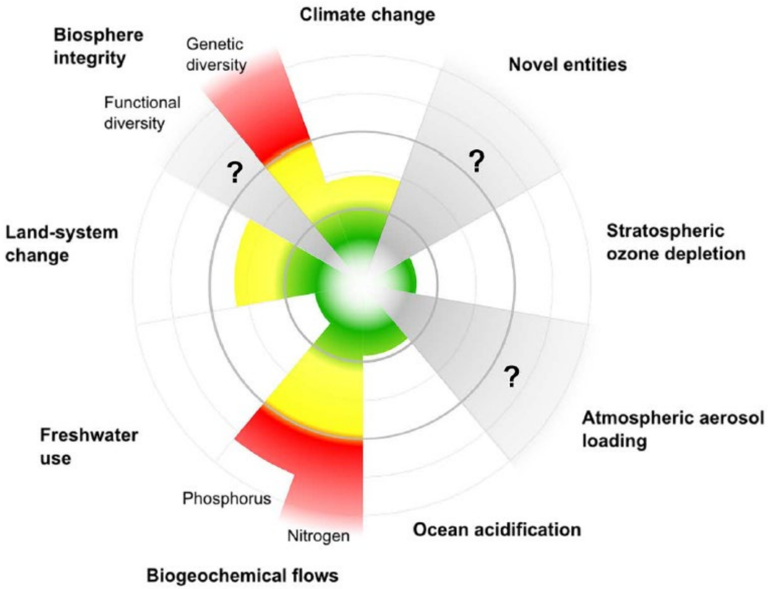
Performing AESA

- Identify biophysical boundaries and determine safe operating spaces
  - PBs or LCIA

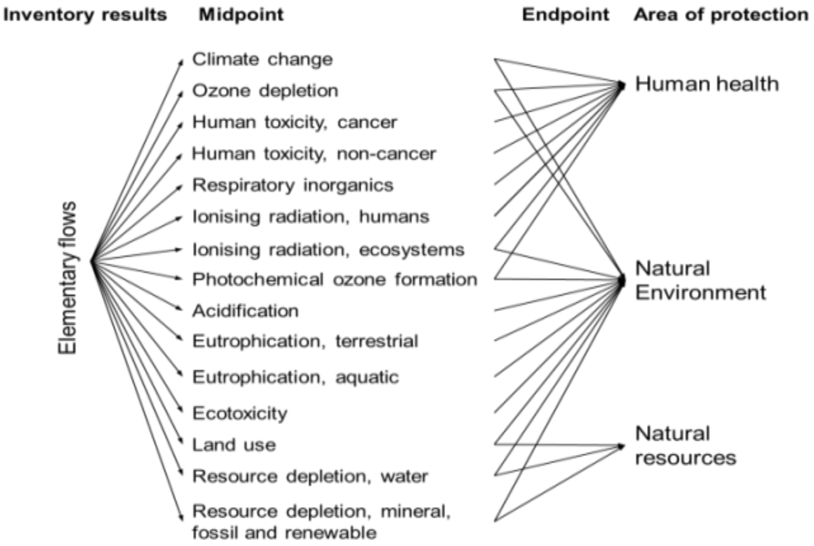
Where is the boundary?



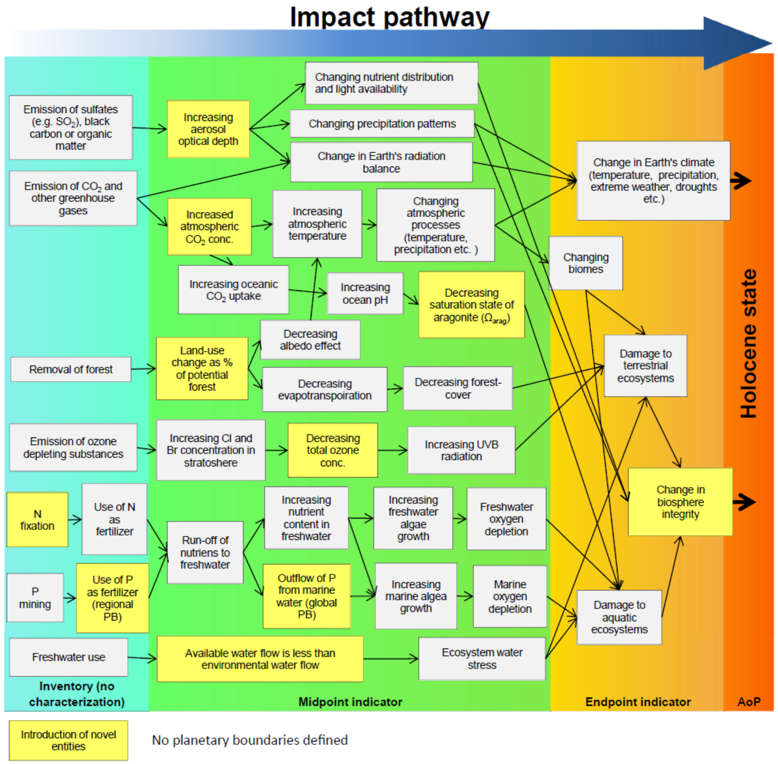
ILCD recommended characterization models (Hauschild et al. 2013)



Planetary Boundaries and LCIA



Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, De Schryver A, Humbert S, Laurent A, Sala S, Pant, R (2014) Identifying best existing practice for characterization modelling in Life Cycle Impact Assessment. Int J Life Cycle Assess 18(3), 683-697

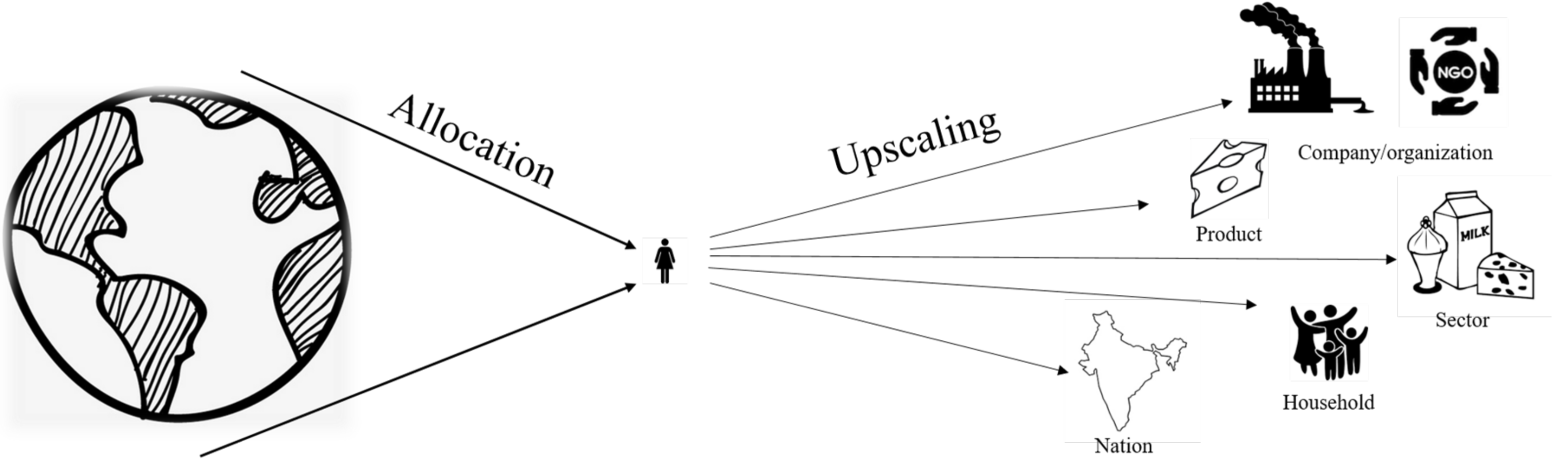


Ryberg M, Owsianiak M, Richardson K, Hauschild MZ (2016) Challenges in implementing a Planetary Boundaries based Life-Cycle Impact Assessment Methodology. Journal of Cleaner Production 139, 450-459.

Performing AESA

- Identify biophysical boundaries and determine safe operating spaces
  - PBs or LCIA
- Allocate the safe operating space to different activities

Allocating the operating space



Hjalsted AW, Laurent A, Andersen MM, Olsen KH, Ryberg M, Hauschild MZ (2021) Sharing the safe operating space: Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels. Journal of Industrial Ecology 25(1) 6-19, https://doi.org/10.1111/jiec.13050.

Allocating the operating space

Name	Description	Ethical norm (tentative)
Equal per capita (EPC)	Assigned share is the same for all individuals	Egalitarian
Capability to reduce (CR)	Assigned share is negatively correl-ated with a region's gross domestic product per capita	Prioritarian
Historical debt (HD)	Assigned share is negatively cor-related with a region's cumulative environmental impact per capita	Prioritarian

Allocating the operating space

Name	Description	Ethical norm (tentative)
Grandfathering (GF)	Assigned share is proportional with environmental impact in a reference year	Inegalitarian
Economic value added (EVA)	Assigned share is proportional to economic value added	Utilitarian
Cost efficiency (CE)	Assigned share is inversely proportional with the cost of reducing environmental impact of production	Utilitarian
Final consumption expenditure (FCE)	Assigned share is proportional with final consumption expenditure	Utilitarian

Bjørn A, Chandrakumar C, Boulay A-M, Doka G, Fang K, Gondran N, Hauschild MZ, Kerkhof A, King H, Margni M, Mclaren S, Mueller C, Owsianiak M, Peters G, Roos S, Sala S, Sandin G, Sim S, Vargas-Gonzalez M, Ryberg M (2020) Review of life-cycle based methods for absolute environmental sustainability assessment. Environ. Res. Lett. 15, 083001

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

Planetary Boundaries-based LCIA

Science of the Total Environment 634 (2018) 1406–1416

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology

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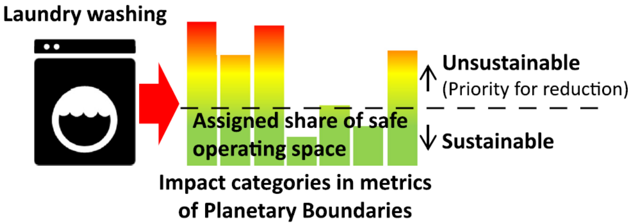
[b] *Safety and Environmental Assurance Centre (SEAC), Unilever, Colworth Park, Sharnbrook, Bedford, UK*

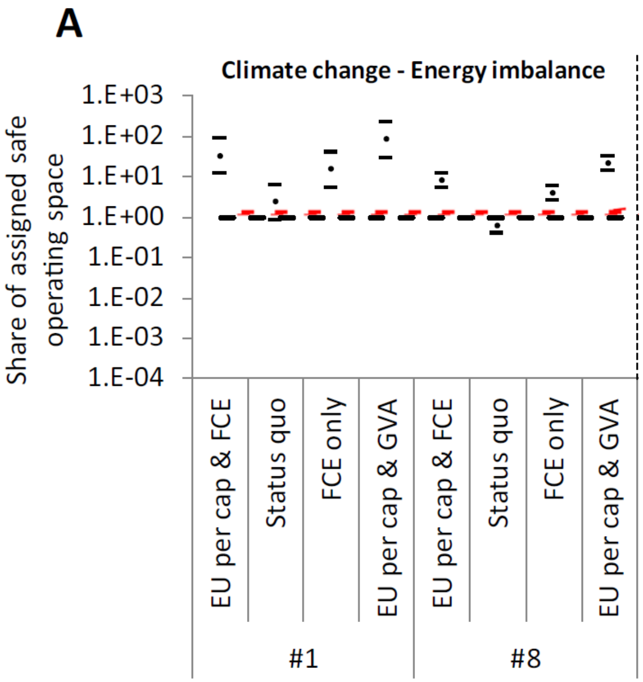
HIGHLIGHTS

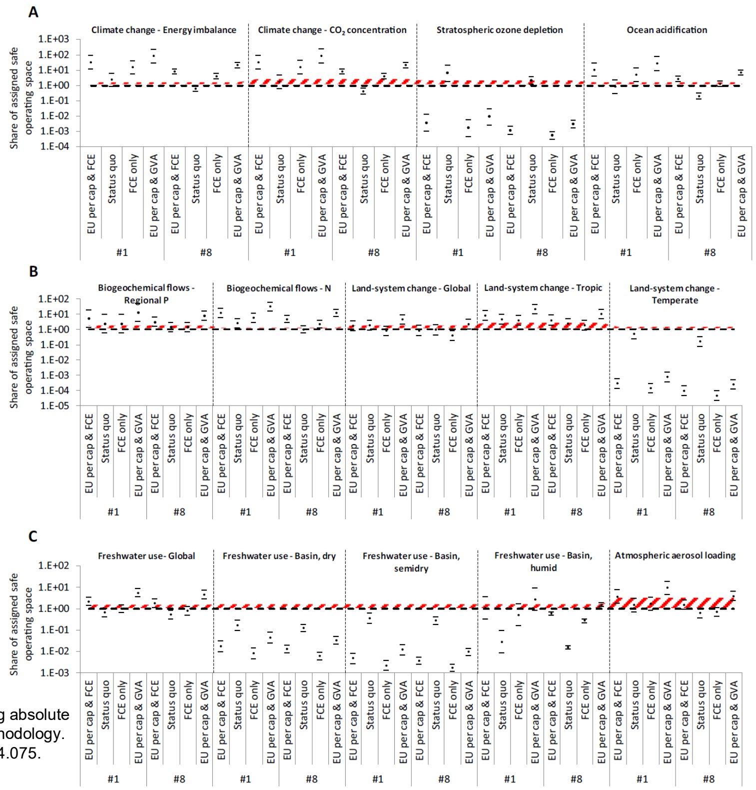
- Applied novel Planetary Boundaries based LCIA methodology in case study
- Characterized impacts in metrics of the Planetary Boundaries
- Assessed absolute sustainability of activity relative to Planetary Boundaries
- Assignment of safe operating space found to be largest source of uncertainty
- Allowed for quantifying impact reductions required to be absolutely sustainable

GRAPHICAL ABSTRACT



Planetary Boundaries-based LCIA





Ryberg MW, Owsianiak M, Clavreul J, Mueller C, Sim S, King H, Hauschild MZ (2018) How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology. Science of the Total Environment 634C, 1406–1416. doi: https://doi.org/10.1016/j.scitotenv.2018.04.075.

Summarizing

- Absolute environmental sustainability assessment, AESA, **builds on LCA**
- AESA relates environmental impacts to the assigned operating space to **measure whether an activity is sustainable or not**
- AESA covers **all relevant environmental impacts**

Examples of other absolute sustainability metrics

Michael Hauschild
Technical University of Denmark
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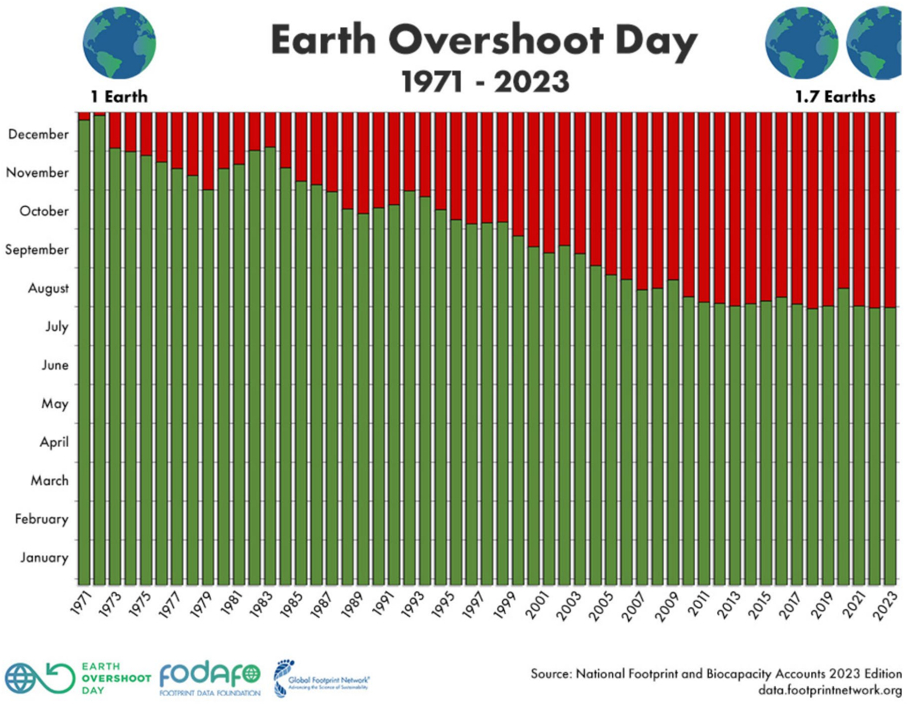
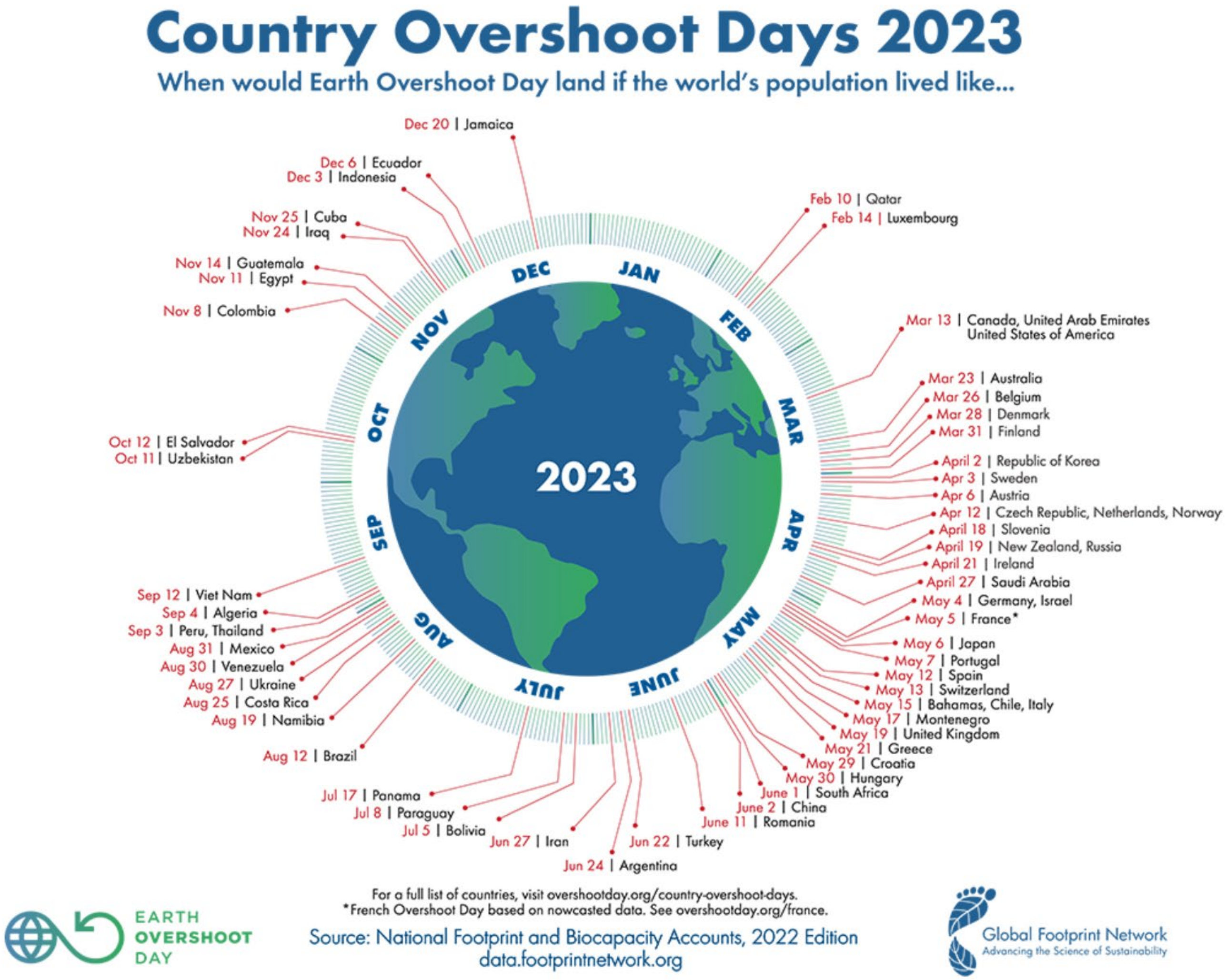
Ecological footprint

- Focus on land use and CO_2 emissions
- Life cycle perspective
- Product footprints and national footprints
- Earth overshoot day
  - 2015: 7 August
  - 2016: 9 August
  - 2017: 5 August
  - 2018: 1 August
  - 2019: 3 August
  - 2020: 16 August!
  - 2021: 3 August
  - 2022: 1 August
  - 2023: 2 August




Country Overshoot Days 2023
When would Earth Overshoot Day land if the world's population lived like...
2023
Dec 20 | Jamaica
Dec 6 | Ecuador
Dec 3 | Indonesia
Nov 25 | Cuba
Nov 24 | Iraq
Nov 14 | Guatemala
Nov 11 | Egypt
Nov 8 | Colombia
Oct 12 | El Salvador
Oct 11 | Uzbekistan
Sep 12 | Viet Nam
Sep 4 | Algeria
Sep 3 | Peru, Thailand
Aug 31 | Mexico
Aug 30 | Venezuela
Aug 27 | Ukraine
Aug 25 | Costa Rica
Aug 19 | Namibia
Aug 12 | Brazil
Jul 17 | Panama
Jul 8 | Paraguay
Jul 5 | Bolivia
Jun 27 | Iran
Jun 24 | Argentina
Jun 22 | Turkey
June 11 | Romania
June 2 | China
June 1 | South Africa
May 30 | Hungary
May 29 | Croatia
May 21 | Greece
May 19 | United Kingdom
May 17 | Montenegro
May 15 | Bahamas, Chile, Italy
May 13 | Switzerland
May 12 | Spain
May 7 | Portugal
May 6 | Japan
May 5 | France*
May 4 | Germany, Israel
April 27 | Saudi Arabia
April 21 | Ireland
April 19 | New Zealand, Russia
April 18 | Slovenia
Apr 12 | Czech Republic, Netherlands, Norway
Apr 6 | Austria
Apr 3 | Sweden
April 2 | Republic of Korea
Mar 31 | Finland
Mar 28 | Denmark
Mar 26 | Belgium
Mar 23 | Australia
Mar 13 | Canada, United Arab Emirates United States of America
Feb 14 | Luxembourg
Feb 10 | Qatar
JAN FEB MAR APR MAY JUNE JULY AUG SEP OCT NOV DEC
For a full list of countries, visit overshootday.org/country-overshoot-days.
*French Overshoot Day based on nowcasted data. See overshootday.org/france.
Source: National Footprint and Biocapacity Accounts, 2022 Edition
data.footprintnetwork.org
EARTH OVERSHOOT DAY
Global Footprint Network
Advancing the Science of Sustainability

DTU

The Science Based Targets Initiative (SBTi)

- SBTi established in 2015

- *"…**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/

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

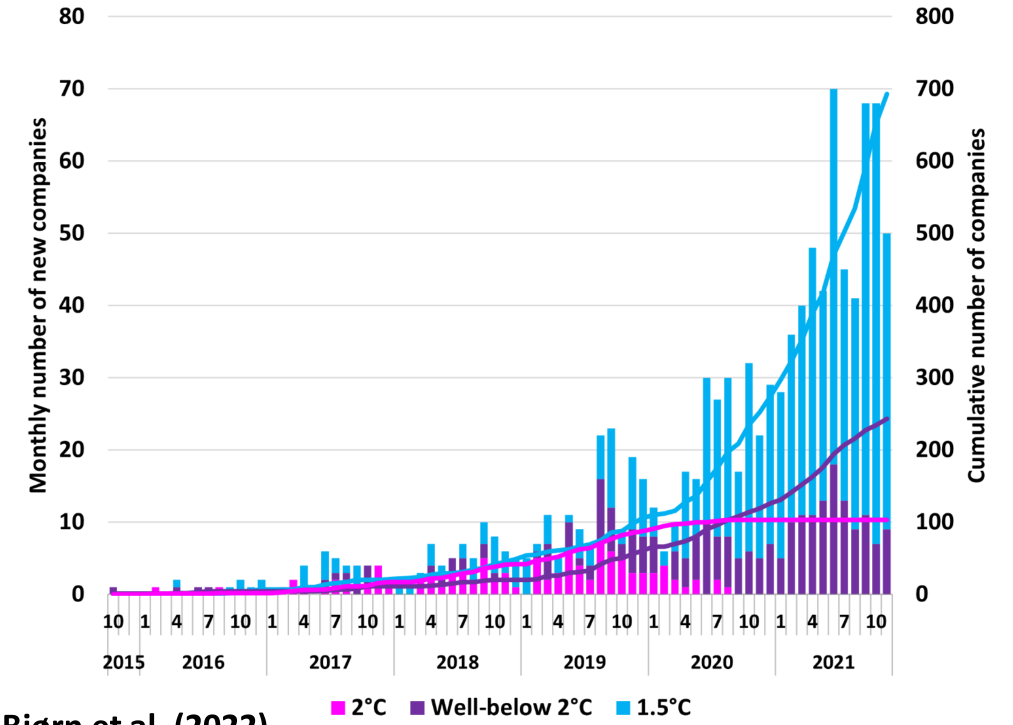
COMMUNICATE

Announce your target and inform your stakeholders

DISCLOSE

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

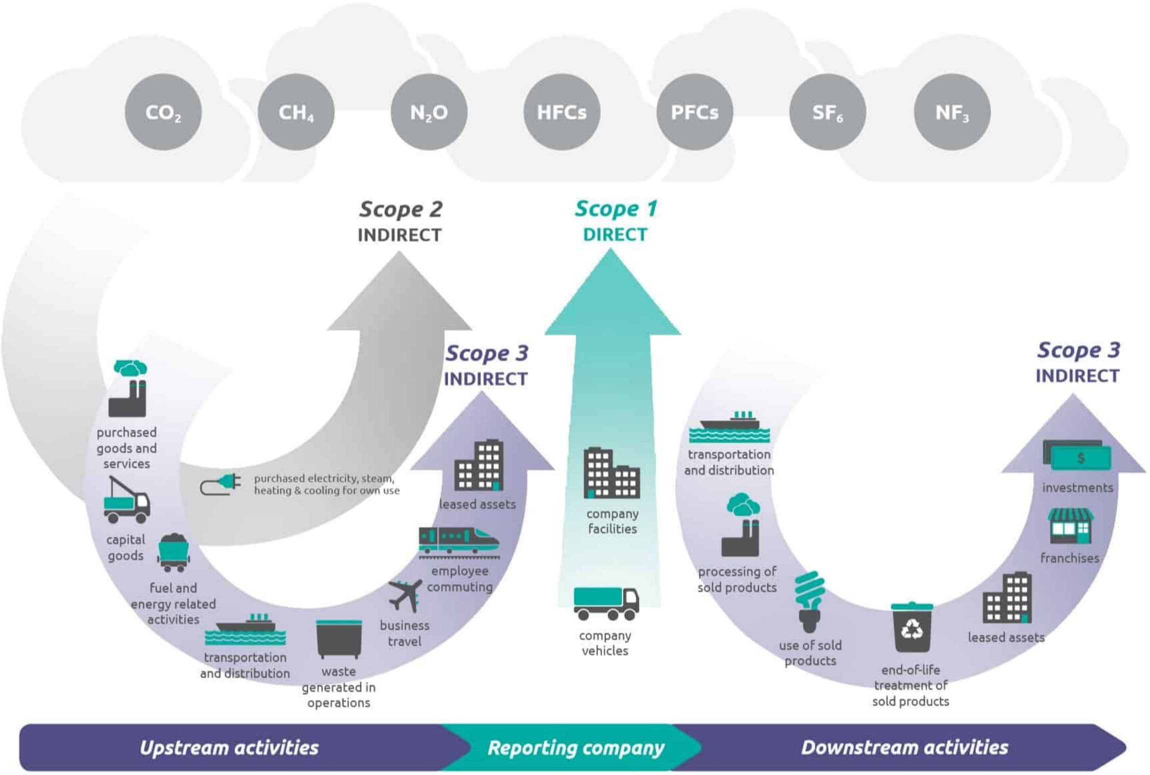
Rapidly growing



Bjørn et al. (2022)

As of April 19th 2023:

The three scopes



Setting targets

- Science-based, i.e. in accordance with the Paris agreement's 1.5 or well below 2.0 degree scenario
  - Sectoral approach
  - Absolute contraction approach (grandfathering)
  - 95% of scope 1 and 2
  - Min. 67% of scope 3 (if it is more than 40% of total emissions)
- Absolute or intensity depending on sector
- Short term (5-10 years)
  - Min. 4.2% linear annual contraction
- and long term (2050 or sooner)
  - 90% reduction

Two examples

Coca-Cola European Partners commits to reduce absolute scope 1, 2 and 3 GHG emissions 30% by 2030 from a 2019 base year. Within that target, Coca-Cola European Partners commits to reduce absolute scope 1 and 2 GHG emissions 47% by 2030 from a 2019 base year and reduce absolute scope 3 GHG emissions 29% by 2030 from a 2019 base year.

HeidelbergCement commits to reduce scope 1 GHG emissions 22% per ton of cementitious materials by 2030 from a 2016 base year. HeidelbergCement also commits to reduce scope 2 GHG emissions 65% per ton of cementitious materials within the same timeframe.* *The target boundary includes biogenic emissions and removals associated with the use of bioenergy.

Differences in:

- Base year
- Target year
- Targeted reduction
- Absolute/intensity
- Emission scope

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

Summarizing

Absolute sustainability metrics

- relate performance to a target that is based on environmental limits
  - stability of the climate system
  - available area of land
- inform about the size of improvements that are needed to achieve the target
- shift the focus from efficiency to effectiveness
  - from ”better” in the relative assessments
  - … to ”good enough” in the absolute assessments

From relative to absolute sustainability

Michael Hauschild
Technical University of Denmark
mzha@dtu.dk

The sustainability challenge

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

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.

- *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

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
- The environmental impact already exceeds sustainable levels in many areas
- So what is the challenge?

Eco-efficiency

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

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

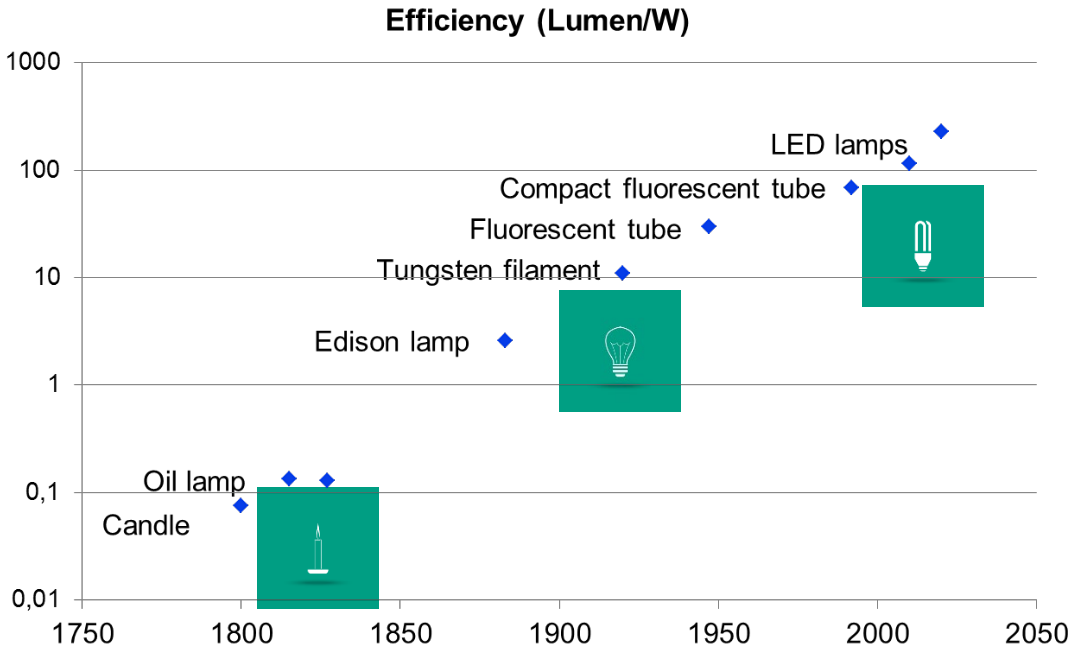
Eco-efficiency is the reciprocal of the technology factor in the IPAT equation

Eco-efficiency is determined with Life cycle assessment, LCA

Eco-efficiency has to grow strongly to achieve the needed reduction in impact with growing population and affluence

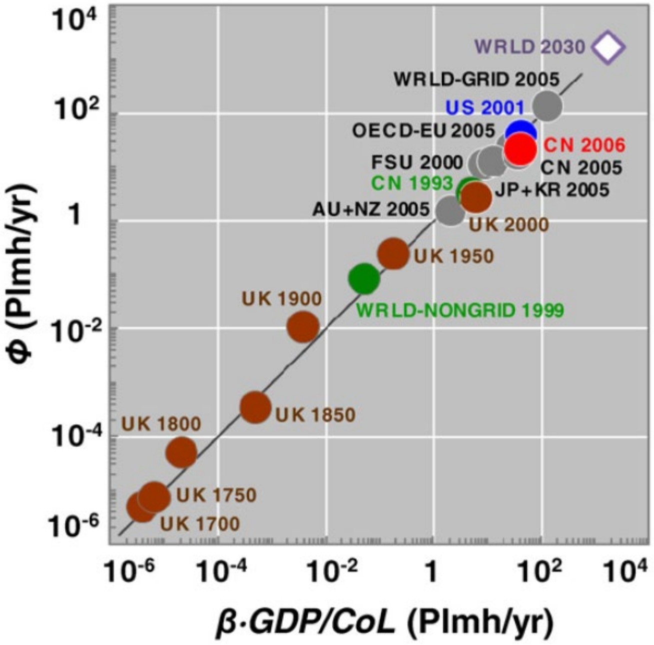
Developments in efficiency

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)

Relative and absolute sustainability

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

- Same or higher functionality with less environmental impact

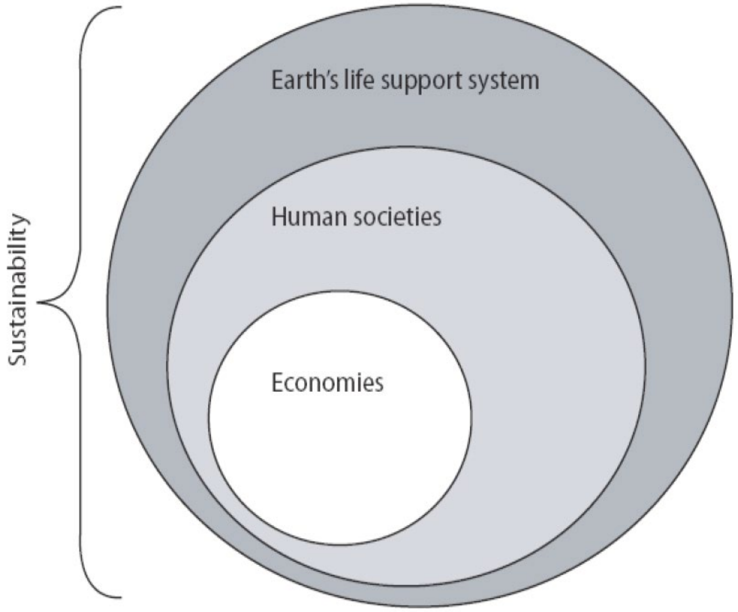
Absolute sustainability (*"sustain-able"*)?

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

A sustainable level of impact?

- Sustainability: Fulfilment of needs
  - Today and in the future
  - Which needs?
  - How to fulfil them?
  - For how many?

- Planetary boundaries
  - Top-down prescription of sustainable level of impact



Summarizing

- **Eco-efficiency** is the ratio between created value and caused environmental impact
- Sustainability requires **strong improvements in eco-efficiency**
- Our current focus on eco-efficiency must be informed by an **absolute sustainability perspective** to ensure that solutions are also **eco-effective**

Sustainability tools for Society II

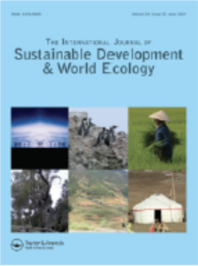
Professor Karyn Morrissey,

Department of Technology, Management and Economics

- 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 company-level 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 life-cycle of EVs
  - Quantitatively assess the health impacts of EVs using DALY’s

Tools



Taylor & Francis
Taylor & Francis Group

International Journal of Sustainable Development & World Ecology

ISSN: 1350-4509 (Print) 1745-2627 (Online) Journal homepage: https://www.tandfonline.com/loi/tsdw20

Sustainability assessment tools – their comprehensiveness and utilisation in company-level sustainability assessments in Finland

Tanja Myllyviita, Riina Antikainen & Pekka Leskinen

To cite this article: Tanja Myllyviita, Riina Antikainen & Pekka Leskinen (2017) Sustainability assessment tools – their comprehensiveness and utilisation in company-level sustainability assessments in Finland, International Journal of Sustainable Development & World Ecology, 24:3, 236-247, DOI: 10.1080/13504509.2016.1204636

To link to this article: https://doi.org/10.1080/13504509.2016.1204636

- multi-criteria decision analysis (MCDA),
- material flow analysis,
- life cycle cost assessment (LCCA),
- input–output models,
- sustainability indicators and indices,
- cost–benefit analysis (CBA) and
- optimisation methods.

Social life cycle assessment (S-LCA)

- As introduced in Module 5:
  - *Life cycle costing (LCC) is an approach that assesses the total cost of an asset over its life cycle, including initial capital costs, maintenance costs, operating costs and the asset's residual value at the end of its life*
- Here we look at:
  - *Social LCA (SLCA) is developed towards evaluating social impacts, such as employment, workplace health and equity*
  - *Assesses the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle*
  - *Increasingly established*
  - *UNDP -* Social Life Cycle Assessment (2020)

Social life cycle assessment (S-LCA)

- Process:
  - *objects: products and services, and*
  - *scope: the entire life cycle.*
- Social and socio- economic aspects assessed in S-LCA are those that may directly affect **stakeholders** positively or negatively during the life cycle of a product.
  - *indirect impacts on stakeholders may also be considered.*
- S-LCA does not have the goal nor pretends to provide information on the question of whether a product should be produced or not.
- Lots of similarities with LCCA
  - *Not least it’s data requirements!*

s-LCA & impact assessment

- Social impact assessment is the phase in S-LCA aimed at calculating, understanding and evaluating the magnitude and significance of the potential social impacts of a product system throughout the life cycle of the product
- 2 approaches
- Reference Scale
  - *social performance or social risk of a product*
- Impact Assessment
  - *consequential social impacts from a product by characterizing the cause-effect chain*

impact pathway approaches

- The main target within the IP S-LCIA is to assess and model relations between the cause (social activities/stressors) that arises from a company´s activity and their effect.
- This is usually done by establishing what we call impact pathways.
- Involves tracing the inventory data through the relevant social and socioeconomic mechanism to define the socioeconomic impact
  - *Can be established qualitatively and quantitatively.*
  - *Focus is increasingly on effects on human health measured in terms of DALY’s: Disability Adjusted Life Years*

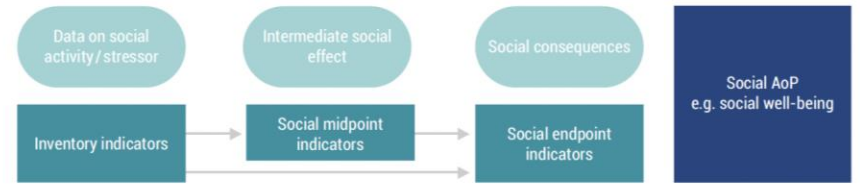
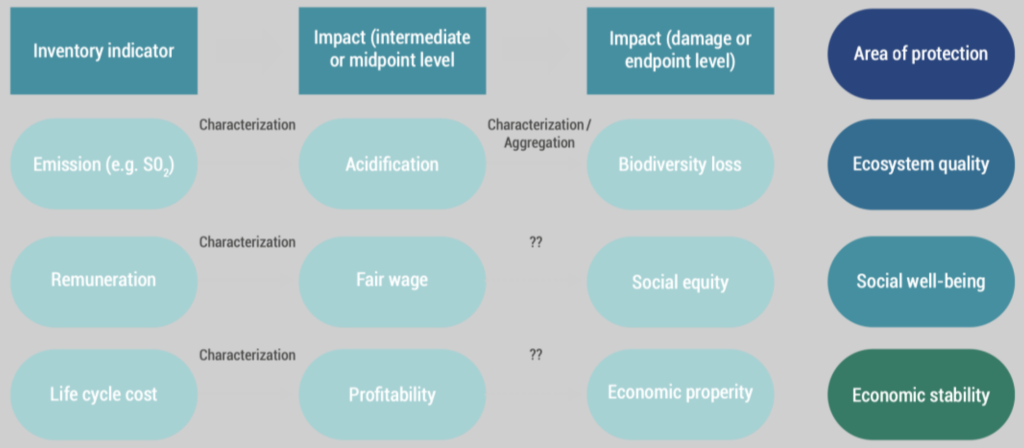


Figure 27: Illustration of the social impact pathway scheme applicable to type II S-LCA. See figure 4 and main text for examples of midpoint and endpoint indicators.

BOX 16: THE LOGIC OF MIDPOINT AND ENDPOINT CATEGORIES FROM E-LCA TO S-LCA (DERIVED FROM NEUGEBAUER, 2016)

Impact categories within life cycle based methods should cover the complete impact pathway by including inventory indicators, midpoint, and endpoint categories (Bare et al., 2000; JRC, 2010). Inventory indicators may be defined as simple variables (e.g. working hours), whereas midpoint impact indicators are seen as parameters in the (social) mechanism network (Bare et al., 2000). Endpoint impact indicators are then understood as measurement endpoints determining damage levels to the Area of Protection (Jolliet et al., 2004).

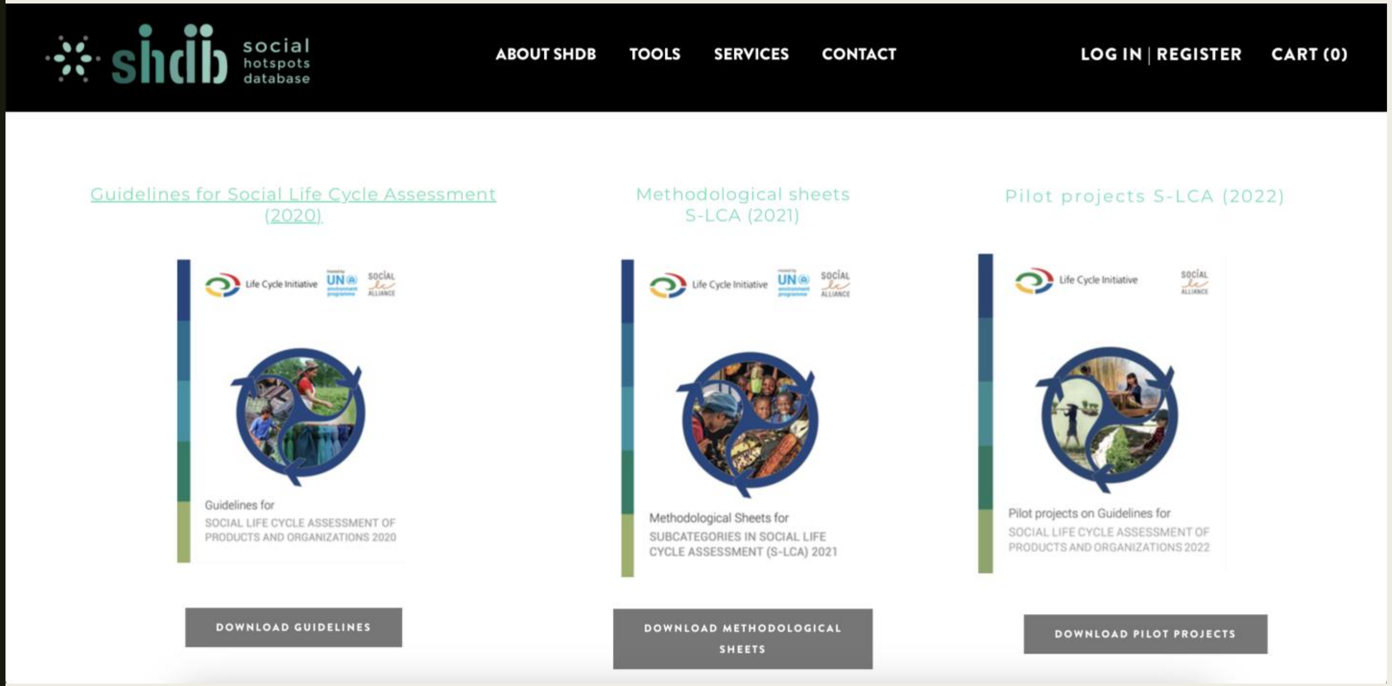


ure 26: Exemplary impact pathway schemes for LCSA (adapted from Neugebauer 2016).

Development of an IP S-LCIA method, just as for E-LCIA, usually consists of linking inventory data that undergoes a **characterization step**, and which results **in midpoint and/or endpoint impact indicators.**

Data & databases

- S-LCA case studies,
  - *the Social Hotspot Database (SHDB) and*
  - *the Product Social Impact Life Cycle Assessment (PSILCA) database remain the main sources for generic social*
- Both databases assume pathways exist across value chains and are commonly used to provide country- and sector-specific data on some of the social indicators specified in the UNEP/SETAC



Activity

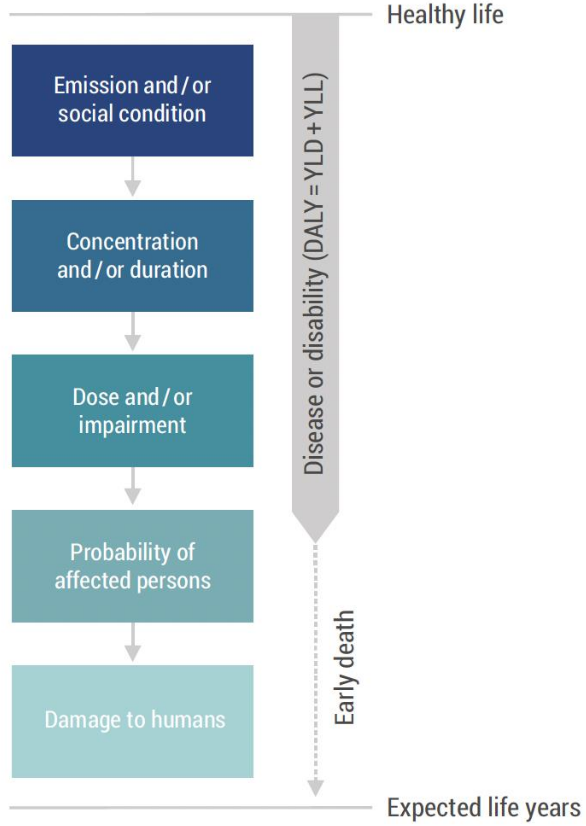


Figure 31: Illustration of a DALY (disability adjusted life years) impact pathway representing the mecha elling approach. YLD = years of life disabled and YLL = years of life lost. Based on figures from Crettaz e Frischknecht et al. (2000) and Golsteijn (N.D).

- 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

Social aspects and health

Health quantitative assessment

Olivier Jolliet, PhD

DTU

Introduction to Global Burden of Disease

Purpose of the GBD

Olivier Jolliet, PhD

Learning objectives

- 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 impacts

Global Burden of Disease

19 MAIN RISK FACTORS:

Air pollution 5H
Alcohol use
Childhood maltreatment
Dietary risks
Drug use 2H
High blood pressure
High body mass index 4H
High fasting plasma glucose 1H
High low density cholesterol (LDL)
Impaired kidney function
Intimate partner violence
Low bone mineral density
Low physical activity 3H
Malnutrition 8H
Occupational risks
Other environmental *(lead, radon)*
Tobacco smoking “H
Unsafe sex
Unsafe water & sanitation 2H

Global Burden of Disease: General Approach

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

Measured in ***"Disability Adjusted Life Years"***

1 DALY = 1 equivalent year of healthy life lost

DALYs are calculated by taking the sum of 'Years of Life Lost' (YLL) and 'Years Lived with Disability' (YLD)

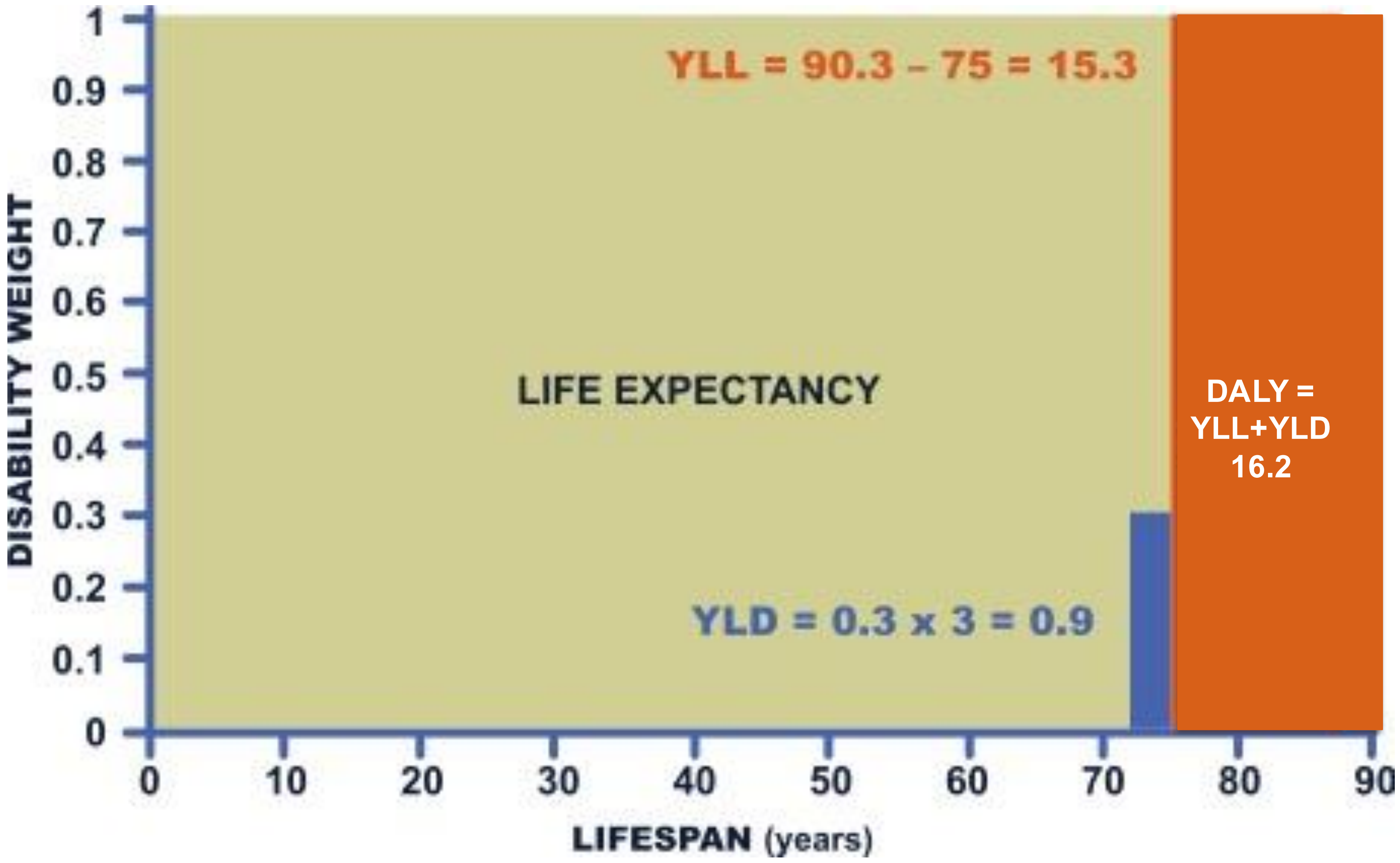
DALY = YLL + YLD

Burden in Disability-Adjusted Life Years (DALY)

DALY = Years Life Disabled (**YLD**)
+ Years Life Lost (**YLL**)

Illustration: Person gets a cancer at 72 years old and dies at 75

At age 75: life expectancy is 90.3



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

Disability weights: Examples

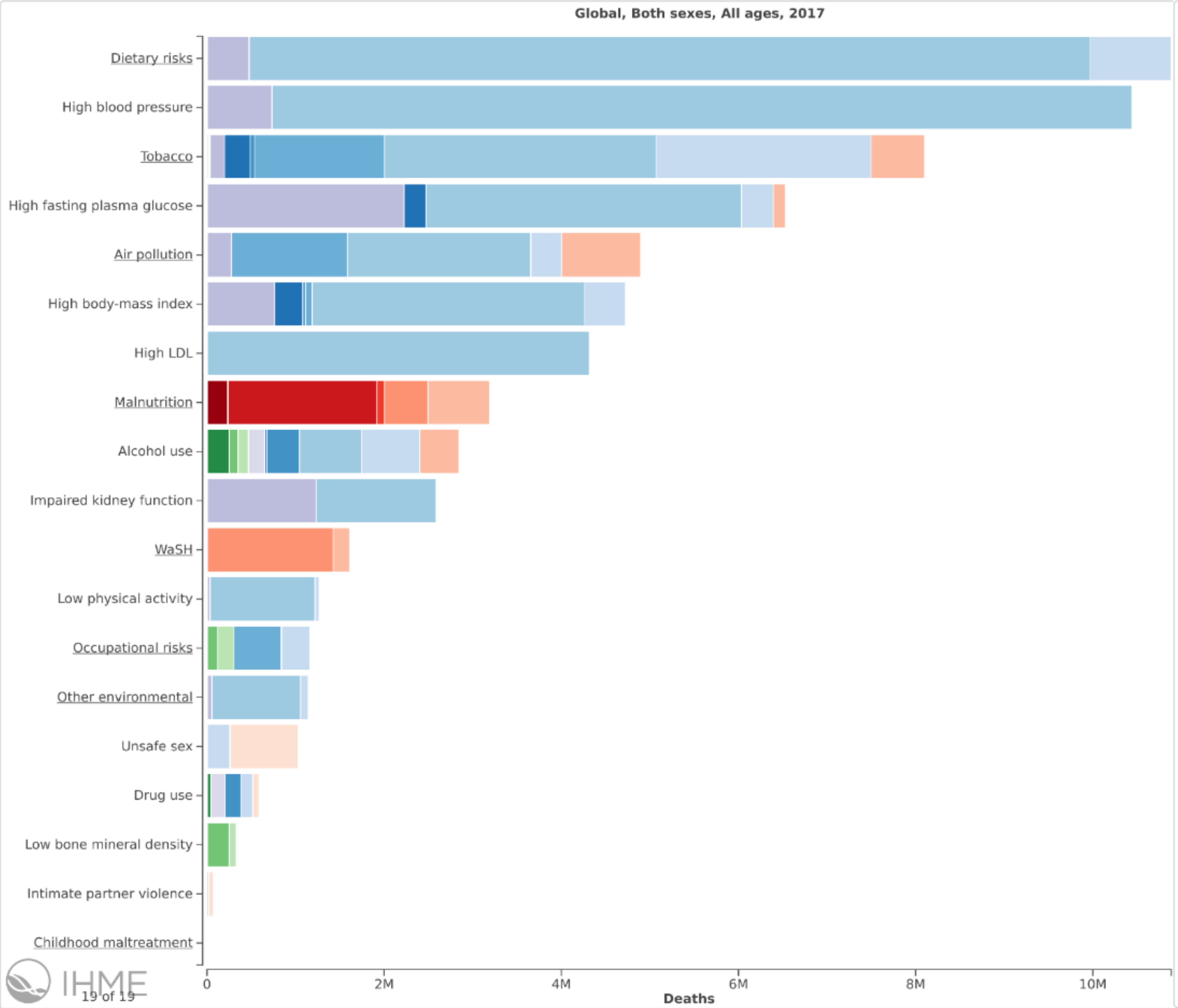
YDL = I x DW x L

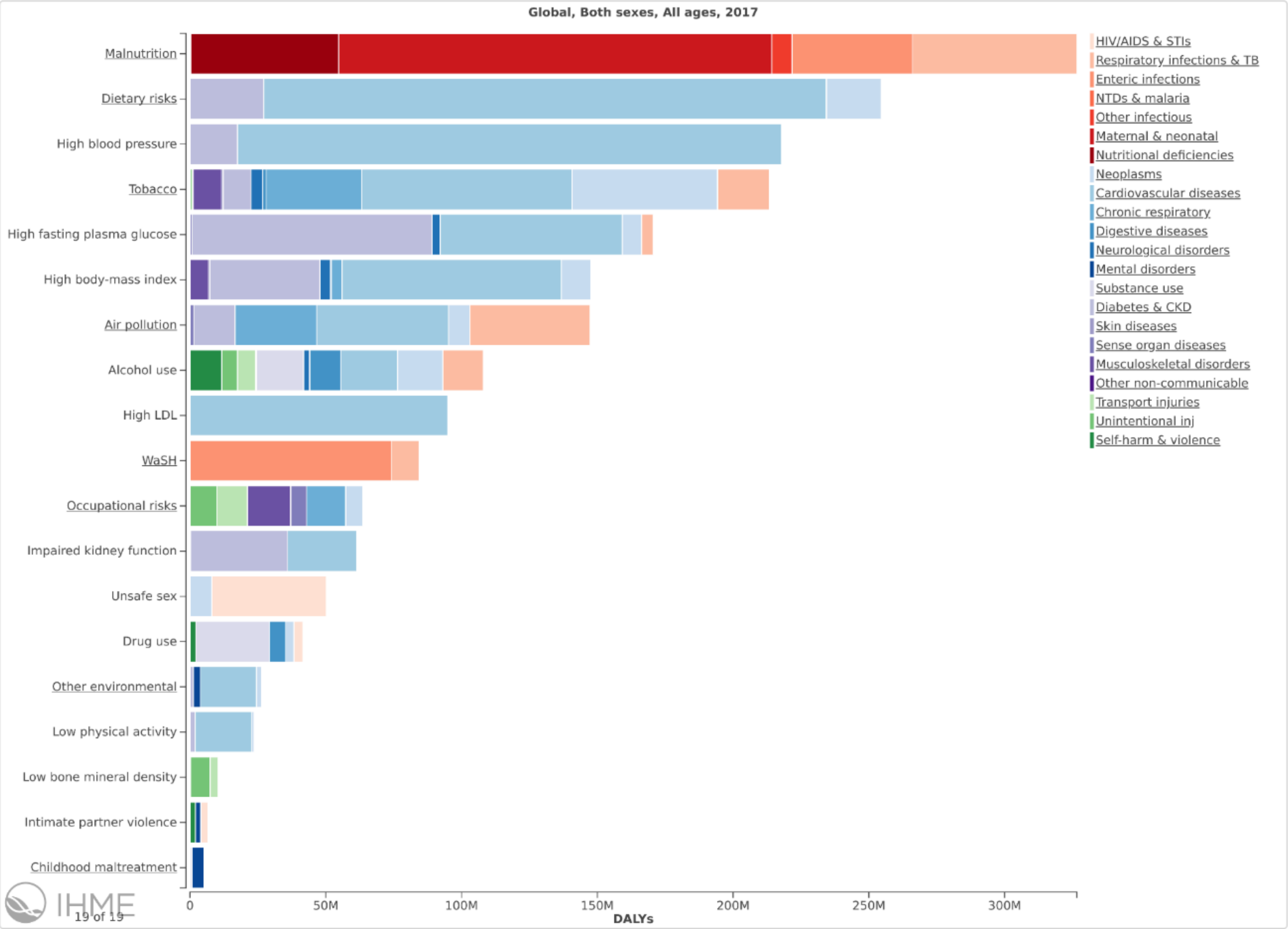
I = number of incident cases
DW = disability weight
L = average duration of the case until remission or death (years)

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)*

Number of death in the World

Number of DALYs





Institute for Health Metrics and Evaluation (IHME). GBD Compare. Seattle, WA: IHME, University of Washington, 2015. Available from http://vizhub.healthdata.org/gbd-compare. (Accessed 08/12/2020)

What is the main difference between death and DALYs ?

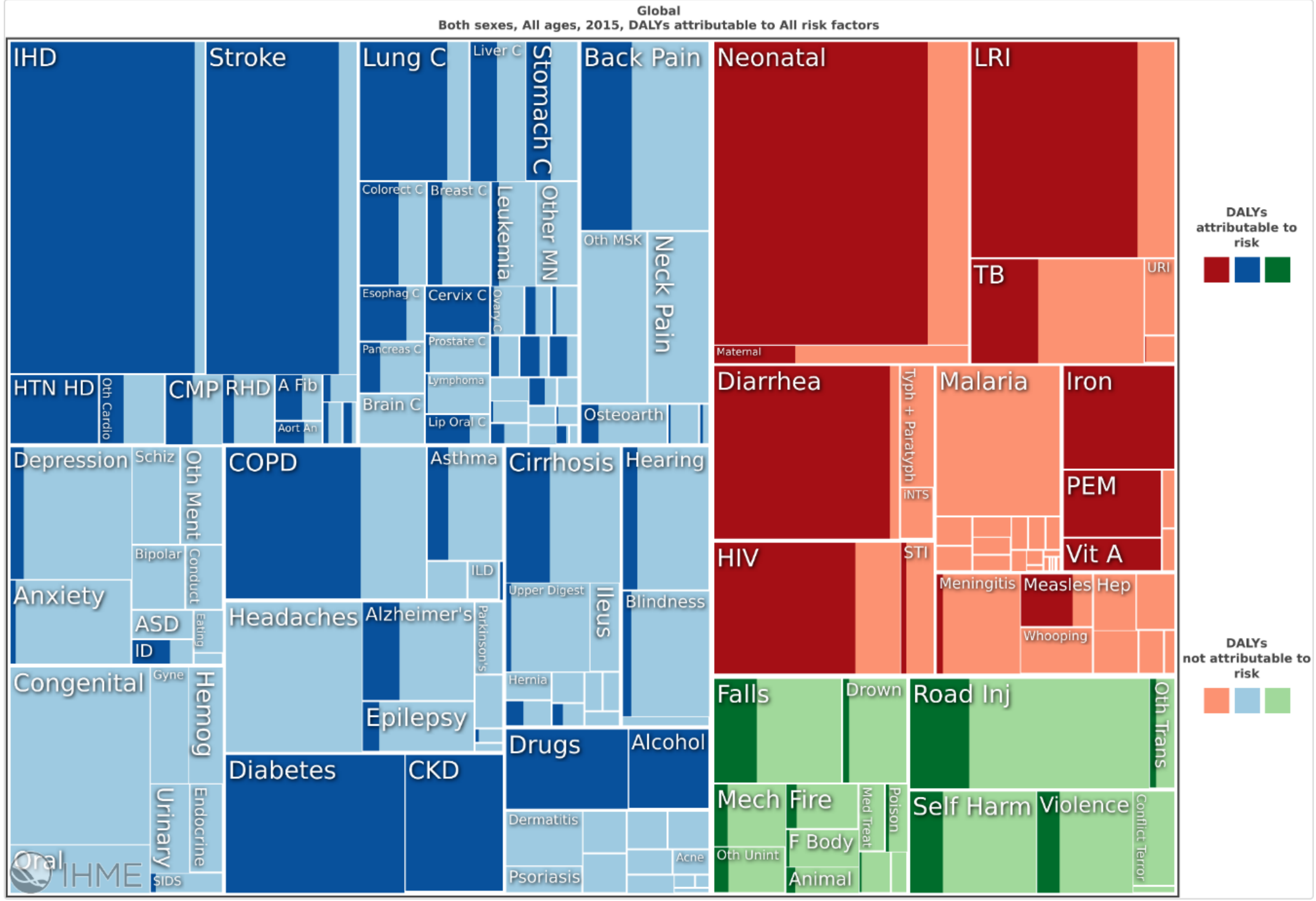
Malnutrition is ranked **8th** risk factor of death, but becomes the first risk factor for **DALYs**, since each child death is associated with elevated **YLL**.

Two main views: Causes and ...

Causes define the illnesses or types of injuries to which **DALYs** are attributed to. On this map, areas are proportional to the magnitude of **DALYs** attributed to each cause.

What are the dominant causes?

Risk factor are potentially modifiable causes of disease and injury.



Institute for Health Metrics and Evaluation (IHME). GBD Compare. Seattle, WA: IHME, University of Washington, 2015. Available from http://vizhub.healthdata.org/gbd-compare. (Accessed 08/12/2020)

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

Exercise

Thus far, we have introduced DALYs and the Global Burden of Disease. Now, it is your turn to take some time to interact with the rich data set that this research has created. In this activity, you will learn step-by-step how to use the Global Burden of Disease visualization tool. The questions below are designed to walk you through examples that demonstrate use cases for such a visualization tool. To complete this activity, work through each of the question prompts below and select the correct answer for each.

To begin, open the Global Burden of Disease visualization tool

Open Quiz module 6 “**Health Activity: Exploring the Global Burden of Disease Visualization” and answer the different questions.**

Health assessment

Gasoline vs electric vehicles vs bike

Olivier Jolliet, DTU-Sustain, Quantitative Sustainability Assessment

DTU

Learning Objectives

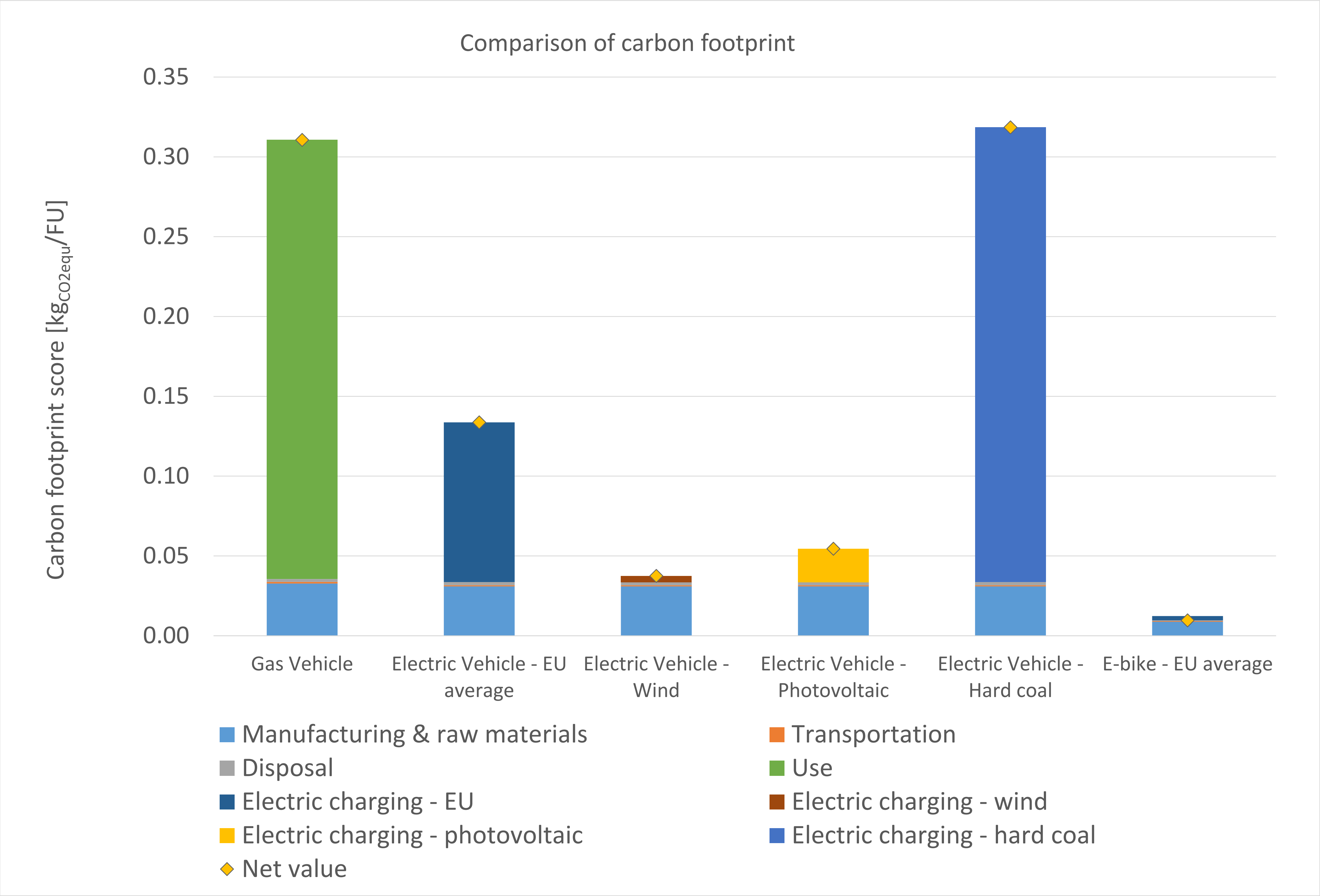
- Define a process to establish health impacts of transportation
- Compare different the health impacts of types of cars and modes of transportation

Case study: Gasoline vs electric vehicle vs bike

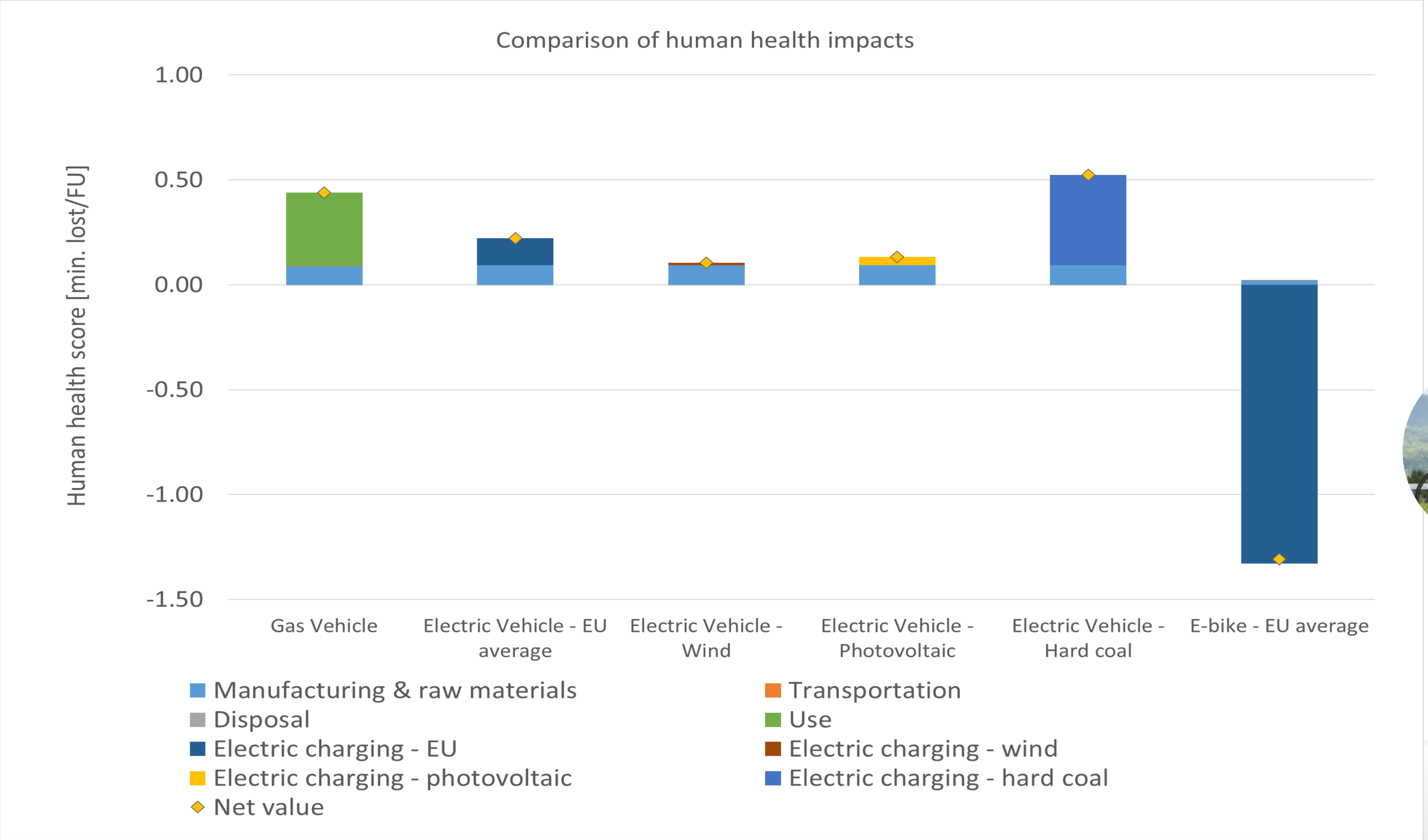
The ecoinvent database combined with Life Cycle Impact method

	B	C	D	E	F	G	H	I	J	L
2	Conversion factors	kg_to_g	g/kg	1000		Category	climate change	total: human health	total: ecosystem quality	energy resources: non-renewable
3						Indicator	global warming potential (GWP100)	human health	ecosystem quality	energy content (HHV)
4	Process #	Activity Name	Geography	Reference Product Name	Reference Product Unit	Reference Product Amount	kg CO2-Eq	min.lost	species.yr	MJ-Eq
5	17446	steel production, low-alloyed, hot rolled	RER	steel, low-alloyed, hot rolled	kg	1	2.181	8.00	9.8E-09	25.56
6	17078	sheet rolling, steel	RER	sheet rolling, steel	kg	1	0.312	0.73	1.4E-09	4.93
7	323	aluminium production, primary, ingot	IAI Area, EU27 & EFTA	aluminium, primary, ingot	kg	1	7.210	13.33	3.3E-08	115.04
8	17076	sheet rolling, copper	RER	sheet rolling, copper	kg	1	0.482	4.96	9.8E-09	7.19
9	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
10	12104	market for polyethylene, high density, granulate	GLO	polyethylene, high density, granulate	kg	1	2.328	2.35	9.4E-09	80.67
11	5070	electronics production, for control units	RER	electronics, for control units	kg	1	31.865	91.05	2.1E-07	451.55
12	5253	ethylene production, average	RER	ethylene	kg	1	1.447	1.12	5.3E-09	67.93
13	17736	tap water production, conventional treatment	RoW	tap water	kg	1	0.00044	0.00	1.9E-12	0.01
14	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
15	14708	market group for electricity, medium voltage	UCTE	electricity, medium voltage	kWh	1	0.385	0.49	1.8E-09	8.88

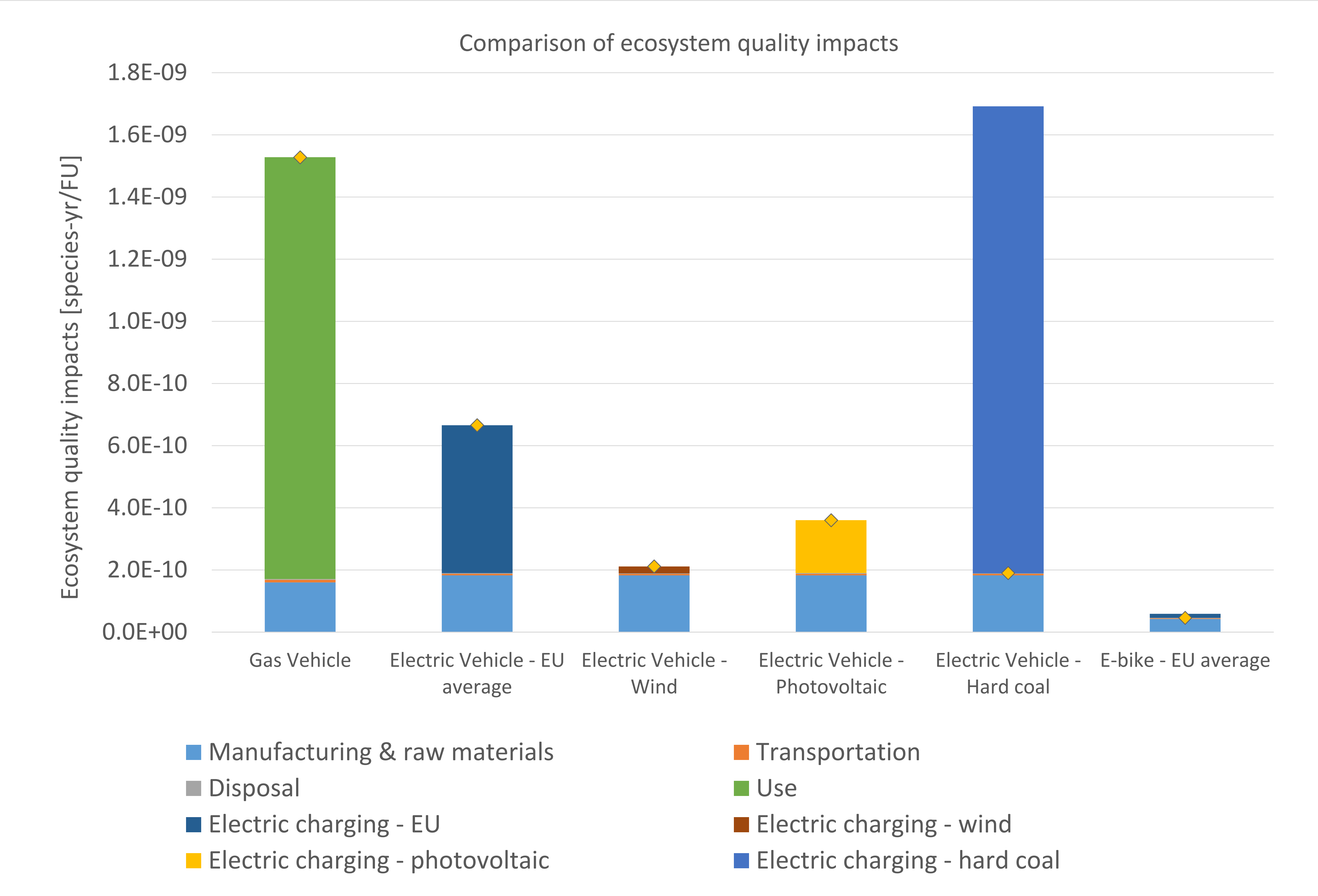
Car vs bike carbon footprint



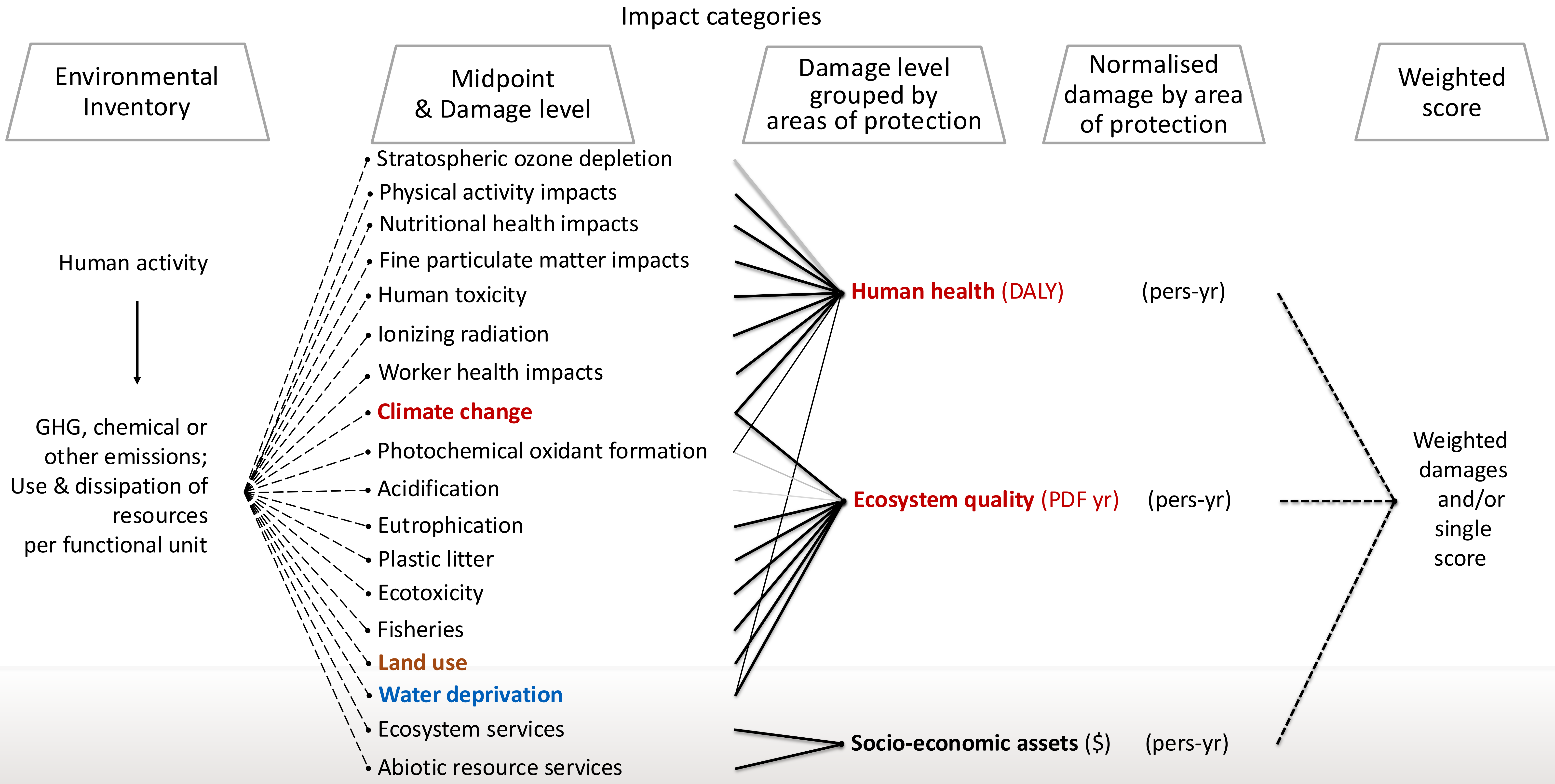
Car vs bike human health impacts



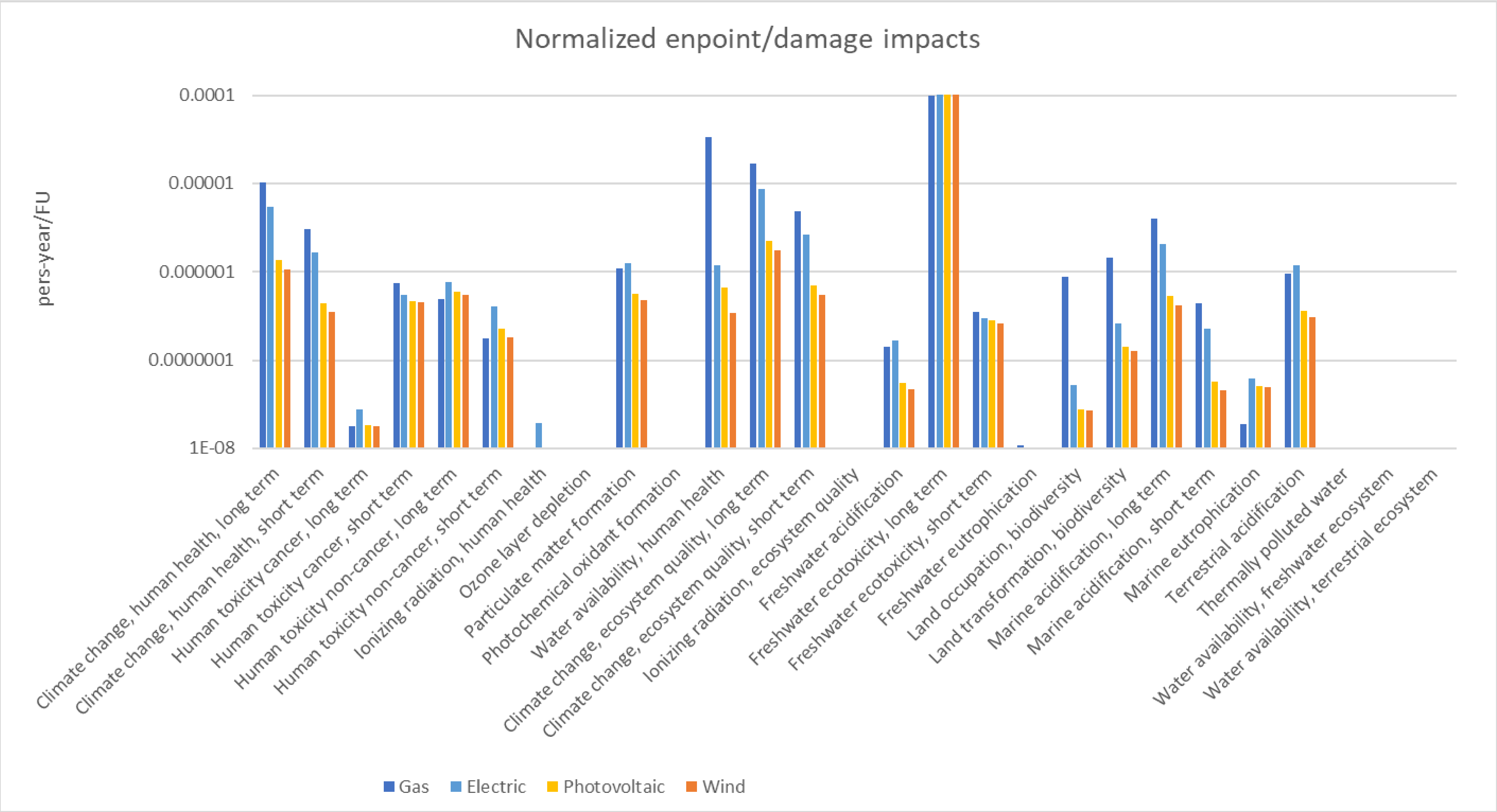
Car vs bike ecosystem impacts



UNEP - GLAM: the global life cycle impact assessment framework



Comparison of normalized damage Impact World+ Life cycle impact Assessment



Consumption, products and health

Exposome and health impacts

Olivier Jolliet, PhD

Learning Objectives

- 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

Exposome definition (Wild 2012)

Published by Oxford University Press on behalf of the International Epidemiological Association
 Advance Access publication 31 January 2012

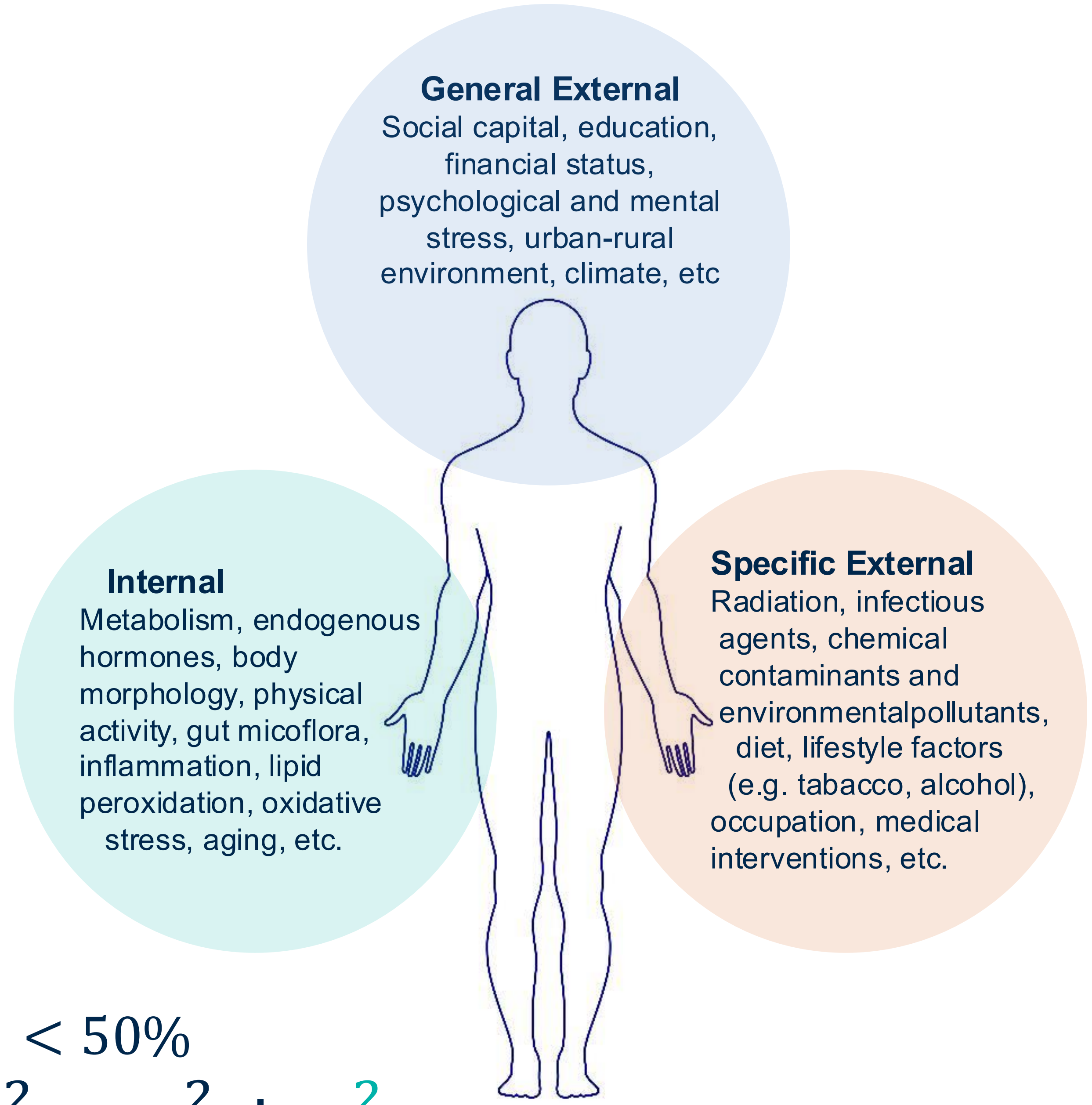
International Journal of Epidemiology 2012;**41**:24–32
doi:10.1093/ije/dyr236

REVIEW

The exposome: from concept to utility

Christopher Paul Wild

The exposome is composed of every exposure to which an individual is subjected from conception to death. Therefore, it requires consideration of both the nature of those exposures and their changes over time. For ease of description, three broad categories of non-genetic exposures may be considered: internal, specific external and general external.



Phenotype = f (Genome, Exposome)

$< 50\%$

Variability: $\sigma_P^2 = \sigma_G^2 + \sigma_E^2$

Inclusion of various impacts on human health

- Climate change

- Fine particulate impacts

- Nutrition impacts

- Physical exercise

- Chemicals in products

Exposome – vision

2. Outdoor & indoor exposure to $PM_{2.5}$

1. Chemicals in consumer products

3. Nutritional exposure

Tell me
when & where
you lived and worked,
How much you exercised
what you consumed
and ate…

and I will tell you
who you are!

5. Physical exercise

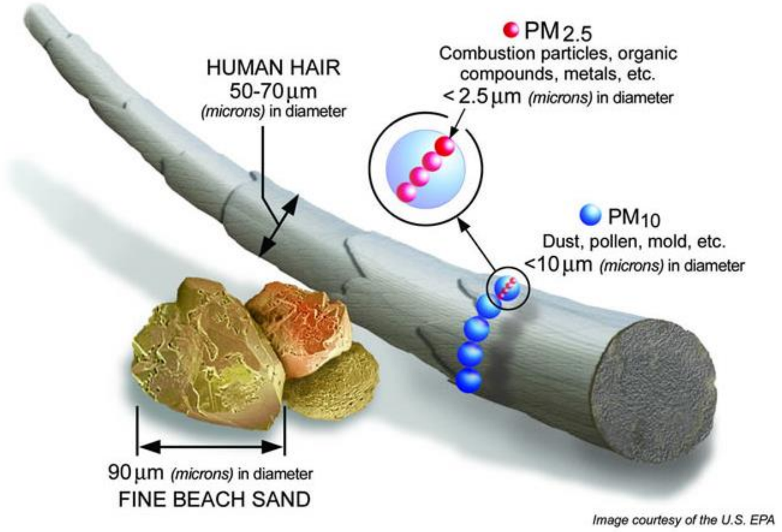
4. Worker exposure

The exposome is composed of every exposure to which an individual is subjected from conception to death.

Air pollution impacts on human health

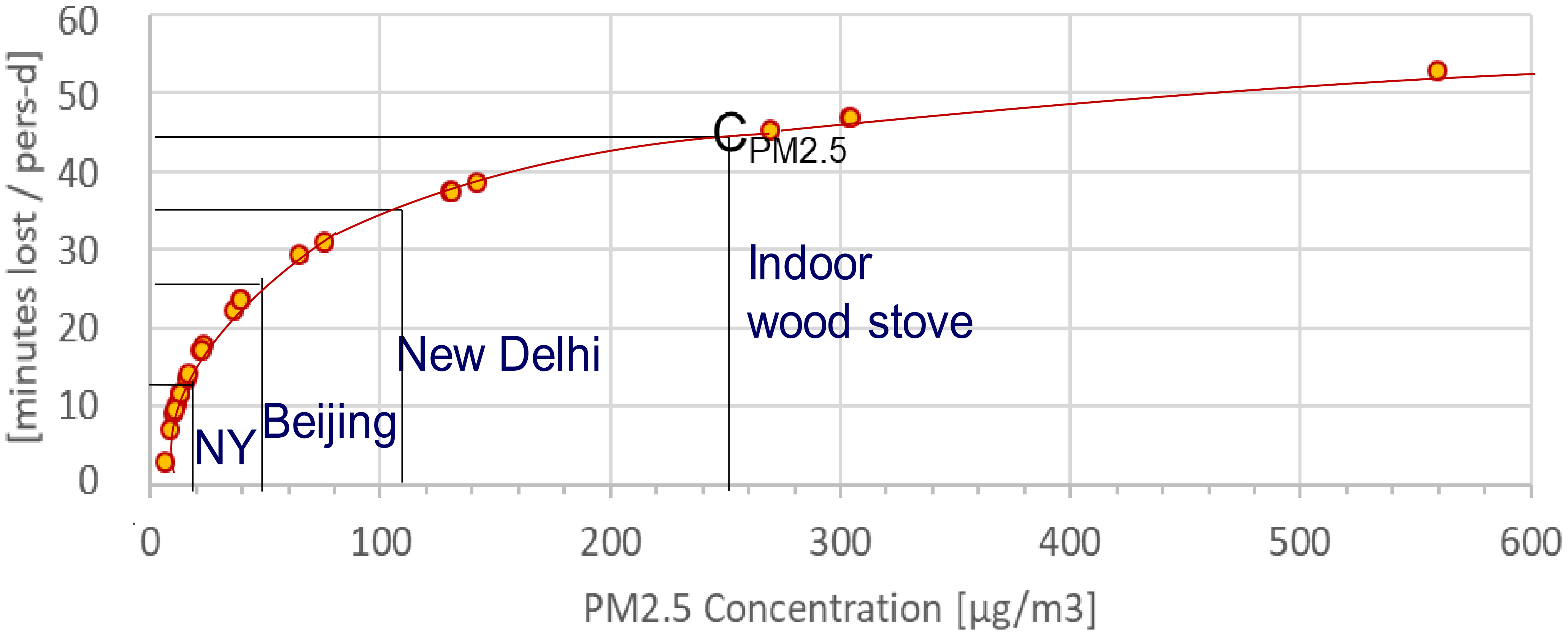
6.5 mil deaths per year, **65% in Asia**, largely cardiovascular disease

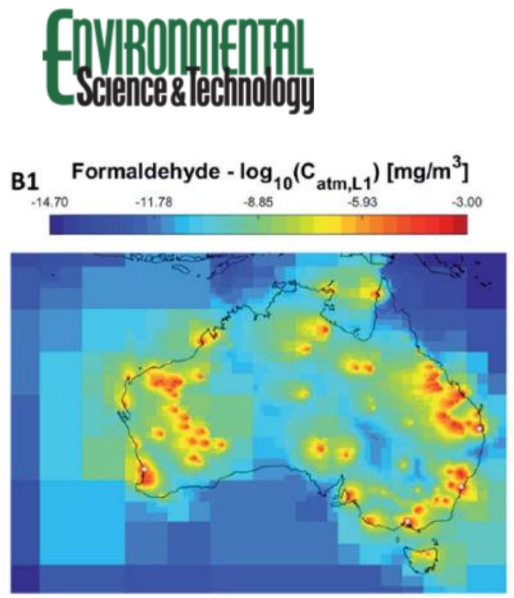
17,800 deaths/day, equivalent to 60 Malaysian airplane crashes **per day**



A sunny day in Beijing!

2. Indoor and outdoor $PM_{2.5}$ burden of disease

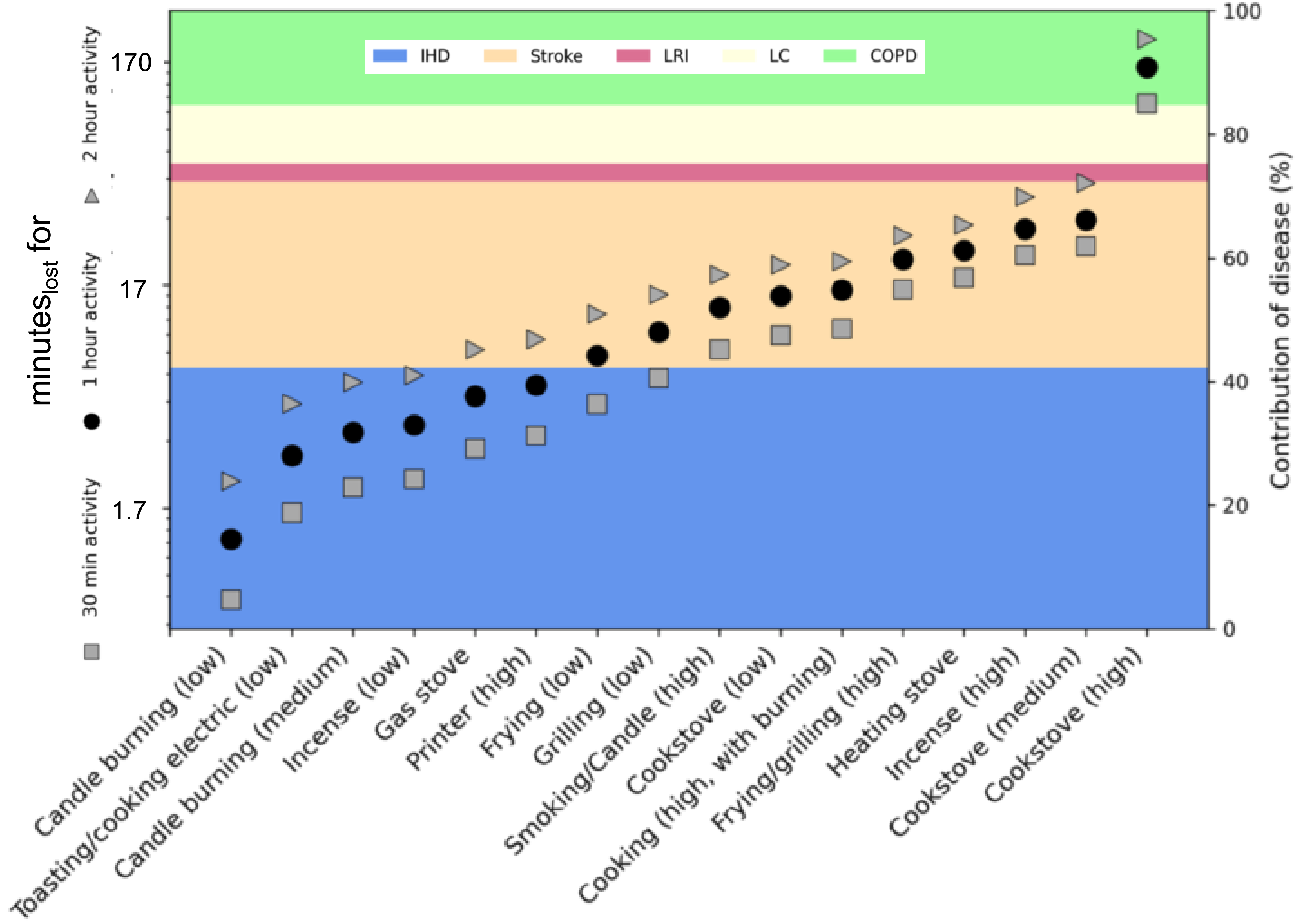




Formaldehyde
from industrial
sources in Australia
< 0.1 minutes/pers-d
<< $PM_{2.5}$

Adapted from Apte et al. 2015, ES&T 49: 8057-8066, Wannaz, 2018, Environ. Sci.: Processes Impacts, 2018, 20, 13 ES&T, 52 (2), 701-711

Impact of indoor sources of fine particulates



1 – 17 min.(medium 3.5) of healthy life lost for 1 hour indoor “huggely” candle,

USEtox: A new series of interfaces for consumer products

USEtox

USEtox Framework

Inventory flow: $\mathrm{kg}_{\text{chemical in products}}/\mathrm{FU}$
Characterization factors: $\mathrm{DALY}/\ \mathrm{kg}_{\text{chemical in products}}$

Building materials

Environmental emissions

Personal care products

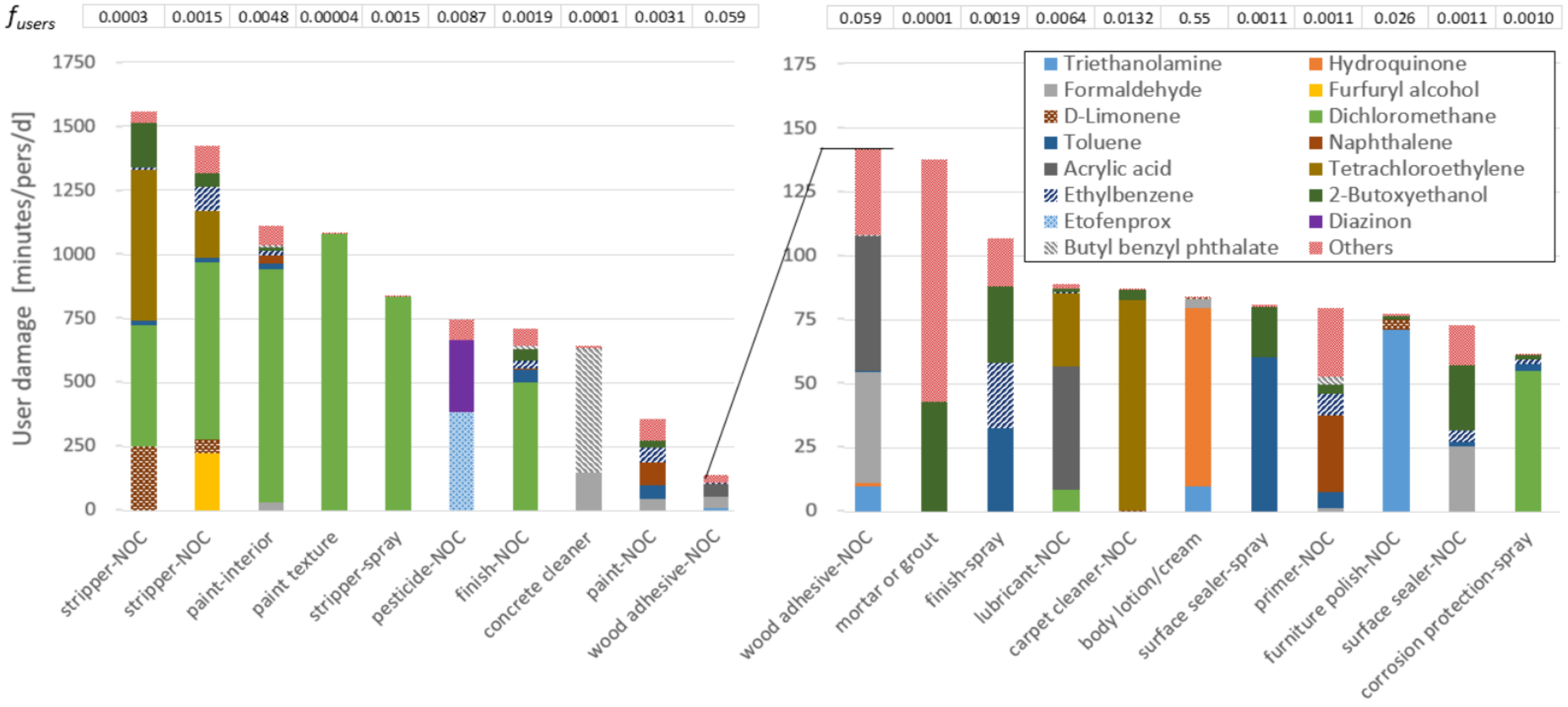
Food contact materials

Pesticides

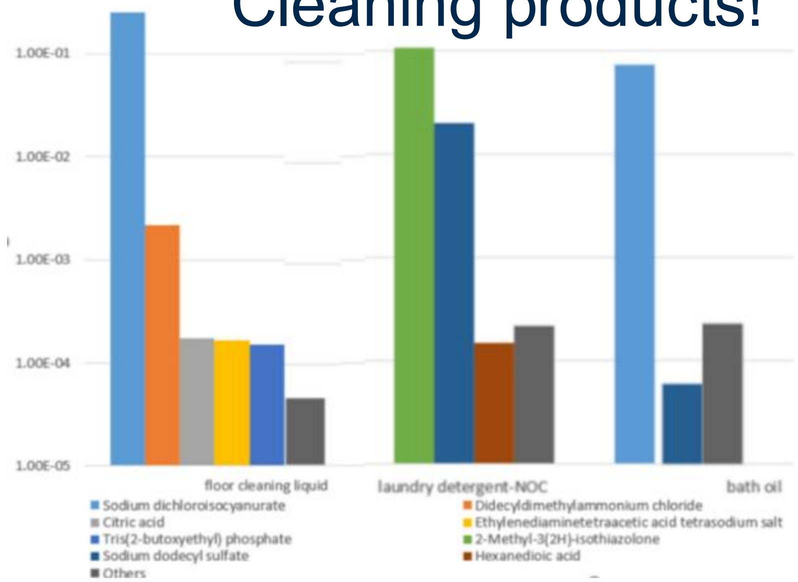
Paints

Toys, incl. mouthing

Chemicals in household products: Human Health impacts on users



Impacts on freshwater ecosystems:
Cleaning products!

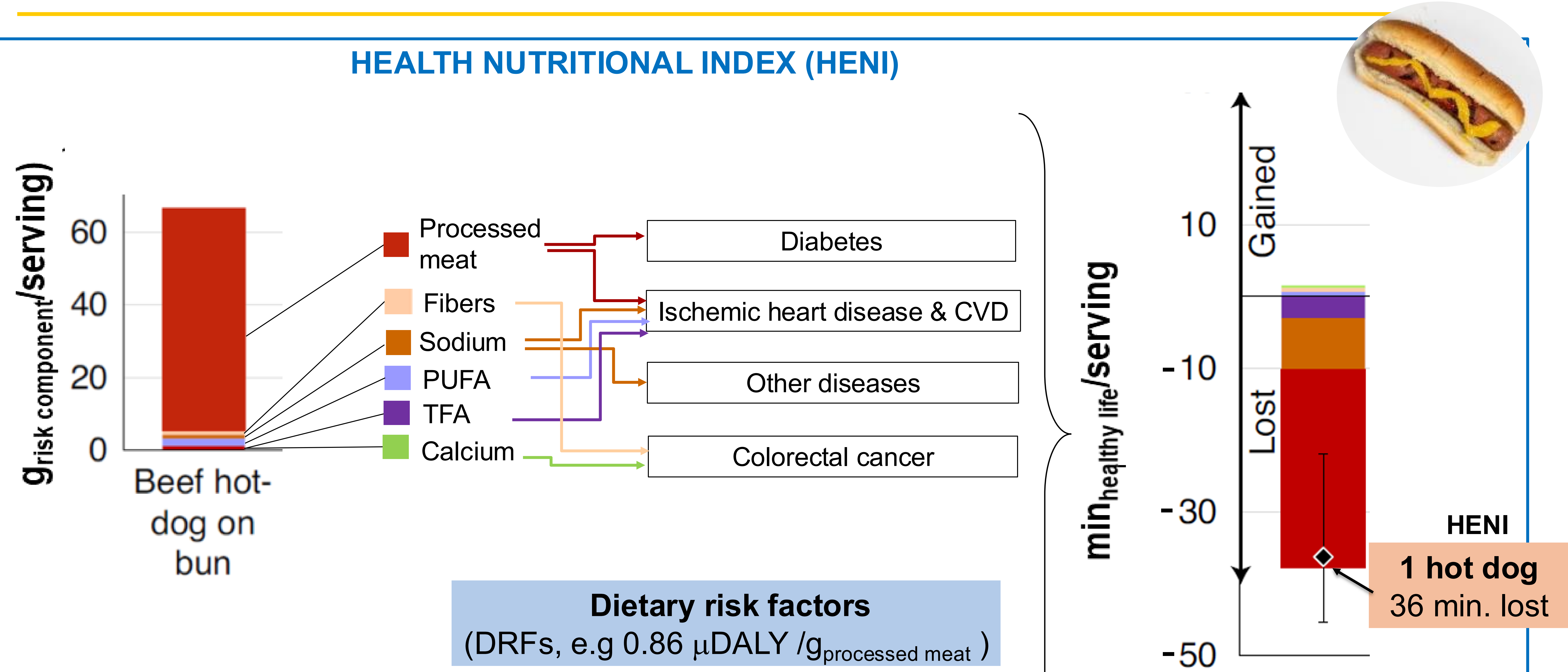


Several home maintenance, cosmetics & cleaning product with substantial impacts on users, 20-1500 minutes lost per user per day → product-chemical combinations to further study or replace in priority

Jolliet et al., 2020. Risk analysis – https://doi.org/10.1111/risa.13604

Health Nutritional Index (HENI) for a beef hot dog (140g)

HEALTH NUTRITIONAL INDEX (HENI)



Food composition
(e.g. 61 $g_{processed\ meat}$/serving)

x

Rescale factor
(DRFs, e.g 0.52 min. lost / μDALY)

HENI score
(e.g. 27 min lost/serving)

Health Nutrient Index HENI: Stylianou et al., 2021 Nature food

ARTICLES
https://doi.org/10.1038/s43016-021-00343-4
nature food

Check for updates

Small targeted dietary changes can yield substantial gains for human and environmental health

Katerina S. Stylianou[1], Victor L. Fulgoni III[2] and Olivier Jolliet[1]

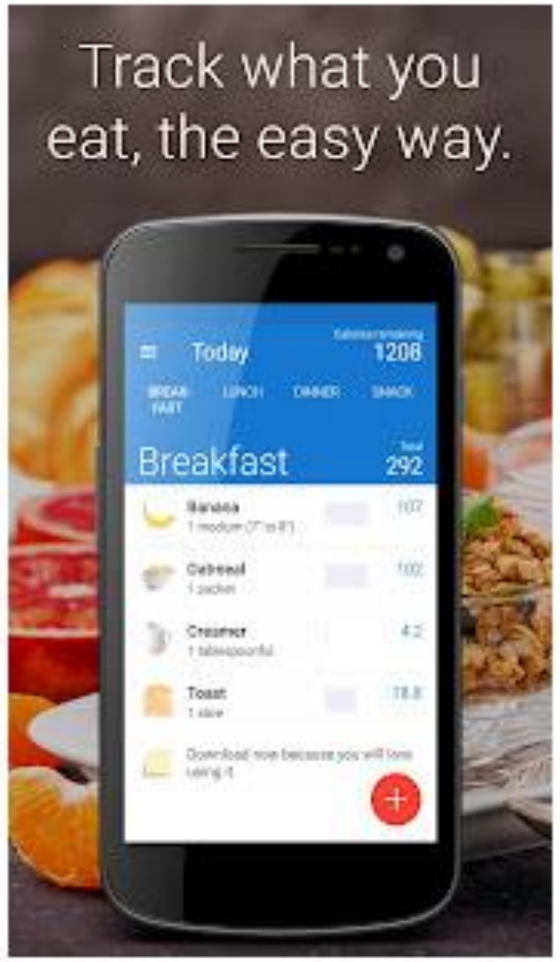
To identify environmentally sustainable foods that promote health, we combined nutritional health-based and 18 environmental indicators to evaluate, classify and prioritize individual foods. Specifically for nutrition, we developed the Health Nutritional Index to quantify marginal health effects in minutes of healthy life gained or lost of 5,853 foods in the US diet, ranging from 74 min lost to 80 min gained per serving. Environmental impacts showed large variations and were found to be correlated with global warming, except those related to water use. Our analysis also indicated that substituting only 10% of daily caloric intake from beef and processed meat for fruits, vegetables, nuts, legumes and selected seafood could offer substantial health improvements of 48 min gained per person per day and a 33% reduction in dietary carbon footprint.

Minutes of healthy life https://rdcu.be/cuVht
Gained or lost for 5800+ foods

120,000 likes on CNN Instagram

High impact research >1000 news media with potential reach of 1.3 billion people

iEatBetter app - exercise



Install the iEatBetter app, and sign in with your e-mail

Once you have the latest version, you can go to:

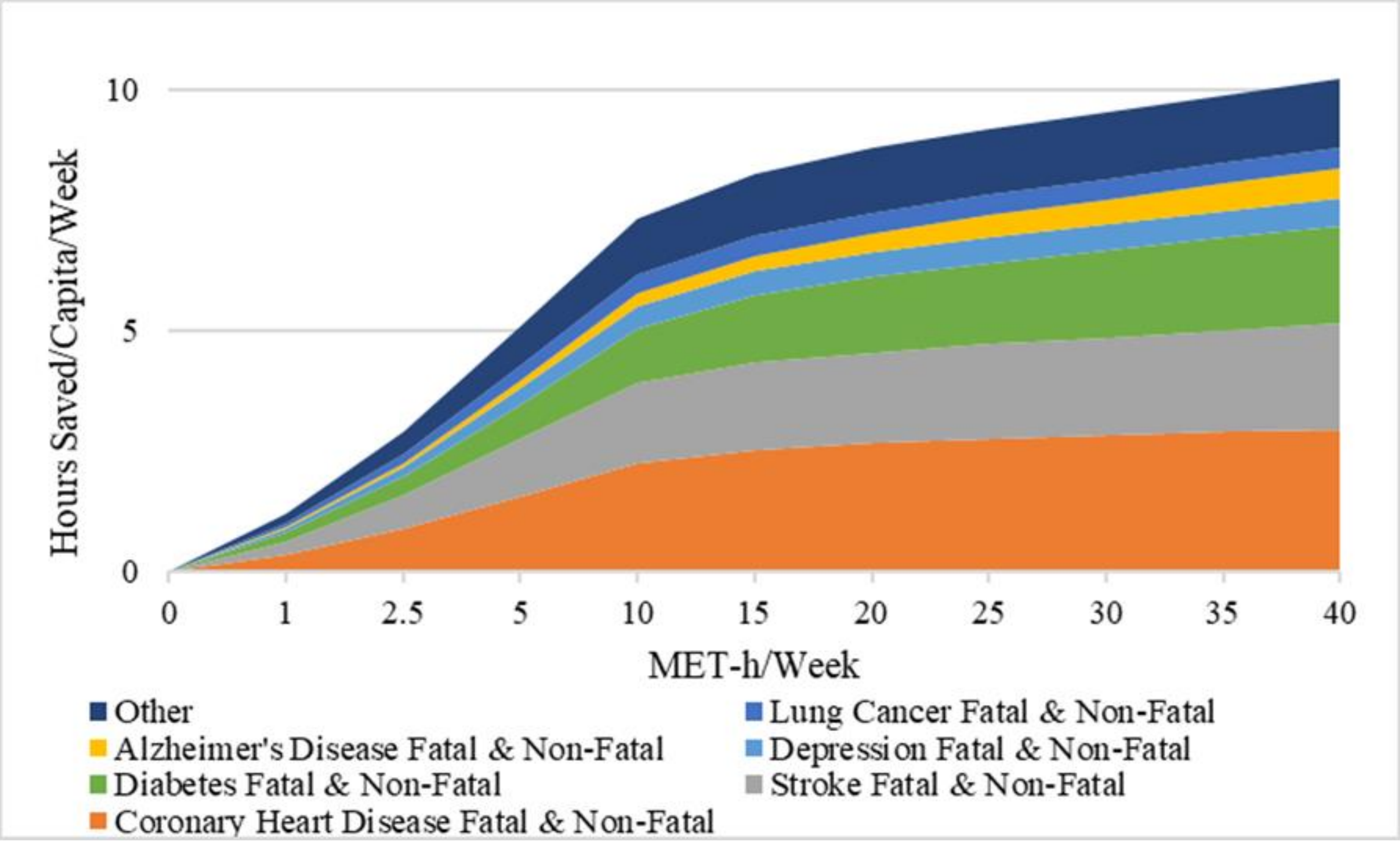
Profile => Settings (top right) => Subscription => Subscribe now => Choose subscription => Enter Promo Code

The promo code is “mooc@ieatbetter.com” (without quotes). This will unlock a “permanently free” purchase option.

Use iEatBetter for one or a few days and then in Q4 from activity 7b

- Report the dominant food items in your daily diet
- Look at 2 alternative foods for how to improve the health and environmental impact of your diet
- Comment on what you have learned using the app, including suggestions to improve the app.

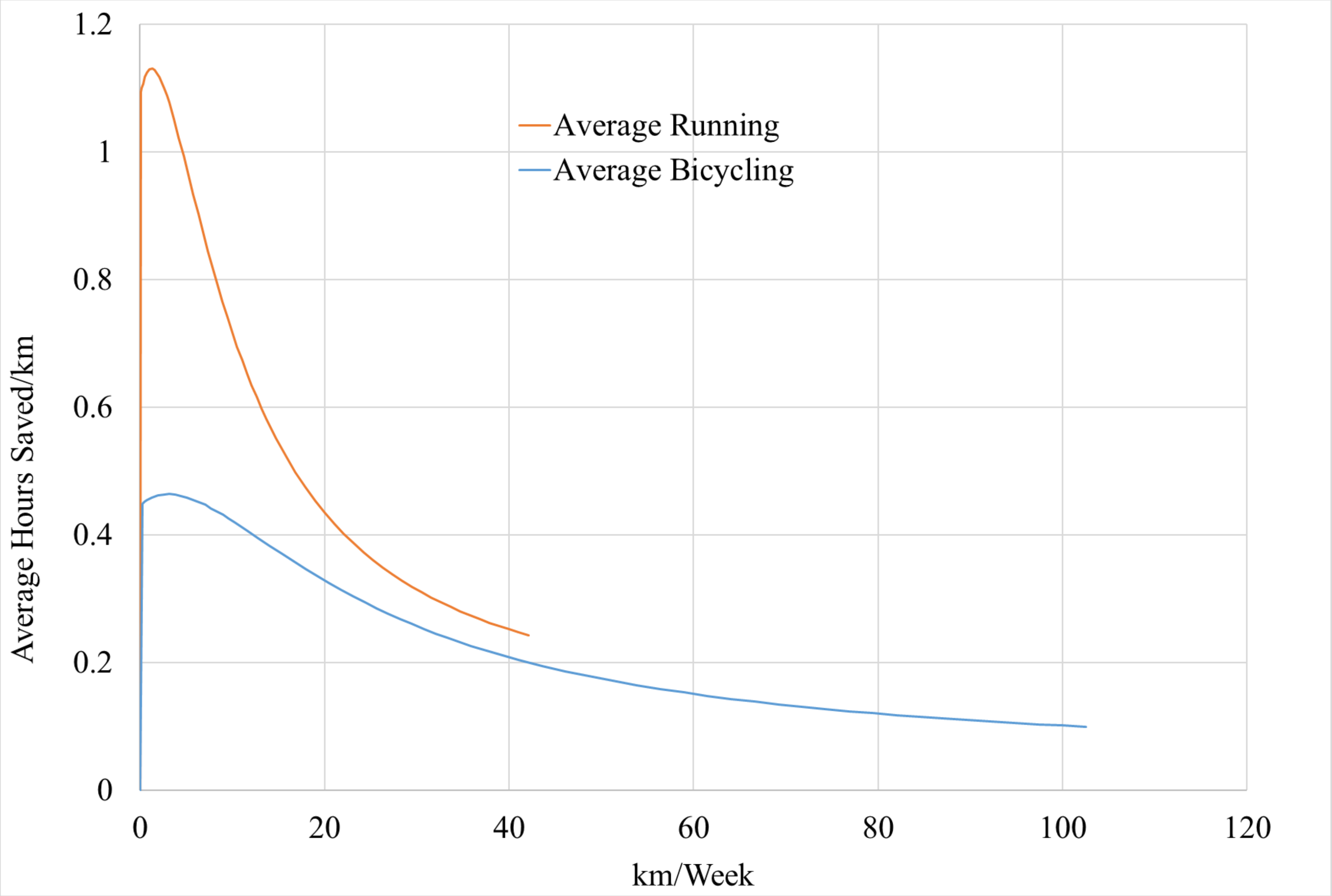
Physical exercise: benefits of 825 physical activities



2011 Compendium of Physical Activities

CODE	METS	MAJOR HEADING	SPECIFIC ACTIVITIES
01015	7.5	bicycling	bicycling, general
21050	4.3	volunteer activities	walking, 3.5 mph, brisk speed, not carrying anything

Physical activity gains per km walking/running and cycling: hours of healthy life gained per km

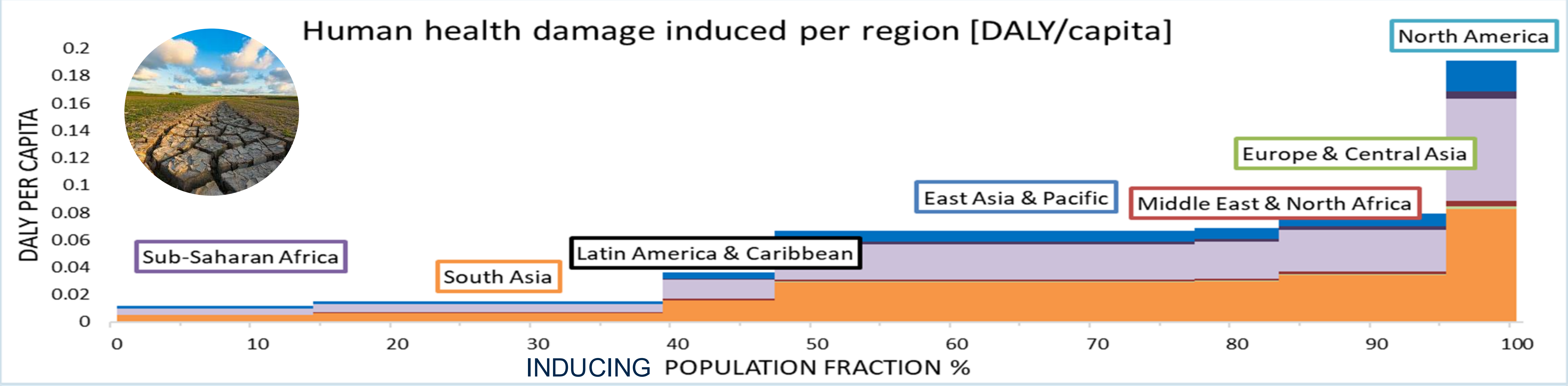


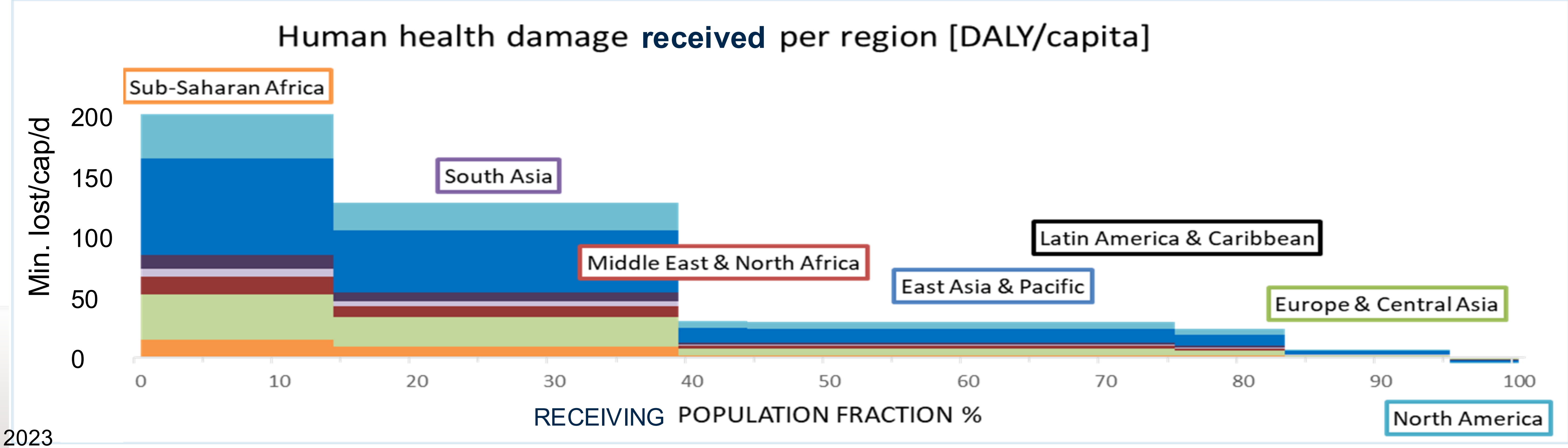
2011 Compendium of Physical Activities

Duration of trip compensate for the MET → min_{gained} / $km_{activity}$ very comparable Across walking or running, but depends on overall weekly physical activity

As long as not as not in New Delhi or forest fire area, much more beneficial to bike

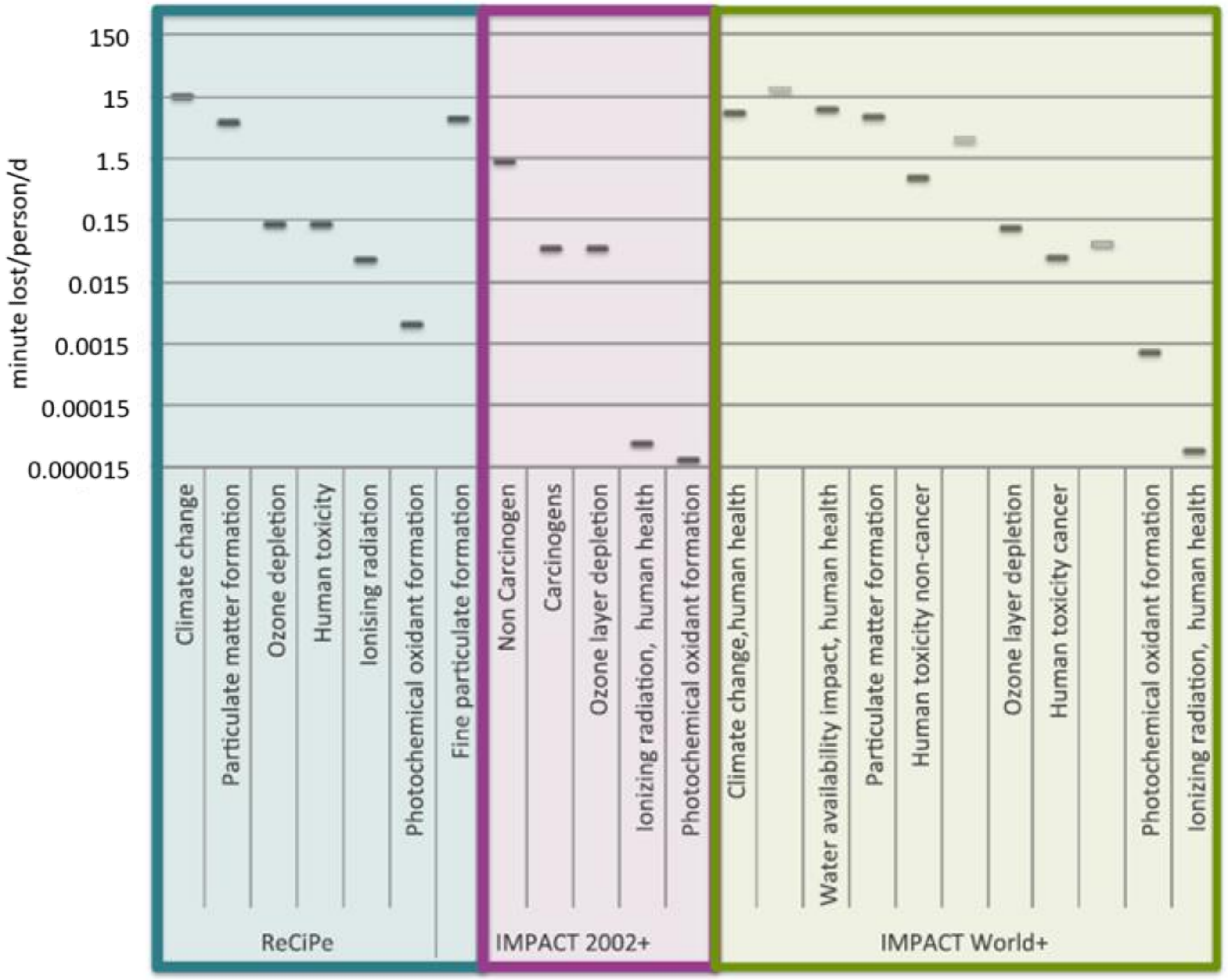
Disparities: Climate change impacts of heat and cold on health





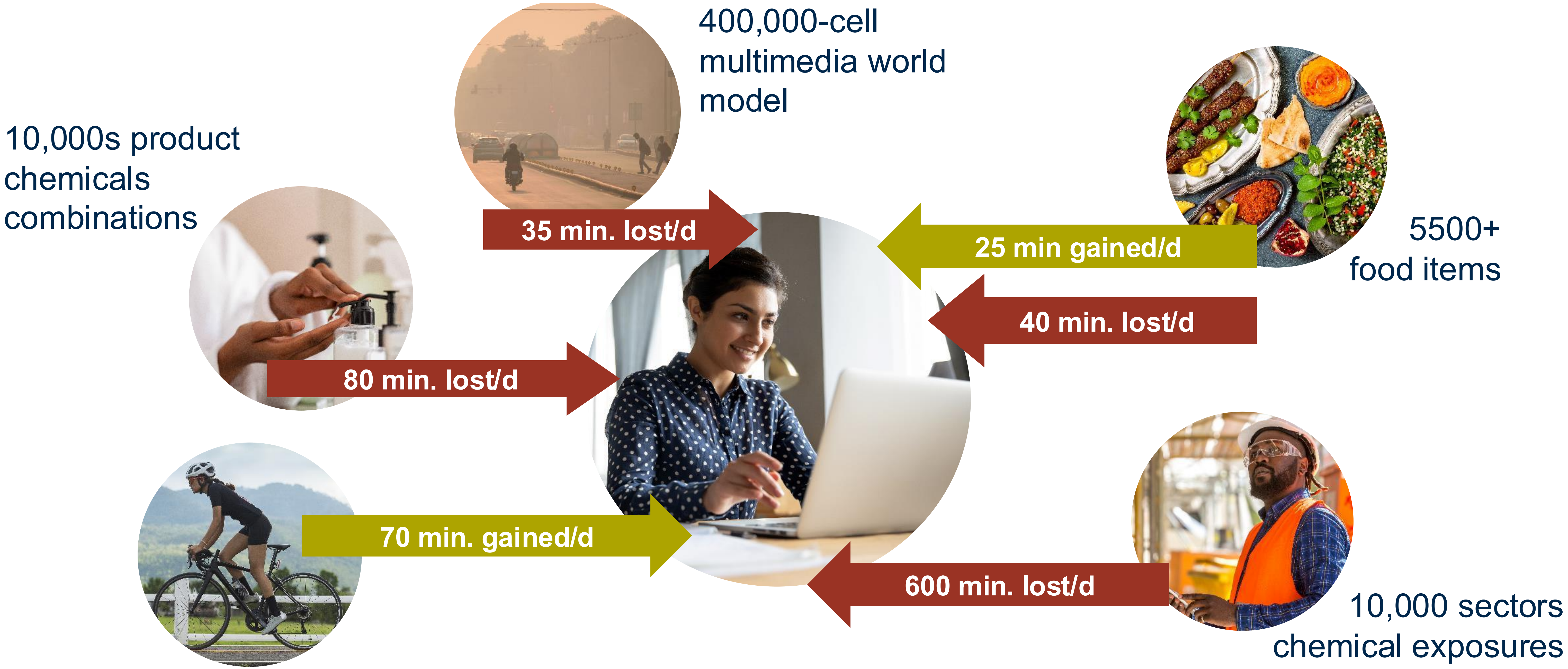
Rupcic, 2023

Worldwide environmental impacts on human health



Bulle et al 2019

Quantitative screening of impacts per pers per day



Global Trade

Part A - Using LCA to Explore how our Consumption Impacts Global Health

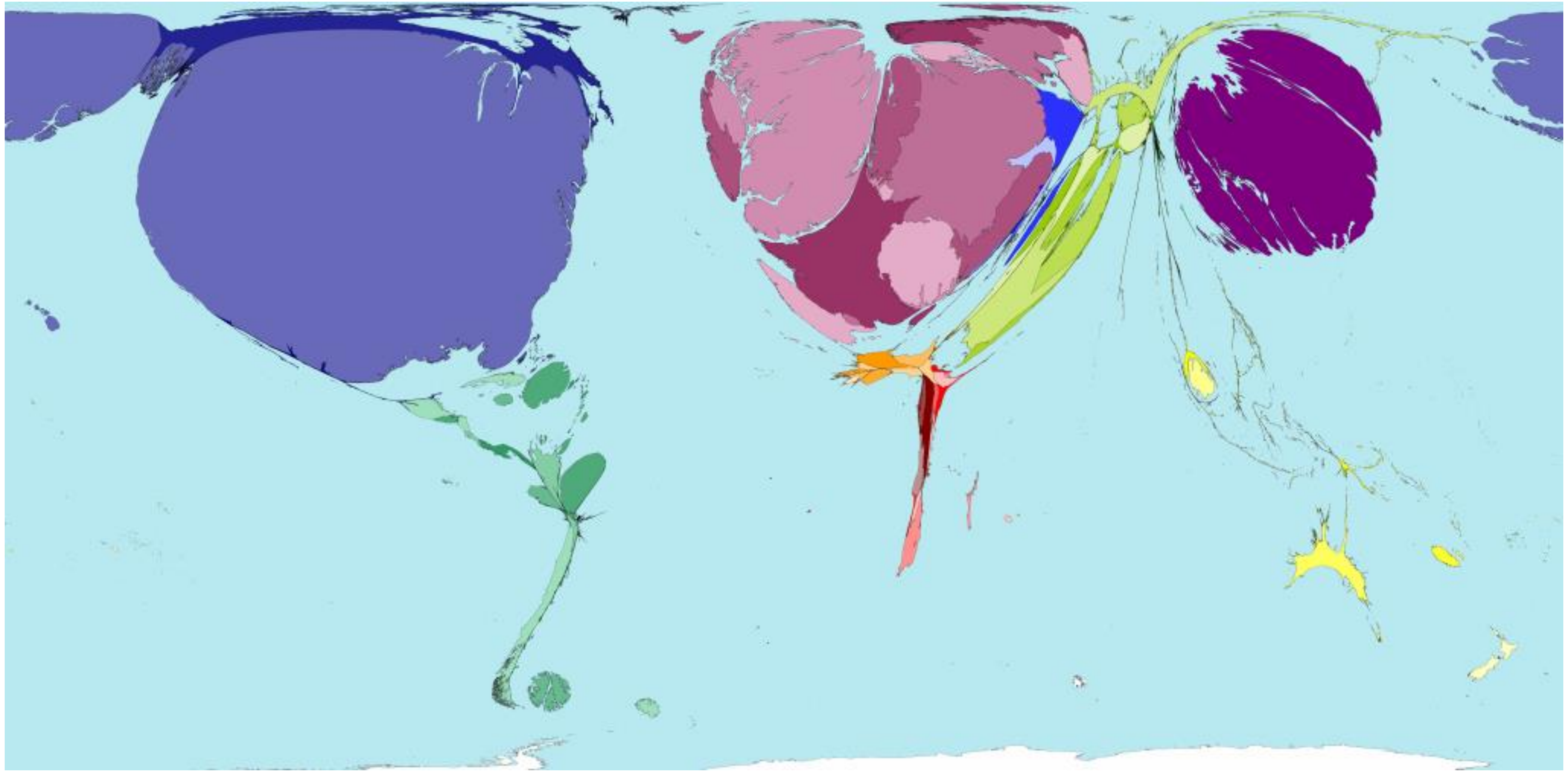
Shanna Shaked, PhD; Olivier Jolliet, PhD; Damien Friot, PhD

DTU

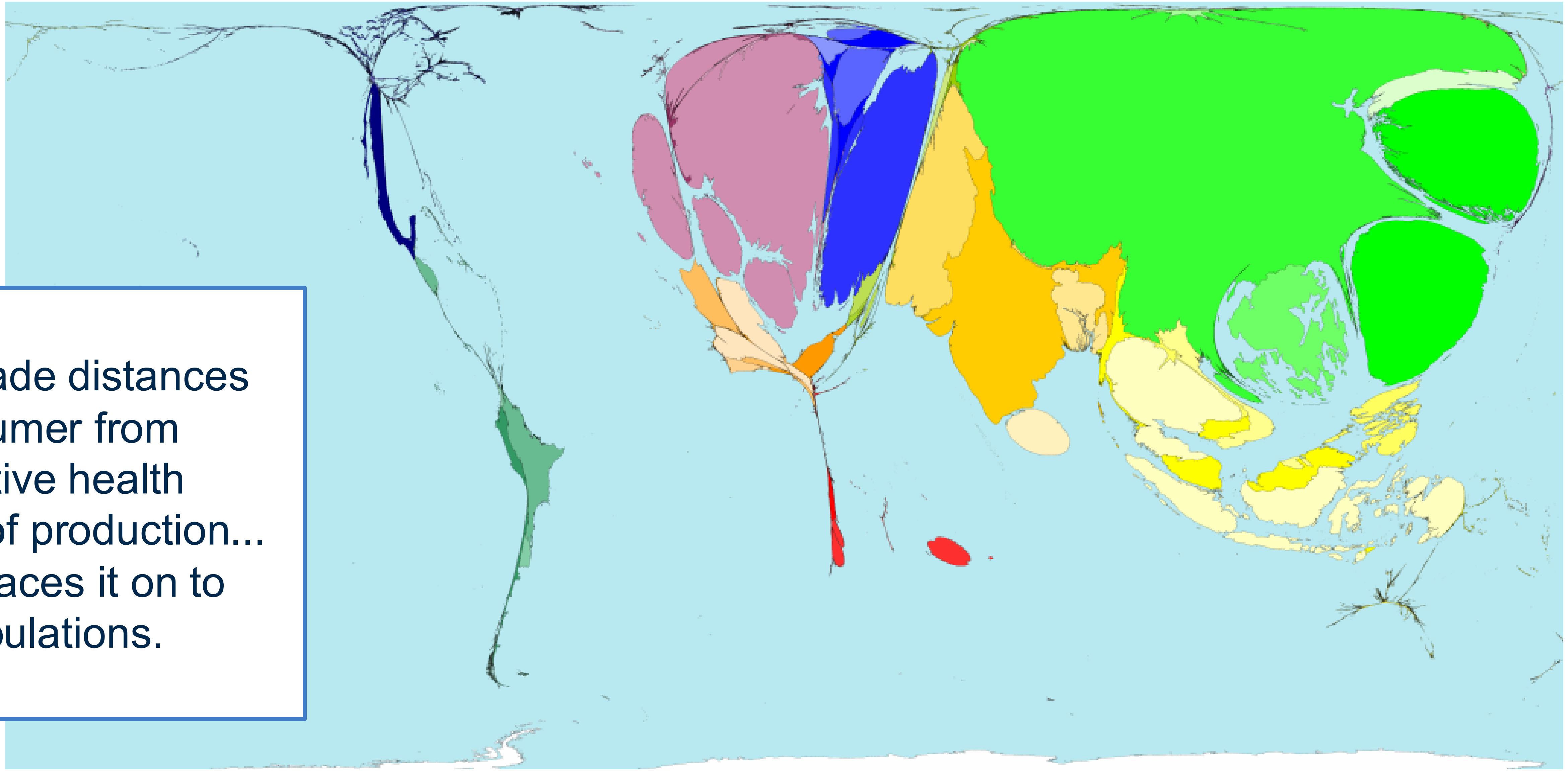
Learning Objectives

- 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

Clothing Imports



Clothing Exports



Global trade distances the consumer from the negative health impacts of production... and displaces it on to other populations.

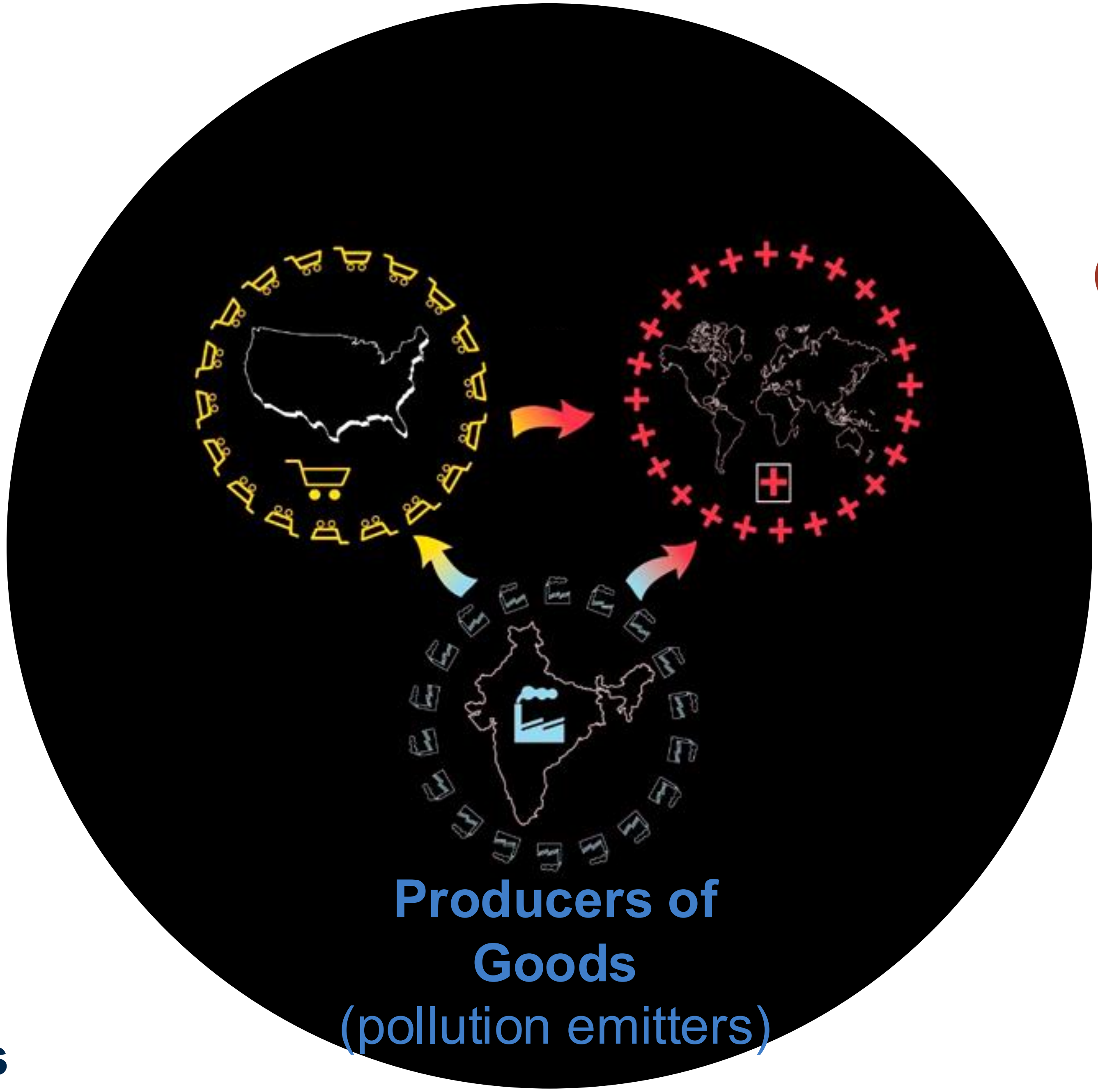
Think about…

To what extent are ***we*** responsible for the deaths due to PM in Asia?

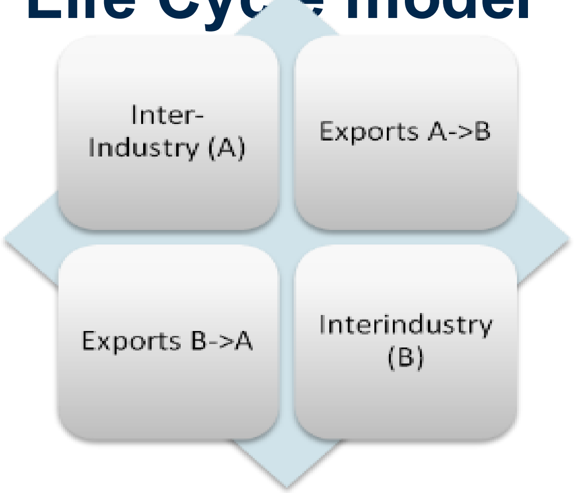
Combining models to calculate health impacts of global trade

Benefactors of Goods
(consumers)

Population Affected by Pollution
(emitters, consumers or 3rd party)



1 **Economic Trade & Life Cycle model**

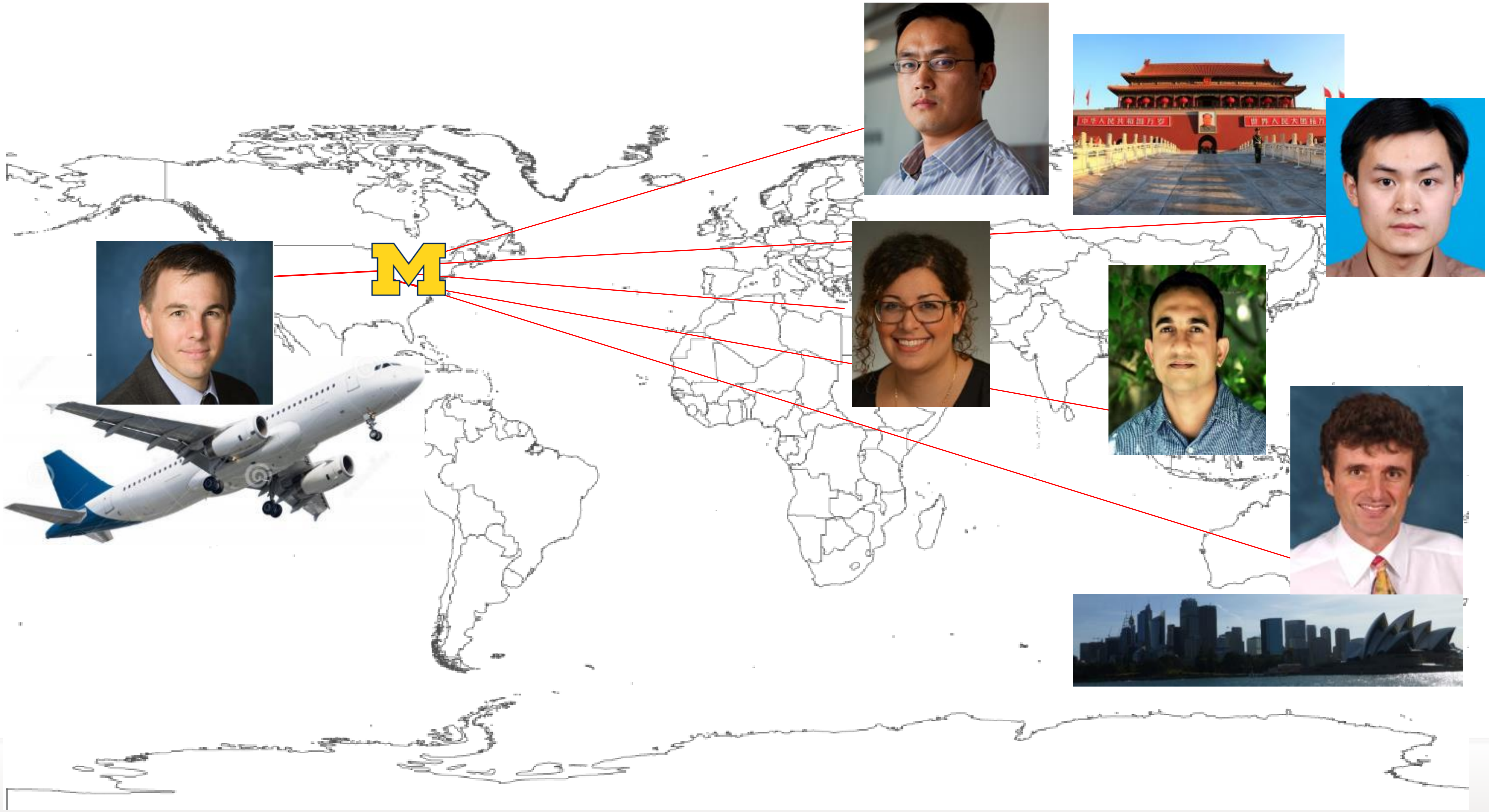


→ **Global emissions**

2 **IMPACT: World Multimedia Transport Model (U of M)**

Health impacts (DALY)
in US, EU, India, China

Setup of our M-cubed project

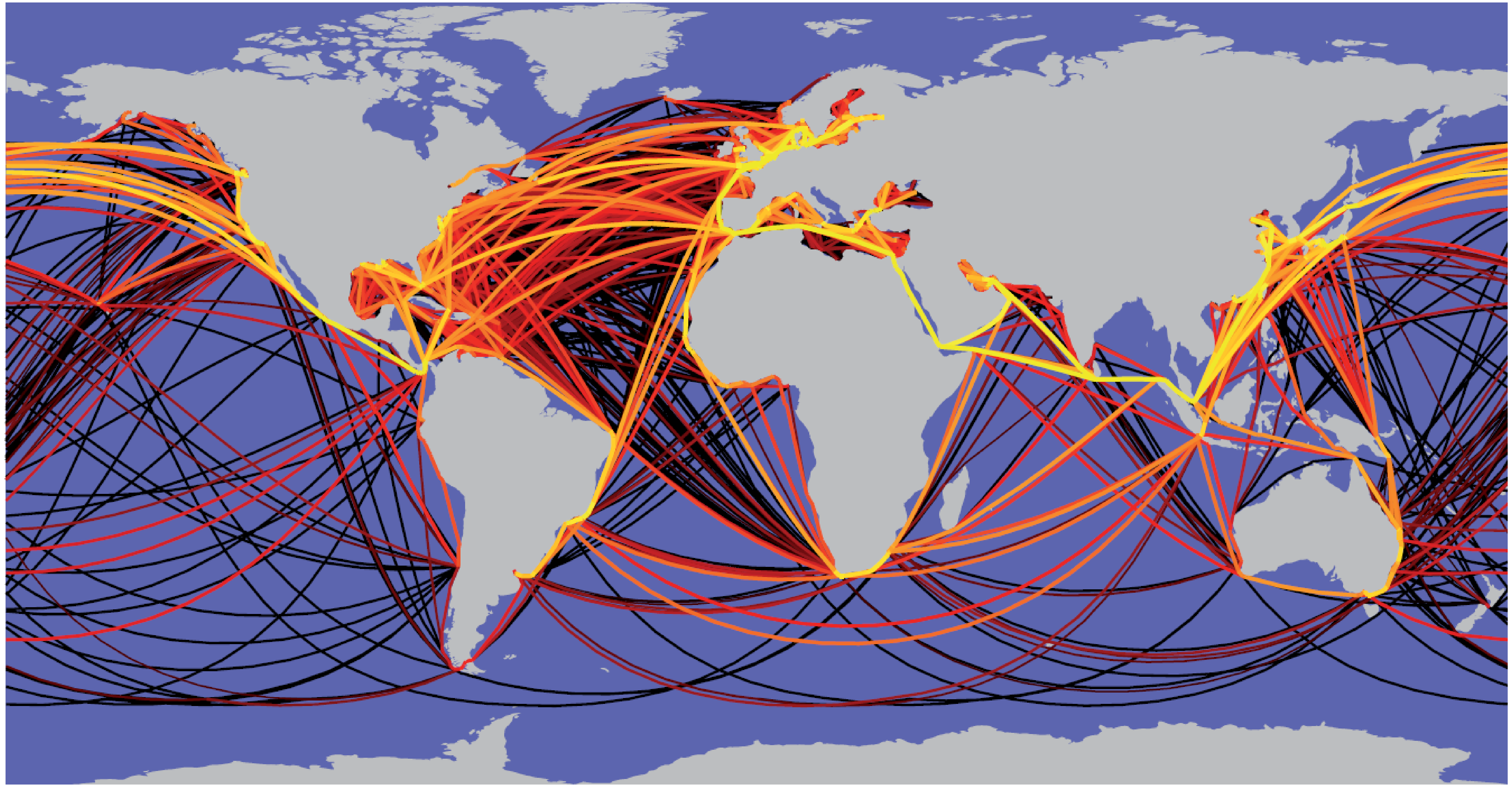


Add global economic trade model

	Stages	Focus, units and key factors
Environmentally Extended Multiregional Economic Trade model	Regional consumption	Final goods: by good and country of origin [USD]
	↓	**Production system**
	Regional production	Final and intermediary goods: by sector [USD]
	↓	**Emission intensities**
	Regional emissions	Pollutant: by sector [$kg_{emitted}$]
	↓	**Substance fate**
Pollutant Transport and Impact model	Regional concentrations	Pollutant: in air, water, vegetation, etc. [kg/m^3]
	↓	**Medium intake**
	Regional population exposure	Pollutant: by inhalation and ingestion [kg_{intake}]
	↓	**Dose-response**
	Regional human health impacts	Pollutant: damage by region [DALY]

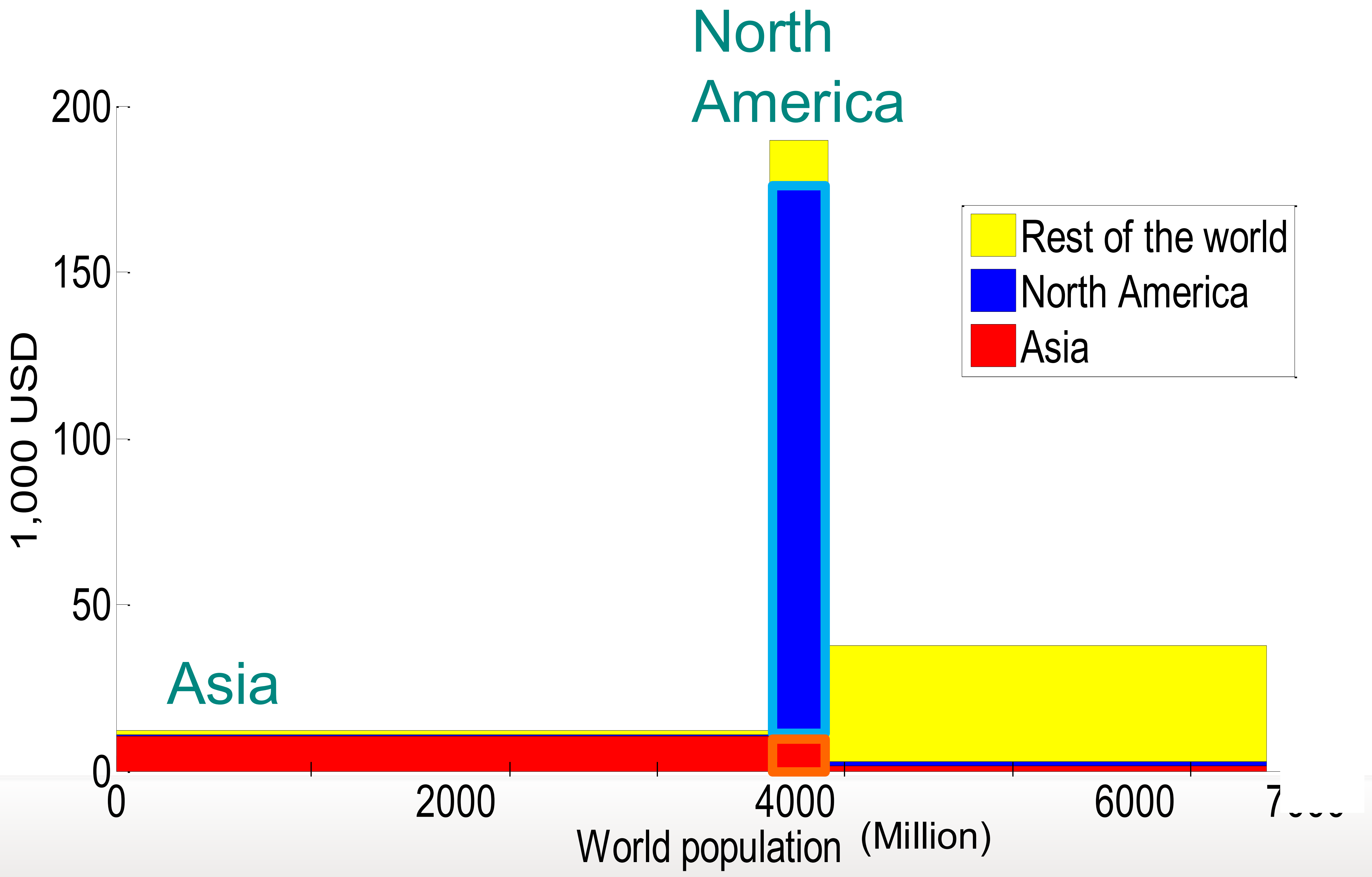
Where are the impacts associated with ALL global trade?

Full global trade network exchange between 15,000 country-sectors

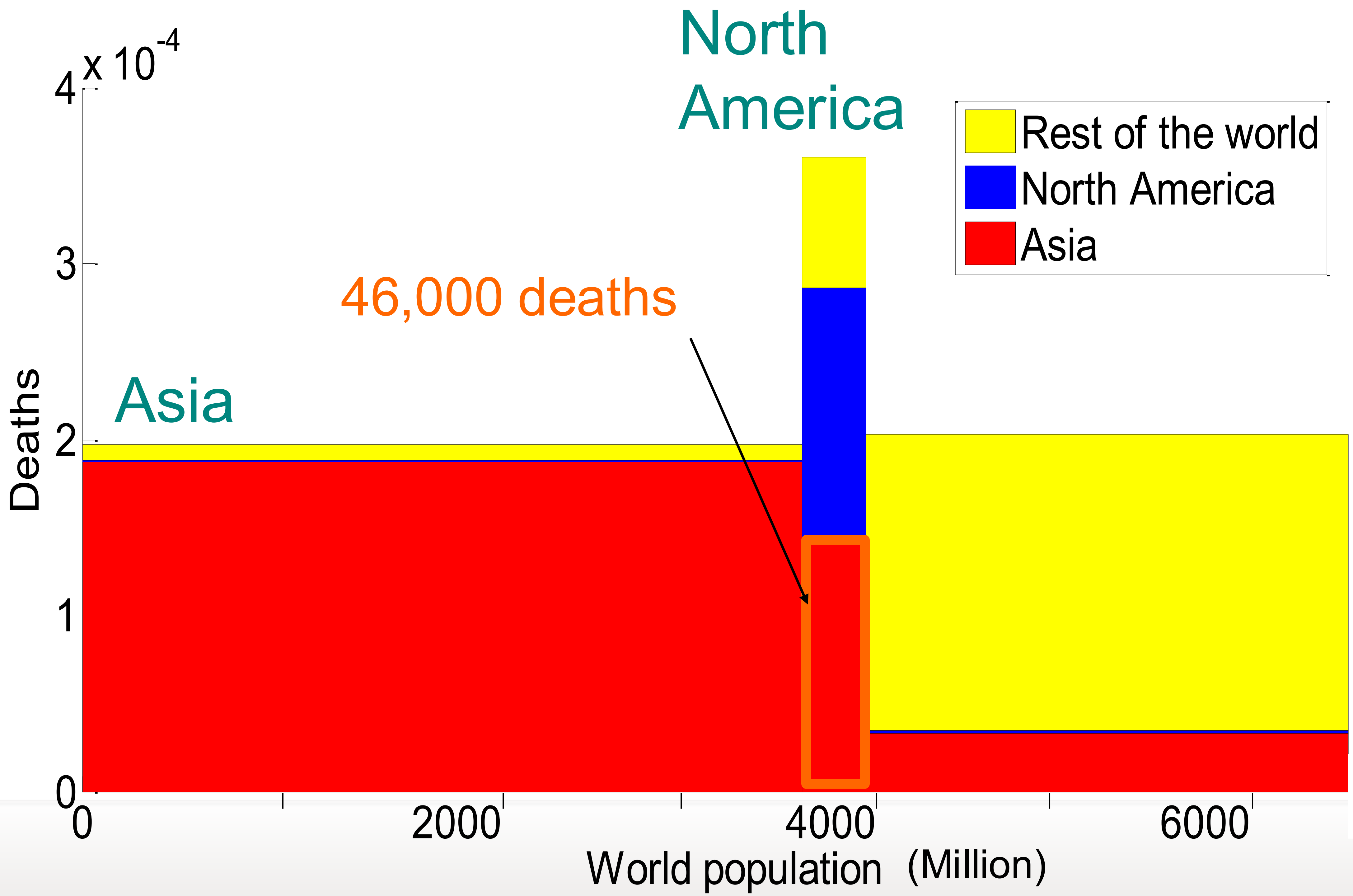


Kaluza, et al., 2010

World Production per capita



Particulate Matter related deaths induced by consumption per capita



Particulate Matter Control Technology is Effective

Best available control technology available with 99-99.9% removal efficiency

Choices

Global burden of disease 2019 – in class activity

Take 15 minutes to rank these risk factors from highest to lowest for global number of deaths.

Estimate the total annual number of death in the world associated with the highest and lowest factors.

Without using Internet (just give your best guess!)

19 **MAIN RISK FACTORS:**

Air pollution
Alcohol use
Childhood maltreatment
Dietary risks
Drug use

High blood pressure
High body mass index
High fasting plasma glucose
High low density cholesterol (LDL)
Impaired kidney function
Intimate partner violence
Low bone mineral density

Low physical activity
Malnutrition
Occupational risks
Other environmental *(lead, radon)*
Tobacco smoking
Unsafe sex
Unsafe water & sanitation

Each of you takes a photo of the group ranking

Social aspects and health

In person session

Olivier Jolliet, PhD

DTU

In person teaching session – format & learning objectives

- Plenum lecture (OJ-60B): Understand how we can quantify health of foods (15’)

- Group interpretation (All): Interpret the coffee case study results
  Evaluate the direct effect of coffee on health and compare it with the health impacts with th eproduction (30’)

Break – move to topics rooms

- OJ: Introduce data for the bike compared to car exercise. (5’)

- In group: 7.3 Perform the health assessment of biking versus car driving (15’). perform sensitivity on the car case study.

Global Burden of Disease and food impacts

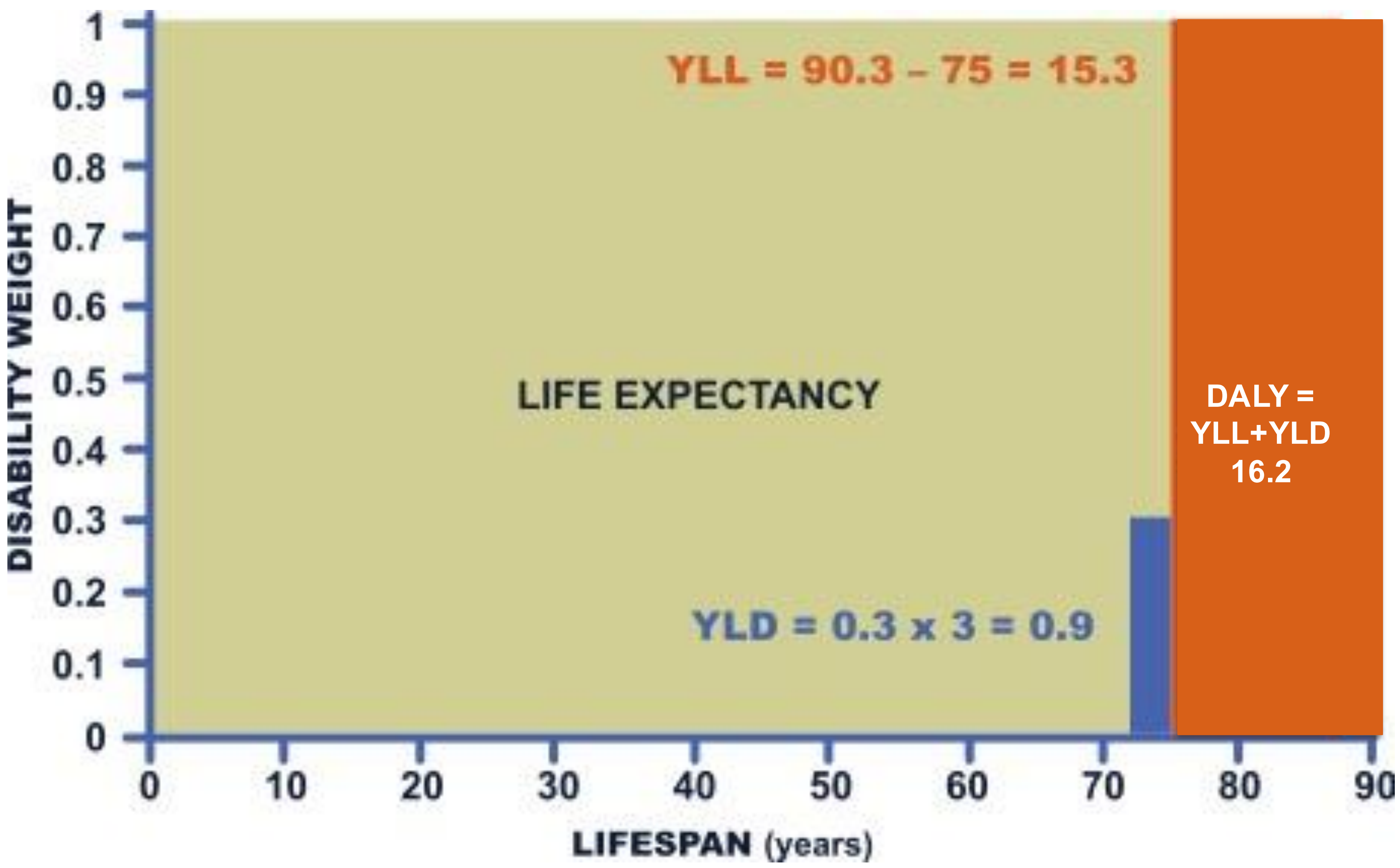
Olivier Jolliet, PhD

Burden in Disability-Adjusted Life Years (DALY)

DALY = Years Life Disabled (**YLD**) + Years Life Lost (**YLL**)

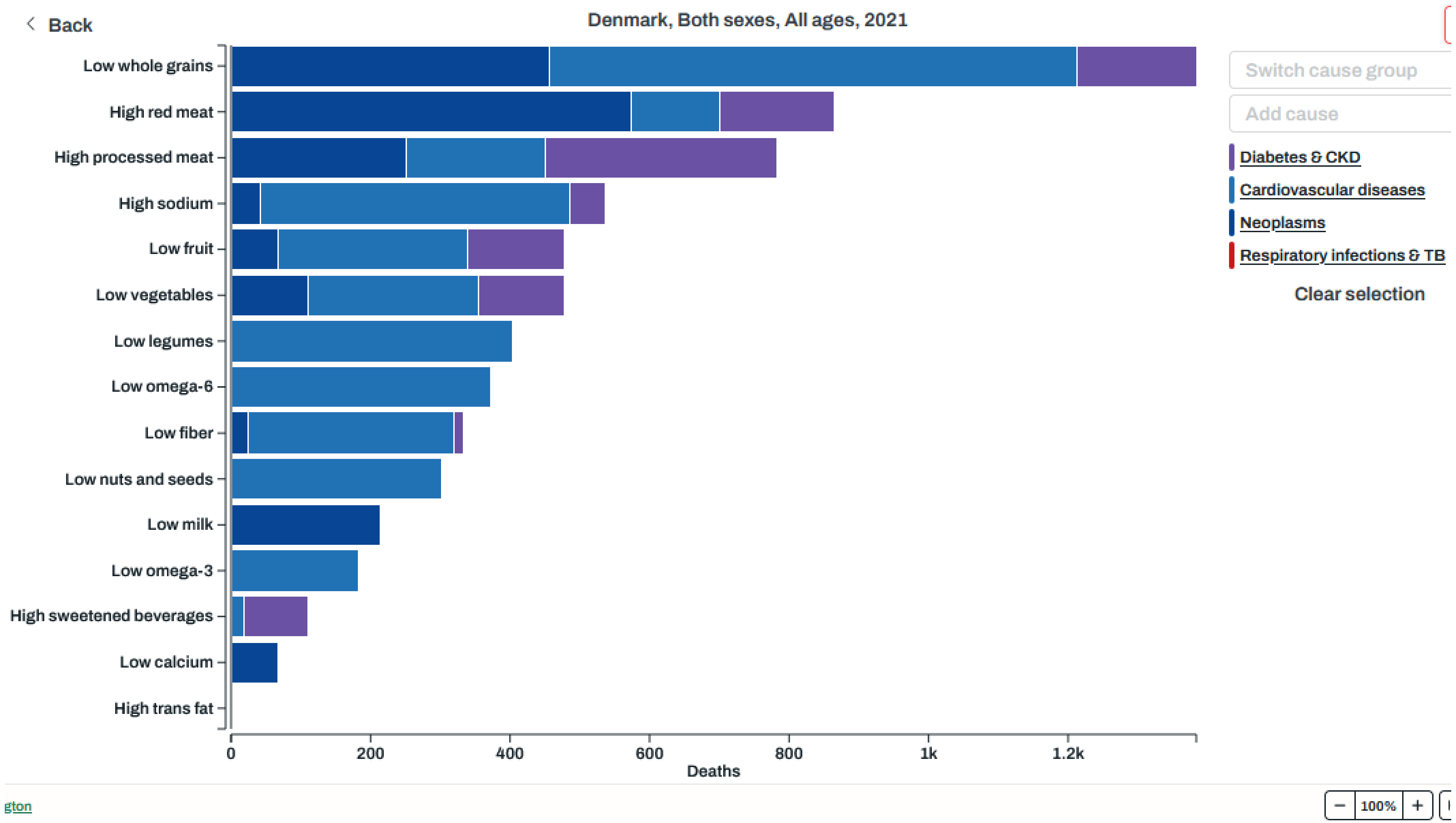
Illustration: Person gets a cancer at 72 years old and dies at 75

At age 75: life expectancy is 90.3



- The Global Burden of Disease project provides worldwide comparison of health status, causes for death and risk factors for 153 countries

Dietary burden of disease Denmark – 5000 death/yr or 100000 DALYs/yr



Nutrition: From GBD risk ratios to Dietary risk factors (DRFs)

Marginal disease burden (+) or benefit (-) Effect of individual foods in the context of the diet

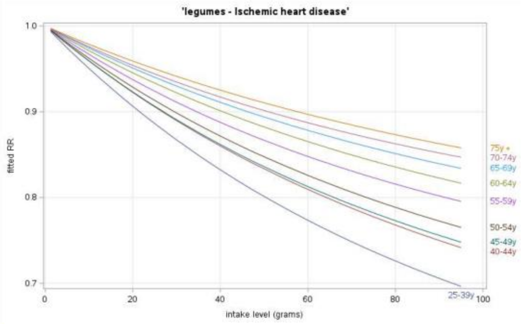
Impact per gram intake of risk component (→ DALY/g processed meat, avoided DALY/g legumes)

DIETS LOW IN

- Whole Grains
- Fruits
- Vegetables
- Nuts and Seeds
- Seafood Omega-3 Fatty Acids
- Legumes
- Fiber
- Calcium
- Milk
- Polyunsaturated Fatty Acids

DIETS HIGH IN

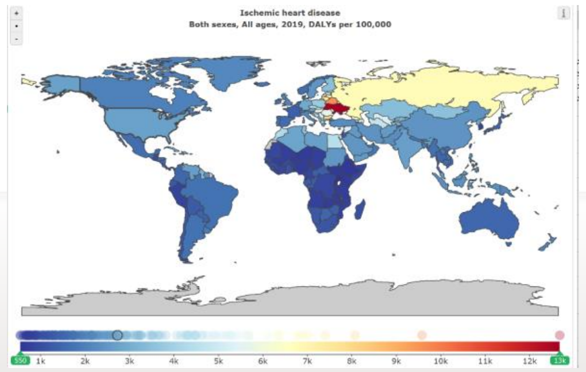
- Sugar-Sweetened Beverages
- Red Meat
- Trans Fatty Acids
- Processed Meat
- Sodium



16 dietary risks

49 health outcomes

IHD -GBD



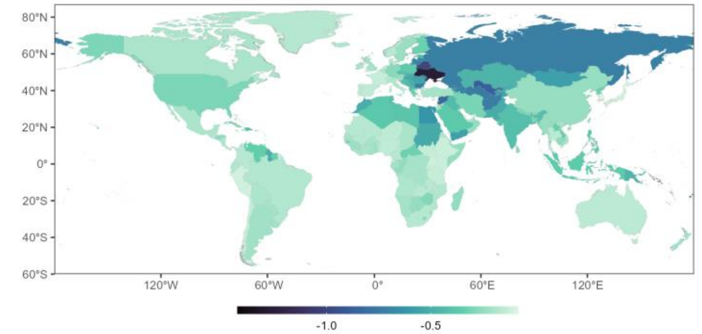
Relative Risks – (IHD)

479 Risk Ratios (RR)

2,940 outcome-specific burden rates

15 age groups
2 genders
YLL/YLD

Avoided DALY/g legumes, 204 countries



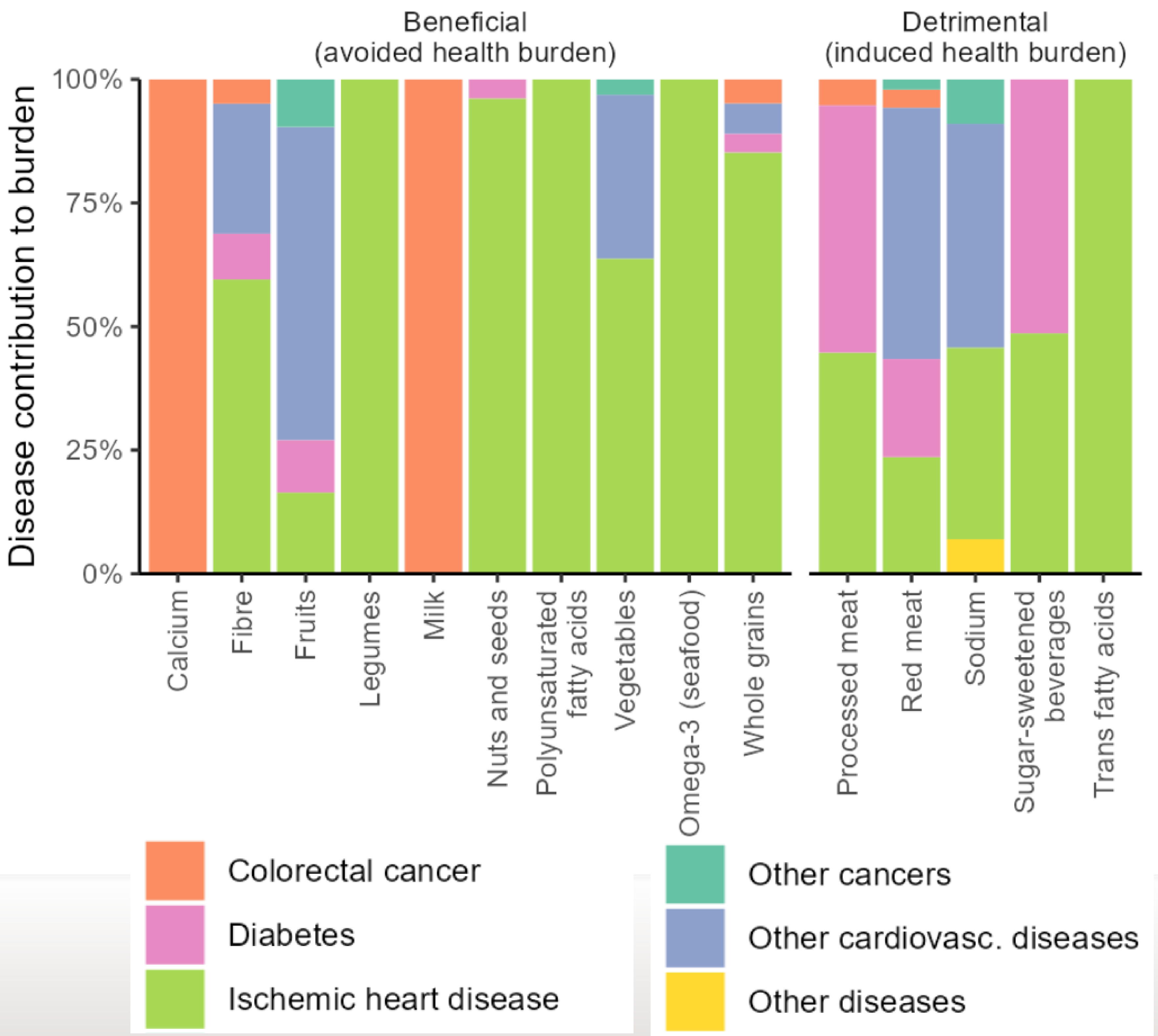
~6,200 DRFs

16 Cumulative DRFs, adjusted for age and gender

Weighted sum assuming independent & additive effect for marginal changes

Nutritional health impacts of foods

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



Health Nutrient Index HENI: Stylianou et al., 2021 Nature food

ARTICLES
https://doi.org/10.1038/s43016-021-00343-4
nature food

Check for updates

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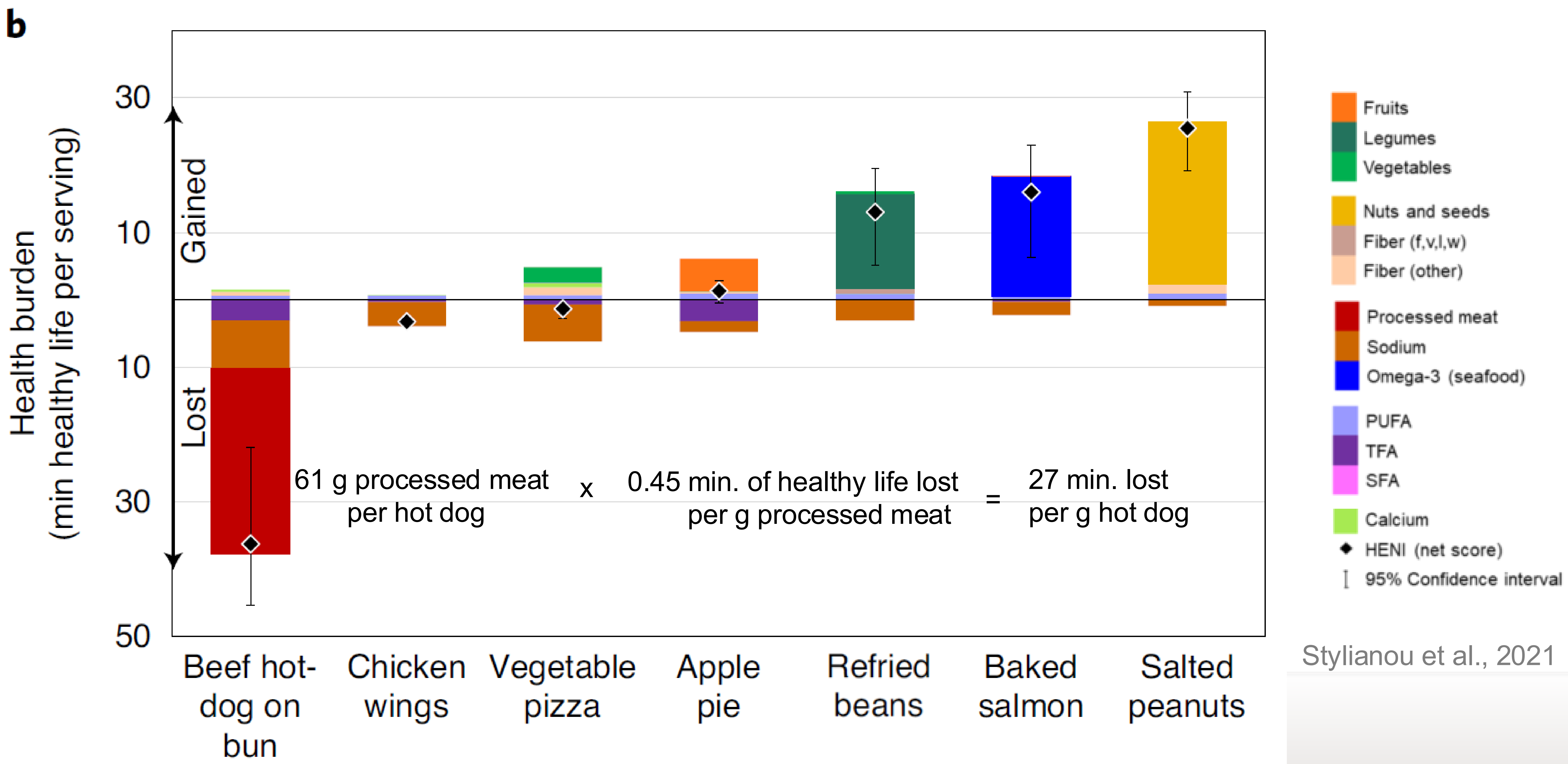
Minutes of healthy life https://rdcu.be/cuVht
Gained or lost for 5800+ foods

120,000 likes on CNN Instagram

High impact research >1000 news media with potential reach of 1.3 billion people

Comparison of HENI for several food items (available for 5000foods)



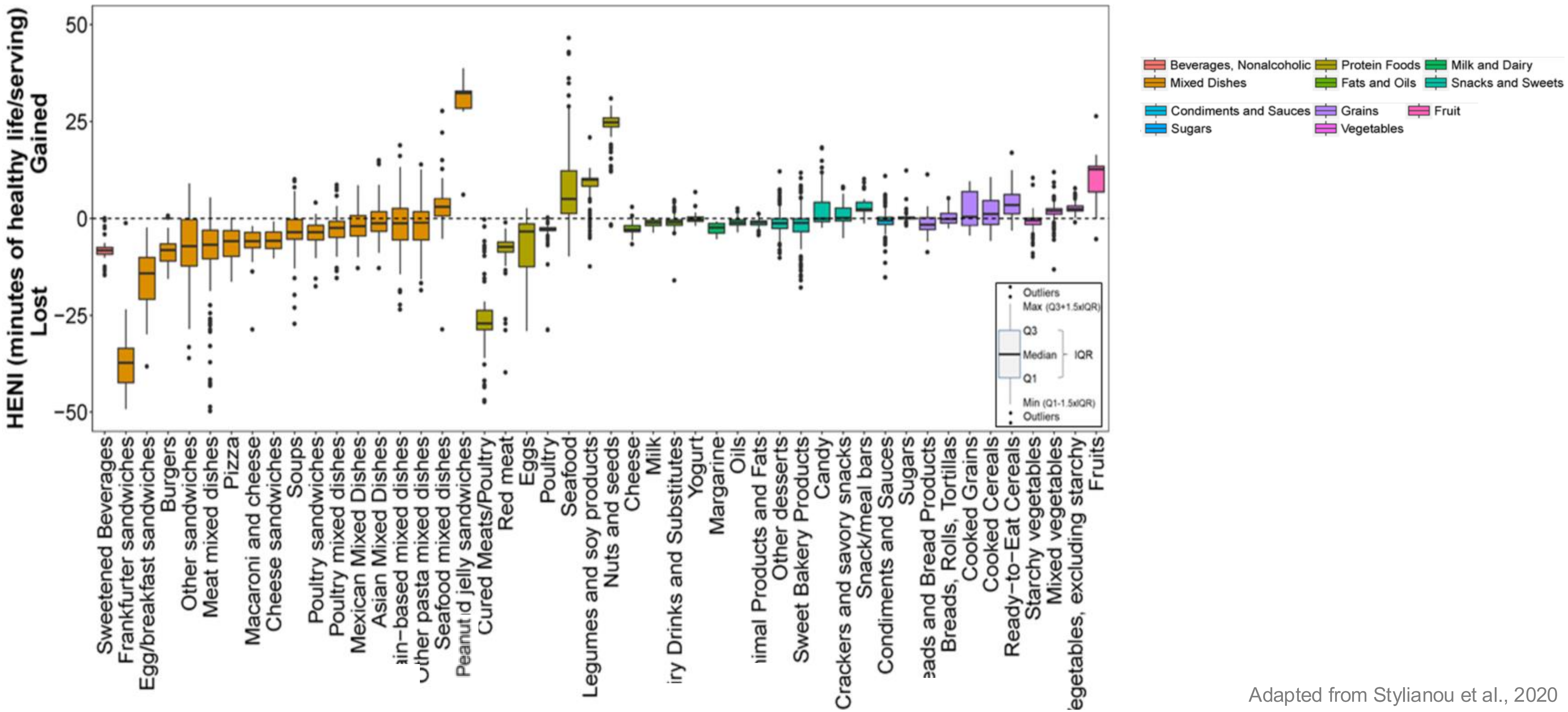
Stylianou et al., 2021

Huge variety of food choices

On a given day ~5,800 foods consumed in the US

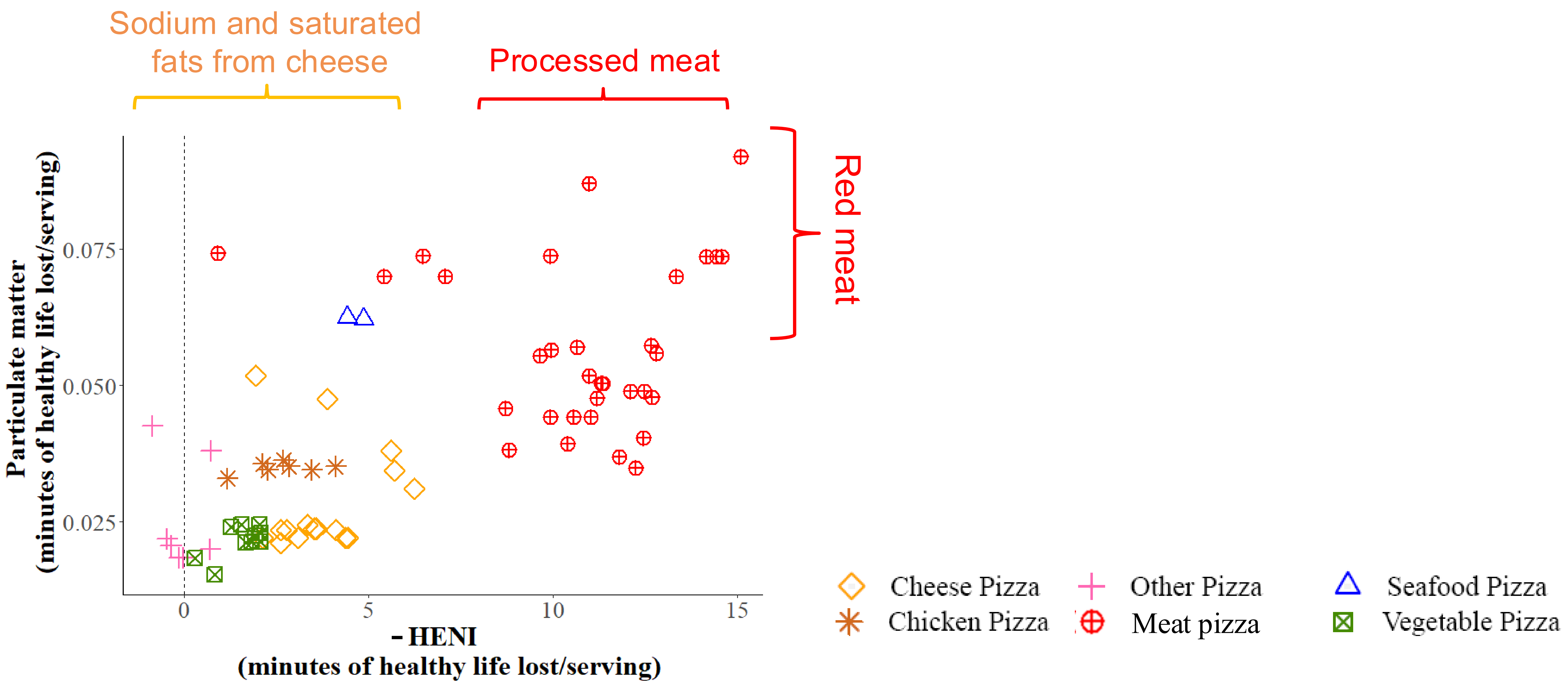
(NHANES, 2016)

Marginal nutritional impacts and benefits of 5,853 foods in US Diet

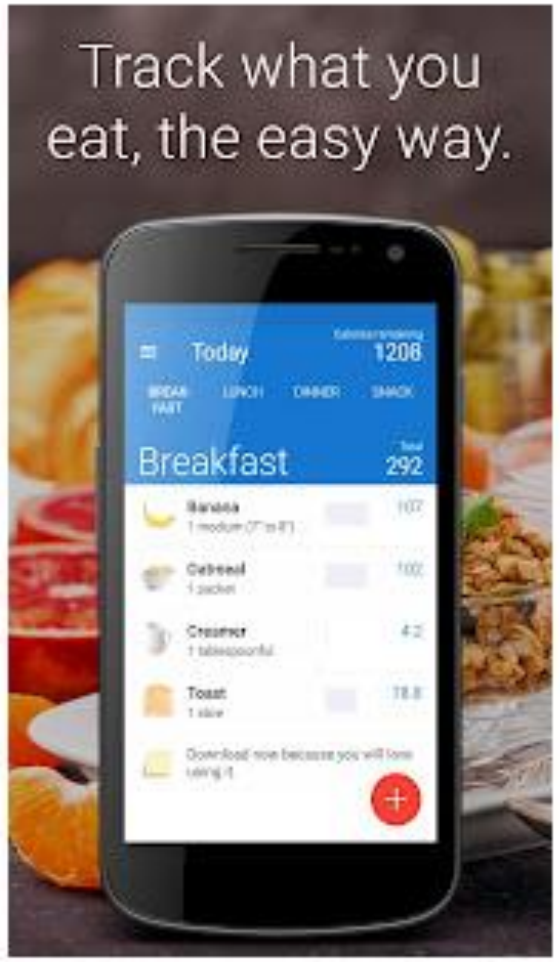


Adapted from Stylianou et al., 2020

Health impacts from pizza: Environmental vs nutritional (N=78)



iEatBetter app -



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Use iEatBetter for one or a few days and then in Q4 from activity 7b

- Report the dominant food items in your daily diet
- Look at 2 alternative foods for how to improve the health and environmental impact of your diet
- Comment on what you have learned using the app, including suggestions to improve the app.

Health impact or benefit in min.gained or lost per cup of coffee

In this exercise, we will first estimate the health impact or benefit in min. per cup of coffee

We will combine

a) Epidemiological evidence from a meta-analysis study from Poole et al, 2017
b) Background DALYs rates from the Global Burden of Disease translated in minutes per day

To obtain these health benefits and/or impacts

We will then compare these impacts with

a) The nutrition health impacts of ingesting servings of various foods
b) the min. lost per cup of coffee for production of this cup of coffee over its life cycle

other servings of food.

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:

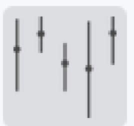
Harmful associations

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).

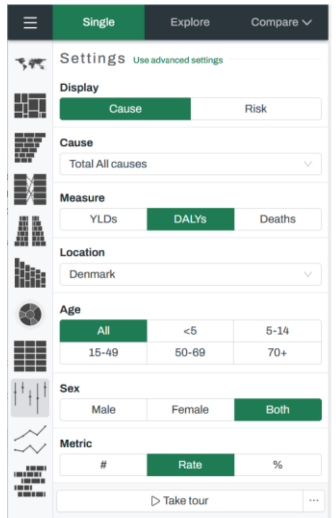
1d. Give an advice about coffee consumption during pregnancy:

2. Get from the GBD the background rate

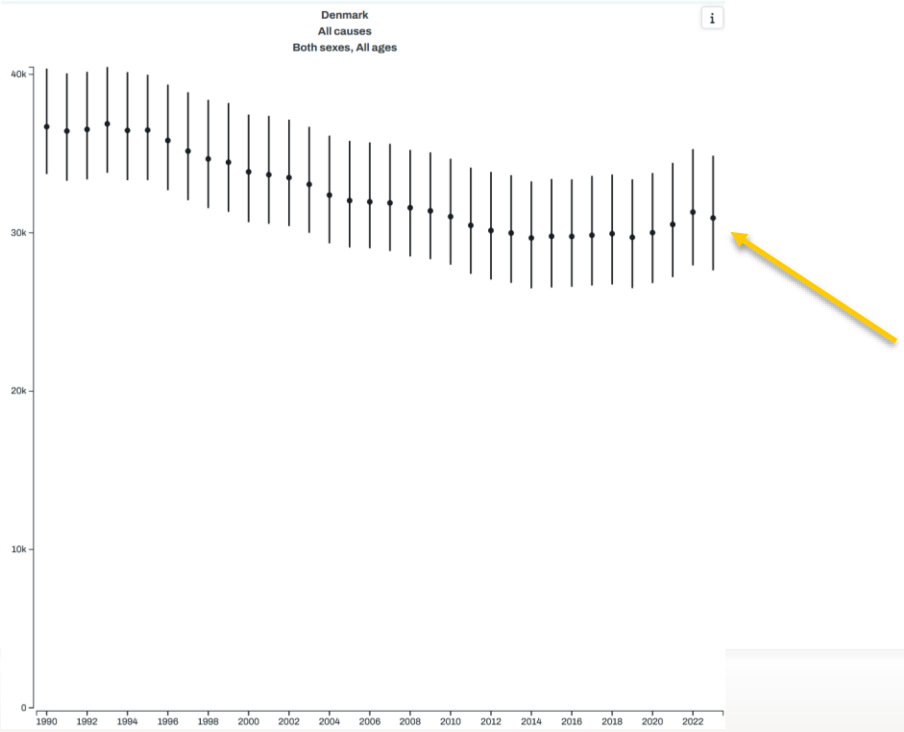
Google GBD compare and enter the GBD (you might have to register now).

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:

Also do it for selecting as causes

b) B.2 Cardiovascular disease:

c) B.1 Neoplasm (=cancer):

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 x 60 = 1440 minutes in a day, the burden rate will correspond to

0.05 **days** lost/pers/day x 1440 =

3. Calculate the burden rates and their confidence interval in min./pers./day for

a) All causes:

b) B.2 Cardiovascular disease:

c) B.1 Neoplasm (=cancer):

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

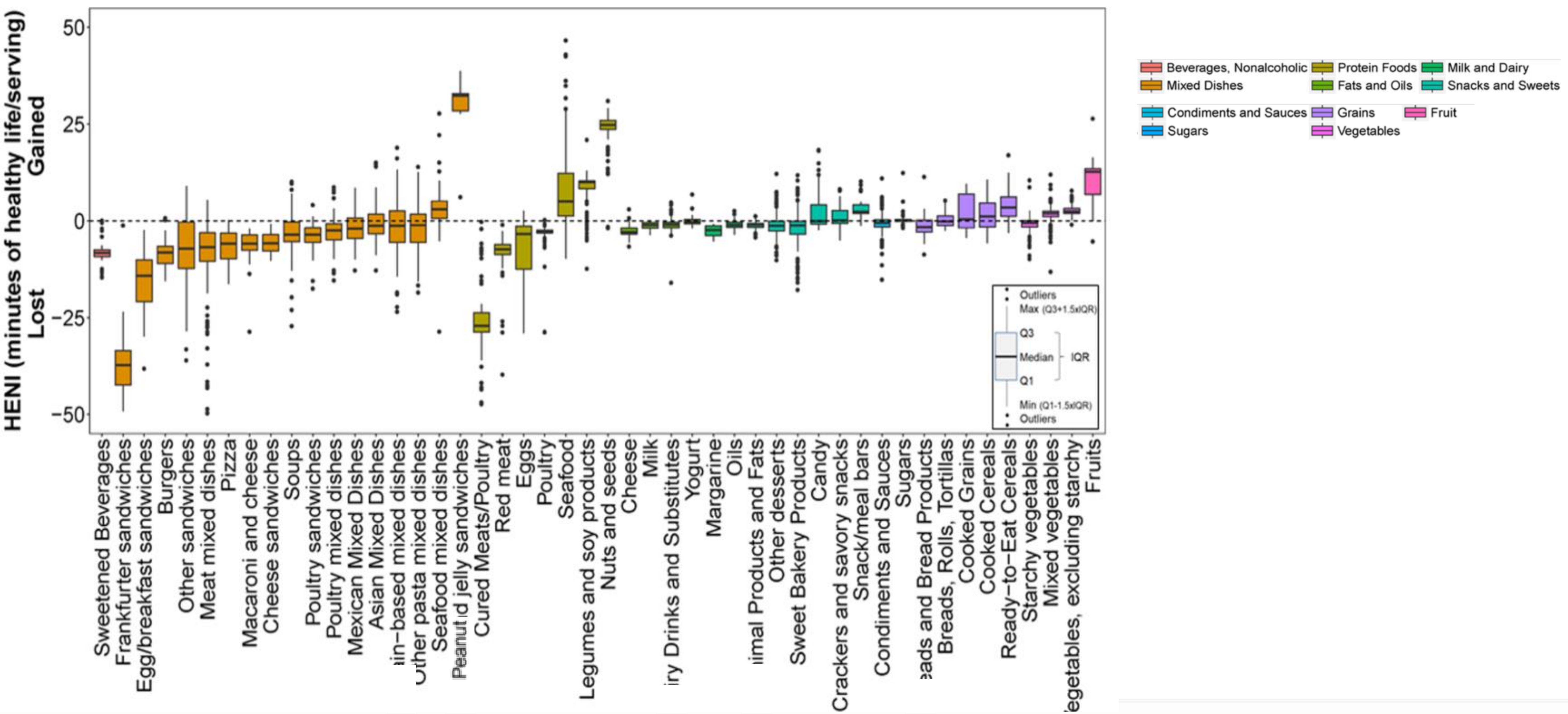
a) All causes:

b) B.2 Cardiovascular disease:

c) B.1 Neoplasm (=cancer):

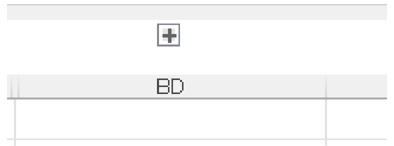
Also obtain a confidence interval by using the low-low values of 1 & 3 and the high-high values from 1-3.

5. Compare and discuss the min. lost per cup of coffee with other food servings



6. Compare the health benefit per cup of coffee with the min. lost per cup of coffee for its production over its life cycleCoffee exercise

Open the morning coffee solutions
(available in the teaching session of module 7)



Press on the “+” on the top of column U to expand the sheet (same on top of BD)

You obtain “free” the human health, ecosystem impacts and energy resource results.

Find the minutes lost per cup of coffee in the totals of column L (you might have to click on the top of column U) and discuss how it compares to the direct effect of ingesting coffee. Which one is higher

Looking at the different scenario to get a range for the different coffees, is your conclusion robust considering the various confidence intervals.

Interpret the coffee case study results for health (based on table and graphs):

- How far are results for human health, ecosystem quality and energy resource similar or different from the carbon footprint for these different coffees
- Certain part of the life cycle have a higher share of impacts on ecosystem quality than on climate change? Which part and why?
- What is the magnitude of the effect in term of minute lost per cup of coffee for the production

The ecoinvent database combined with Life Cycle Impact method

	B	C	D	E	F	G	H	I	J	L
2	Conversion factors	kg_to_g	g/kg	1000		Category	climate change	total: human health	total: ecosystem quality	energy resources: non-renewable
3						Indicator	global warming potential (GWP100)	human health	ecosystem quality	energy content (HHV)
4	**Process #**	**Activity Name**	**Geography**	**Reference Product Name**	**Reference Product Unit**	**Reference Product Amount**	**kg CO2-Eq**	**min.lost**	**species.yr**	**MJ-Eq**
5	17446	steel production, low-alloyed, hot rolled	RER	steel, low-alloyed, hot rolled	kg	1	2.181	8.00	9.8E-09	25.56
6	17078	sheet rolling, steel	RER	sheet rolling, steel	kg	1	0.312	0.73	1.4E-09	4.93
7	323	aluminium production, primary, ingot	IAI Area, EU27 & EFTA	aluminium, primary, ingot	kg	1	7.210	13.33	3.3E-08	115.04
8	17076	sheet rolling, copper	RER	sheet rolling, copper	kg	1	0.482	4.96	9.8E-09	7.19
9	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
10	12104	market for polyethylene, high density, granulate	GLO	polyethylene, high density, granulate	kg	1	2.328	2.35	9.4E-09	80.67
11	5070	electronics production, for control units	RER	electronics, for control units	kg	1	31.865	91.05	2.1E-07	451.55
12	5253	ethylene production, average	RER	ethylene	kg	1	1.447	1.12	5.3E-09	67.93
13	17736	tap water production, conventional treatment	RoW	tap water	kg	1	0.00044	0.00	1.9E-12	0.01
14	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
15	14708	market group for electricity, medium voltage	UCTE	electricity, medium voltage	kWh	1	0.385	0.49	1.8E-09	8.88

Finding sustainable trade-offs in resource management

Resource management

David Lusseau

Fishing

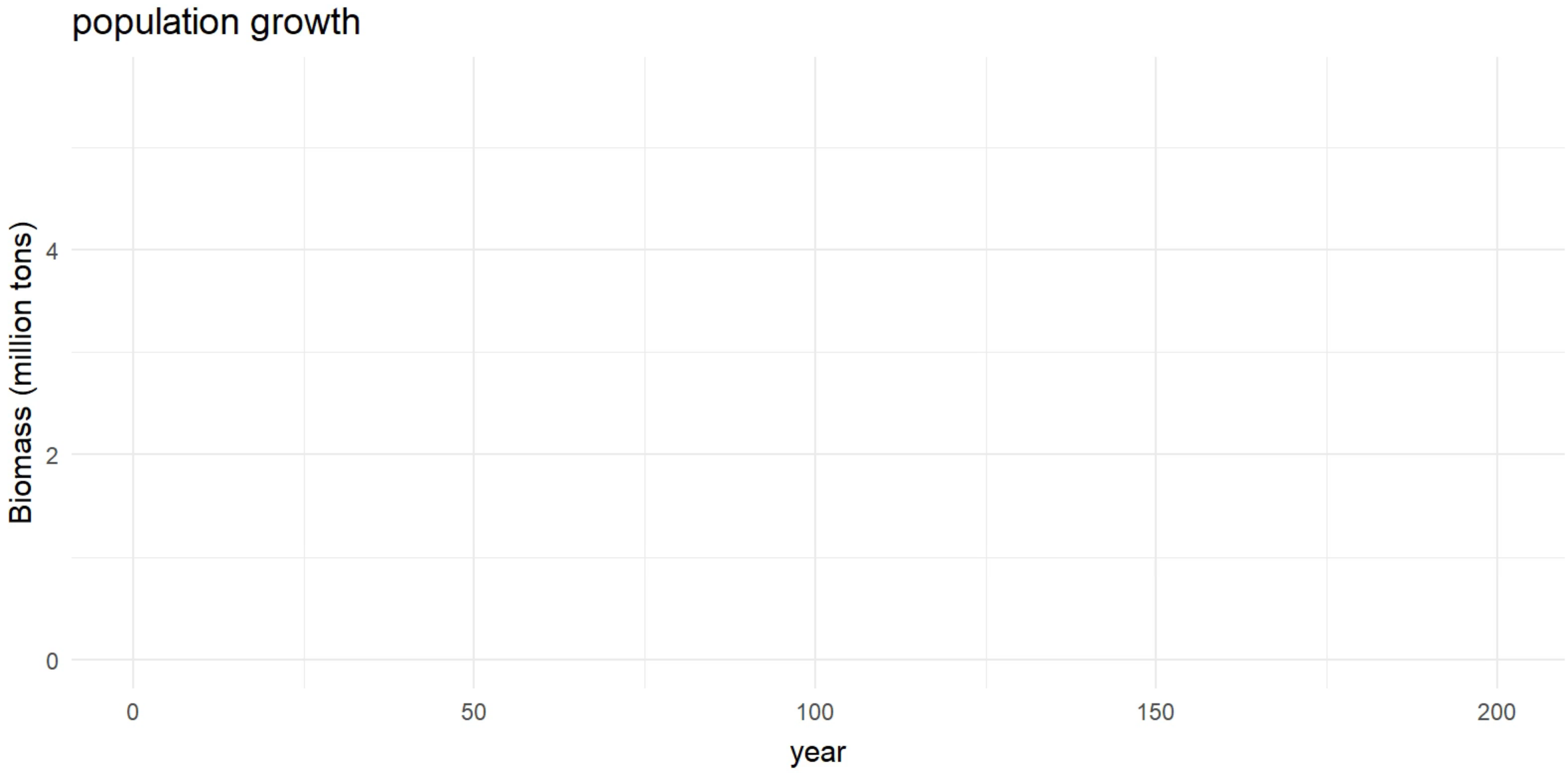
Population model of the Fish stock

- Let's formulate an equation describing the rate at which a resource renews itself

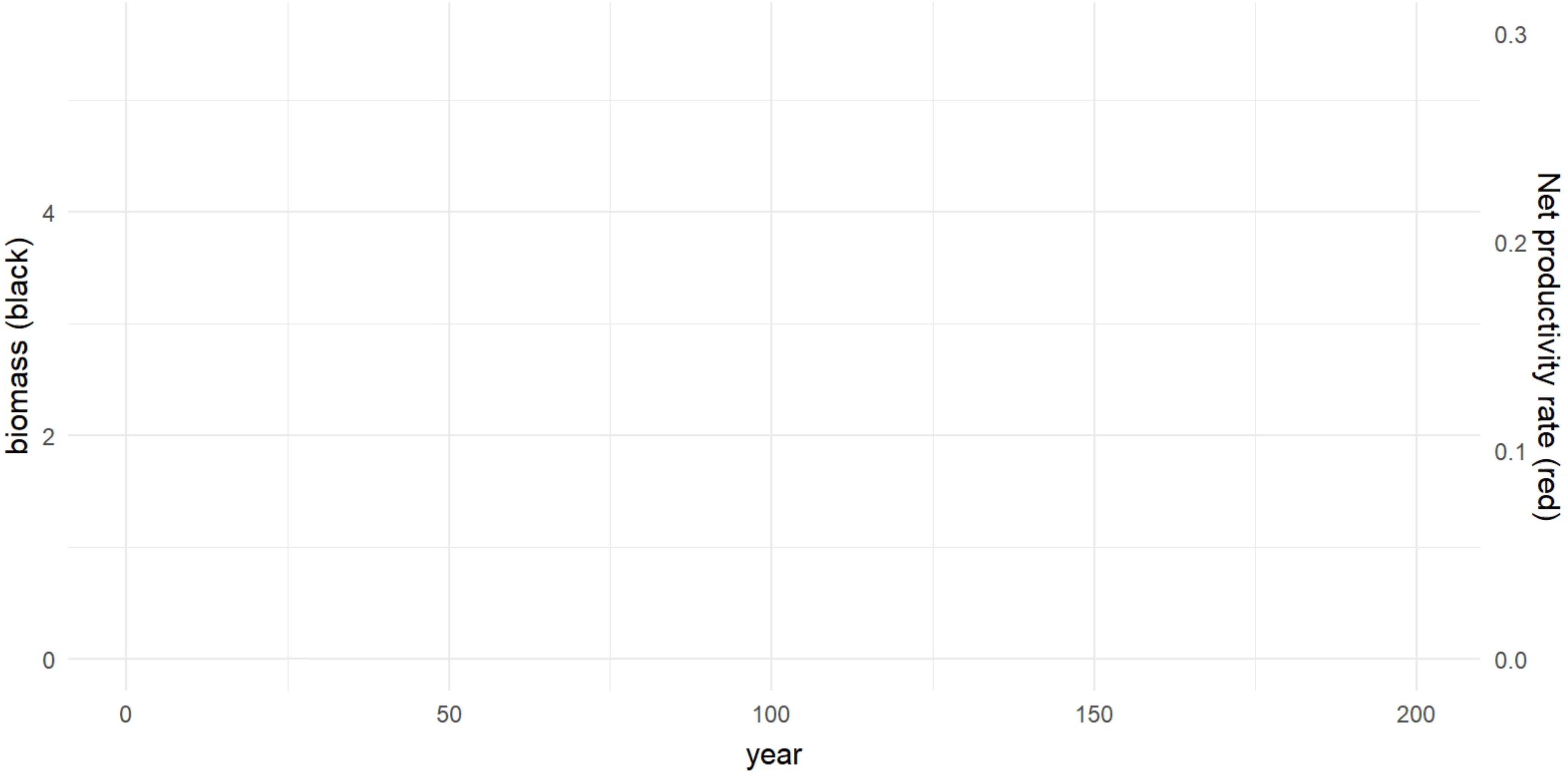
$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$$

- Where B is biomass, r is the intrinsic growth rate, C is catches and K is the carrying capacity (how much of that species the ecosystem can sustain)

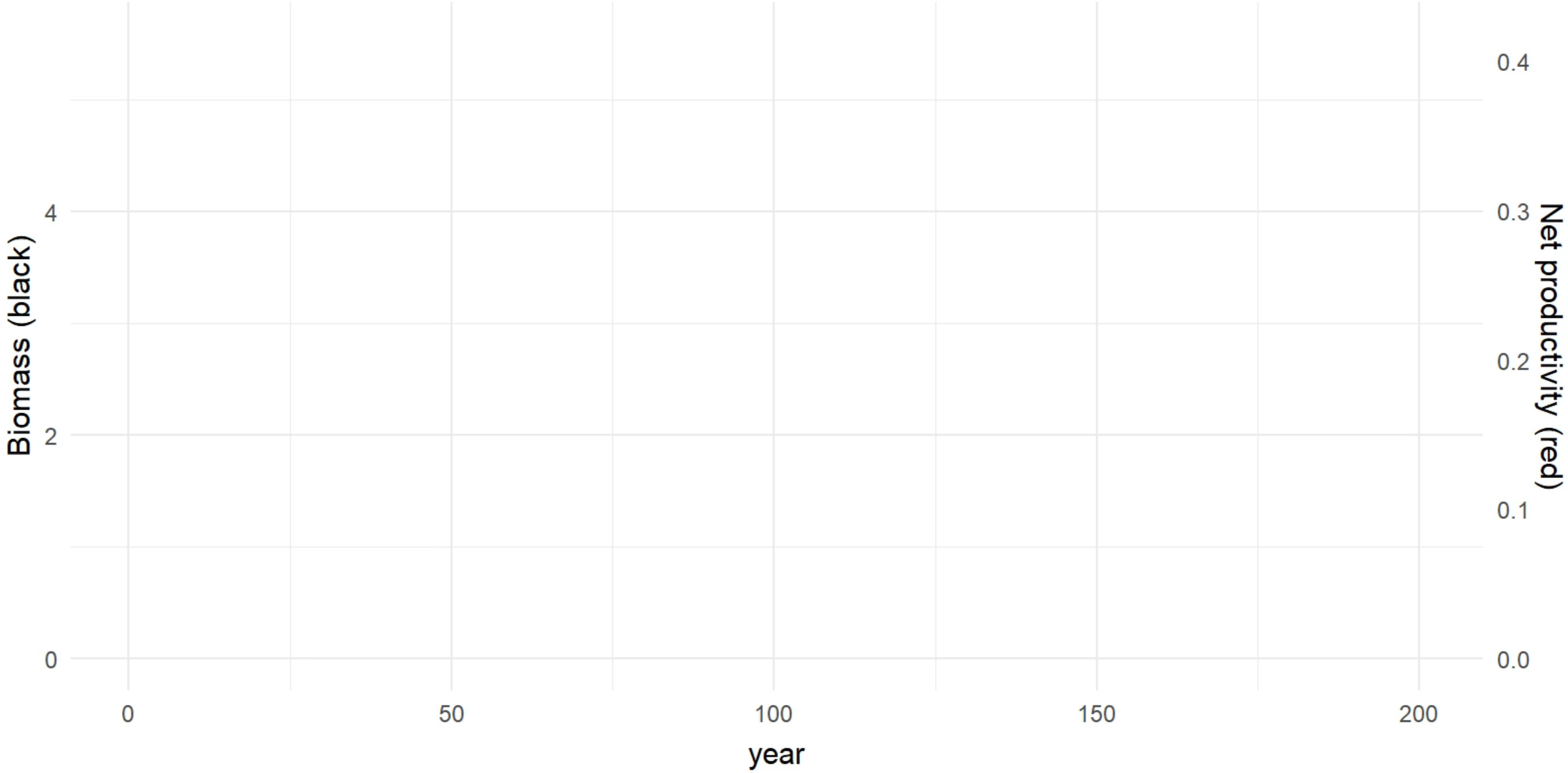
$K=5.6 \cdot 10^6$ tons, r=0.3, no catches, starting at 1 ton (cod)



At what rate is the population growing?



How much tons of cod is yielded each year?



Maximum sustainable yield

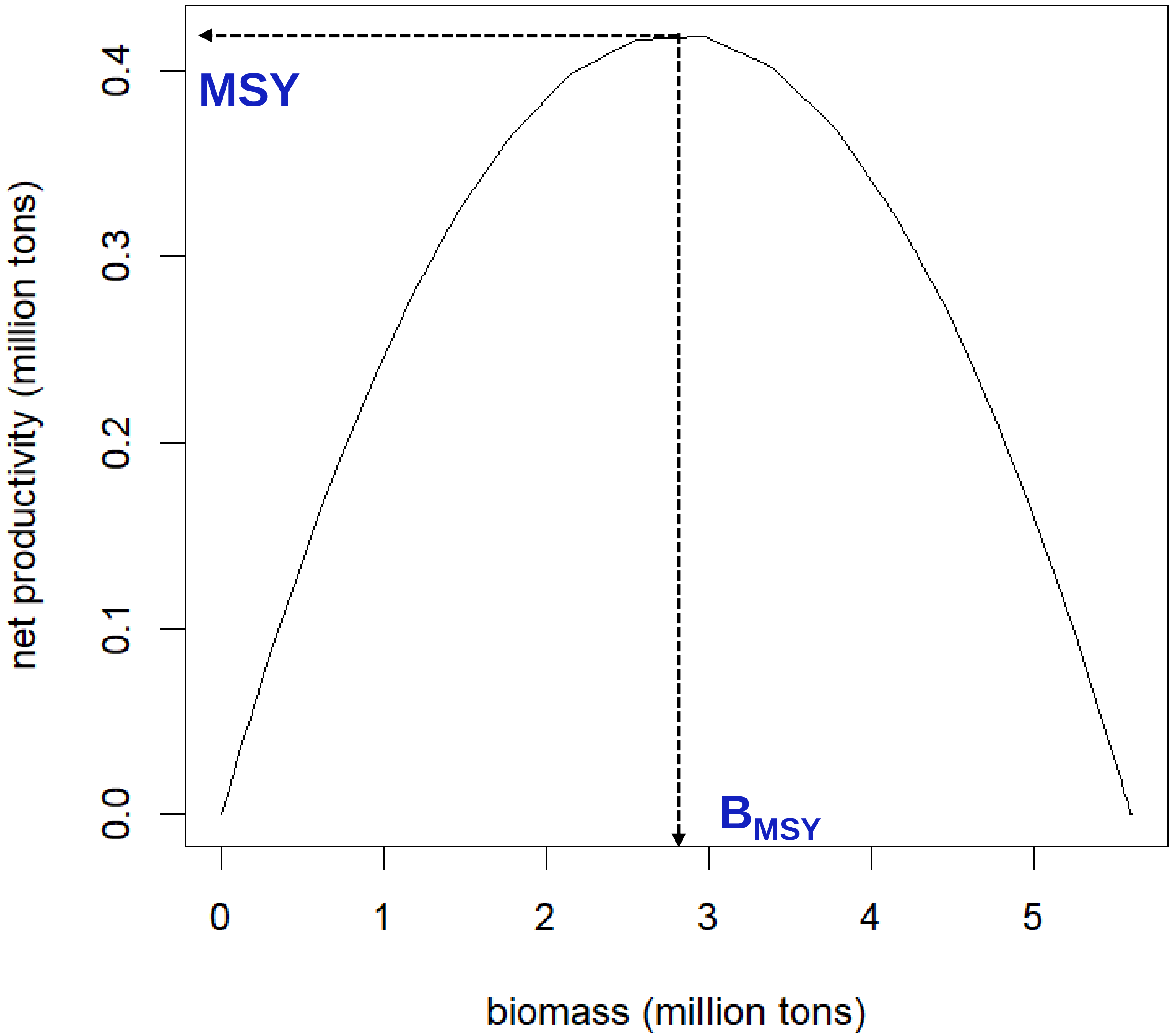
$B_{MSY} = K/2$

$MSY = rK/4$

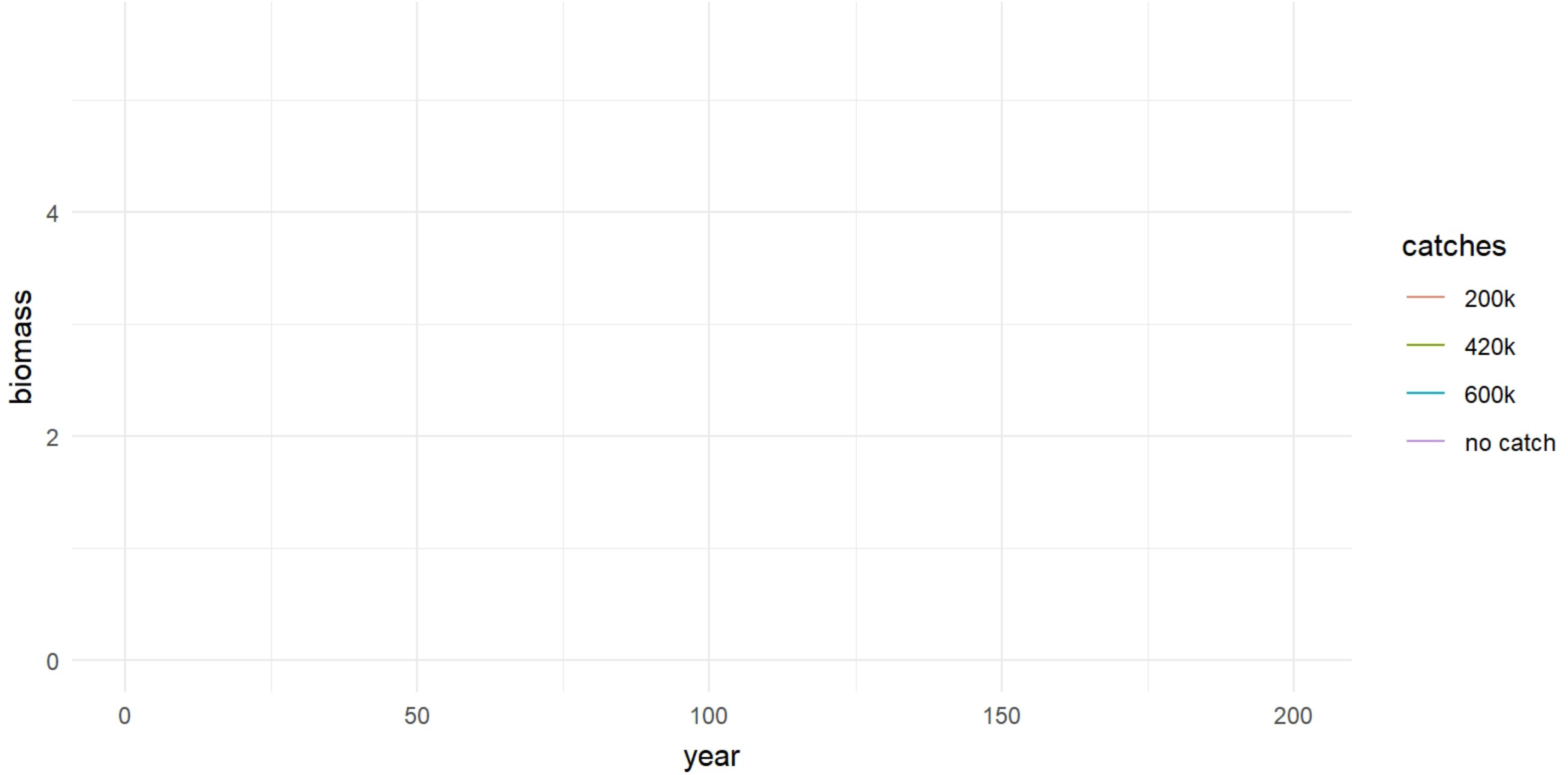
In the real world:

we don’t know r & K;

we have time series of catches and how much effort was needed to achieve them



So what happens around MSY? [catches start at 100 years]



Catch per unit effort

All things equal, catches should increase at the same rate I increase my effort:

$$C_t = qE_tB_t$$

So the catch per unit effort is related to biomass or abundance:

$$\frac{C_t}{E_t} = qB_t = \mathrm{CPUE}_t$$

This is the Schaefer model; we now know this is a lot more complicated, eg q (catchability coefficient) is rarely constant, exploited population equilibrium is complicated

One dimension in isolation of others

- Bioeconomics of catches (efficiency, supply/demand, quality)
  - associated with fuel consumption (and hence C footprint)
  - Gordon-Schaefer model

- Biodiversity footprint
  - Incidental catches, habitat deterioration
  - Multi-criteria approach

- Can I find the effort which will be profitable, have acceptable biodiversity footprint, and yield sufficient catches?

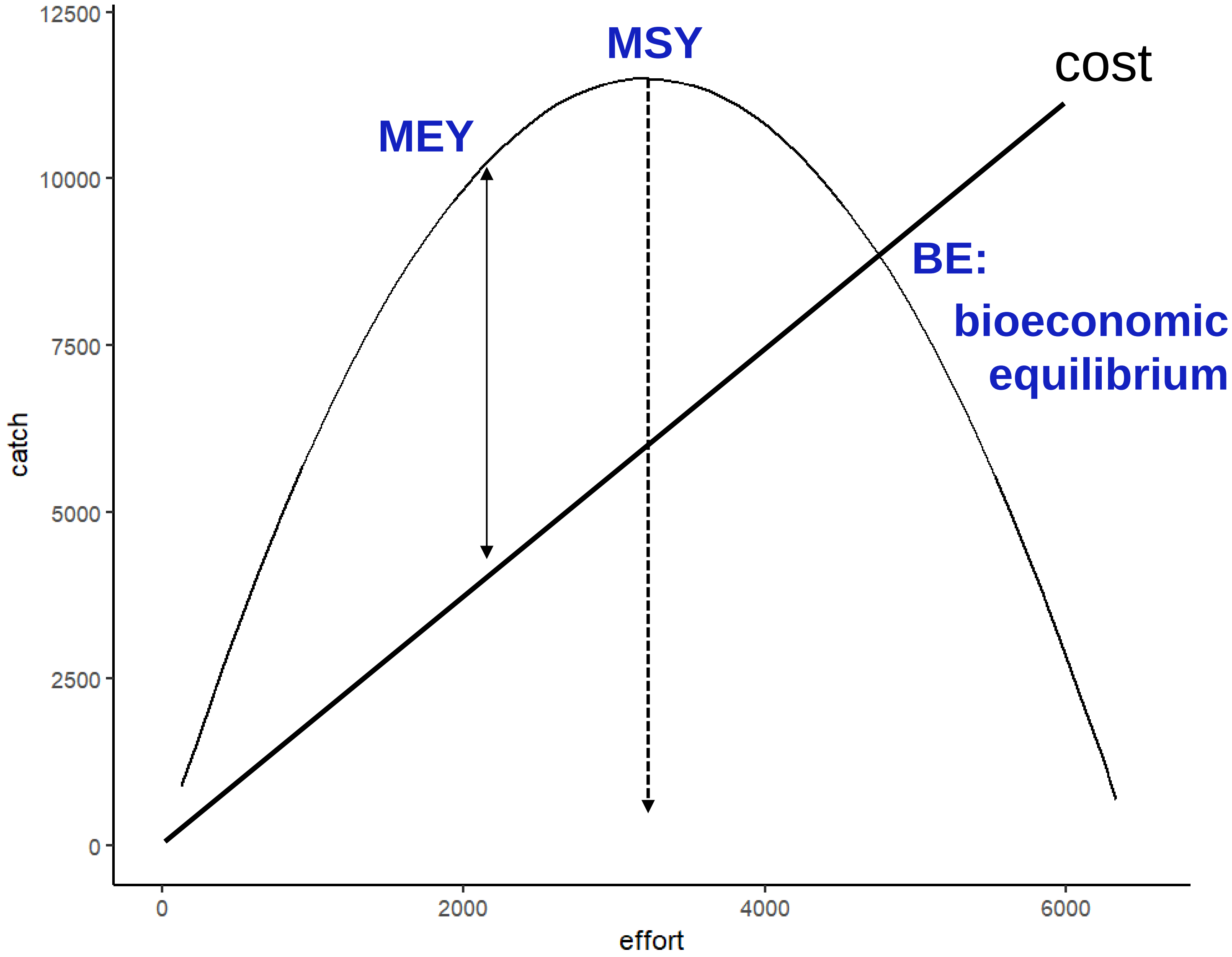
Gordon–Schaefer bioeconomic model

Revenue=aC-bE

Maximum Economic Yield < MSY

MEY can be > MSY

if there are external revenues (subsidies)



Biodiversity impact: bycatch

- There is a bycatch probability associated with fishing practices for varying sensitive and socially important species.

- Total bycatch is not optimised: an independent threshold is set to ensure conservation/restoration objectives are met

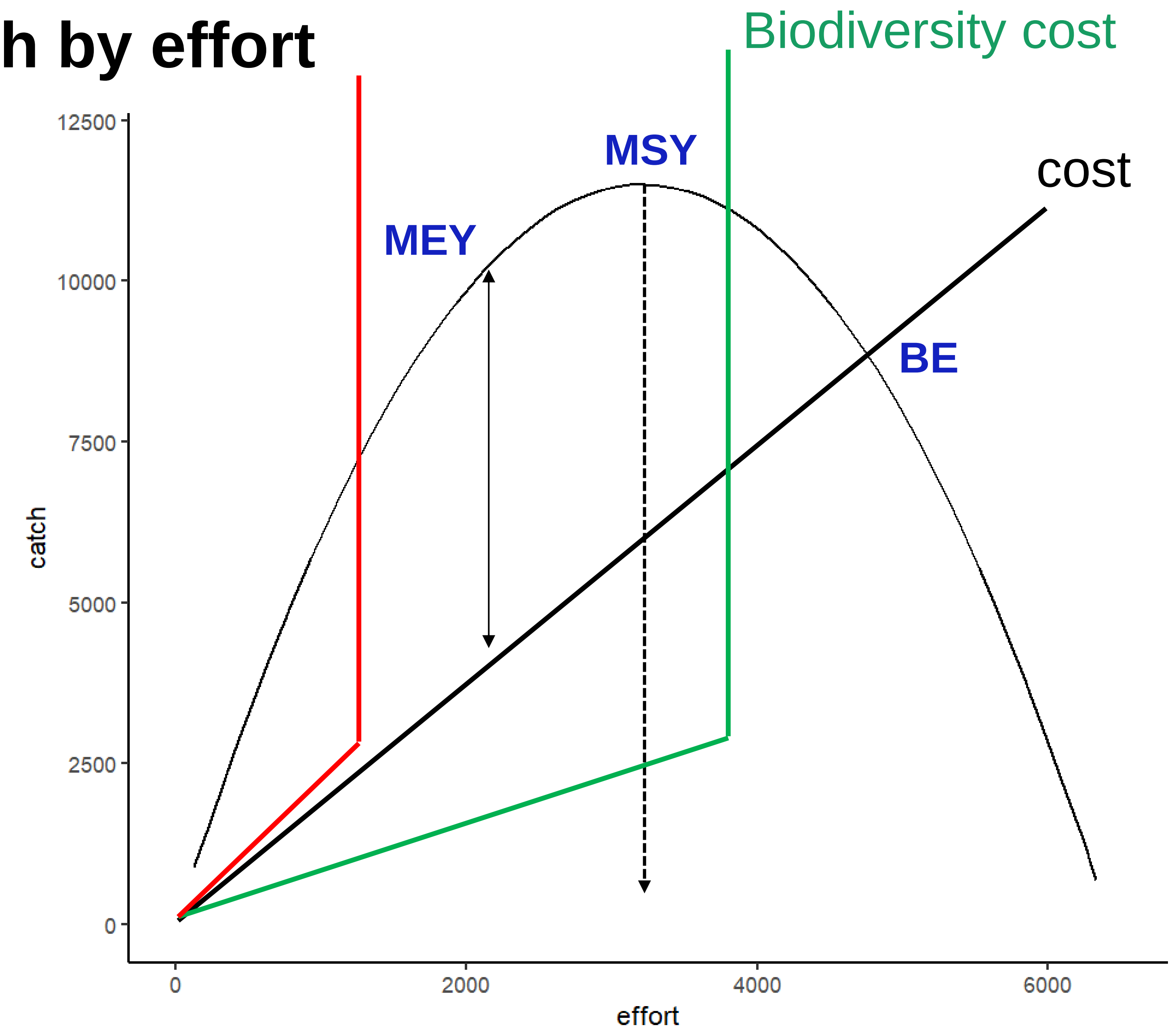
- Globally prevailing: Potential Biological Removal (PBR):
  - a la Schaefer model:
  - $PBR = N_{min} \times R_{\text{"MSY"}} \times F_r$

Incorporating in catch by effort

- Biodiversity cost is independent of MEY and MSY

- Biodiversity cost can be reduced with mitigation
    - mitigations are species dependent

    - mitigations can affect MSY and MEY



12100 Quantitative Sustainability

Resource Management

David Lusseau
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@lusseau

outline

- **Concepts**
  - Types of resources
  - Exploitation patterns
  - Tragedy of the commons
  - Ecosystem services and indirect effects

- **Applications**
  - Exploitation model
  - Introducing biodiversity trade-offs in exploitation patterns

- **Exercises**

Concepts

Natural resources

- Can the resource I exploit harness earth systems to make more of itself within a timeframe suitable for my exploitation?

- No: **Non-renewable resource**
  - Minerals, oil, gas

- Yes: **Renewable resource**
  - Soil, plants, animals, water, wind

Exploitation types

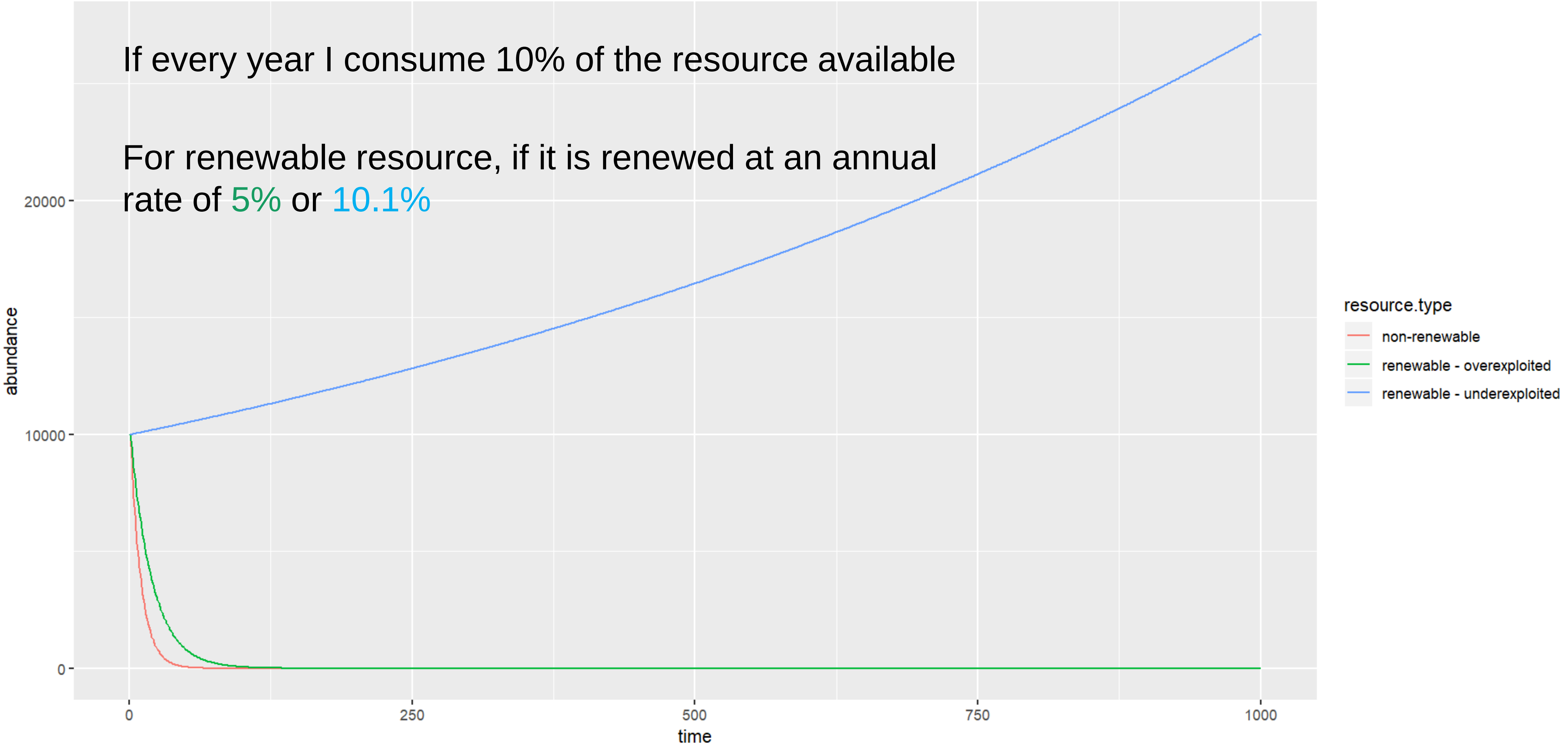
- Do we extract resources or use products generated by resources
  - **Consumptive, non-consumptive**

- When using products generated by resources, do we impair resource renewing when doing so?
  - Consumptive?

What does this mean?

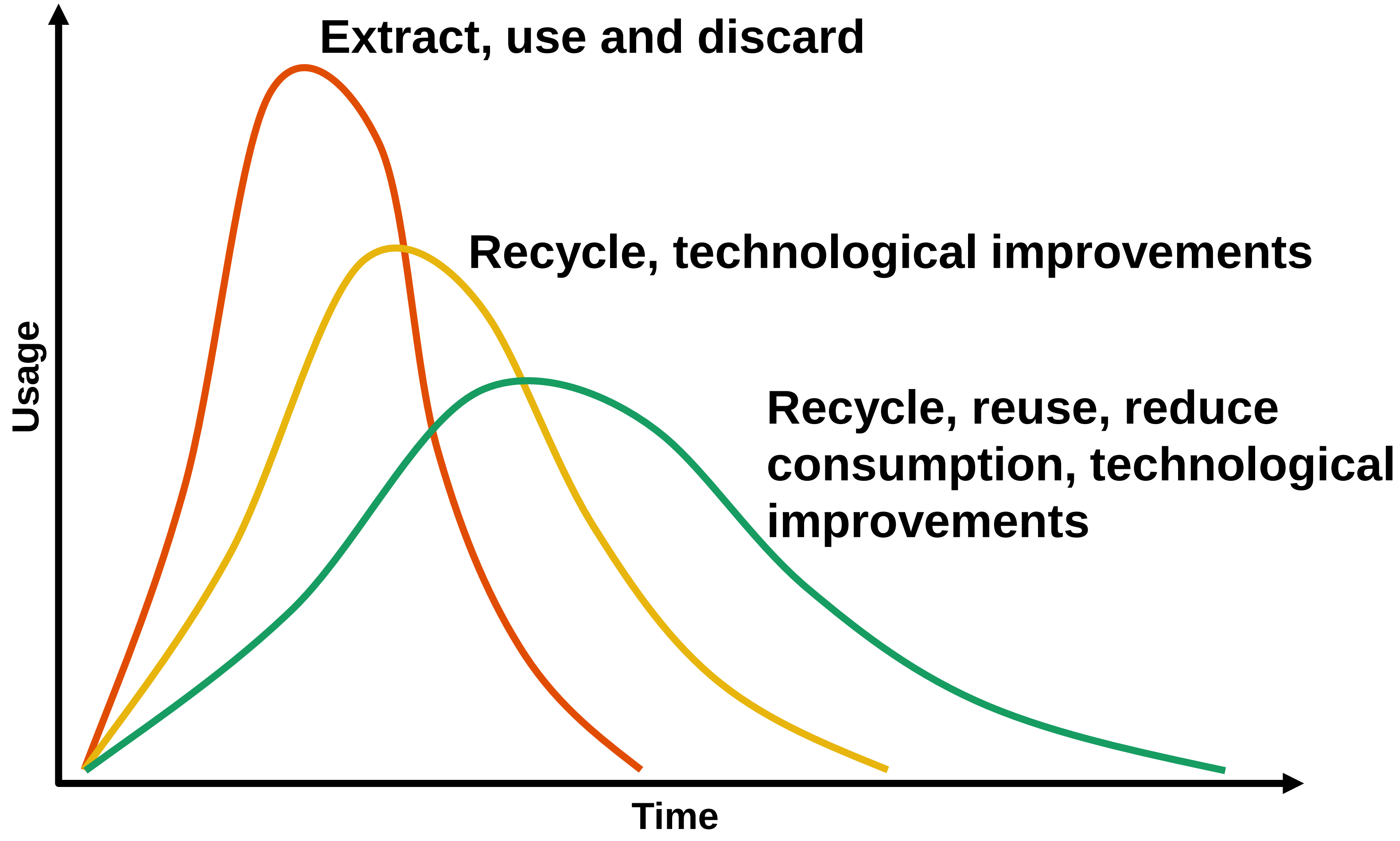
If every year I consume 10% of the resource available

For renewable resource, if it is renewed at an annual rate of 5% or 10.1%



Non-renewable resource use pattern

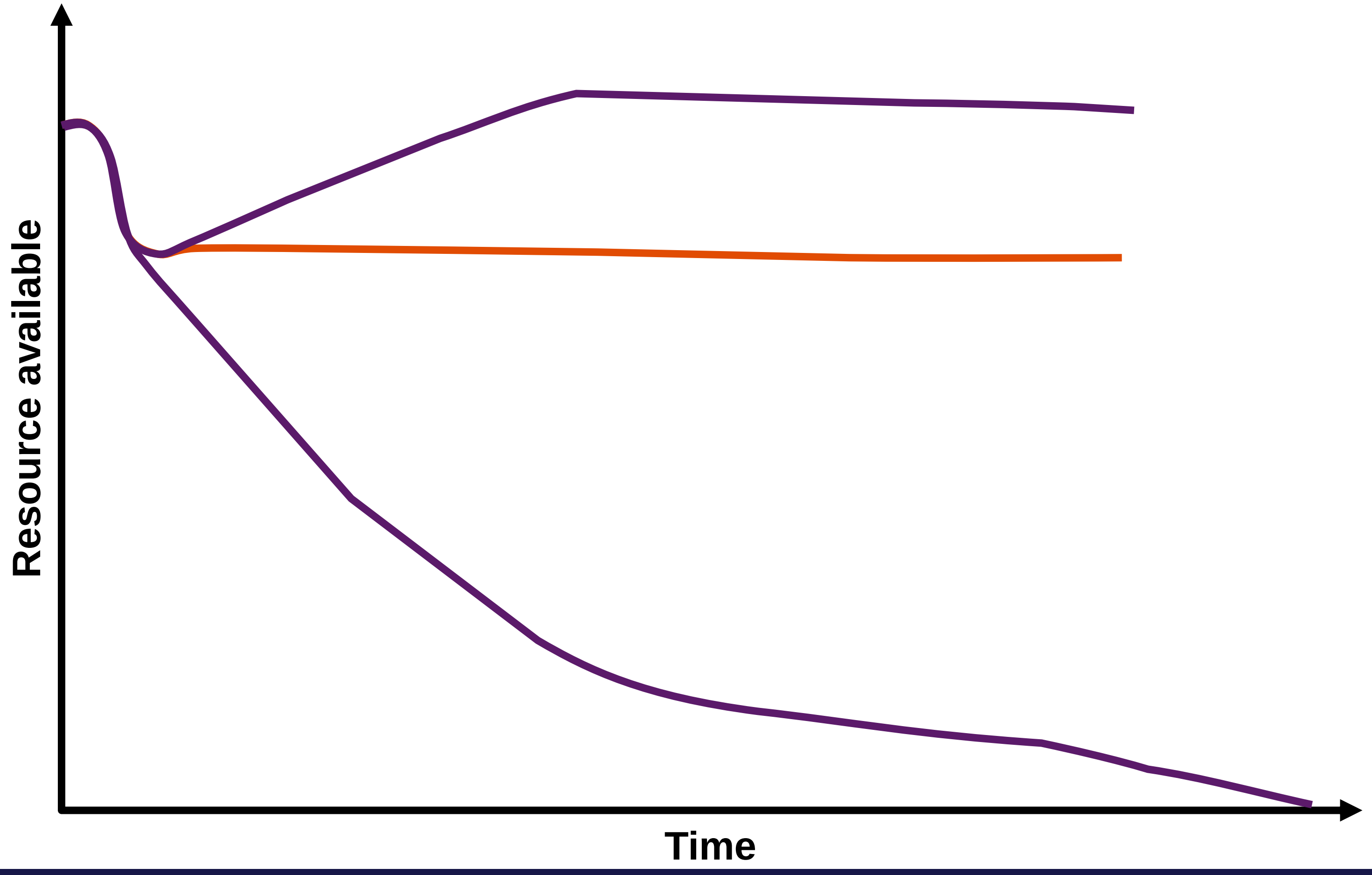
Adoption → demand peak → transition/abandonment



Renewable resource use pattern

Adoption → demand peak → transition/abandonment

Adoption → demand peak → sustained



Sustainability of exploitation

- Ability to manage depends on:
  - Whether extractions by one actor will diminish ability to extract by another
  - Actors can be excluded from extraction

Resource types

	Excludable	Non-excludable
Rivalrous	Private good	Common good
Non-rivalrous	Club good	Public good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

Private good

- Competitors can be prevented to access the resource (private property rights can be assigned)
- use of that good (consumption) prevent others to use it
- e.g. parking space, bread, a field

Club good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

- Property rights can be assigned
- Using that good does not prevent others to use it
- Eg, a cinema, alliance/club/union (services provided to members excluding non-members), a private nature park

Public good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

- Access cannot be restricted
- The use of the resource does not prevent others from using it
- E.g., knowledge, streetlights, public park

Common good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

- Short for common-pool resource
- Access cannot be restricted
- The use of the resource prevent others from using it
- E.g., fish stocks, but also… public park
  - If the use of a natural place degrades it, then some of its use is prevented by the use of others.


SHOCK DISCLOSURE. BEAR ADMITS POSING AS A FOX.

THE GUARDIAN

Printed in Manchester and London

Wednesday June 2 1976

10p

Crosland nets £3M defeat in cod war

From Mark Goldsmith in Oslo and Patrick Keatley in London

FISHING INDUSTRY

Pound sinks to new low

Action on SA sales

Yard may lose tanker order

By JOHN CARVEL

Oceans: a unique global challenge

- Primary production is not spatially fixed
- We can’t put fences around most renewable resources

Regulating and Cultural Ecosystem Services

- Degrading common resources affect the ability for others to extract benefits from them

Geography Compass 1/4 (2007): 850–870, 10.1111/j.1749-8198.2007.00048.x

Call It Consumption! Re-Conceptualizing Ecotourism as Consumption and Consumptive

Zoë A. Meletis* and Lisa M. Campbell
Nicholas School of the Environment and Earth Sciences, Duke University

Tragedy of the Commons

- 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

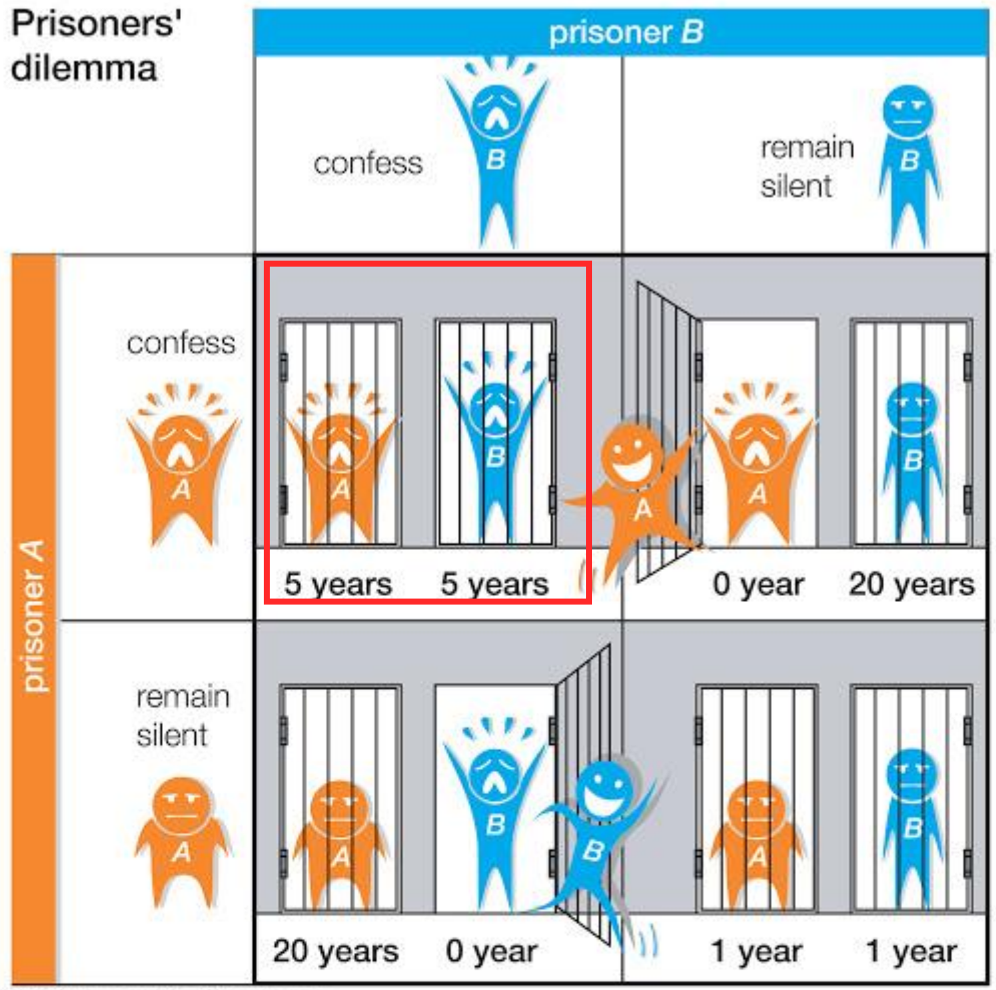
- Without interventions – recall exclusion interventions are not possible – it will always be beneficial to defect

- Leads to a race to the bottom and resource collapse

ToC game theory: Prisoner's dilemma

Decision consequences

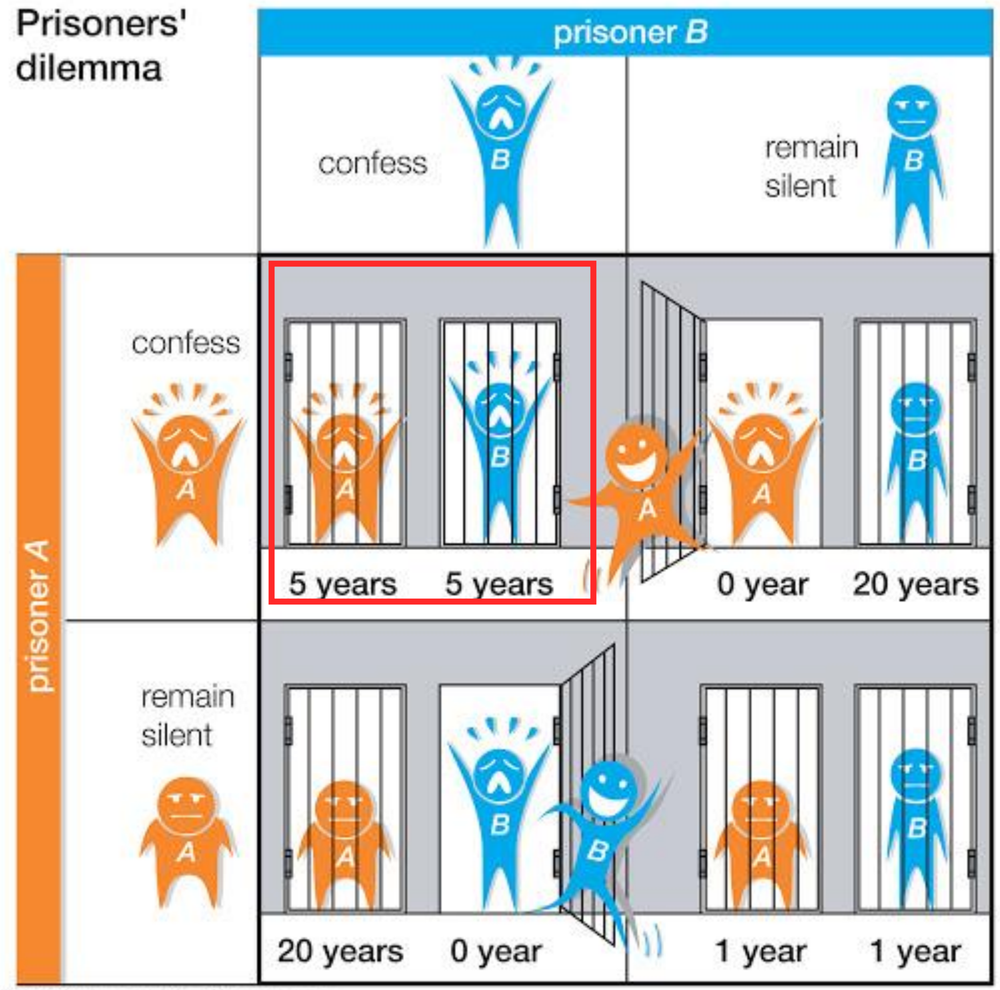
- both confess, both go to jail for five years;
- neither confesses, both go to jail for 1 year (concealed weapons);
- one confesses & the other not, confessor is free (witness) and the silent one is jailed 20 years.



ToC game theory: Prisoner’s dilemma

• *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



ToC - fixes

- Assign property rights!
  - Then common goods become private [/club] goods (e.g., quotas)
    - European “common policies” approach: common to club goods
  - (this is still a failure of common good governance)
- Can we actually sustain common goods exploitation?

summary

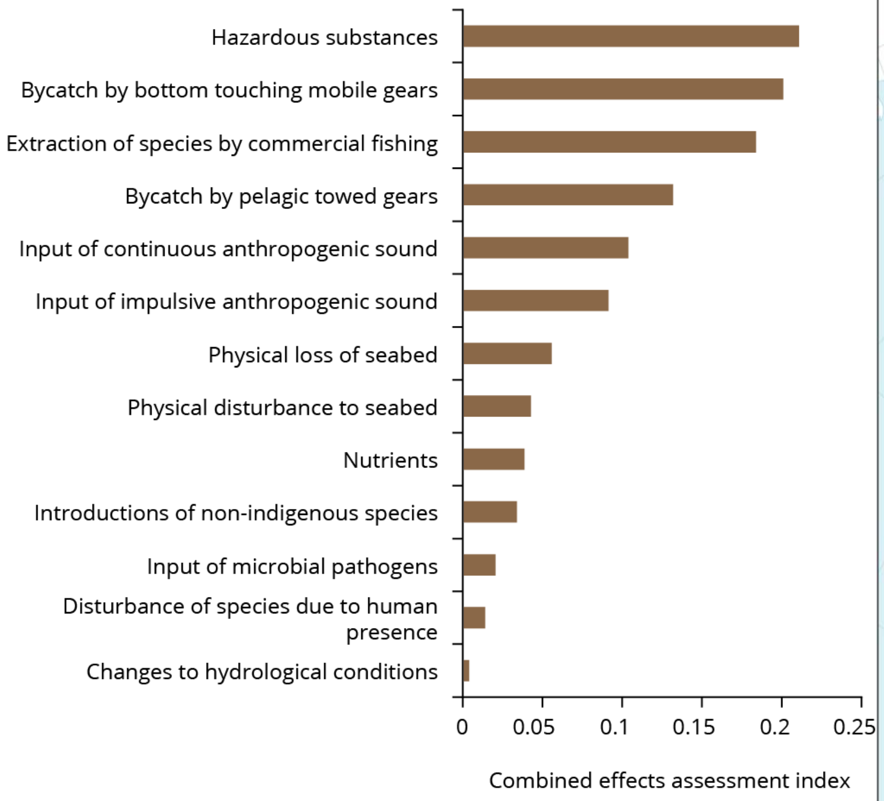
- Renewable natural resources lead to different exploitation patterns because they need not become exhausted.

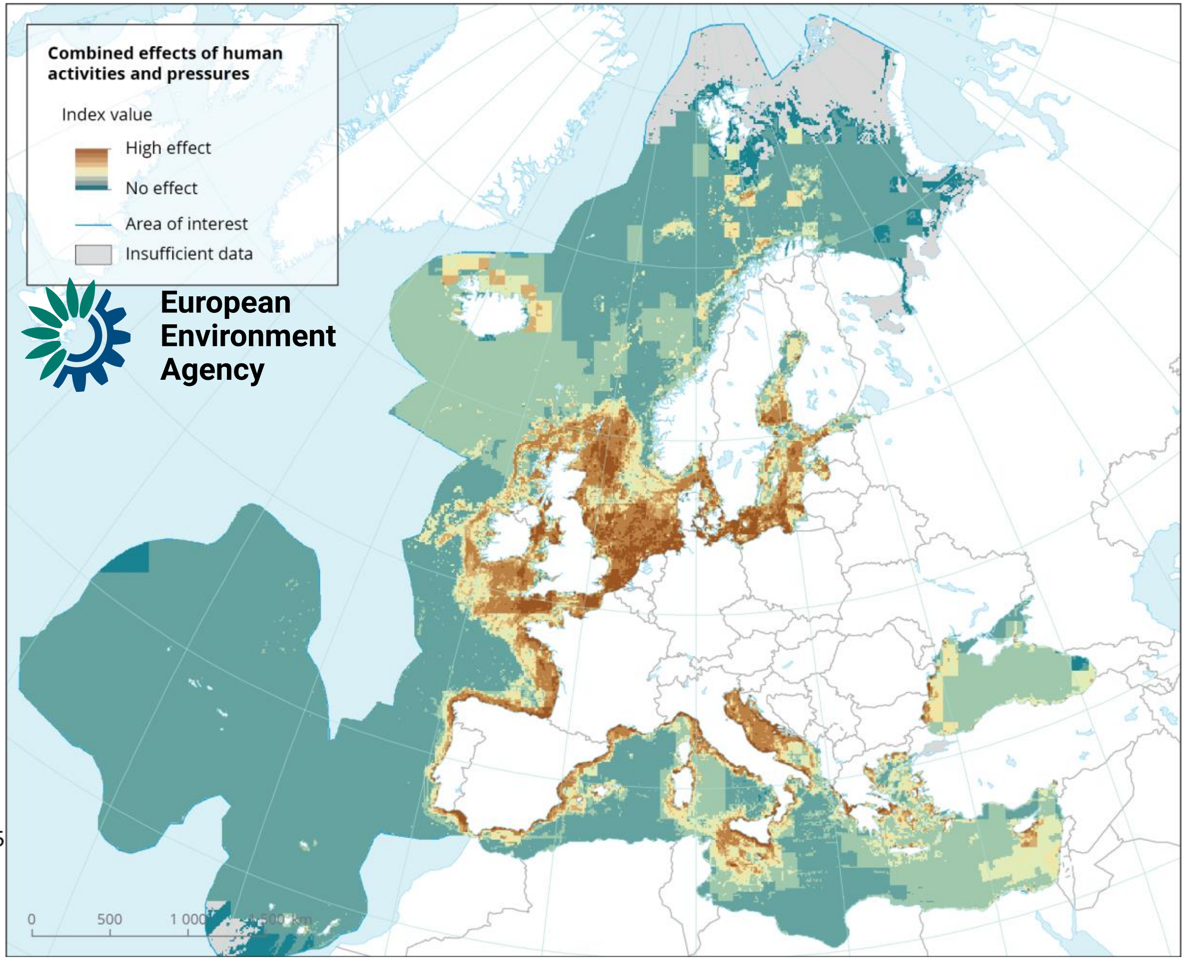
- Our means and abilities to govern resource exploitation depends on whether people can be excluded from its exploitation and whether resource use by some diminish resource use opportunities for others

- Common goods are complex to govern, unfortunately most regulating and cultural ecosystem services are common goods.

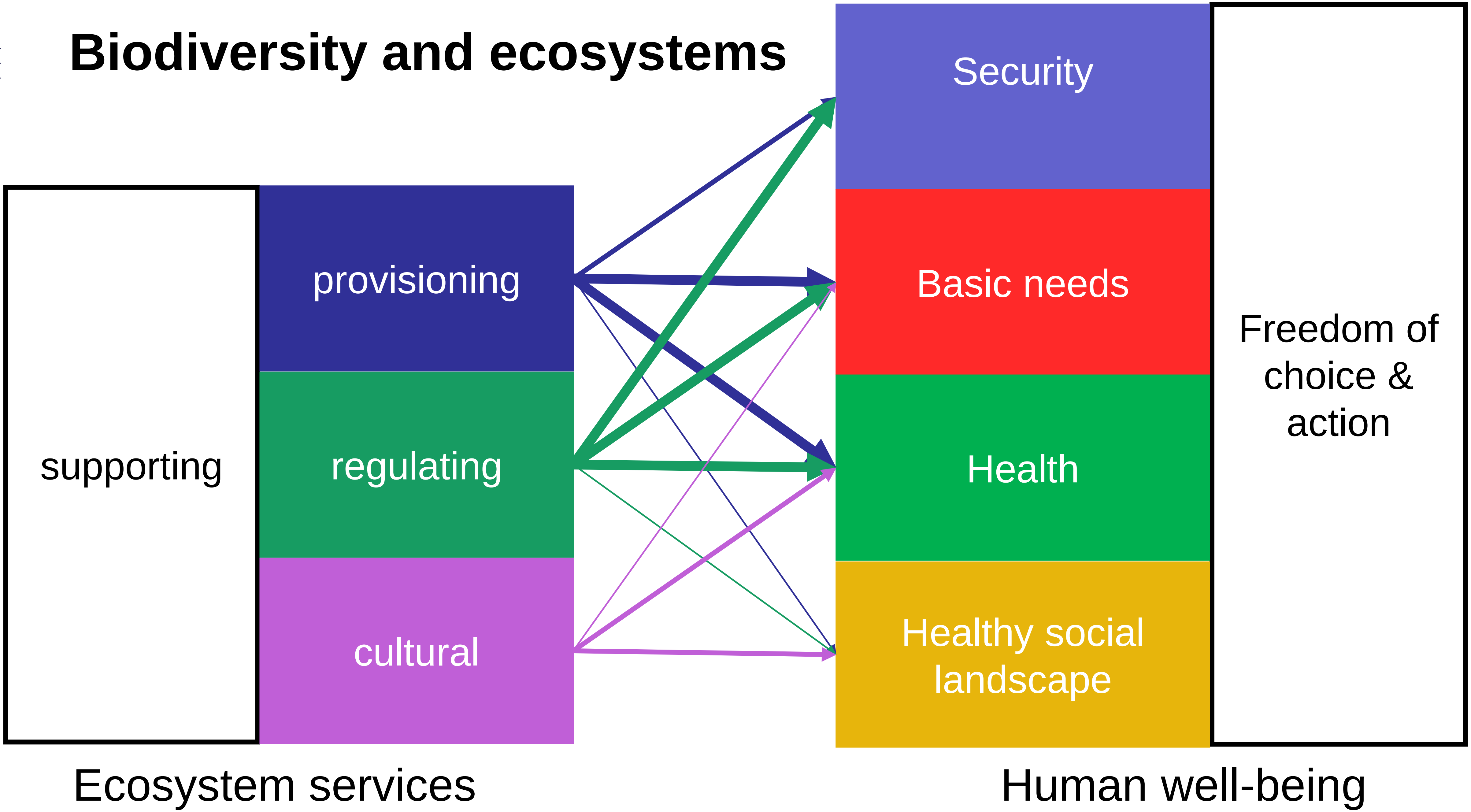
Indirect use of resources

- Our activities can impose pressures on resources which are not the source of exploitation
  - Climate
  - Air pollution
  - Biodiversity
  - Habitat



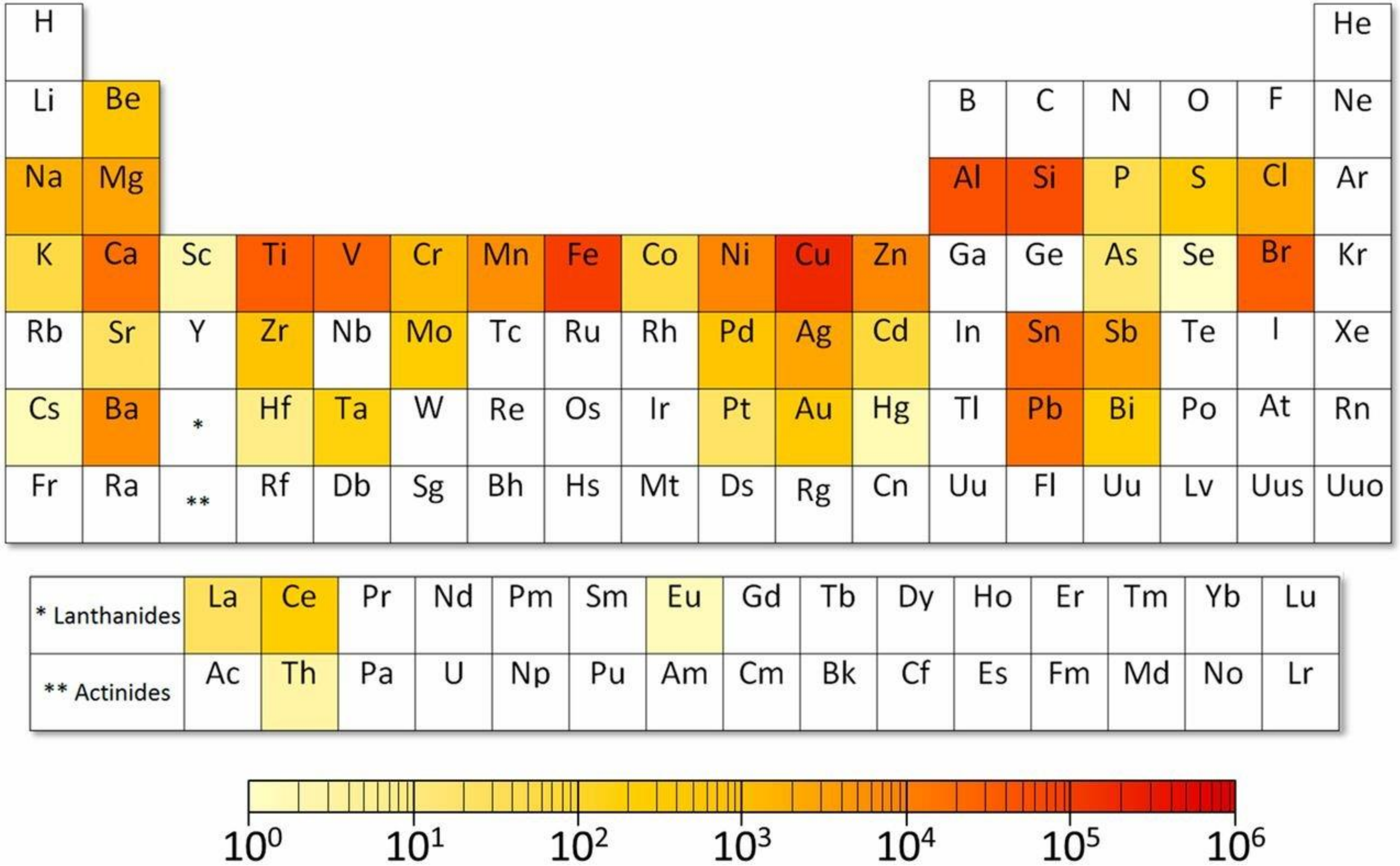


Biodiversity and ecosystems



Millennium Ecosystem Assessment 2005

applications

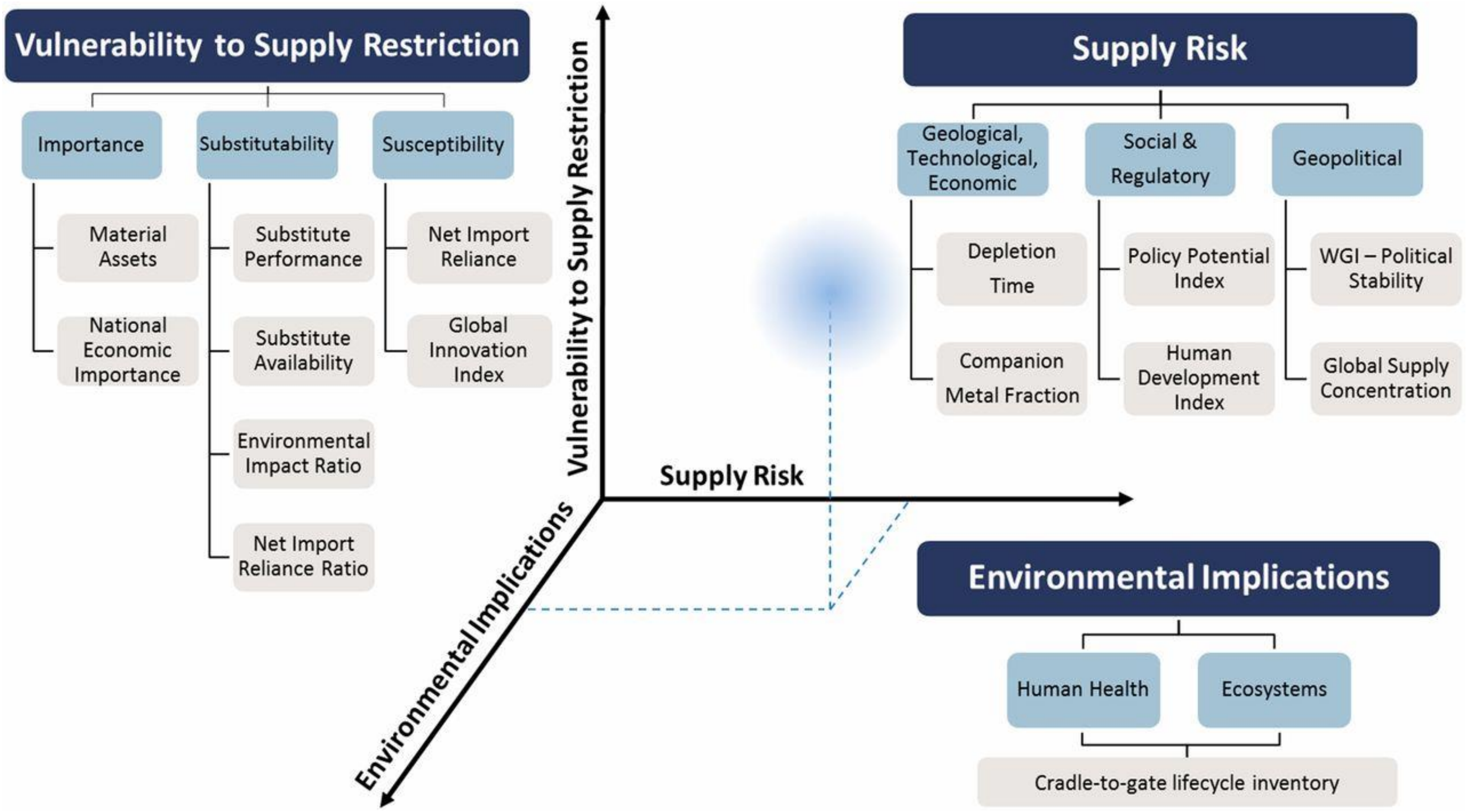


Concentration (ppm) of 44 elements found on circuit boards

(Graedel et al. 2015 PNAS)

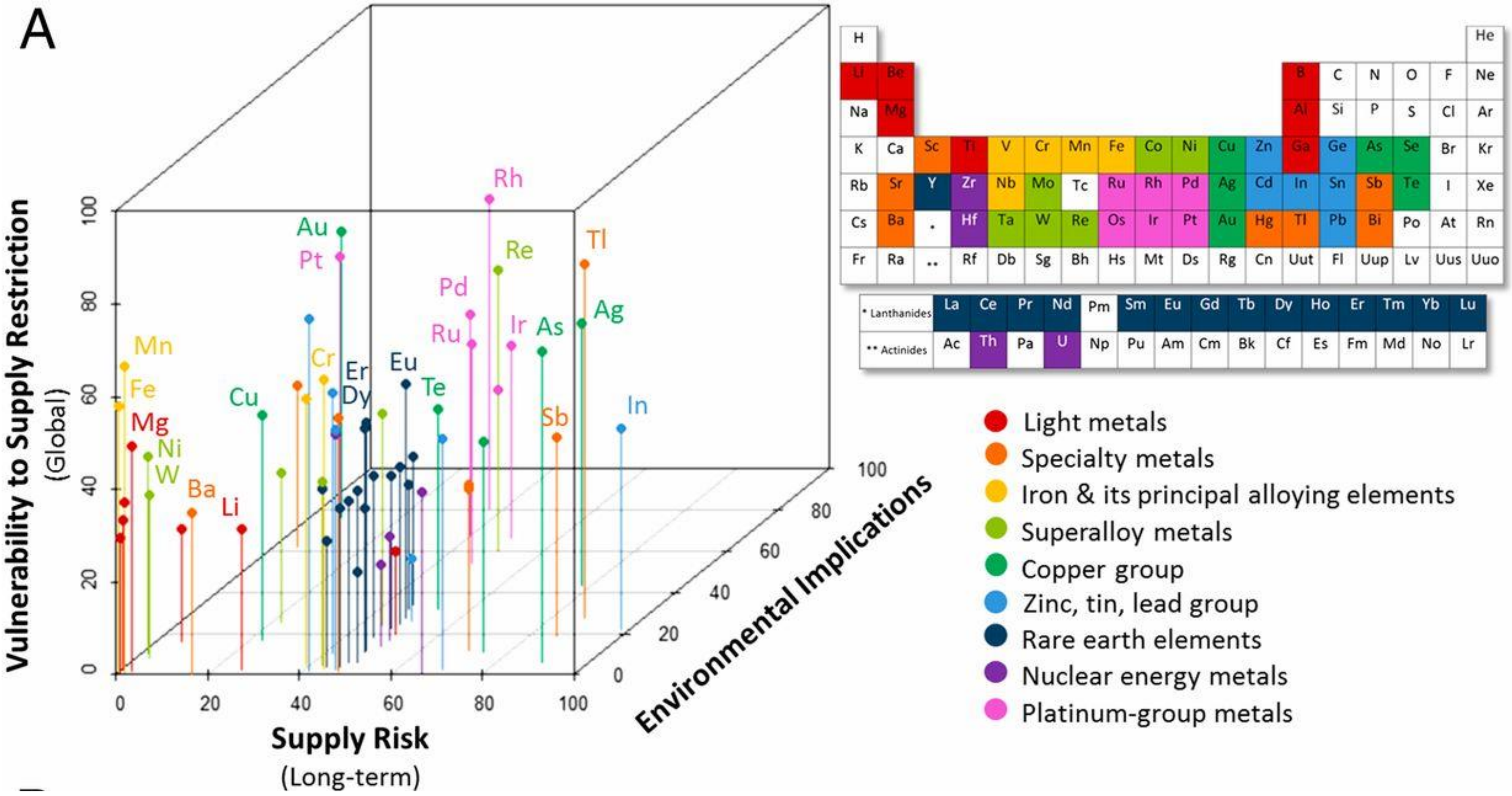
Criticality analysis

Metal criticality: risk appraisal



Graedel et al. 2015 PNAS; Graedel et al. 2012 Env Sci Tech

Criticality outcomes



Graedel et al. 2015 PNAS; Graedel et al. 2012 Env Sci Tech

Fisheries example – including trade-offs

Measuring maximum sustainable yield

Population model

- Principles described are applicable to all renewable resources

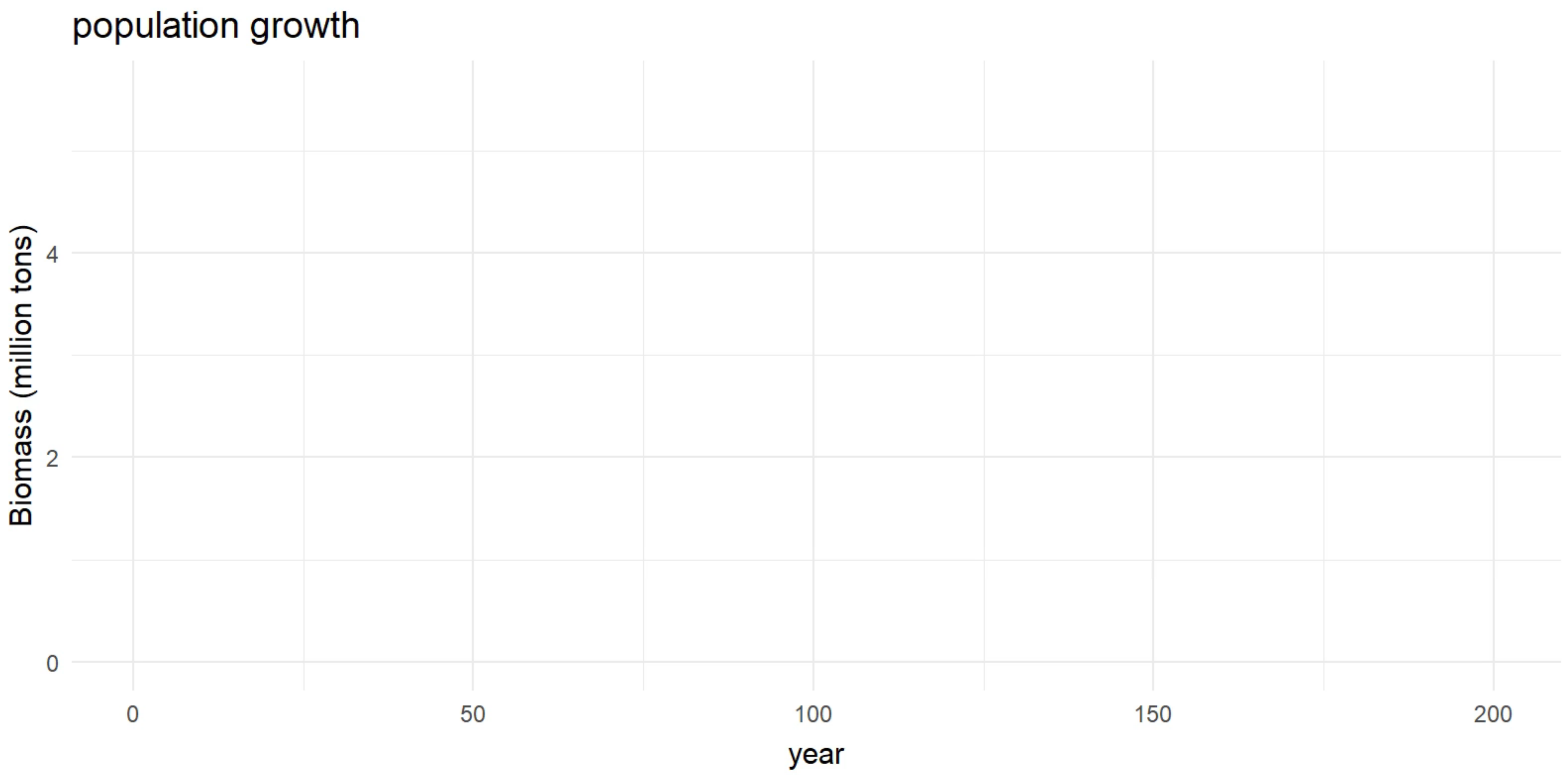
- Let's formulate an equation describing the rate at which a resource renews itself

- $B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$

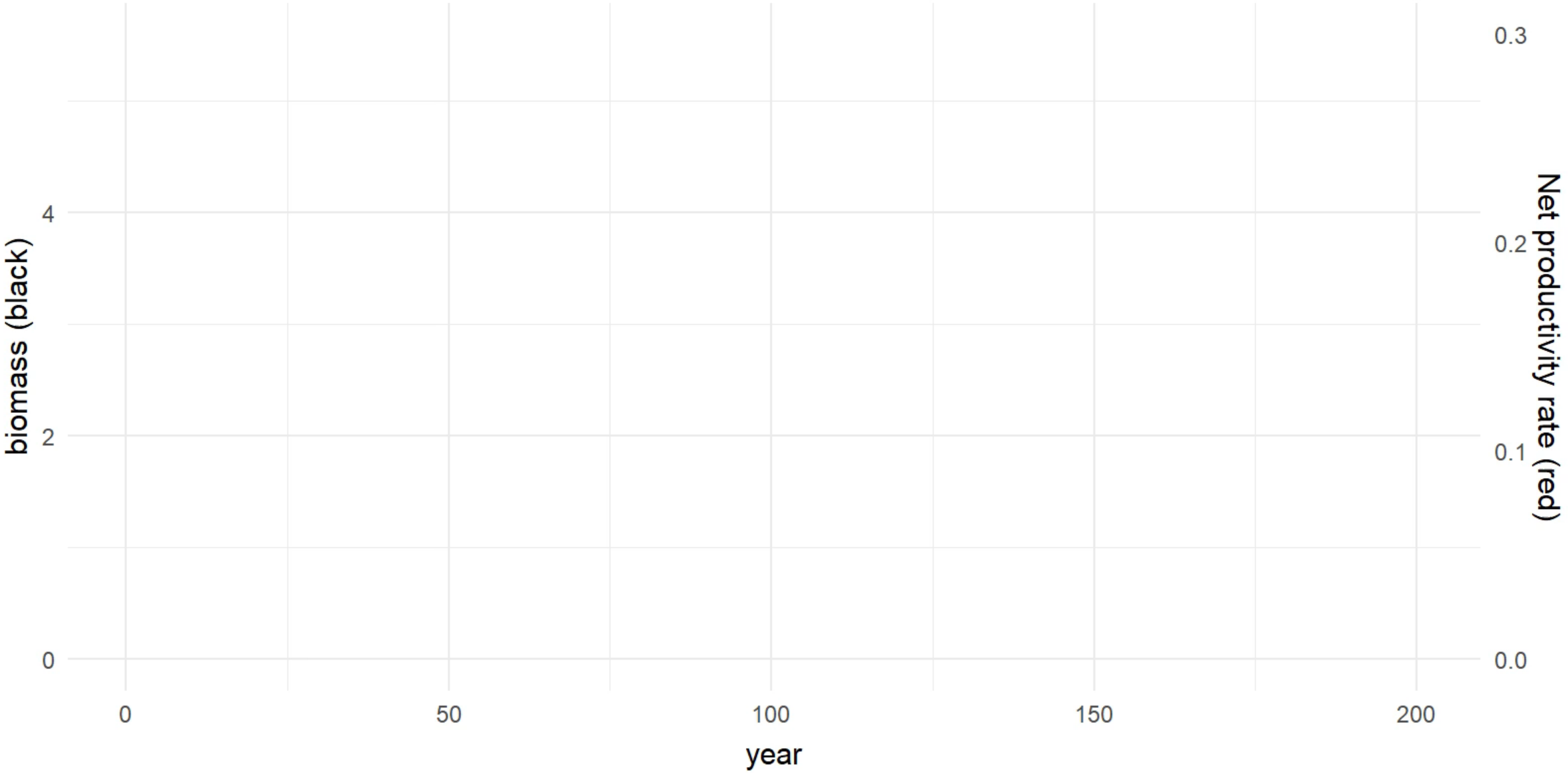
- Where B is biomass, r is the intrinsic growth rate, C is catches and K is the carrying capacity (how much of that species the ecosystem can sustain)

- What does this look like?

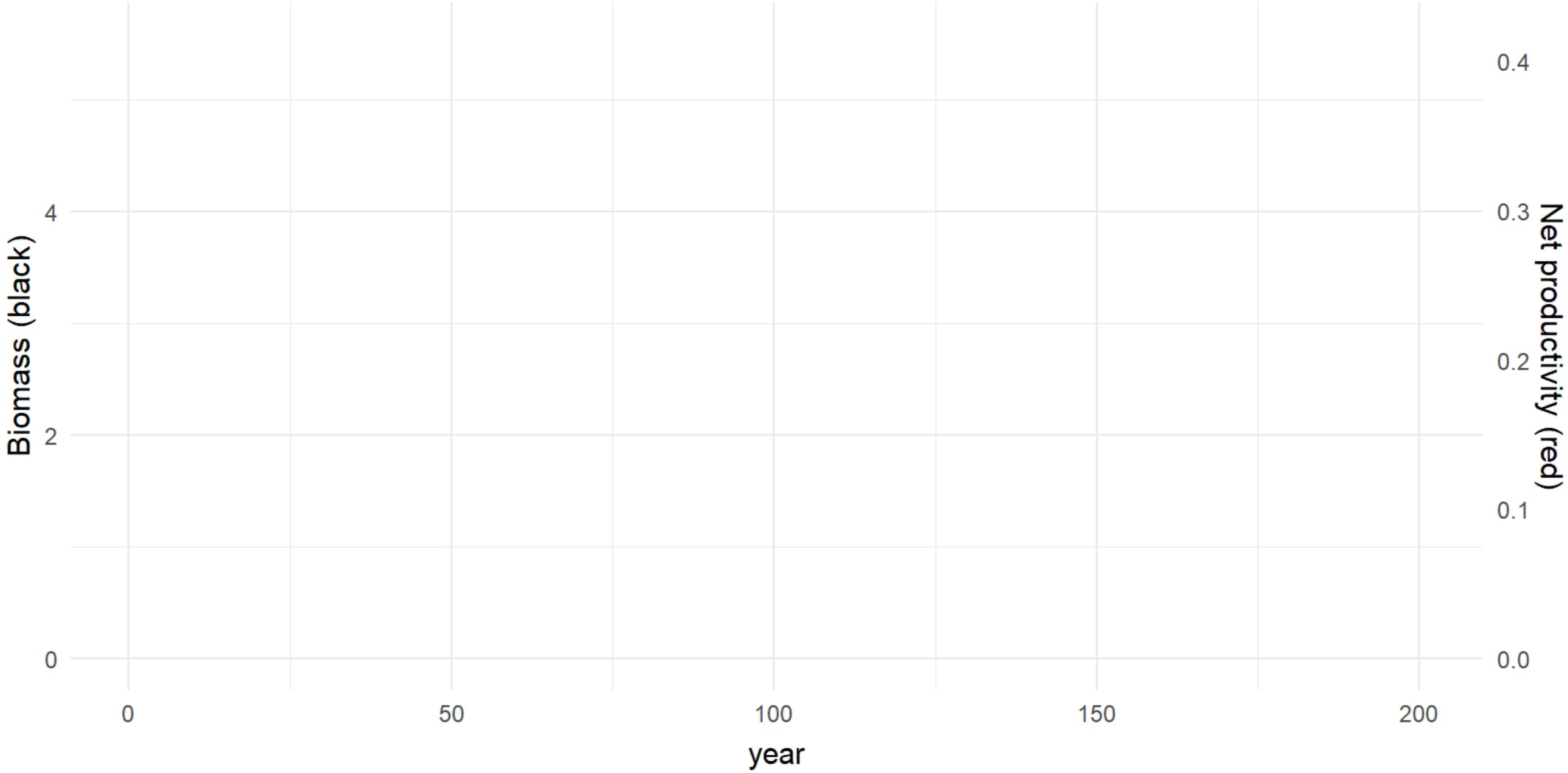
$K=5.6 \cdot 10^6$ tons, r=0.3, no catches, starting at 1 ton (cod)



At what rate is the population growing?



How much tons of cod is yielded each year?



Maximum sustainable yield

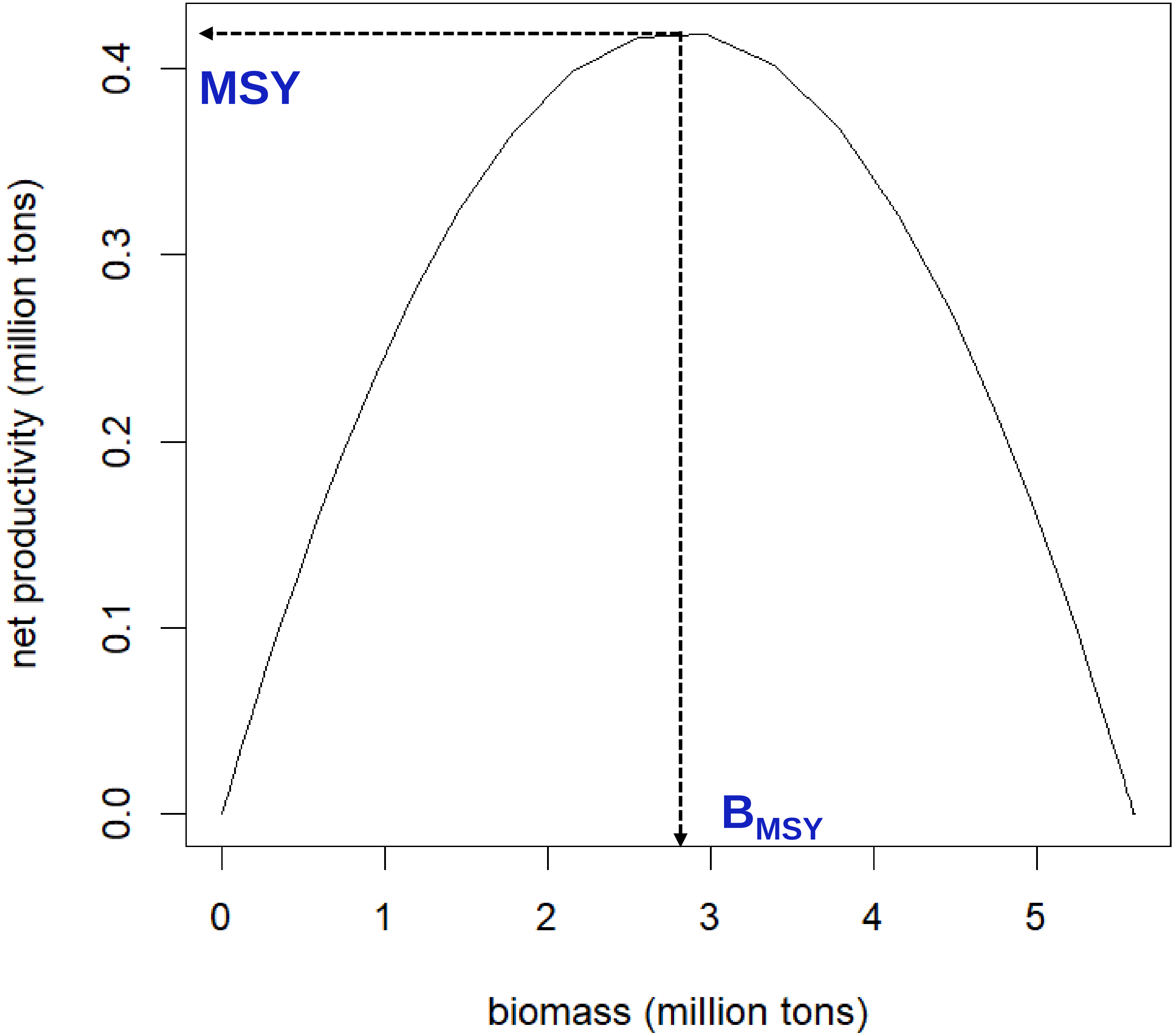
$B_{MSY} = K/2$

$MSY = rK/4$

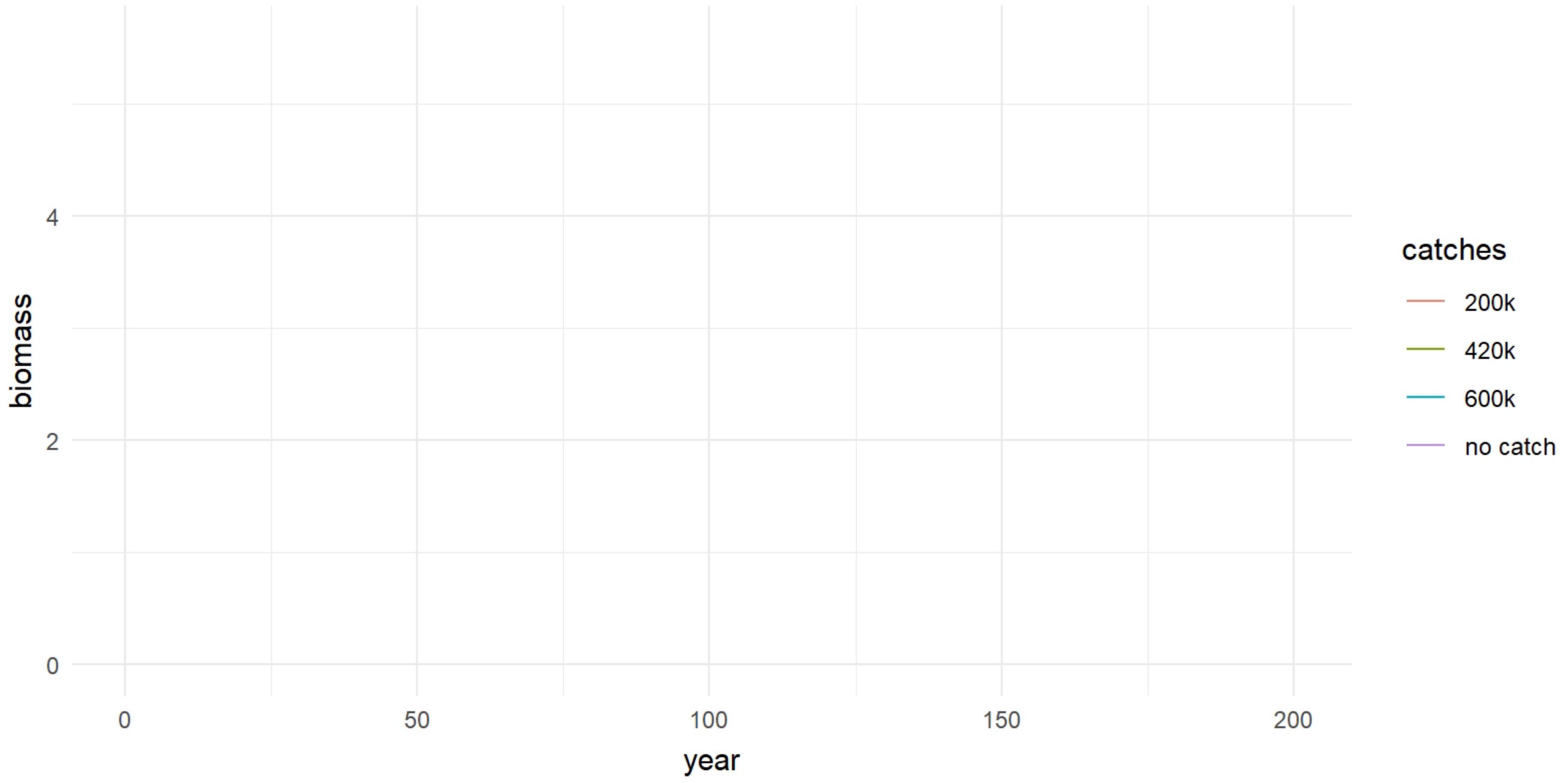
In the real world:

we don't know r & K;

we have time series of catches and how much effort was needed to achieve them



So what happens around MSY? [catches start at 100 years]



Catch per unit effort

All things equal, catches should increase at the same rate I increase my effort:

$$C_t = qE_tB_t$$

So the catch per unit effort is related to biomass or abundance:

$$\frac{C_t}{E_t} = qB_t = \text{CPUE}_t$$

This is the Schaefer model; we now know this is a lot more complicated, eg q (catchability coefficient) is rarely constant, exploited population equilibrium is complicated

at equilibrium, we remove all the growth and growth=0

$$\frac{dB}{dt} = rB_t\left(1 - \frac{B_t}{K}\right) - C_t = 0$$

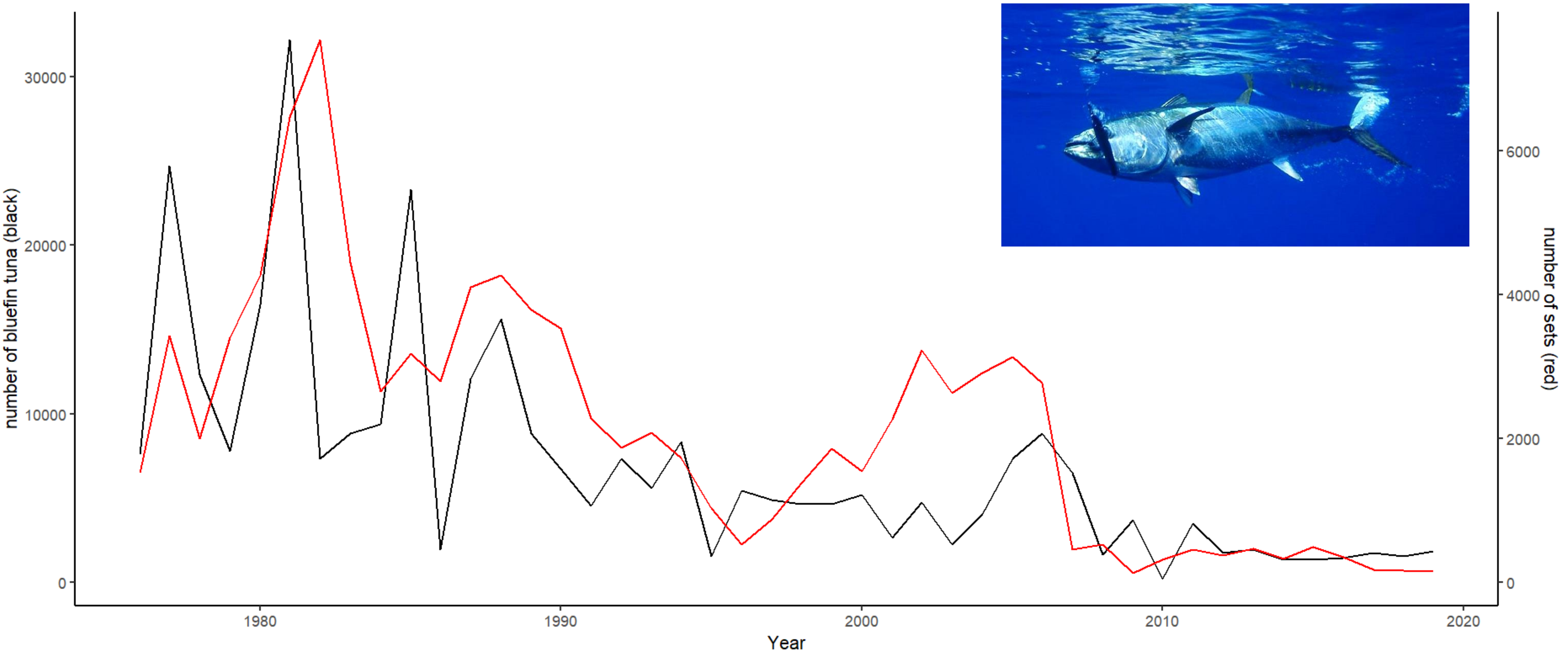
$$B_t = \frac{CPUE_t}{q}$$

$$C_t = r\frac{CPUE_t}{q}(1 - \frac{CPUE_t}{CPUE_{max}})$$

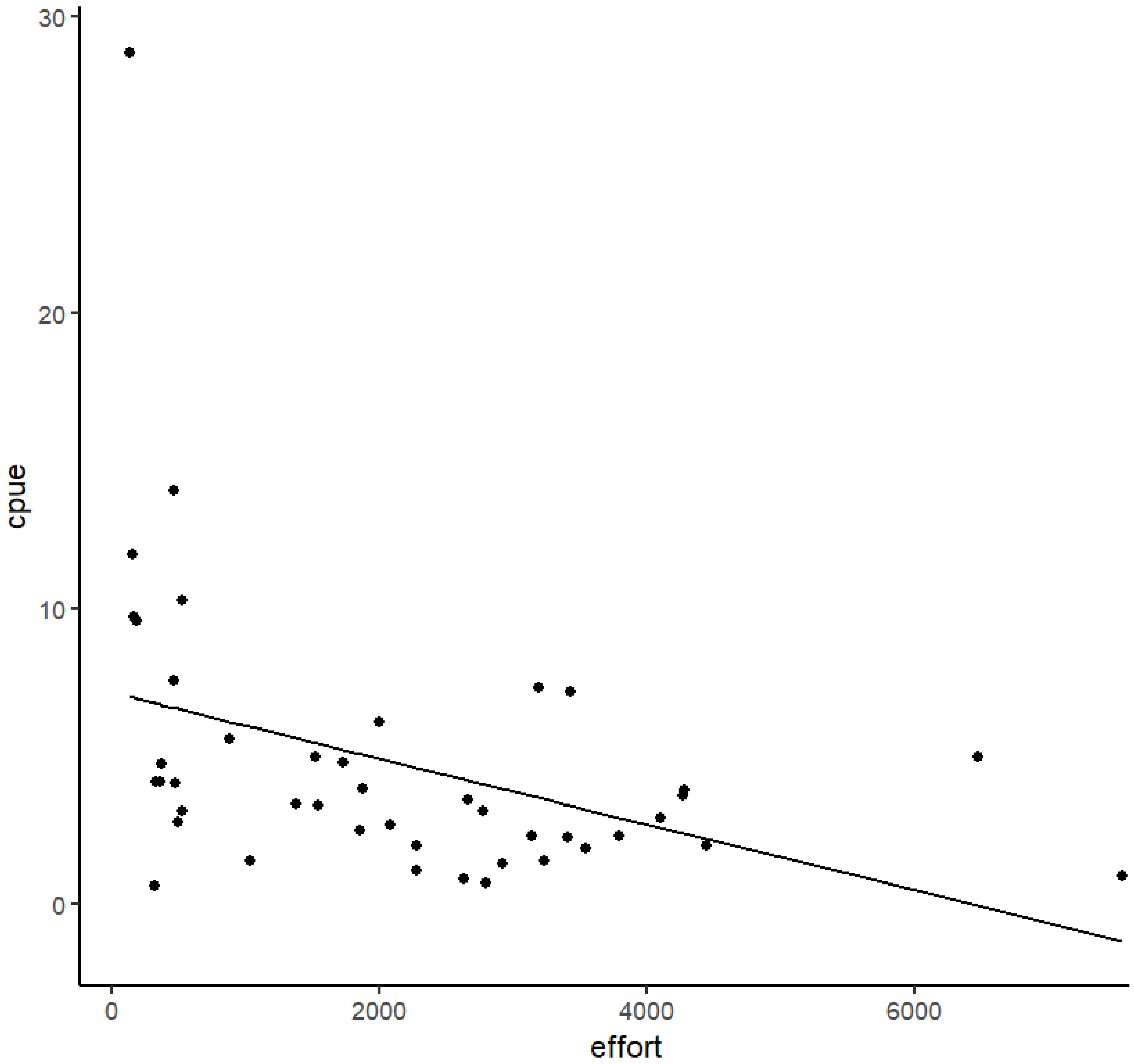
$$\frac{C_t}{CPUE_t} = \quad E_t = \frac{r}{q} - r\frac{CPUE_t}{qCPUE_{max}}$$

$CPUE_t = CPUE_{max} - (\frac{q}{r}CPUE_{max})\ E_t$ and $C_t = CPUE_{max}E_t - (\frac{q}{r}CPUE_{max})\ E_t^2$ **!**

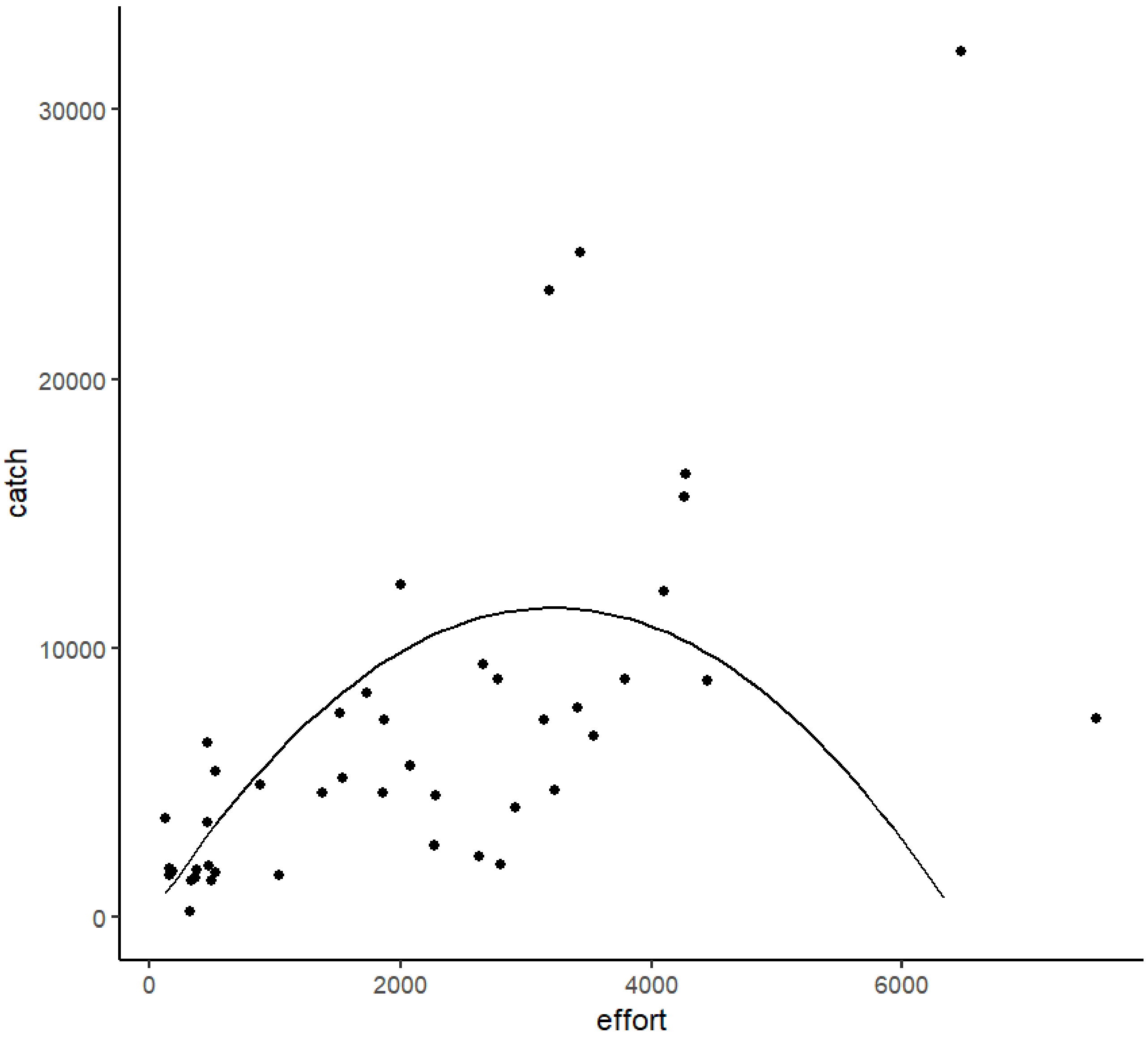
Let’s try: Blue fin tuna Japanese longline W Atlantic



 https://www.iccat.int/Documents/CVSP/CV076_2019/n_2/CV076020497.pdf

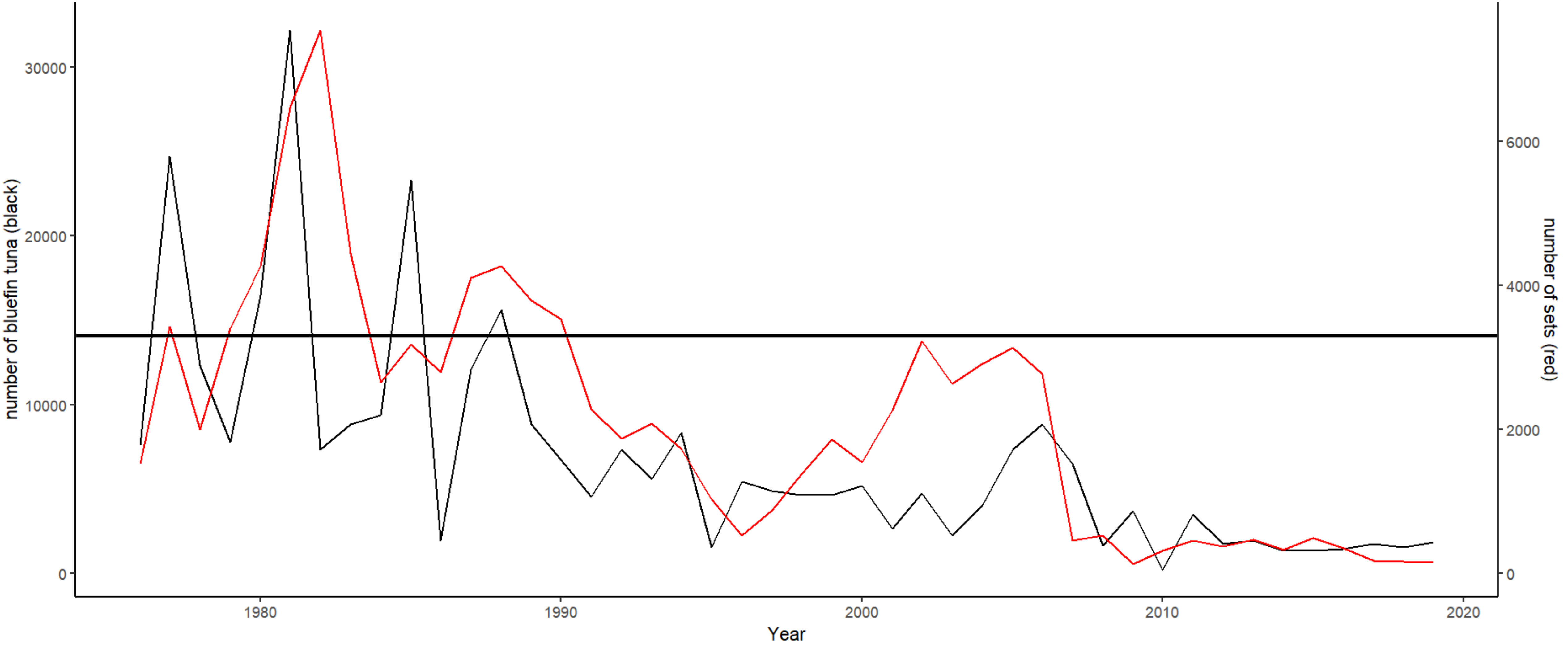


cpue
30
20
10
0
0
2000
4000
6000
effort

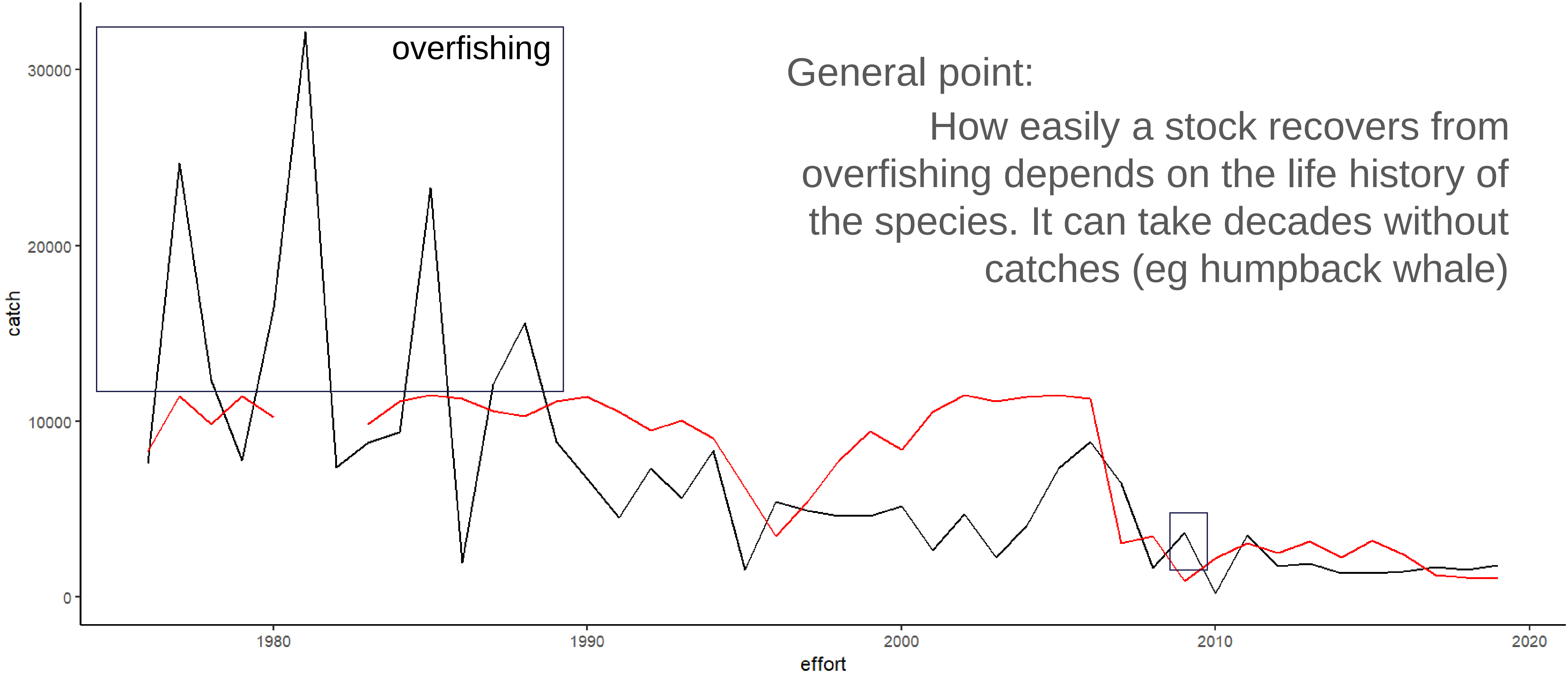


catch
30000
20000
10000
0
0
2000
4000
6000
effort

Excess effort



Catch > surplus



General point:

How easily a stock recovers from overfishing depends on the life history of the species. It can take decades without catches (eg humpback whale)

One dimension in isolation of others

- Bioeconomics of catches (efficiency, supply/demand, quality)
  - associated with fuel consumption (and hence C footprint)
  - Gordon-Schaefer model

- Biodiversity footprint
  - Incidental catches, habitat deterioration
  - Multi-criteria approach

- Can I find the effort which will be profitable, have acceptable biodiversity footprint, and yield sufficient catches?

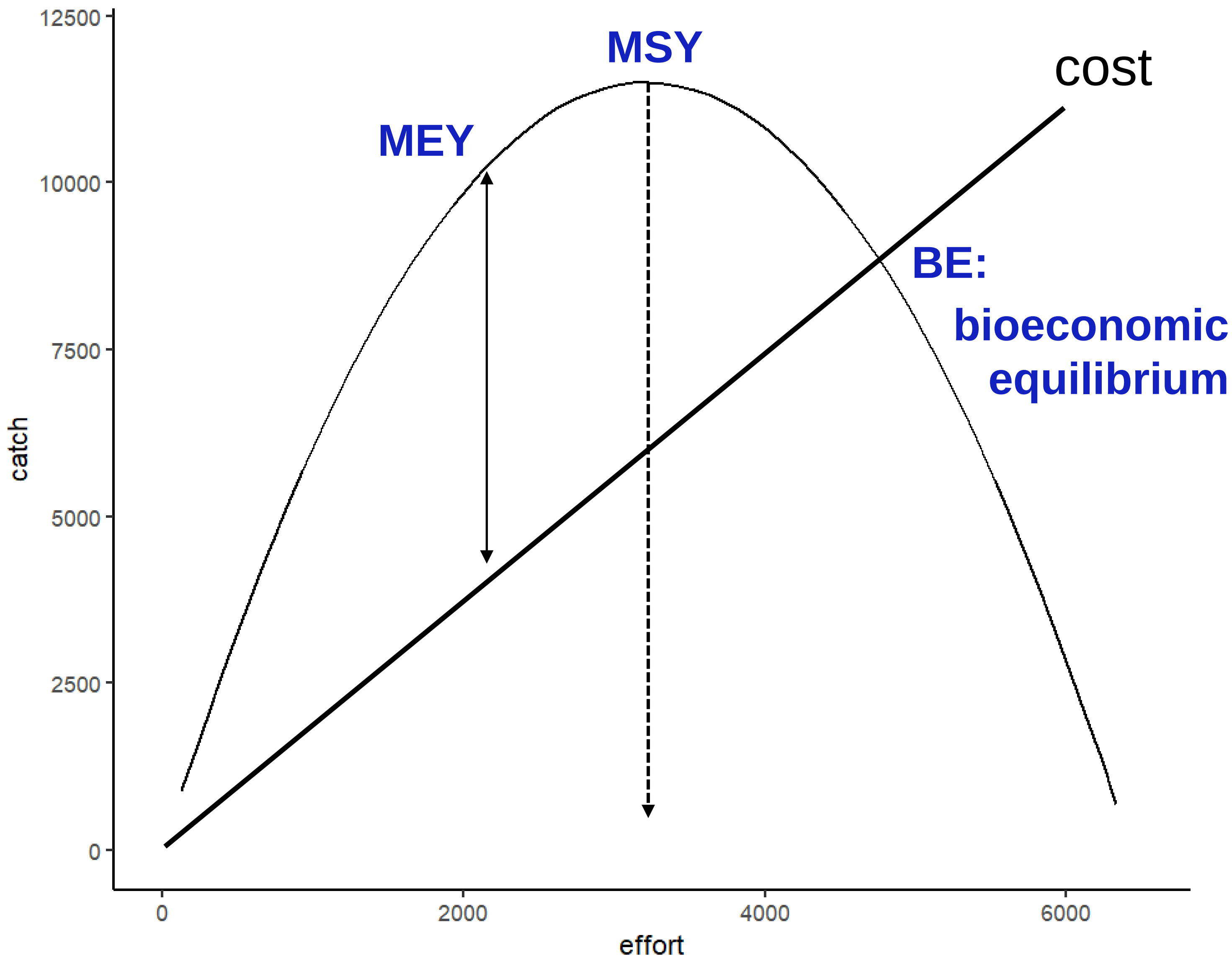
Gordon–Schaefer bioeconomic model

Revenue=aC-bE

Maximum Economic Yield < MSY

MEY can be > MSY

if there are external revenues (subsidies)



Biodiversity impact: bycatch

- There is a bycatch probability associated with fishing practices for varying sensitive and socially important species.

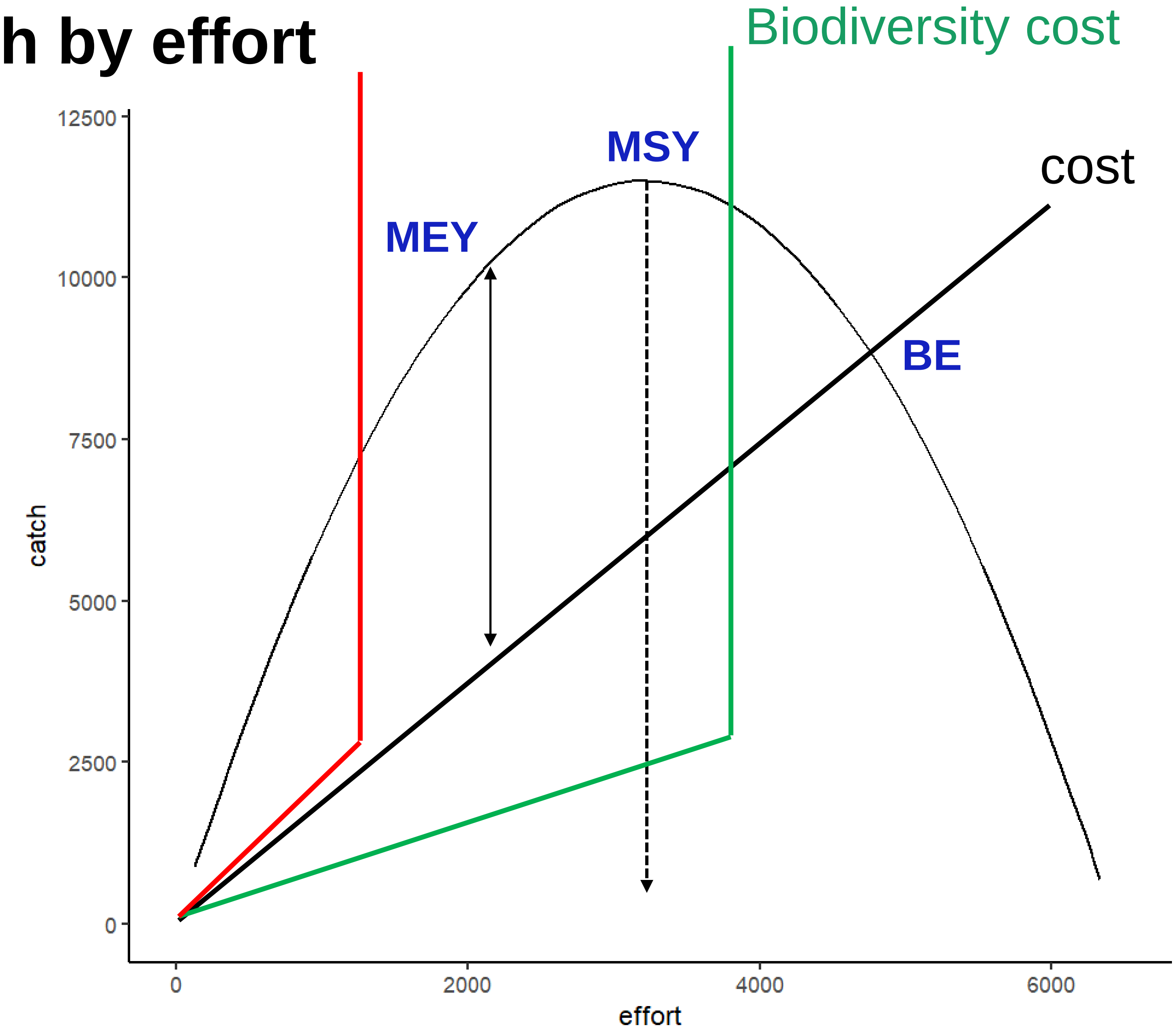
- Total bycatch is not optimised: an independent threshold is set to ensure conservation/restoration objectives are met

- Globally prevailing: Potential Biological Removal (PBR):
  - a la Schaefer model:
  - $PBR = N_{min} \times R_{\text{"MSY"}} \times F_r$

Incorporating in catch by effort

- Biodiversity cost is independent of MEY and MSY

- Biodiversity cost can be reduced with mitigation
    - mitigations are species dependent



Try it out

Gillnetting example

- Let's take a look at the exercise sheet (word docx)
- You can carry out the exercise in whichever way you want (xl, R, python, etc)

Fundamental concepts

Resource management

David Lusseau

Natural resources

- Can the resource I exploit harness earth systems to make more of itself within a timeframe suitable for my exploitation?

No: **Non-renewable resource**

Minerals, oil, gas

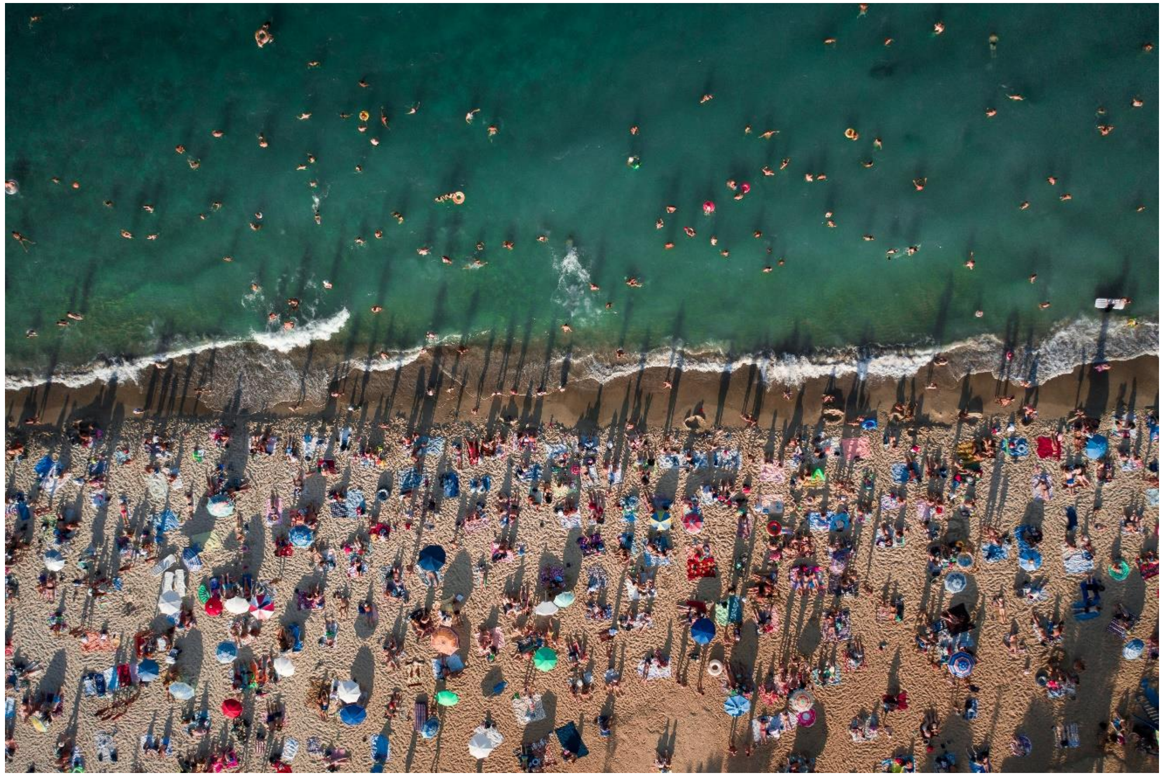
Yes: **Renewable resource**

Soil, plants, animals, water, wind

Exploitation types

Do we extract resources or use products generated by resources

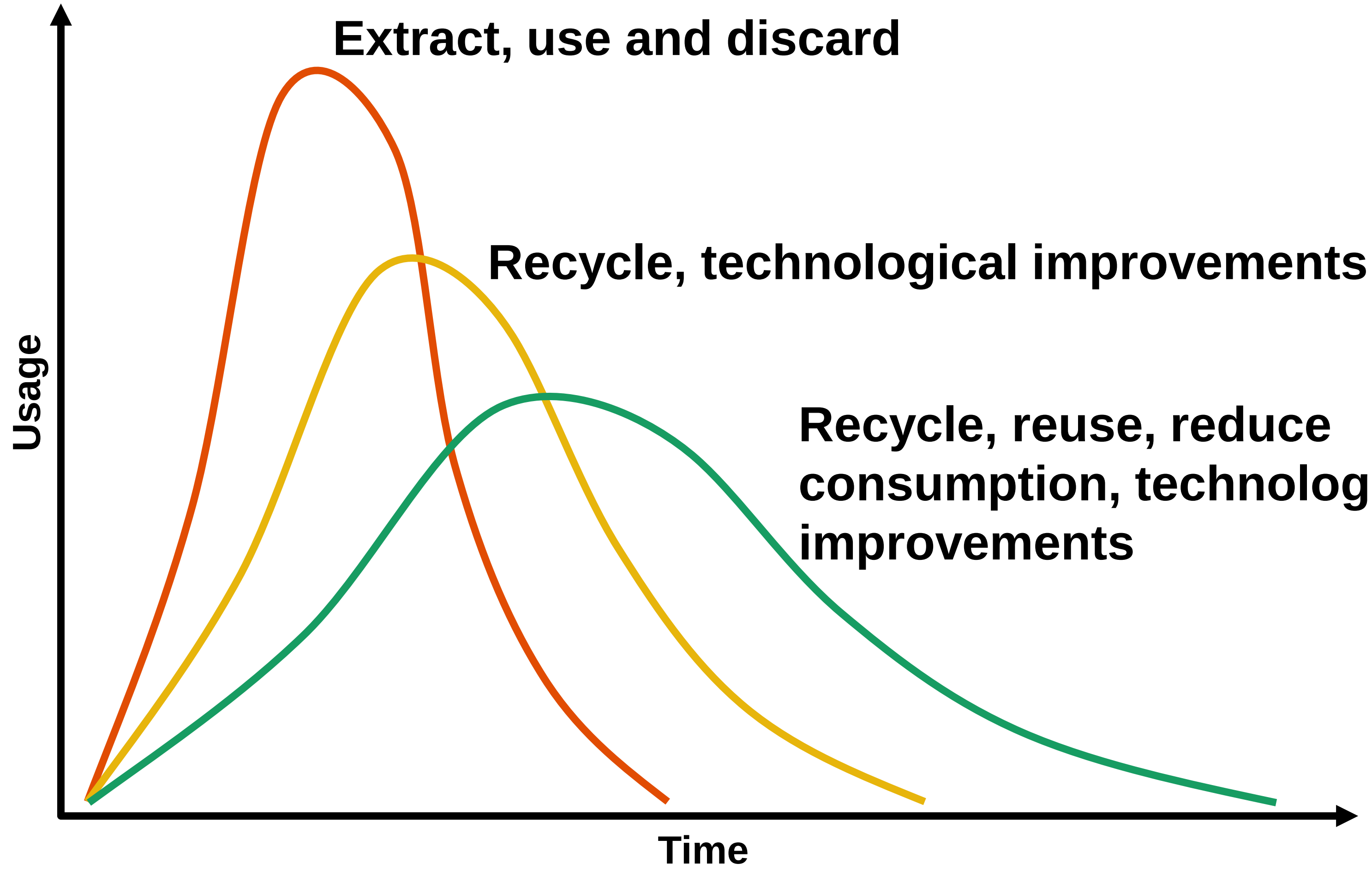
Consumptive, non-consumptive



When using products generated by resources, do we impair resource renewing when doing so? Consumptive?

Non-renewable resource use pattern

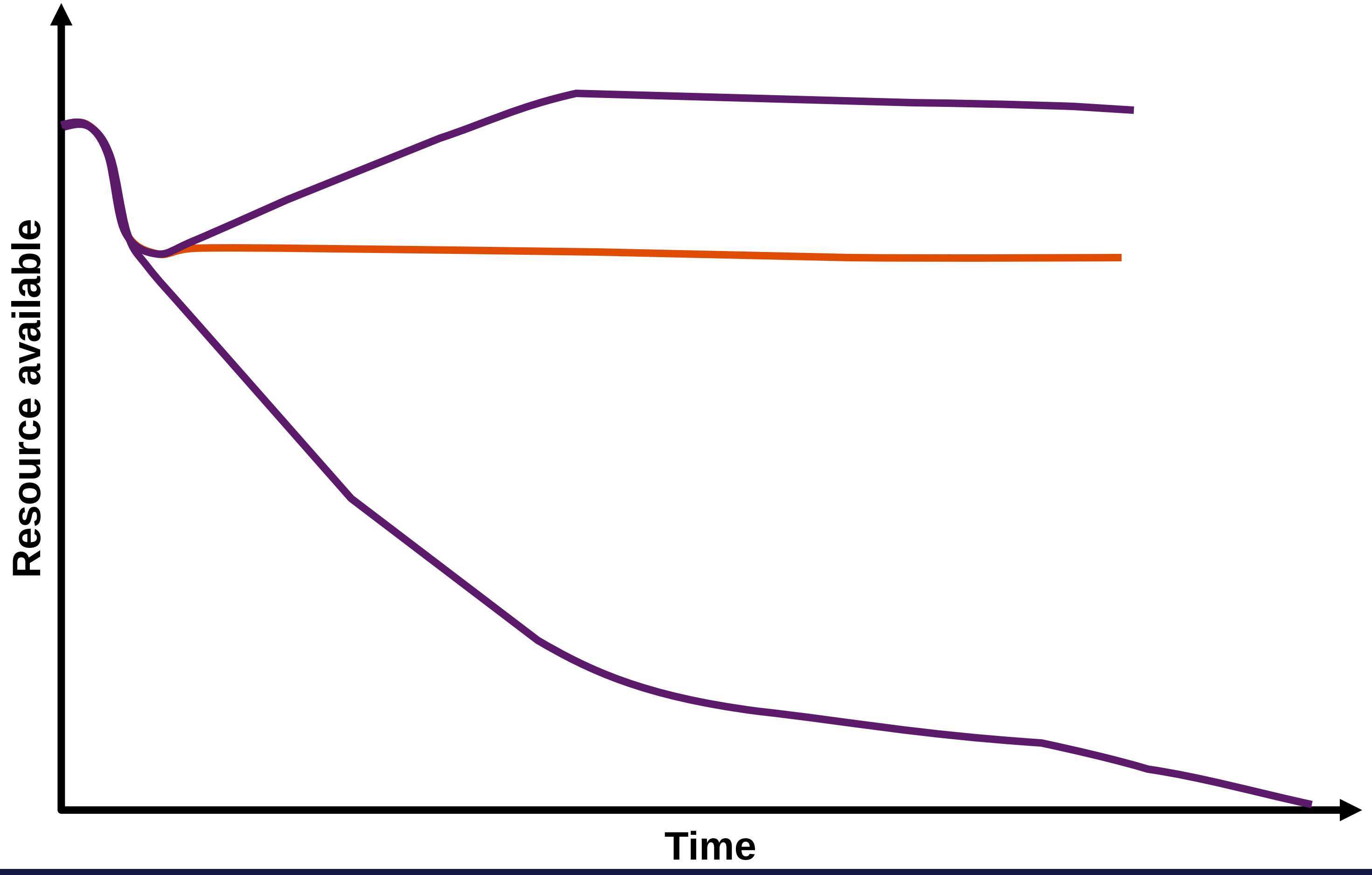
Adoption → demand peak → transition/abandonment



Renewable resource use pattern

Adoption → demand peak → transition/abandonment

Adoption → demand peak → sustained



Sustainability of exploitation

- Ability to manage depends on:
  - Whether extractions by one actor will diminish ability to extract by another
  - Actors can be excluded from extraction

Resource types

	Excludable	Non-excludable
Rivalrous	Private good	Common good
Non-rivalrous	Club good	Public good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

Private good

- Competitors can be prevented to access the resource (private property rights can be assigned)

- use of that good (consumption) prevent others to use it

- e.g. parking space, bread, a field

Club good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

- Property rights can be assigned
- Using that good does not prevent others to use it
- Eg, a cinema, alliance/club/union (services provided to members excluding non-members), a private nature park

Public good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

- Access cannot be restricted

- The use of the resource does not prevent others from using it

- E.g., knowledge, streetlights, public park

Common good

	Excludable	Non-excludable
Rivalrous		
Non-rivalrous		

- Short for common-pool resource
- Access cannot be restricted
- The use of the resource prevent others from using it
- E.g., fish stocks, but also… public park
  - If the use of a natural place degrades it, then some of its use is prevented by the use of others.

Conclusions

- Renewable natural resources lead to different exploitation patterns because they need not become exhausted.

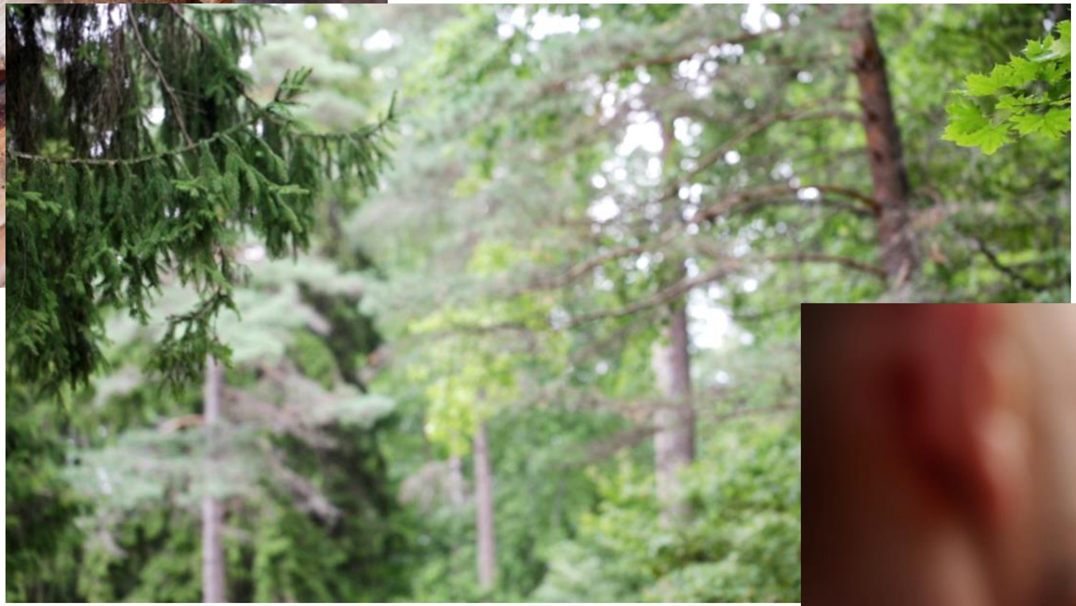
- Our means and abilities to govern resource exploitation depends on whether people can be excluded from its exploitation and whether resource use by some diminish resource use opportunities for others

The tragedy of the commons

Resource management

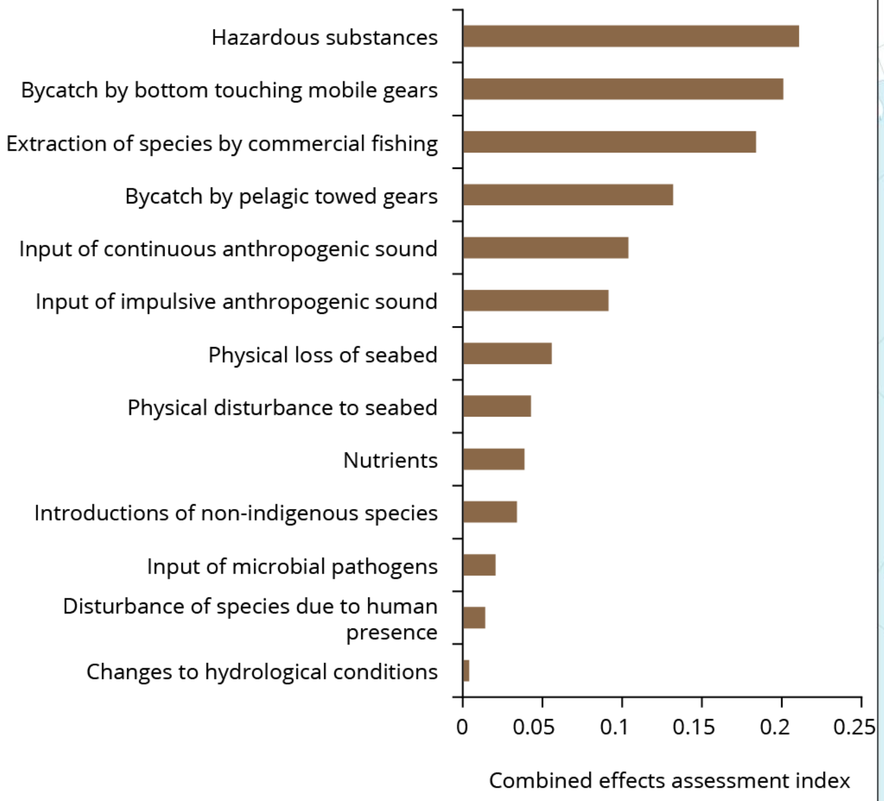
David Lusseau

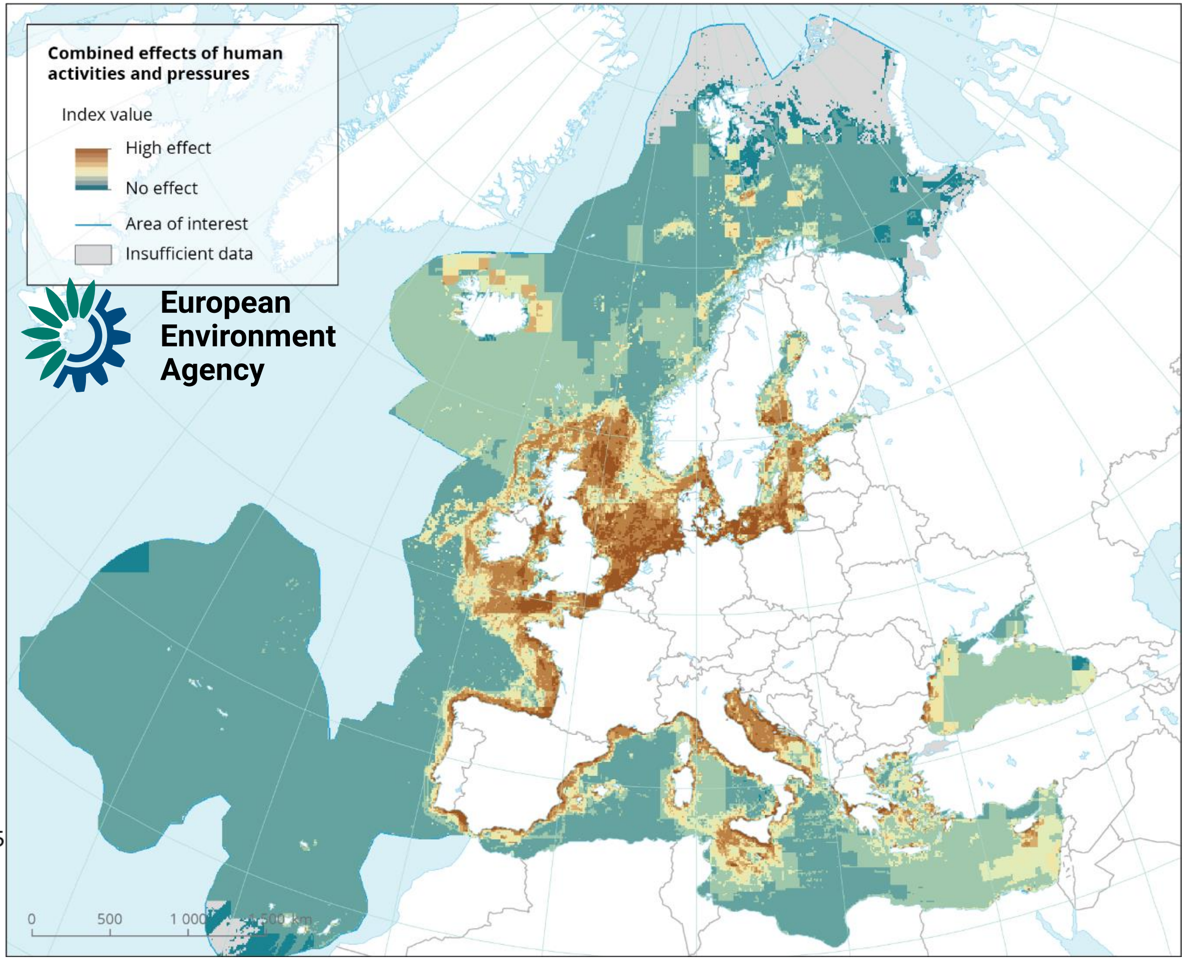
Diversity in natural resource use



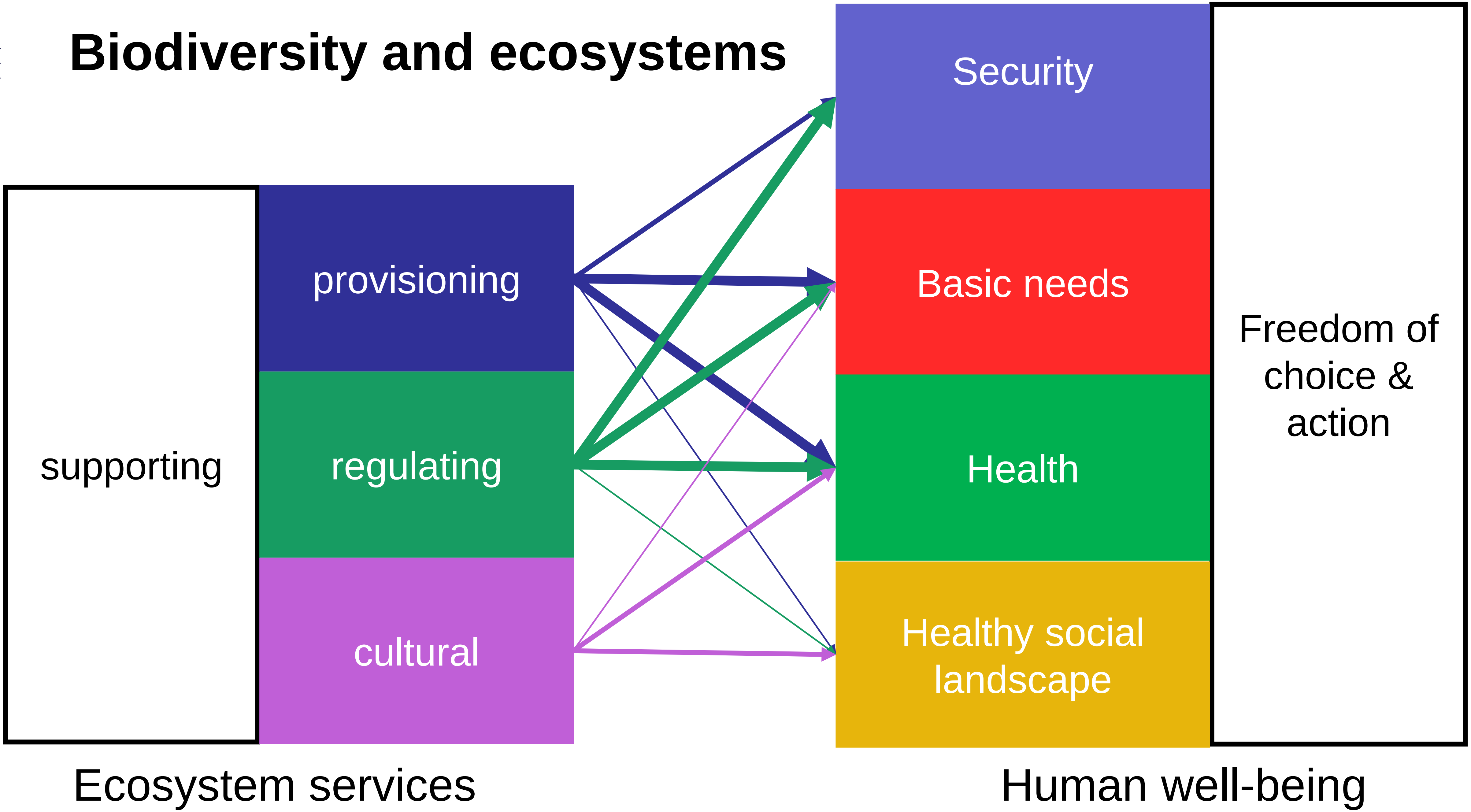
Indirect use of resources

- Our activities can impose pressures on resources which are not the source of exploitation
  - Climate
  - Air pollution
  - Biodiversity
  - Habitat





Biodiversity and ecosystems



Millennium Ecosystem Assessment 2005

Regulating and Cultural Ecosystem Services

- Degrading common resources affect the ability for others to extract benefits from them

Geography Compass 1/4 (2007): 850–870, 10.1111/j.1749-8198.2007.00048.x

Call It Consumption! Re-Conceptualizing Ecotourism as Consumption and Consumptive

Zoë A. Meletis* and Lisa M. Campbell
Nicholas School of the Environment and Earth Sciences, Duke University

Tragedy of the Commons

- 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

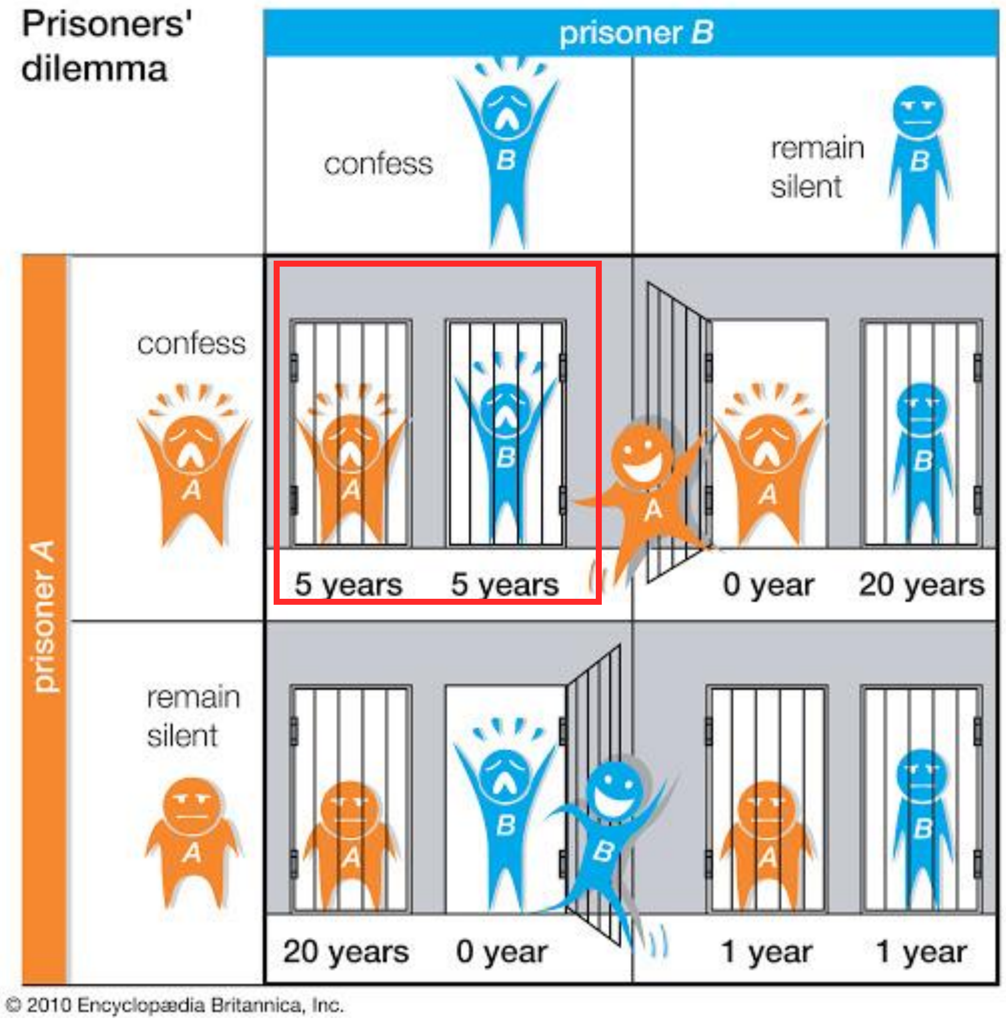
- Without interventions – recall exclusion interventions are not possible – it will always be beneficial to defect

- Leads to a race to the bottom and resource collapse

ToC game theory: Prisoner’s dilemma

Decision consequences

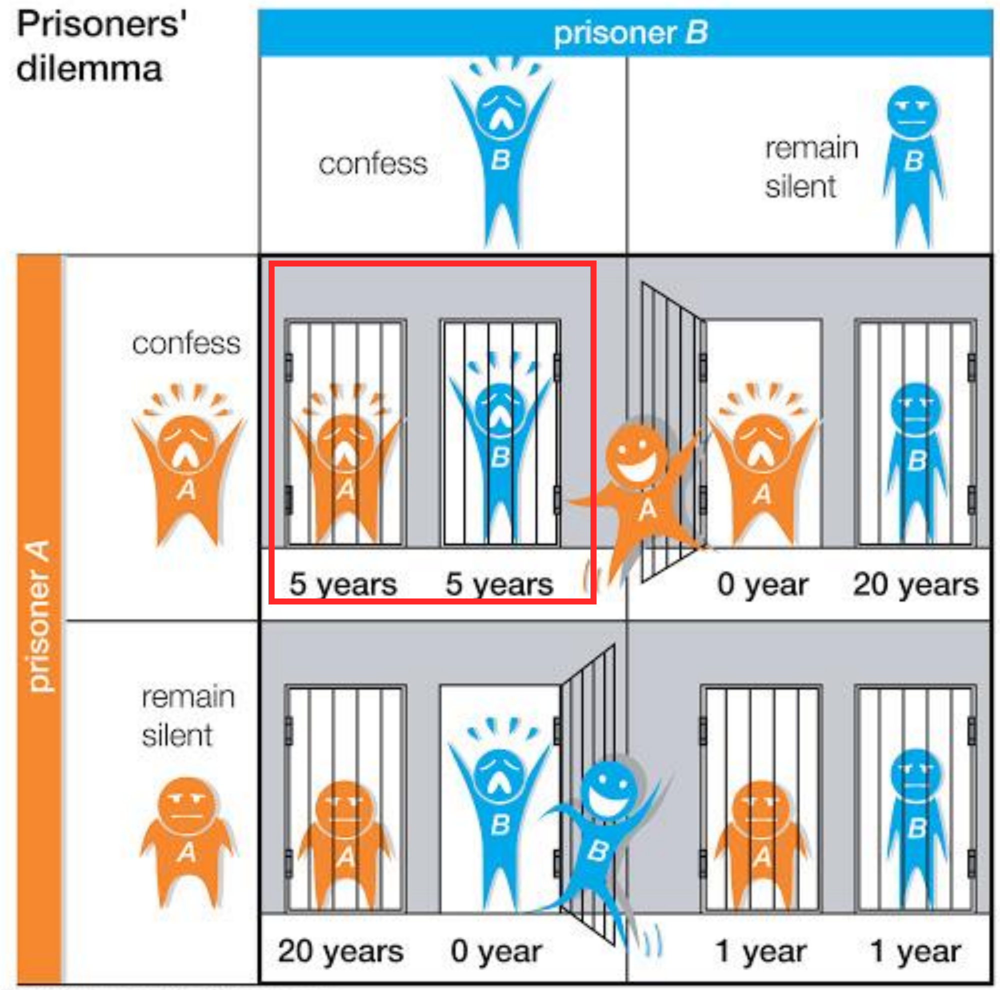
- both confess, both go to jail for five years;
- neither confesses, both go to jail for 1 year (concealed weapons);
- one confesses & the other not, confessor is free (witness) and the silent one is jailed 20 years.



ToC game theory: Prisoner's dilemma

- *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



Conclusions

- Common goods are complex to govern, unfortunately most regulating and cultural ecosystem services are common goods.

- How do we fix it? Assign property rights!
  - Then common goods become private [/club] goods (e.g., quotas)
    - European “common policies” approach: common to club goods

- Can we actually sustain common goods exploitation?
  - Ostrom: polycentric governance

Decarbonizing energy systems
DTU course on Quantitative Sustainability

Lecture 1 Decarbonizing energy systems
Lecture 2 Wind Energy as example
Lecture 3 Exercise : Violation of planetary boundary of Global Warming Potential due to electricity mix

Asger Bech Abrahamsen, Senior Researcher
DTU Wind and Energy Systems, DTU Risø Campus, Roskilde
Technical University of Denmark
Contact : asab@dtu.dk

How sustainable is Wind Energy?

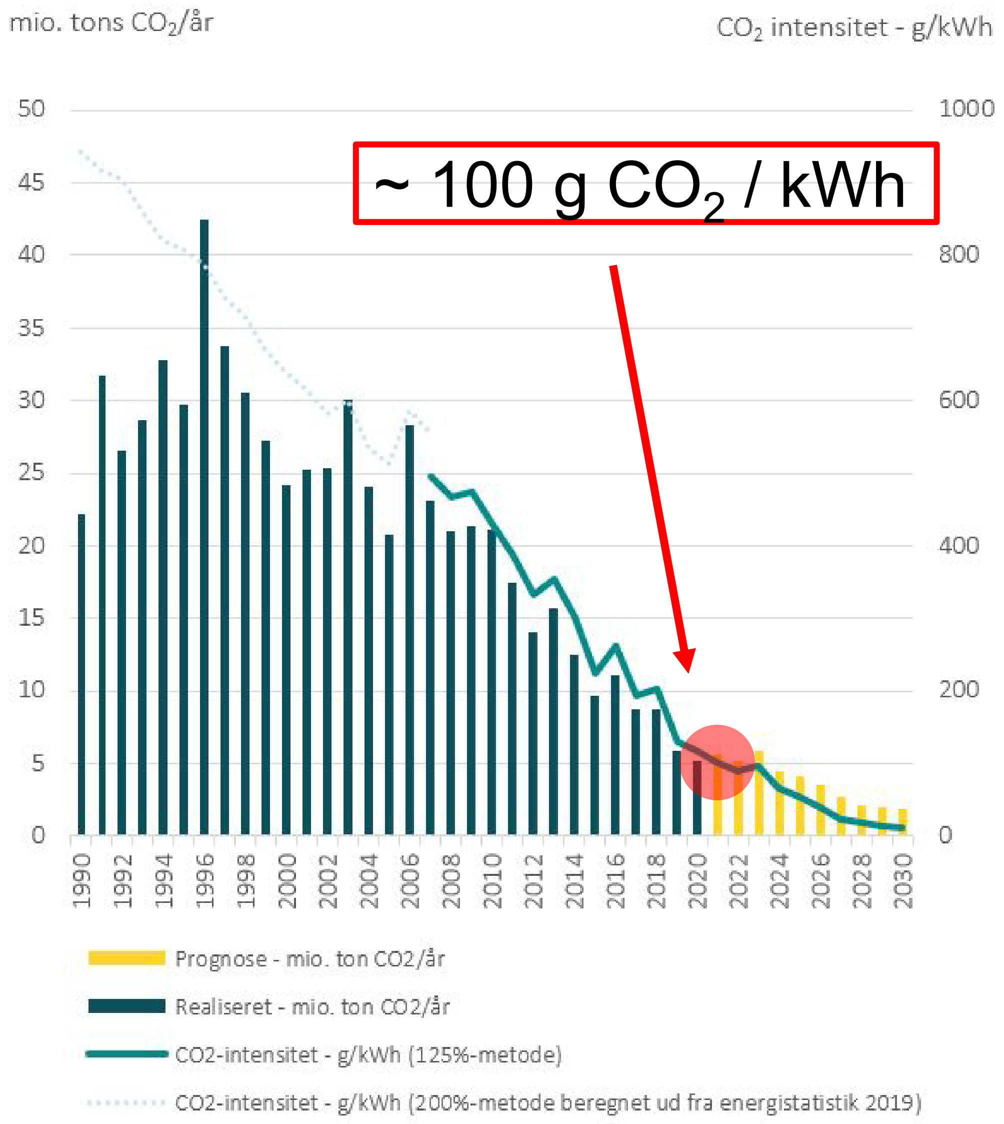
“Wind Energy is by definition green and once it supplies all production processed then the world will become purely green” (Wind sector around 2010)

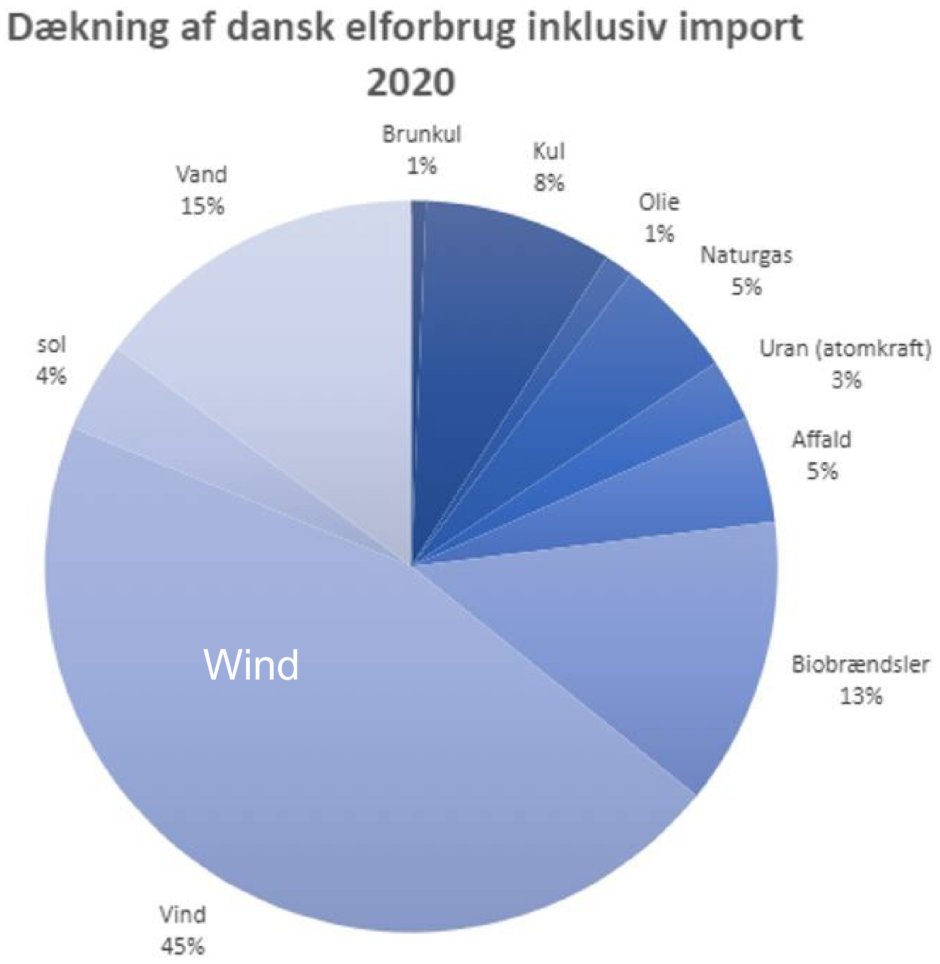
There are however some challenges related to this point of view:

- The production of the materials will need energy that might not be green
- The production of materials might result in direct chemical emissions
- The installation and Operation and Maintenance might be fossil-based
- There are many emissions to the environment and how to define limits?
- Is the turbine fleet operated in a circular manner with zero waste, or are new materials needed to compensate for the waste?

- Life Cycle Analysis (LCA) is a method to quantify the impact on the environment (CO_2 emission per kWh produced energy as example, but 17 others exist).

CO_2 emission from electricity of Denmark





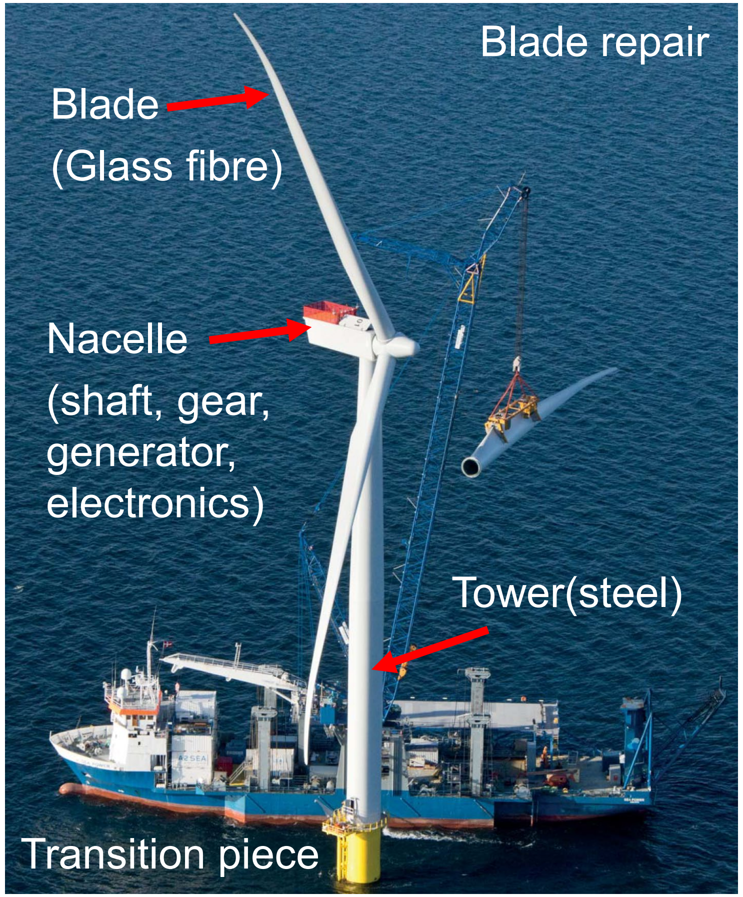
Source: EnergiNet Miljøredegørelse 2020

The life cycle of offshore wind farms

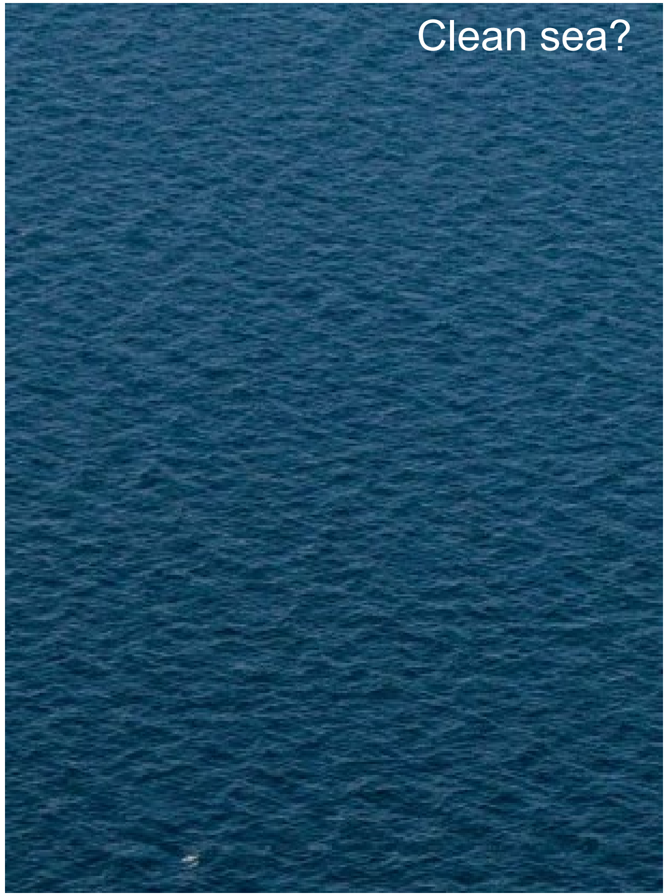
Manufacturing & Installation

Steel

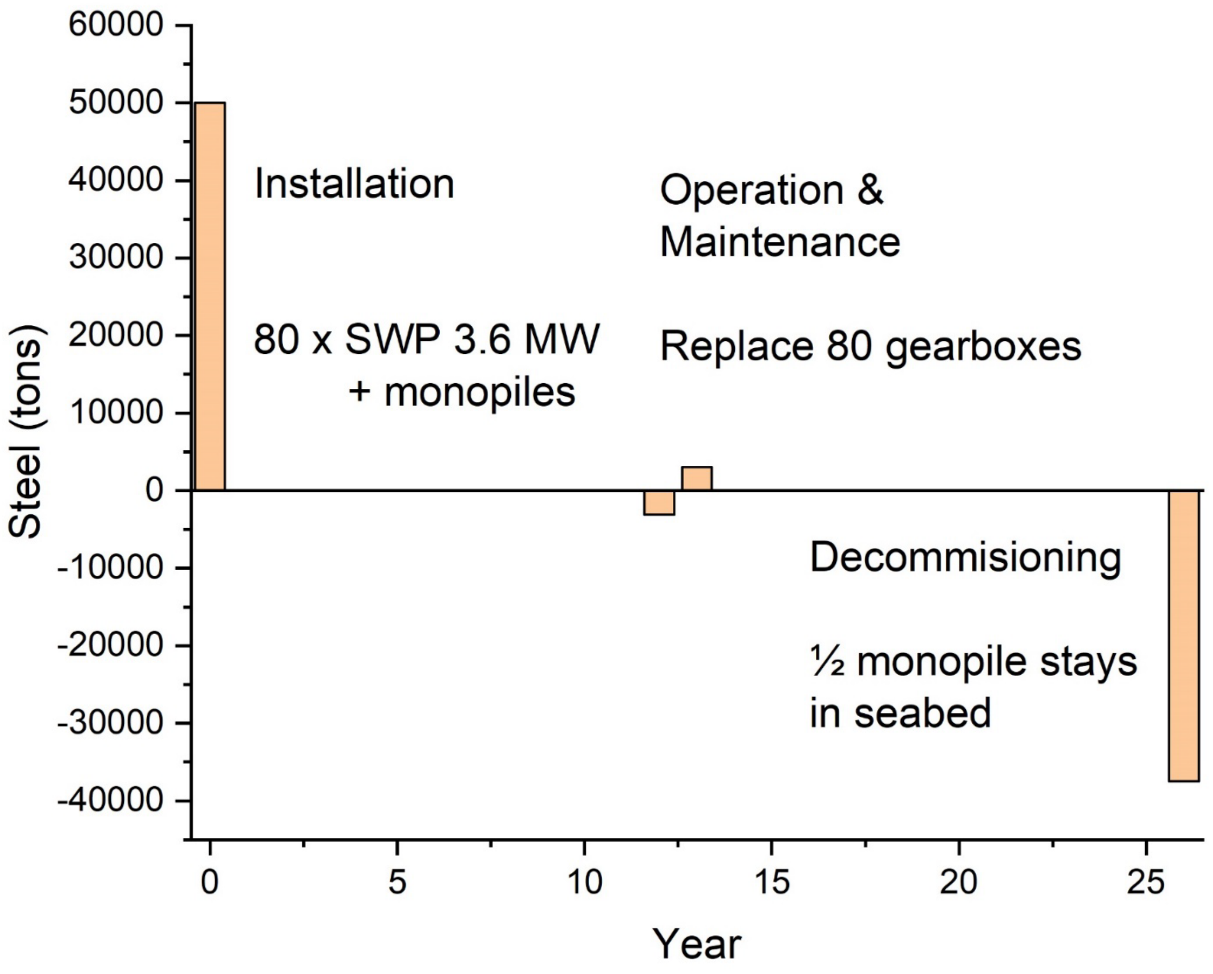
Operation & Maintenance



Decommissioning after 25 year design life time



The steel life cycle balance of an offshore wind farm



CO_2 emission =

Bill of Material x **emission per material +**

Energy consumption x emision from energy +

Transport x **emission per length +**

- **Recycled material (?)**

Normalization:

Total energy produced in operational lifetime of the wind farm [kWh]

Manufacturing of iron : From mine ore to metal

Blast furnace operating at 2000 °C

$$Fe_2O_3 + 3CO \rightarrow 2Fe(L) + 3CO_2$$

$$C + O_2 \rightarrow 2CO$$

$$2Fe_2O_3 + 3C \rightarrow 4Fe(L) + 3CO_2$$

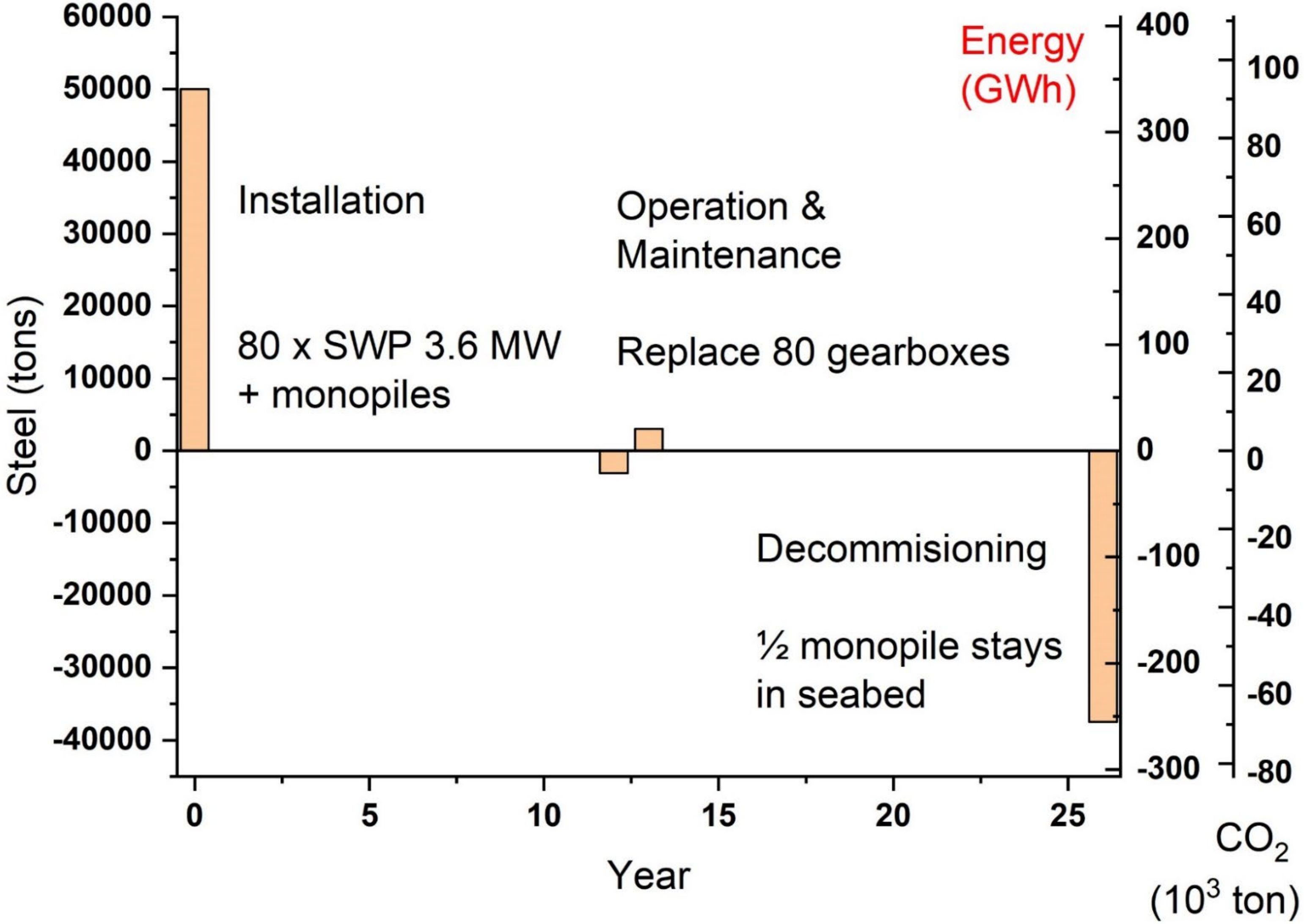
Burn iron mineral with coal ➡ **Liquid iron + CO_2**

$E = 6.8\ MWh/ton_{Fe}$

$m_{CO2} = 1.9$ ton CO_2 eq/ton_{Fe}

Iannuzzi, M., Frankel, G.S. The carbon footprint of steel corrosion. *npj Mater Degrad* **6**, 101 (2022)

Energy usage and CO_2 emissions due to steel balance



Emission

m_{CO2} = 90 $\cdot 10^3$ tons CO_2

Wind energy produced

E = 80 turbines x 3.6 MW/turbine x 365 days/year x 24 hours/day x 25 years x CF

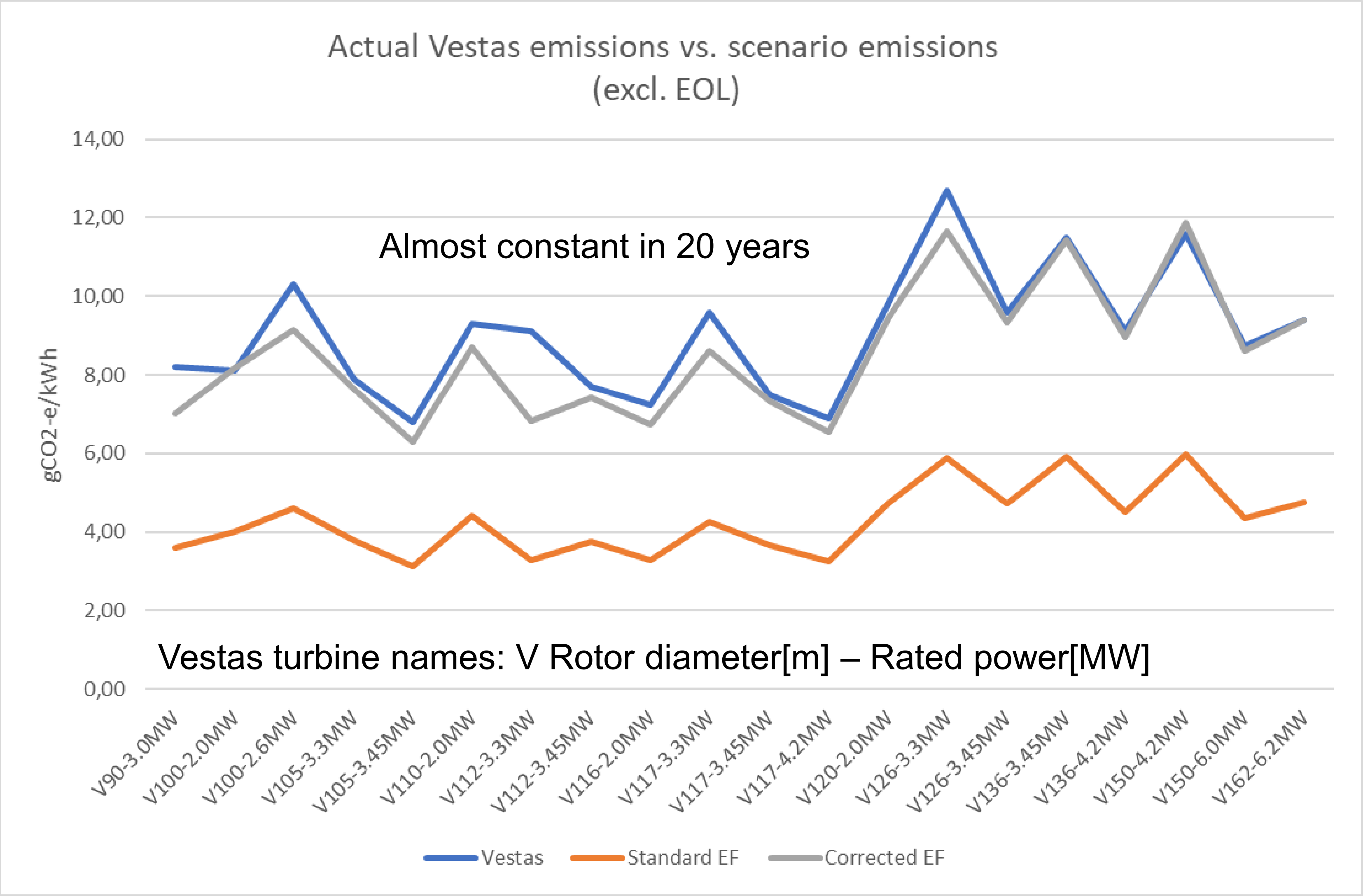
= $25.2 \cdot 10^9$ kWh (25 TWh)

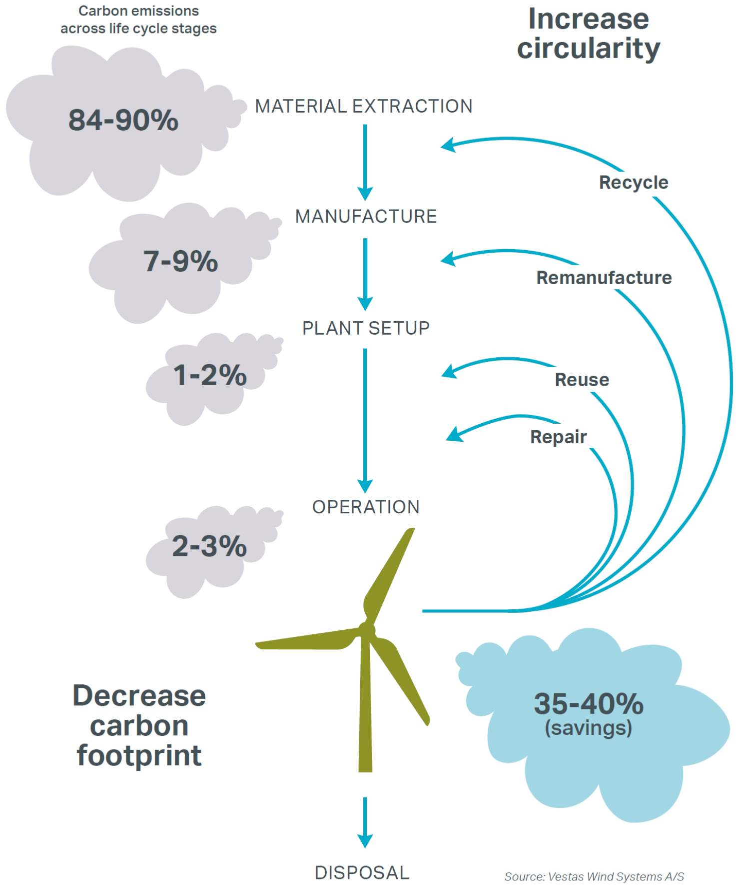
The capacity factor(CF) of the wind farms is assumed to be 0.4, which describes the average production due to the fluctuating wind.

Normalized emission

$$\frac{m_{CO2}}{E} = \frac{90 \cdot 10^9 \ g\ CO_2}{25 \cdot 10^9 \ kWh} \sim 4 \ \frac{g\ CO_2}{kWh}$$

Onshore turbine emission from LCA studies of Vestas





MegaVind : https://megavind.greenpowerdenmark.dk/files/media/document/Sustainability-in-the-wind-industry-oct22.pdf

Kjeldsen & Mwiseneza, DTU Bachelor thesis summer 2023. Harden, Bachelor project 2021. Fauerskov & Laurberg, Bachelor project 2022.

UN ranking of electricity producing technologies

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

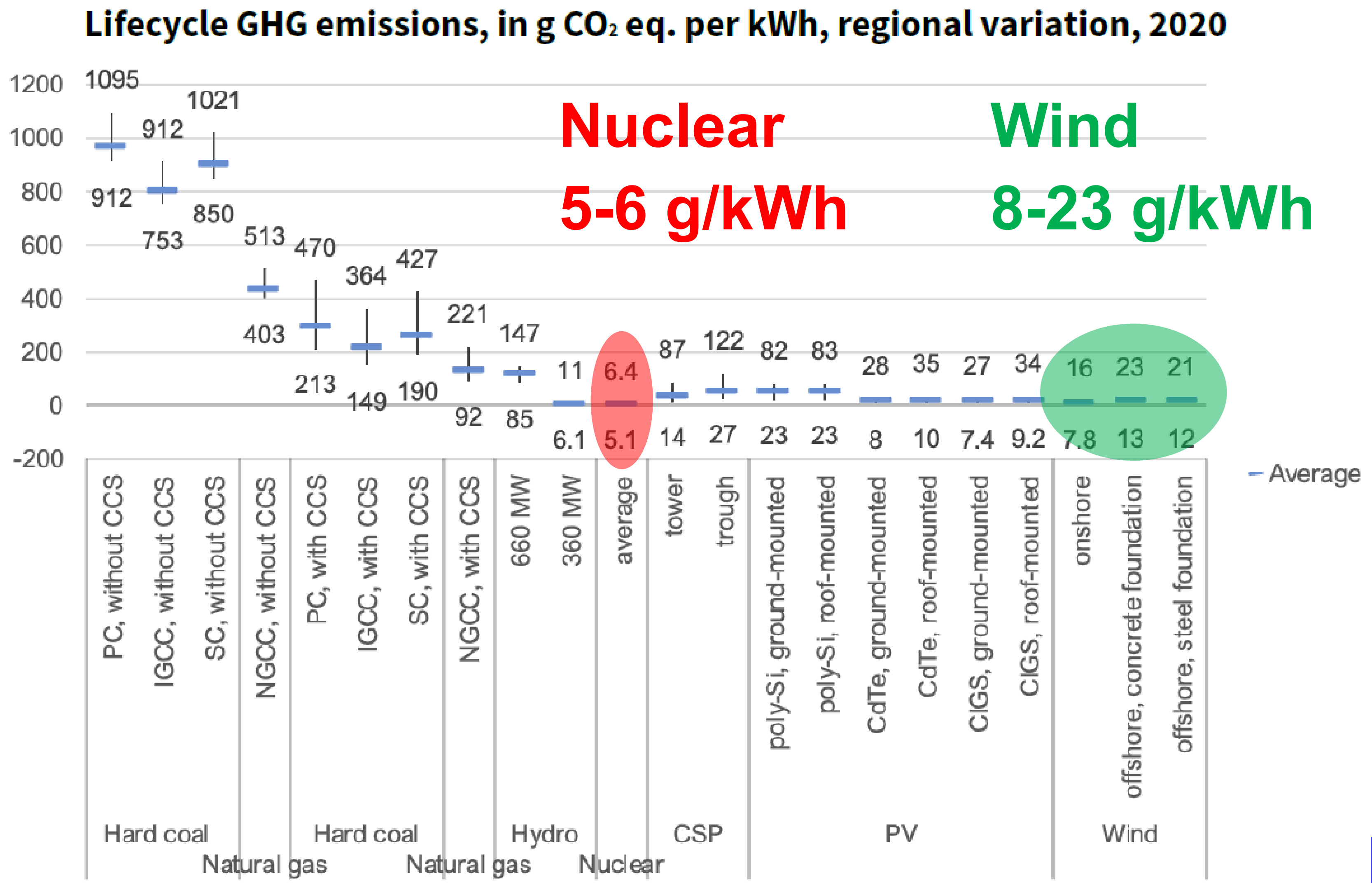
Life Cycle Assessment of Electricity Generation Options

2021

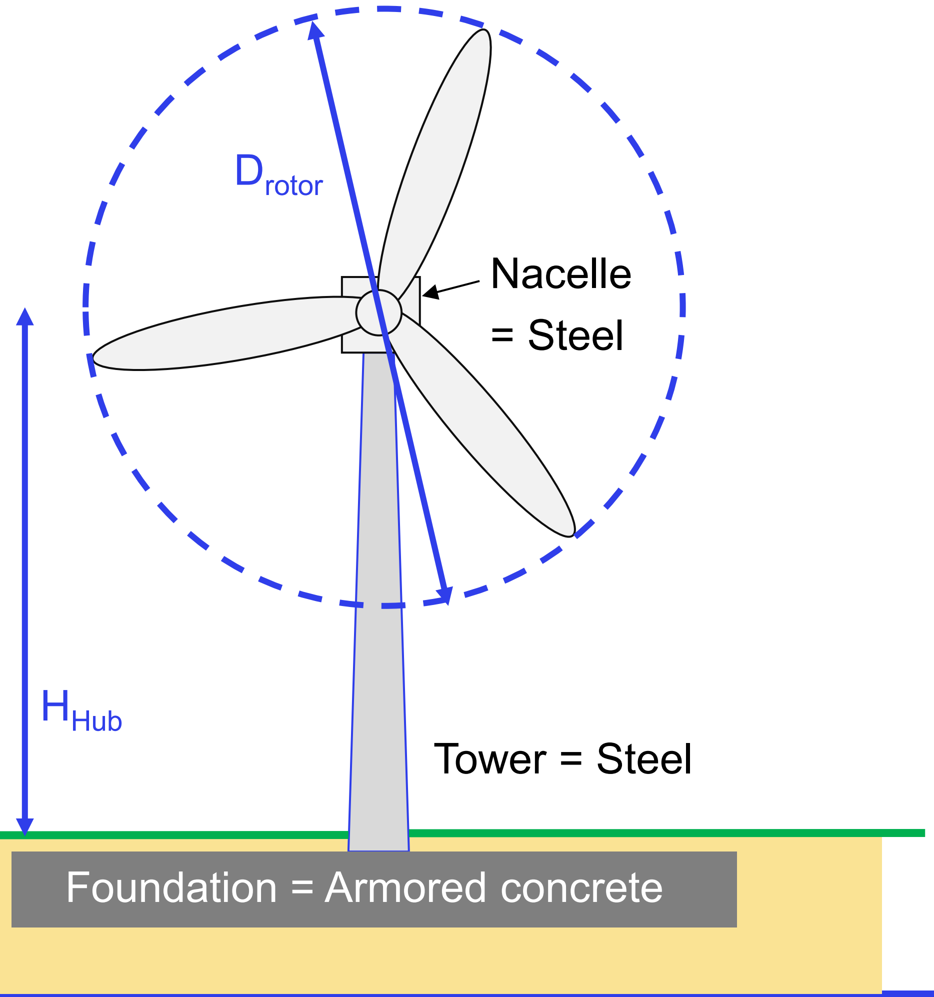
UNECE

https://unece.org/sites/default/files/2021-10/LCA-2.pdf

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies



Simple model for estimating Global Warming Potential (g_{CO2eq}/kWh) of onshore wind turbine



Vestas V162 onshore wind turbine (example)

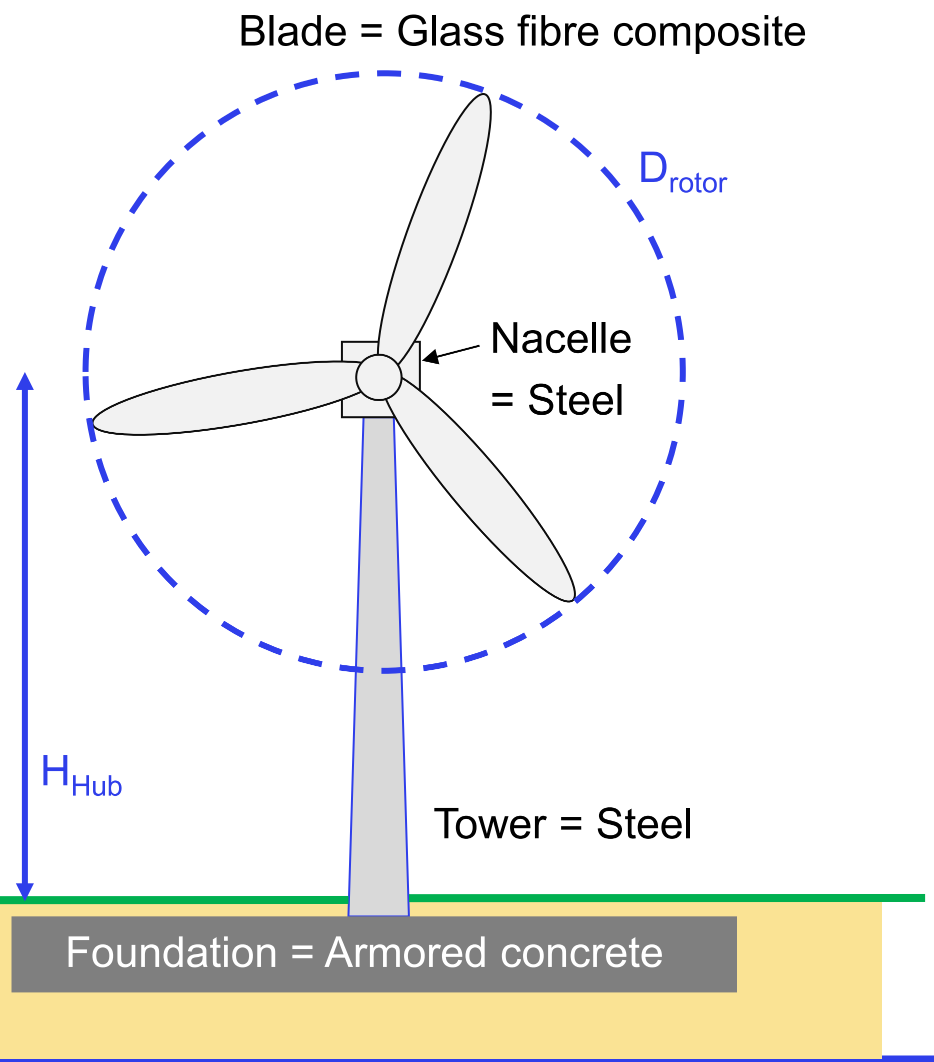
Rotor diameter	D_{rotor} = 162 m
Power rating	P_{Gen} = 6.2 MW
Hub height	H_{Hub} = 149 m
Design Lifetime	LT = 20 years
Annual Energy Production	AEP = 21.6 GWh/year (u_{ave} = 7.4 m/s)
Capacity factor	CP = AEP / (P_{gen} x 365 days x 24 hours) ~ 40 %

Simple Bill of Materials (BOM) per V162 turbine

Concrete	$m_{concrete}$	=	2453.6 tonnes	72 %
Steel	m_{steel}	=	819.2 tonnes	24 %
Glass fibre composite	m_{GFC}	=	59.0 tonnes	2 %
Other (Cu, Al, plastics,..)	m_{other}	=	85.8 tonnes	3 %
Total	m_{total}	=	3417.6 tonnes	100 %

Source : https://www.vestas.com/en/sustainability/environment/lifecycle-assessments

Simple model for estimating Global Warming Potential



Wind energy sector simple emission factor suggestion

Concrete	$EF_{concrete}$ =	0.17 g_{CO2eq} / $g_{concrete}$
Steel	EF_{steel} =	3.62 g_{CO2eq} / g_{steel}
Glass fibre composite	EF_{GFC} =	11.40 g_{CO2eq} / g_{GFC}

Simple total emission model

Emission factor material *i*, EF_i

Mass of material *i*, m_i

$$EM[g_{CO2\ eq}] = \sum_{i=1}^{N} EF_i \cdot m_i \ [g_{co2eq}]$$

The simple model includes the lifetime emissions of manufacturing, installing, and operating an onshore wind farm in Europe, but no recycling. These numbers are estimated from an analysis of the Life Cycle Assessment(LCA) reports of Vestas and represent approximate wind energy sector numbers for a typical European wind farm sourced from the European supply chain in 2023. This means that the energy mix of European countries have been used to determine the emissions resulting from the energy consumptions.

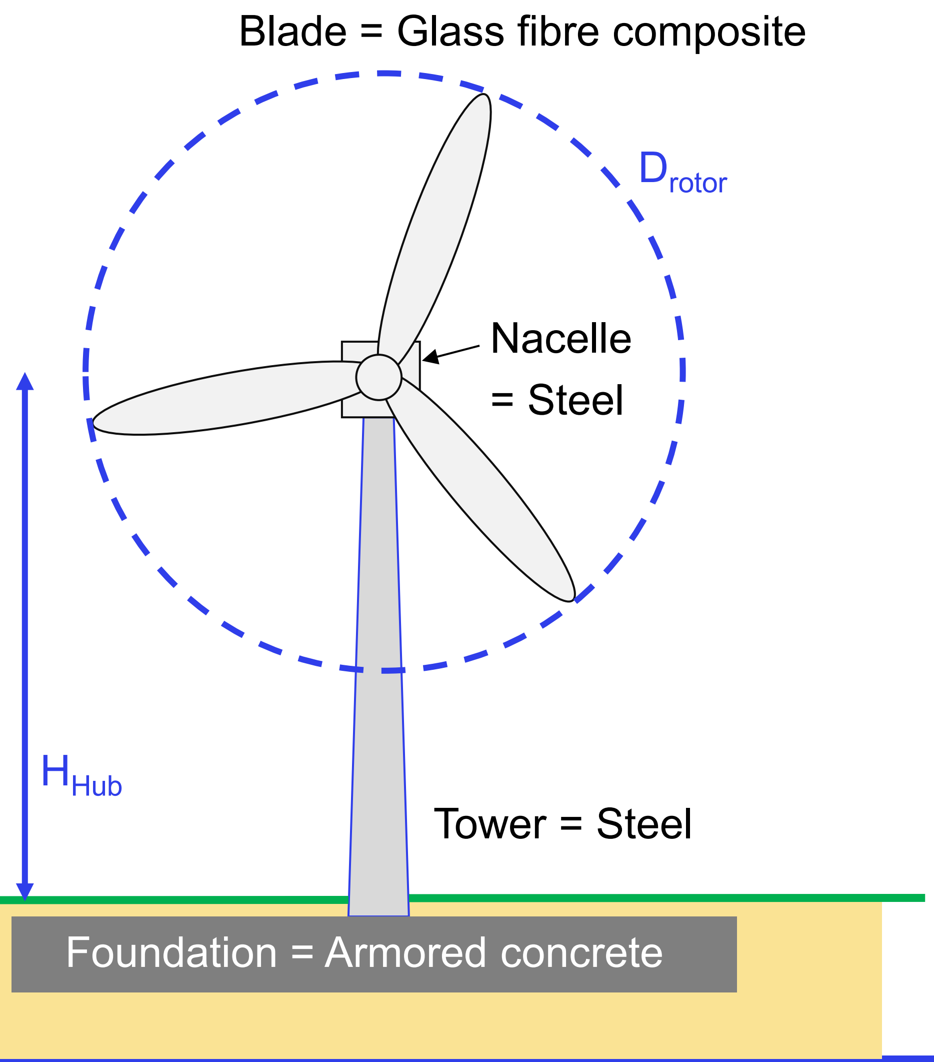
Source : https://orbit.dtu.dk/en/projects/simple-model-for-estimating-co2-emissions-of-wind-turbines

Simple model for estimating Global Warming Potential

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



Transportation specifications

Component	Truck (km)	Ship (km)
Nacelle	600	9000
Hub	600	8600
Blades	1450	5100
Tower	425	0
Foundation	50	0
Other site parts	600	0

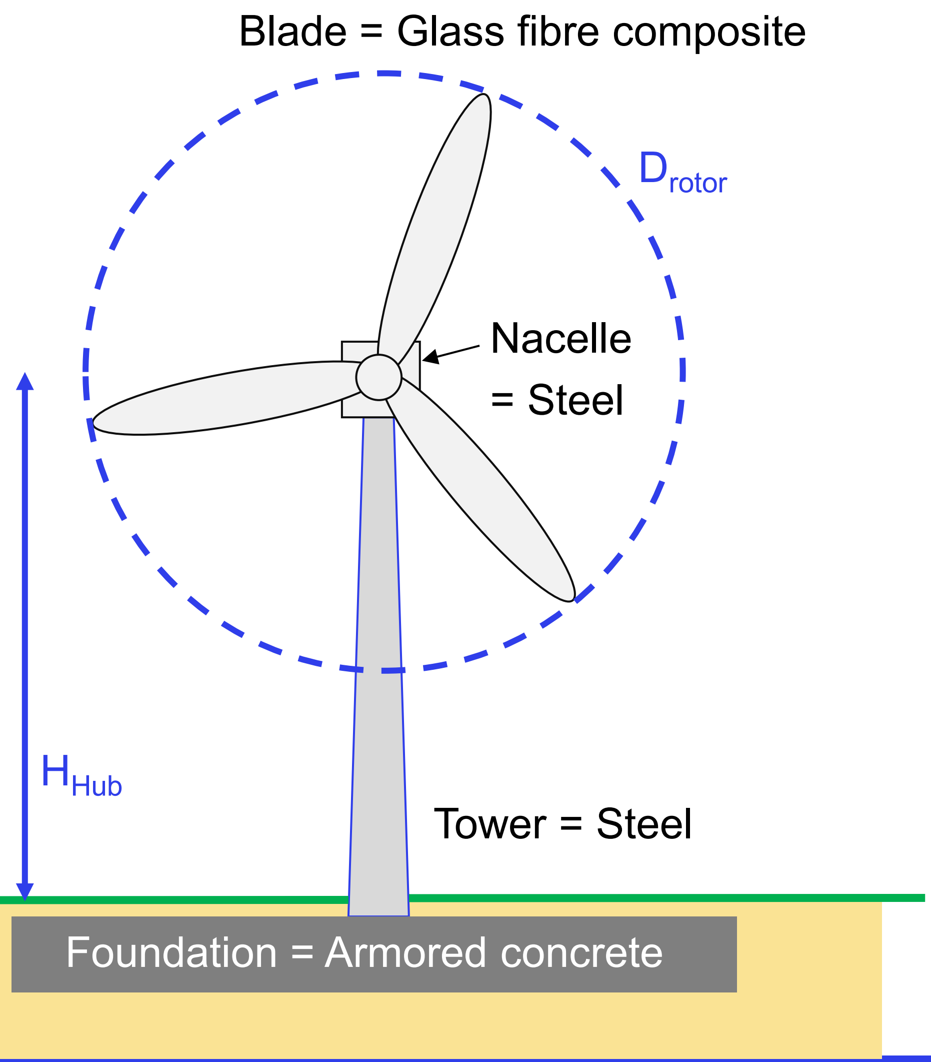
Installation site of the windfarm is Europe (Germany, see Table 15 in Vestas LCA report of V162)

Materials recycling is specified in table 3 on page 32 in report below.

Source : Sagar Mali & Peter Garrett, " Life Cycle Assessment of Electricity Production from an onshore EnVentus V162-6.2 MW Wind Plant ", Vestas, Version: 1.0 Date: 31.01.2023

https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/reports-and-ratings/lcas/LCA%20of%20Electricity%20Production%20from%20an%20onshore%20EnVentus%20V162-6.2.pdf.coredownload.inline.pdf

Simple model for estimating Levelized cost of Energy of onshore wind turbine electricity production



Cost of onshore wind turbines

Capital cost	CAPEX	~ 1.4 M€/MW (inflation corrected)
Operational cost	$OPEX_{fixed}$	~ 12600 €/MW/year
	$OPEX_{variable}$	~ 1.35 €/MWh
Discount rate	w	~ 4-6 %/year

Levelized Cost of Energy (LCoE) = ?

Source : Danish Energy Agency, Technology data, page 225 and 2030 scenario
https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh.pdf

Levelized Cost of Energy estimate of onshore wind energy from Vestas V162-6.2 MW turbine

The levelized cost of energy can in a simple form be defined as

$$LCoE = \frac{\sum_{i=0}^{LT} \frac{C_i}{(1+w)^i}}{\sum_{j=0}^{LT} \frac{E_j}{(1+w)^j}} = \frac{C_{CAXEX,0}}{E_{AEP}} \cdot CRF + \frac{C_{OPEX,Annual}}{E_{AEP}} + \boldsymbol{LCoE_{OPEX,variable}} = \mathbf{32.2}\,\frac{\boldsymbol{€}}{\boldsymbol{MWh}} + \mathbf{3.6}\,\frac{\boldsymbol{€}}{\boldsymbol{MWh}} + \mathbf{1.4}\,\frac{\boldsymbol{€}}{\boldsymbol{MWh}} = \mathbf{37.2}\,\frac{\boldsymbol{€}}{\boldsymbol{MWh}}$$

Where

- The capital expenditure(CAPEX) is
  - $C_{CAPEX,0}$ = 1.4 M€/MW x 6.2 MW = 8.6 M€ (see slide 14)
- The annual operational expenditure (OPEX) is
  - $C_{OPEX,Annual}$ = 12600 €/MW/year x 6.2 MW = 78120 €/year (see slide 14)
- The variable operational expenditure is $LCOE_{OPEX,variable}$ = 1.35 €/MWh (see slide 14)
- The Annual Energy Production E_{AEP} = 21.6 GWh/year (see slide 10)
- The Capital Return Factor(CRF) is given below using an interest rate w = 5 % and a design life time LT = 20 years (see slide 14)

$$\boldsymbol{CRF} = \frac{1}{\sum_{t=1}^{LT} \frac{1}{(1+\boldsymbol{w})^{t}}} = \frac{w}{1-(1+w)^{-LT}} = \frac{0.05\,\frac{1}{year}}{1-(1+0.05)^{-20}} = 0.080\,\frac{1}{year}$$

LCoE levels of electricity sources of Europe

Figure 0-1 LCOE results for EU27 - main technologies' comparison - percentage change between 2008 and 2018

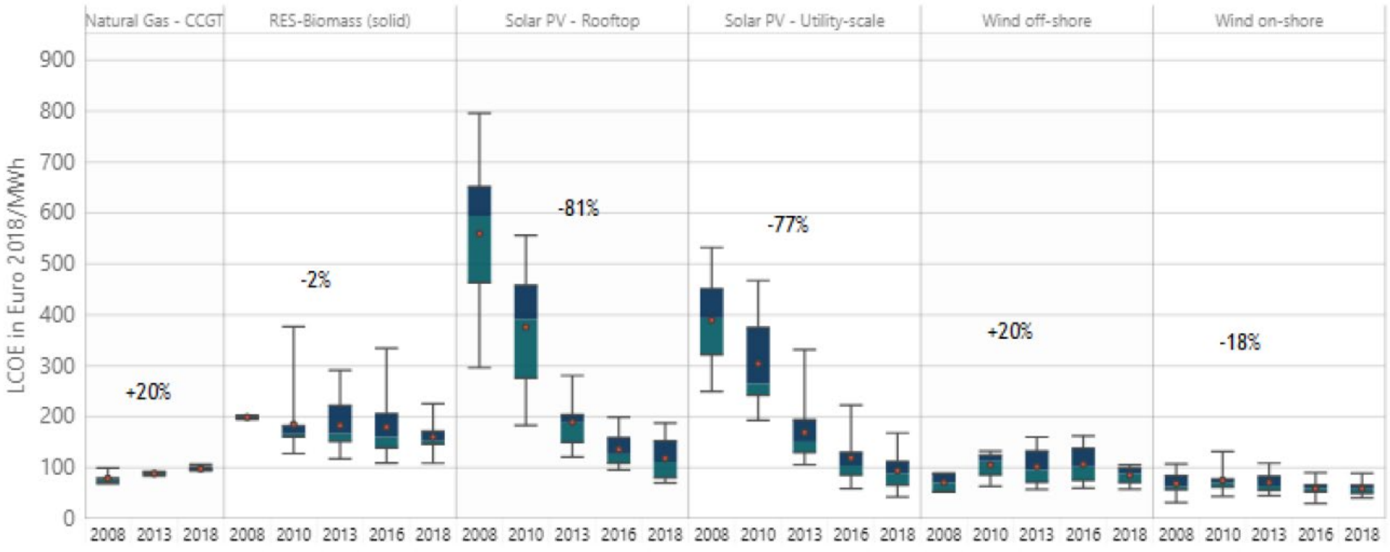
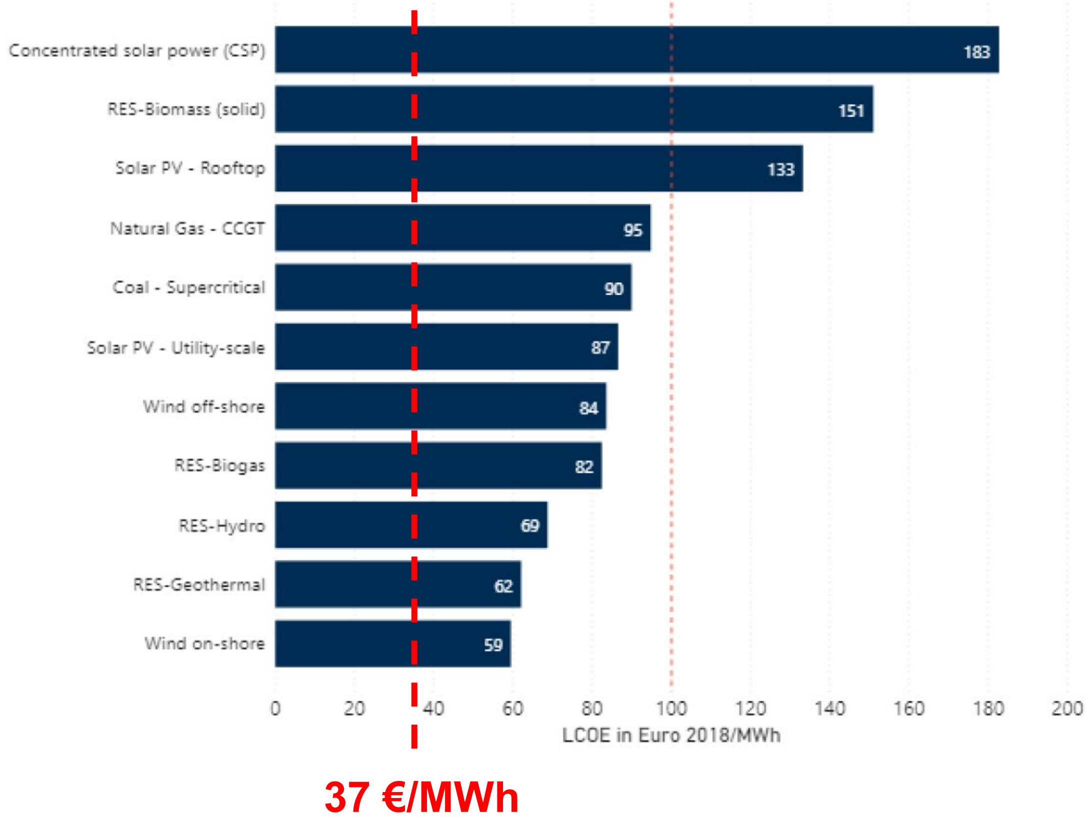


Figure 0-2 LCOE results for EU27 - in 2018



Thierry Badouard, Débora Moreira de Oliveira, Jessica Yearwood and Perla Torres, "Final Report

Cost of Energy (LCOE). Energy costs, taxes and the impact of government interventions on investments", European Commission ENER/2018-A4/2018-471 (2020)

Circularity of wind turbine blades

Glass fibre fabric
Balza wood / Foam
Resin

Blade → Decommissioning

↓

Transport → Landfill

↓

Cutting / shredding →
- Cement production
- Noise screens

↓

Separation
- Pyrolysis
- Chemical
-

→
Short glass fibres
Balza / Foam pieces
Resin rest products

↓

Other products ?

Circular material flow ?

Abrahamsen *et al.*, "Ch. 15: Towards sustainable wind energy", DTU International Energy Report 2021

DTU

DTU Wind Energy

Great news on turbine blade recycling in 2023

DecomBlades and 3B-Fibreglass are ready to unlock circular recycling of glass fibre in wind turbine blades

Remelting recycled glass fibers

1) Cut turbine blades (5-10 tons)
2) Shredding
3) Grinding
4) Pyrolysis to remove epoxy
5) Milling recycled glass fiber

Mix 1-5 % recycled glass fibers into melt of production for new glass fibers by 3B (72 metric ton)

DTU Wind and Energy Systems showed mechanical properties of remelted glass fibers are as good a normal wind turbine grade fibers.

This can enable a fully blade to blade circularity of the glass fibers of the wind industry.

Vestas

Ørsted

HJHANSEN RECYCLING

MAKEEN ENERGY

FLSMIDTH

SDU

SIEMENS Gamesa RENEWABLE ENERGY

LM WIND POWER a GE Renewable Energy business

energy CLUSTER DENMARK

Conclusion

- CO_2 emission of the Danish Energy mix is expected to reach ~ 10-15 g CO_{2eq}/ kWh using only wind turbines unless the production method of the materials used to build the turbines is changed.
- The main materials used in the wind turbines are: steel, concrete and glass fibre composite
- For offshore wind turbines the emissions will depend on the amount of recycled steel from monopiles
- Circularity in material recycling of wind turbines is improving by new blade recycling technologies

- New solutions
  – Turbine designs with less material usage (especially concrete in the foundation of onshore)
  – Usage of Green Steel and Green Cement?
  – Low CO_2 footprint steel in tower and monopile by utilizing remelted steel
  – Refining iron ore to iron using hydrogen route (water as chemical emission instead of CO_2)
  – Turbines based on completely different materials (wood in towers?)

  – Turbine design standards dictate current material usage (IEC 61400-1 and IEC 61400-3) since the turbine manufacturers have to guarantee that the chance of major failures of the turbines is small during the design lifetime.

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Quantitative DTU Sustainability

Self-assessment quiz of the Decarbonizing the Energy System module

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Quiz questions

1) What is the CO_2 emissions per produced kWh of electricity of a coal-fired power plant?
    a. 0-200 g CO_2e / KWh
    b. 200-400 g CO_2e / KWh
    c. 400-600 g CO_2e / KWh
    d. 600-800 g CO_2e / KWh
    e. 800-1000 g CO_2e / KWh
2) What is the main process contributing to the CO_2 emissions from a coal-fired power plant?
    a. The making of the steel of the power plant
    b. The making of the concrete of the power plant
    c. Burning carbon in air
    d. The energy of running the cooling water of the power plant
    e. The making of spare parts for the power plant
3) What is the CO_2 emissions per produced kWh of electricity of a natural gas-fired power plant?
    a. 0-200 g CO_2e / KWh
    b. 200-400 g CO_2e / KWh
    c. 400-600 g CO_2e / KWh
    d. 600-800 g CO_2e / KWh
    e. 800-1000 g CO_2e / KWh
4) What is the CO_2 emissions per produced kWh of electricity of the low-emission renewable technologies like wind and solar PV?
    a. 0-100 g CO_2e / KWh
    b. 100-200 g CO_2e / KWh
    c. 200-300 g CO_2e / KWh
    d. 300-400 g CO_2e / KWh
    e. 400-500 g CO_2e / KWh
5) What is the main process contributing to the CO_2 emissions from a renewable technologies?
    a. The making of the materials of the wind or solar farm
    b. Installing the wind or solar farms
    c. Operating and maintaining the wind or solar farm
    d. Decommissioning the wind or solar farm
    e. Recycling the materials of the wind or solar farm
6) What were the equivalent CO_2e emissions of the planet in 2020 [Giga ton of CO_2e emissions] according to the UN Gap report of 2022?
    a. 0-15 Gt CO_2e / year

b. 15-30 Gt CO_2e / year
c. 30-45 Gt CO_2e / year
d. 45-60 Gt CO_2e / year
e. 60-75 Gt CO_2e / year

7) What are the target emissions of the planet in 2050 according to a global warming target of 1.5 degrees Celsius in the Paris Agreement at the end of the century as described in the UN Gap report of 2023?
   a. 0-15 Gt CO_2e / year
   b. 15-30 Gt CO_2e / year
   c. 30-45 Gt CO_2e / year
   d. 45-60 Gt CO_2e / year
   e. 60-75 Gt CO_2e / year
8) If the world consumption of coal-fired electricity was 9500 TWh/year in 2019, what were the equivalent CO_2e emissions?
   a. 0-15 Gt CO_2e / year
   b. 15-30 Gt CO_2e / year
   c. 30-45 Gt CO_2e / year
   d. 45-60 Gt CO_2e / year
   e. 60-75 Gt CO_2e / year
9) What year will the 2019 CO_2e emission of the previous questions be equivalent to the planetary boundary according to the 1.5 Degree global warming scenario of the Paris Agreement?
   a. 2020-2030
   b. 2030-2035
   c. 2035-2040
   d. 2040-2045
   e. 2045-2050
10) If the coal-fired electricity consumption of 9500 TWh/year in 2019 is replaced by wind energy what are the resulting CO_2e emissions?
   a. 0.0-0.2 Gt CO_2e / year
   b. 0.2-0.4 Gt CO_2e / year
   c. 0.4-0.6 Gt CO_2e / year
   d. 0.6-0.8 Gt CO_2e / year
   e. 0.8-1.0 Gt CO_2e / year

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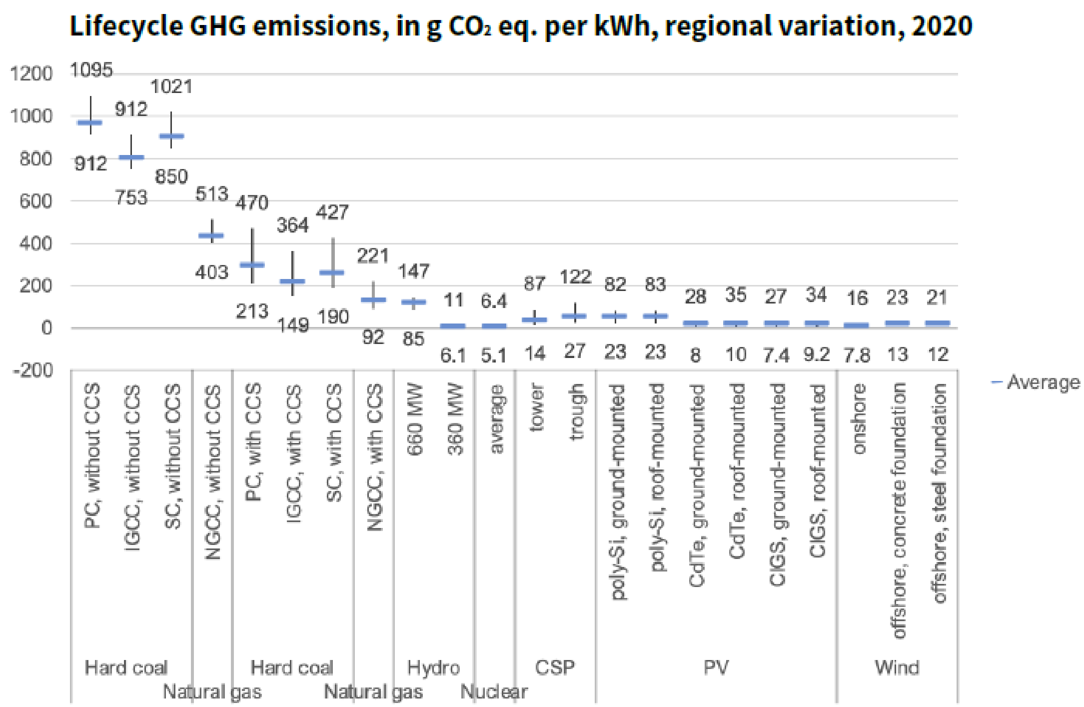
Solutions to quiz questions

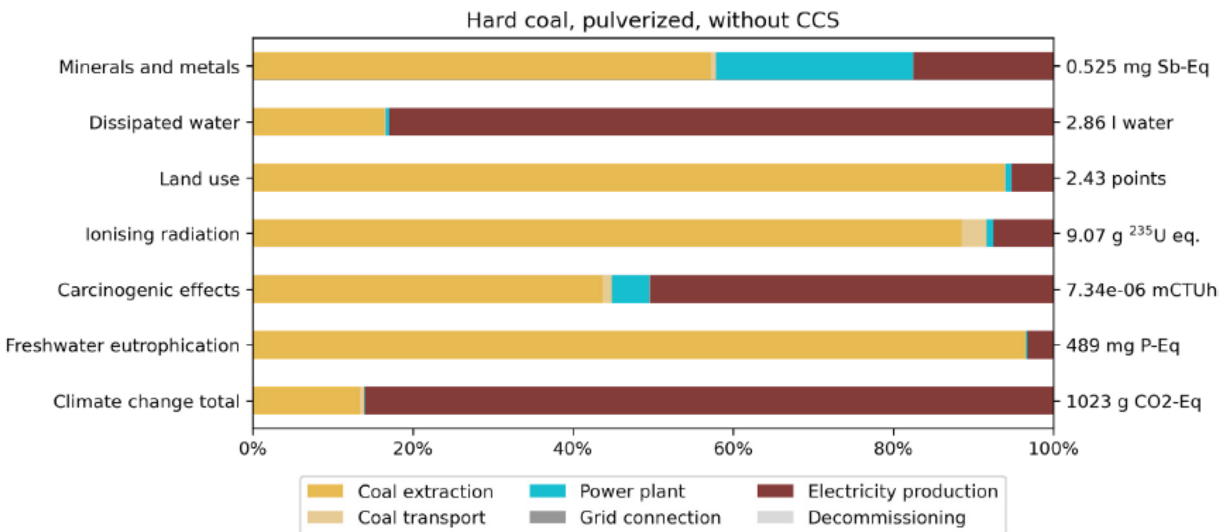
1) The UN report “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” is showing the CO_2e emissions of most electricity producing technologies and by looking at Figure 1 one will find that the CO2e emissions are in the range of 912-1095 g CO2e / kWh produced electricity. Thus the correct range is 800-1000 g CO_2e / KWh.

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies



2) The main contribution to the CO_2e emissions of a coal fires power plant can be seen from Figure 4 in the UN report and it shows that the electricity generation is responsible for 85 % of the CO_2e emission, which is coming from burning the coal in air $C + O_2 \rightarrow CO_2$. Thus the correct answer is “c. Burning carbon in air ”.

Figure 4 Life cycle impacts from 1 kWh of coal power production, pulverised coal, Europe, 2020



3) Again looking at Figure 1 of the question 1) one sees that the CO_2e emissions of a natural gas fired power plant is in the range of 403-513 g CO_2e / kWh. Thus the correct range is 400-600 g CO_2e / KWh.
4) Once more looking at Figure 1 one sees that the CO_2e emissions wind turbines are in the range of 8-16 g CO_2e / kWh for onshore turbines and 12-23 g CO_2e / kWh for offshore turbines. Similarly it is seen that CO_2e emissions of solar PV are in range of 8-83 g CO_2e / kWh. Thus the correct answer is the range 0-100 g CO_2e / kWh
5) The main contribution to the CO_2e emissions of wind turbines and solar PV farms can be seen from Figure 12 of the UN report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources". It can be seen that the largest contribution to the CO2e emission result from the tower and is related to the production of the steel used to construct the tower. It should be noted that the operation phase only contribute with a few procent to the CO2e emissions. Similarly the contributions for offshore wind turbines is seen in Figure 13, which is showing that the foundation and installation of the turbines are the main contributions.

Figure 12 Life cycle impacts from 1 kWh of onshore wind power production, Europe, 2020

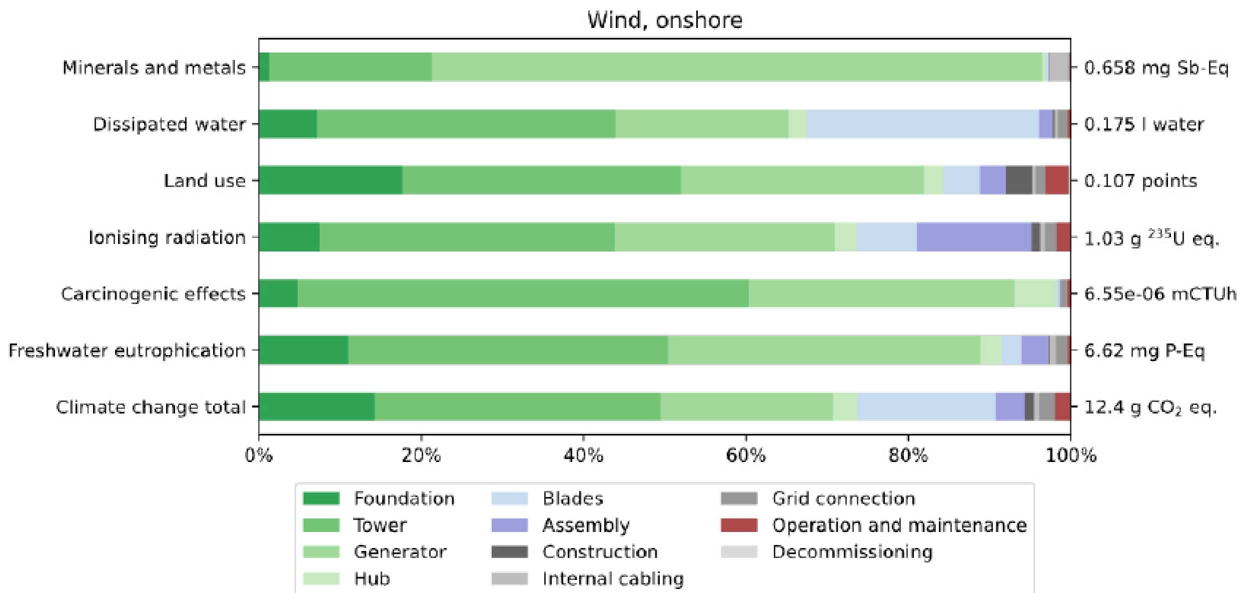
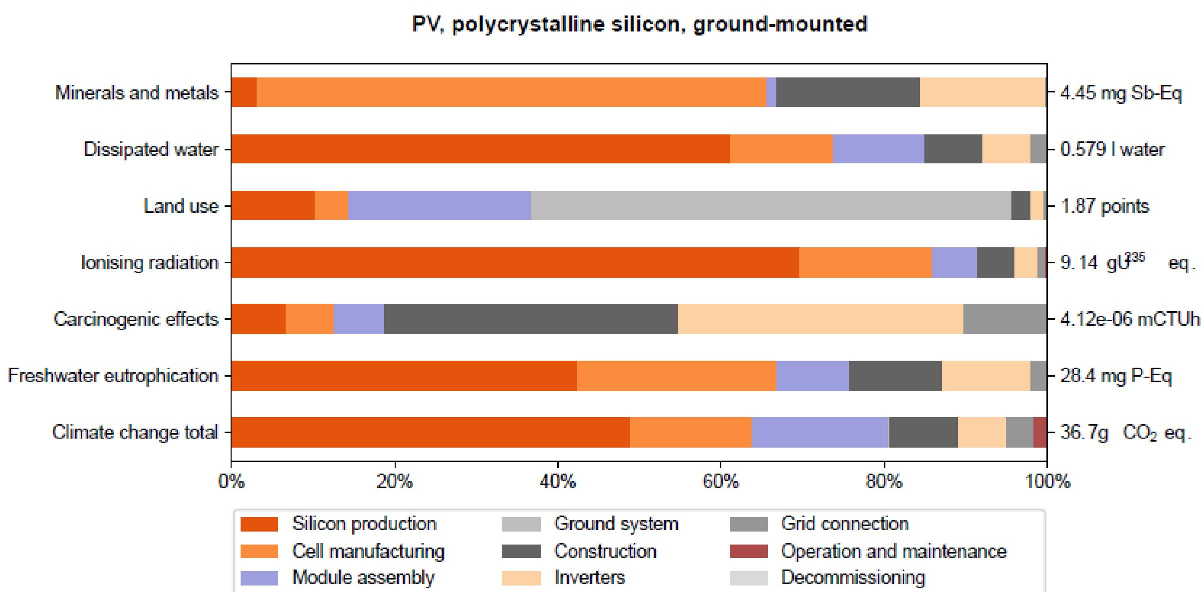


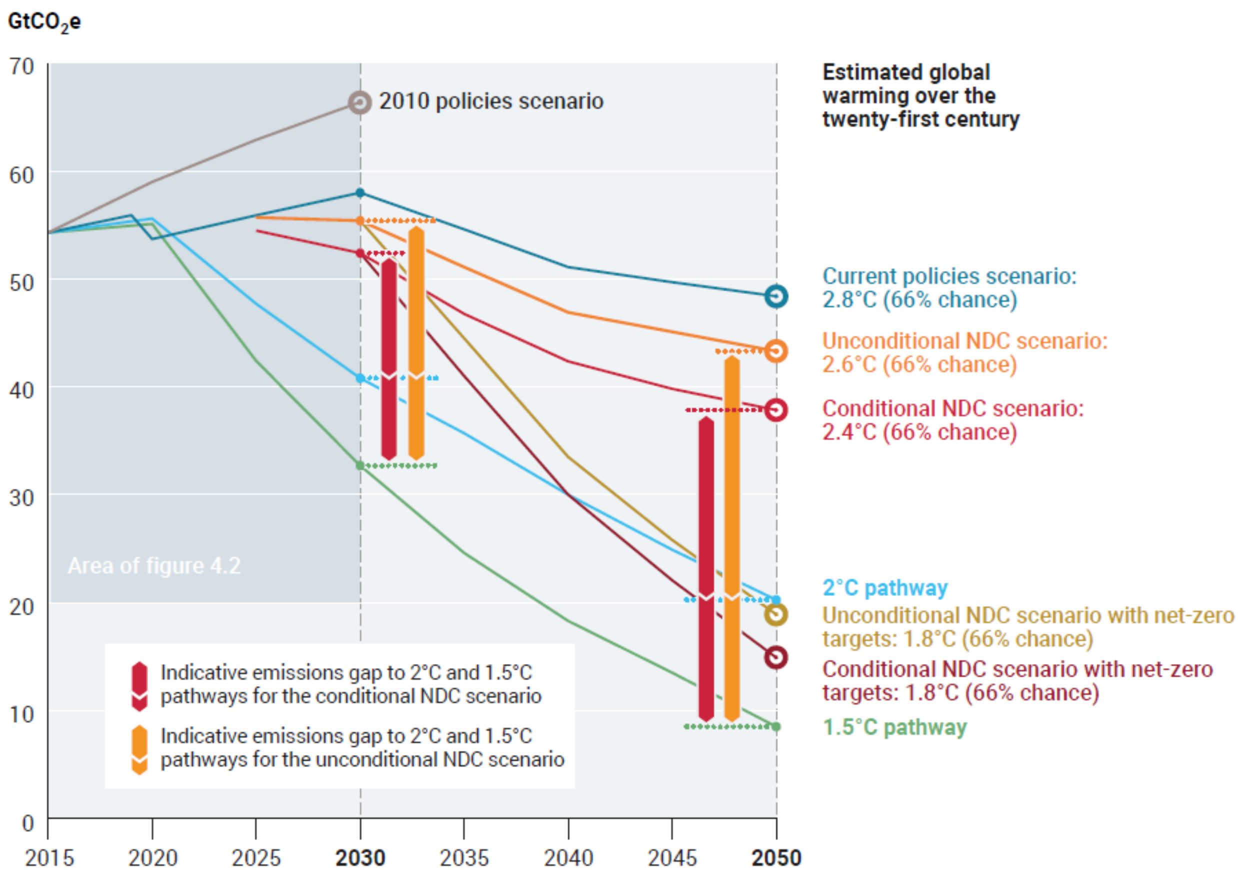
Figure 25 shows the contribution to the CO_2e emission from a ground-mounted solar PV farm and it can be seen that the production of the silicon is the main contribution to the CO_2e emissions. Thus the correct answer is "The making of the materials of the wind or solar farm"

Figure 25 Life cycle impacts from 1 kWh of poly-Si, ground-mounted, photovoltaic power production, Europe, 2020



6) By looking at the UN gap report 2022 Figure 4.3 one can see the Paris Agreement targets in terms of the global CO_2e emission to be meet towards 2050. Reading off the y-axis at the year 2020 one obtain about 54-56 Gigaton of CO_2e emissions / year. Thus the correct answer is “45-60 Gt CO_2e / year”

Figure 4.3 Projections of GHG emissions under different scenarios to 2050 and indications of emissions gap and global warming implications over this century (medians only)



7) Looking at Figure 4.3 from the UN Gap report 2022 then one can see that the global CO_2e emissions are expected to reach 9 Giga tons of CO_2e emissions per year in 2050. Thus the correct answer is “0-15 Gt CO_2e / year”.

8) The CO_2e emission m_{CO2e} resulting from E = 9500 TWh/year of coal-fired electricity production in 2019 can be estimated from the emission factor of coal EM_{coal} as seen from Figure 1 of the UN report. “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources”

$$m_{CO2e,coal} = EM_{coal} \cdot E = 1\,\frac{kg\ CO_2e}{kWh} \cdot 9500\frac{TWh}{year} = 9.5 \cdot 10^{15}\frac{kg\ CO_2e}{year}$$
$$= 9.5 \cdot 10^{12}\frac{ton\ CO_2e}{year} = 9.5\frac{Giga - ton\ CO_2e}{year} = 9.5\frac{Gt\ CO_2e}{year}$$

Thus the correct answer is “0-15 Gt CO_2e / year”.

9) By looking at the Figure 4.3 of the UN gap report 2022 one can see that an annual CO2e emission equivalent to the emissions of the coal-based electricity production of 2019 being around 10 Gt CO2e/year is crossing the 1.5 degree global warming planetary boundary of the Paris Agreement by approximately 2047. The just the worldwide electricity production by coal of 2019 will by itself violate the planetary 1.5 degree boundary in 2047. Thus the correct answer is “2045-2050”
10) If the coal-based electricity production of 2019 with E = 9500 TWh/year is replaced by onshore wind having an emission factor EM_{wind} ~ 10 g CO_2e / kWh then the global emission will be

$$m_{CO2e,wind} = EM_{wind} \cdot E = 10\,\frac{g\ CO_2e}{kWh} \cdot 9500\frac{TWh}{year} = 0.1\frac{Gt\ CO_2e}{year}$$

This will correspond to a (0.1 Gt CO_2e/year) / (9 Gt CO_2e/year) = 1 % fraction of the planetary CO_2e emission boundary in 2050 of the 1.5 Degree Paris Agreement scenario and is often interpreted as “that we do have technologies needed for the green transition”. There are many challenges related to operating an electricity system fully on wind energy sources, and a combination of many low-emission electricity production technologies combined with energy storage technologies is believed to be the most likely solution. Thus the correct answer is “0.0-0.2 Gt CO_2e / year”.

It is the hope that this quiz has provided hands-on knowledge about the CO_2e emissions of electricity producing technologies and how they relate to the planetary boundaries of CO_2e emissions.

Decarbonizing energy systems
DTU course on Quantitative Sustainability

Lecture 1 Decarbonizing energy systems
Lecture 2 Wind Energy as example
Lecture 3 Exercise : Violation of planetary boundary of Global Warming Potential due to electricity mix

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Outline of Decarbonizing energy systems

The intention of the module “Decarbonizing the energy systems” in the course Quantitative Sustainability is to enable the student to calculate the resulting Global Warming Potential emission from electricity production given a specific technology mix of a country or region. By scaling up the emission to the equivalent global emission one can compare the CO_2 emission to the global planetary boundary as dictated by the Paris agreement of a 1.5 degree global warming limit. The students will then be able to determine if a future electricity mix will violate the global planetary boundary of the Global Warming Potential.

Since there is a trend towards electrification of the energy system, then the focus of the module is on the electricity part of the energy system and especially the renewable energy technologies.

The following lectures are provided as part of the module

- Lecture 1 Decarbonizing the energy system
- Lecture 2 Wind Energy as example
- Lecture 3 Case: Violation of planetary boundary of Global Warming Potential due to electricity mix

Learning objectives of decarbonizing the energy system

The student should be able to

- **Describe** the main electricity generating technologies used around the world
- **Explain** the origin of CO_2 emissions from electricity producing units
- **Describe** the typical technology mix used for electricity production in different countries

- **Estimate** the resulting CO_2 emission of the electricity mix when producing 1 kWh electricity

- **Discuss** the expected future CO_2 emission of electricity production and propose strategies of decarbonizing the electricity system
- **Discuss** which additional technologies that might be needed in the electricity system

- **Analyse** expected CO_2 emission from a specific country or region and compare the Global Warming Potential with the UN CO_2 emission scenarios.

- **Evaluate** if the planetary CO_2 boundary is violated by the electricity generation

Outline of Lecture 1 Decarbonizing the energy system

- Electricity fraction of energy production
- Electricity-producing technologies
- Life phases of electricity-producing units
- Life cycle analysis overview of electricity producing unit as defined by the United Nations (UN)
- Environmental indicators
- Technology mix of electricity production
- The planetary boundary of Global Warming Potential of the Paris Agreement
- Strategies for decarbonizing the electricity system

Electricity fraction of energy consumption

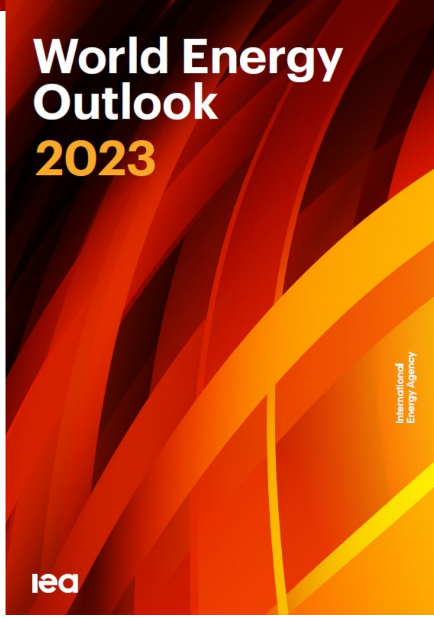
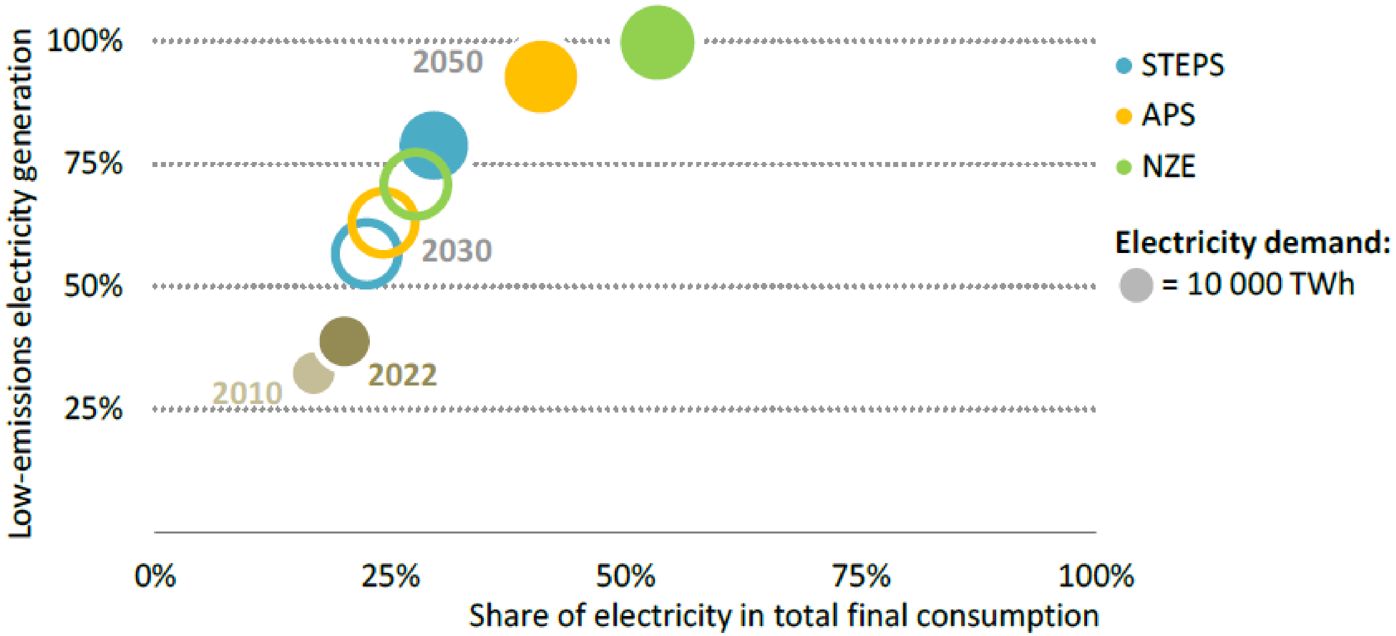


Figure 3.2 ▷ **Electricity in total final consumption and low-emissions sources in electricity generation by scenario, 2010-2050**



Power sector decarbonisation advances more rapidly than end-use electrification in each scenario, but both are key pillars of the transition to a clean energy economy

Notes: TWh = terawatt-hours. Bubble size is proportional to total electricity demand.

Source: IEA Energy Outlook 2023

Technologies for electricity production

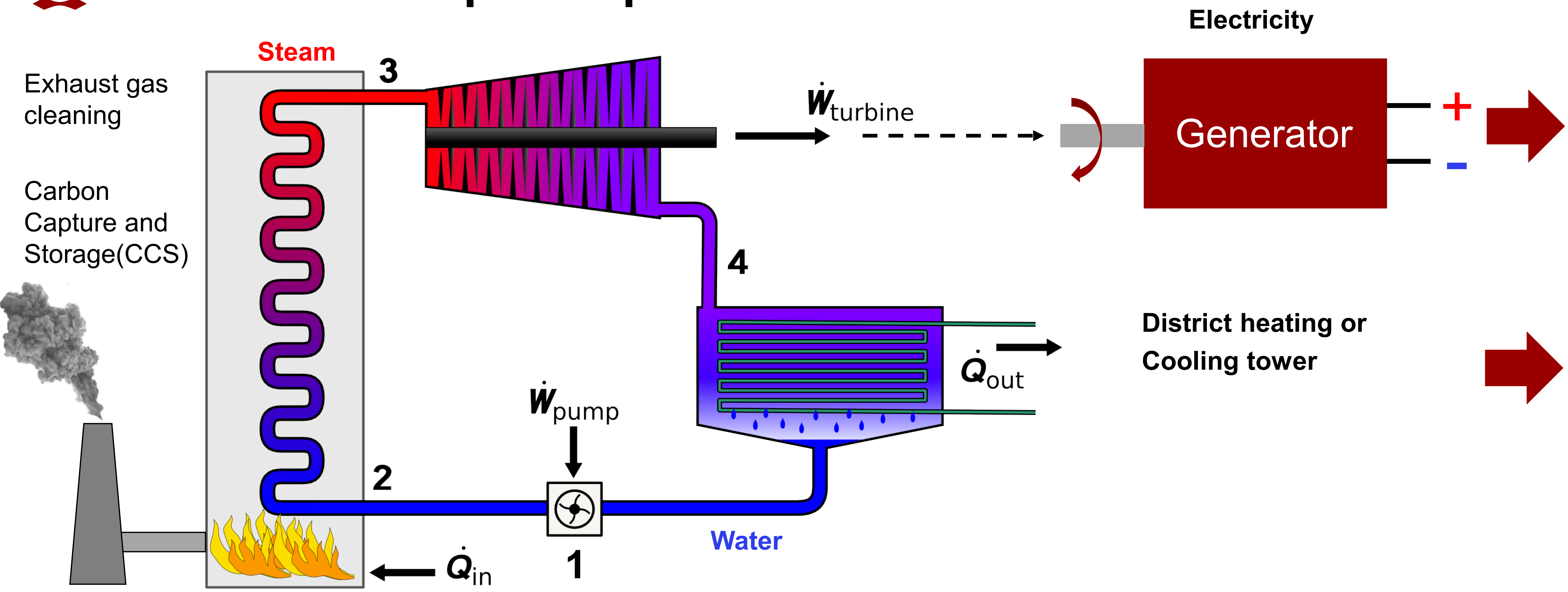
Fuel based

- Coal
- Gas
- Biomass
- Nuclear

Renewables

- Wind
- Solar
- Hydro
- Tidal
- Geothermal

Fuel based power plants



Fuel burned

concentrated solar
or nuclear process

1: Pump **2**: Boiler **3**: turbine **4**: condenser

Source: Rankine cycle (Wikimedia.org)

Burning fuels causes CO_2 emissions

Coal	C	$+ O_2$	$\rightarrow$	CO_2		+ Heat +
Methane	CH_4	$+ O_2$	$\rightarrow$	CO_2	$+ H_2O$	+ Heat +
Oil	C_xH_y	$+ O_2$	$\rightarrow$	CO_2	$+ H_2O$	+ Heat +
Wood	$C_6H_{12}O_6$	$+ O_2$	$\rightarrow$	CO_2	$+ H_2O$	+ Heat +
Plastic (PET)	$C_{10}H_8O_4$	$+ O_2$	$\rightarrow$	CO_2	$+ H_2O$	+ Heat +
Hydrogen	H_2	$+ O_2$	$\rightarrow$		H_2O	+ Heat +
Ammonia	NH_3	$+ O_2$	$\rightarrow$	NO_x	$+ H_2O$	+ Heat +
Fission	^{238}U		$\rightarrow$	^{234}U +…	+ Neutrons	+ Heat
Fusion	${}_1^2D + {}_1^3T$		$\rightarrow$	${}_2^4He$	+ Neutron	+ Heat

Remember that burning fuels in air will also include nitrogen and some sulfer, whereby NO_X and SOx can result

$$C + O_2 + N_2 \rightarrow CO_2 + NO_X$$
$$C + S_2 + O_2 \rightarrow CO_2 + SO_X$$

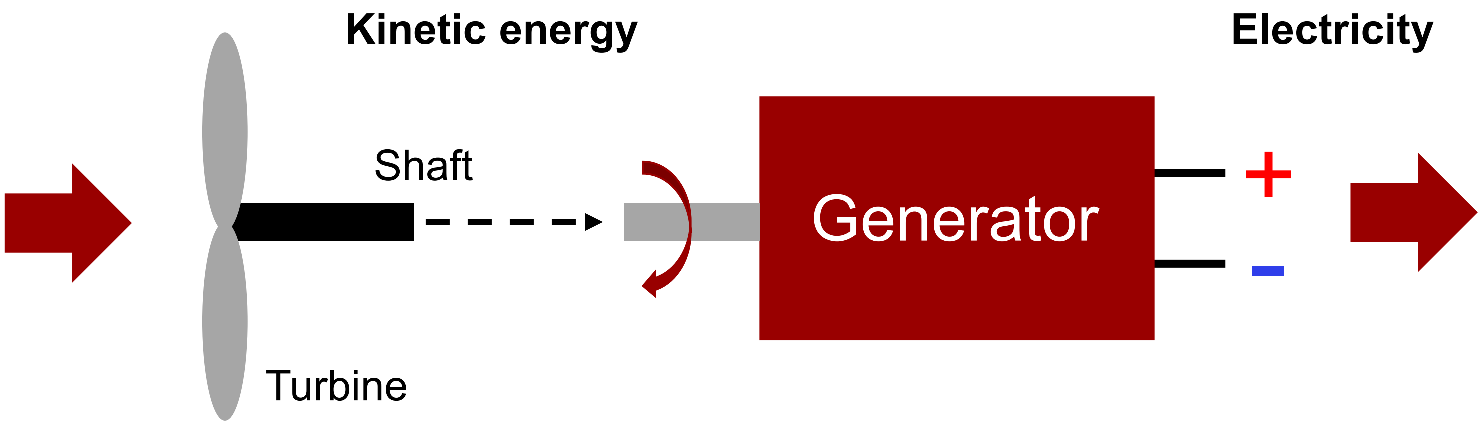
Note : Chemical formula not balanced for simplicity

Renewable based power plants

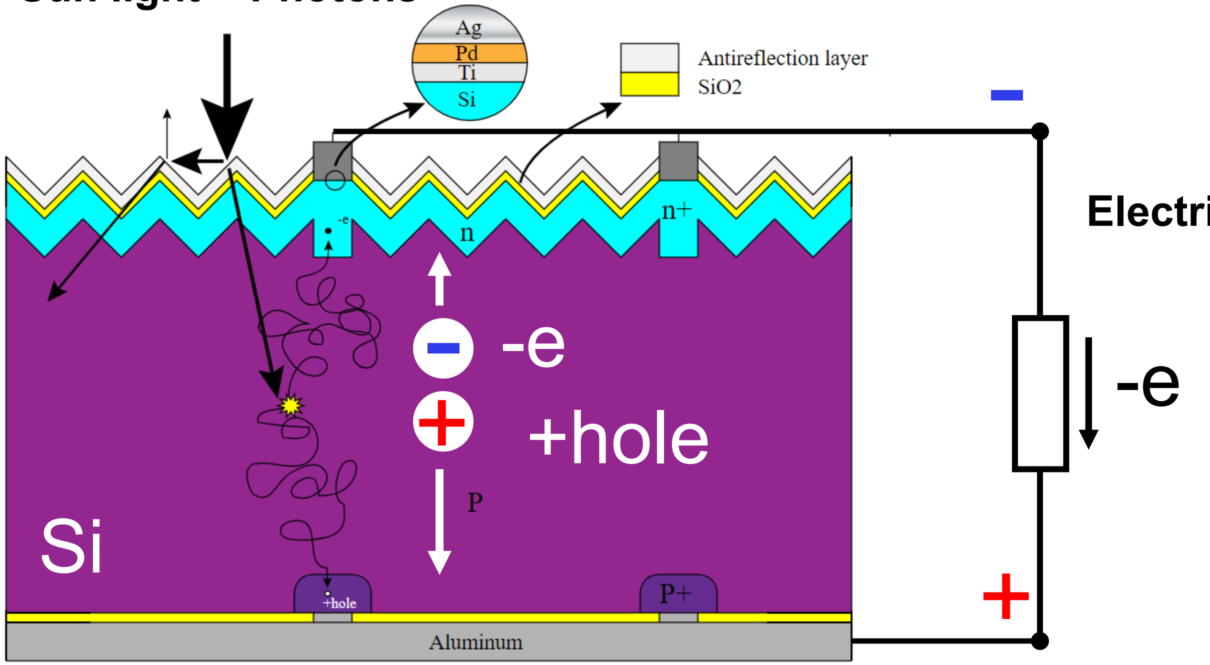
Wind flow

Water flow

- Dam
- River
- Tidal



Sun light = Photons

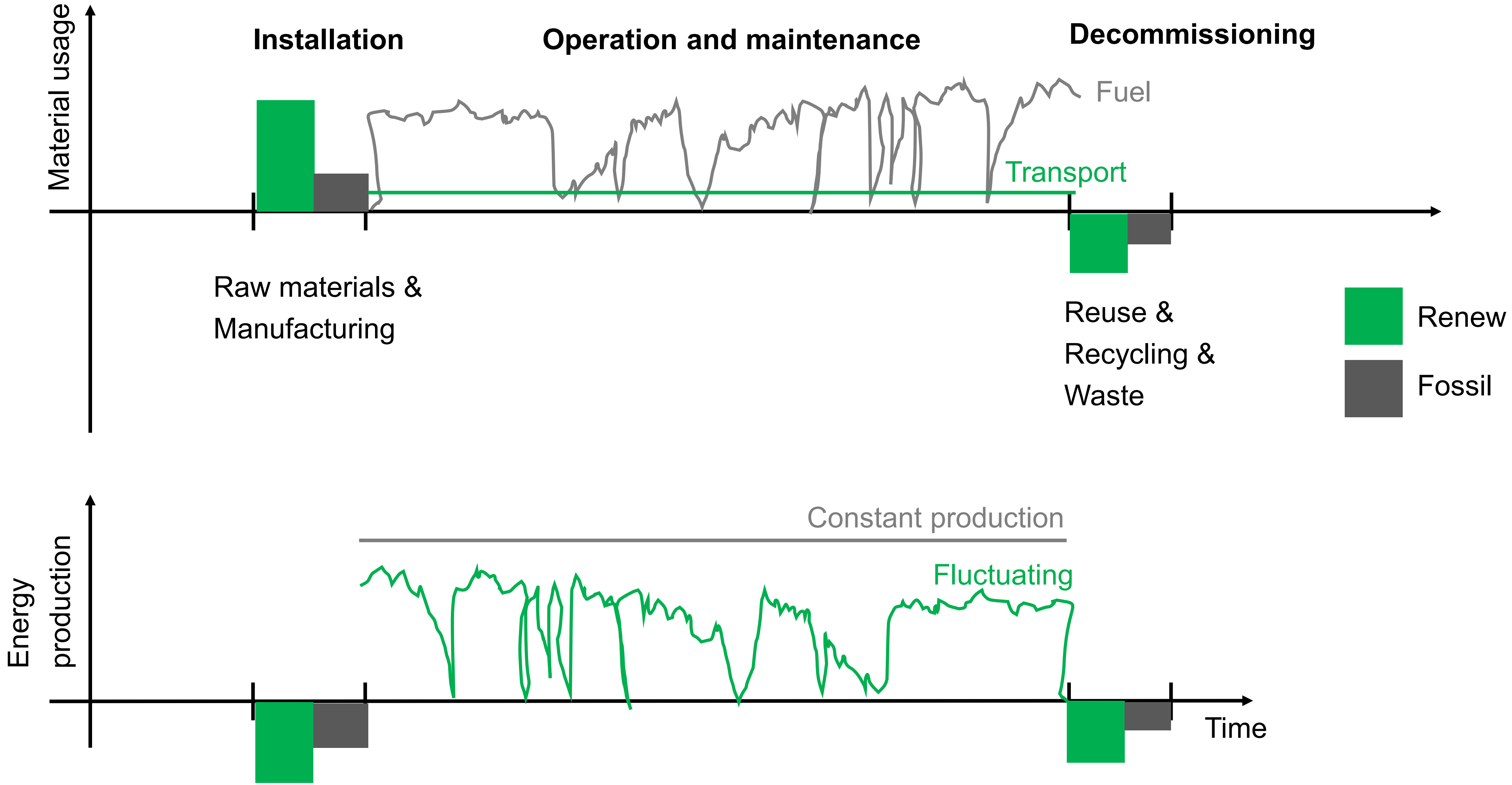


Source: Solar cell (Wikipedia.org)

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 + $\rightarrow$ 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 $\rightarrow$ 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

Life cycle of energy plants



Normalization of emissions [emission / kWh]

- The bill of material (BOM) of an energy plant accounts for the usage of the different materials m_i used to manufacture the energy plant
- The life time fuel consumption m_f is the sum of the annual fuel consumptions *AFC* used during the life time *LT* of the energy plant
- The recycling masses $m_{r,i}$ are the masses of the original bill of material recovered during the decommissioning phase, which can replace raw materials for the production of new energy plants. This means that emissions can be subtracted.
- The life time energy production *E* is then sum of the annual energy production *AEP* of the energy plant over the life time *LT* of the plant
- Total emission factors of the technology EF_j are now calculated from the specific emission factors $\varepsilon_{i,j}$ of the materials and normalized by the life time energy produced

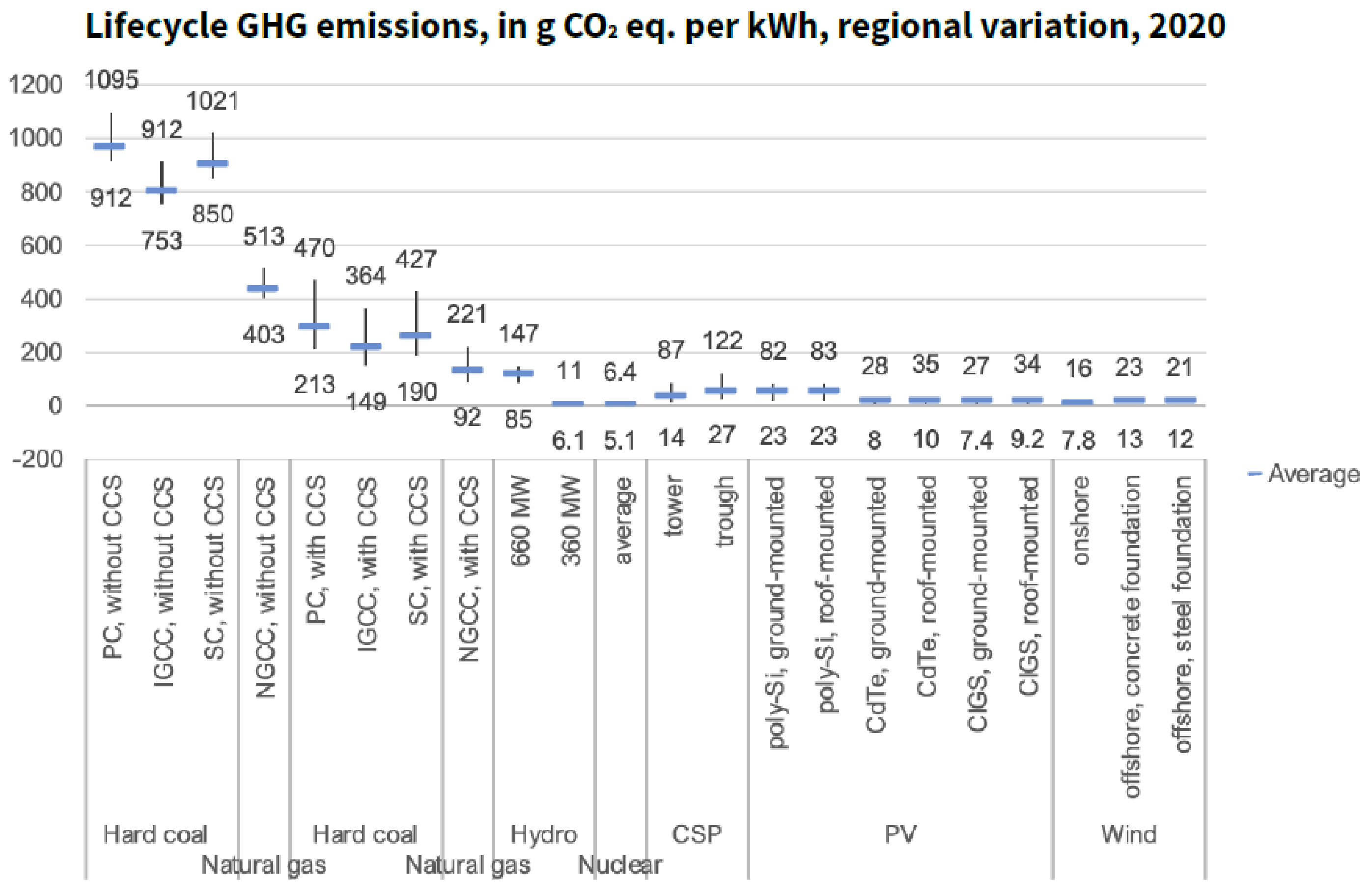
Example:

Gram CO_2 / kWh

$$EF_j = \frac{\sum_{i=1}^{N} m_i \varepsilon_{i,j} + m_f \varepsilon_{f,j} + \sum_{i=1}^{N} m_{r,i} \varepsilon_{r,i,j}}{E}$$

LCA overview of electricity producing technologies

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies



UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

Carbon Neutrality in the UNECE Region:
Integrated Life-cycle Assessment of Electricity Sources

UNECE

Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Energy technologies

Table 1 Summary of life cycle inventories' scopes, per type of technology

Recycling of materials in UN report is absent !

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

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 emit-ted, 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

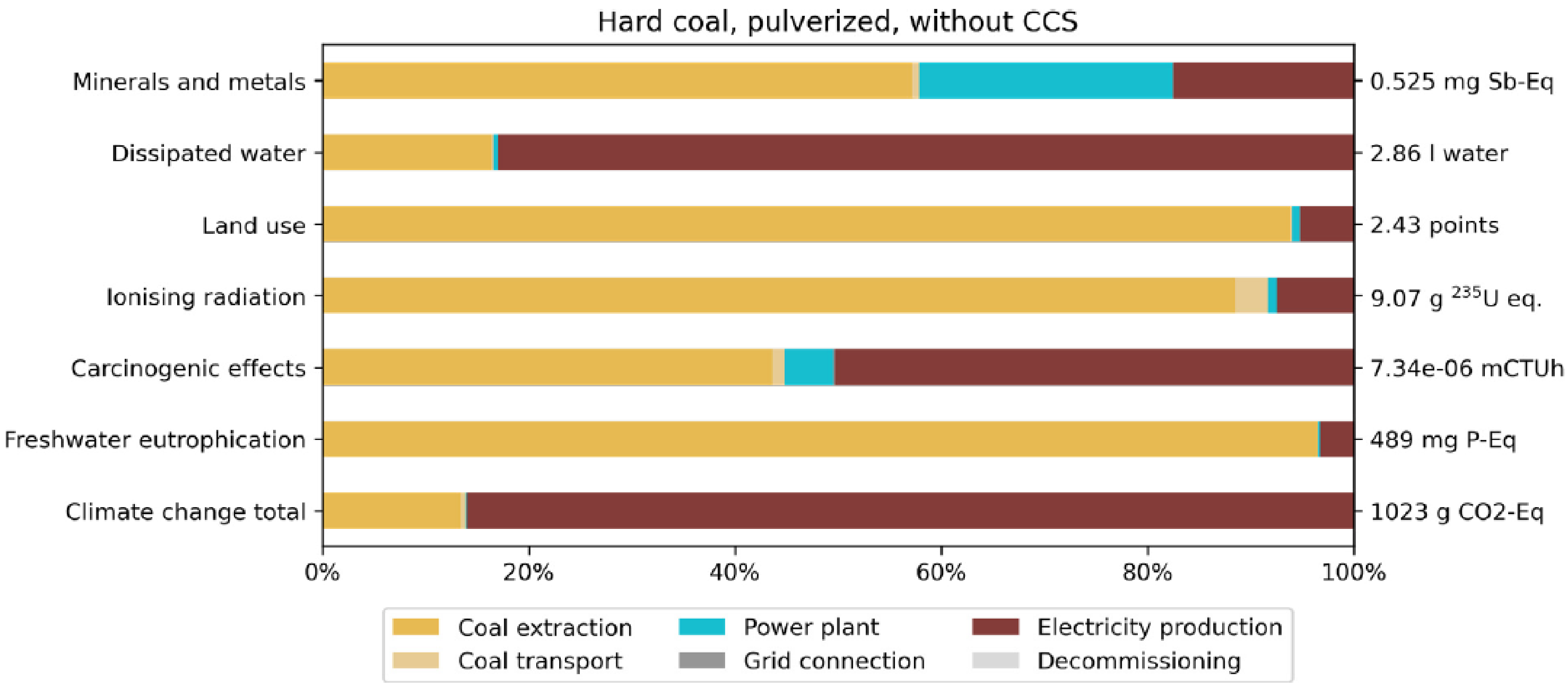
Impacts (continued)

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 re-source depletion	kg Sb eq.	Van Oers, De Koning [22]	Scarcity of resource in relation to that of antimony. Scarcity is calculated as « reserve base ».

Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

Technology examples : coal

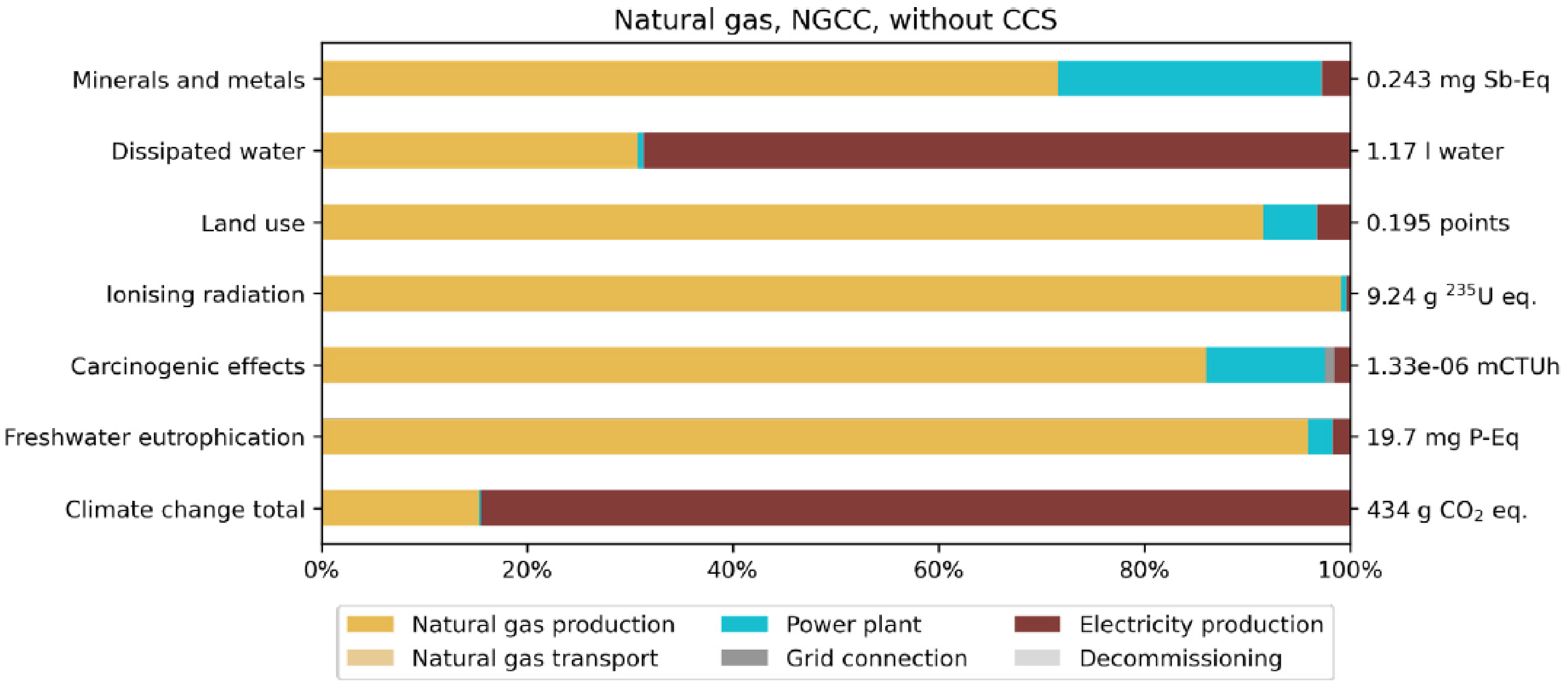
Figure 4 Life cycle impacts from 1 kWh of coal power production, pulverised coal, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Natural gas

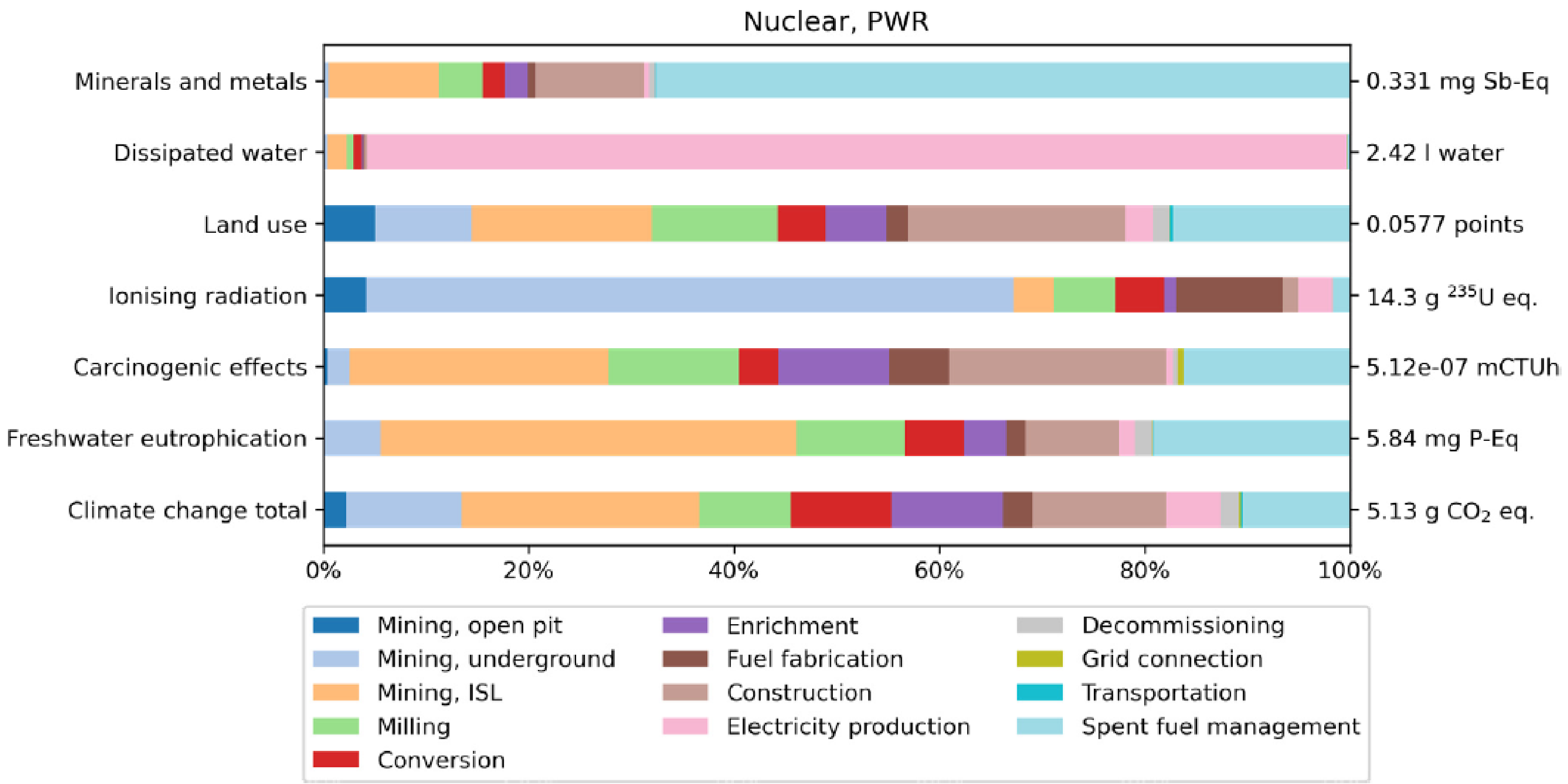
Figure 9 Life cycle impacts from 1 kWh of natural gas power production, NGCC without carbon dioxide capture and storage, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Nuclear

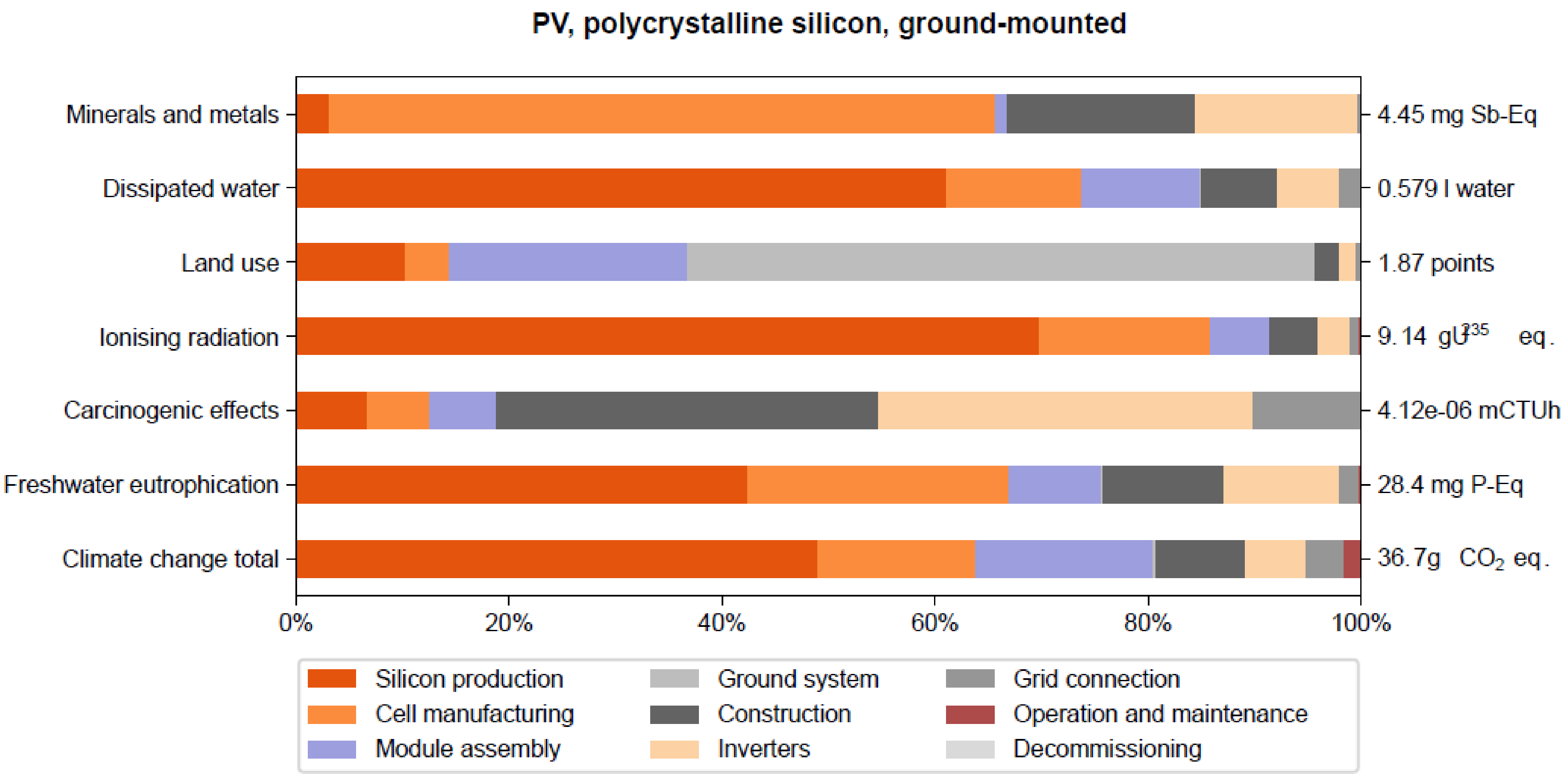
Figure 35 Lifecycle impacts of nuclear power, global average reactor, per kWh and activity



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Solar PV

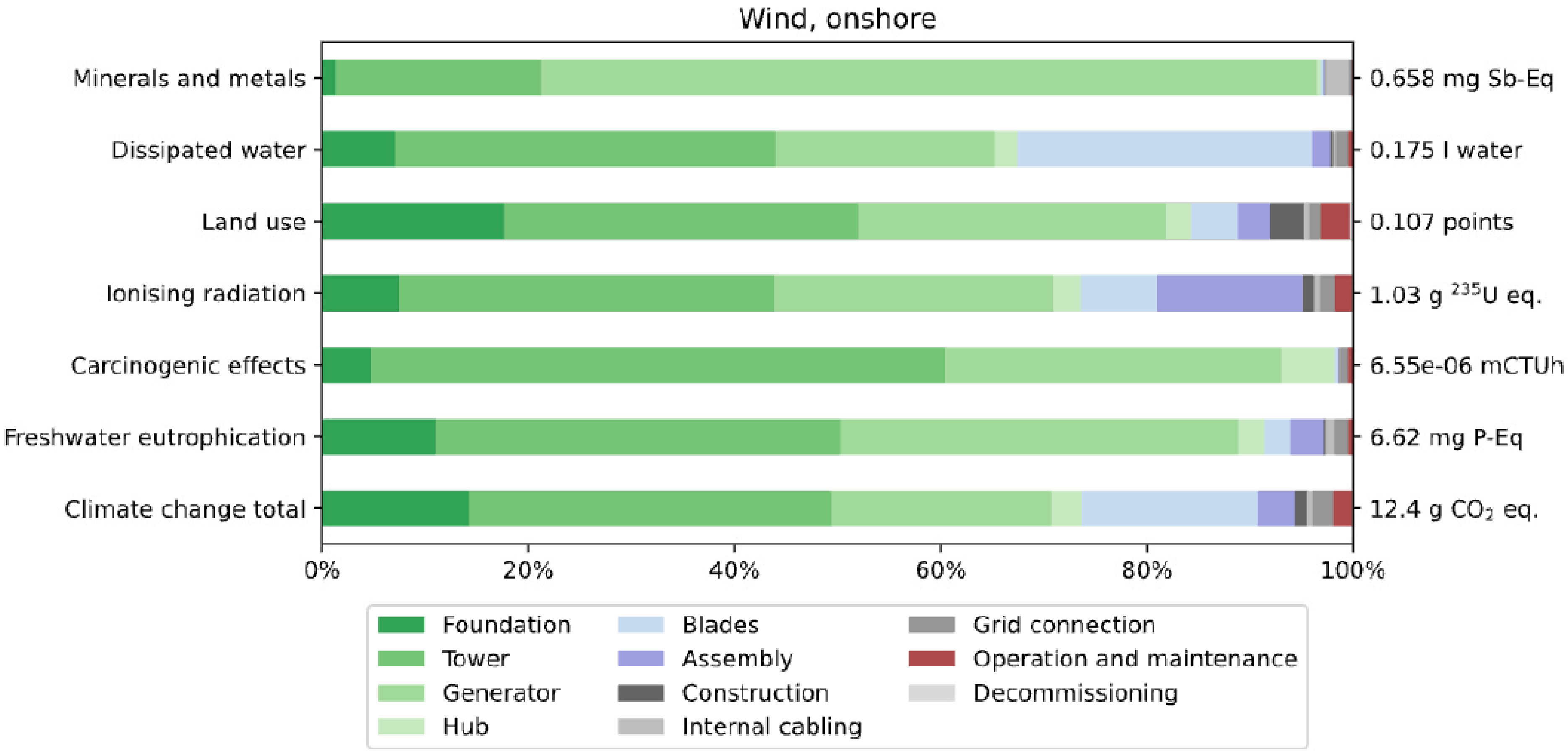
Figure 25 Life cycle impacts from 1 kWh of poly-Si, ground-mounted, photovoltaic power production, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Onshore wind

Figure 12 Life cycle impacts from 1 kWh of onshore wind power production, Europe, 2020



Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

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**

Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

Table 13 LCIA results for region EUR (Europe EU28), per kWh, in 2020, for select indicators, rounded to two significant figures.

PER KWH		CLIMATE CHANGE [g CO_2 eq.]	FRESHWATER EUTROPHICATION [mg P eq.]	CARCINOGENIC EFFECTS [µCTUh]	IONISING RADIATION [g ^{235}U 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

DTU

Full LCIA results

Table 14 is summarizing the resulting emission per kWh electricity produces in Europe

Table 14 LCIA results for region EUR (Europe EU 28), in 2020, all ILCD 2.0 indicators, three significant figures . Climate change

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	4.62E-05
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	5.12E-05
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	1.27E-05
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

Full LCIA results

Table 14 is summarizing the resulting emission per kWh electricity produces in Europe

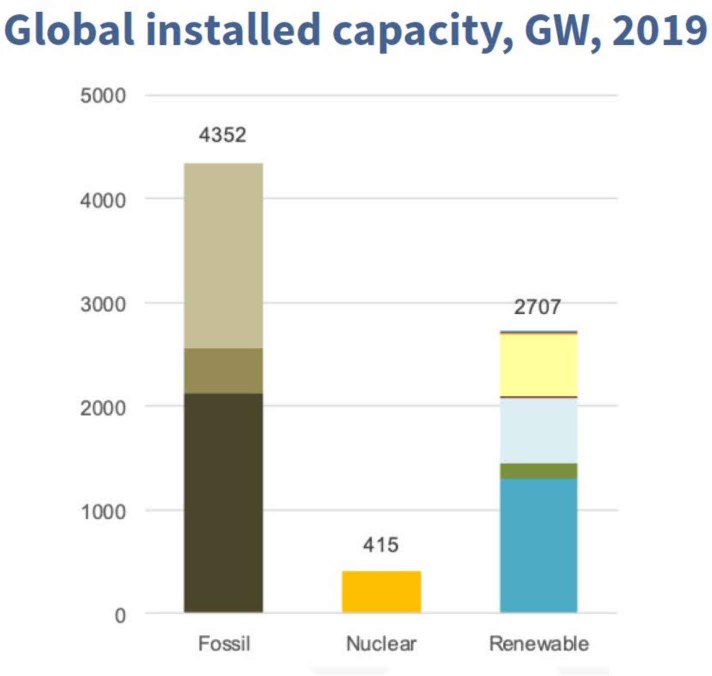
Continued from previous slide

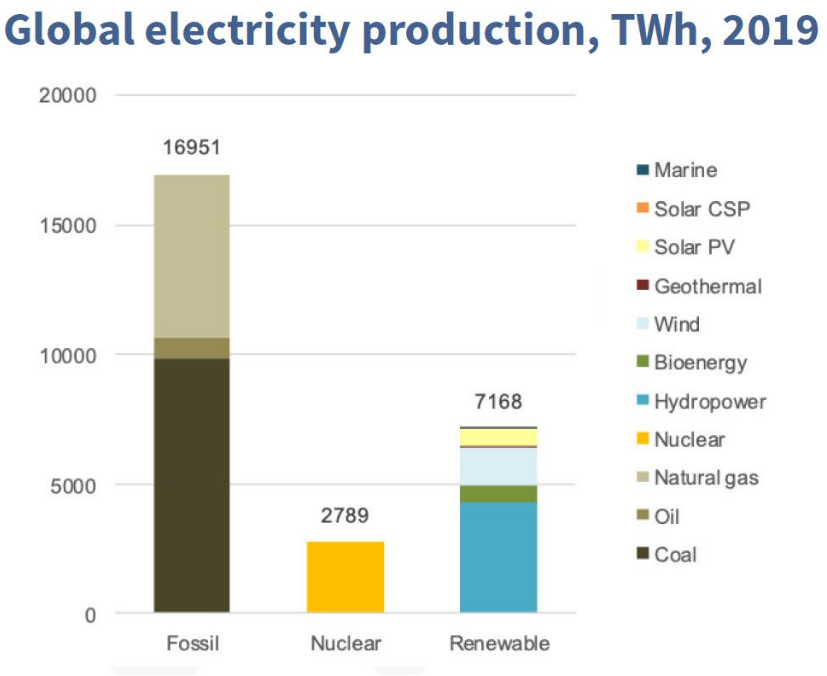
TERRESTRIAL EUTROPHICATION	CARCINOGENIC EFFECTS	IONISING RADIATION	NON-CARCINOGENIC EFFECTS	OZONE LAYER DEPLETION	PHOTOCHEMICAL OZONE CREATION	RESPIRATORY EFFECTS, INORGANICS	DISSIPATED WATER	FOSSILS	LAND USE	MINERALS AND METALS
[mol N-Eq]	[CTUh]	[kg U235-Eq]	[CTUh]	[kg CFC-11.]	[kg NMVOC-.]	[disease 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	7.43E-07
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	3.14E-07
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

Estimating the consequence of an electricity mix

If we know the mix of the electricity producing technologies and the total production then we can estimate the impact and compare this with a defined limit

Figure 2 Global installed capacity, and production, of electricity-generating plants in 2019



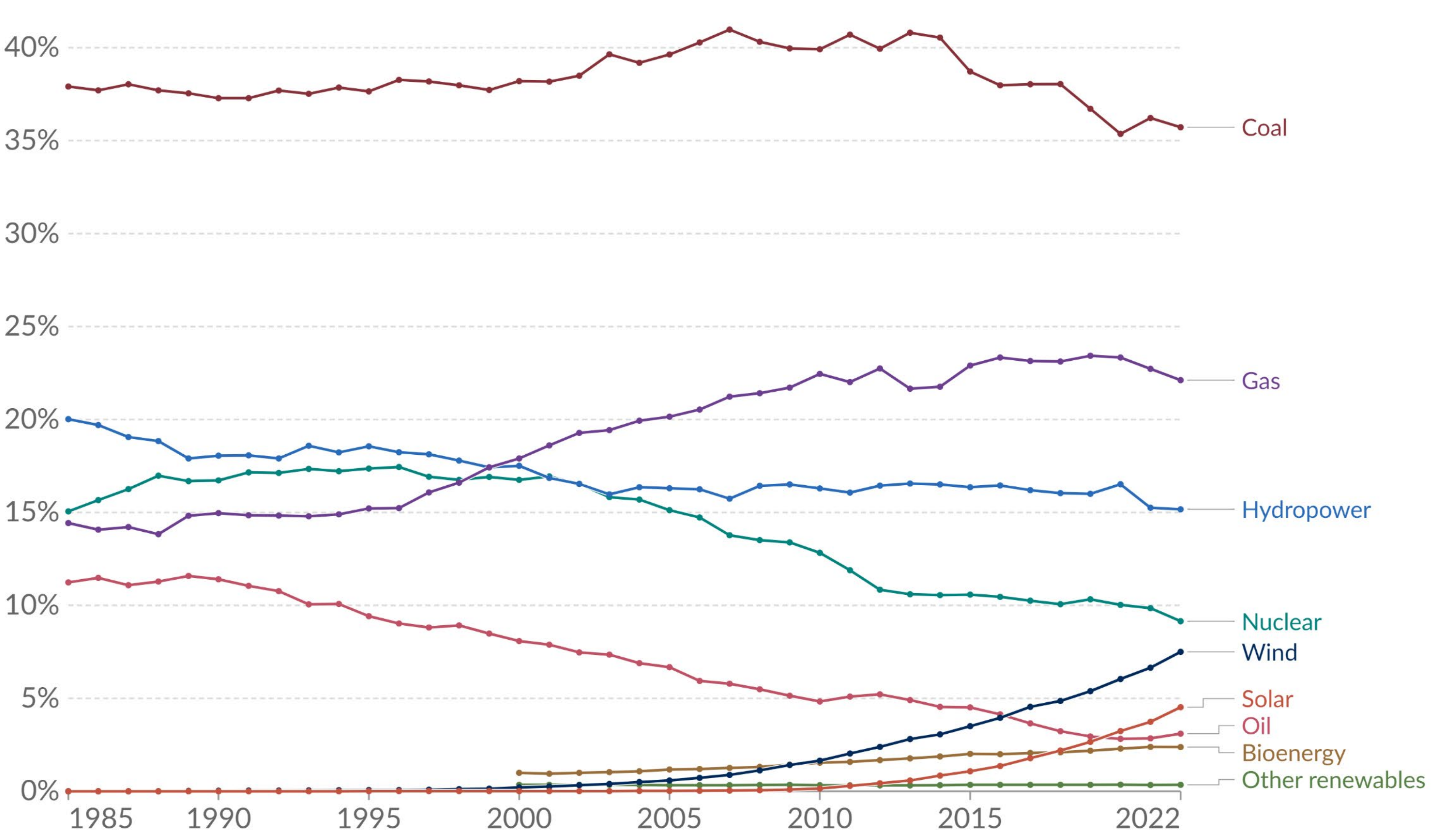


Source: *International Energy Agency [4].*

Total production in 2019 : 26908 TWh

Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Share of electricity production by source, World



Data source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy
OurWorldInData.org/energy | CC BY

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

$$1\ \text{Gt} = 10^9 \cdot 10^3\ \text{kg} = 10^{12}\ \text{kg}$$

Global boundary on green house gas

- The UN Emission Gap Report 2022 provides an estimate of the difference between the global emissions and the needed trajectory to fulfill the Paris agreement of a 1.5 °C, 1.8 °C and 2.0 °C global temperature increase by 2100. It is the accumulation of green house gasses in the atmosphere that dictates the future allowed emission levels.
- Currently the global emissions are approximately 53 Gt CO_2e per year.
- Given the global electricity mix and resulting emissions one can estimate the fraction of the total permitted emission that is provided by electricity generation.

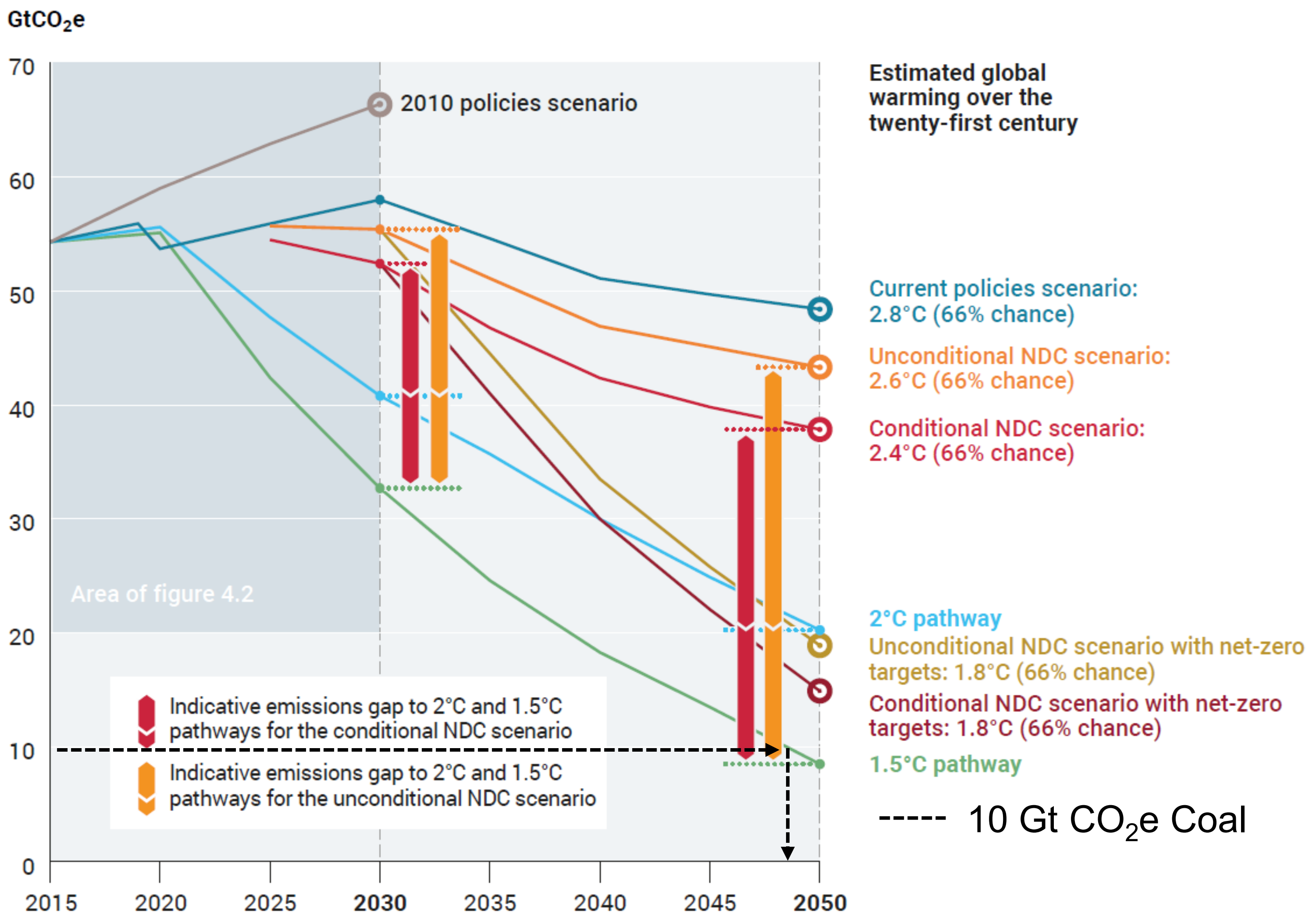
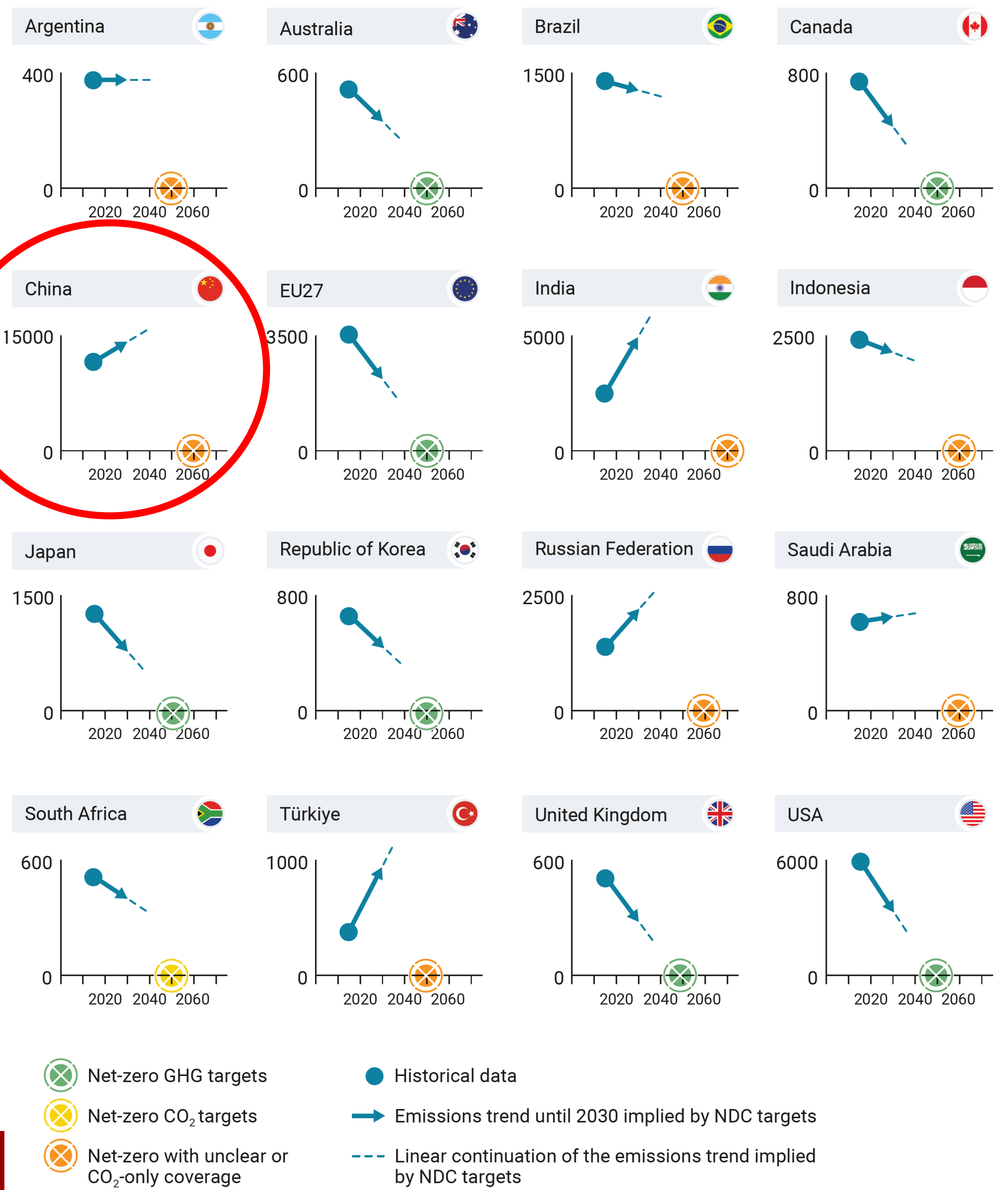


Figure 4.3 in the UN Report ”The closing window – Emission gap report 2022”

Source: UN Emission Gap Report 2022

Country specific development trends and targets

Figure ES.4 Emissions trajectories implied by NDC and net-zero targets of G20 members. National emissions in $MtCO_2e$/year over time.



The electricity climate change emission from coal and gas is comparable to the current total climate change emission of China !

$$EM_{\text{Climate change, Coal}} + EM_{\text{Climate change, gas}} = 12.5 \quad \text{Gt } CO_2e$$

Source : UN Emission Gap Report 2022

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 ^{o}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.

Strategies for decarbonizing the electricity production

ELECTRICITY SUPPLY

Actor	Actions
National governments	› Remove fossil fuel subsidies in a socially acceptable manner › Remove barriers to expansion of renewables › Stop expansion of fossil fuel infrastructure › Plan for a just fossil fuel phase-out › Adapt market rules of electricity system for high shares of renewables
International cooperation	› Cooperate on a just coal phase-out › Support initiatives on emissions-free electricity, power system flexibility and interconnection solutions
Subnational governments	› Set 100 per cent renewable targets › Plan for a just fossil fuel phase-out
Businesses	› Support a 100 per cent renewable electricity future
Investors, private and development banks	› Engage with or divest from fossil fuel electricity utility companies › Do not invest in or insure new fossil fuel infrastructure
Citizens	› Purchase 100 per cent renewable electricity

Source : Table ES.3 UN Emission Gap Report 2022

Conclusion

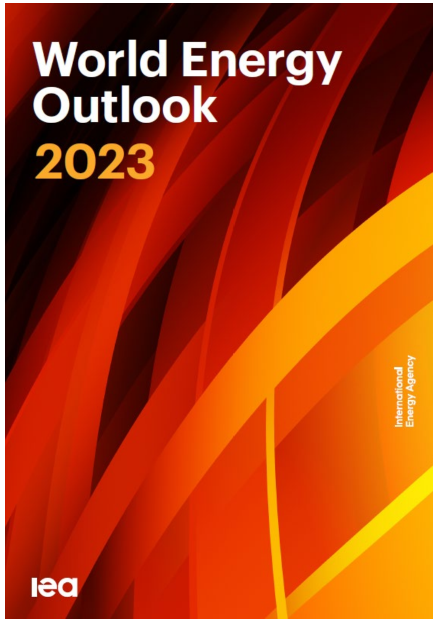
- The United National report “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources “ (2022) provides a baseline reference on the emission expected from the technologies of the electricity mix of countries and regions.

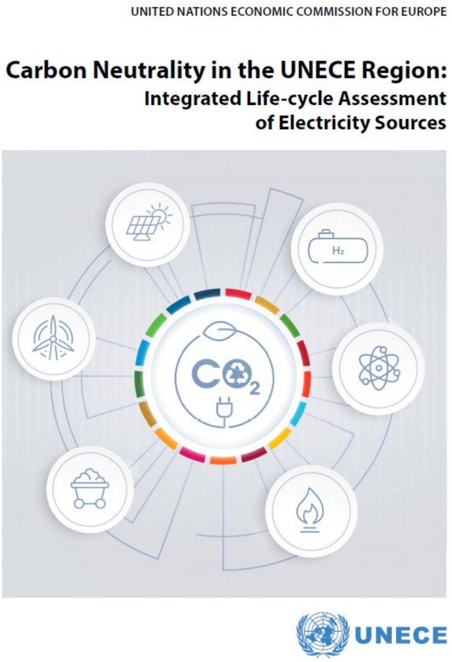
- The electricity mix of different countries and regions can be found from statistical sources (Hannah Ritchie and Pablo Rosado (2020) - “Electricity Mix” Published online at OurWorldInData.org.)

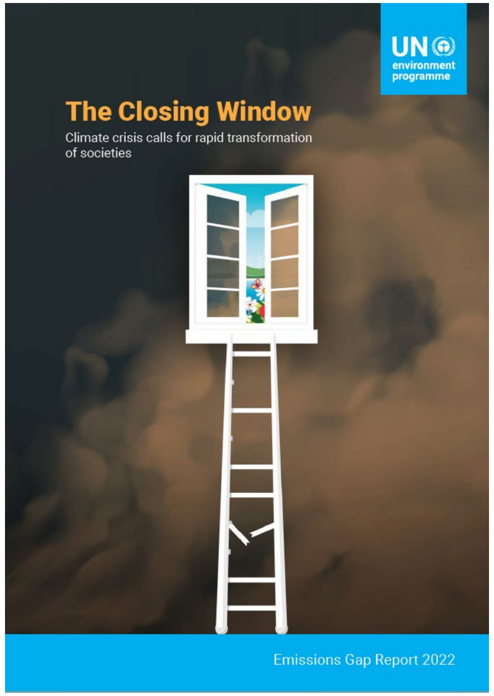
- Impacts from the electricity mix can then be estimated using the reference values and compared to the UN emission gap report in order to understand how close the planetary climate change emission is to the planetary boundary.

The student of the course is encouraged to examine possible decarbonization strategies in the exercise in the following lectures.

Sources







- IEA Energy Outlook 2023
- UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE : “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)
- United Nations Environment Programme (2022). Emissions Gap Report 2022: The Closing Window — Climate crisis calls for rapid transformation of societies. Nairobi.

Decarbonizing energy systems
DTU course on Quantitative Sustainability

Lecture 1 Decarbonizing energy systems
Lecture 2 Wind Energy as case
Lecture 3 Exercise : Violation of planetary boundary of Global Warming Potential due to electricity mix

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Technical University of Denmark
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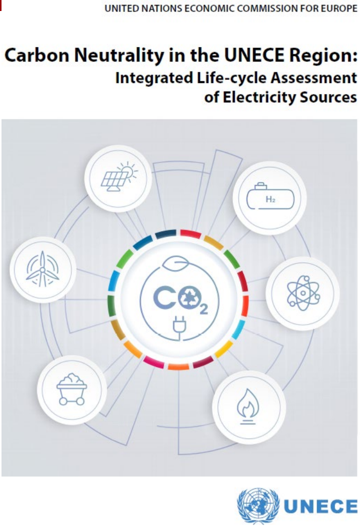
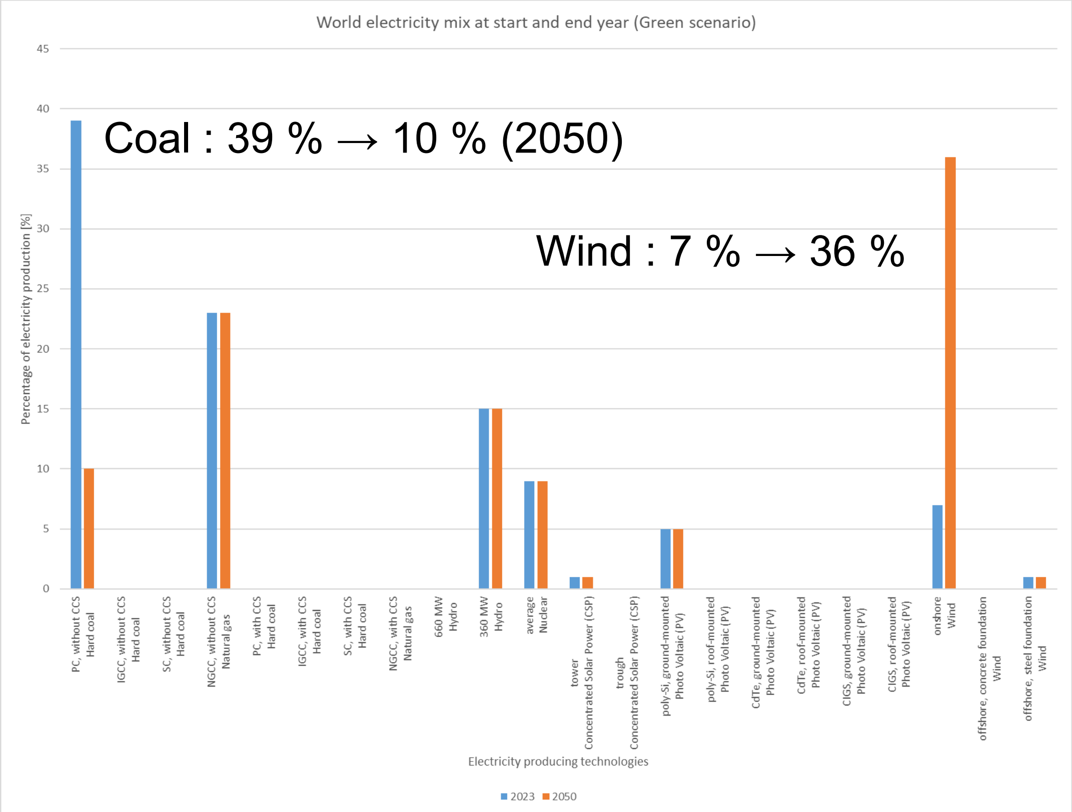
Violation of planetary boundary of Global Warming Potential due to electricity mix

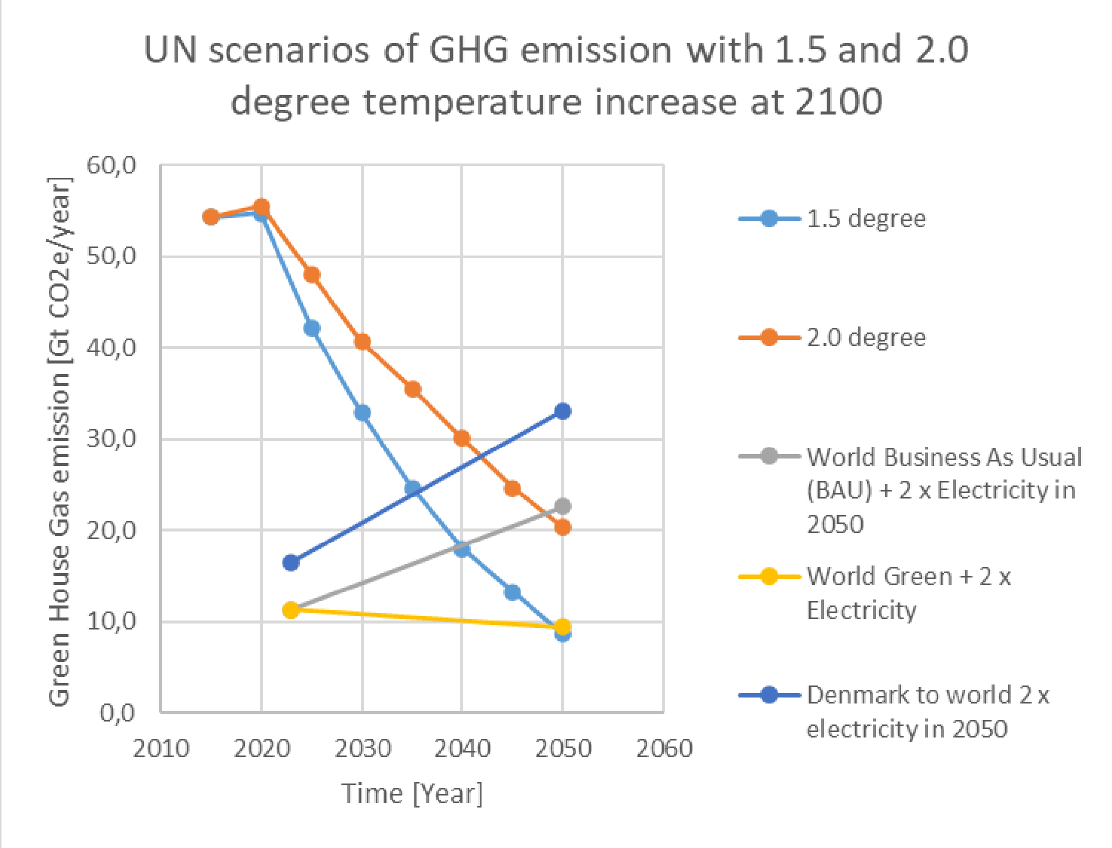


This exercise has been created to illustrate the Global Warming Potential or CO_{2e} emission resulting from a mix of electricty producing technologies on the scale of planet Earth and then to compare the emissions to the planetary boundary of 1.5 °C heating in 2100 as formulated in the Paris agreement. The students should suggest a future technology mix of 2050 and determine if the planetary boundary is violated. Secondly they should analyse a country scaled to planet scale.

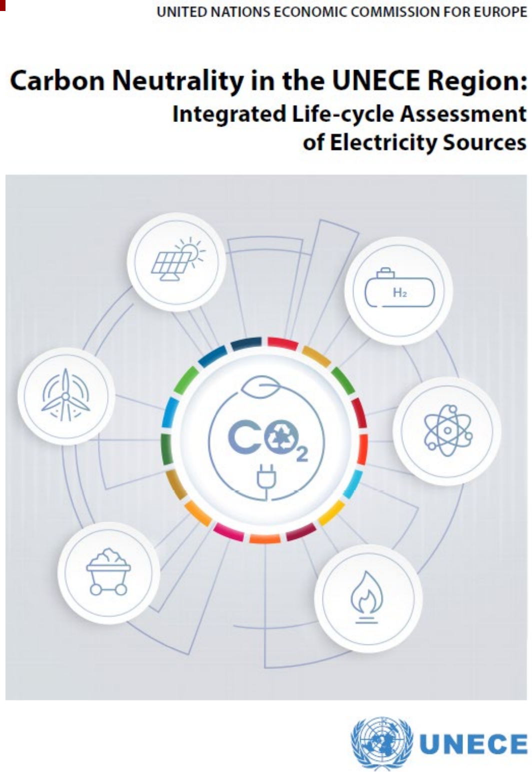


Green scenario

- Double electricity demand in 2050
- Reduce coal
- Increase wind
- 6 million Danes
- 8 billion people on earth



Violation of planetary boundary of Global Warming Potential due to electricity mix – Learning objectives



The objectives with the GWP violation exercise is to learn the students how to

- Evaluate the $CO_{2,eq}$ emissions resulting from a mix of electricity-producing technologies of planet Earth.
- Compare the $CO_{2,eq}$ emissions with the planetary boundary according to the UN global warming scenario of 1.5 ^{o}C temperature increase by end of the century and determine if the boundary is violated.
- Formulate an electricity technology mix of 2050 and evaluate if the planetary $CO_{2,eq}$ boundary is violated with the assumption that electricity demand double in 2050 due to the electrification of heating, transport and other sectors.
- Determine the $CO_{2,eq}$ emission of a specific country if the electricity consumption is scaled to the population of the planet and determine if the planetary boundary is violated. Thus, one can ask the question, “What will the emissions be if the planet lives like the Danes in 2050?”

Simple method of evaluating Global Warming Potential of the electricity mix of the world

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:

$$E_m = EF_{average} \cdot E$$

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

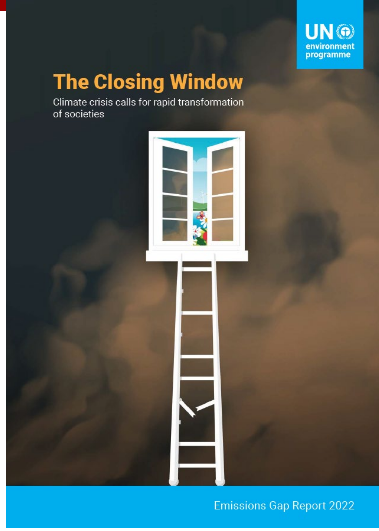
- $I_{country}$ is the impact of the country in terms of CO_2 emission in Gt CO_{2e}/year
- $P_{country}$ in the population of the country in the unit of [persons]
- A is the affluence in terms of energy consumption per citizen per year [kWh/ person / year]
- T is the emission of the technology mix in 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].

Comparison to planetary boundary of Global Warming Potential(GWP)



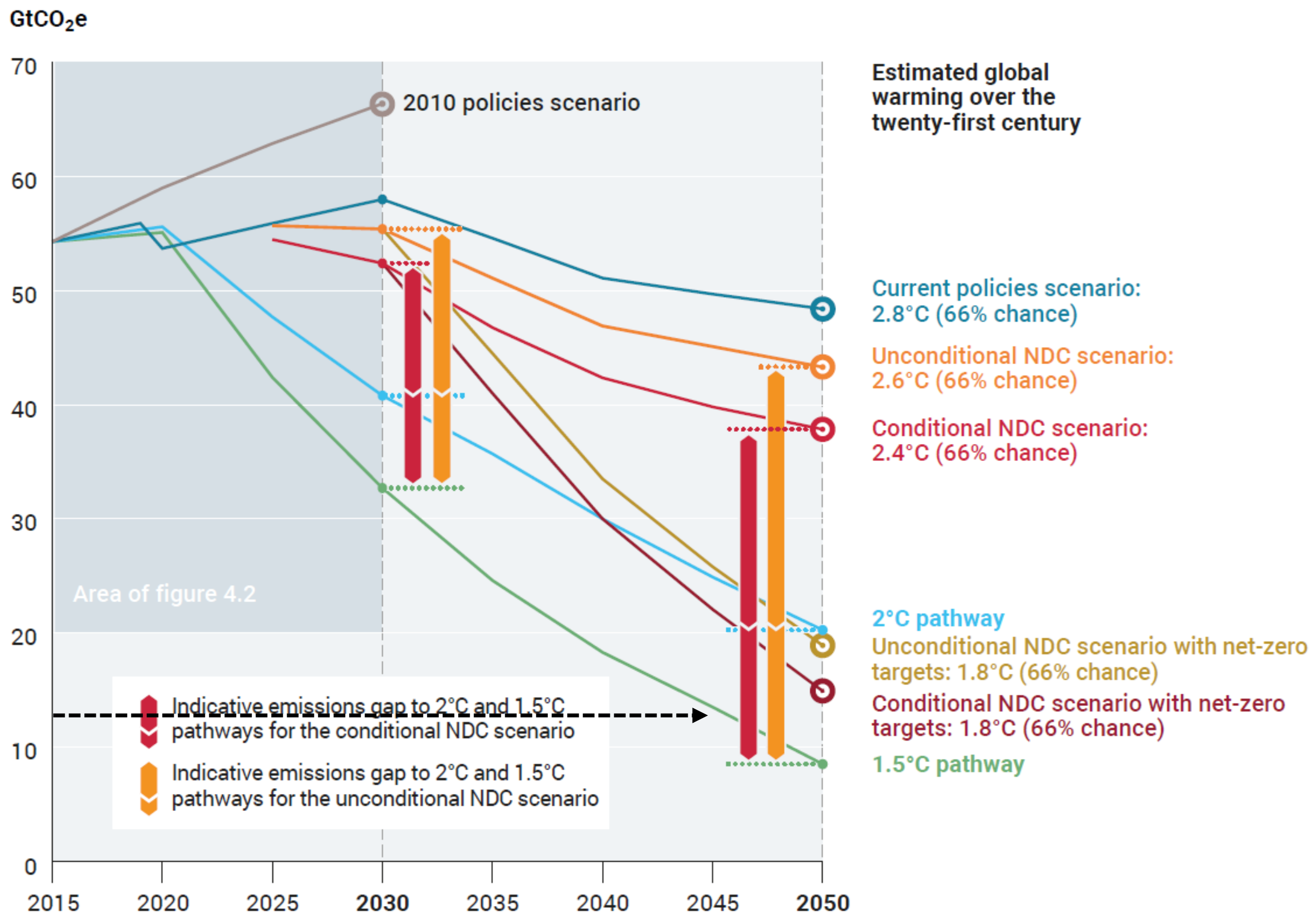


Figure 4.3 in the UN Report "The closing window – Emission gap report 2022"

- The estimated global emission can be compared directly to the UN report on the emission gap of 2022.
- Different formulations of the planetary boundary have been formulated, but the 1.5 ^{o}C pathway is used for the comparison.
- It should be noted that the 13 $GtCO_2e$ of coal and gas emission from electricity production in 2022 from Lecture 1 will violate the 1.5 ^{o}C path around 2045.
- An excel spread sheet has been created for calculating the impact of an electricity system and should be used to solve the exercise.

Instruction of exercise

A tool facilitating emission calculations has been created as an Excel sheet and is called

PlanetaryCO2Boundary_ElectricityTechnologyMix_v2_Abrahamsen.xlsx

It can be downloaded either from the DTU Learn page of the Quantitative Sustainability course or from this orbit project page :

https://orbit.dtu.dk/en/projects/decarbonizing-energy-systems

Open the Excel sheet on your computer and check if the numbers and plots are updating when some input data (grey fields) are changed. Check that your decimal sign ”.” or ”,” is set correctly. Some users with an Apple computer might need to review the settings of Excel.

The following slides will explain the different sheets of the tool and how to use the tool.

Overview of PlaneraryCO2boundary tool

Planetary CO2 boundary

This excel sheet has been created as part of the course 12100 Quantitative sustainability at the Technical University of Denmark (DTU) in 2023
The purpose of the spread sheet is to be able to specify the electricity technology mix of the world and then estimate the resulting emissions using the LCA results
of the United Nation report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)
The global warming potential (gCO2e) of the world is estimated and compared to the global CO2 emission target of the 1.5 degree Celcius scenario of the Paris agreement
The students can then enter an electricity technology mix of 2050 and determine if the planetary boundary of the global warming potential is violated.
Finally the students can enter an electricity technology mix of a country or region and determine if the planetary boundary of global warming potential is violated if the population of the region is scaled to the population of the planet.

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	Version	1
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Sheets

1) Introduction

2) Emissions of world Business As Usual (BAU)

3) Emissions of the world green scenario

4) Emissions of Denmark

5) Result plot

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Emission input from UN report on LCA of electricity producing technologies

	A	B	C	D	E	F	G	H	I	J	K	L	
1	**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	FRESHWATER AND TERRESTRIAL ACIDIFICATION	FRESHWATER ECOTOXICITY	FRESHWATER EUTROPHICATION	MARINE EUTROPHICATION	TER EUT N
2			[%]	[%]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]	[mc
3	Hard coal	PC, without CCS	39	39	6,87E-05	1,02E+00	1,67E-04	1,02E+00	1,73E-03	4,72E-01	4,89E-04	5,14E-04	
4	Hard coal	IGCC, without CCS	0	0	5,38E-05	8,49E-01	1,40E-04	8,49E-01	1,05E-03	3,46E-01	4,24E-04	4,18E-04	
5	Hard coal	SC, without CCS	0	0	6,45E-05	9,53E-01	1,56E-04	9,53E-01	1,63E-03	4,33E-01	4,58E-04	4,82E-04	
6	Natural gas	NGCC, without CCS	23	23	7,78E-05	4,34E-01	8,21E-05	4,34E-01	3,26E-04	1,16E-01	1,97E-05	4,96E-05	
7	Hard coal	PC, with CCS	0	0	1,06E-04	3,68E-01	2,47E-04	3,69E-01	1,80E-03	8,26E-01	6,90E-04	7,29E-04	
8	Hard coal	IGCC, with CCS	0	0	7,23E-05	2,79E-01	1,89E-04	2,79E-01	1,35E-03	4,94E-01	5,71E-04	5,36E-04	
9	Hard coal	SC, with CCS	0	0	9,90E-05	3,33E-01	2,34E-04	3,33E-01	2,25E-03	7,51E-01	6,37E-04	6,92E-04	
10	Natural gas	NGCC, with CCS	0	0	9,39E-05	1,28E-01	9,93E-05	1,28E-01	6,07E-04	2,34E-01	2,40E-05	7,42E-05	
11	Hydro	660 MW	0	0	5,32E-05	1,47E-01	1,09E-04	1,47E-01	4,15E-04	3,97E-01	1,26E-05	9,54E-05	
12	Hydro	360 MW	15	15	1,80E-05	1,07E-02	9,21E-06	1,07E-02	4,45E-05	2,73E-02	1,33E-06	1,23E-05	
13	Nuclear	average	9	9	2,56E-05	5,24E-03	2,26E-05	5,29E-03	4,28E-05	2,70E-02	6,45E-06	8,20E-05	
14	Concentrated Solar Power (CSP)	tower	1	1	3,02E-05	2,16E-02	3,36E-05	2,17E-02	9,24E-05	3,65E-02	1,11E-05	2,21E-05	
15	Concentrated Solar Power (CSP)	trough	0	0	4,57E-05	4,19E-02	5,60E-05	4,20E-02	1,51E-04	1,10E-01	1,38E-05	2,88E-05	
16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04	3,62E-02	1,51E-04	3,67E-02	3,01E-04	7,91E-02	2,84E-05	4,62E-05	
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	3,67E-02	1,69E-04	3,72E-02	3,34E-04	6,99E-02	3,93E-05	5,12E-05	
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	1,18E-02	2,54E-05	1,19E-02	6,27E-05	5,59E-02	8,75E-06	1,27E-05	
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	1,45E-02	4,38E-05	1,46E-02	8,82E-05	3,96E-02	1,42E-05	1,54E-05	
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	1,13E-02	2,52E-05	1,14E-02	6,11E-05	5,58E-02	8,76E-06	1,25E-05	
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	1,40E-02	4,33E-05	1,41E-02	8,64E-05	4,02E-02	1,42E-05	1,52E-05	
22	Wind	onshore	7	7	1,87E-05	1,24E-02	1,99E-05	1,24E-02	5,28E-05	7,48E-02	6,67E-06	1,39E-05	
23	Wind	offshore, concrete foundation	0	0	1,74E-05	1,42E-02	2,58E-05	1,42E-02	1,00E-04	6,62E-02	6,98E-06	2,84E-05	
24	Wind	offshore, steel foundation	1	1	1,87E-05	1,33E-02	2,46E-05	1,33E-02	9,45E-05	7,94E-02	6,84E-06	2,69E-05	
25	Total		100	100									
26						Electricity technology normalization unit : 1 kWh							

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Technologies **Mix Now & Future** **Impacts from UN LCA report**

Specification of present and future year, energy production and population

16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04	3,62E-02	1,51E-04	3,67E-02	3,01E-04	7,91E-02	2,84E-05	4,62E-05
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	3,67E-02	1,69E-04	3,72E-02	3,34E-04	6,99E-02	3,93E-05	5,12E-05
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	1,18E-02	2,54E-05	1,19E-02	6,27E-05	5,59E-02	8,75E-06	1,27E-05
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	1,45E-02	4,38E-05	1,46E-02	8,82E-05	3,96E-02	1,42E-05	1,54E-05
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	1,13E-02	2,52E-05	1,14E-02	6,11E-05	5,58E-02	8,76E-06	1,25E-05
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	1,40E-02	4,33E-05	1,41E-02	8,64E-05	4,02E-02	1,42E-05	1,52E-05
22	Wind	onshore	7	7	1,87E-05	1,24E-02	1,99E-05	1,24E-02	5,28E-05	7,48E-02	6,67E-06	1,39E-05
23	Wind	offshore, concrete foundation	0	0	1,74E-05	1,42E-02	2,58E-05	1,42E-02	1,00E-04	6,62E-02	6,98E-06	2,84E-05
24	Wind	offshore, steel foundation	1	1	1,87E-05	1,33E-02	2,46E-05	1,33E-02	9,45E-05	7,94E-02	6,84E-06	2,69E-05
25	Total		100	100								
26						Electricity technology normalization unit : 1 kWh						
27	Start & End year		2023	2050								
28	Start & End production [kWh/year]	World	2,25E+13	4,50E+13								
29	Start & End population [Citicenz]	World	8,00E+09	8,E+09								
30												
							Climate		FRESHWATER AND		FRESHWATE	

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

World electricity production = $2.25 \cdot 10^{13}$ kWh/year in 2023

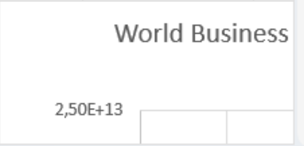
World population = 8 Billion people in 2023

Scenario : Double electricity production in 2050 due to electrification
World population constant at 8 billion people

Resulting impacts

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	FRESHWATER AND TERRESTRIAL ACIDIFICATION	FRESHWATER ECOTOXICITY	FRESHWATER EUTROPHICATION	MARINE EUTROPHICATION	TER EUT N
Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	[kg CO2-Eq/kWh]	[kg CO2-Eq/kWh]	[mol H+-Eq/kWh]	[CTU/kWh]	[kg P-Eq/kWh]	[kg N-Eq/kWh]	[mo
Impact at start per kWh		2023		6,86E-05	5,03E-01	9,70E-05	5,03E-01	7,81E-04	2,28E-01	1,98E-04	2,25E-04	
Impact at end per kWh			2050	6,86E-05	5,03E-01	9,70E-05	5,03E-01	7,81E-04	2,28E-01	1,98E-04	2,25E-04	
Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]	[mo
Absolute impact at start of production		2023		1,54E+09	1,13E+13	2,18E+09	1,13E+13	1,76E+10	5,12E+12	4,46E+09	5,06E+09	
Absolute impact at end of production			2050	3,09E+09	2,26E+13	4,36E+09	2,26E+13	3,51E+10	1,02E+13	8,91E+09	1,01E+10	

Green house Gas emissions	**Scenario:**	World Business As Usual (BAU) + 2 x Electricity in 2050	Climate change Total
Equavalent world emssion start	[Gt CO2e]		1,13E+01
Equavalent world emssion end	[Gt CO2e]		2,26E+01
GHG start fraction of UN 1.5 Degree	[%]		27
GHG end fraction of UN 1.5 Degree	[%]		263



Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Impacts weighted with electricity technology mix per kWh

$$EF_{average} = \sum_{i=1}^{N} EF_i \cdot f_i$$

Impacts on planet scale

$$E_m = EF_{average} \cdot E$$

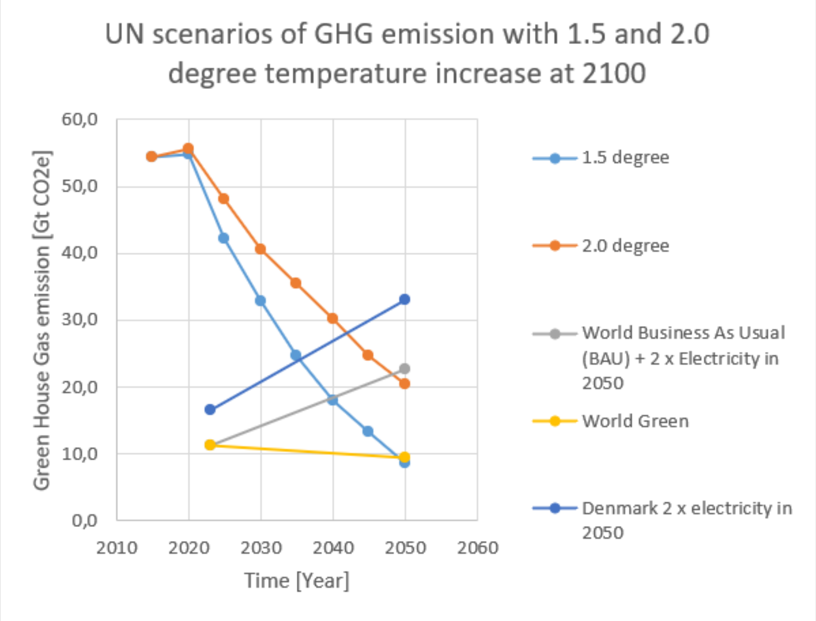
Green house gas emission and comparison to planetary boundary

Comparison to planetary boundary given by the Paris Agreement

UN Green House Gas (GHG) emission scenarios

Year	1.5 degree [Gt CO2e]	2.0 degree [Gt CO2e]		Year	World Business As Usual (BAU [Gt CO2e]	World Green [Gt CO2e]	Denmark 2 x electricity in 2050 [Gt CO2e]
2015	54,4	54,4		2023	1,13E+01	1,13E+01	1,66E+01
2020	54,7	55,5		2050	2,26E+01	9,47E+00	3,31E+01
2025	42,2	48,1					
2030	32,8	40,7					
2035	24,6	35,6					
2040	18,0	30,1					
2045	13,3	24,6					
2050	8,6	20,3					

Source : UN Emission Gap Report 2022
https://www.unep.org/resources/emissions-gap-report-2022



Planetary boundary of Global Warming Potential

Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

World business as usual scenario to violate GPW planetary boundary by 263 % in 2050

Scenario : World green mix coal ↓ and onshore wind ↑

	A	B	C	D	E	
1	**World Green**	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$	change biogenic	Clima chan
2			[%]	[%]	[kg CO2-Eq]	[kg C
3	Hard coal	PC, without CCS	39	10	6,87E-05	
4	Hard coal	IGCC, without CCS	0	0	5,38E-05	
5	Hard coal	SC, without CCS	0	0	6,45E-05	
6	Natural gas	NGCC, without CCS	23	23	7,78E-05	
7	Hard coal	PC, with CCS	0	0	1,06E-04	
8	Hard coal	IGCC, with CCS	0	0	7,23E-05	
9	Hard coal	SC, with CCS	0	0	9,90E-05	
10	Natural gas	NGCC, with CCS	0	0	9,39E-05	
11	Hydro	660 MW	0	0	5,32E-05	
12	Hydro	360 MW	15	15	1,80E-05	
13	Nuclear	average	9	9	2,56E-05	
14	Concentrated Solar Power (CSP)	tower	1	1	3,02E-05	
15	Concentrated Solar Power (CSP)	trough	0	0	4,57E-05	
16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04	
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	
22	Wind	onshore	7	36	1,37E-05	
23	Wind	offshore, concrete foundation	0	0	1,74E-05	
24	Wind	offshore, steel foundation	1	1	1,87E-05	
25	Total		100	100		
26						Elect

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

27	Start & End year		2023	2050				
28	Start & End production [kWh/year]	World	2,25E+13	4,50E+13				
29	Start & End population [Citicenz]	World	8,00E+09	8,E+09				
30								
31	**LCA impacts**	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
32	Unit				[kg CO_2-Eq / kWh]	[kg CO_2-Eq/ kWh]	[kg CO_2-Eq/kWh]	[kg CO_2-Eq/kWh]
33	Impact at start per kWh		2023		6,86E-05	5,03E-01	9,70E-05	5,03E-01
34	Impact at end per kWh			2050	5,41E-05	2,11E-01	5,43E-05	2,11E-01
35	Unit				[kg CO_2-Eq]	[kg CO_2-Eq]	[kg CO_2-Eq]	[kg CO_2-Eq]
36	Absolute impact at start of production		2023		1,54E+09	1,13E+13	2,18E+09	1,13E+13
37	Absolute impact at end of production			2050	2,44E+09	9,47E+12	2,44E+09	9,47E+12
38								
39	**Green house Gas emissions**	**Scenario:**	World Green					Climate change Total
40	Equavalent world emssion start	[Gt CO_2e]						1,13E+01
41	Equavalent world emssion end	[Gt CO_2e]						9,47E+00
42	GHG start fraction of UN 1.5 Degree	[%]						27
43	GHG end fraction of UN 1.5 Degree	[%]						110
44								

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

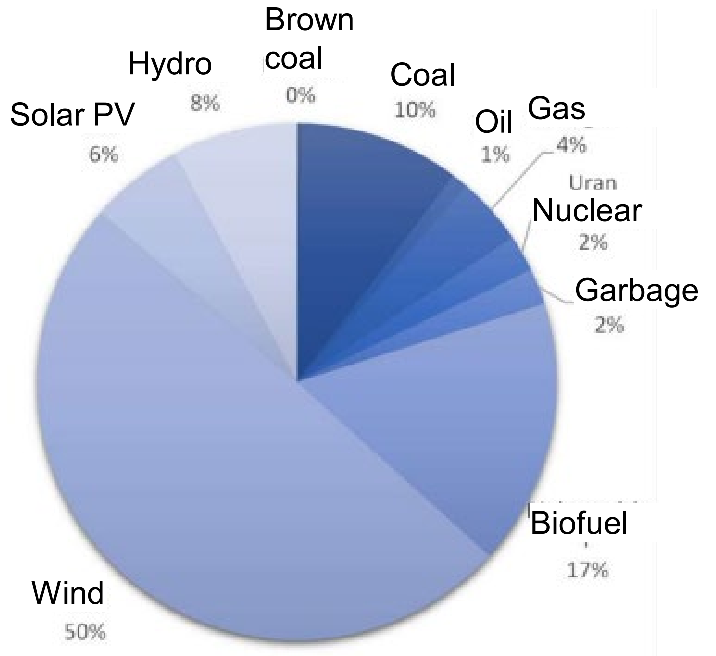
World Green scenario to violate GPW planetary boundary by 110 % in 2050

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

Electricity production : Denmark in 2022

Population of region : Denmark

Population of World

Equivalent World electricity production

	A	B	C	D	E	F	G	H
27	Start & End year		2023	2050				
28	Start & End production [kWh/year]	Denmark	3,55E+10	7,10E+10				
29	Start & End region population [Citicenz]	Denmark	5,90E+06	6,E+06				
30	Start & End world population [Citicenz]	World	8,00E+09	8,E+09				
31	Start & End equivalent World production [kWh/year]	Equivalent world	4,81E+13	9,63E+13				
32								
33	**LCA impacts**	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
34	Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	[kg CO2-Eq/kWh]	[kg CO2-Eq/kWh]
35	Impact at start per kWh		2023		5,84E-05	3,44E-01	8,26E-05	3,44E-01
36	Impact at end per kWh			2050	5,84E-05	3,44E-01	8,26E-05	3,44E-01
37	Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]
38	Absolute impact at start of production of region		2023		2,07E+06	1,22E+10	2,93E+06	1,22E+10
39	Absolute impact at end of production og region			2050	4,15E+06	2,44E+10	5,87E+06	2,44E+10
40	Absolute impact at start of production eq. World		2023		2,81E+09	1,65E+13	3,98E+09	1,66E+13
41	Absolute impact at end of production eq. World			2050	5,62E+09	3,31E+13	7,95E+09	3,31E+13
42								
43	**Green house Gas emissions**	**Scenario:**	Denmark 2 x electricity in 2050					Climate change Total
44	Region emission start	[Gt CO2e]						1,22E-02
45	Region emission end	[Gt CO2e]						2,44E-02
46	Equavalent world emssion of Region start	[Gt CO2e]						1,66E+01
47	Equavalent world emssion of Region end	[Gt CO2e]						3,31E+01
48	GHG start fraction of UN 1.5 Degree	[%]						39
49	GHG end fraction of UN 1.5 Degree	[%]						385
50								

Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Denmark scenario scaled to World production to violate GPW planetary boundary by 385 % in 2050

This scenario used the electricity production of Denmark.

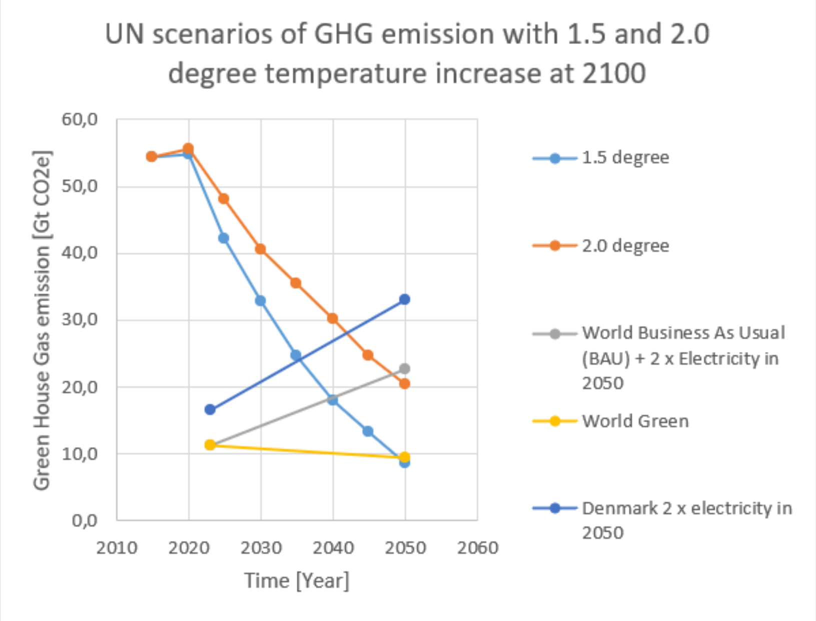
Comparison to planetary boundary given by the Paris Agreement of scenarios

UN Green House Gas (GHG) emission scenarios

Year	1.5 degree	2.0 degree		Year	World Business As Usual (BAU	World Green	Denmark 2 x electricity in 2050
	[Gt CO2e]	[Gt CO2e]			[Gt CO2e]	[Gt CO2e]	[Gt CO2e]
2015	54,4	54,4		2023	1,13E+01	1,13E+01	1,66E+01
2020	54,7	55,5		2050	2,26E+01	9,47E+00	3,31E+01
2025	42,2	48,1					
2030	32,8	40,7					
2035	24,6	35,6					
2040	18,0	30,1					
2045	13,3	24,6					
2050	8,6	20,3					

Source : UN Emission Gap Report 2022
https://www.unep.org/resources/emissions-gap-report-2022

Chart Area



Planetary boundary of Global Warming Potential

Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

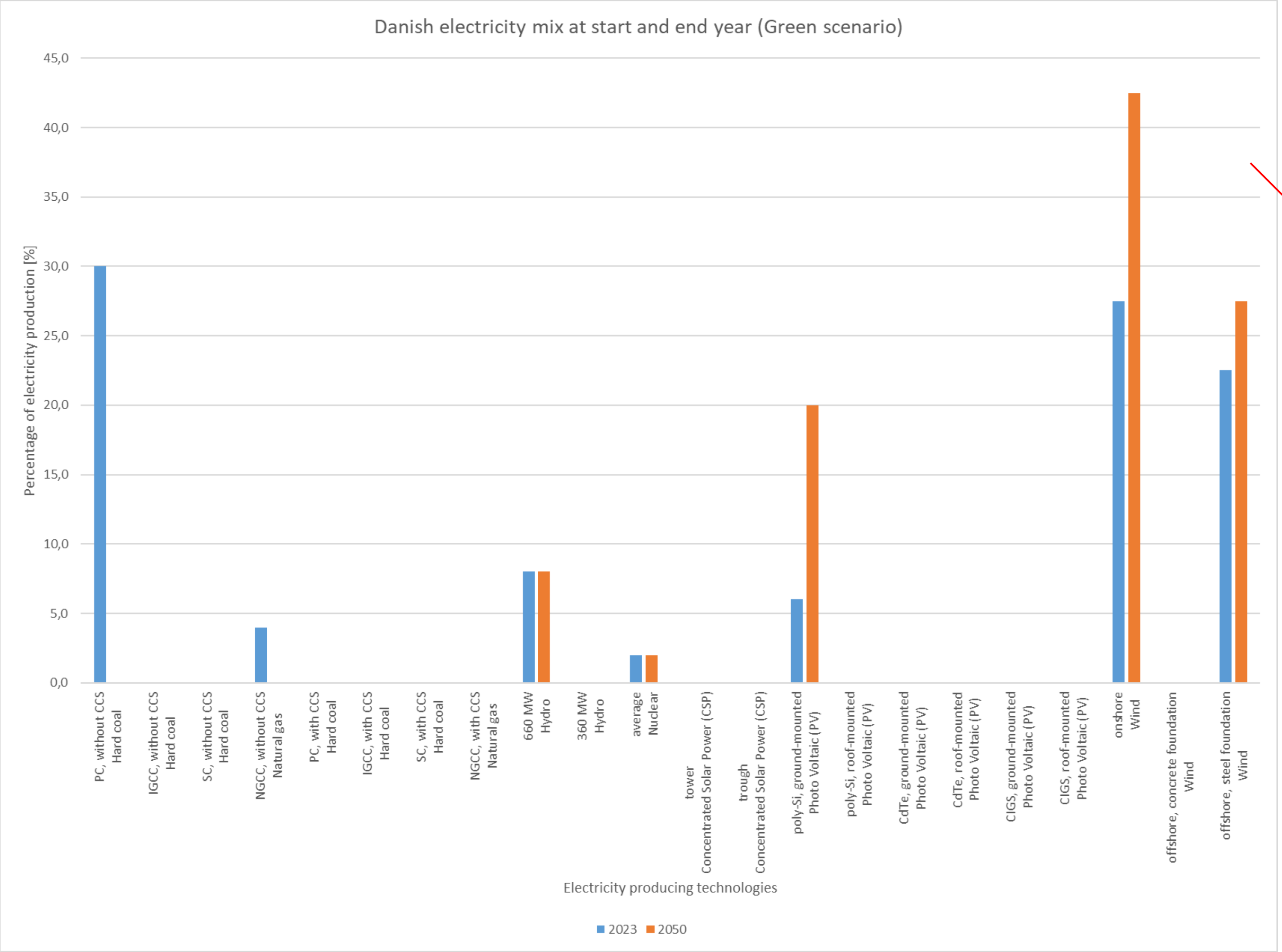
Rather large changes of the electricity systems are needed to comply with GPW planetary boundary in 2050 !

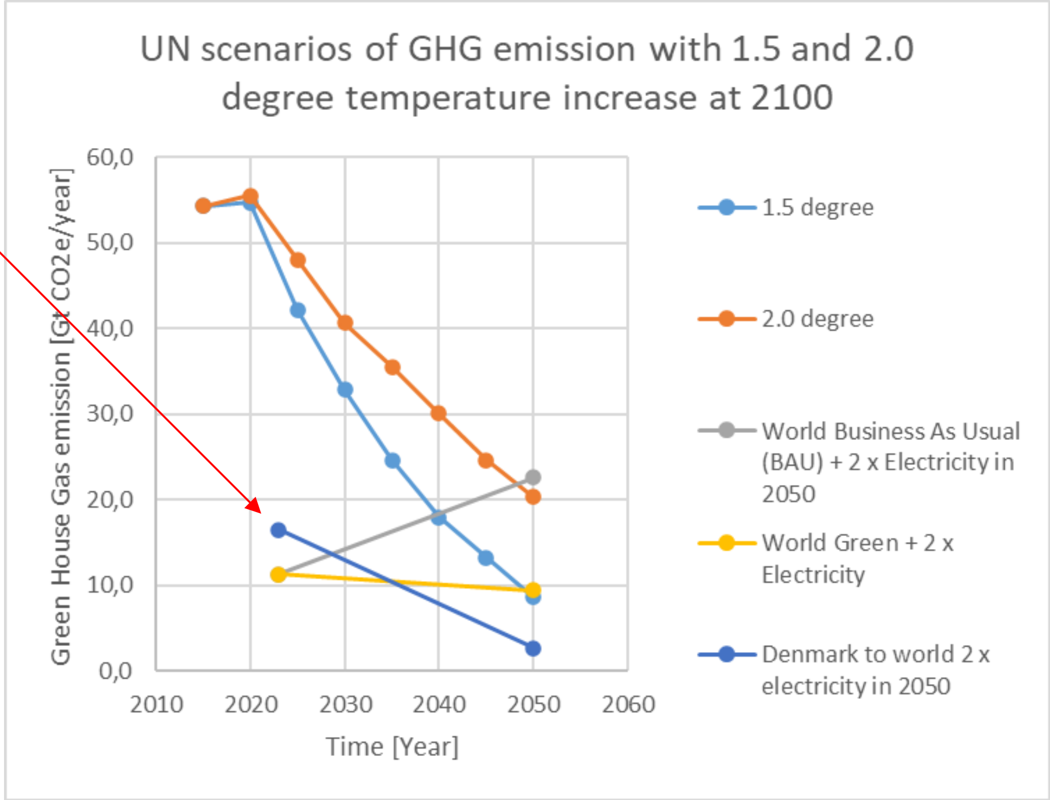
Exercise for all students

- 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?

Result example of green Denmark scaled to planet impact





Scaling up the usage of known renewable electricity producing technologies will help to comply with the Paris agreement in 2050. However the emissions of the Danish scenario above is ~ 28 g CO_{2e} / kWh and is expected to level out at around 5-20 g CO_{2e} / kWh. Thus low carbon material manufacturing will be needed after 2050.

Learning objectives of decarbonizing the energy system

The student should be able to

- **Describe** the main electricity generating technologies used around the world
- **Explain** the origin of CO_2 emissions from electricity producing units
- **Describe** the typical technology mix used for electricity production in different countries

- **Estimate** the resulting CO_2 emission of the electricity mix when producing 1 kWh of electricity

- **Discuss** the expected future CO_2 emission of electricity production and propose strategies of decarbonizing the electricity system
- **Discuss** which additional technologies that might be needed in the electricity system

- **Analyse** expected CO_2 emissions from a specific country or region and compare the Global Warming Potential with the UN CO_2 emission scenarios.

- **Evaluate** if the planetary CO_2 boundary is violated by the electricity generation ?

Circular Economy

Tim C. McAloone
Professor, PhD

Circular Economy

Lecture 1: What's the problem?

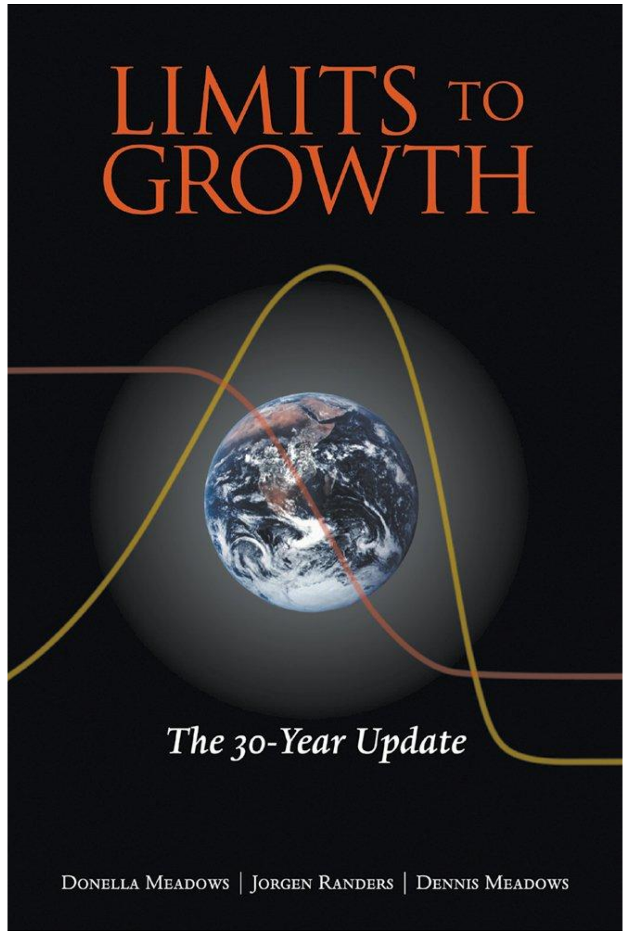
Lecture 2: The promise of circularity

Lecture 3: Deploying CE strategies

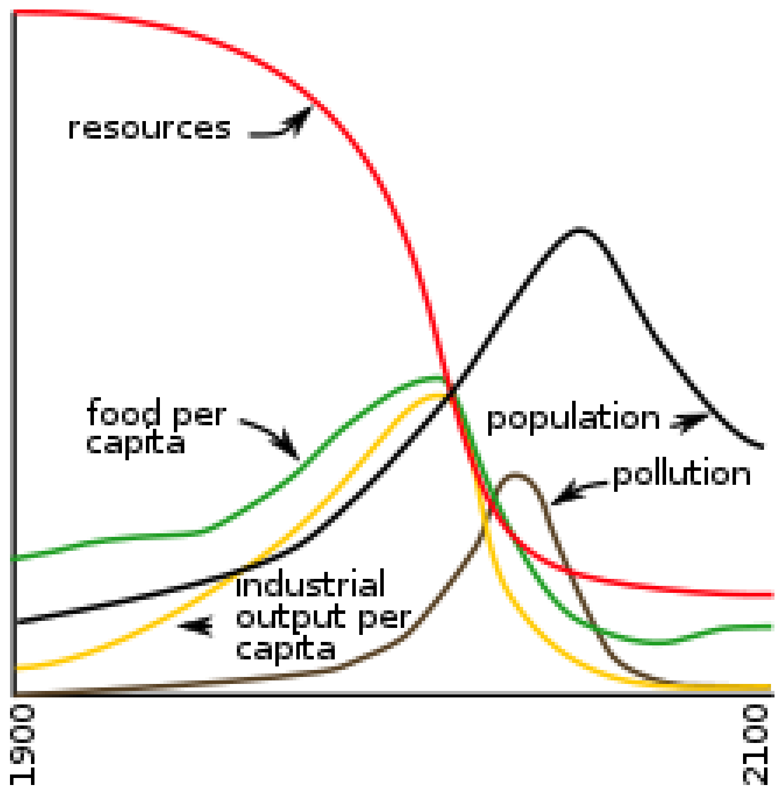
Lecture 4: CE Readiness

Tim C. McAloone
Professor, PhD

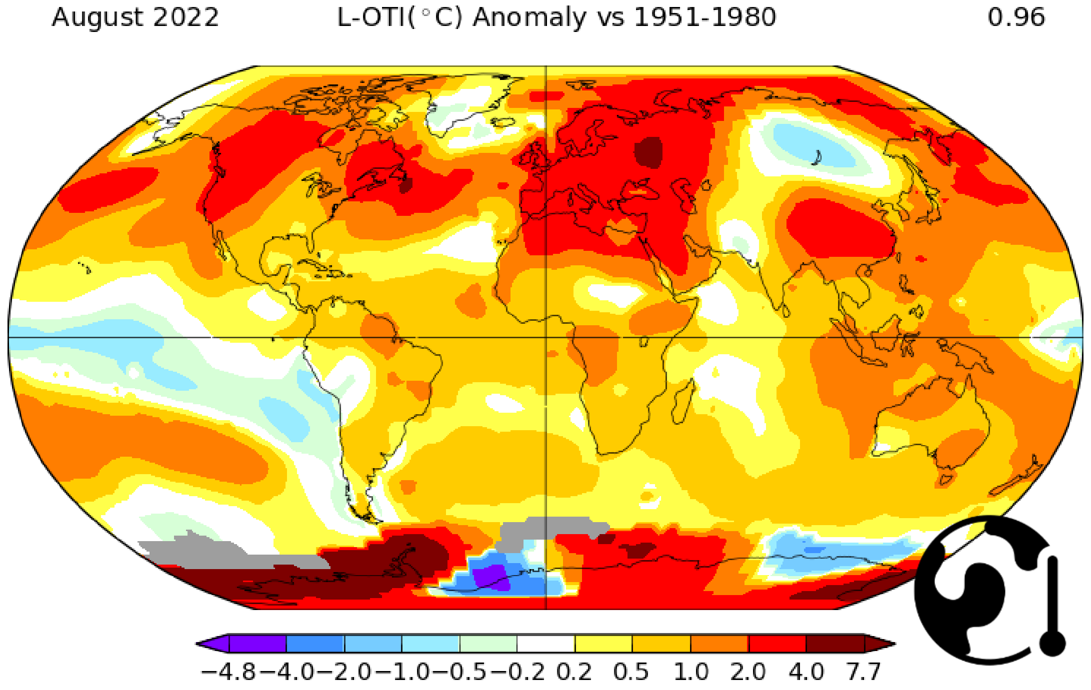
Urgent need for radically different measures to address anthropocentric sustainability



[Meadows et al., 1972]



Urgent needs to boost environmental sustainability



[DTU Centre for Absolute Sustainability]

Urgent needs to boost environmental sustainability

WorldChanging

How we’re doing in the linear economy

44.7 million	20 percent	$11.5 billion	5 grams	575 grams
tonnes of e-waste were generated globally*	e-waste is collected and recycled under appropriate conditions*	recovery potential of materials through recycling for smartphones*	concentration of gold per tonne from ore**	concentration of gold per tonne of e-waste PCBs**
			(0.17 oz)	(20 oz)

* The Global e-waste monitor, 2017

** Tickner et al, “Measurement of gold and other metals in electronic and automotive waste”, 2016

The problem with the linear economy

LINEAR ECONOMY

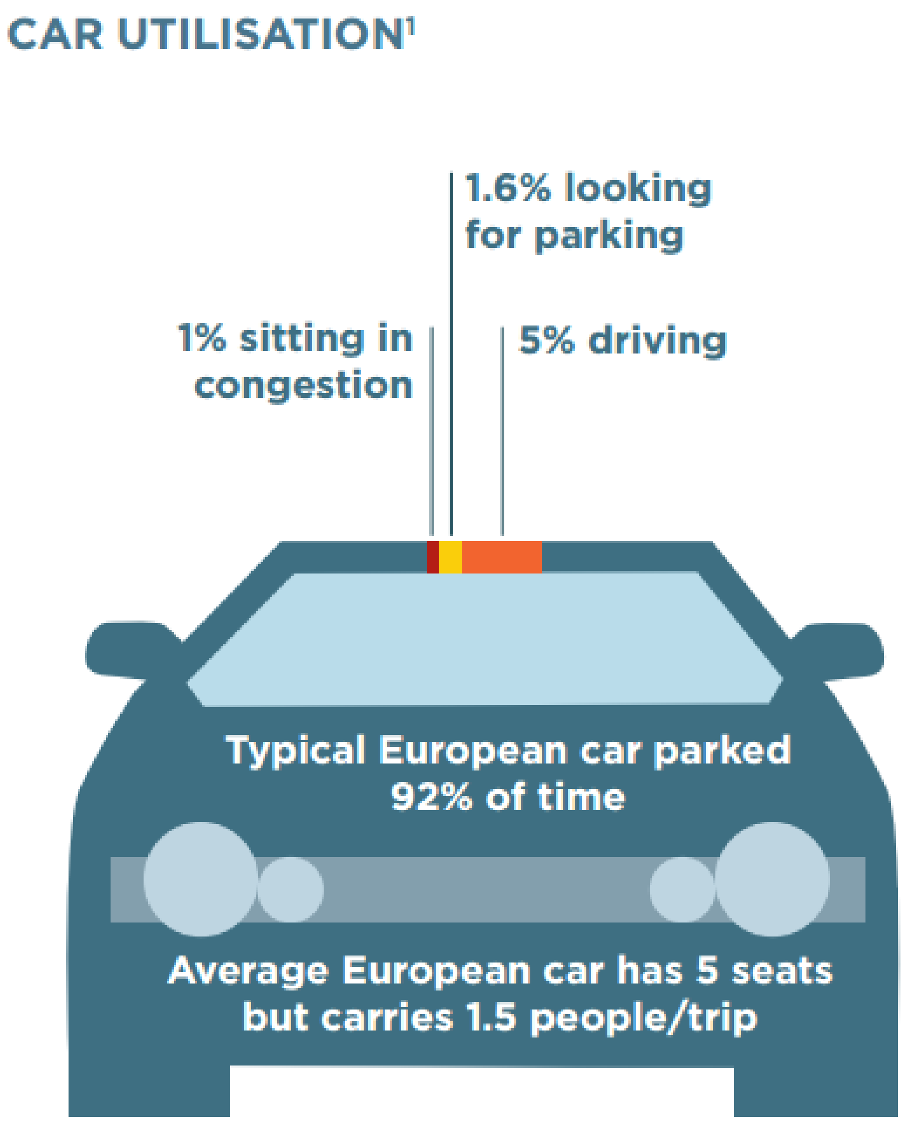
Take

Make

Use

Dispose

The problem with the linear economy



[Ellen MacArthur Foundation, based on EU Commission]

DTU

Deep dive: plastics

Plastics as a proxy for our *<u>un</u>*circularity

...or why we desparately need to revisit our relationship to resources


[WWF]

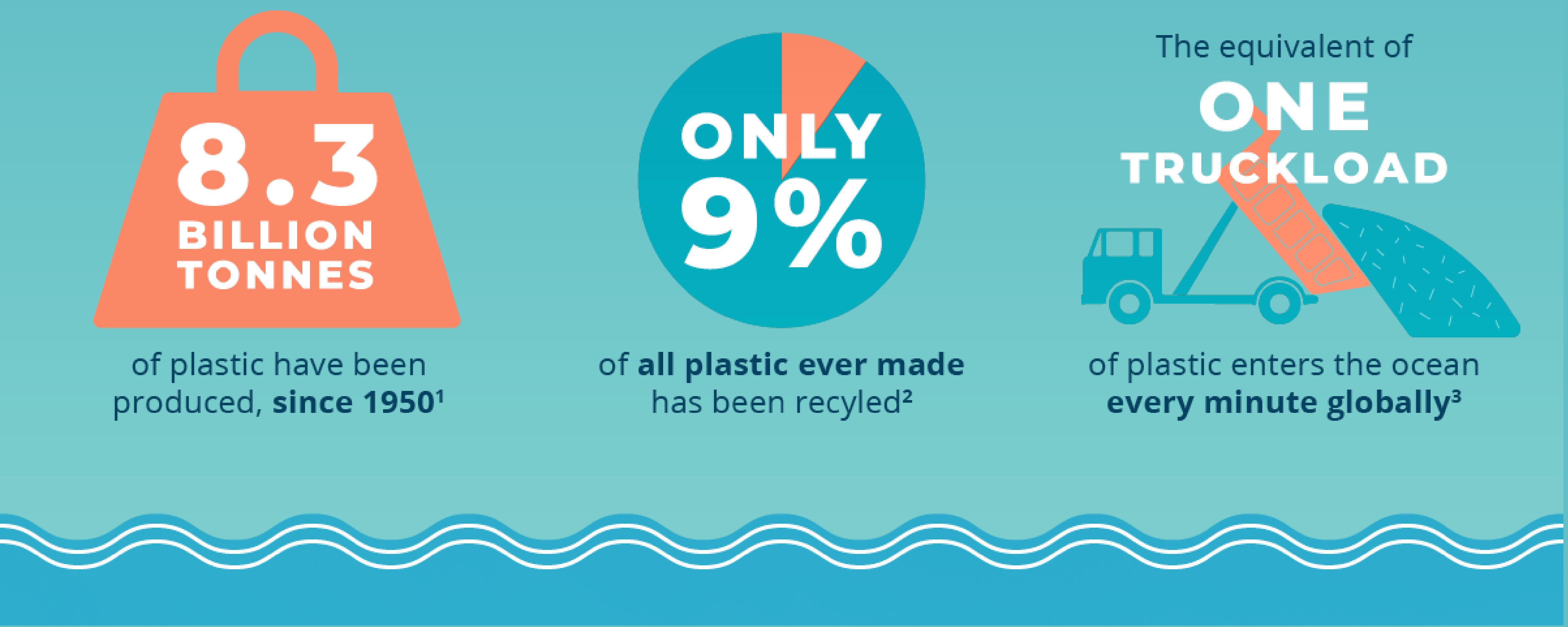
[Shutterstock]


[shine.cn]

Rebound effects

[Marine Photobank]

The plastics problem

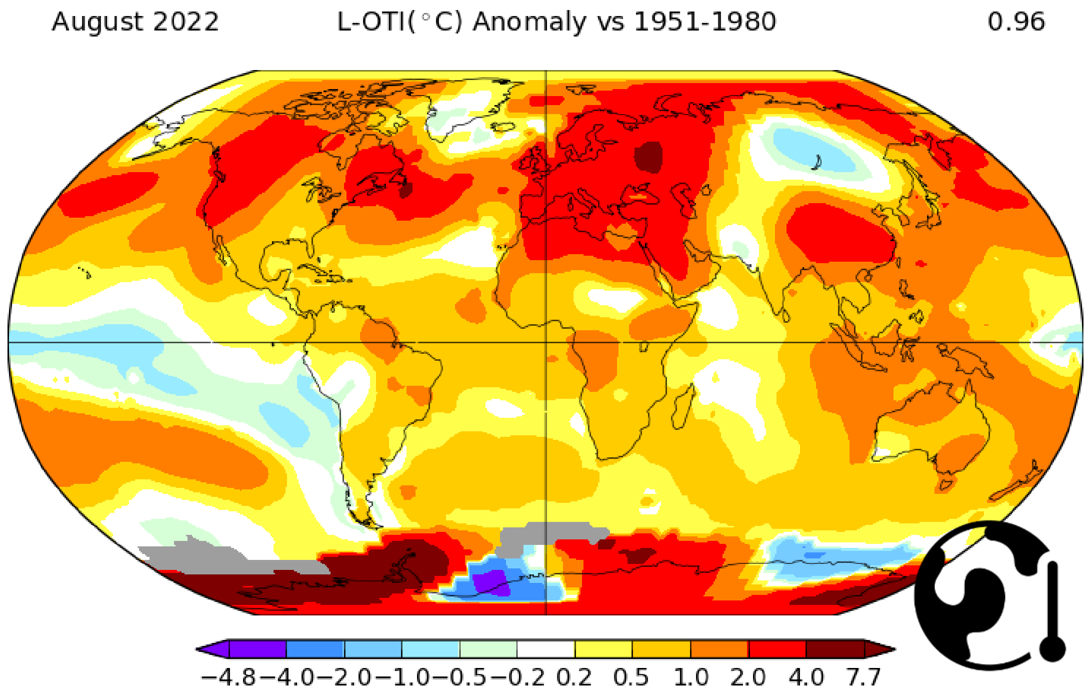


[Graphic: Greenpeace], [1. fao.org], [2. Advances in Science], [3. Weforum]

WorldChanging

How we’re doing in the linear economy

Urgent needs to boost environmental sustainability



[DTU Centre for Absolute Sustainability]

Urgent needs to boost environmental sustainability

[DTU Centre for Absolute Sustainability]

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Circular Economy

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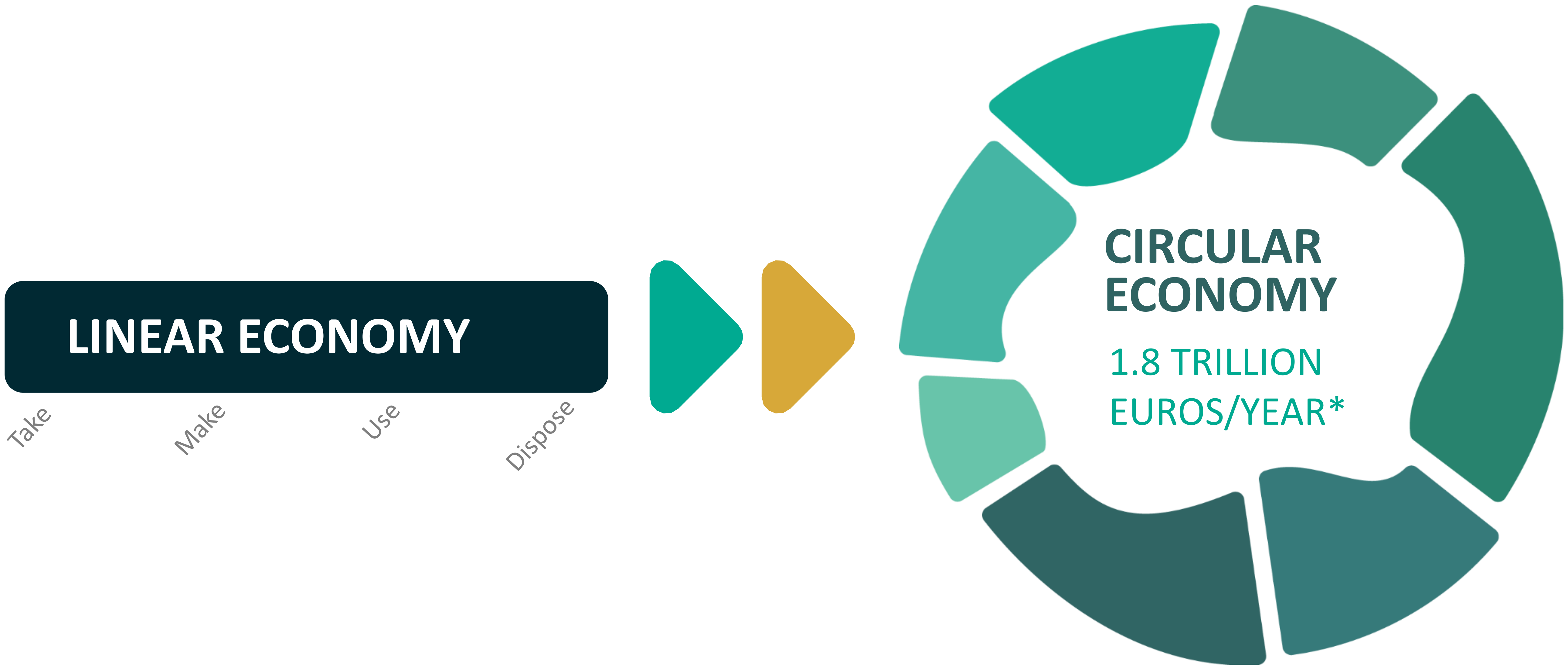
CIRCULAR ECONOMY

- Fastest growing business strategy area in Europe
- Closing the loops
- Decoupling value creation from resource consumption
- Requires a systemic approach

The promise of the circular economy



*McKinsey & Ellen MacArthur Foundation

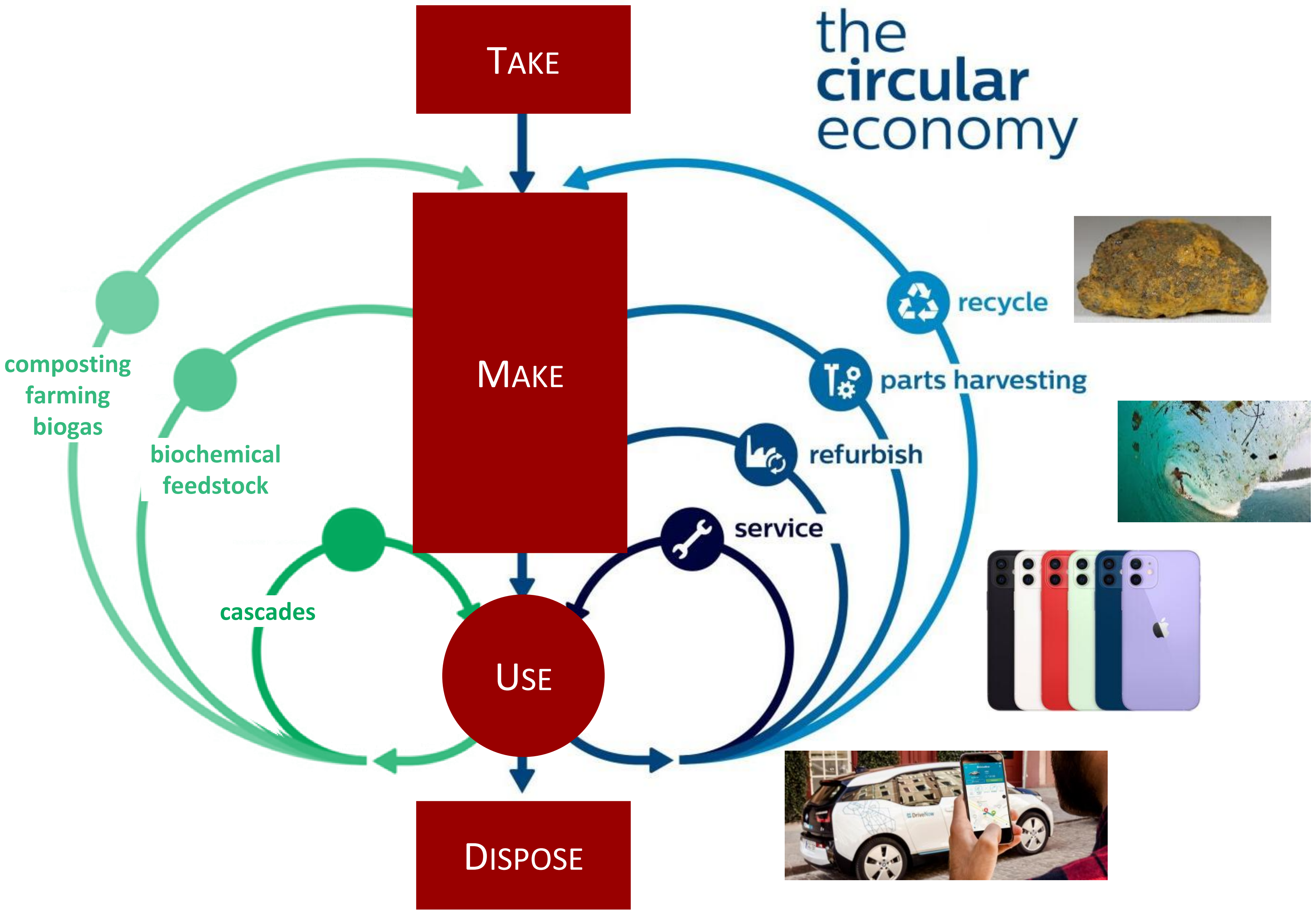
Definition of a circular economy

“an economy that provides multiple value creation mechanisms, which are decoupled from consumption of finite resources”

[Ellen MacArthur Foundation]

Circular Economy

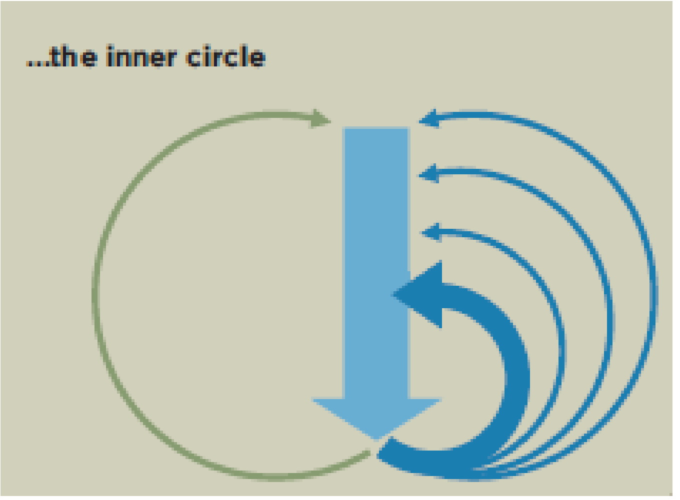
… decoupling value creation from resource consumption!



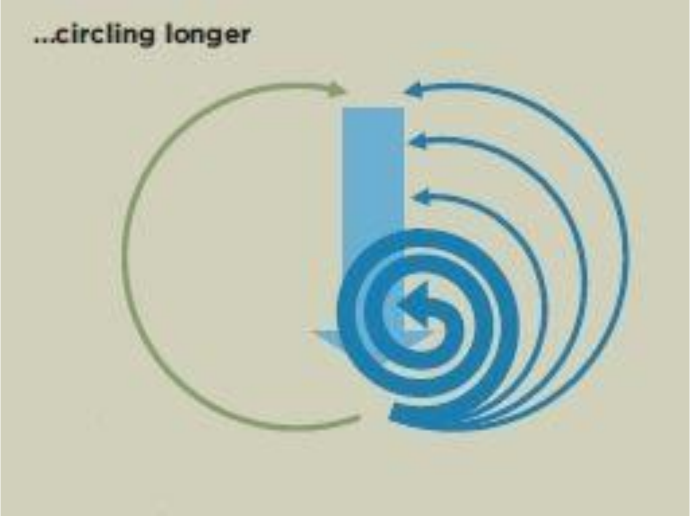
[The "Butterfly Diagram" of CE, adapted from Philips]

Value Creation

- **Inner Circle** – Minimising comparative materials use, through re-use. The tighter the circle, the less it has to be changed to be returned to use (with higher savings)

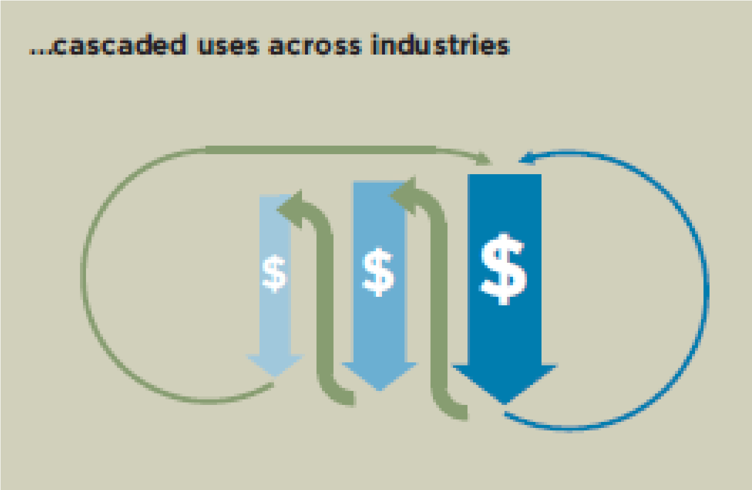


- **Circling Longer** – Maximising the number of consecutive cycles of reuse, to avoid production of a new component

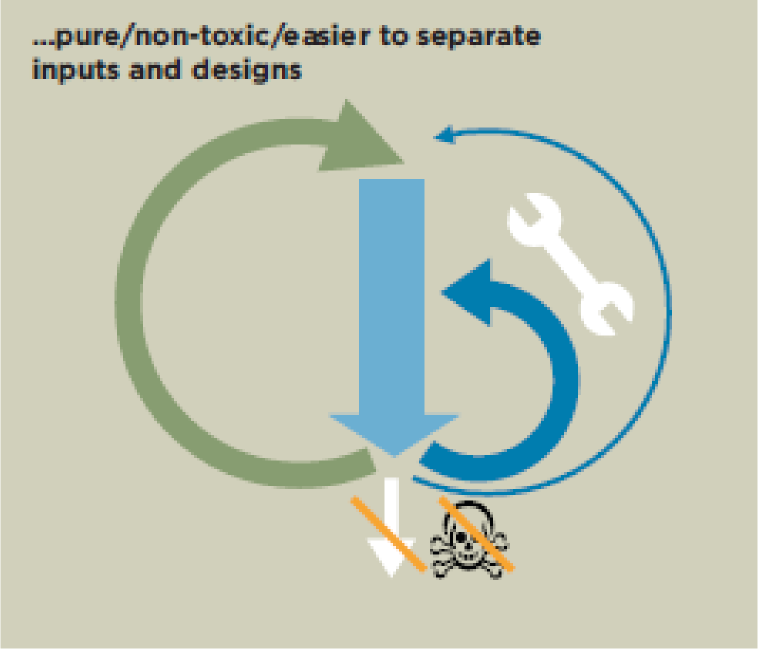


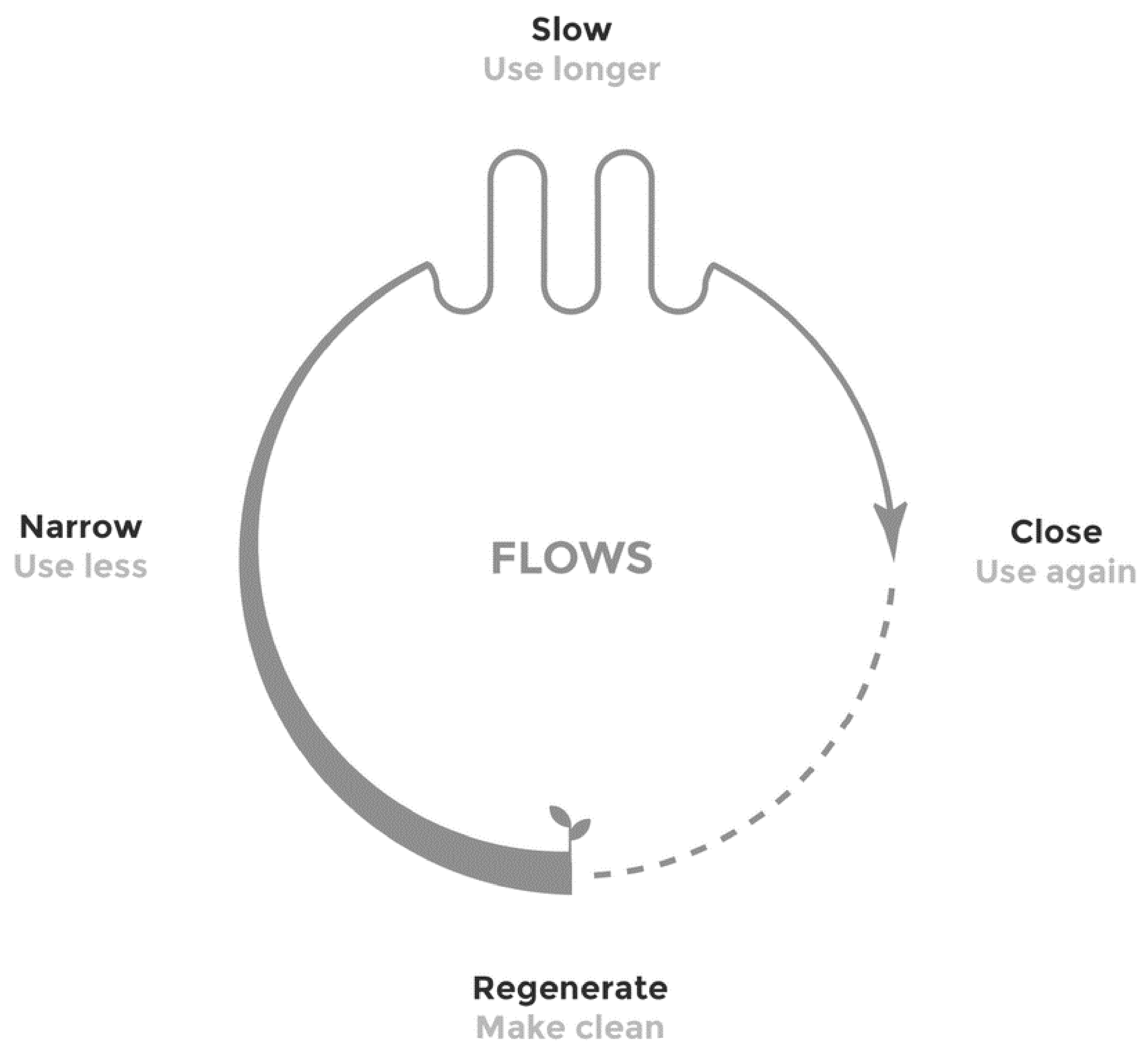
Value Creation

- **Cascading** – Diversified re-use across the value chain, substituting previously used virgin materials with existing materials (including symbiosis);



- **Pure inputs** – Avoidance of contaminated materials to increase collection and re-use efficiency whilst maintaining quality.




Slow
Use longer
Narrow
Use less
FLOWS
Close
Use again
Regenerate
Make clean

Narrow
Use less

Narrow

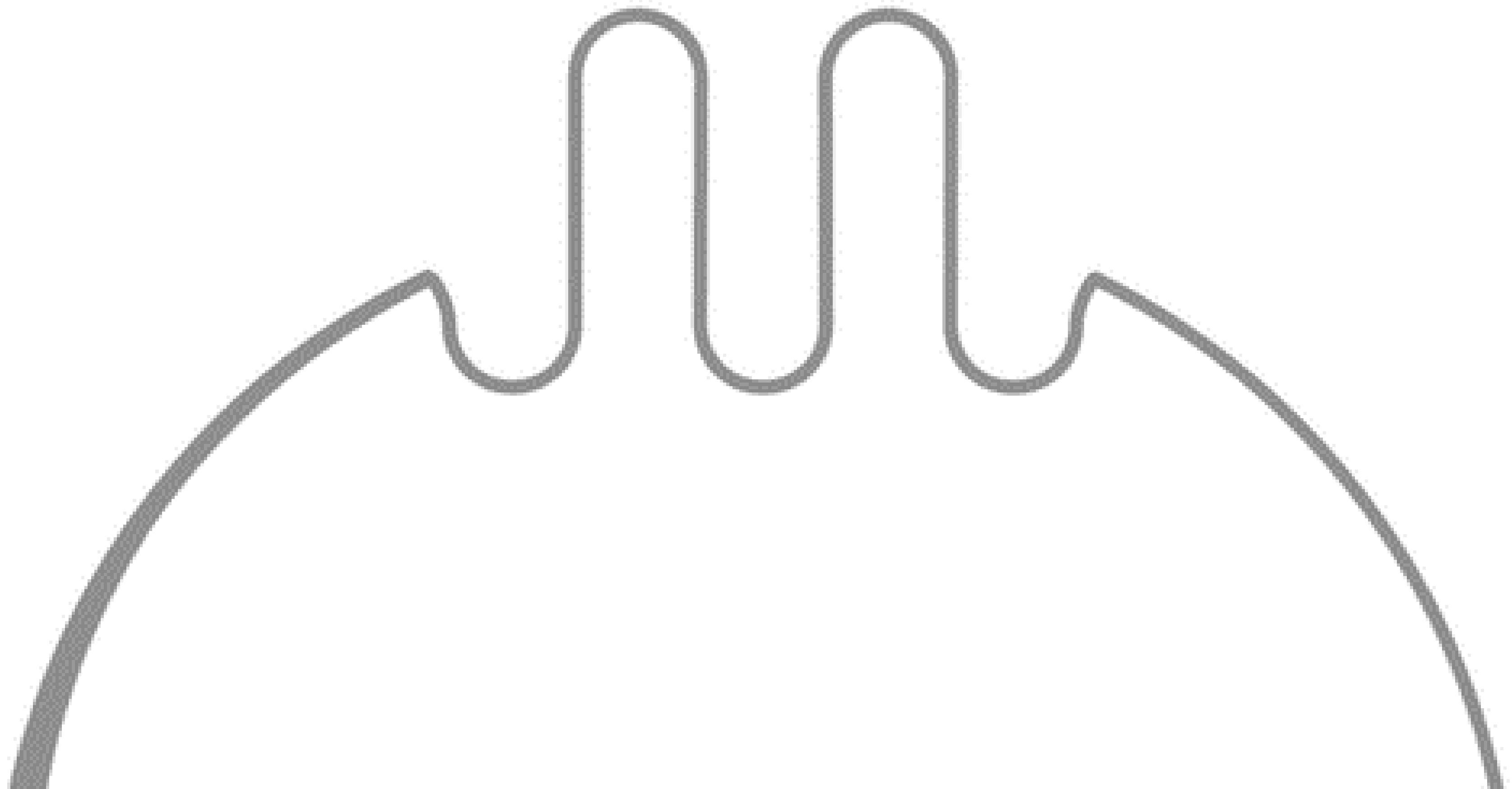
Use less

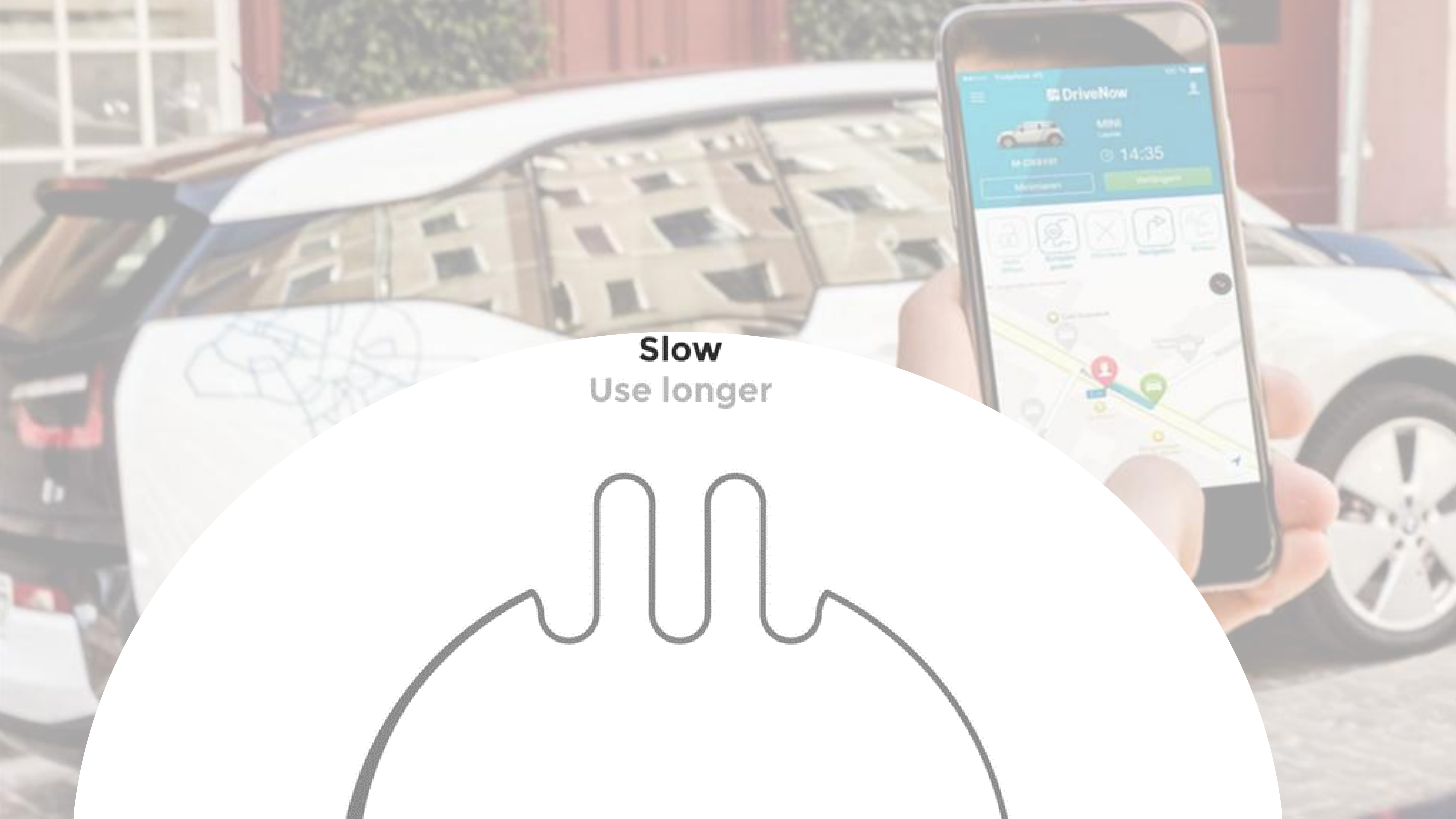
FL

Narrow
Use less

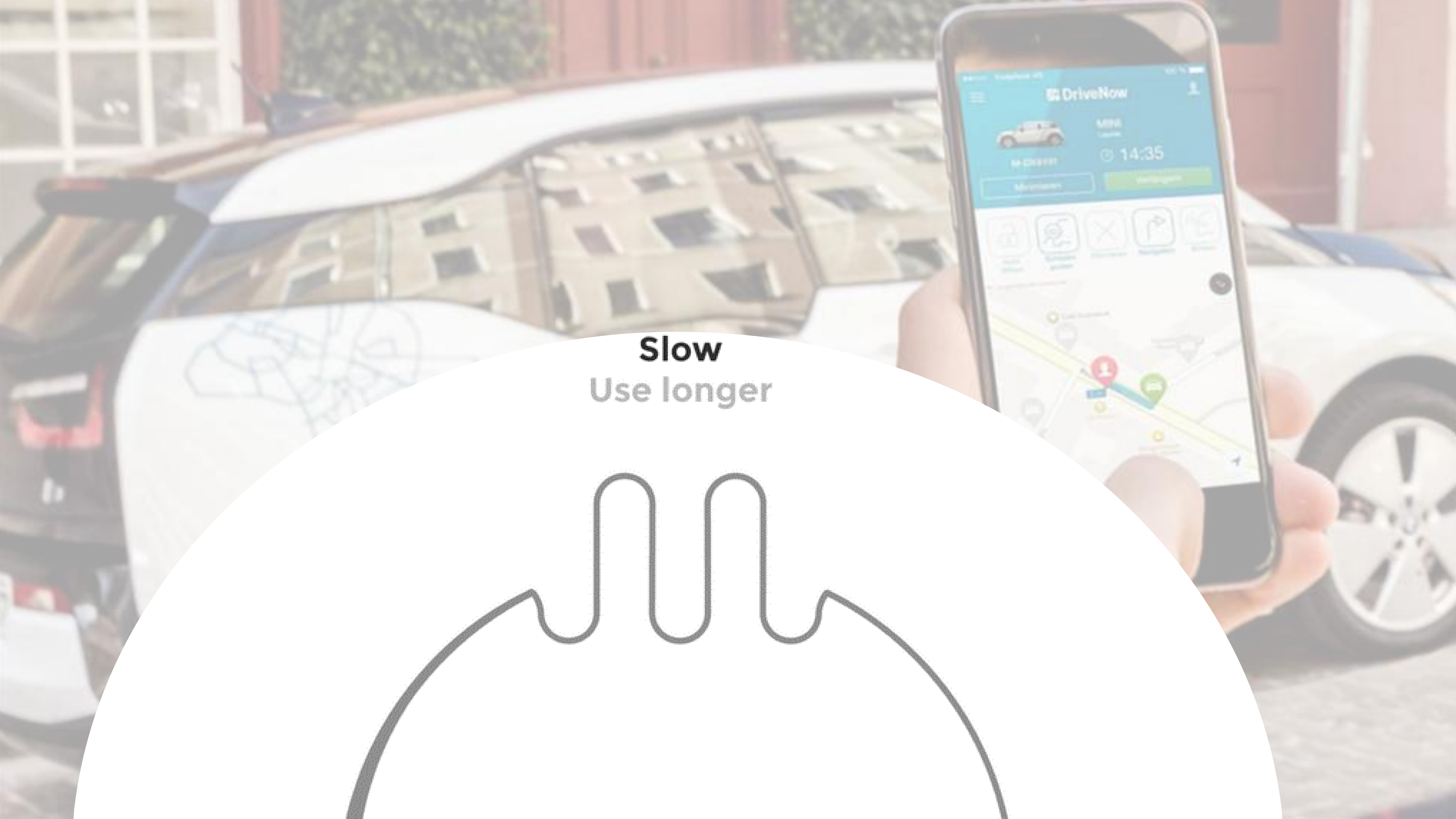
Slow

Use longer



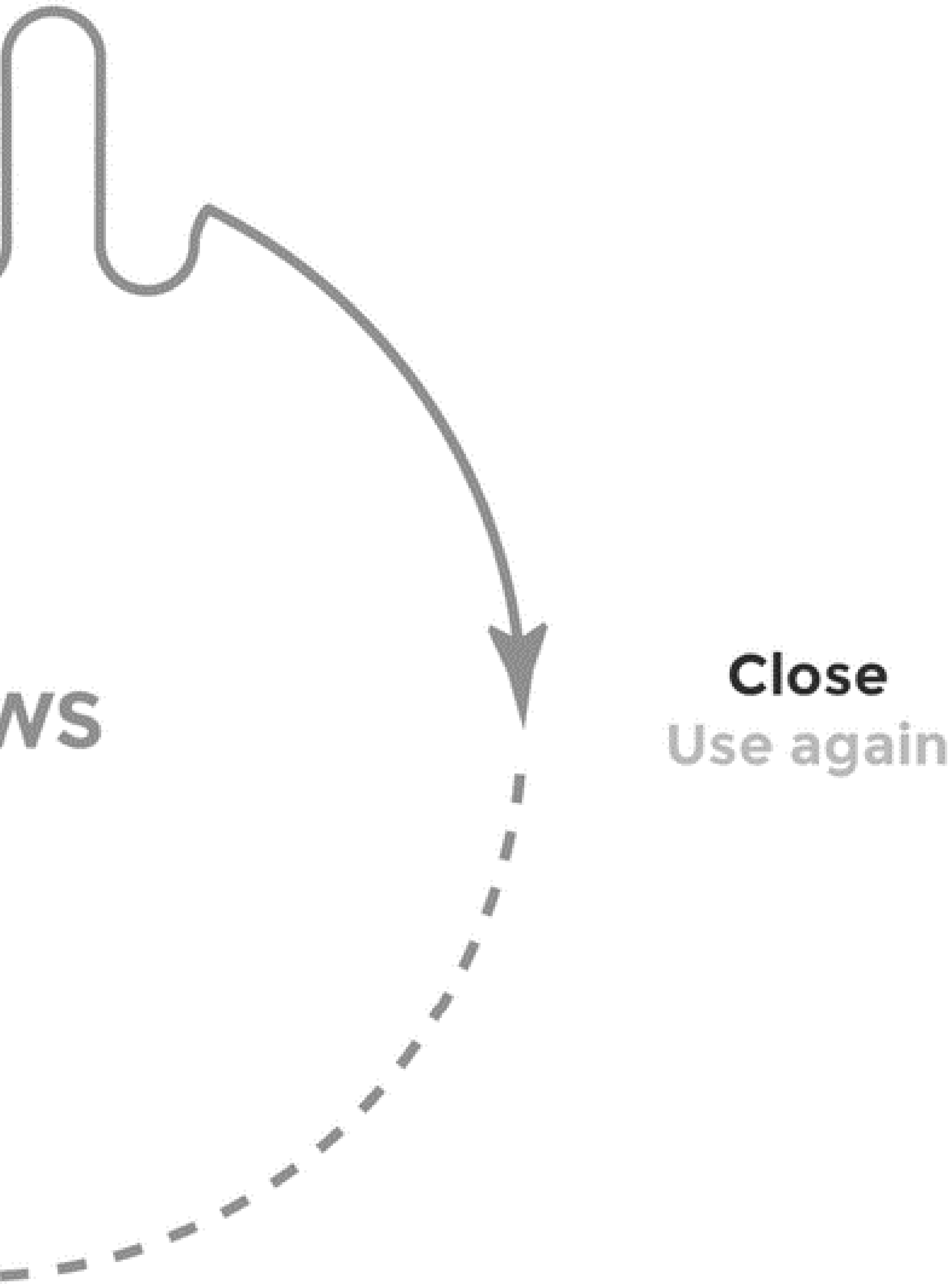

DriveNow
MINI
14:35
Slow
Use longer

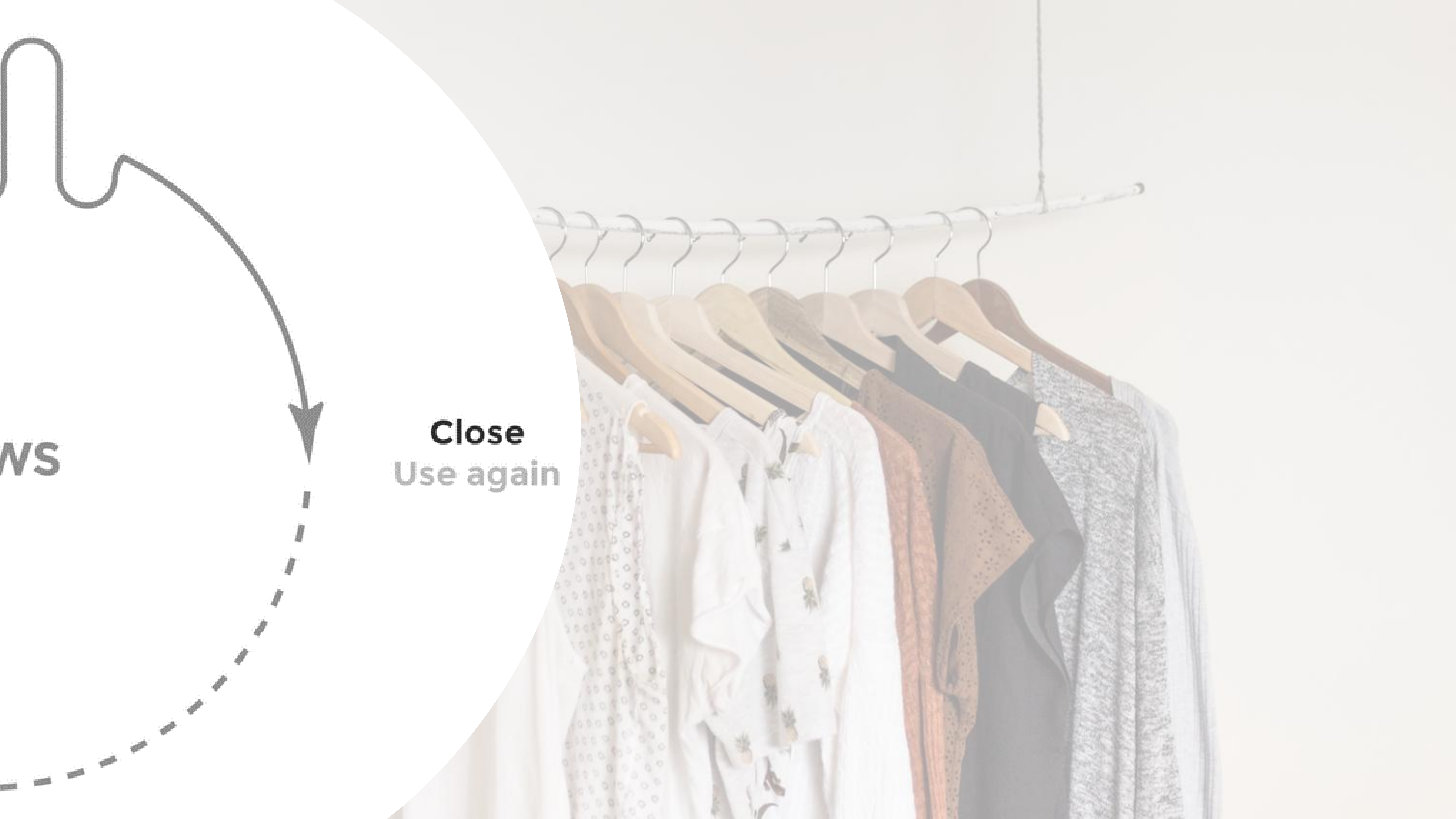

DriveNow
MINI
14:35
Verlängern
DriveNow



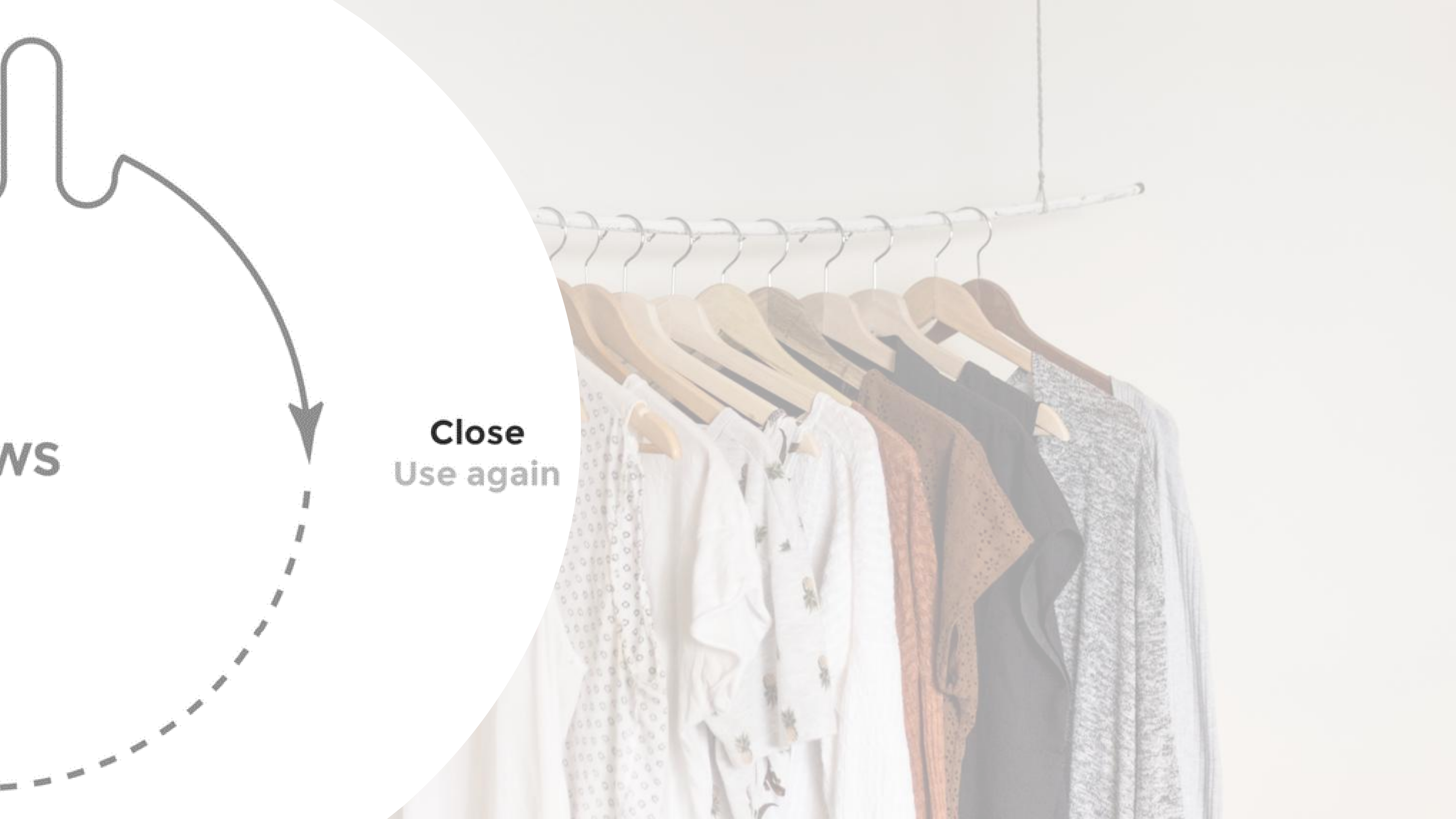
Slow

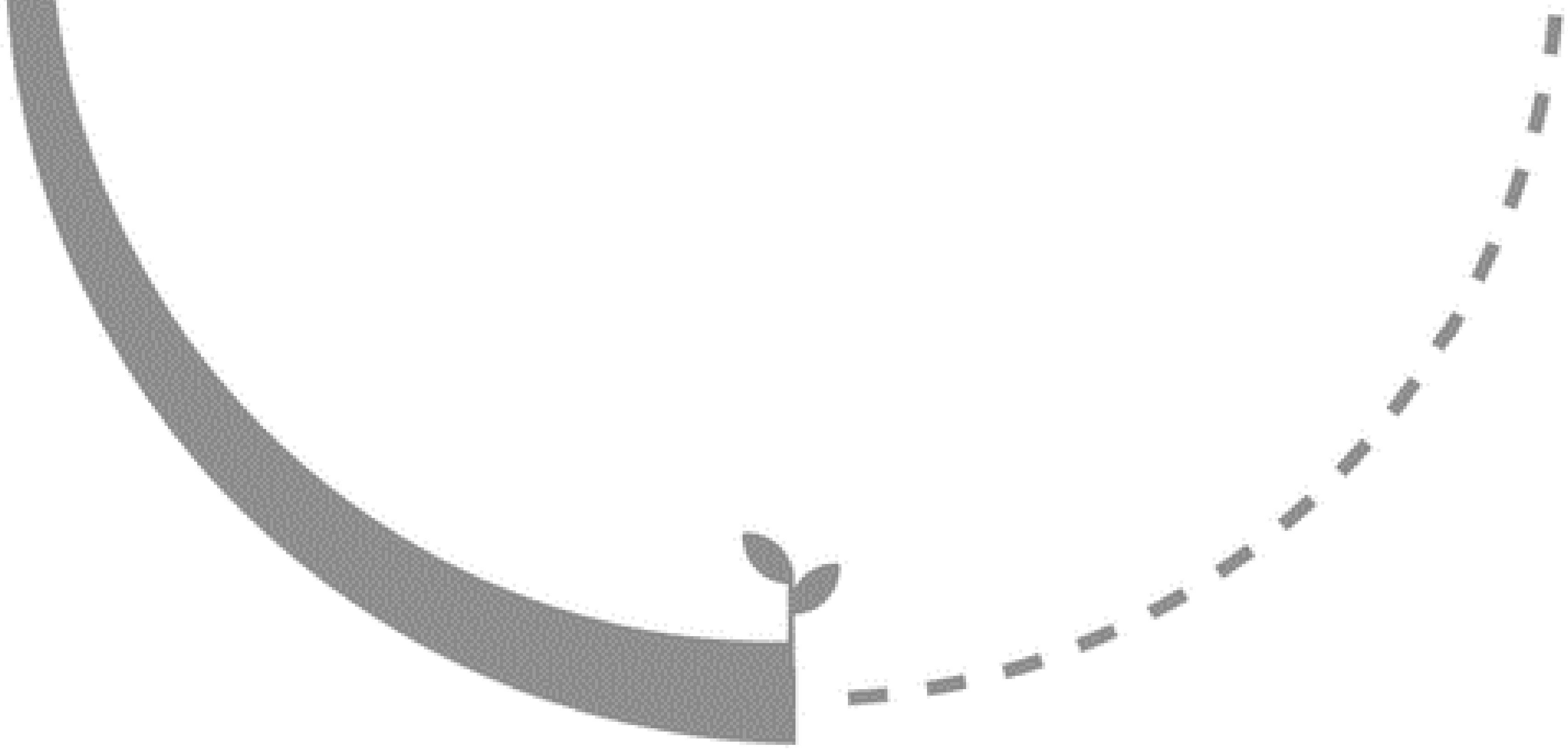
Use longer


Close
Use again



Close
Use again


WS
Close
Use again



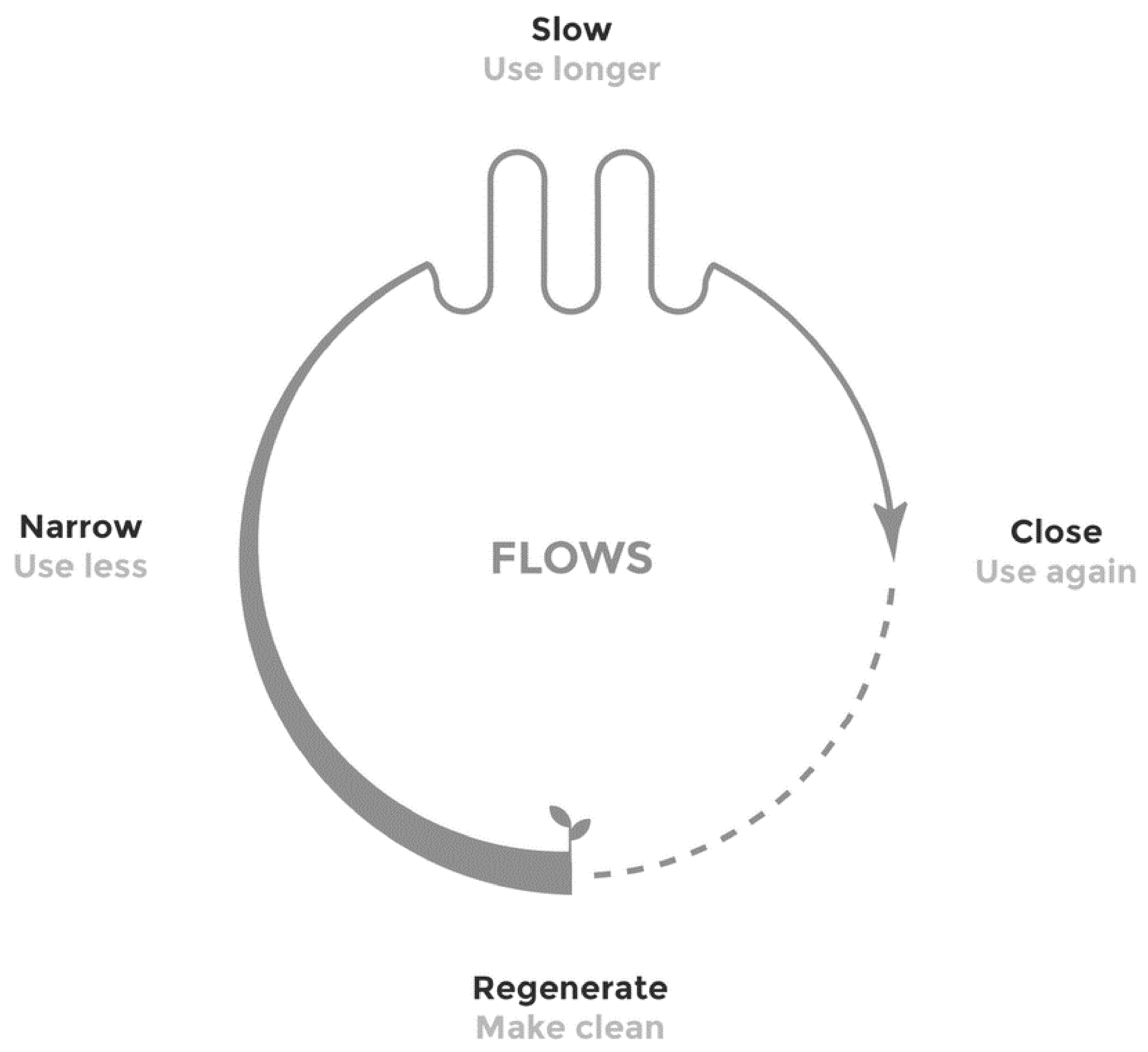
Regenerate

Make clean

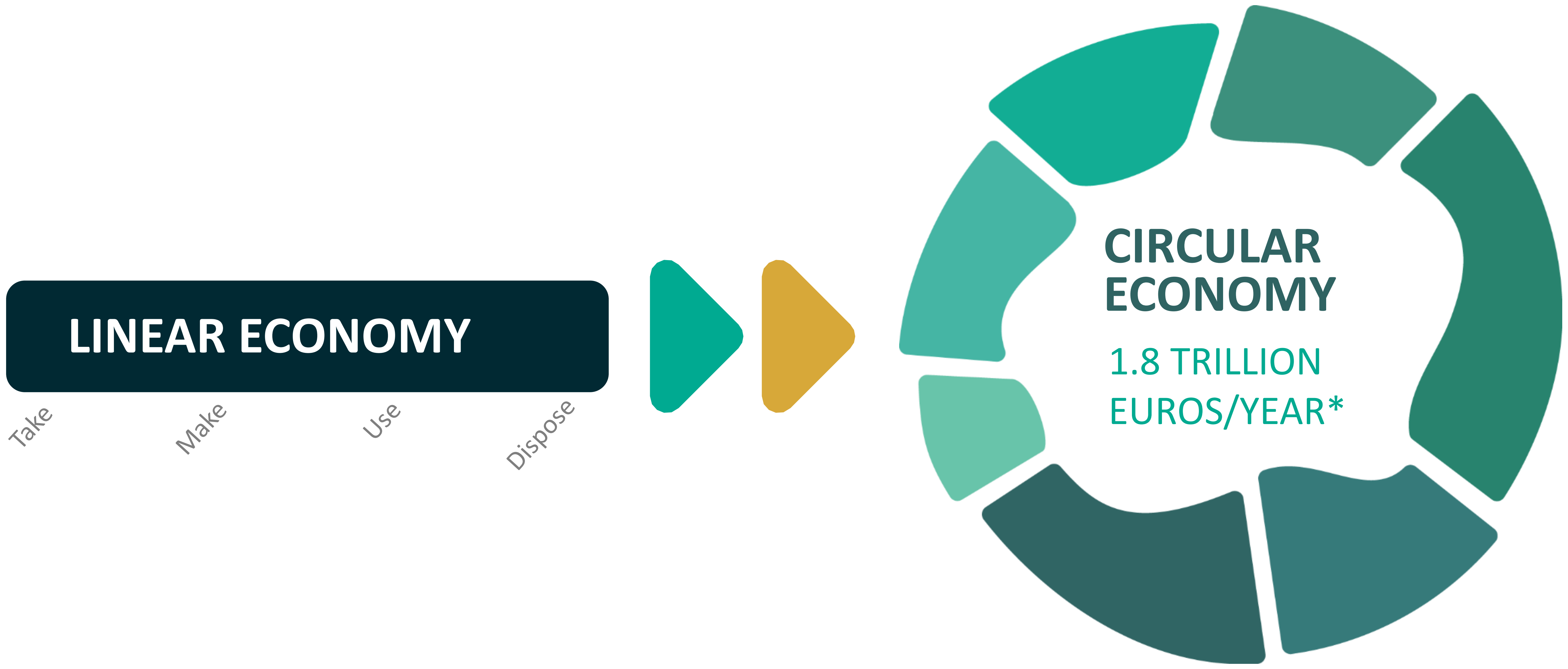

Regenerate
Make clean
Carlsberg
PILSNER


DTU
Carlsberg
DANISH
PILSNER


Regenerate
Make clean
Carlsberg
PILSNER


Slow
Use longer
Narrow
Use less
FLOWS
Close
Use again
Regenerate
Make clean

The promise of the circular economy



*McKinsey & Ellen MacArthur Foundation

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Circular Economy

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DTU

Circular Economy

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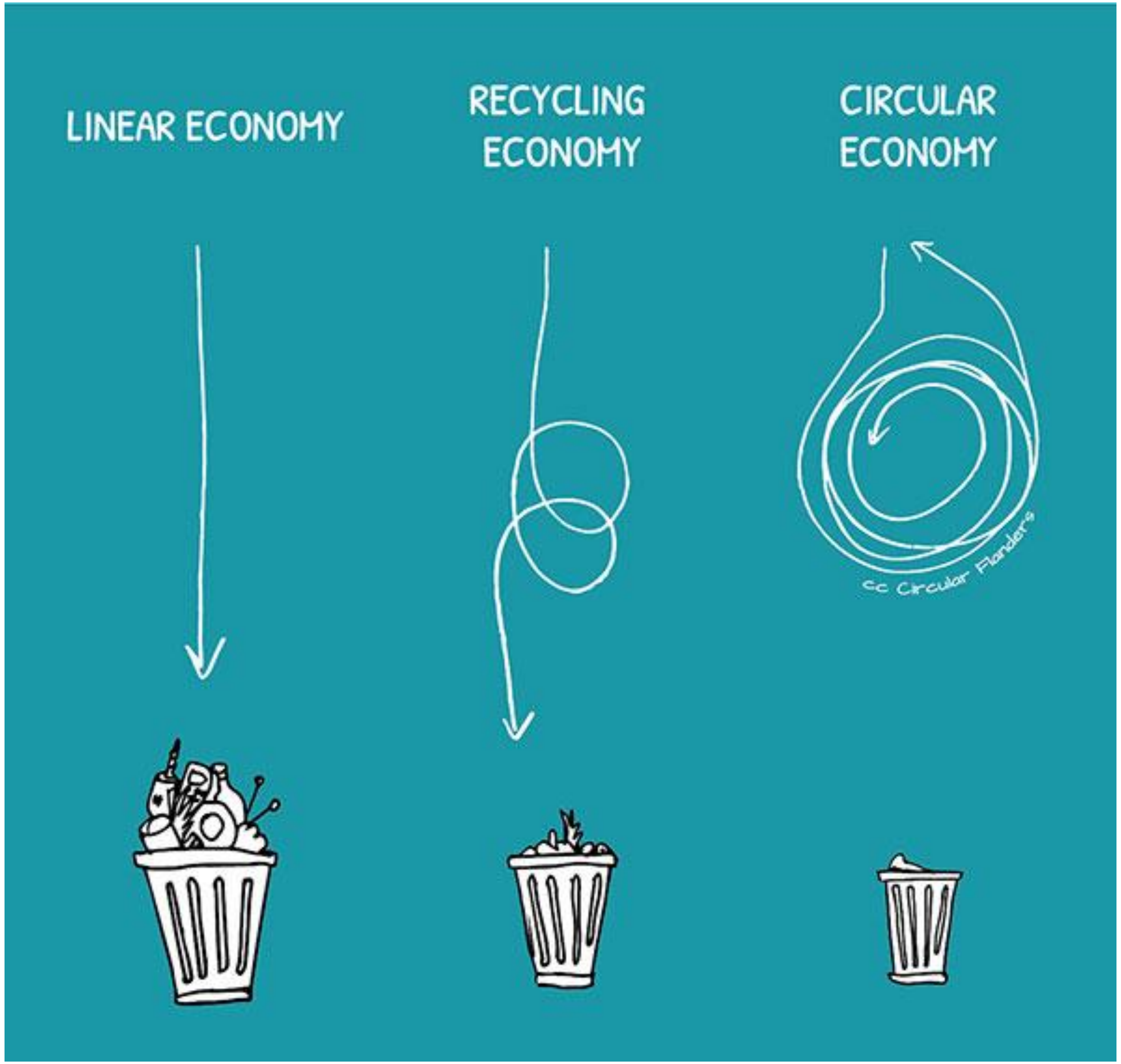
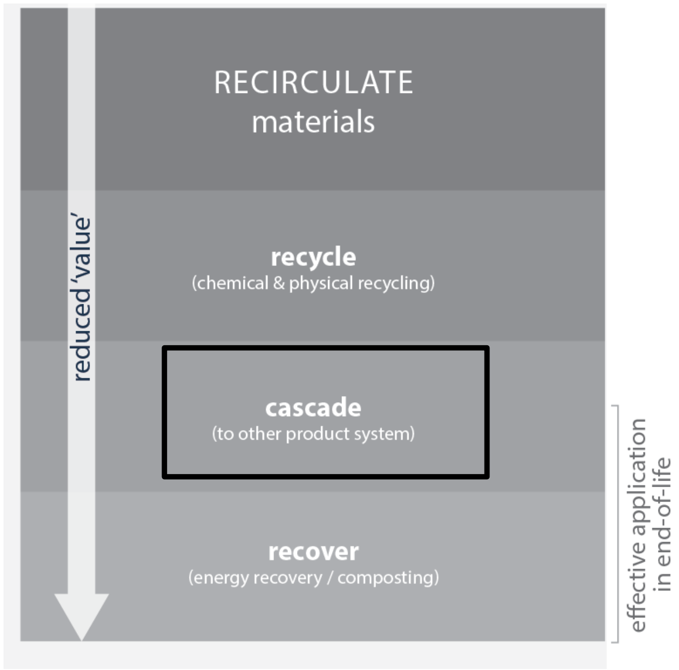
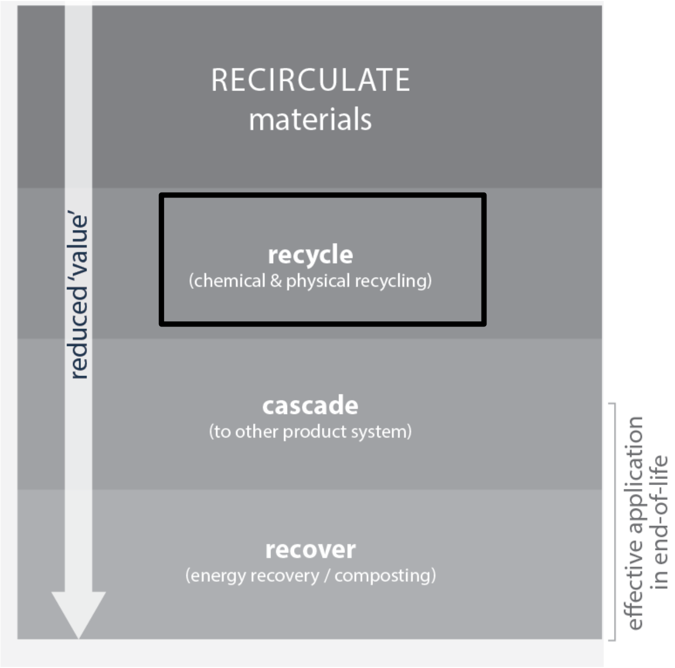
Circular Strategies Scanner:
32 opportunities to go circular!




RECIRCULATE
materials
reduced 'value'
recycle
(chemical & physical recycling)
cascade
(to other product system)
recover
(energy recovery / composting)
effective application
in end-of-life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materials
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(chemical & physical recycling)
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(to other product system)
recover
(energy recovery / composting)
reduced 'value'
effective application
in end-of-life


NATALIE'S BIRTHDAY
Precise.
Reliable.
Original
HP Inks.
56
Eco Highlights
HP Deskjet D2545 Printer
· Made from 83% recycled plastic material
· Packaging is 100% recyclable
· HP 60 Black cartridges are molded from 75% recycled plastic
· ENERGY STAR® qualified; decreased power consumption by 40%*
* In idle and sleep mode as compared to its predecessor
HP makes it easy to recycle computer hardware and printing supplies responsibly. HP's goal is to recover 2 billion pounds (900,000 tonnes) of electronic products and supplies by the end of 2010.
Visit www.hp.com/go/ecohighlights

RECIRCULATE
parts & products

reduced 'value'

upgrade

repair & maintenance

reuse

refurbish

remanufacture

repurpose

Extend existing use-cycle

Extend to new use-cycles

RESTORE, REDUCE & AVOID impacts in the areas of:		
RAW MATERIALS & SOURCING	MANUFACTURING	PRODUCT USE & OPERATION
renewables	lean manufacturing & cleaner production	product longevity
recyclable materials	rework (pre-user refurbish or remanufacturing)	low consumables (energy, water, materials)
secondary source sourcing	recycle (pre-user)	Use idle product capacity
restorative sourcing	cascade (industrial symbiosis)	
non-toxic & benign materials	recover (energy recovery, composting)	
lowest suitable grade		

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Steelcase ”Think” chair

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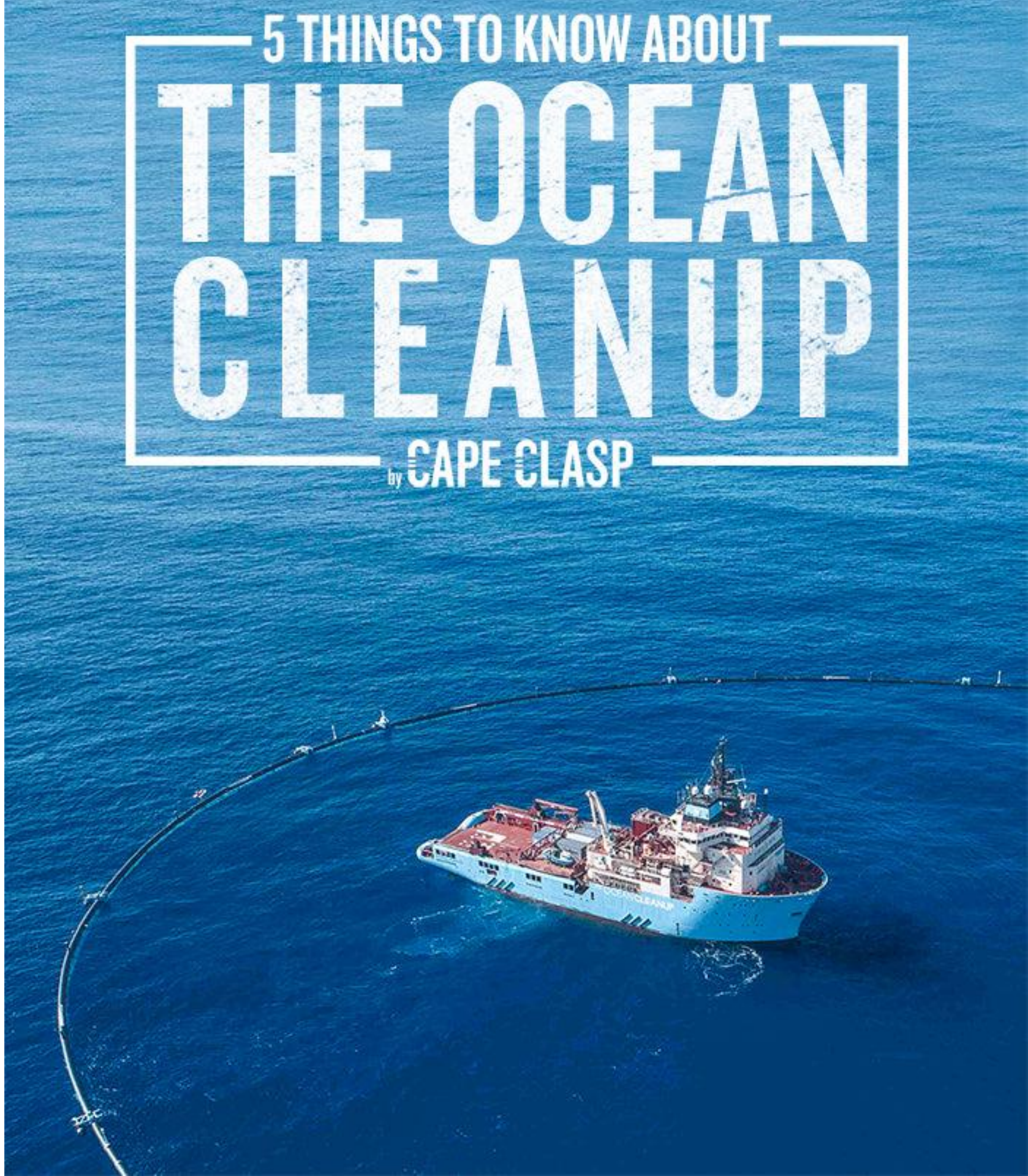

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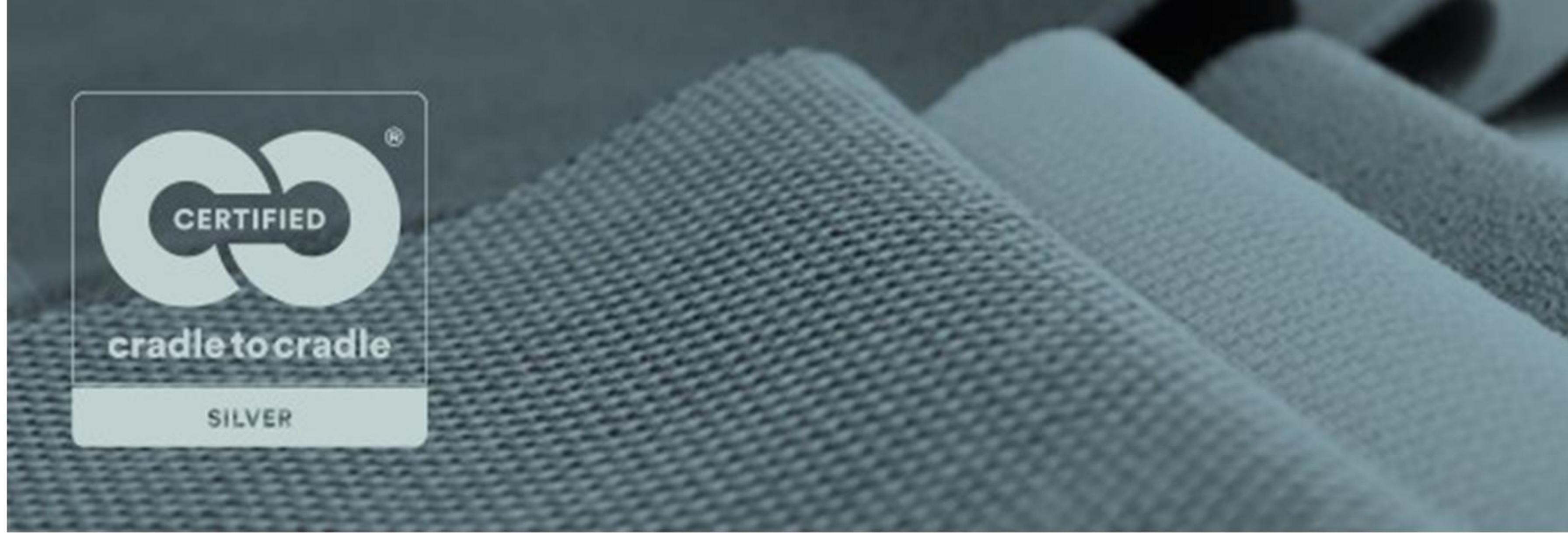
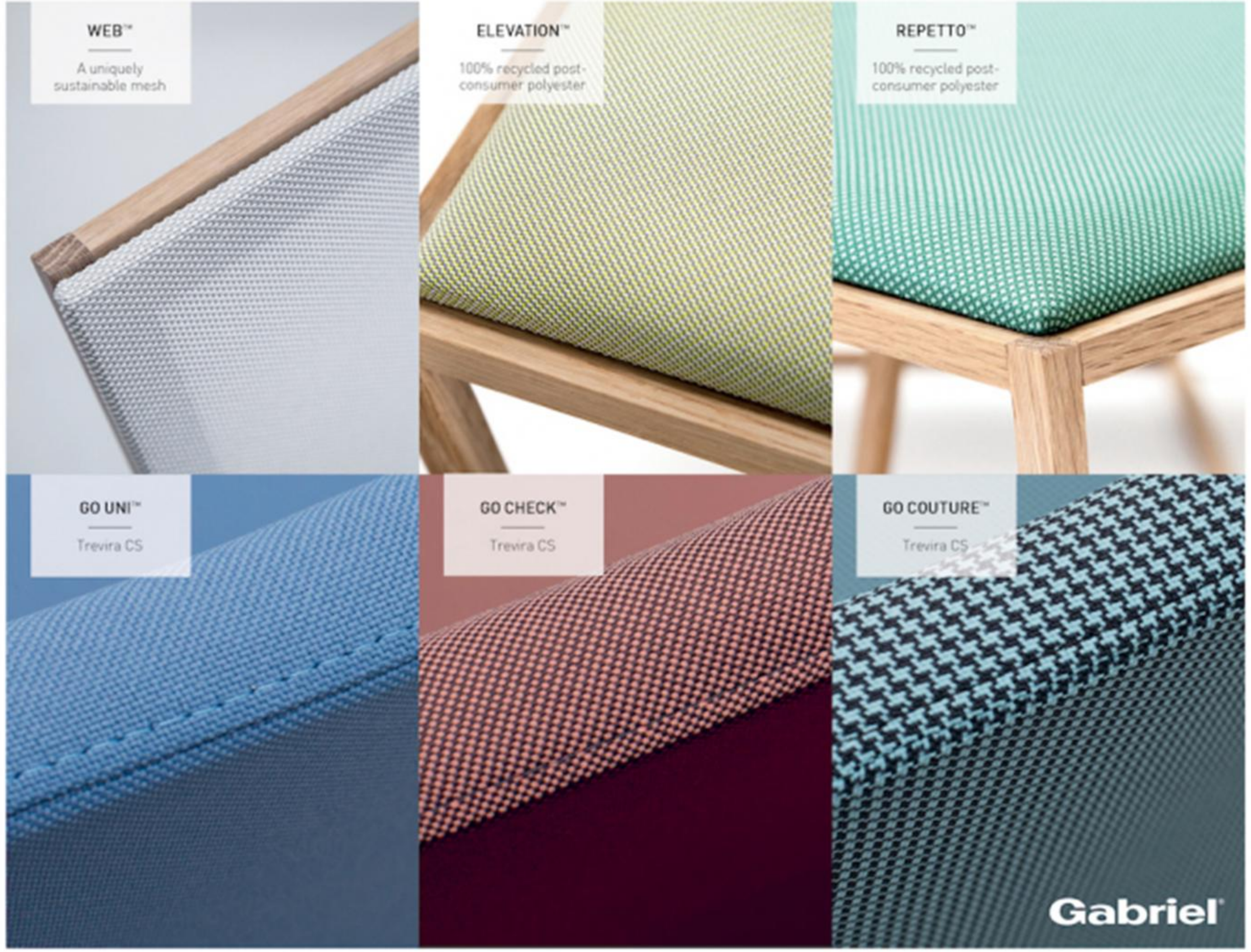
$\boxed{\text{non-toxic \& benign materials}}$	recover (energy recovery, composting)	
lowest suitable grade		





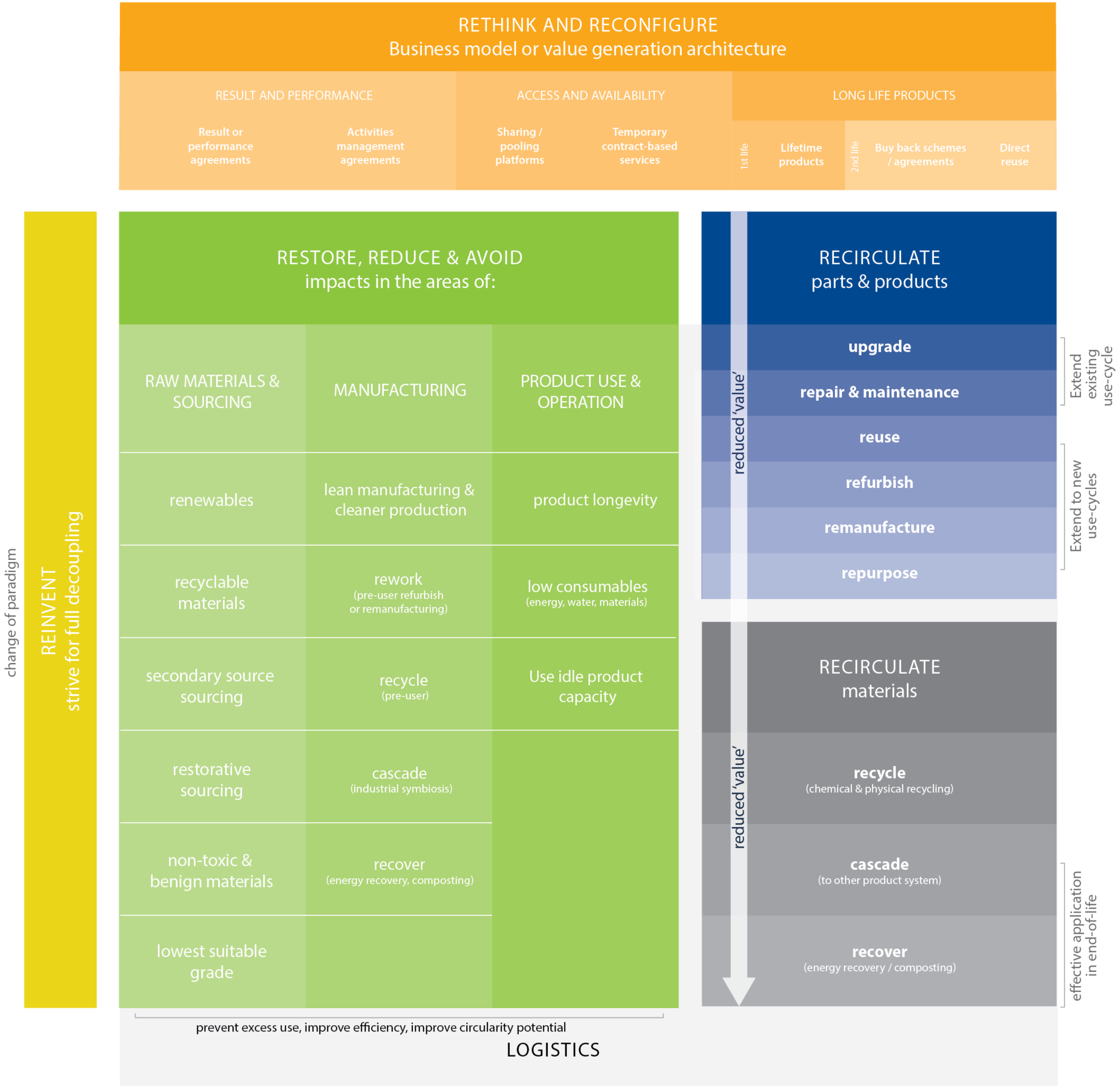
RETHINK AND RECONFIGURE Business model or value generation architecture								
RESULT AND PERFORMANCE		ACCESS AND AVAILABILITY		LONG LIFE PRODUCTS				
$\boxed{\text{Result or performance agreements}}$	Activities management agreements	Sharing / pooling platforms	Temporary contract-based services	1st life	Lifetime products	2nd life	Buy back schemes / agreements	Direct reuse

change of paradigm

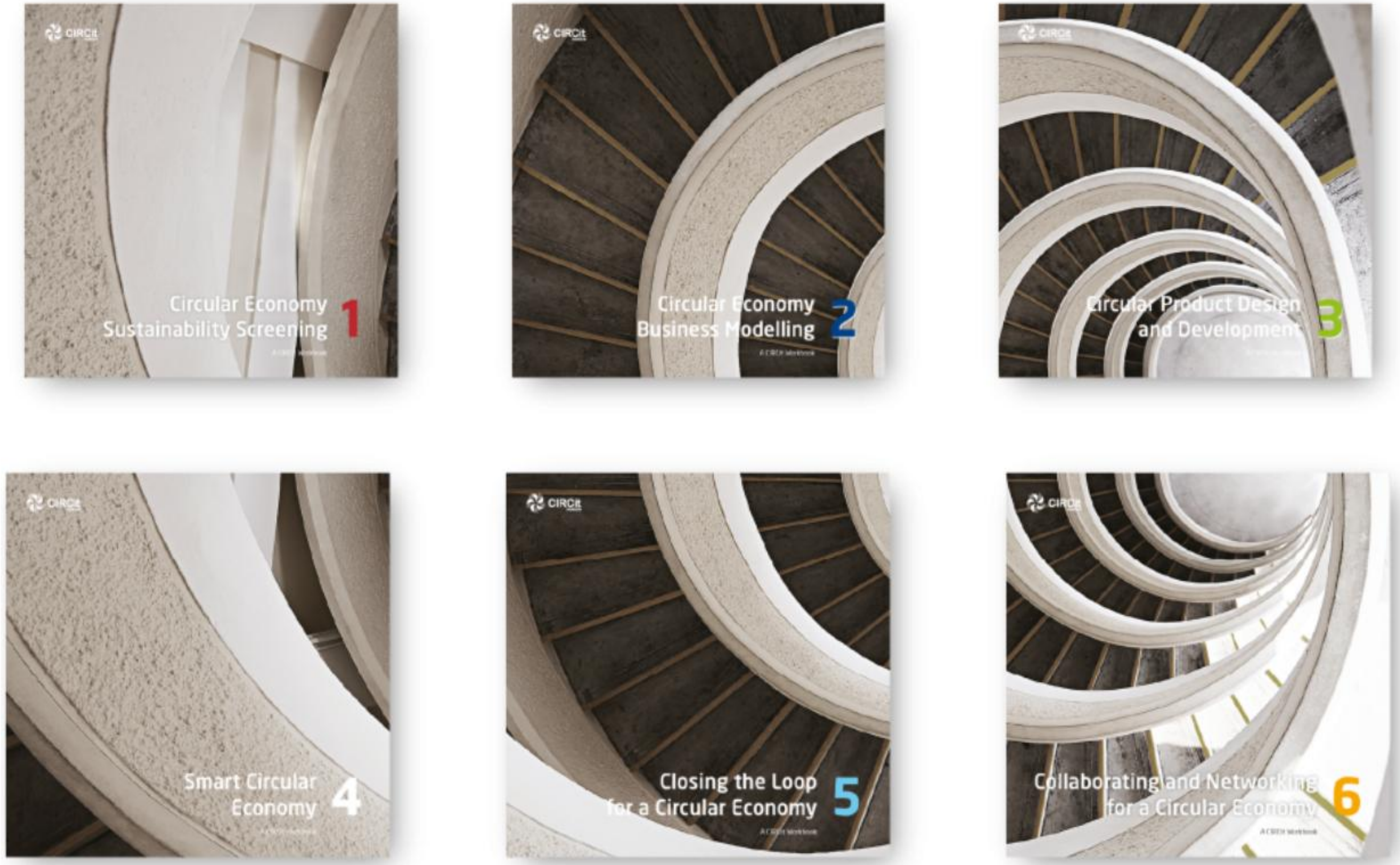
REINVENT
strive for full decoupling

Circular Strategies Scanner:

32 opportunities to go circular!



[Blomsma et al., 2019]



Circular Economy Workbooks from DTU and Nordic colleagues

www.circitnord.com

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DTU

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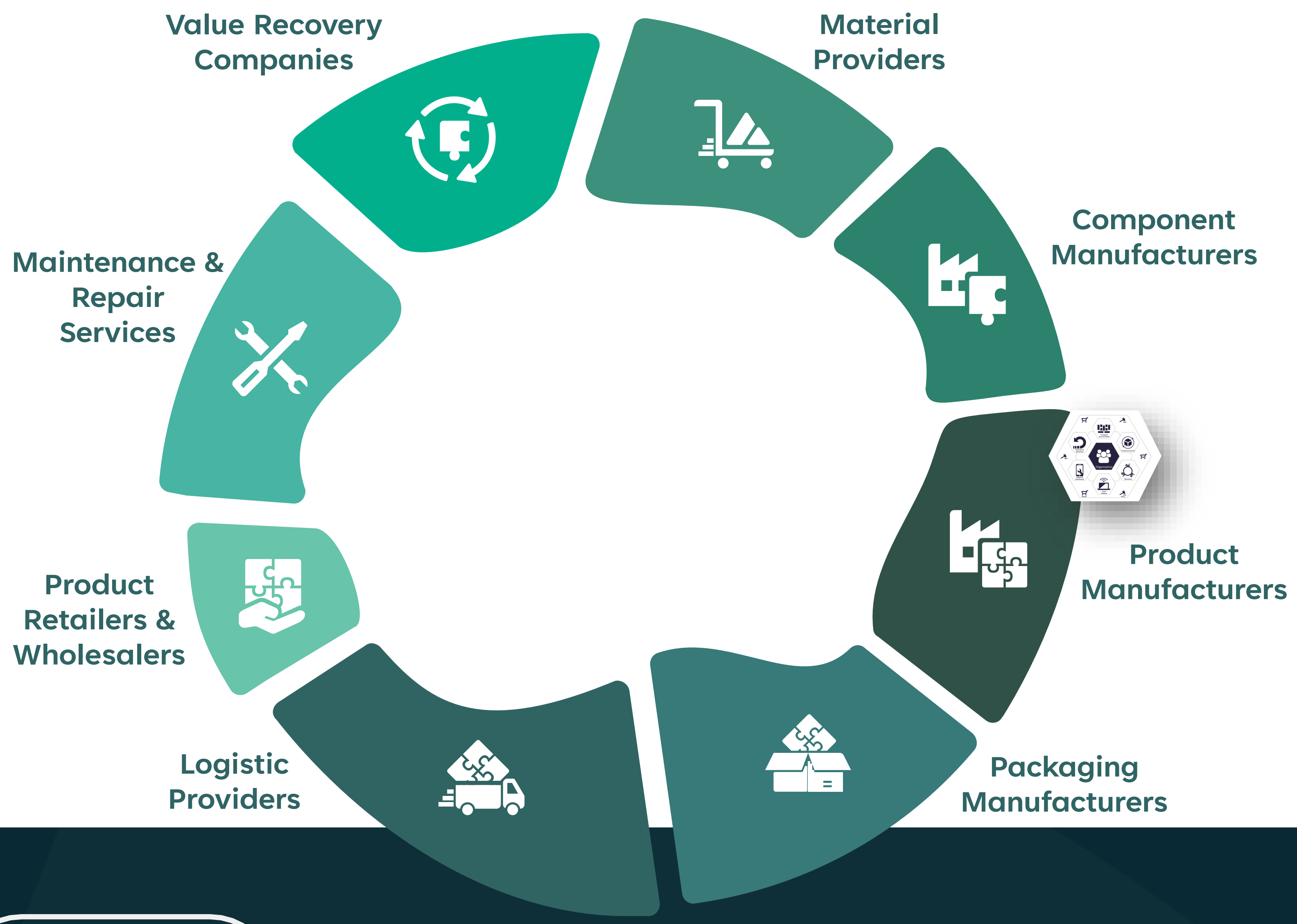
ready2LOOP

REALISING CIRCULAR ECONOMY

REQUIRES A SYSTEMIC APPROACH

Focus on a holistic shift to circular economy is important…

…PLUS circular economy only arises when there is cooperation across the value chain.



800+
Companies

16
Sectors

38
Countries

ready2LOOP powered by MATCHE

INDUSTRIENS FOND

[www.ready2loop.org]

8 dimensions for the CE transition

ready2LOOP

Strategy & Business Model Innovation

Strategy & Business Model Innovation

Readiness of 'Strategy & Business Model Innovation' measures the capabilities to enable a long-term strategy to be developed, which is linked to the development of new business models that can effectively deliver enhanced competitiveness and growth.

Mobike

Bike sharing scheme

Product & Service Innovation

Product & Service Innovation

Readiness of 'Product & Service Innovation' measures the capabilities necessary to develop new solutions (incl. products and services) that are suitable in a Circular Economy context.

RePack

Reusable packaging for e-commerce

Manufacturing & Value Chain

Manufacturing & Value Chain

Readiness of 'Manufacturing & Value Chain' measures the capabilities that will help you to create new value chain engagements and partnerships, aimed at maximum value creation from finite resources.

Carlsberg
Green Fibre Bottle

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.

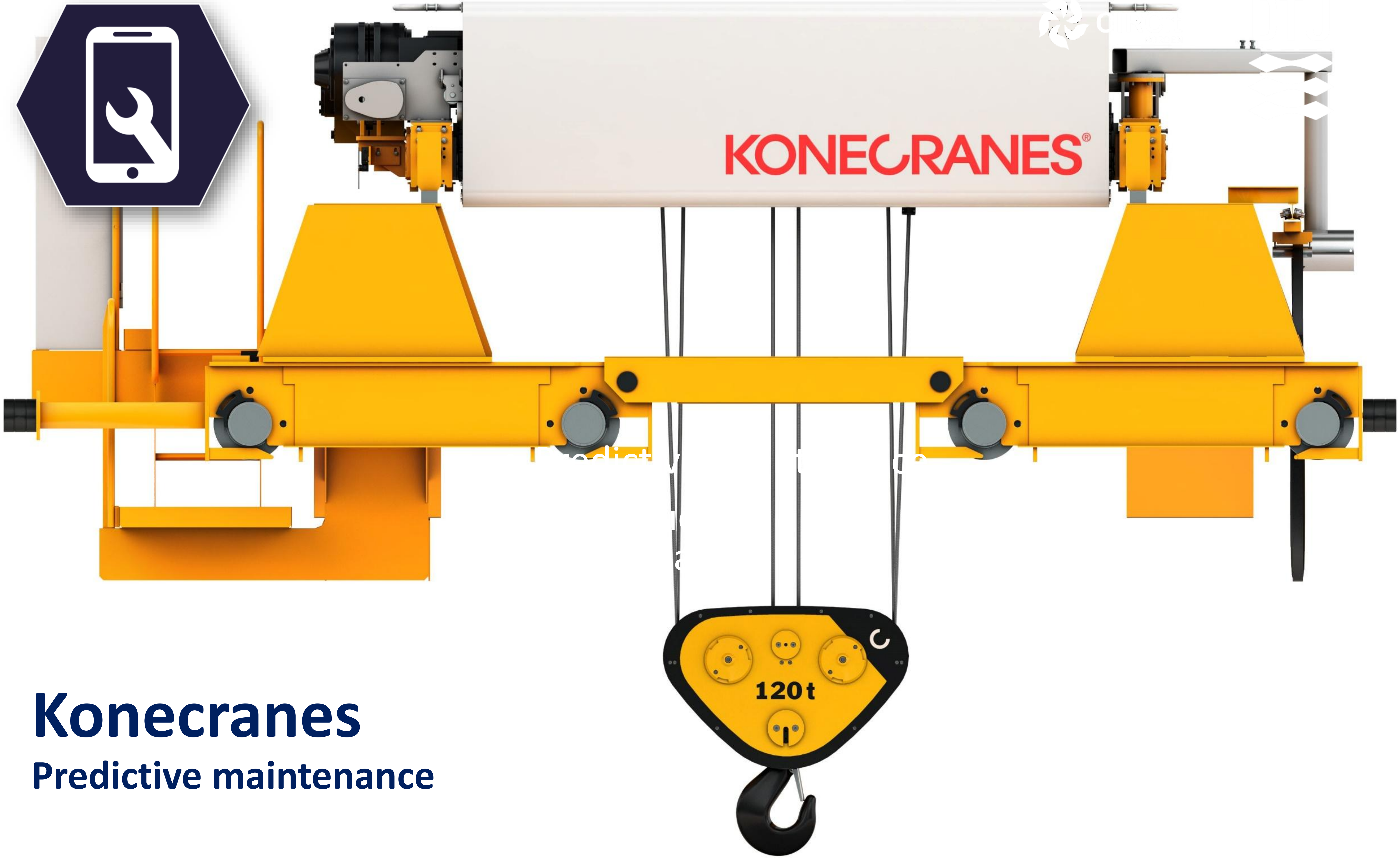
WasteIQ

Smart waste management

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.



Konecranes

Predictive maintenance

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.


Refurb
Repair > Refurbish > Resell

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.

Copenhagen Village

affordable housing as a total service-system

Organisation

Organisation

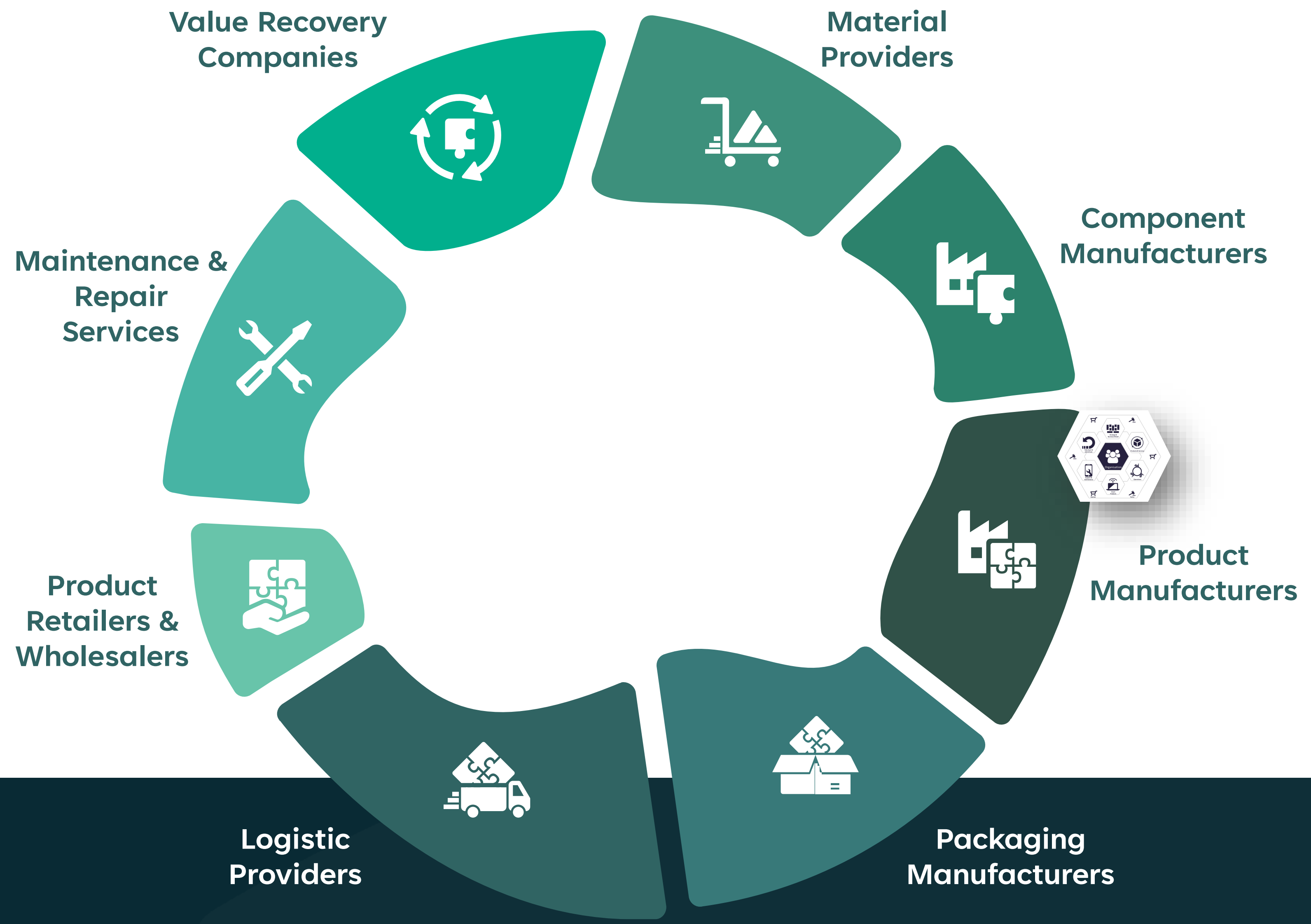
Readiness of 'Organisation' measures the internal business capabilities of your company to be able to implement new concepts, such as the Circular Economy.

Bose
sustainability maturity

8 dimensions for the CE transition

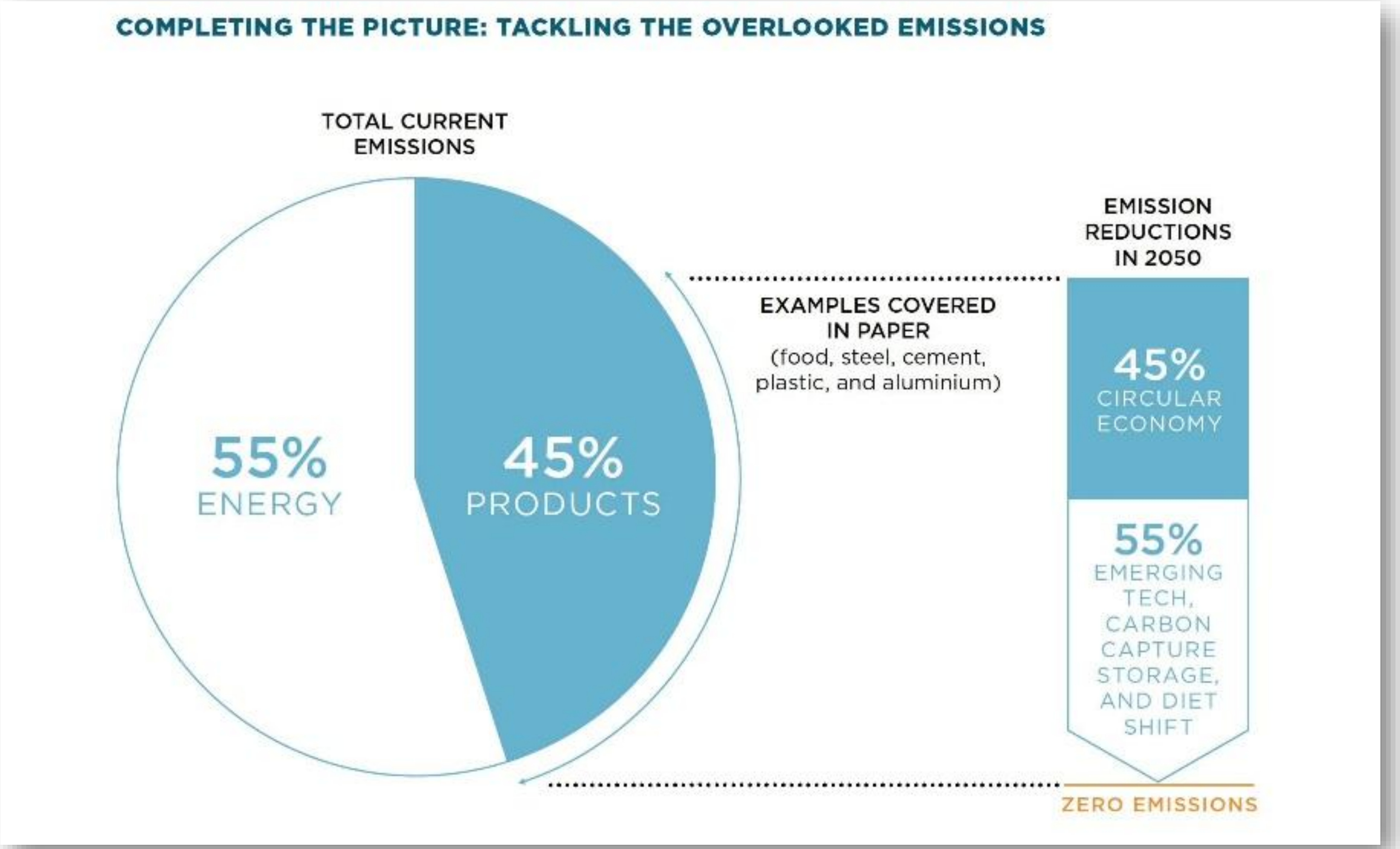
REALISING CIRCULAR ECONOMY

REQUIRES A SYSTEMIC APPROACH



[www.ready2loop.org]

Circularity increasingly recognised as a means to net-zero



Summary

Bringing it all together

Tim C. McAloone
Professor, PhD

In summary

- Consider what type of circularity pattern(s) your project might best be suited to follow: narrowing, slowing, closing, regenerating..?

- Which of the 32 circular strategies could/should you follow? Make a consideration and find a workbook to aid you!
  www.circitnord.com

- How ready do you think you/your case company is to transition to a circular economy? Try it out!
  www.ready2loop.org

- Read the appended articles for deeper theoretical understanding and guidance

Tim C. McAloone
tmca@dtu.dk

READY2LOOP FOR CONSULTANCIES AND UNIVERSITIES

Boost your knowledge about Circular Economy with ready2LOOP

ready2 LOOP

powered by MATCHE

HOW TO USE READY2LOOP?

ready2LOOP is a platform designed to assist companies in the ***manufacturing value chain*** by evaluating their ***readiness for the Circular Economy***. It helps in planning their transition to a circular model and offers tools to facilitate this journey.

ready2LOOP has experienced ***significant interest from universities and consultancies***. At ready2LOOP, the goal is to enlighten everyone about the importance of Circular Economy and ensure that as many as possible benefit from the platform.

To achieve this, we have created this ***template to guide*** universities and consultancies through the ***sign-up process and the usage of ready2LOOP***. By following this guide, users can engage with the platform without interfering with the results needed by actual companies in the manufacturing value chain.

Please reach out at info@ready2loop.org if you have **any questions** on how to use ready2LOOP as a university or consultancy.

WHAT CAN YOU DO?


Register at ready2LOOP


Create a business unit


Do the readiness assessment


Prioritise dimensions


Define a transition plan


Browse the tools

REGISTER AT READY2LOOP

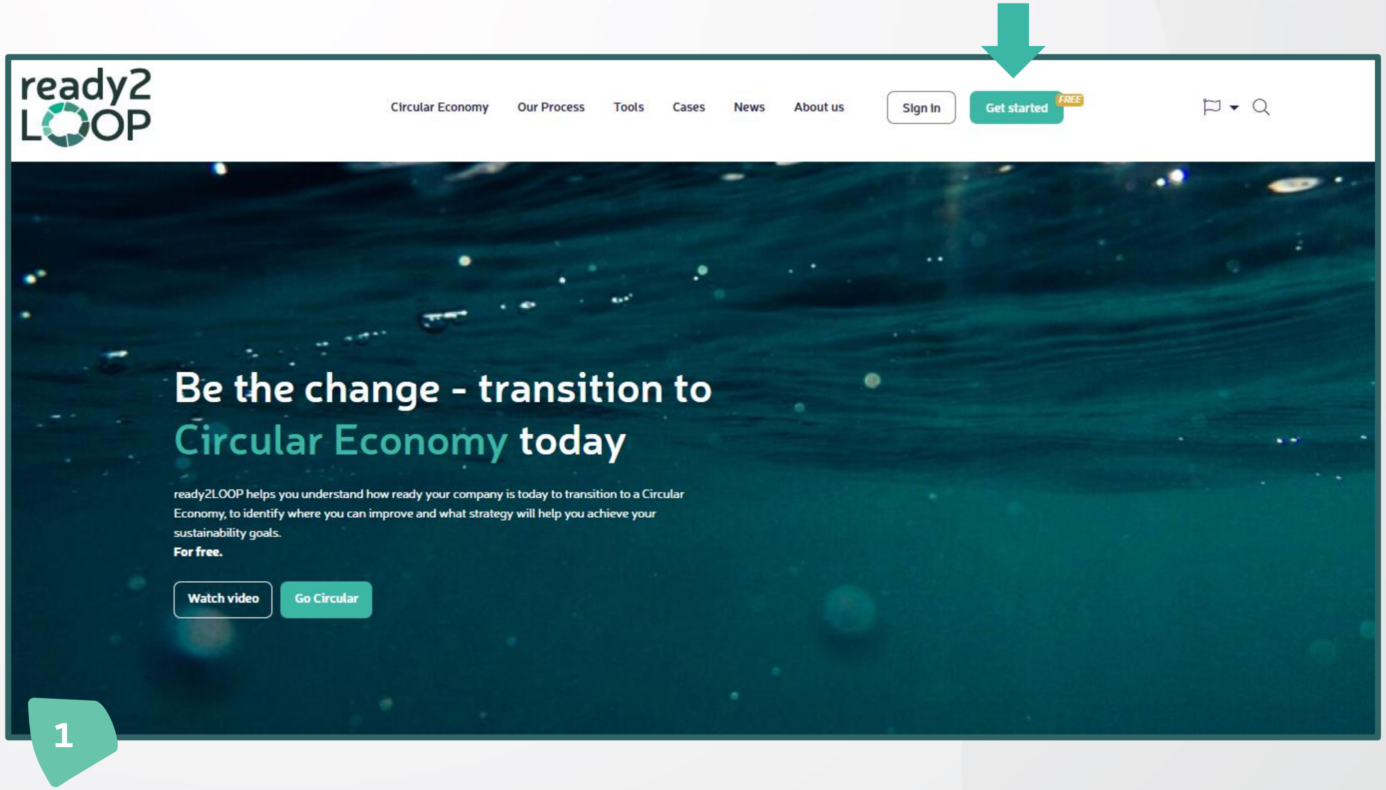
Please complete the required information about yourself, your company (i.e., university/consultancy), and the type of company. See the guide from slide 5 to 7.

As a university or consultancy, please select "Out of scope" when asked, "What kind of company do you represent?"

You will ***still have access*** to the Product Manufacturers layer, can do the ***Readiness Assessment*** as a Product Manufacturer company and can ***explore the toolbox***.

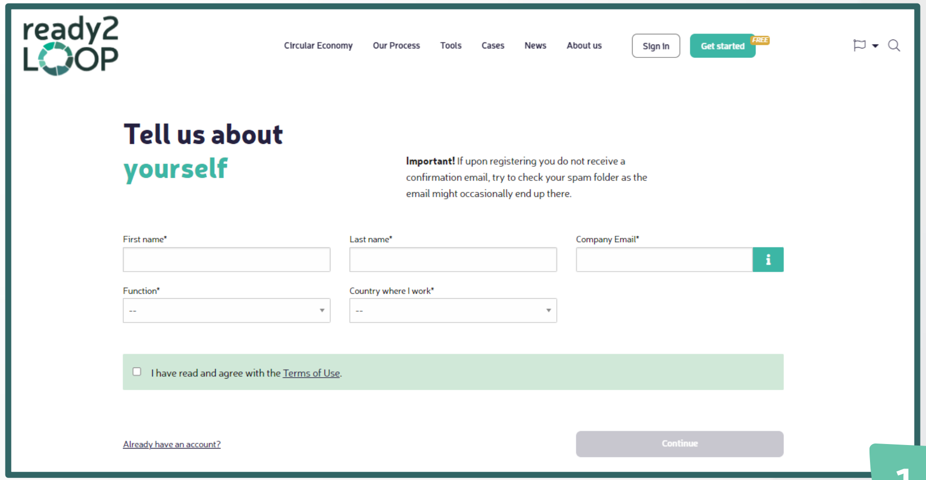
REGISTER AT READY2LOOP

- Go to ready2loop.org
- Press ***Get started*** **(1)** .



REGISTER AT READY2LOOP

- Fill in the information about yourself and your company **(1)**.
- Please use your ***correct company name*** (university/consultancy).
- If you would like to use the readiness assessment at ready2LOOP to ***explore other companies'*** readiness you can create that once you have registered correctly.



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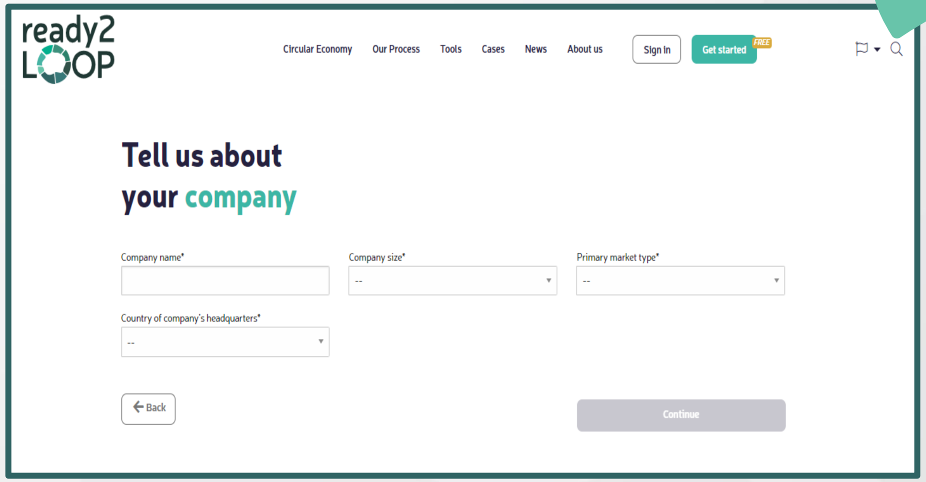
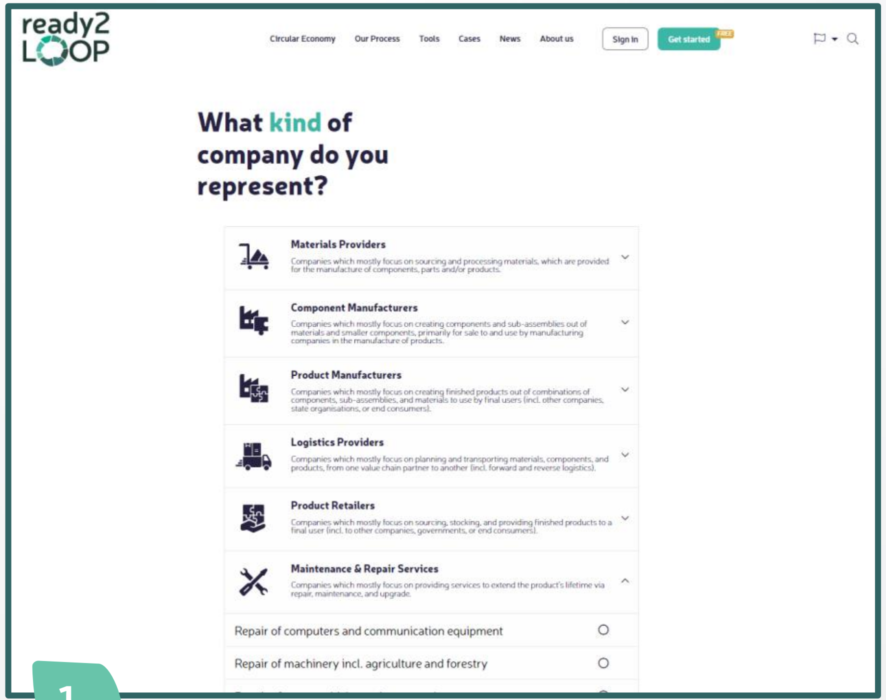


REGISTER AT READY2LOOP

- Choose ***Other*** and then ***Out-of-scope organisation*** when asked: ”What kind of company do you represent?” **(1)**

- Press ***Okay, fine with me!*** To continue and create an account **(2)**.

- <u>***Remember*** you still have access to ***many features*** at ready2LOOP.</u>



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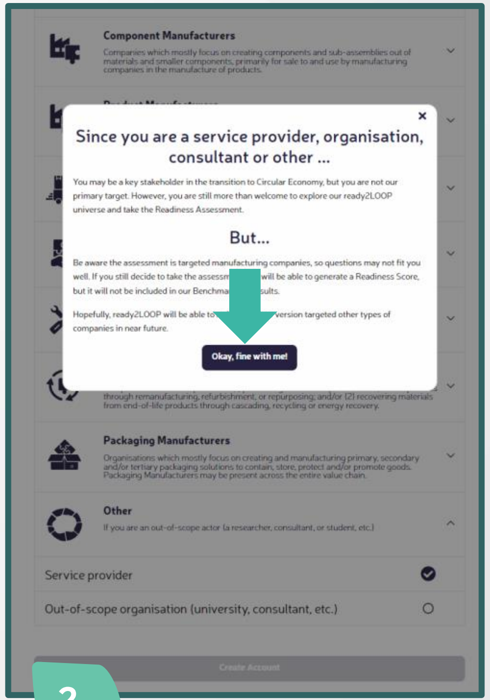


2

CREATE A BUSINESS UNIT

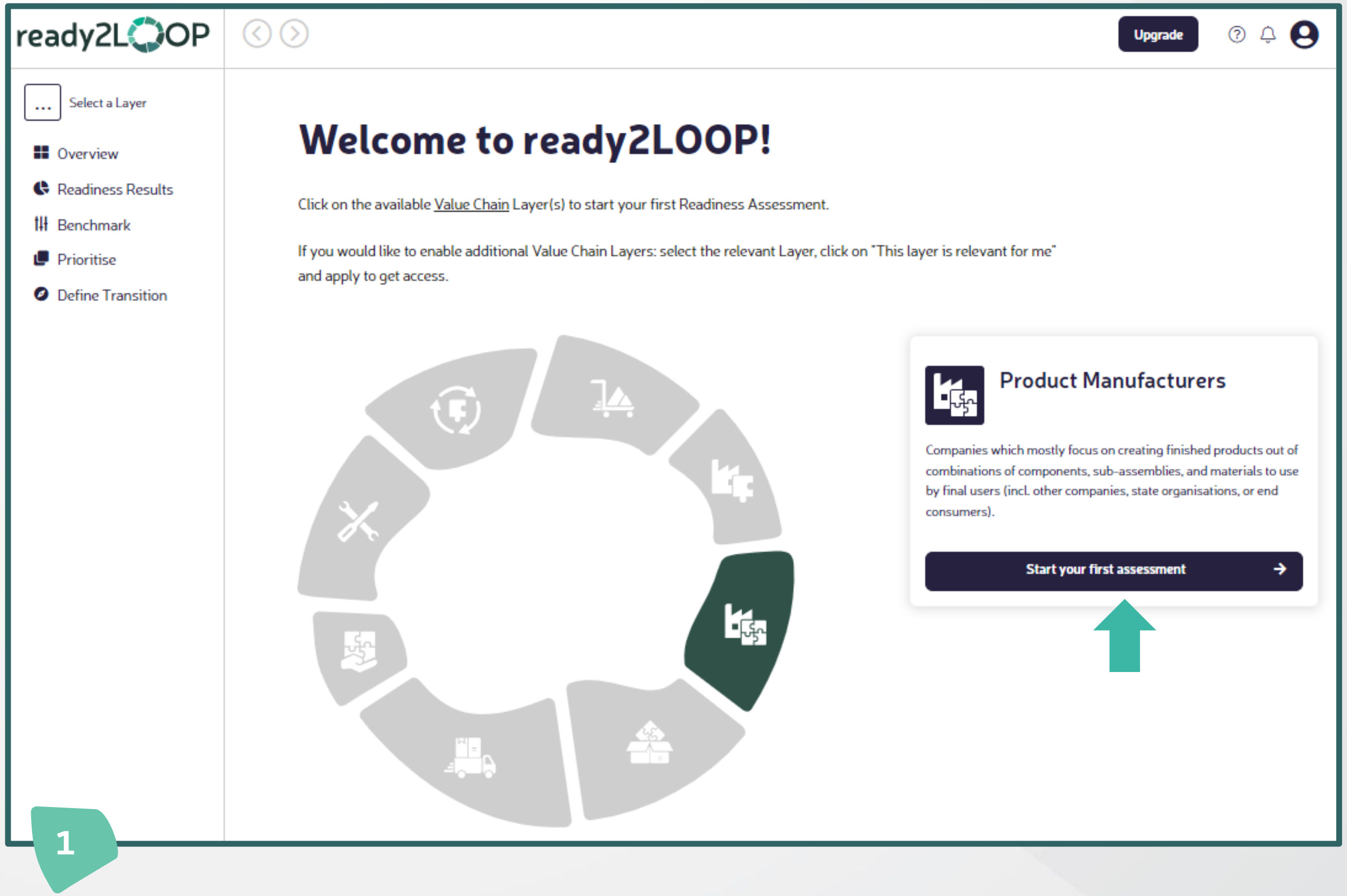
If you would like to use ready2LOOP to ***explore the readiness of a case company*** (i.e. not your own university/consultancy), you can create a ***Business Unit***.

This feature can be particularly ***useful in e.g. education*** to explore how a case company addresses the concept of Circular Economy.

Feel free to create ***as many business units as you would like.***

CREATE A BUSINESS UNIT

- Go to ***My LOOP***
- Press ***Start your first assessment (1)***

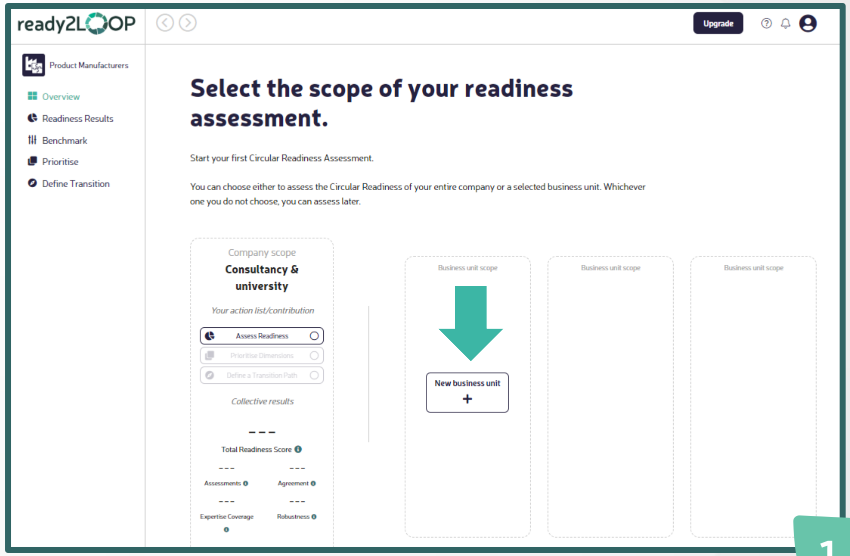


CREATE A BUSINESS UNIT

- A Business Unit can be created if you wish to ***assess different departments of your own company*** (university/consultancy) **(1)**.

Or

- A Business Unit can be created if you wish to use the readiness assessment at ready2LOOP to explore the ***readiness of a case company*** (i.e., not your own university/consultancy) **(1)**.



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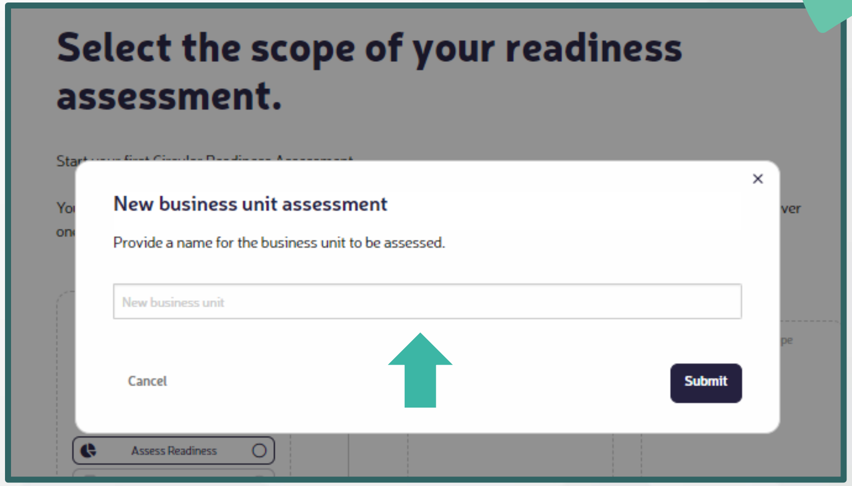


COMPLETE THE READINESS ASSESSMENT

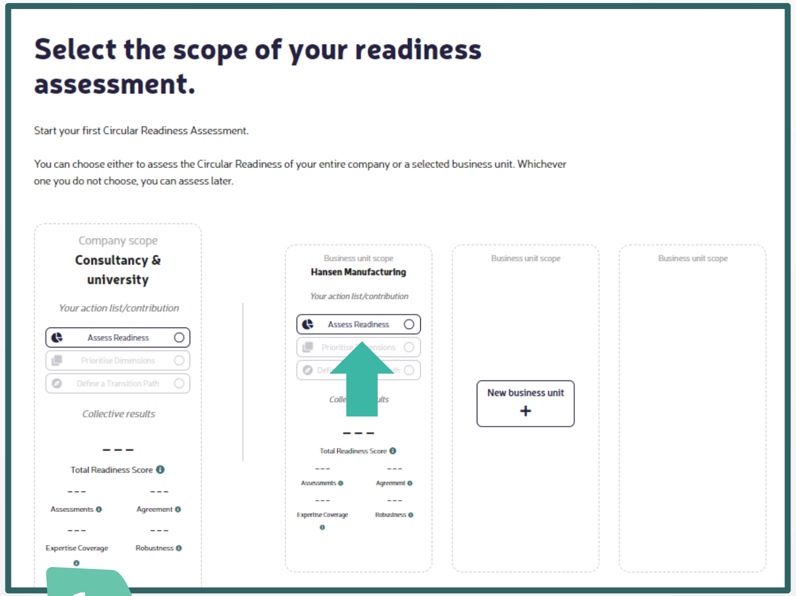
Complete the readiness assessment in relation to the ***company under investigation***.

For instance, if a company other than your own is being examined, some ***research on the company*** should have been conducted prior to the assessment to provide the ***most realistic answers***.

After the assessment has been submitted, the ***Readiness Score*** can be viewed, and the ***Current Status*** of the company can be read.

COMPLETE THE READINESS ASSESSMENT

- Press '***Assess Readiness***' on the unit to be assessed **(1)**.
- Select a ***Dimension*** to begin the assessment **(2)**.
- Answer the questions with ***respect to the company being assessed***.



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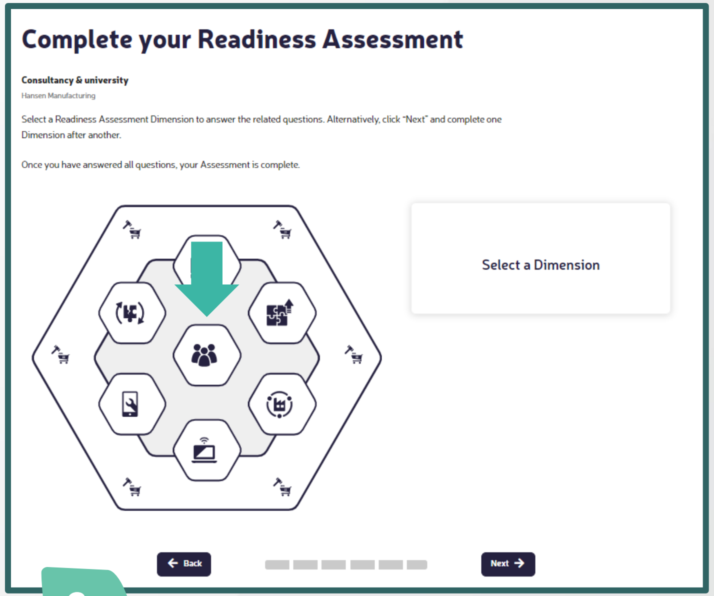
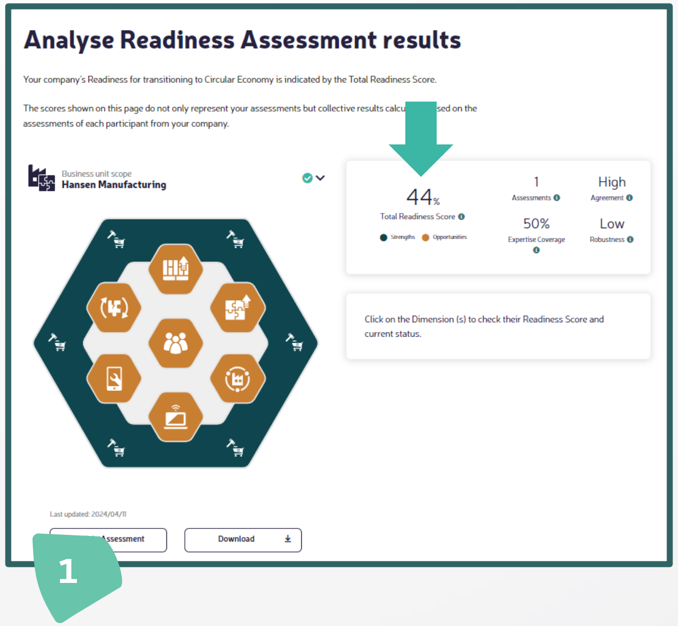
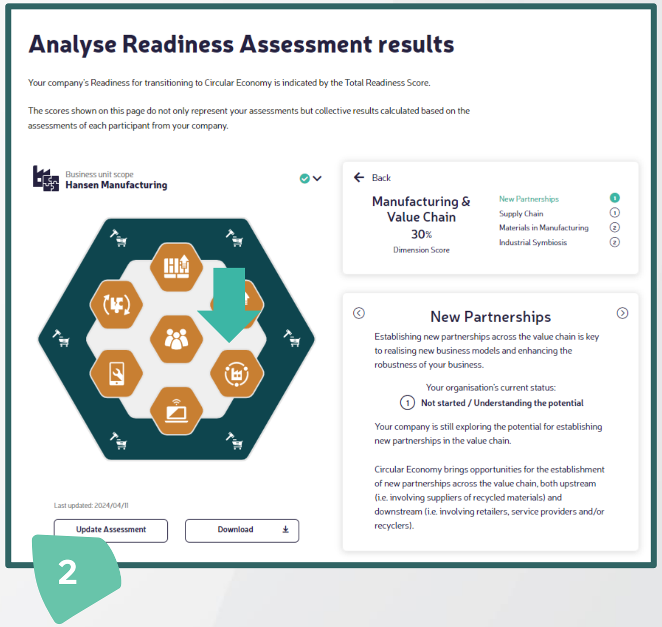


2

COMPLETE THE READINESS ASSESSMENT

- Submit the assessment to view the the overall ***Readiness Score*** (1).
- Click on a Dimension to view the ***Readiness Score of a Dimension*** and read about the ***Current Status*** (2).



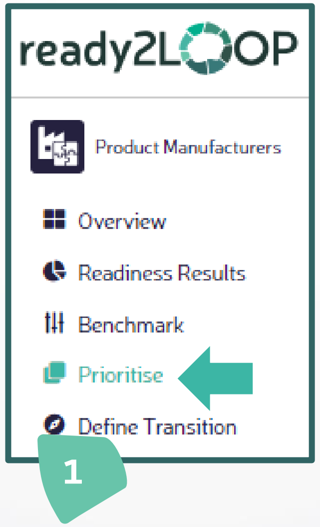


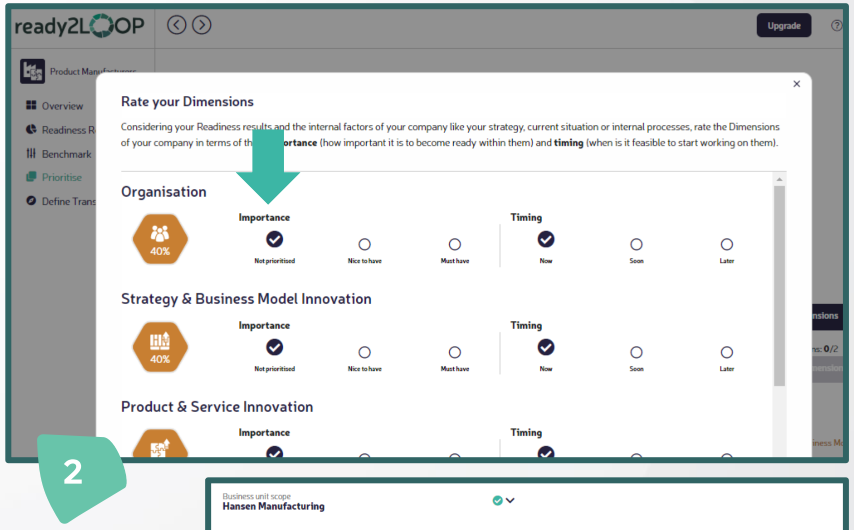
PRIORITISE DIMENSIONS

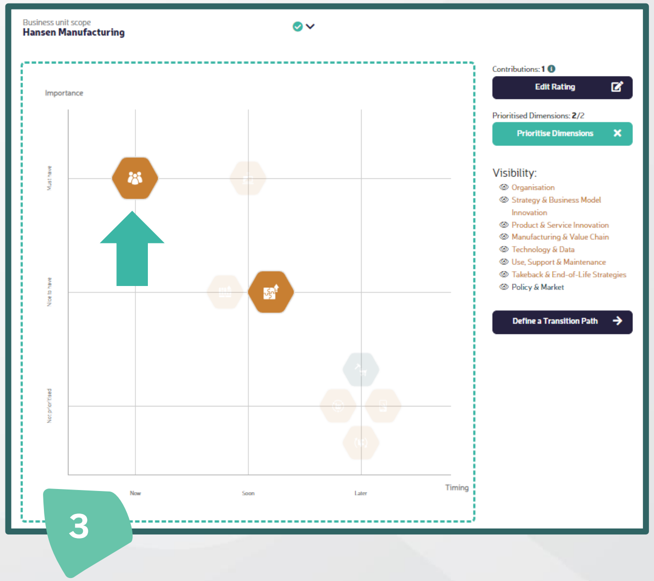
After the assessment, you can ***prioritise which dimensions*** are relevant for the assessed company or business unit to work on, along with the ***timeframe*** for when the company should start addressing those prioritised dimensions.

PRIORITISE DIMENSIONS

- Press ***Prioritise*** in the menu to the left **(1)**.
- ***Rate your Dimensions*** **(2)**.
- Press the two Dimensions, that you would like to ***improve on*** **(3)**.







DEFINE A TRANSITION PATH

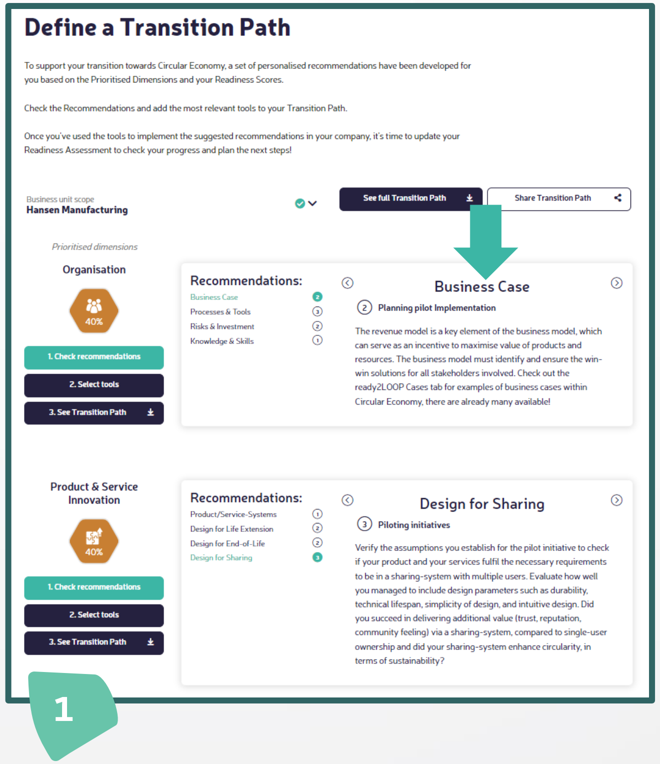
Explore how the company or business unit can begin their ***transition*** towards a Circular Economy.

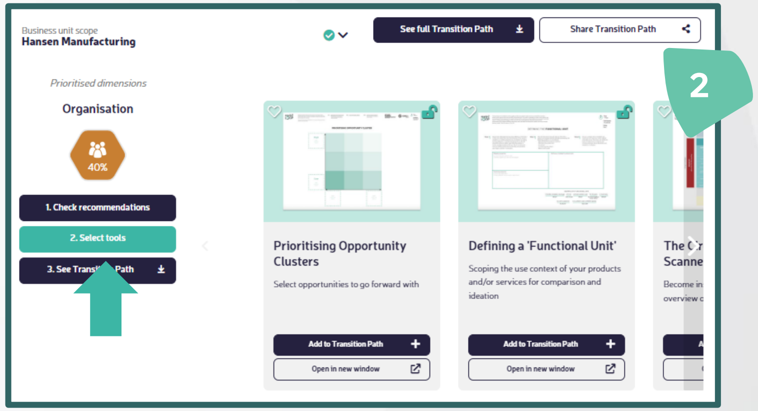
Begin by reading the set of ***Recommendations*** regarding the dimension you have prioritized. The Recommendations are based on your answers in the assessment.

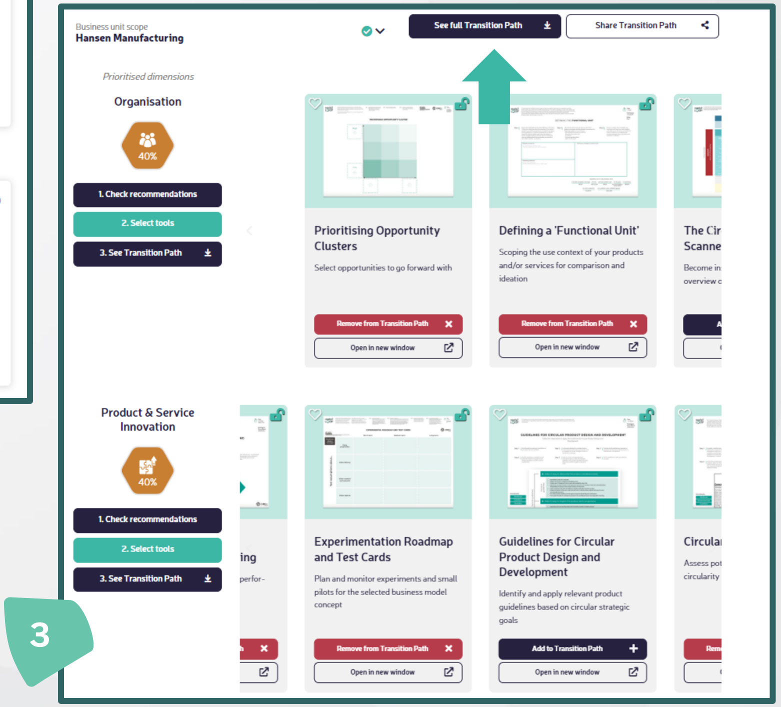
After reading the Recommendations, you can ***select the tools*** that you would like to include in your Transition Path.

DEFINE A TRANSITION PATH

- Read the ***Recommendations*** **(1)**.
- ***Select the tools*** you would like to include in the Transition Path **(2)**.
- Download the ***full Transition path*** once you have selected the tools **(3)**.







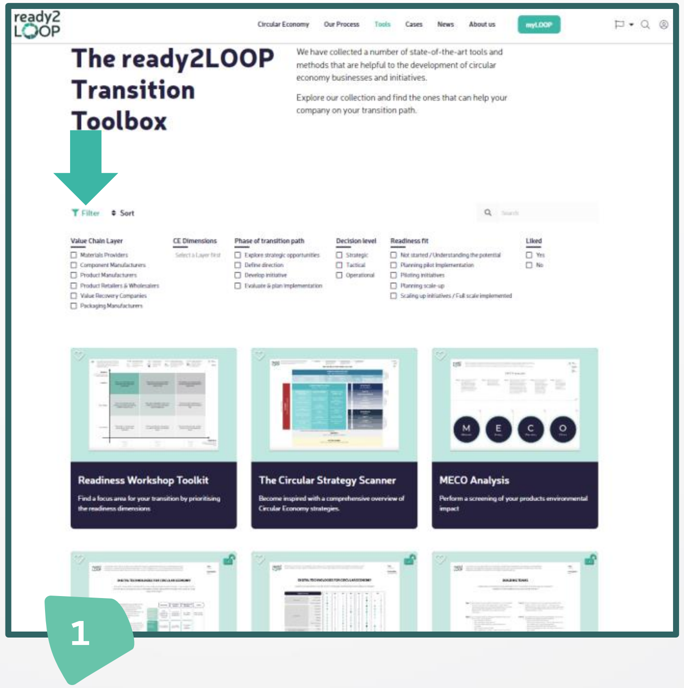
BROWSE THE TOOLS

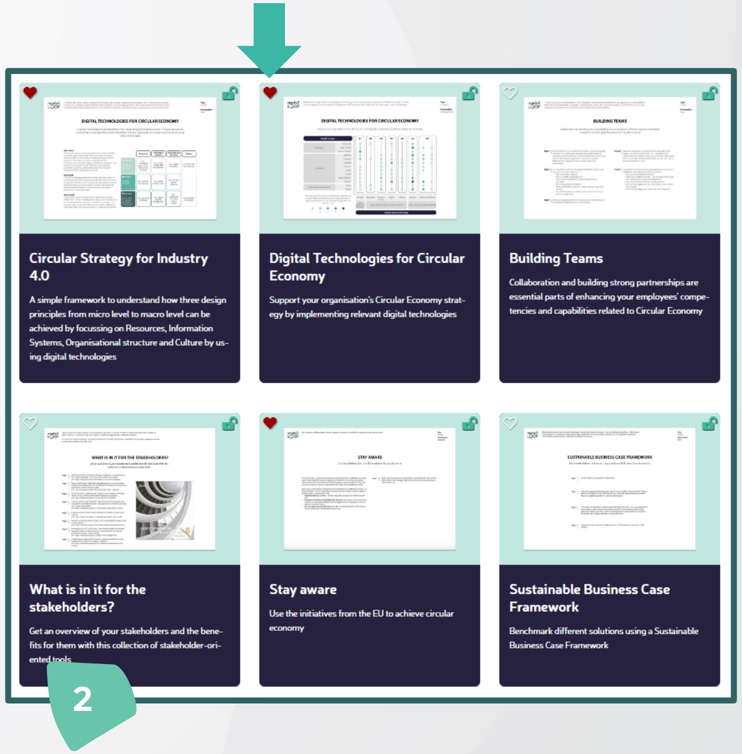
There are more than ***100 free tools*** at ready2LOOP.

Use them to get inspired and start working on ***your transition towards a Circular Economy***.

BROWSE THE TOOLS

- ***100+ free tools*** with printable templates.
- Filter the tools to ***fit your focus area*** (1).
- Like the tools to create your ***personal toolbox*** (2).





THANK YOU

Please reach out at info@ready2loop.org if you have any questions.

ready2LOOP

www.ready2loop.org

Decarbonizing energy systems
DTU course on Quantitative Sustainability

Lecture 1 Decarbonizing energy systems

Lecture 2 Wind Energy as example

Lecture 3 Exercise : Violation of planetary boundary of Global Warming Potential due to electricity mix

Asger Bech Abrahamsen, Senior Researcher
DTU Wind and Energy Systems, DTU Risø Campus, Roskilde
Technical University of Denmark
Contact : asab@dtu.dk

How sustainable is Wind Energy?

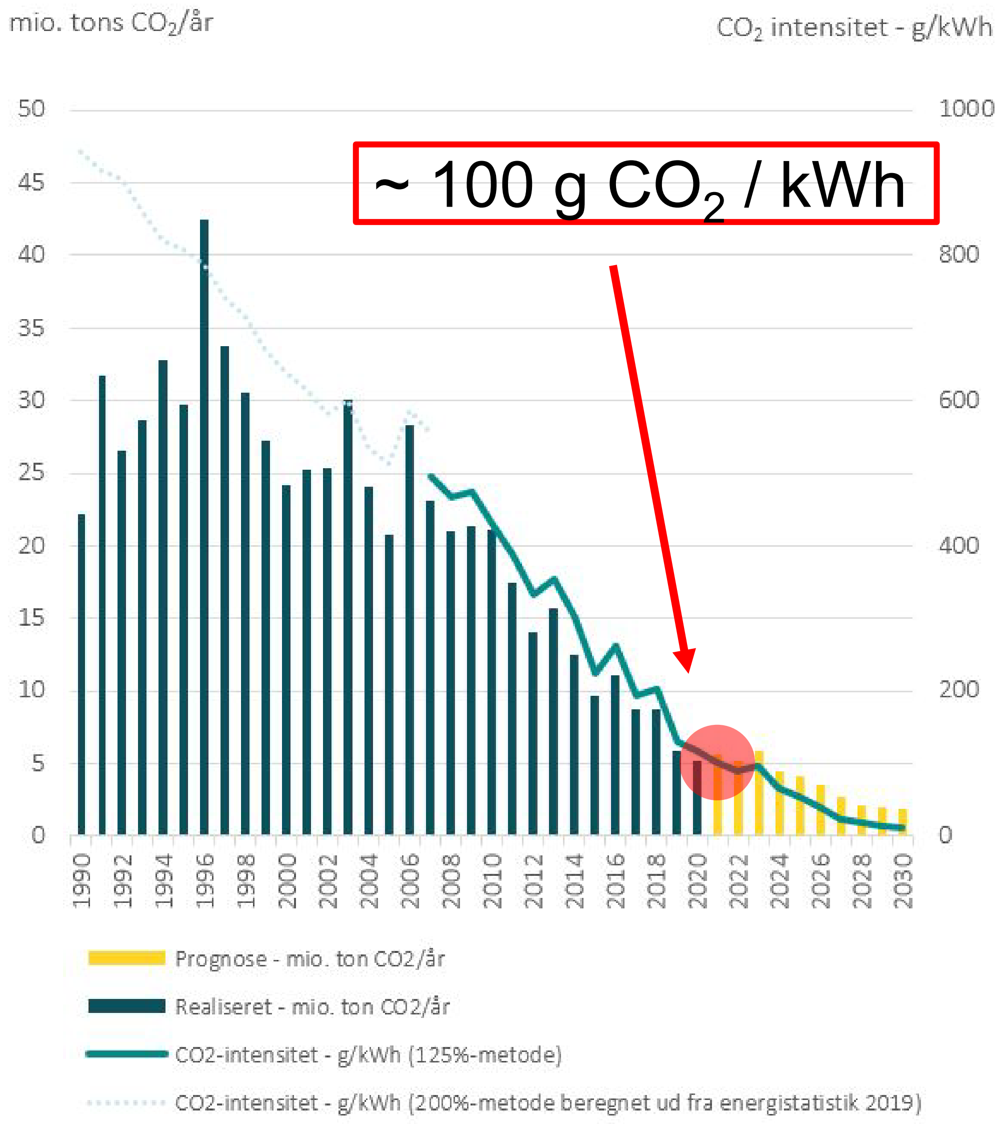
"Wind Energy is by definition green and once it supplies all production processed then the world will become purely green" (Wind sector around 2010)

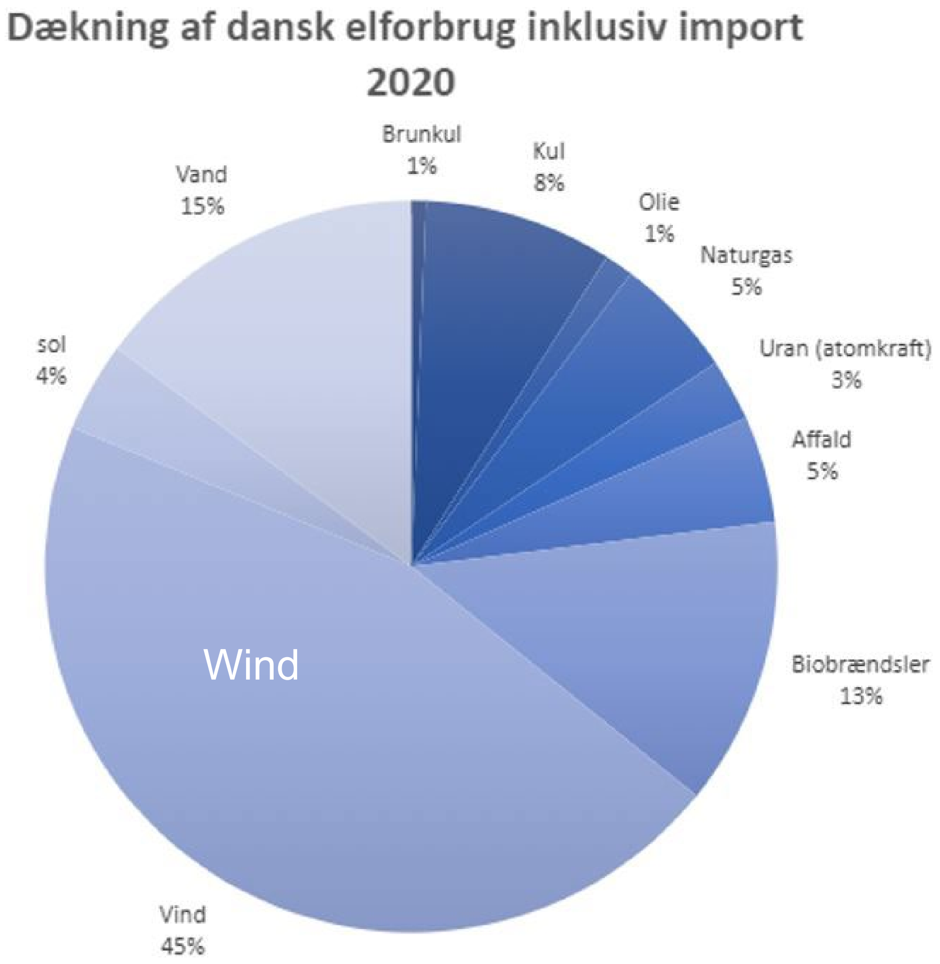
There are however some challenges related to this point of view:

- The production of the materials will need energy that might not be green
- The production of materials might result in direct chemical emissions
- The installation and Operation and Maintenance might be fossil-based
- There are many emissions to the environment and how to define limits?
- Is the turbine fleet operated in a circular manner with zero waste, or are new materials needed to compensate for the waste?

- Life Cycle Analysis (LCA) is a method to quantify the impact on the environment (CO_2 emission per kWh produced energy as example, but 17 others exist).

CO_2 emission from electricity of Denmark





Source: EnergiNet Miljøredegørelse 2020

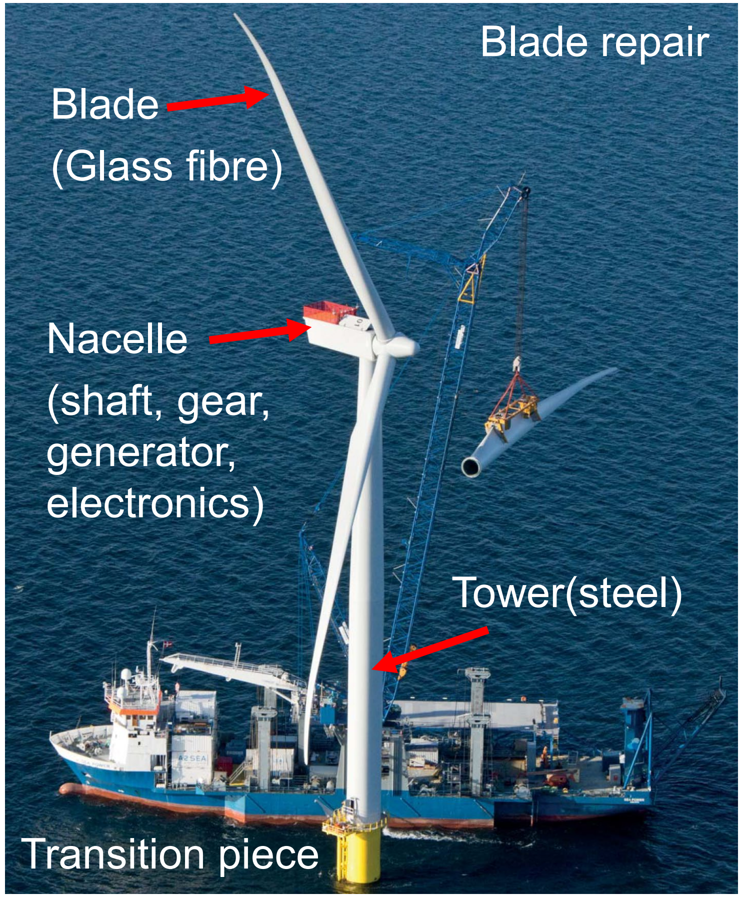
The life cycle of offshore wind farms

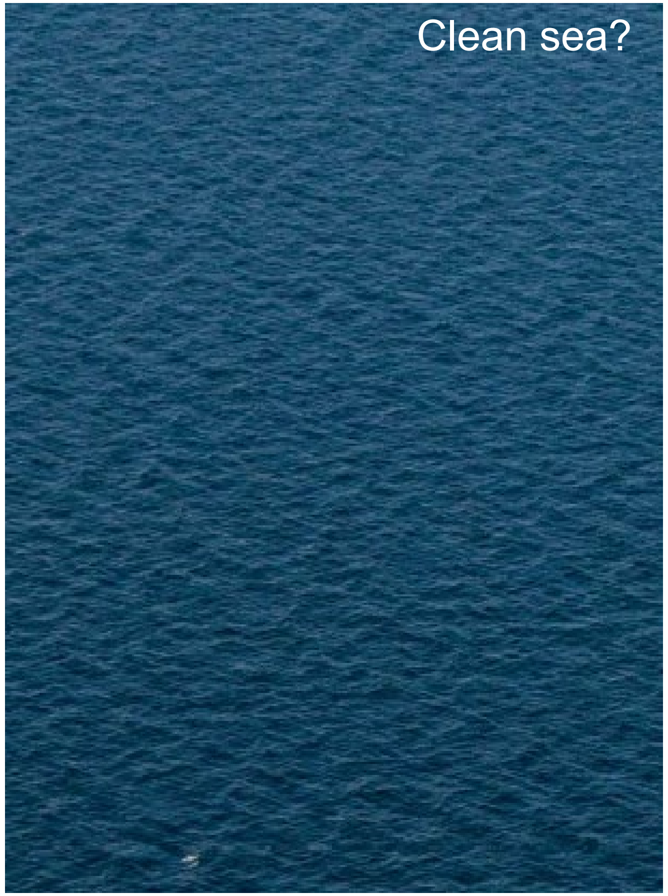
Manufacturing & Installation

Operation & Maintenance

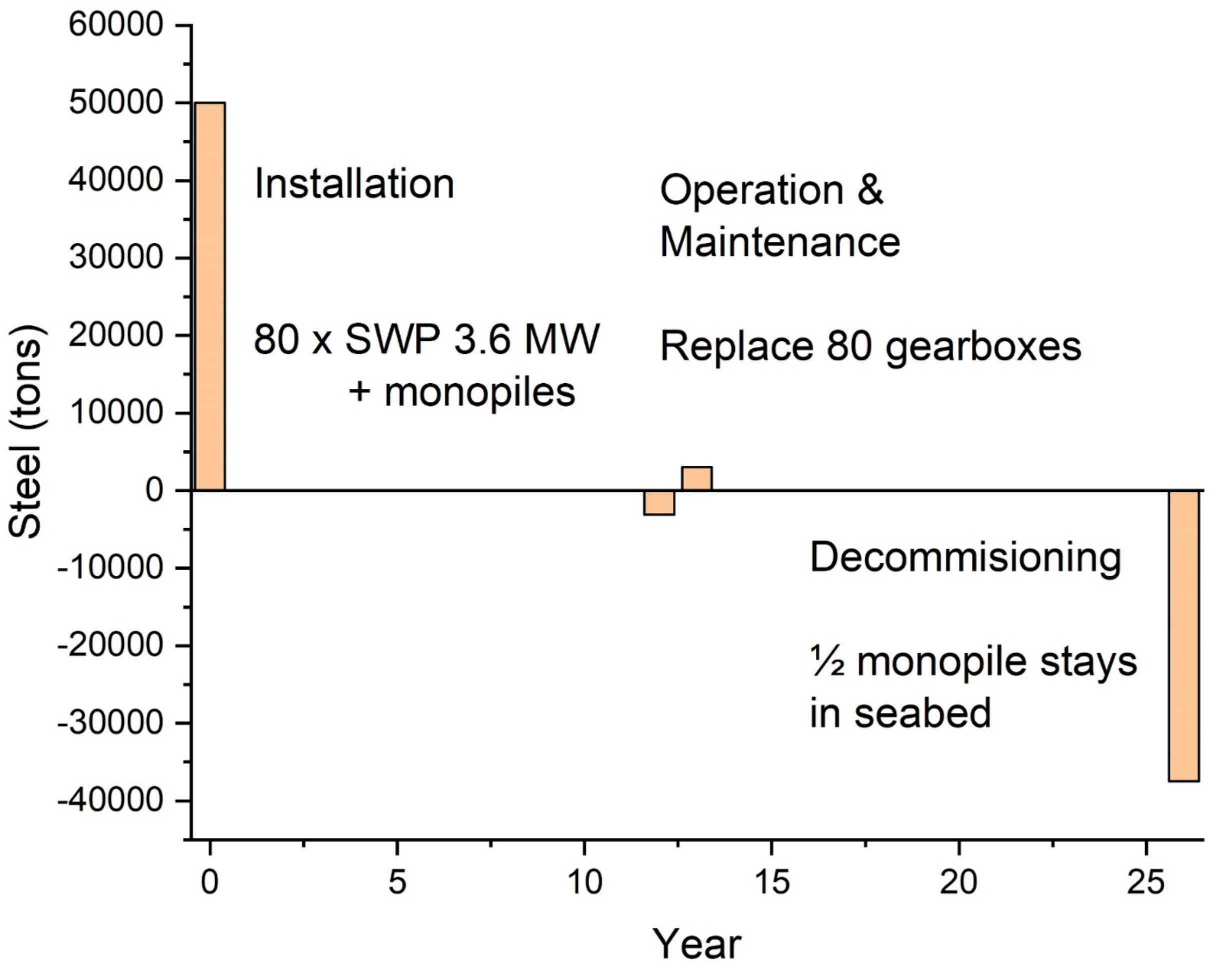
Decommissioning after 25 year design life time

Steel





The steel life cycle balance of an offshore wind farm



CO_2 emission =

Bill of Material x **emission per material +**

Energy consumption x emision from energy +

Transport x **emission per length +**

- **Recycled material (?)**

Normalization:

Total energy produced in operational lifetime of the wind farm [kWh]

Manufacturing of iron : From mine ore to metal

Blast furnace operating at 2000 °C

$$Fe_2O_3 + 3CO \rightarrow 2Fe(L) + 3CO_2$$

$$C + O_2 \rightarrow 2CO$$

$$2Fe_2O_3 + 3C \rightarrow 4Fe(L) + 3CO_2$$

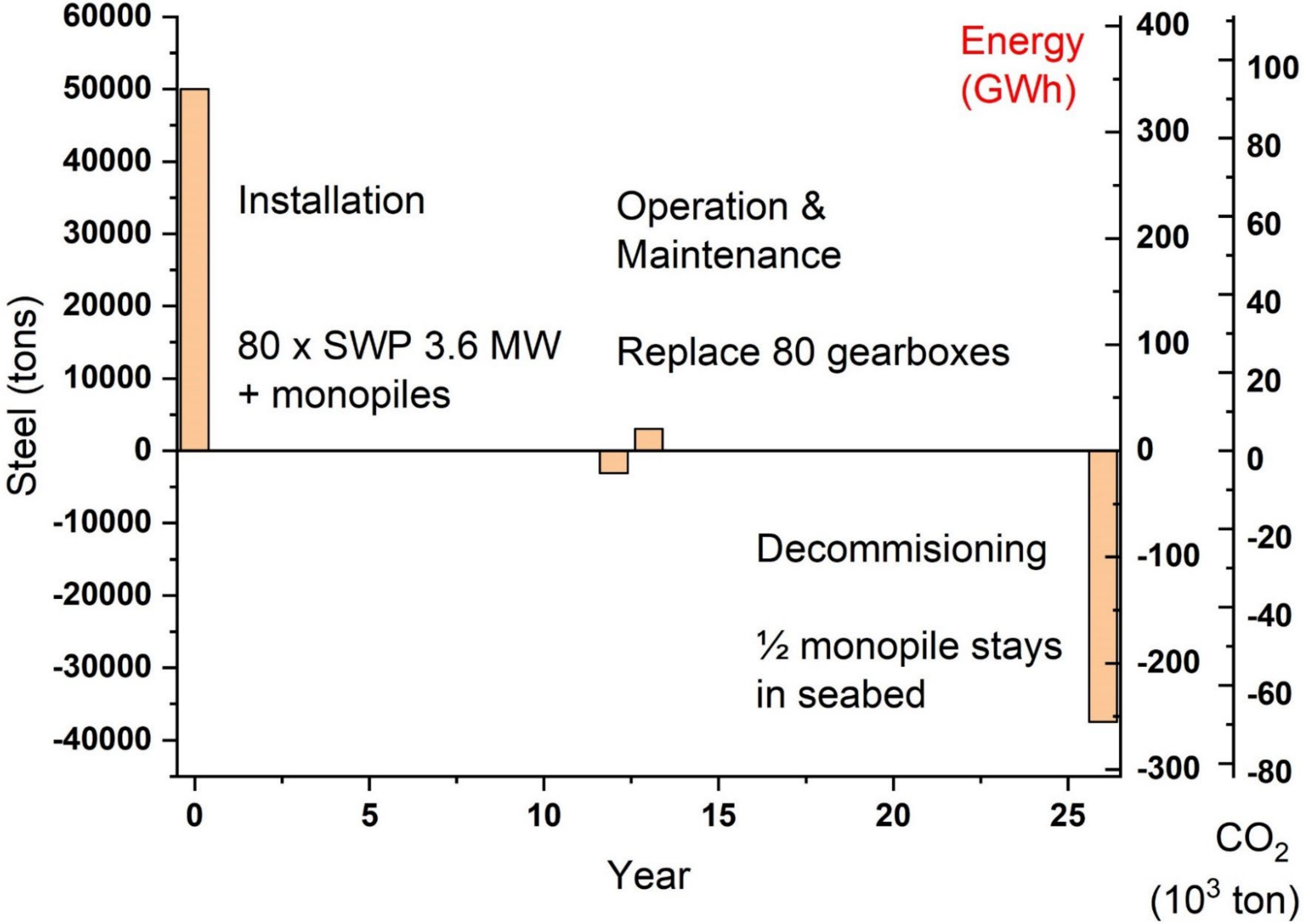
Burn iron mineral with coal ➡ **Liquid iron + CO_2**

$E = 6.8$ MWh/ton$_{Fe}$

$m_{CO2} = 1.9$ ton CO_2 eq/ton$_{Fe}$

Iannuzzi, M., Frankel, G.S. The carbon footprint of steel corrosion. *npj Mater Degrad* **6**, 101 (2022)

Energy usage and CO_2 emissions due to steel balance



Emission

$m_{CO2} = 90 \cdot 10^3$ tons CO_2

Wind energy produced

E = 80 turbines x 3.6 MW/turbine x 365 days/year x 24 hours/day x 25 years x CF

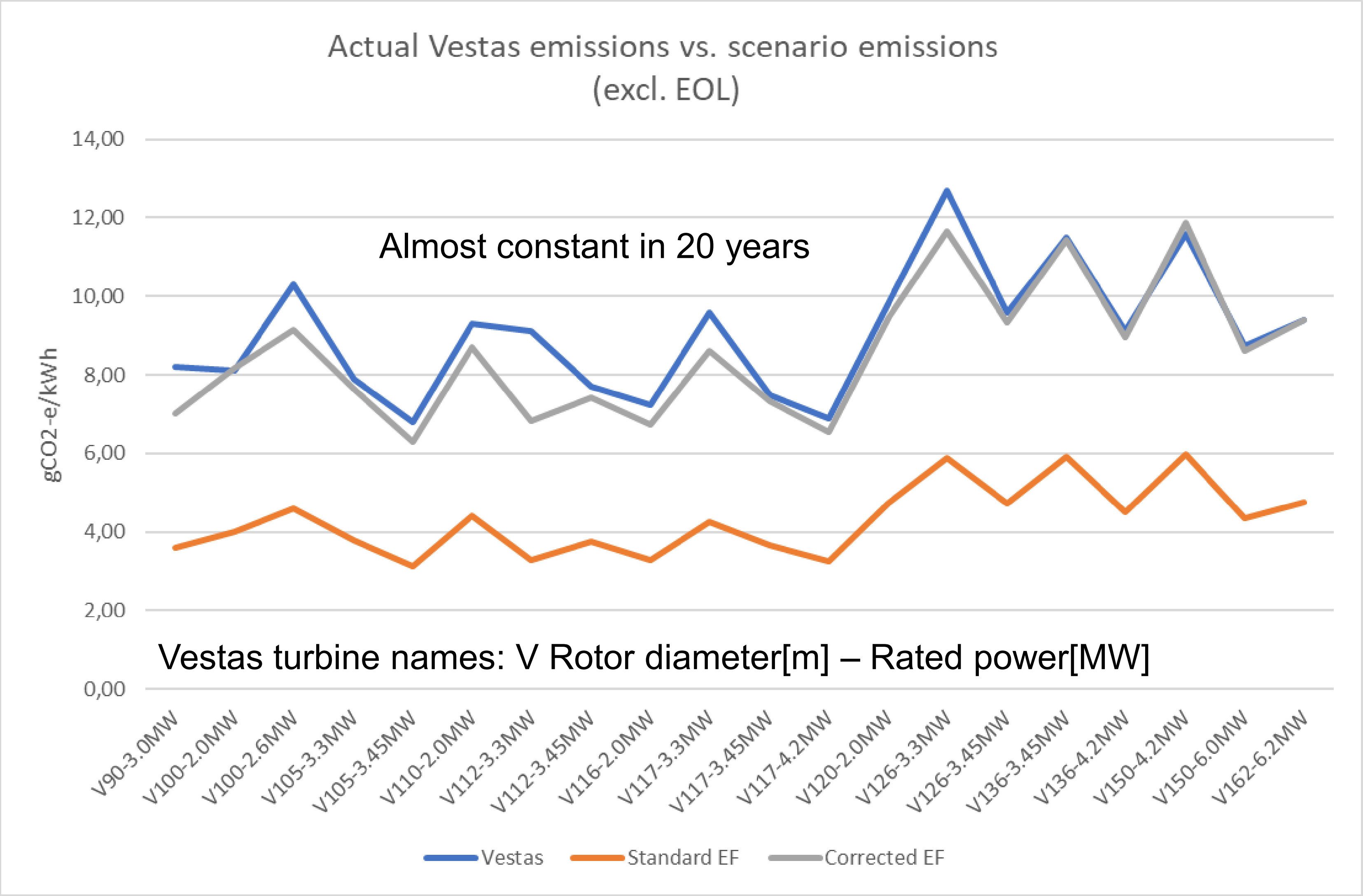
= $25.2 \cdot 10^9$ kWh (25 TWh)

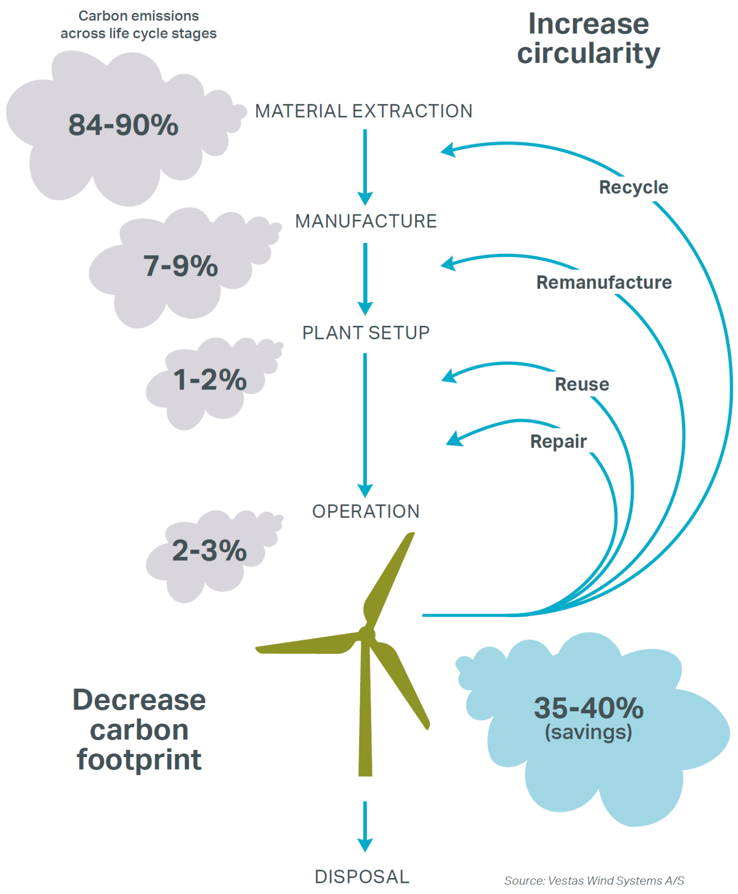
The capacity factor(CF) of the wind farms is assumed to be 0.4, which describes the average production due to the fluctuating wind.

Normalized emission

$$\frac{m_{CO2}}{E} = \frac{90 \cdot 10^9 \ g\ CO_2}{25 \cdot 10^9 \ kWh} \sim 4 \ \frac{g\ CO_2}{kWh}$$

Onshore turbine emission from LCA studies of Vestas





MegaVind :
https://megavind.greenpowerdenmark.dk/files/media/document/Sustainability-in-the-wind-industry-oct22.pdf

Kjeldsen & Mwiseneza, DTU Bachelor thesis summer 2023. Harden, Bachelor project 2021. Fauerskov & Laurberg, Bachelor project 2022.

UN ranking of electricity producing technologies

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

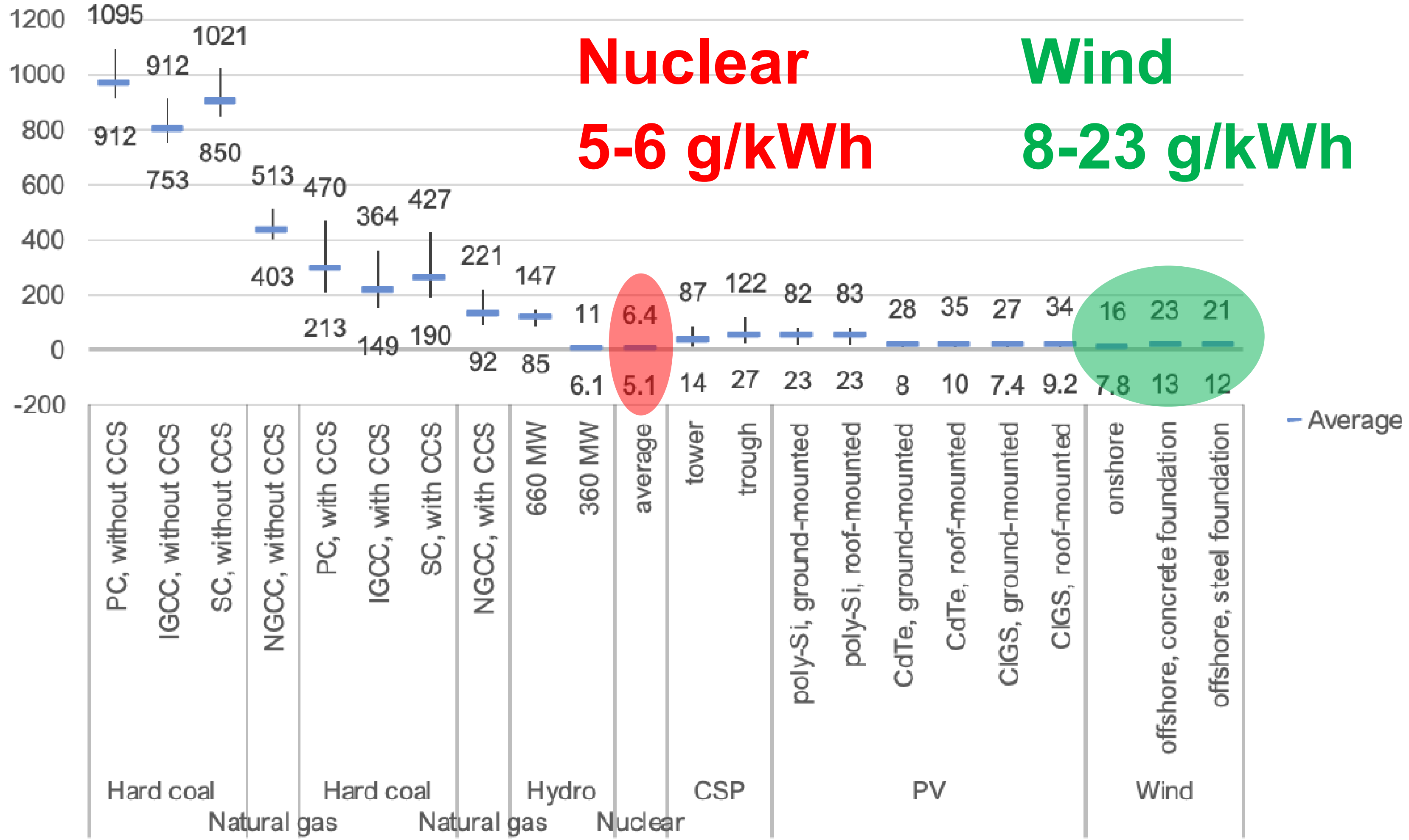
Life Cycle Assessment of Electricity Generation Options

2021

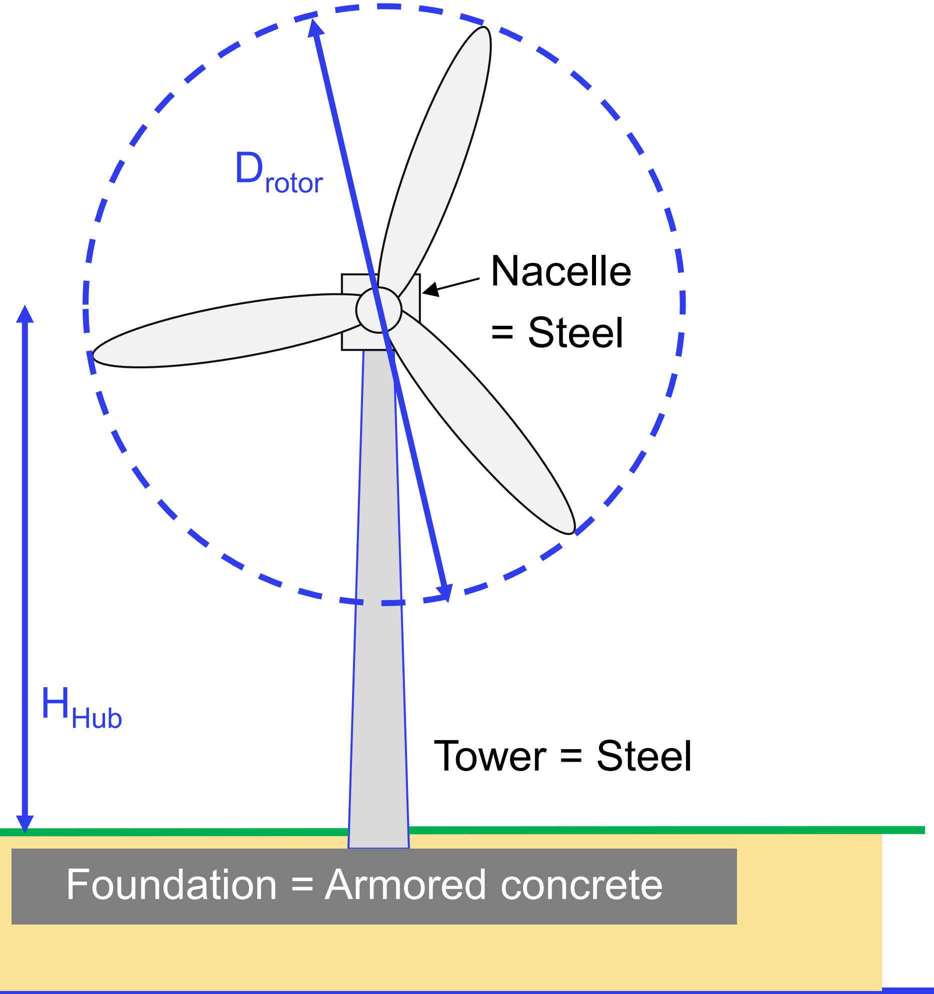
UNECE

https://unece.org/sites/default/files/2021-10/LCA-2.pdf

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies



Simple model for estimating Global Warming Potential (g_{CO2eq}/kWh) of onshore wind turbine



Vestas V162 onshore wind turbine (example)

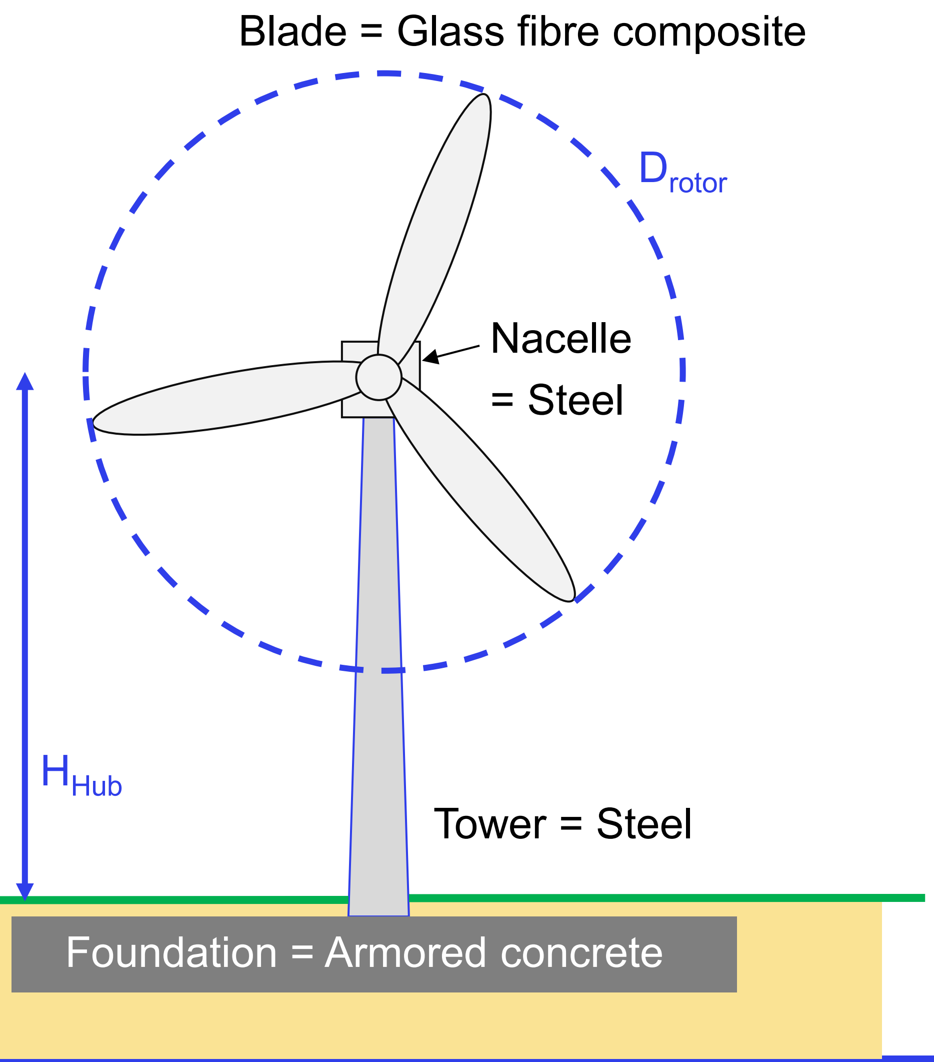
Rotor diameter	D_{rotor} = 162 m
Power rating	P_{Gen} = 6.2 MW
Hub height	H_{Hub} = 149 m
Design Lifetime	LT = 20 years
Annual Energy Production	AEP = 21.6 GWh/year (u_{ave} = 7.4 m/s)
Capacity factor	CP = AEP / (P_{gen} x 365 days x 24 hours) ~ 40 %

Simple Bill of Materials (BOM) per V162 turbine

Concrete	$m_{concrete}$	=	2453.6 tonnes	72 %
Steel	m_{steel}	=	819.2 tonnes	24 %
Glass fibre composite	m_{GFC}	=	59.0 tonnes	2 %
Other (Cu, Al, plastics,..)	m_{other}	=	85.8 tonnes	3 %
Total	m_{total}	=	3417.6 tonnes	100 %

Source : https://www.vestas.com/en/sustainability/environment/lifecycle-assessments

Simple model for estimating Global Warming Potential



Wind energy sector simple emission factor suggestion

Concrete	$EF_{concrete}$ =	0.17 g_{CO2eq} / $g_{concrete}$
Steel	EF_{steel} =	3.62 g_{CO2eq} / g_{steel}
Glass fibre composite	EF_{GFC} =	11.40 g_{CO2eq} / g_{GFC}

Simple total emission model

Emission factor material *i*, EF_i

Mass of material *i*, m_i

$$EM[g_{CO2\ eq}] = \sum_{i=1}^{N} EF_i \cdot m_i \ [g_{co2eq}]$$

The simple model includes the lifetime emissions of manufacturing, installing, and operating an onshore wind farm in Europe, but no recycling. These numbers are estimated from an analysis of the Life Cycle Assessment(LCA) reports of Vestas and represent approximate wind energy sector numbers for a typical European wind farm sourced from the European supply chain in 2023. This means that the energy mix of European countries have been used to determine the emissions resulting from the energy consumptions.

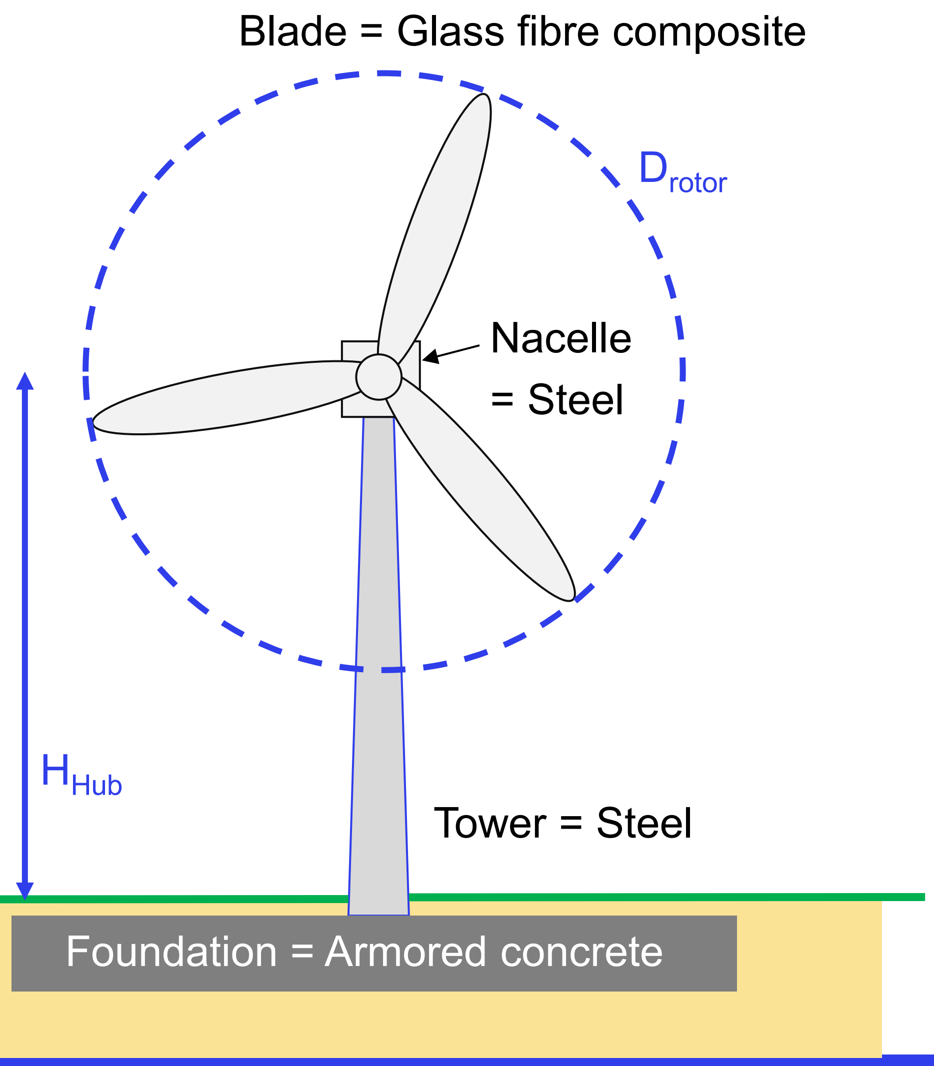
Source : https://orbit.dtu.dk/en/projects/simple-model-for-estimating-co2-emissions-of-wind-turbines

Simple model for estimating Global Warming Potential

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



Transportation specifications

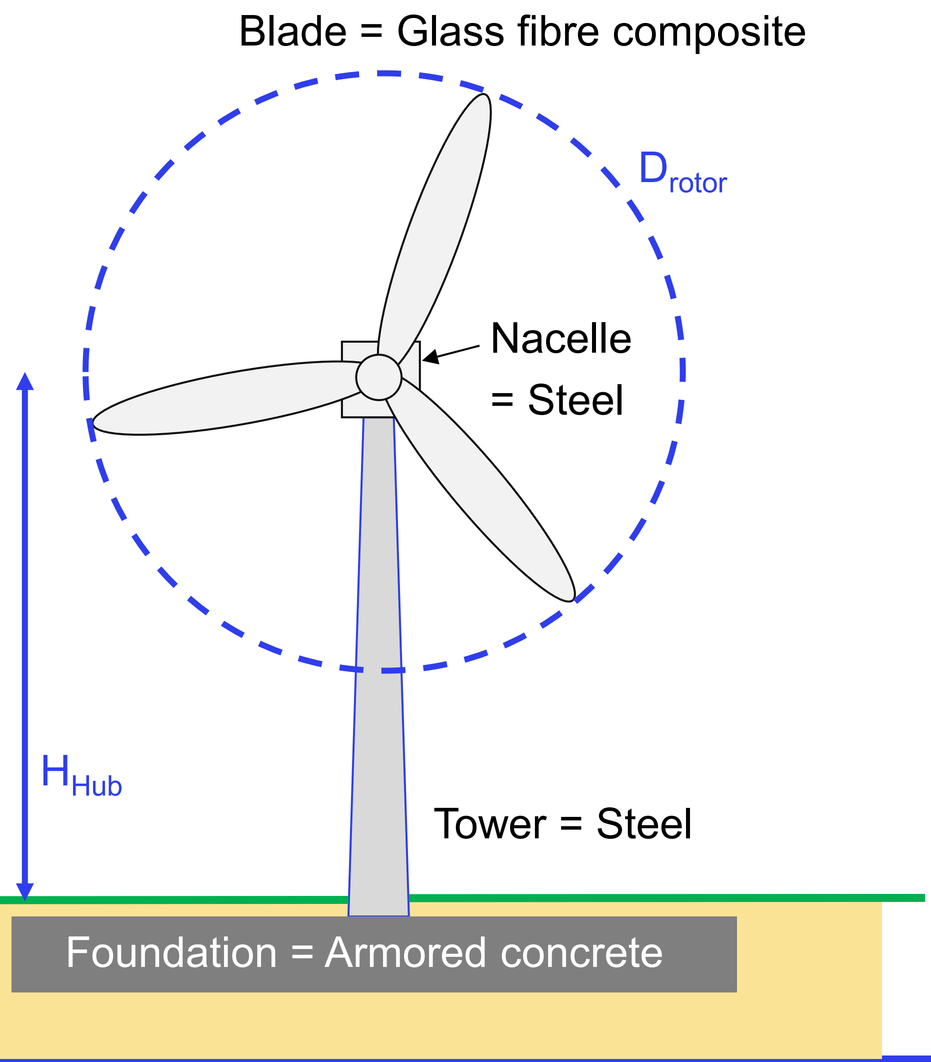
Component	Truck (km)	Ship (km)
Nacelle	600	9000
Hub	600	8600
Blades	1450	5100
Tower	425	0
Foundation	50	0
Other site parts	600	0

Installation site of the windfarm is Europe (Germany, see Table 15 in Vestas LCA report of V162)

Materials recycling is specified in table 3 on page 32 in report below.

Source : Sagar Mali & Peter Garrett, " Life Cycle Assessment of Electricity Production from an onshore EnVentus V162-6.2 MW Wind Plant ", Vestas, Version: 1.0 Date: 31.01.2023
https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/reports-and-ratings/lcas/LCA%20of%20Electricity%20Production%20from%20an%20onshore%20EnVentus%20V162-6.2.pdf.coredownload.inline.pdf

Simple model for estimating Levelized cost of Energy of onshore wind turbine electricity production



Cost of onshore wind turbines

Capital cost	CAPEX	~ 1.4 M€/MW (inflation corrected)
Operational cost	$OPEX_{fixed}$	~ 12600 €/MW/year
	$OPEX_{variable}$	~ 1.35 €/MWh
Discount rate	w	~ 4-6 %/year

Levelized Cost of Energy (LCoE) = ?

Source : Danish Energy Agency, Technology data, page 225 and 2030 scenario
https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh.pdf

Levelized Cost of Energy estimate of onshore wind energy from Vestas V162-6.2 MW turbine

The levelized cost of energy can in a simple form be defined as

$$LCoE = \frac{\sum_{i=0}^{LT} \frac{C_i}{(1+w)^i}}{\sum_{j=0}^{LT} \frac{E_j}{(1+w)^j}} = \frac{C_{CAXEX,0}}{E_{AEP}} \cdot CRF + \frac{C_{OPEX,Annual}}{E_{AEP}} + \boldsymbol{LCoE_{OPEX,variable}} = \mathbf{32.2}\,\frac{\text{€}}{\boldsymbol{MWh}} + \mathbf{3.6}\,\frac{\text{€}}{\boldsymbol{MWh}} + \mathbf{1.4}\,\frac{\text{€}}{\boldsymbol{MWh}} = \mathbf{37.2}\,\frac{\text{€}}{\boldsymbol{MWh}}$$

Where

- The capital expenditure(CAPEX) is
  - $C_{CAPEX,0}$ = 1.4 M€/MW x 6.2 MW = 8.6 M€ (see slide 14)
- The annual operational expenditure (OPEX) is
  - $C_{OPEX,Annual}$ = 12600 €/MW/year x 6.2 MW = 78120 €/year (see slide 14)
- The variable operational expenditure is $LCOE_{OPEX,variable}$ = 1.35 €/MWh (see slide 14)
- The Annual Energy Production E_{AEP} = 21.6 GWh/year (see slide 10)
- The Capital Return Factor(CRF) is given below using an interest rate w = 5 % and a design life time LT = 20 years (see slide 14)

$$\boldsymbol{CRF} = \frac{1}{\sum_{\boldsymbol{t}=1}^{\boldsymbol{LT}} \frac{1}{(1+\boldsymbol{w})^{\boldsymbol{t}}}} = \frac{w}{1-(1+w)^{-LT}} = \frac{0.05\,\frac{1}{year}}{1-(1+0.05)^{-20}} = 0.080\,\frac{1}{year}$$

LCoE levels of electricity sources of Europe

Figure 0-1 LCOE results for EU27 - main technologies' comparison - percentage change between 2008 and 2018

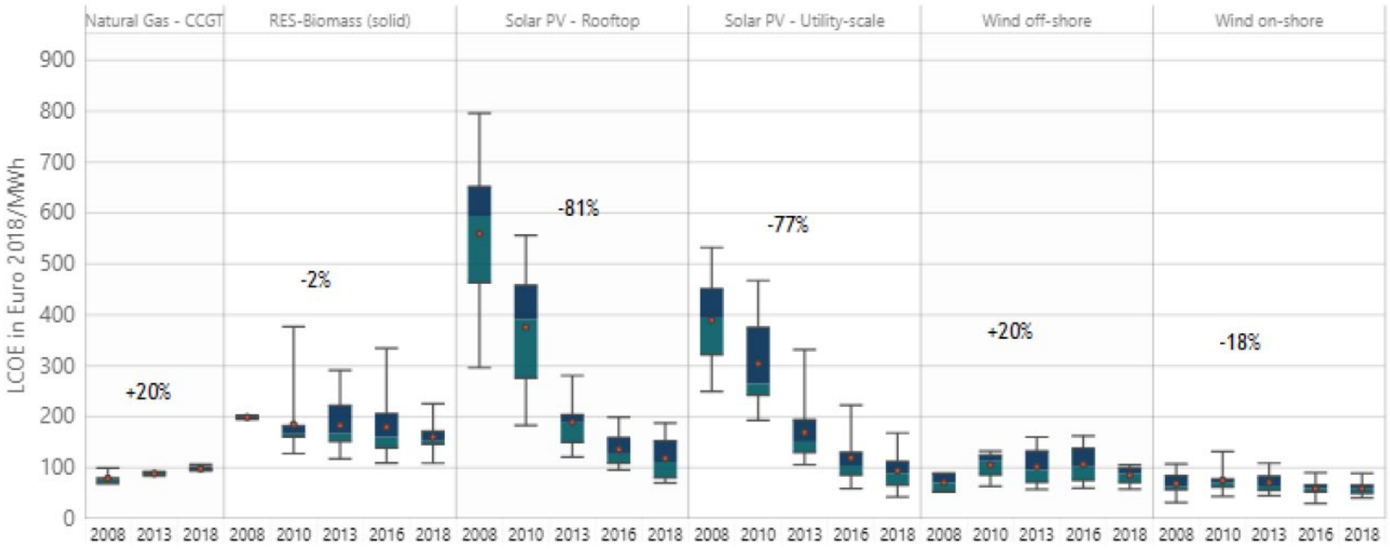
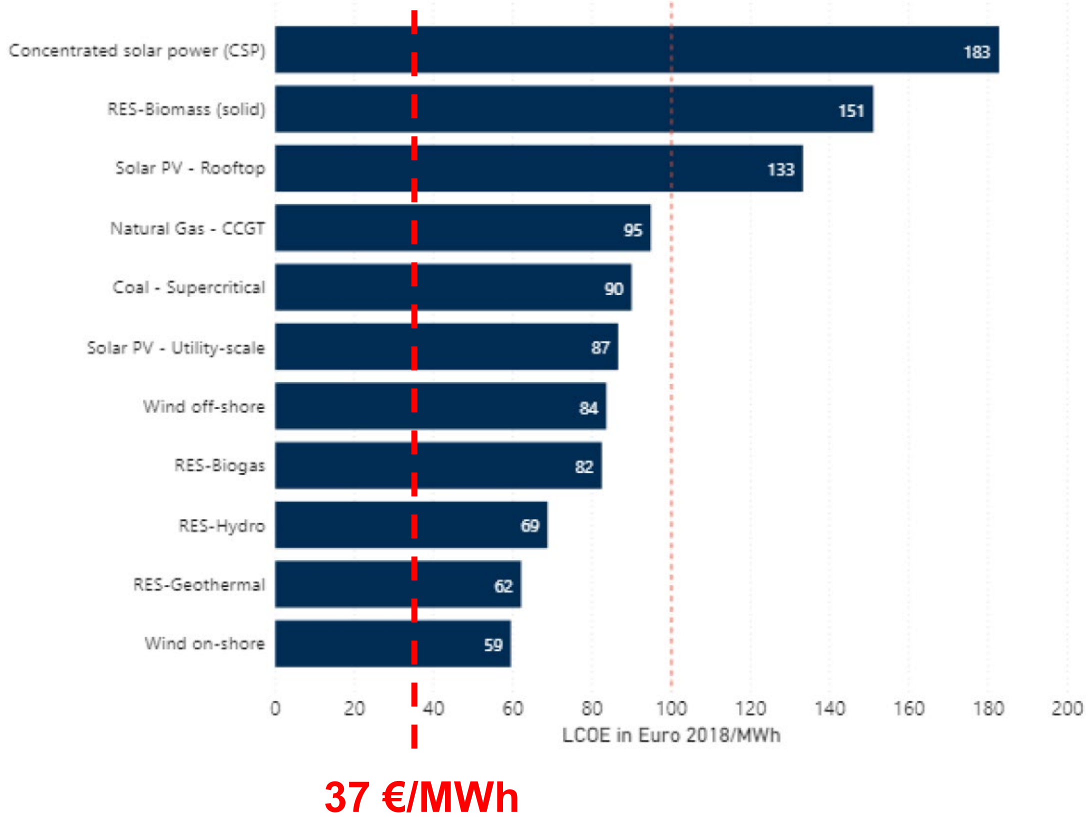


Figure 0-2 LCOE results for EU27 - in 2018



Thierry Badouard, Débora Moreira de Oliveira, Jessica Yearwood and Perla Torres, "Final Report

Cost of Energy (LCOE). Energy costs, taxes and the impact of government interventions on investments", European Commission ENER/2018-A4/2018-471 (2020)

Circularity of wind turbine blades

Glass fibre fabric
Balza wood / Foam → **Blade** → **Decommissioning**
Resin

Decommissioning
↓
Transport → **Landfill**
↓
Cutting / shredding →
- Cement production
- Noise screens

↓
Separation
- Pyrolysis
- Chemical
-

→
Short glass fibres
Balza / Foam pieces
Resin rest products

↓
Other products ?

Circular material flow ?

Abrahamsen *et al.*, "Ch. 15: Towards sustainable wind energy", DTU International Energy Report 2021

DTU Wind Energy

Great news on turbine blade recycling in 2023

DecomBlades and 3B-Fibreglass are ready to unlock circular recycling of glass fibre in wind turbine blades

Remelting recycled glass fibers

1) Cut turbine blades (5-10 tons)
2) Shredding
3) Grinding
4) Pyrolysis to remove epoxy
5) Milling recycled glass fiber

Mix 1-5 % recycled glass fibers into melt of production for new glass fibers by 3B (72 metric ton)

DTU Wind and Energy Systems showed mechanical properties of remelted glass fibers are as good a normal wind turbine grade fibers.

This can enable a fully blade to blade circularity of the glass fibers of the wind industry.

Conclusion

- CO_2 emission of the Danish Energy mix is expected to reach ~ 10-15 g CO_{2eq}/ kWh using only wind turbines unless the production method of the materials used to build the turbines is changed.
- The main materials used in the wind turbines are: steel, concrete and glass fibre composite
- For offshore wind turbines the emissions will depend on the amount of recycled steel from monopiles
- Circularity in material recycling of wind turbines is improving by new blade recycling technologies

- New solutions
  - Turbine designs with less material usage (especially concrete in the foundation of onshore)
  - Usage of Green Steel and Green Cement?
  - Low CO_2 footprint steel in tower and monopile by utilizing remelted steel
  - Refining iron ore to iron using hydrogen route (water as chemical emission instead of CO_2)
  - Turbines based on completely different materials (wood in towers?)

  - Turbine design standards dictate current material usage (IEC 61400-1 and IEC 61400-3) since the turbine manufacturers have to guarantee that the chance of major failures of the turbines is small during the design lifetime.

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Self-assessment quiz of the Decarbonizing the Energy System module

Asger Bech Abrahamsen, DTU Wind and Energy Systems, DTU Risø Campus, Roskilde

30 August 2024

Quiz questions

1) What is the CO_2 emissions per produced kWh of electricity of a coal-fired power plant?
    a. 0-200 g CO_2e / KWh
    b. 200-400 g CO_2e / KWh
    c. 400-600 g CO_2e / KWh
    d. 600-800 g CO_2e / KWh
    e. 800-1000 g CO_2e / KWh
2) What is the main process contributing to the CO_2 emissions from a coal-fired power plant?
    a. The making of the steel of the power plant
    b. The making of the concrete of the power plant
    c. Burning carbon in air
    d. The energy of running the cooling water of the power plant
    e. The making of spare parts for the power plant
3) What is the CO_2 emissions per produced kWh of electricity of a natural gas-fired power plant?
    a. 0-200 g CO_2e / KWh
    b. 200-400 g CO_2e / KWh
    c. 400-600 g CO_2e / KWh
    d. 600-800 g CO_2e / KWh
    e. 800-1000 g CO_2e / KWh
4) What is the CO_2 emissions per produced kWh of electricity of the low-emission renewable technologies like wind and solar PV?
    a. 0-100 g CO_2e / KWh
    b. 100-200 g CO_2e / KWh
    c. 200-300 g CO_2e / KWh
    d. 300-400 g CO_2e / KWh
    e. 400-500 g CO_2e / KWh
5) What is the main process contributing to the CO_2 emissions from a renewable technologies?
    a. The making of the materials of the wind or solar farm
    b. Installing the wind or solar farms
    c. Operating and maintaining the wind or solar farm
    d. Decommissioning the wind or solar farm
    e. Recycling the materials of the wind or solar farm
6) What were the equivalent CO_2e emissions of the planet in 2020 [Giga ton of CO_2e emissions] according to the UN Gap report of 2022?
    a. 0-15 Gt CO_2e / year

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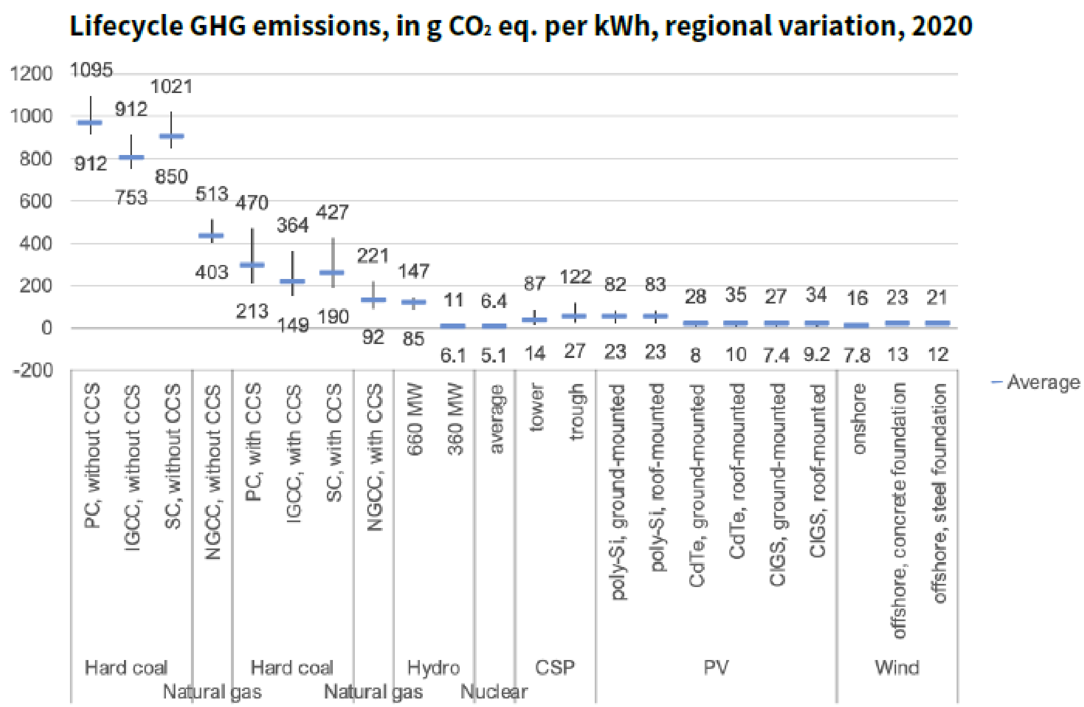
b. 15-30 Gt CO_2e / year
c. 30-45 Gt CO_2e / year
d. 45-60 Gt CO_2e / year
e. 60-75 Gt CO_2e / year

7) What are the target emissions of the planet in 2050 according to a global warming target of 1.5 degrees Celsius in the Paris Agreement at the end of the century as described in the UN Gap report of 2023?
   a. 0-15 Gt CO_2e / year
   b. 15-30 Gt CO_2e / year
   c. 30-45 Gt CO_2e / year
   d. 45-60 Gt CO_2e / year
   e. 60-75 Gt CO_2e / year
8) If the world consumption of coal-fired electricity was 9500 TWh/year in 2019, what were the equivalent CO_2e emissions?
   a. 0-15 Gt CO_2e / year
   b. 15-30 Gt CO_2e / year
   c. 30-45 Gt CO_2e / year
   d. 45-60 Gt CO_2e / year
   e. 60-75 Gt CO_2e / year
9) What year will the 2019 CO_2e emission of the previous questions be equivalent to the planetary boundary according to the 1.5 Degree global warming scenario of the Paris Agreement?
   a. 2020-2030
   b. 2030-2035
   c. 2035-2040
   d. 2040-2045
   e. 2045-2050
10) If the coal-fired electricity consumption of 9500 TWh/year in 2019 is replaced by wind energy what are the resulting CO_2e emissions?
   a. 0.0-0.2 Gt CO_2e / year
   b. 0.2-0.4 Gt CO_2e / year
   c. 0.4-0.6 Gt CO_2e / year
   d. 0.6-0.8 Gt CO_2e / year
   e. 0.8-1.0 Gt CO_2e / year

Solutions to quiz questions

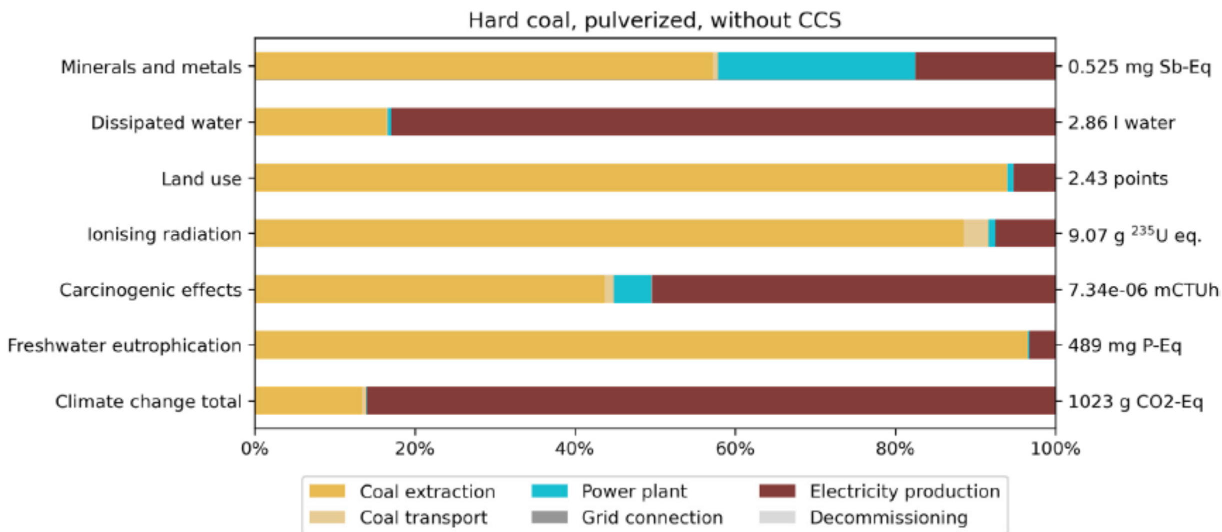
1) The UN report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" is showing the CO_2e emissions of most electricity producing technologies and by looking at Figure 1 one will find that the CO2e emissions are in the range of 912-1095 g CO2e / kWh produced electricity. Thus the correct range is 800-1000 g CO_2e / KWh.

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies



2) The main contribution to the CO_2e emissions of a coal fires power plant can be seen from Figure 4 in the UN report and it shows that the electricity generation is responsible for 85 % of the CO_2e emission, which is coming from burning the coal in air $C + O_2 \rightarrow CO_2$. Thus the correct answer is "c. Burning carbon in air ".

Figure 4 Life cycle impacts from 1 kWh of coal power production, pulverised coal, Europe, 2020



3) Again looking at Figure 1 of the question 1) one sees that the CO_2e emissions of a natural gas fired power plant is in the range of 403-513 g CO_2e / kWh. Thus the correct range is 400-600 g CO_2e / KWh.
4) Once more looking at Figure 1 one sees that the CO_2e emissions wind turbines are in the range of 8-16 g CO_2e / kWh for onshore turbines and 12-23 g CO_2e / kWh for offshore turbines. Similarly it is seen that CO_2e emissions of solar PV are in range of 8-83 g CO_2e / kWh. Thus the correct answer is the range 0-100 g CO_2e / kWh
5) The main contribution to the CO_2e emissions of wind turbines and solar PV farms can be seen from Figure 12 of the UN report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources". It can be seen that the largest contribution to the CO2e emission result from the tower and is related to the production of the steel used to construct the tower. It should be noted that the operation phase only contribute with a few procent to the CO2e emissions. Similarly the contributions for offshore wind turbines is seen in Figure 13, which is showing that the foundation and installation of the turbines are the main contributions.

Figure 12 Life cycle impacts from 1 kWh of onshore wind power production, Europe, 2020

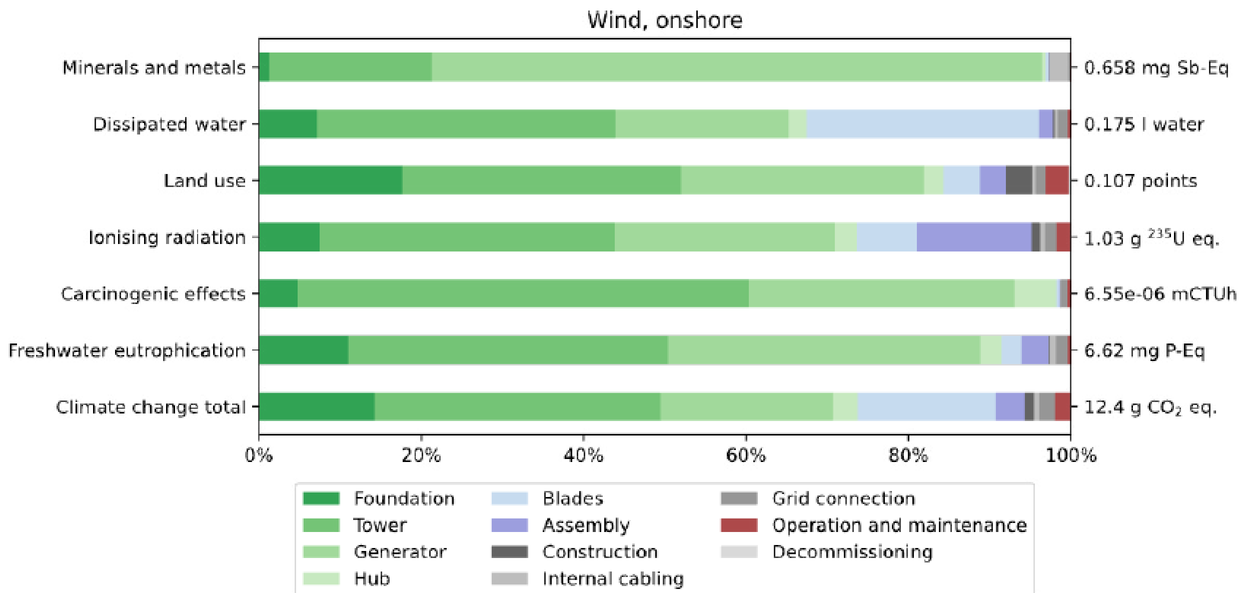
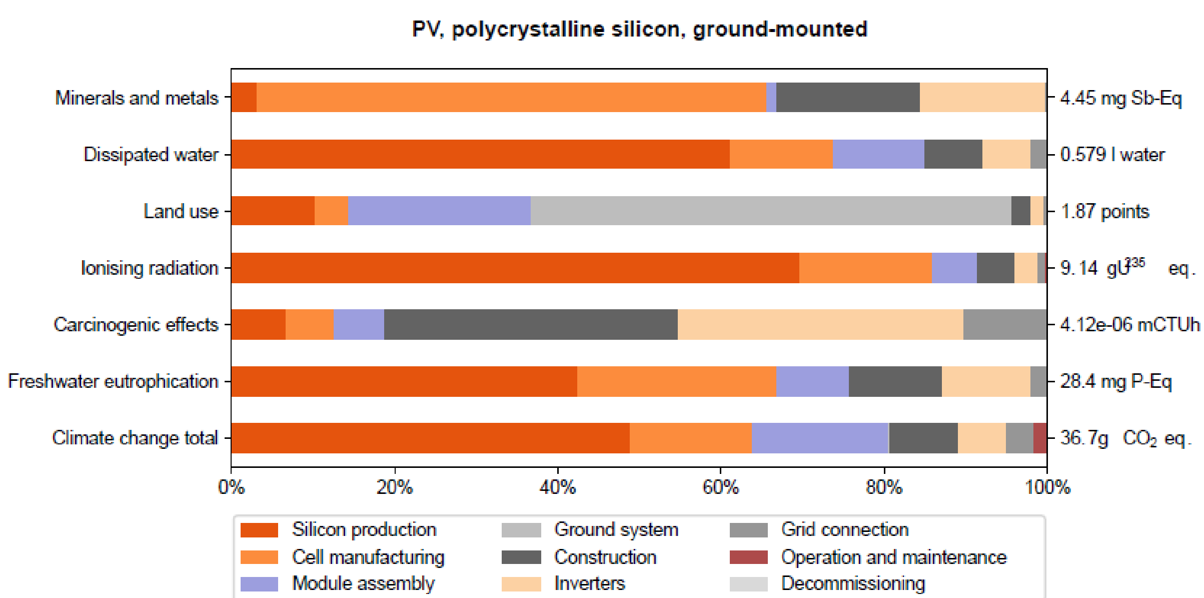


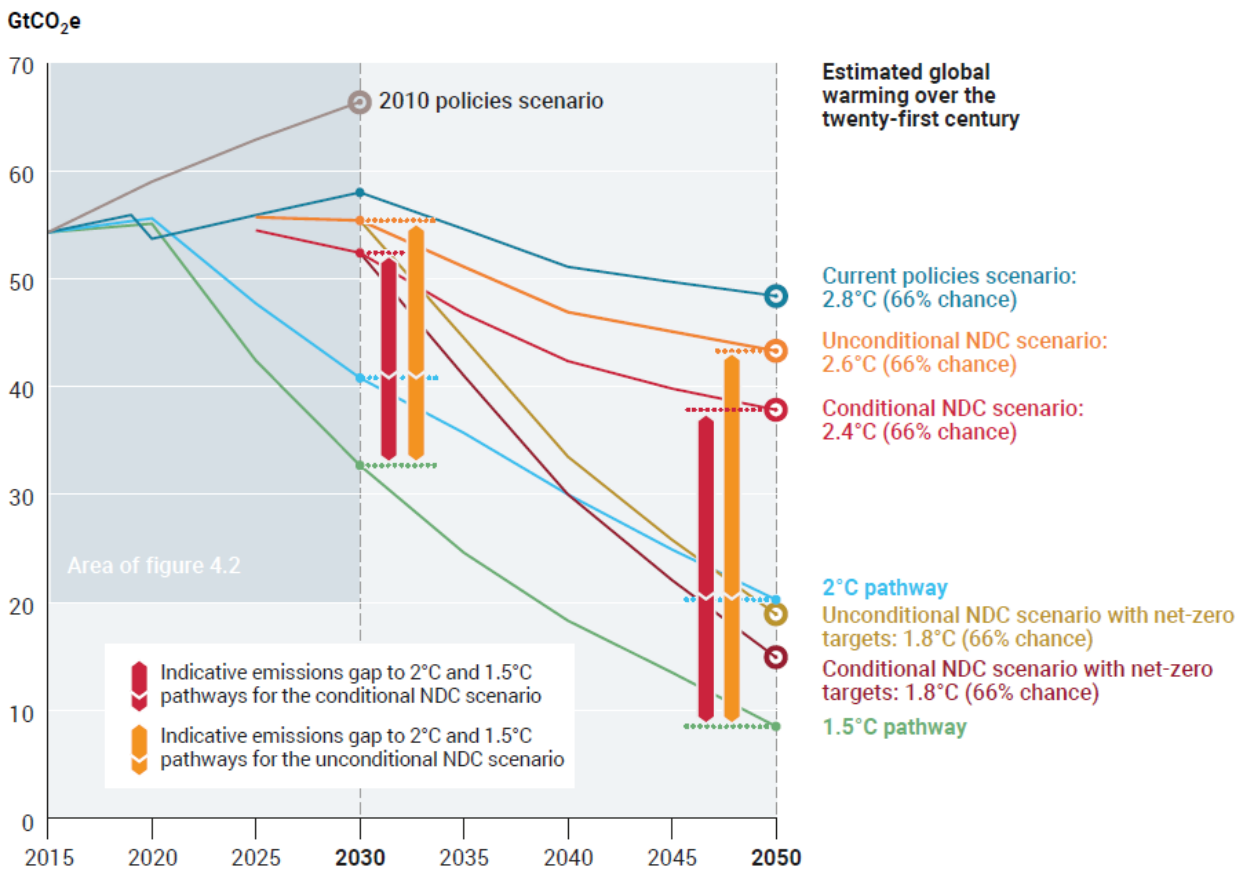
Figure 25 shows the contribution to the CO_2e emission from a ground-mounted solar PV farm and it can be seen that the production of the silicon is the main contribution to the CO_2e emissions. Thus the correct answer is “The making of the materials of the wind or solar farm”

Figure 25 Life cycle impacts from 1 kWh of poly-Si, ground-mounted, photovoltaic power production, Europe, 2020



6) By looking at the UN gap report 2022 Figure 4.3 one can see the Paris Agreement targets in terms of the global CO_2e emission to be meet towards 2050. Reading off the y-axis at the year 2020 one obtain about 54-56 Gigaton of CO_2e emissions / year. Thus the correct answer is “45-60 Gt CO_2e / year”

Figure 4.3 Projections of GHG emissions under different scenarios to 2050 and indications of emissions gap and global warming implications over this century (medians only)



7) Looking at Figure 4.3 from the UN Gap report 2022 then one can see that the global CO_2e emissions are expected to reach 9 Giga tons of CO_2e emissions per year in 2050. Thus the correct answer is “0-15 Gt CO_2e / year”.

8) The CO_2e emission m_{CO2e} resulting from E = 9500 TWh/year of coal-fired electricity production in 2019 can be estimated from the emission factor of coal EM_{coal} as seen from Figure 1 of the UN report. “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources”

$$m_{CO2e,coal} = EM_{coal} \cdot E = 1 \frac{kg\ CO_2e}{kWh} \cdot 9500 \frac{TWh}{year} = 9.5 \cdot 10^{15} \frac{kg\ CO_2e}{year}$$
$$= 9.5 \cdot 10^{12} \frac{ton\ CO_2e}{year} = 9.5 \frac{Giga - ton\ CO_2e}{year} = 9.5 \frac{Gt\ CO_2e}{year}$$

Thus the correct answer is "0-15 Gt CO_2e / year".

9) By looking at the Figure 4.3 of the UN gap report 2022 one can see that an annual CO2e emission equivalent to the emissions of the coal-based electricity production of 2019 being around 10 Gt CO2e/year is crossing the 1.5 degree global warming planetary boundary of the Paris Agreement by approximately 2047. The just the worldwide electricity production by coal of 2019 will by itself violate the planetary 1.5 degree boundary in 2047. Thus the correct answer is "2045-2050"
10) If the coal-based electricity production of 2019 with E = 9500 TWh/year is replaced by onshore wind having an emission factor EM_{wind} ~ 10 g CO_2e / kWh then the global emission will be

$$m_{CO2e,wind} = EM_{wind} \cdot E = 10 \frac{g\ CO_2e}{kWh} \cdot 9500 \frac{TWh}{year} = 0.1 \frac{Gt\ CO_2e}{year}$$

This will correspond to a (0.1 Gt CO_2e/year) / (9 Gt CO_2e/year) = 1 % fraction of the planetary CO_2e emission boundary in 2050 of the 1.5 Degree Paris Agreement scenario and is often interpreted as "that we do have technologies needed for the green transition". There are many challenges related to operating an electricity system fully on wind energy sources, and a combination of many low-emission electricity production technologies combined with energy storage technologies is believed to be the most likely solution. Thus the correct answer is "0.0-0.2 Gt CO_2e / year".

It is the hope that this quiz has provided hands-on knowledge about the CO_2e emissions of electricity producing technologies and how they relate to the planetary boundaries of CO_2e emissions.

Decarbonizing energy systems
DTU course on Quantitative Sustainability

Lecture 1 Decarbonizing energy systems
Lecture 2 Wind Energy as example
Lecture 3 Exercise : Violation of planetary boundary of Global Warming Potential due to electricity mix

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Outline of Decarbonizing energy systems

The intention of the module “Decarbonizing the energy systems” in the course Quantitative Sustainability is to enable the student to calculate the resulting Global Warming Potential emission from electricity production given a specific technology mix of a country or region. By scaling up the emission to the equivalent global emission one can compare the CO_2 emission to the global planetary boundary as dictated by the Paris agreement of a 1.5 degree global warming limit. The students will then be able to determine if a future electricity mix will violate the global planetary boundary of the Global Warming Potential.

Since there is a trend towards electrification of the energy system, then the focus of the module is on the electricity part of the energy system and especially the renewable energy technologies.

The following lectures are provided as part of the module

- Lecture 1 Decarbonizing the energy system
- Lecture 2 Wind Energy as example
- Lecture 3 Case: Violation of planetary boundary of Global Warming Potential due to electricity mix

Learning objectives of decarbonizing the energy system

The student should be able to

- **Describe** the main electricity generating technologies used around the world
- **Explain** the origin of CO_2 emissions from electricity producing units
- **Describe** the typical technology mix used for electricity production in different countries

- **Estimate** the resulting CO_2 emission of the electricity mix when producing 1 kWh electricity

- **Discuss** the expected future CO_2 emission of electricity production and propose strategies of decarbonizing the electricity system
- **Discuss** which additional technologies that might be needed in the electricity system

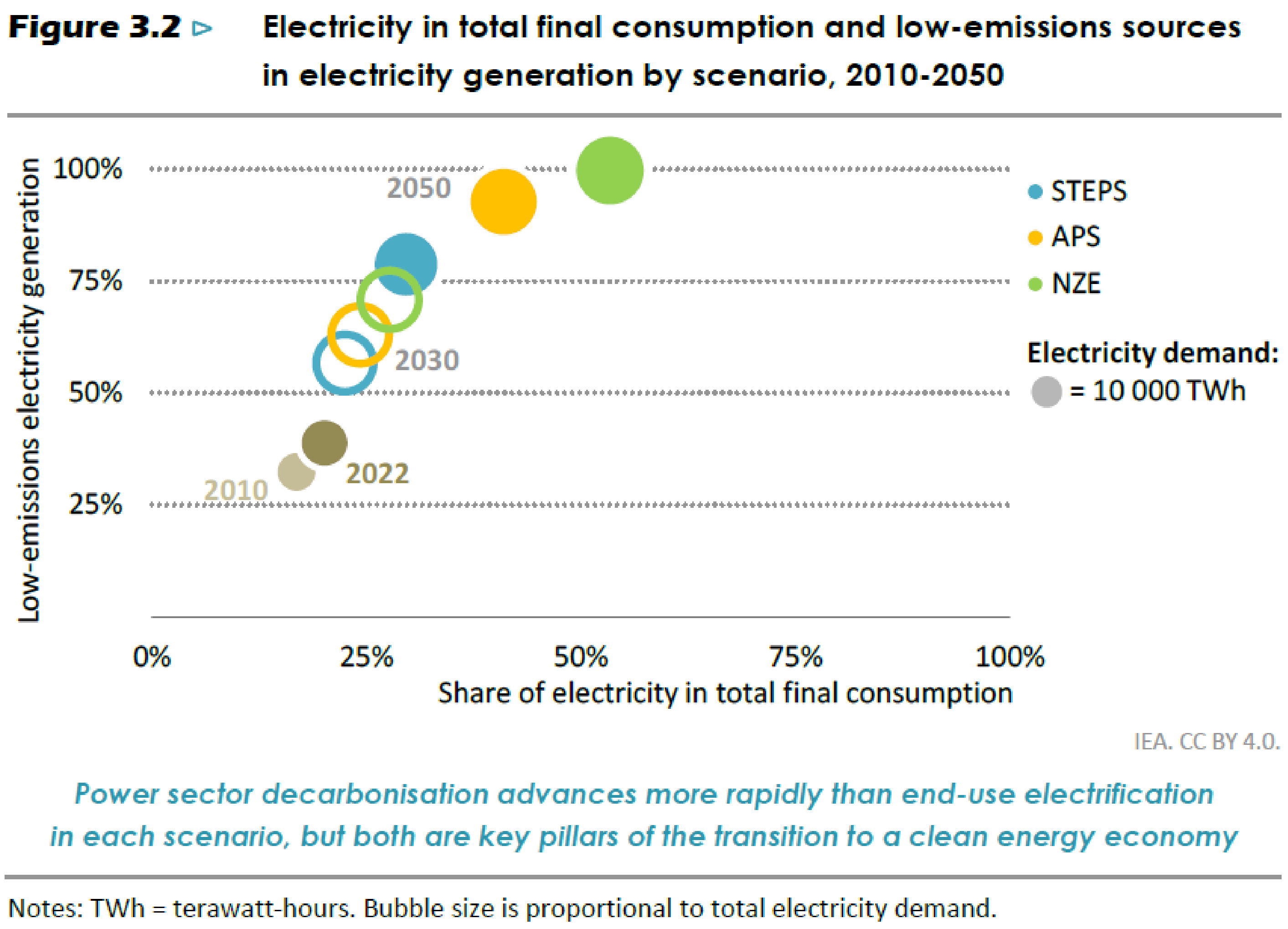
- **Analyse** expected CO_2 emission from a specific country or region and compare the Global Warming Potential with the UN CO_2 emission scenarios.

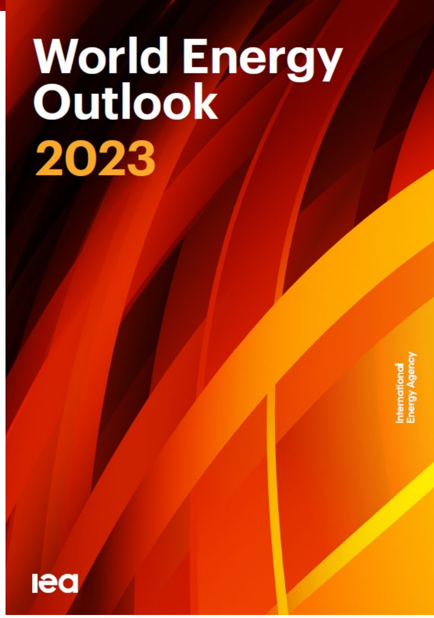
- **Evaluate** if the planetary CO_2 boundary is violated by the electricity generation

Outline of Lecture 1 Decarbonizing the energy system

- Electricity fraction of energy production
- Electricity-producing technologies
- Life phases of electricity-producing units
- Life cycle analysis overview of electricity producing unit as defined by the United Nations (UN)
- Environmental indicators
- Technology mix of electricity production
- The planetary boundary of Global Warming Potential of the Paris Agreement
- Strategies for decarbonizing the electricity system

Electricity fraction of energy consumption





Source: IEA Energy Outlook 2023

Technologies for electricity production

Fuel based

- Coal
- Gas
- Biomass
- Nuclear

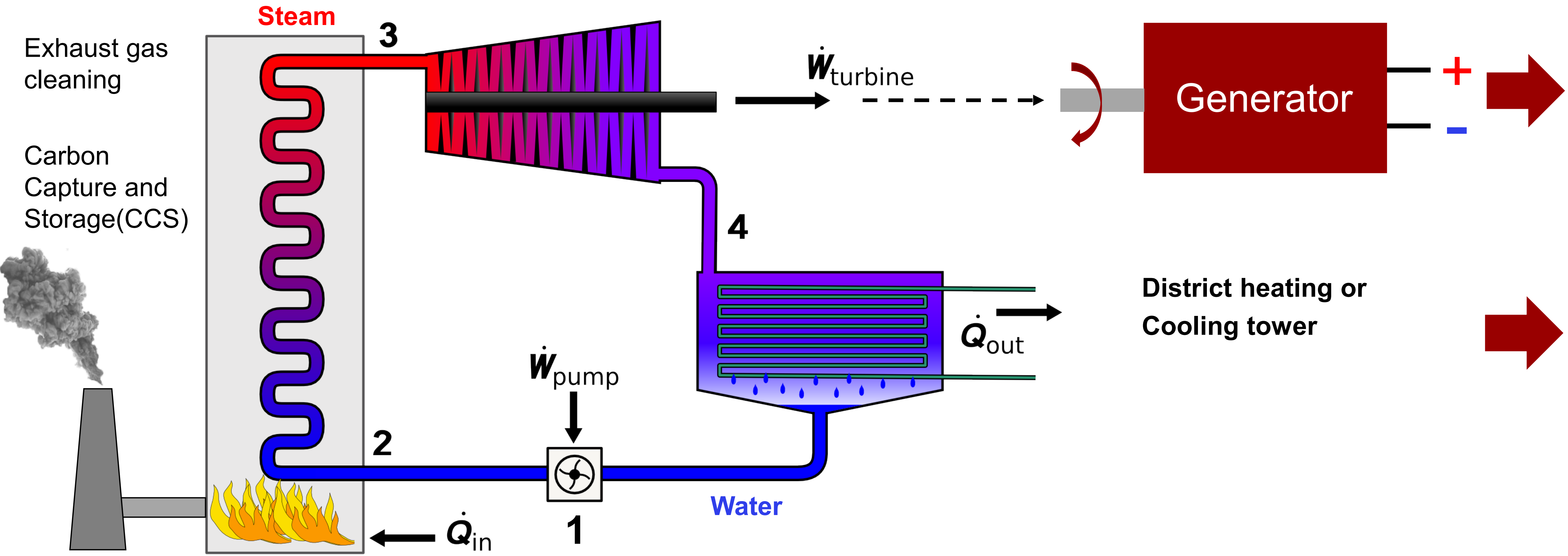
Renewables

- Wind
- Solar
- Hydro
- Tidal
- Geothermal
-

Fuel based power plants

Exhaust gas cleaning

Carbon Capture and Storage(CCS)



Fuel burned

concentrated solar or nuclear process

1: Pump **2**: Boiler **3**: turbine **4**: condenser

Source: Rankine cycle (Wikimedia.org)

Burning fuels causes CO_2 emissions

Coal	C	+ O_2	→	CO_2		+ Heat +
Methane	CH_4	+ O_2	→	CO_2	+ H_2O	+ Heat +
Oil	C_xH_y	+ O_2	→	CO_2	+ H_2O	+ Heat +
Wood	$C_6H_{12}O_6$	+ O_2	→	CO_2	+ H_2O	+ Heat +
Plastic (PET)	$C_{10}H_8O_4$	+ O_2	→	CO_2	+ H_2O	+ Heat +
Hydrogen	H_2	+ O_2	→		H_2O	+ Heat +
Ammonia	NH_3	+ O_2	→	NO_x	+ H_2O	+ Heat +
Fission	^{238}U		→	^{234}U +…	+ Neutrons	+ Heat
Fusion	${}^2_1D + {}^3_1T$		→	${}^4_2He$	+ Neutron	+ Heat

Remember that burning fuels in air will also include nitrogen and some sulfer, whereby NO_X and SOx can result

$C + O_2 + N_2 \rightarrow CO_2 + NO_X$

$C + S_2 + O_2 \rightarrow CO_2 + SO_X$

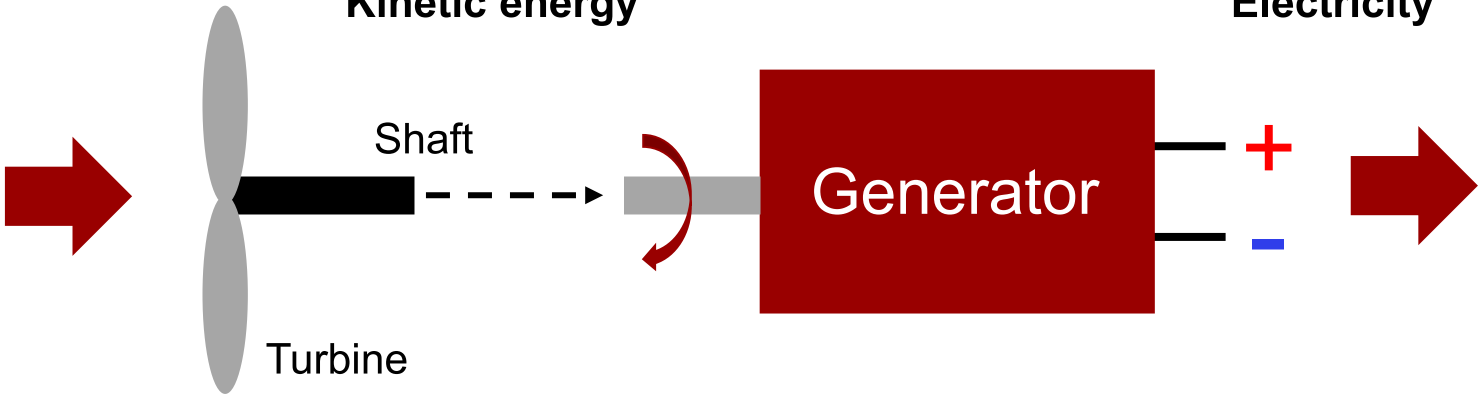
Note : Chemical formula not balanced for simplicity

Renewable based power plants

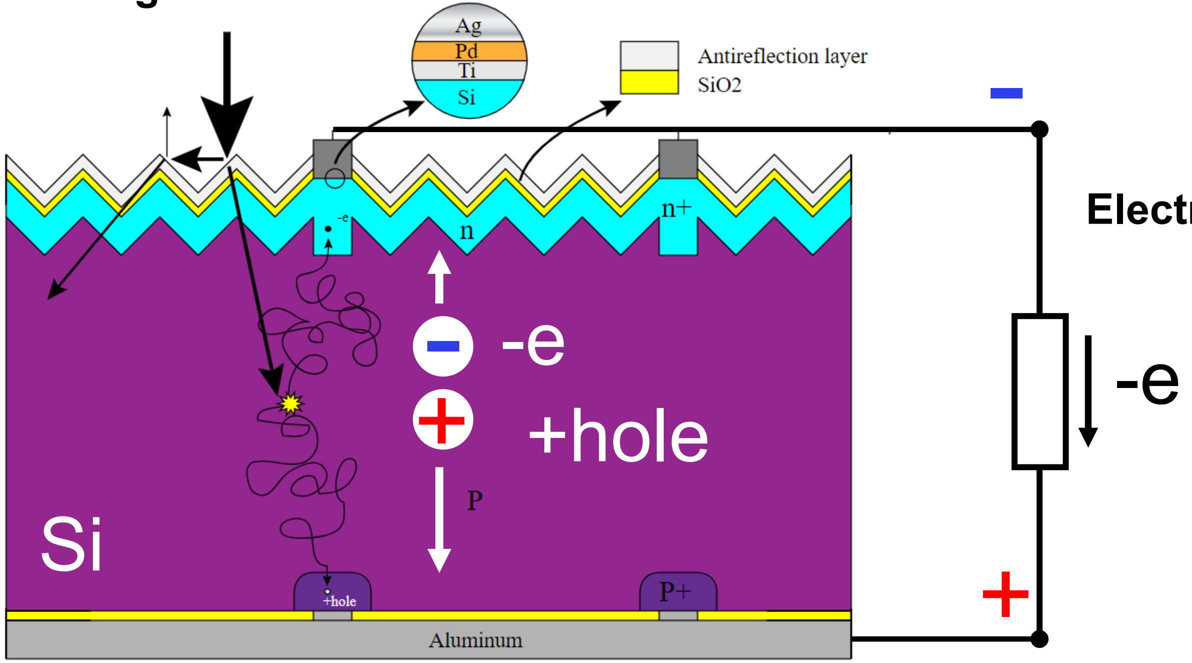
Kinetic energy **Electricity**

Wind flow

Water flow
- Dam
- River
- Tidal



Sun light = Photons



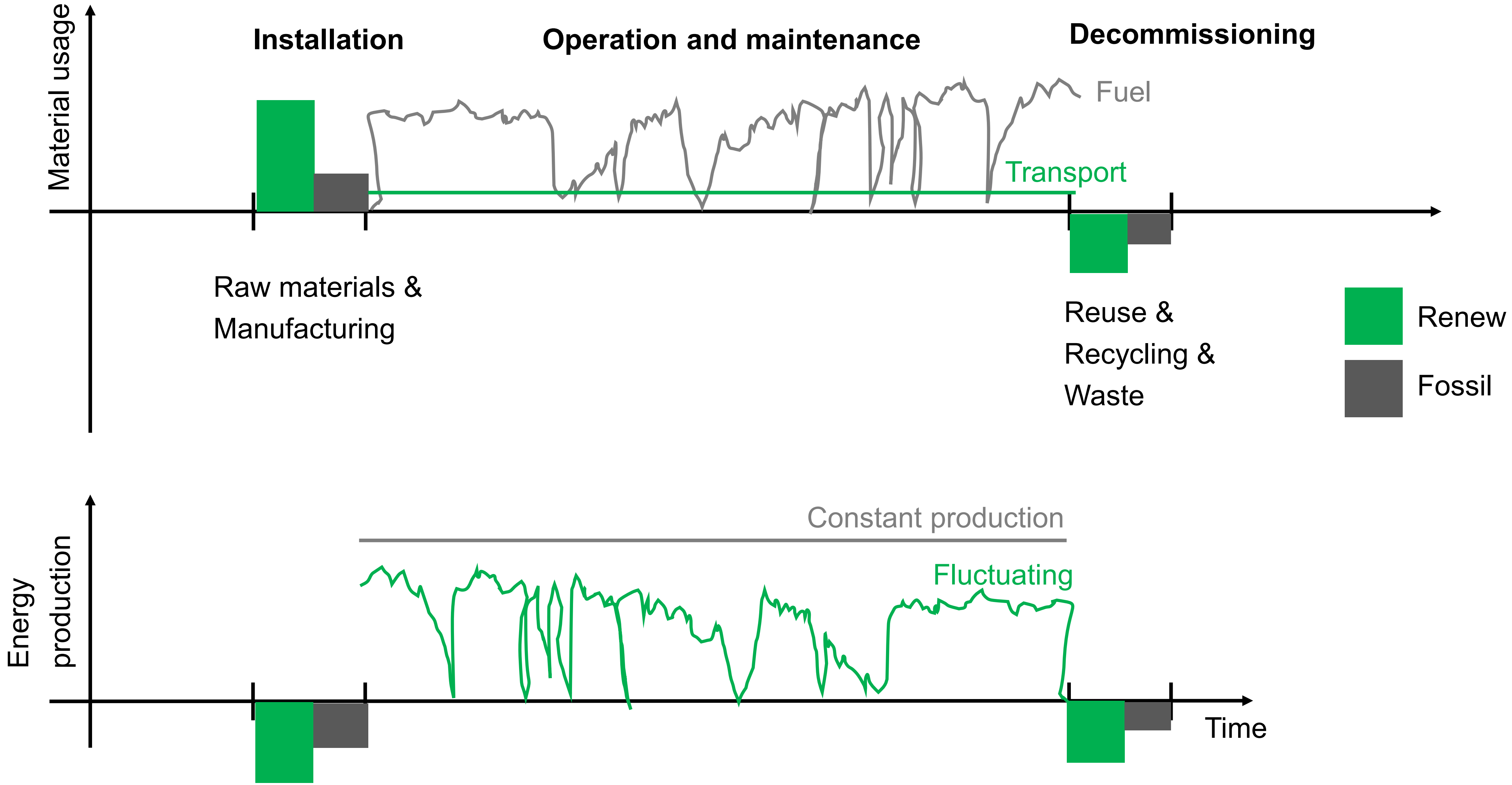
Electricity

Source: Solar cell (Wikipedia.org)

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	$SiO_2 + 2\ C \rightarrow Si + 2\ CO$	5-16 ton CO_2e /ton_{Copper}
Making Copper ore into copper for wires	$2\ Cu_2S + 3\ O_2 \rightarrow 2\ Cu_2O + 2\ SO_2$	3-4 ton CO_2e /ton_{Copper}
	$2\ Cu_2O + Cu_2S \rightarrow 6\ Cu + 2\ SO_2$	SO_2 causes acid rain

Life cycle of energy plants



Normalization of emissions [emission / kWh]

- The bill of material (BOM) of an energy plant accounts for the usage of the different materials m_i used to manufacture the energy plant
- The life time fuel consumption m_f is the sum of the annual fuel consumptions *AFC* used during the life time *LT* of the energy plant
- The recycling masses $m_{r,i}$ are the masses of the original bill of material recovered during the decommissioning phase, which can replace raw materials for the production of new energy plants. This means that emissions can be subtracted.
- The life time energy production *E* is then sum of the annual energy production *AEP* of the energy plant over the life time *LT* of the plant
- Total emission factors of the technology EF_j are now calculated from the specific emission factors $\varepsilon_{i,j}$ of the materials and normalized by the life time energy produced

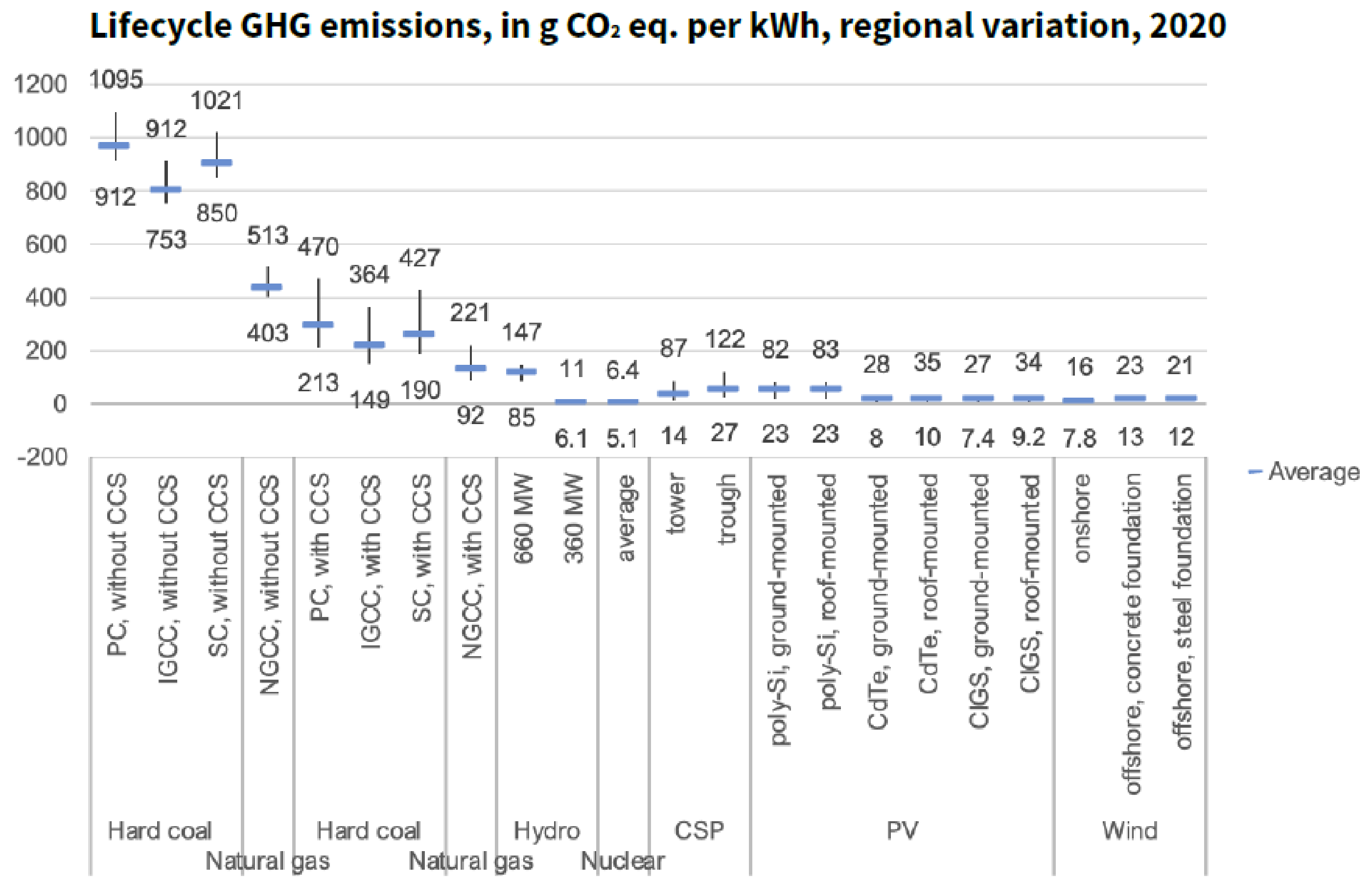
Example:

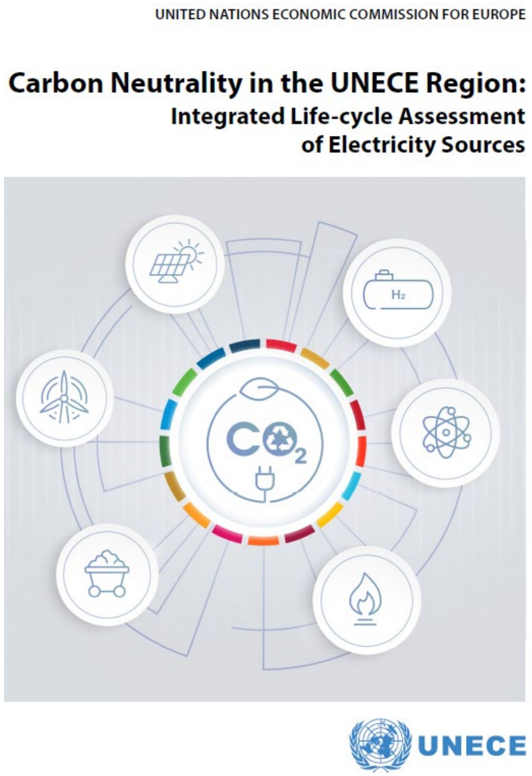
Gram CO_2 / kWh

$$EF_j = \frac{\sum_{i=1}^{N} m_i \varepsilon_{i,j} + m_f \varepsilon_{f,j} + \sum_{i=1}^{N} m_{r,i} \varepsilon_{r,i,j}}{E}$$

LCA overview of electricity producing technologies

Figure 1 Lifecycle greenhouse gas emission ranges for the assessed technologies





Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Energy technologies

Table 1 Summary of life cycle inventories' scopes, per type of technology

Recycling of materials in UN report is absent !

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

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 emit-ted, 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

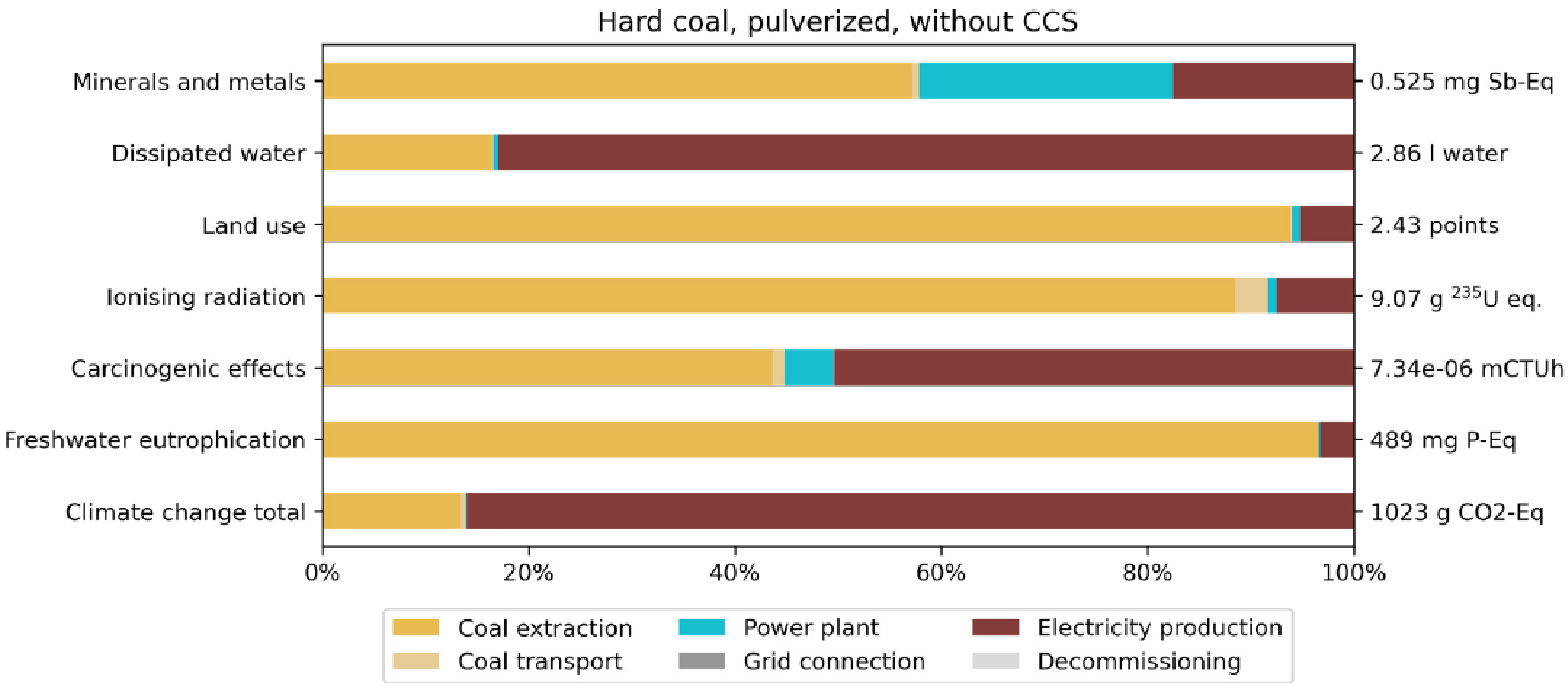
Impacts (continued)

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 re-source depletion	kg Sb eq.	Van Oers, De Koning [22]	Scarcity of resource in relation to that of antimony. Scarcity is calculated as « reserve base ».

Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

Technology examples : coal

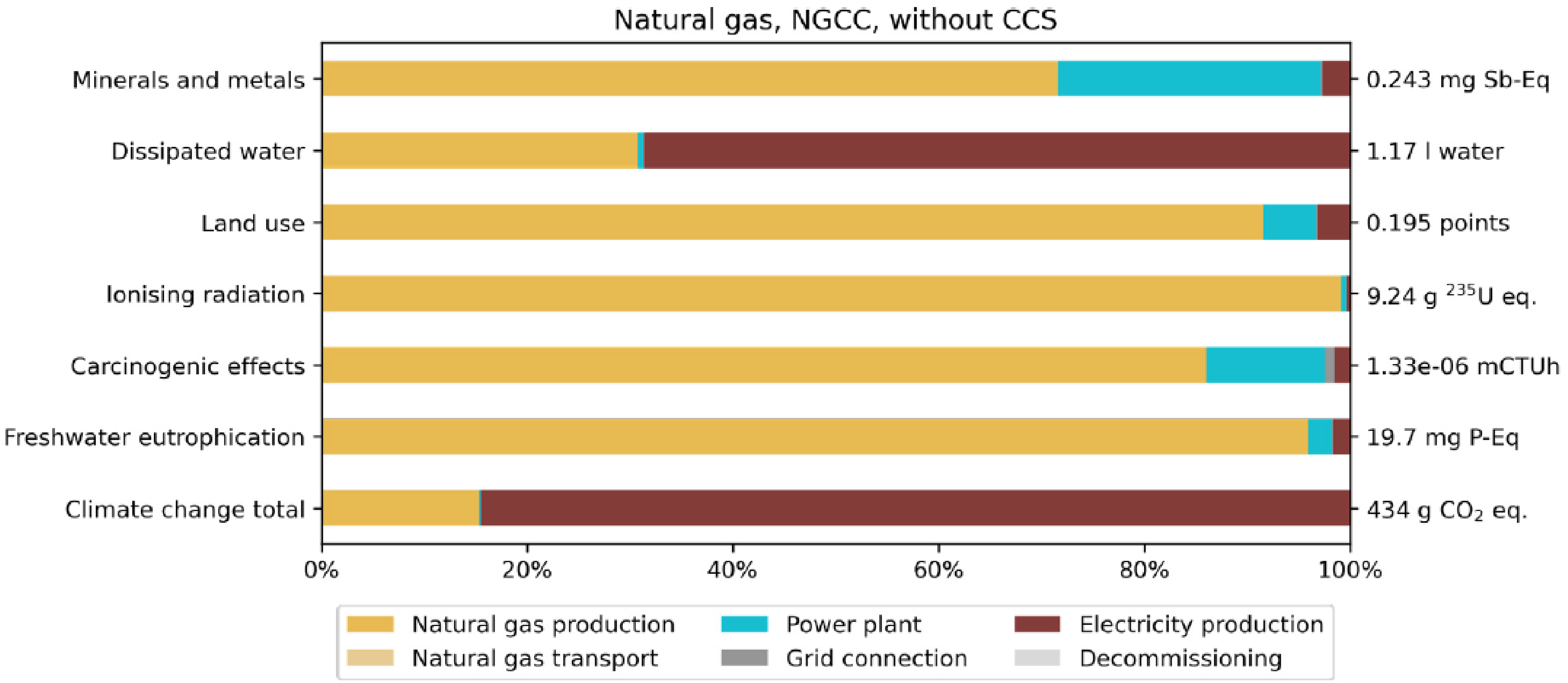
Figure 4 Life cycle impacts from 1 kWh of coal power production, pulverised coal, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Natural gas

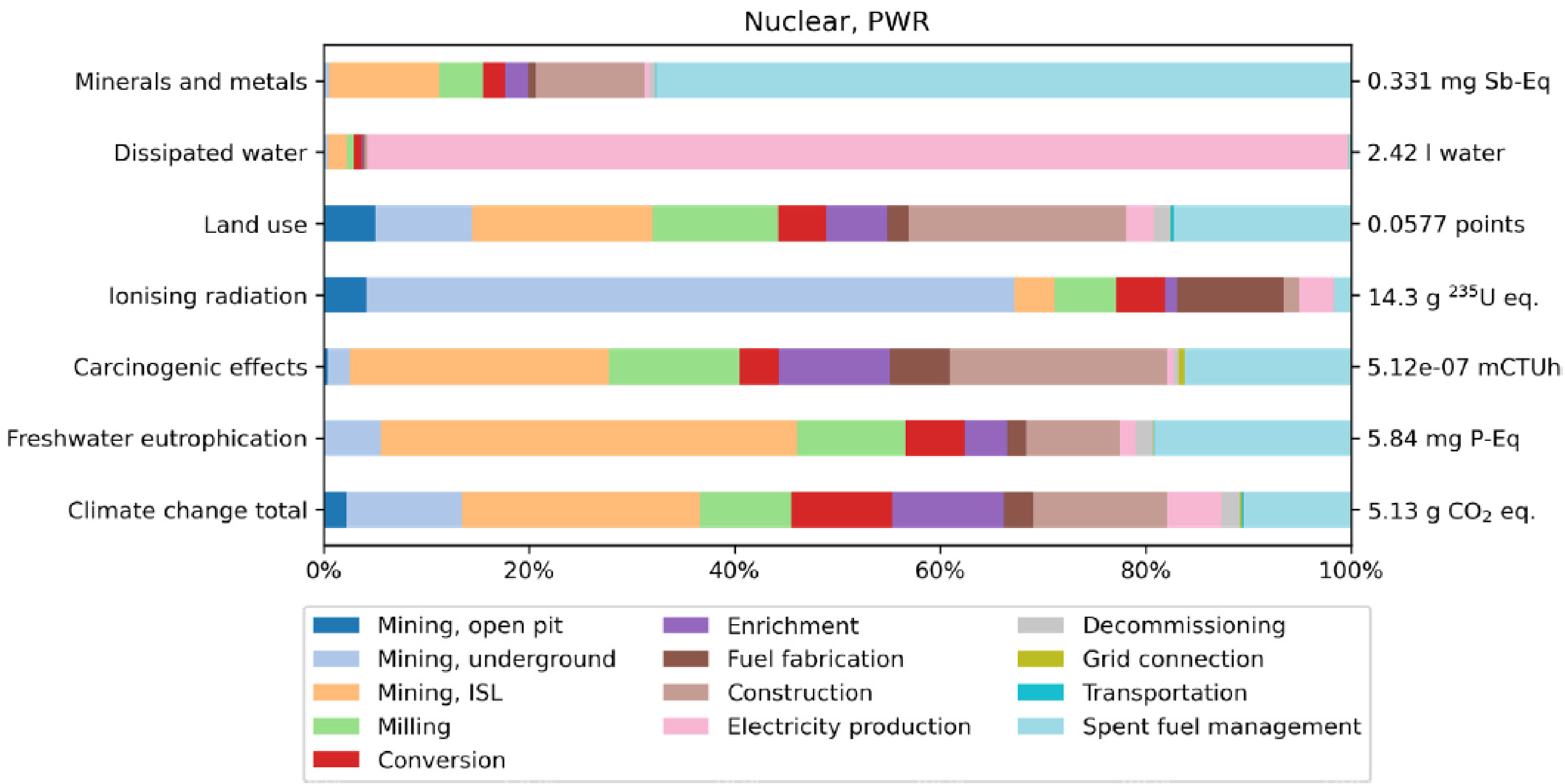
Figure 9 Life cycle impacts from 1 kWh of natural gas power production, NGCC without carbon dioxide capture and storage, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Nuclear

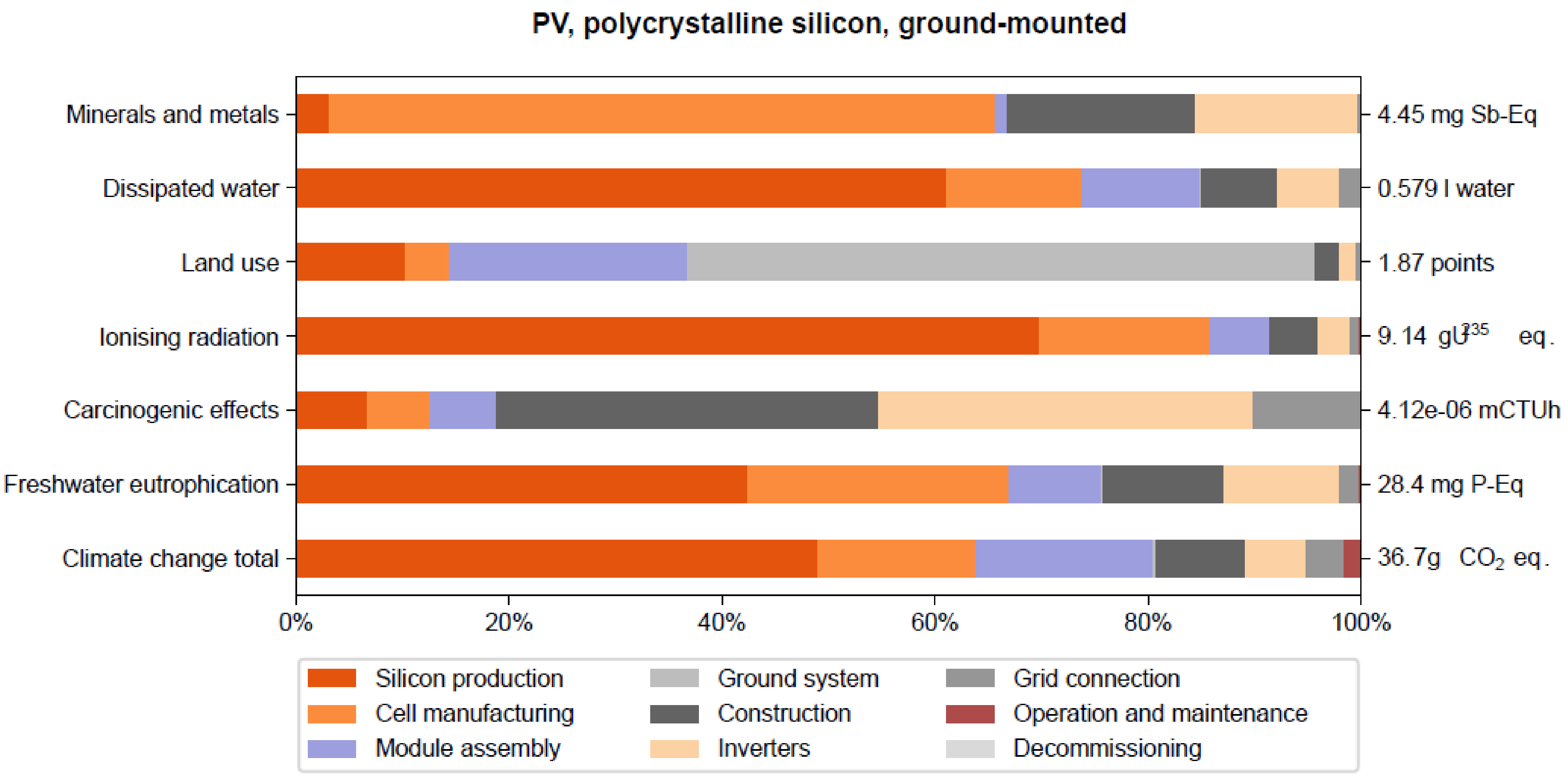
Figure 35 Lifecycle impacts of nuclear power, global average reactor, per kWh and activity



Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

Technology examples : Solar PV

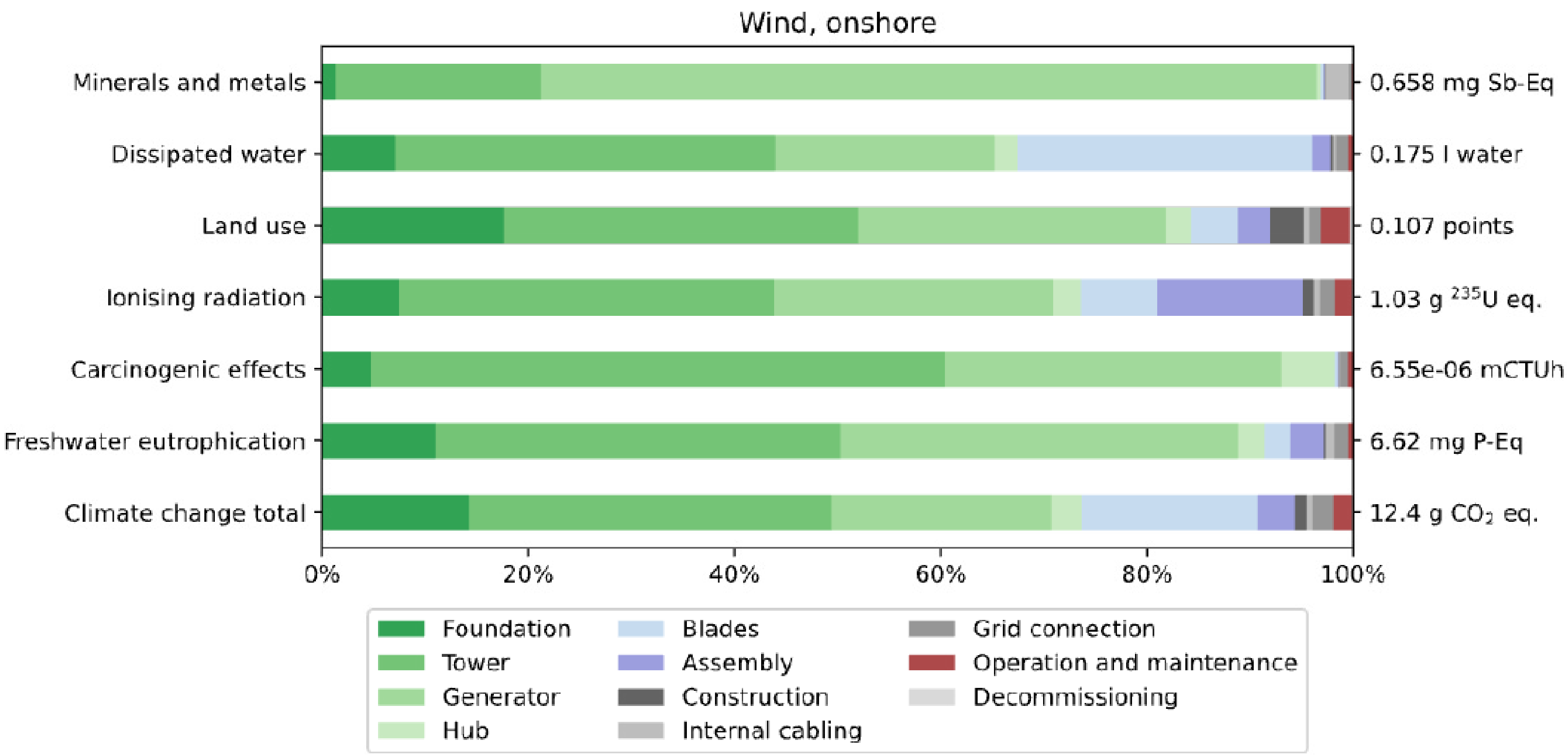
Figure 25 Life cycle impacts from 1 kWh of poly-Si, ground-mounted, photovoltaic power production, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

Technology examples : Onshore wind

Figure 12 Life cycle impacts from 1 kWh of onshore wind power production, Europe, 2020



Source : UN: "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)

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**

Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

Table 13 LCIA results for region EUR (Europe EU28), per kWh, in 2020, for select indicators, rounded to two significant figures.

PER KWH		CLIMATE CHANGE [g CO_2 eq.]	FRESHWATER EUTROPHICATION [mg P eq.]	CARCINOGENIC EFFECTS [µCTUh]	IONISING RADIATION [g ^{235}U 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

DTU

Full LCIA results

Table 14 is summarizing the resulting emission per kWh electricity produces in Europe

Table 14 LCIA results for region EUR (Europe EU 28), in 2020, all ILCD 2.0 indicators, three significant figures . Climate change

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	4.62E-05
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	5.12E-05
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	1.27E-05
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

DTU

Full LCIA results

Table 14 is summarizing the resulting emission per kWh electricity produces in Europe

Continued from previous slide

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	7.43E-07
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	3.14E-07
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

Estimating the consequence of an electricity mix

If we know the mix of the electricity producing technologies and the total production then we can estimate the impact and compare this with a defined limit

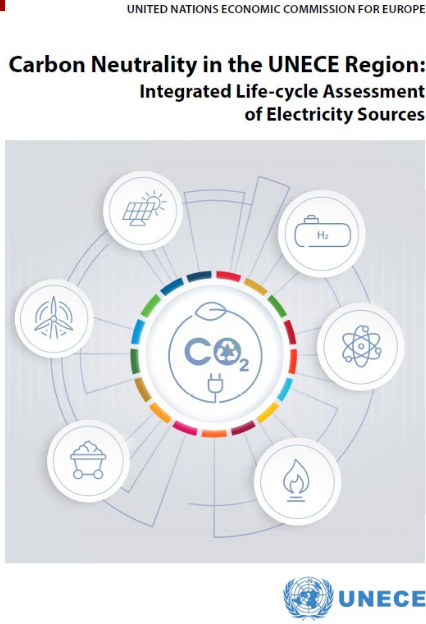
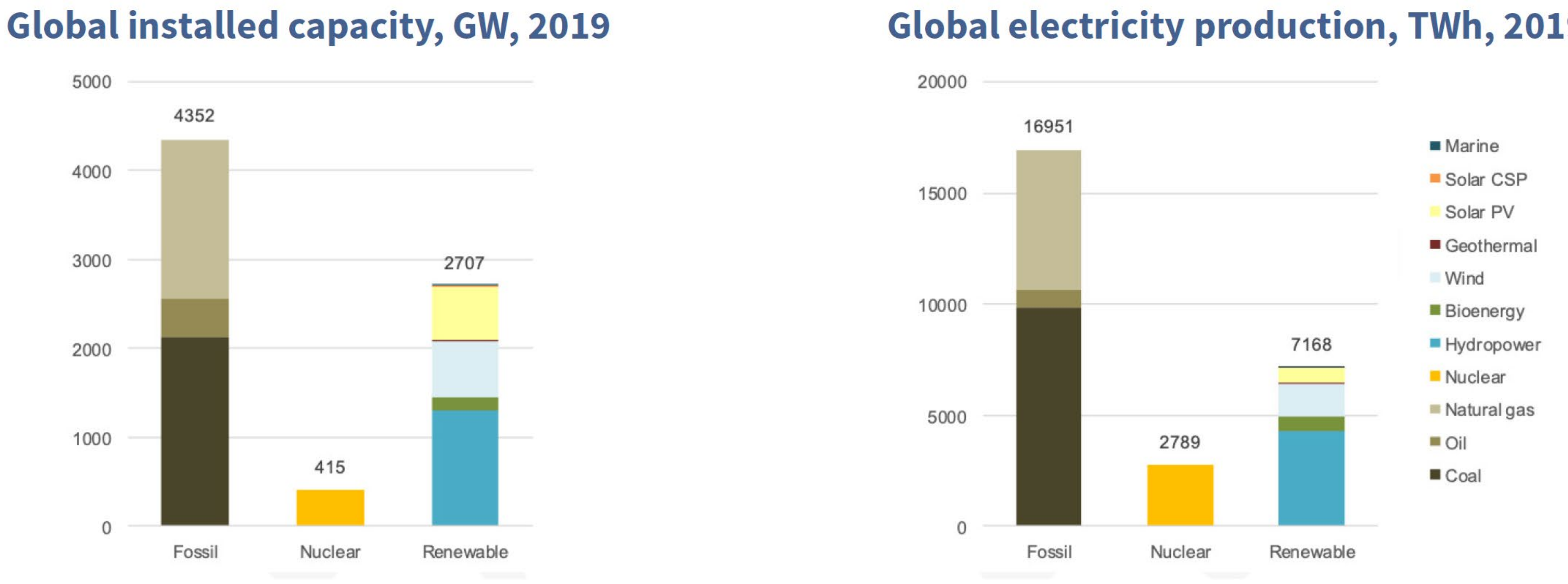


Figure 2 Global installed capacity, and production, of electricity-generating plants in 2019

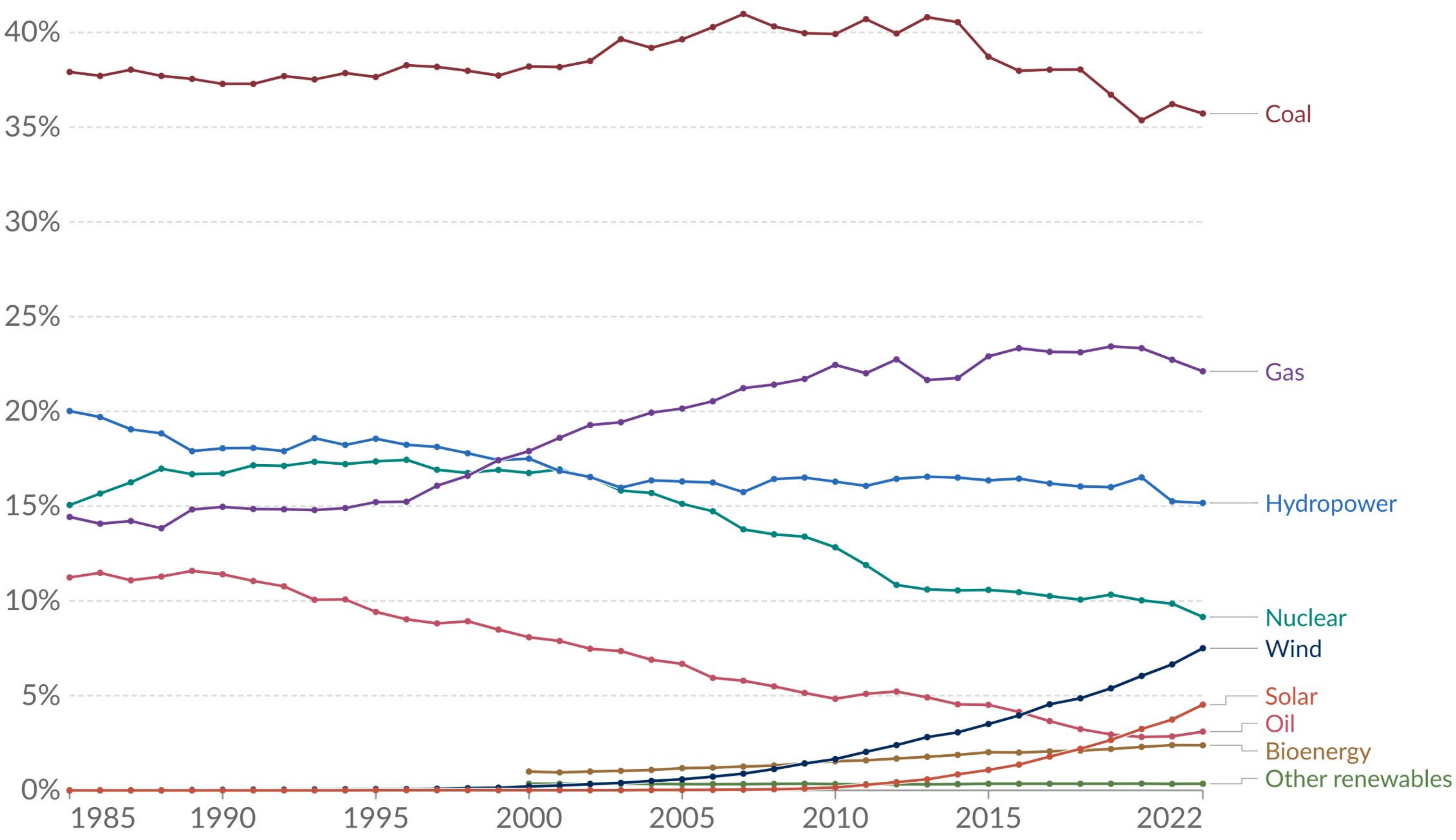


Source: International Energy Agency [4].

Total production in 2019 : 26908 TWh

Source : UN: “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)

Share of electricity production by source, World



Data source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy
OurWorldInData.org/energy | CC BY

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

$$1 \text{ Gt} = 10^9 \cdot 10^3 \text{ kg} = 10^{12} \text{ kg}$$

Global boundary on green house gas

- The UN Emission Gap Report 2022 provides an estimate of the difference between the global emissions and the needed trajectory to fulfill the Paris agreement of a 1.5 ^oC, 1.8 ^oC and 2.0 ^oC global temperature increase by 2100. It is the accumulation of green house gasses in the atmosphere that dictates the future allowed emission levels.
- Currently the global emissions are approximately 53 Gt CO_2e per year.
- Given the global electricity mix and resulting emissions one can estimate the fraction of the total permitted emission that is provided by electricity generation.

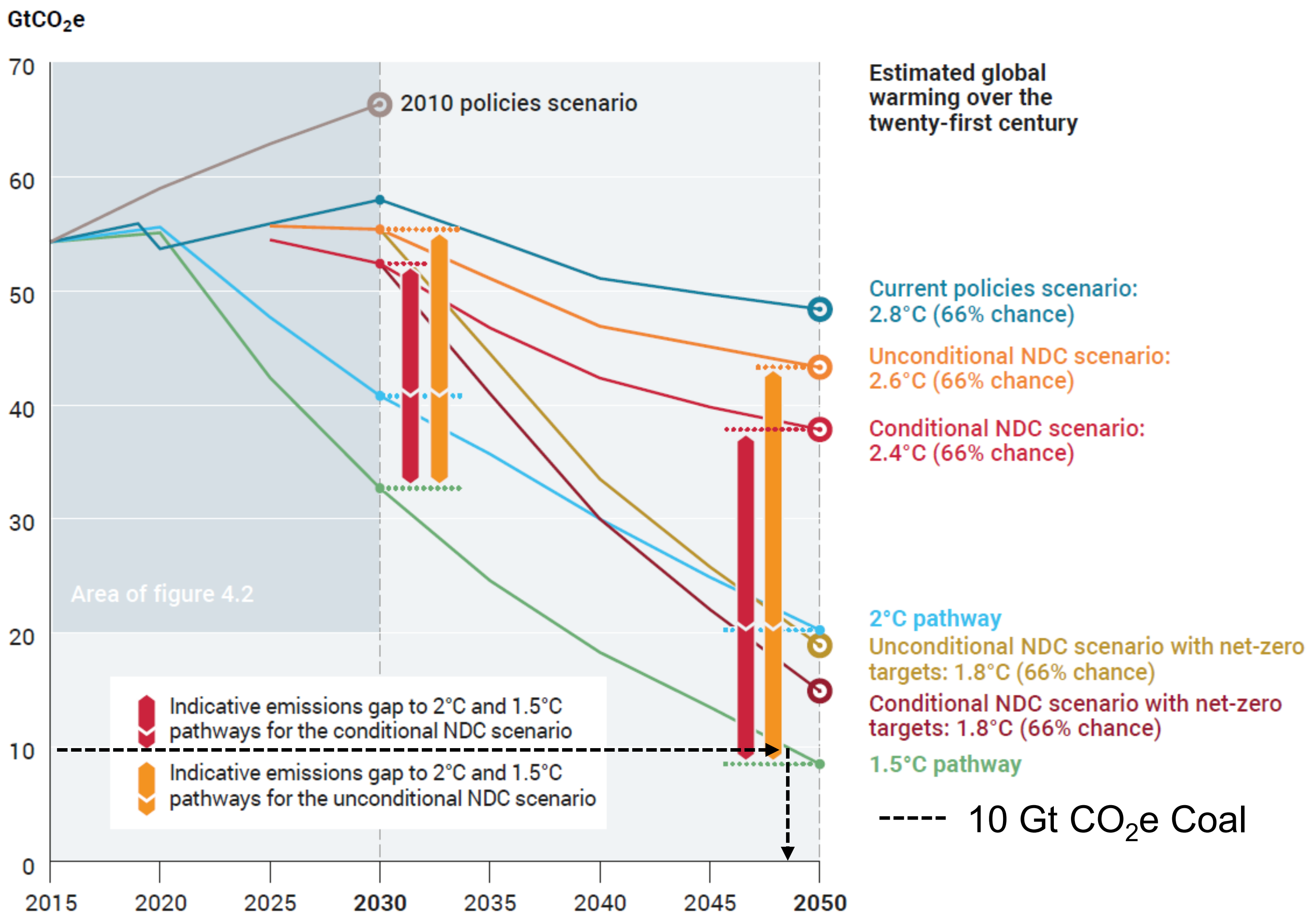


Figure 4.3 in the UN Report ”The closing window – Emission gap report 2022”

Source: UN Emission Gap Report 2022

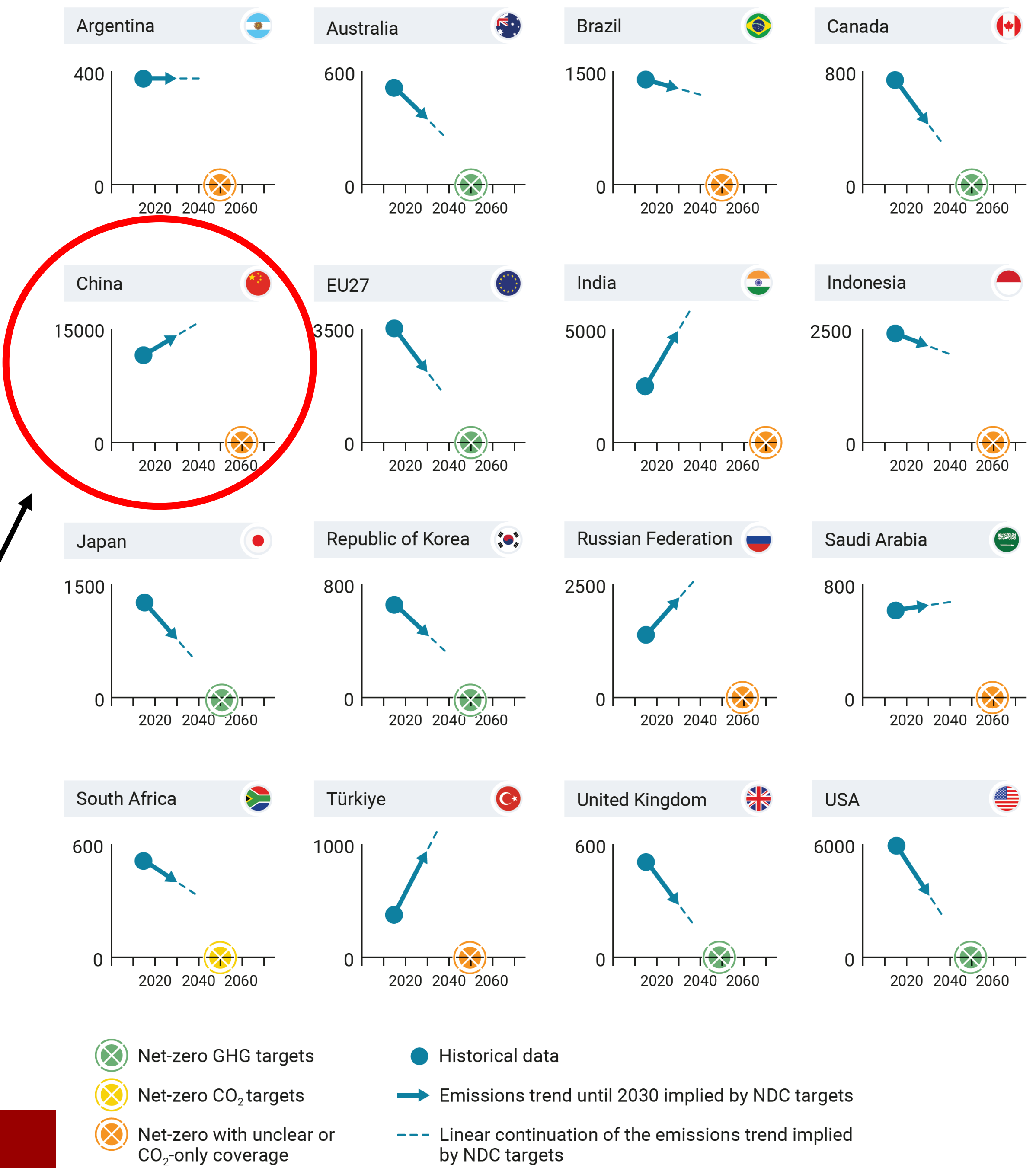
Country specific development trends and targets

The electricity climate change emission from coal and gas is comparable to the current total climate change emission of China !

$$EM_{\text{Climate change, Coal}} + EM_{\text{Climate change, gas}} = 12.5 \quad Gt\ CO_2e$$

Source : UN Emission Gap Report 2022

Figure ES.4 Emissions trajectories implied by NDC and net-zero targets of G20 members. National emissions in $MtCO_2e$/year over time.



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 ^{o}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.

Strategies for decarbonizing the electricity production

ELECTRICITY SUPPLY

National governments	› Remove fossil fuel subsidies in a socially acceptable manner › Remove barriers to expansion of renewables › Stop expansion of fossil fuel infrastructure › Plan for a just fossil fuel phase-out › Adapt market rules of electricity system for high shares of renewables

International cooperation	› Cooperate on a just coal phase-out › Support initiatives on emissions-free electricity, power system flexibility and interconnection solutions
Subnational governments	› Set 100 per cent renewable targets › Plan for a just fossil fuel phase-out

Businesses	› Support a 100 per cent renewable electricity future
Investors, private and development banks	› Engage with or divest from fossil fuel electricity utility companies › Do not invest in or insure new fossil fuel infrastructure
Citizens	› Purchase 100 per cent renewable electricity

Source : Table ES.3 UN Emission Gap Report 2022

Conclusion

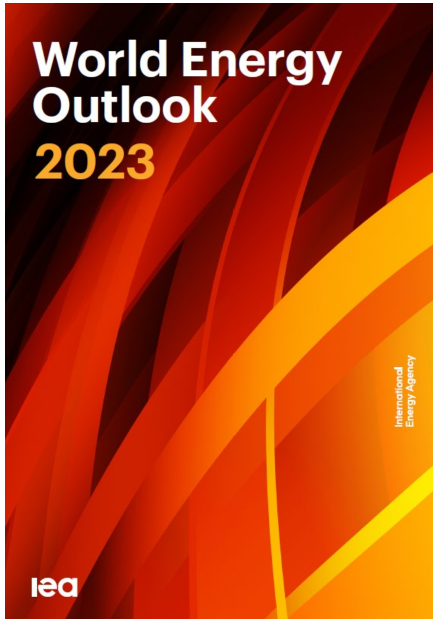
- The United National report “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources “ (2022) provides a baseline reference on the emission expected from the technologies of the electricity mix of countries and regions.

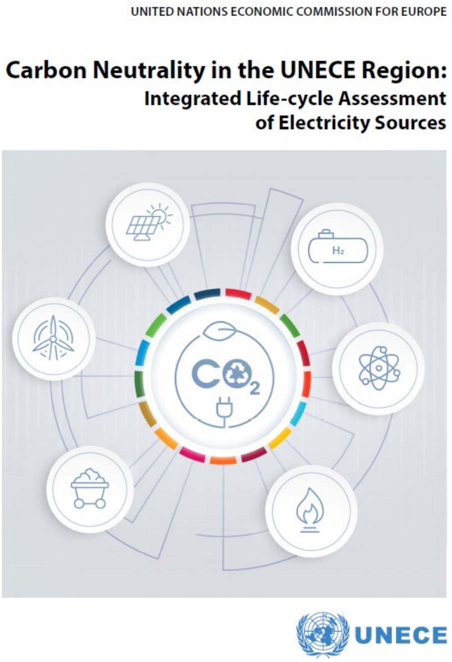
- The electricity mix of different countries and regions can be found from statistical sources (Hannah Ritchie and Pablo Rosado (2020) - “Electricity Mix” Published online at OurWorldInData.org.)

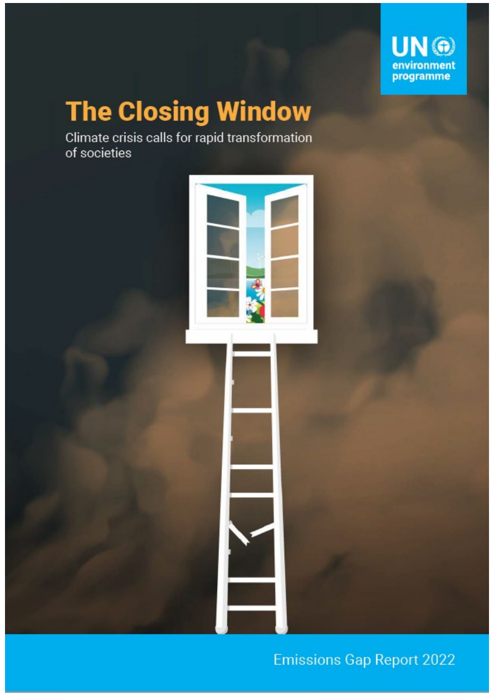
- Impacts from the electricity mix can then be estimated using the reference values and compared to the UN emission gap report in order to understand how close the planetary climate change emission is to the planetary boundary.

The student of the course is encouraged to examine possible decarbonization strategies in the exercise in the following lectures.

Sources







- IEA Energy Outlook 2023
- UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE : “Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources” (2022)
- United Nations Environment Programme (2022). Emissions Gap Report 2022: The Closing Window — Climate crisis calls for rapid transformation of societies. Nairobi.

Decarbonizing energy systems
DTU course on Quantitative Sustainability

Lecture 1 Decarbonizing energy systems
Lecture 2 Wind Energy as case
Lecture 3 Exercise : Violation of planetary boundary of Global Warming Potential due to electricity mix

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Technical University of Denmark
Contact : asab@dtu.dk

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

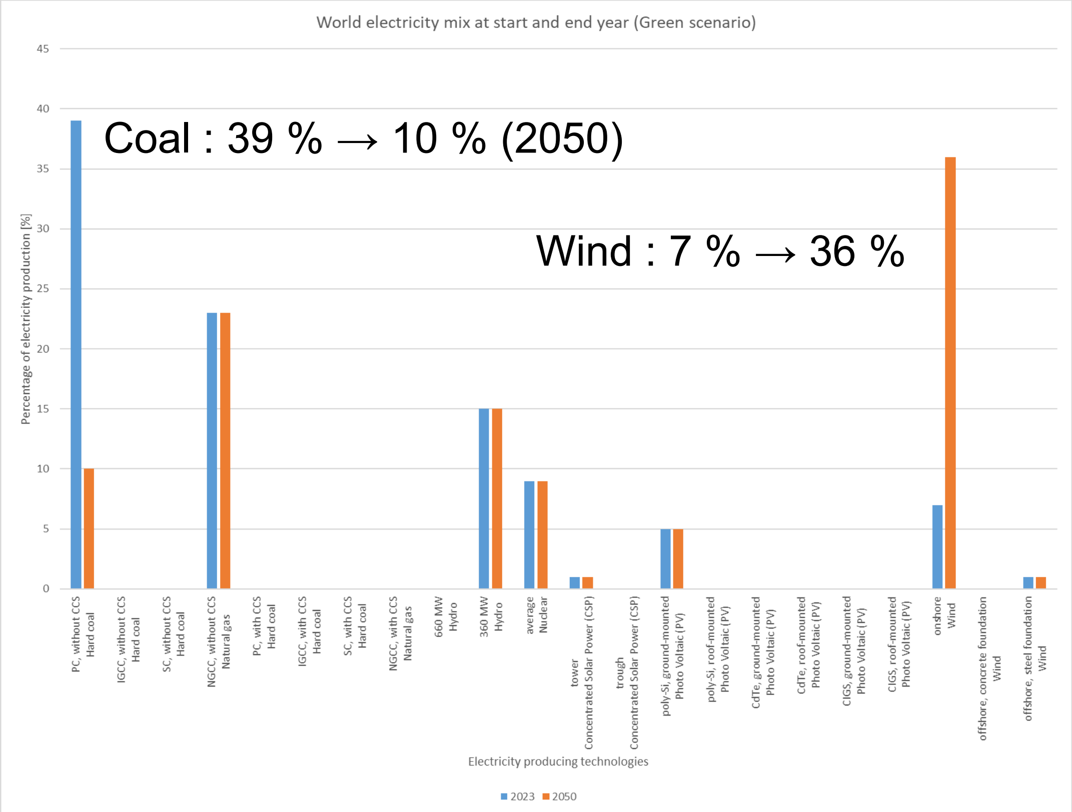
Carbon Neutrality in the UNECE Region:
Integrated Life-cycle Assessment
of Electricity Sources

UNECE

DTU

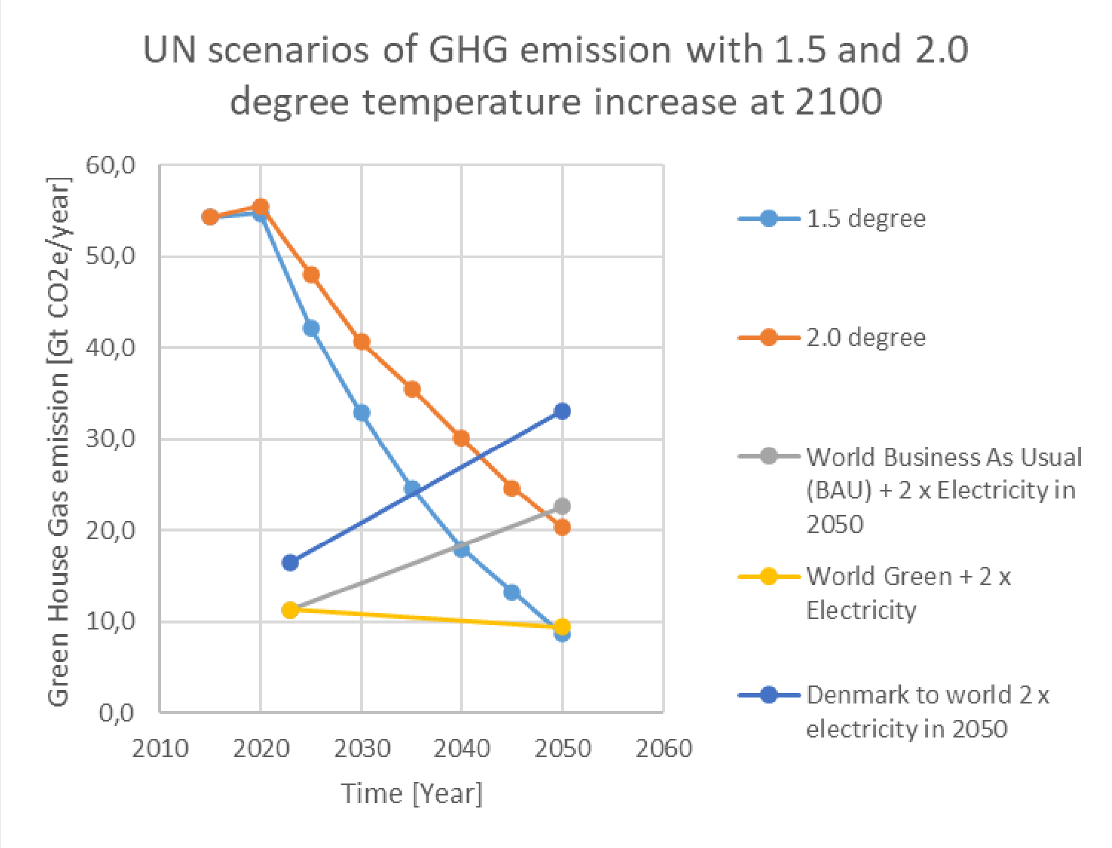
Violation of planetary boundary of Global Warming Potential due to electricity mix

This exercise has been created to illustrate the Global Warming Potential or CO_{2e} emission resulting from a mix of electricty producing technologies on the scale of planet Earth and then to compare the emissions to the planetary boundary of 1.5 °C heating in 2100 as formulated in the Paris agreement. The students should suggest a future technology mix of 2050 and determine if the planetary boundary is violated. Secondly they should analyse a country scaled to planet scale.

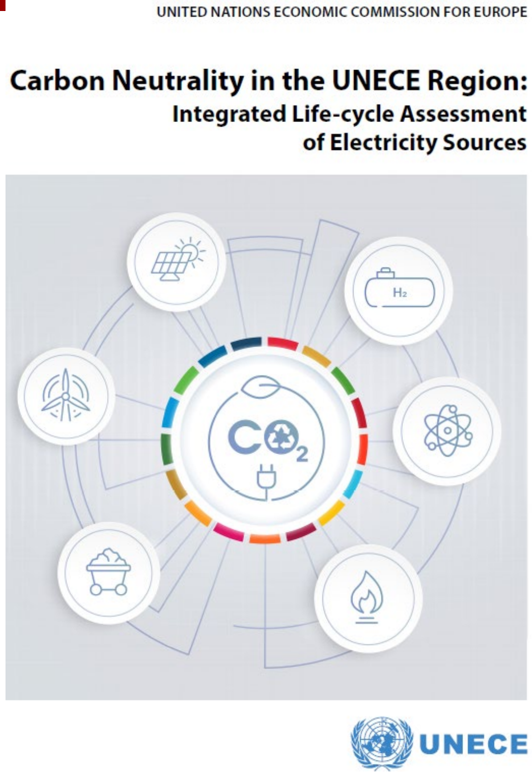


Green scenario

- Double electricity demand in 2050
- Reduce coal
- Increase wind
- 6 million Danes
- 8 billion people on earth



Violation of planetary boundary of Global Warming Potential due to electricity mix – Learning objectives



The objectives with the GWP violation exercise is to learn the students how to

- Evaluate the $CO_{2,eq}$ emissions resulting from a mix of electricity-producing technologies of planet Earth.
- Compare the $CO_{2,eq}$ emissions with the planetary boundary according to the UN global warming scenario of 1.5 ^{o}C temperature increase by end of the century and determine if the boundary is violated.
- Formulate an electricity technology mix of 2050 and evaluate if the planetary $CO_{2,eq}$ boundary is violated with the assumption that electricity demand double in 2050 due to the electrification of heating, transport and other sectors.
- Determine the $CO_{2,eq}$ emission of a specific country if the electricity consumption is scaled to the population of the planet and determine if the planetary boundary is violated. Thus, one can ask the question, “What will the emissions be if the planet lives like the Danes in 2050?”

Simple method of evaluating Global Warming Potential of the electricity mix of the world

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:

$$E_m = EF_{average} \cdot E$$

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].

Comparison to planetary boundary of Global Warming Potential(GWP)

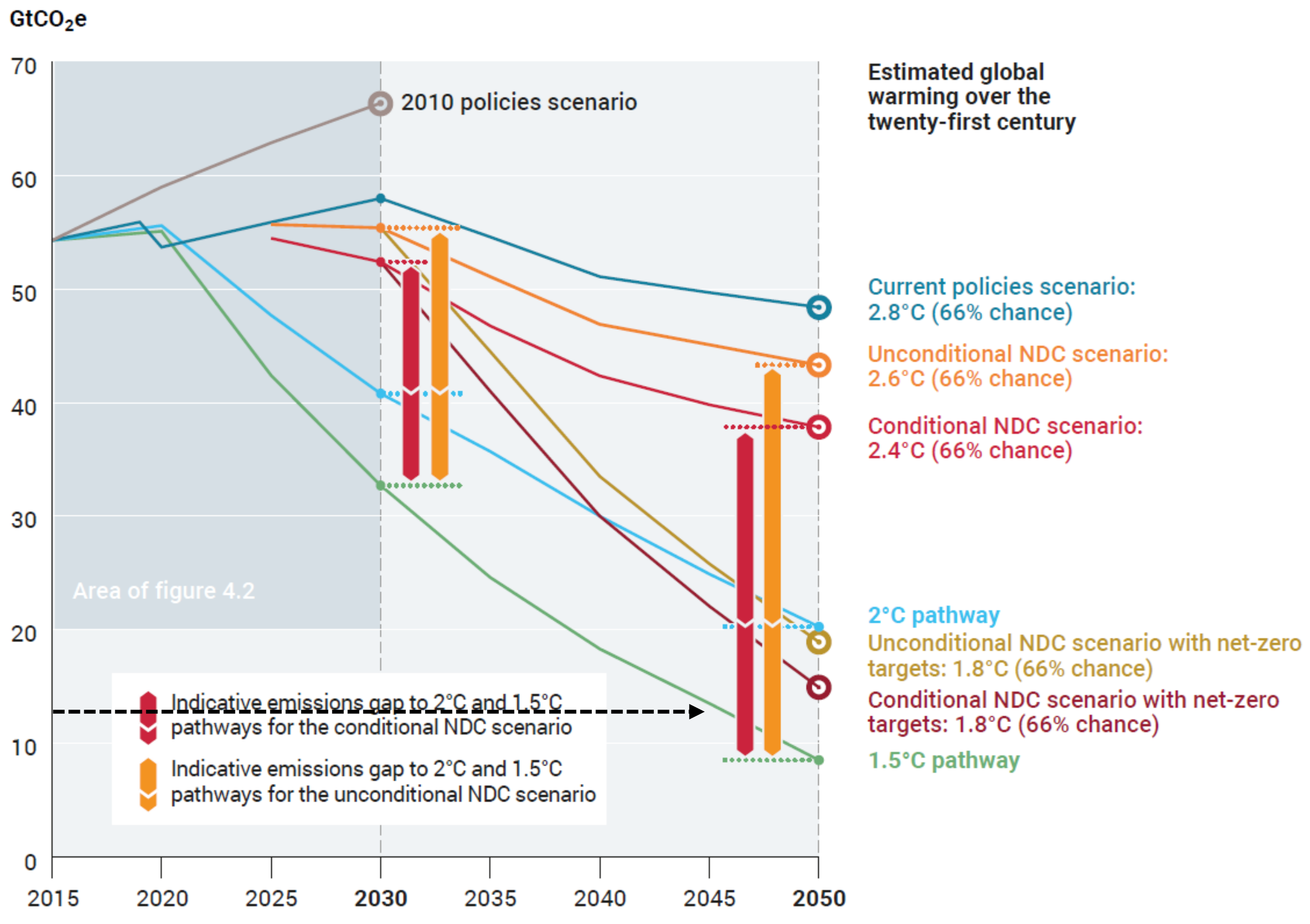
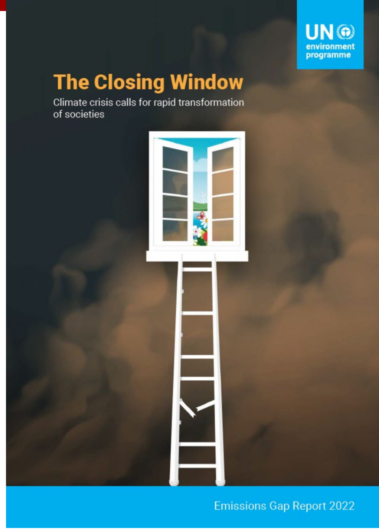


Figure 4.3 in the UN Report ”The closing window – Emission gap report 2022”



- The estimated global emission can be compared directly to the UN report on the emission gap of 2022.
- Different formulations of the planetary boundary have been formulated, but the 1.5 °C pathway is used for the comparison.
- It should be noted that the 13 $GtCO_2e$ of coal and gas emission from electricity production in 2022 from Lecture 1 will violate the 1.5 °C path around 2045.
- An excel spread sheet has been created for calculating the impact of an electricity system and should be used to solve the exercise.

Instruction of exercise

A tool facilitating emission calculations has been created as an Excel sheet and is called

PlanetaryCO2Boundary_ElectricityTechnologyMix_v2_Abrahamsen.xlsx

It can be downloaded either from the DTU Learn page of the Quantitative Sustainability course or from this orbit project page :

https://orbit.dtu.dk/en/projects/decarbonizing-energy-systems

Open the Excel sheet on your computer and check if the numbers and plots are updating when some input data (grey fields) are changed. Check that your decimal sign ”.” or ”,” is set correctly. Some users with an Apple computer might need to review the settings of Excel.

The following slides will explain the different sheets of the tool and how to use the tool.

Overview of PlaneraryCO2boundary tool

Planetary CO2 boundary

This excel sheet has been created as part of the course 12100 Quantitative sustainability at the Technical University of Denmark (DTU) in 2023
The purpose of the spread sheet is to be able to specify the electricity technology mix of the world and then estimate the resulting emissions using the LCA results
of the United Nation report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" (2022)
The global warming potential (gCO2e) of the world is estimated and compared to the global CO2 emission target of the 1.5 degree Celcius scenario of the Paris agreement
The students can then enter an electricity technology mix of 2050 and determine if the planetary boundary of the global warming potential is violated.
Finally the students can enter an electricity technology mix of a country or region and determine if the planetary boundary of global warming potential is violated if the population of the region is scaled to the population of the planet.

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Technical University of Denmark (DTU)
Version 1
Date 23-feb-24

Sheets
1) Introduction
2) Emissions of world Business As Usual (BAU)
3) Emissions of the world green scenario
4) Emissions of Denmark
5) Result plot

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Emission input from UN report on LCA of electricity producing technologies

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**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	FRESHWATER AND TERRESTRIAL ACIDIFICATION	FRESHWATER ECOTOXICITY	FRESHWATER EUTROPHICATION	MARINE EUTROPHICATION	TER EUT N
2			[%]	[%]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]	[mc
3	Hard coal	PC, without CCS	39	39	6,87E-05	1,02E+00	1,67E-04	1,02E+00	1,73E-03	4,72E-01	4,89E-04	5,14E-04	
4	Hard coal	IGCC, without CCS	0	0	5,38E-05	8,49E-01	1,40E-04	8,49E-01	1,05E-03	3,46E-01	4,24E-04	4,18E-04	
5	Hard coal	SC, without CCS	0	0	6,45E-05	9,53E-01	1,56E-04	9,53E-01	1,63E-03	4,33E-01	4,58E-04	4,82E-04	
6	Natural gas	NGCC, without CCS	23	23	7,78E-05	4,34E-01	8,21E-05	4,34E-01	3,26E-04	1,16E-01	1,97E-05	4,96E-05	
7	Hard coal	PC, with CCS	0	0	1,06E-04	3,68E-01	2,47E-04	3,69E-01	1,80E-03	8,26E-01	6,90E-04	7,29E-04	
8	Hard coal	IGCC, with CCS	0	0	7,23E-05	2,79E-01	1,89E-04	2,79E-01	1,35E-03	4,94E-01	5,71E-04	5,36E-04	
9	Hard coal	SC, with CCS	0	0	9,90E-05	3,33E-01	2,34E-04	3,33E-01	2,25E-03	7,51E-01	6,37E-04	6,92E-04	
10	Natural gas	NGCC, with CCS	0	0	9,39E-05	1,28E-01	9,93E-05	1,28E-01	6,07E-04	2,34E-01	2,40E-05	7,42E-05	
11	Hydro	660 MW	0	0	5,32E-05	1,47E-01	1,09E-04	1,47E-01	4,15E-04	3,97E-01	1,26E-05	9,54E-05	
12	Hydro	360 MW	15	15	1,80E-05	1,07E-02	9,21E-06	1,07E-02	4,45E-05	2,73E-02	1,33E-06	1,23E-05	
13	Nuclear	average	9	9	2,56E-05	5,24E-03	2,26E-05	5,29E-03	4,28E-05	2,70E-02	6,45E-06	8,20E-05	
14	Concentrated Solar Power (CSP)	tower	1	1	3,02E-05	2,16E-02	3,36E-05	2,17E-02	9,24E-05	3,65E-02	1,11E-05	2,21E-05	
15	Concentrated Solar Power (CSP)	trough	0	0	4,57E-05	4,19E-02	5,60E-05	4,20E-02	1,51E-04	1,10E-01	1,38E-05	2,88E-05	
16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04	3,62E-02	1,51E-04	3,67E-02	3,01E-04	7,91E-02	2,84E-05	4,62E-05	
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	3,67E-02	1,69E-04	3,72E-02	3,34E-04	6,99E-02	3,93E-05	5,12E-05	
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	1,18E-02	2,54E-05	1,19E-02	6,27E-05	5,59E-02	8,75E-06	1,27E-05	
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	1,45E-02	4,38E-05	1,46E-02	8,82E-05	3,96E-02	1,42E-05	1,54E-05	
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	1,13E-02	2,52E-05	1,14E-02	6,11E-05	5,58E-02	8,76E-06	1,25E-05	
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	1,40E-02	4,33E-05	1,41E-02	8,64E-05	4,02E-02	1,42E-05	1,52E-05	
22	Wind	onshore	7	7	1,87E-05	1,24E-02	1,99E-05	1,24E-02	5,28E-05	7,48E-02	6,67E-06	1,39E-05	
23	Wind	offshore, concrete foundation	0	0	1,74E-05	1,42E-02	2,58E-05	1,42E-02	1,00E-04	6,62E-02	6,98E-06	2,84E-05	
24	Wind	offshore, steel foundation	1	1	1,87E-05	1,33E-02	2,46E-05	1,33E-02	9,45E-05	7,94E-02	6,84E-06	2,69E-05	
25	Total		100	100									
26						Electricity technology normalization unit : 1 kWh							

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Technologies **Mix Now & Future** **Impacts from UN LCA report**

Specification of present and future year, energy production and population

16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04	3,62E-02	1,51E-04	3,67E-02	3,01E-04	7,91E-02	2,84E-05	4,62E-05
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	3,67E-02	1,69E-04	3,72E-02	3,34E-04	6,99E-02	3,93E-05	5,12E-05
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	1,18E-02	2,54E-05	1,19E-02	6,27E-05	5,59E-02	8,75E-06	1,27E-05
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	1,45E-02	4,38E-05	1,46E-02	8,82E-05	3,96E-02	1,42E-05	1,54E-05
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	1,13E-02	2,52E-05	1,14E-02	6,11E-05	5,58E-02	8,76E-06	1,25E-05
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	1,40E-02	4,33E-05	1,41E-02	8,64E-05	4,02E-02	1,42E-05	1,52E-05
22	Wind	onshore	7	7	1,87E-05	1,24E-02	1,99E-05	1,24E-02	5,28E-05	7,48E-02	6,67E-06	1,39E-05
23	Wind	offshore, concrete foundation	0	0	1,74E-05	1,42E-02	2,58E-05	1,42E-02	1,00E-04	6,62E-02	6,98E-06	2,84E-05
24	Wind	offshore, steel foundation	1	1	1,87E-05	1,33E-02	2,46E-05	1,33E-02	9,45E-05	7,94E-02	6,84E-06	2,69E-05
25	Total		100	100								
26						Electricity technology normalization unit : 1 kWh						
27	Start & End year		2023	2050								
28	Start & End production [kWh/year]	World	2,25E+13	4,50E+13								
29	Start & End population [Citicenz]	World	8,00E+09	8,E+09								
30												
							Climate		FRESHWATER AND		FRESHWATE	

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

World electricity production = $2.25 \cdot 10^{13}$ kWh/year in 2023

World population = 8 Billion people in 2023

Scenario : Double electricity production in 2050 due to electrification

World population constant at 8 billion people

Resulting impacts

27	Start & End year		2023	2050									
28	Start & End production [kWh/year]	World	2,25E+13	4,50E+13									
29	Start & End population [Citicenz]	World	8,00E+09	8,E+09									
30													
31	**LCA impacts**	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total	FRESHWATER AND TERRESTRIAL ACIDIFICATIO N	FRESHWATER ECOTOXICITY	FRESHWATE R EUTROPHIC ATION	MARINE EUTROPHICATIO N	TER EUT N
32	Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	[kg CO2-Eq/kWh]	[kg CO2-Eq/kWh]	[mol H+-Eq/kWh]	[CTU/kWh]	[kg P-Eq/kWh]	[kg N-Eq/kWh]	[mc
33	Impact at start per kWh		2023		6,86E-05	5,03E-01	9,70E-05	5,03E-01	7,81E-04	2,28E-01	1,98E-04	2,25E-04	
34	Impact at end per kWh			2050	6,86E-05	5,03E-01	9,70E-05	5,03E-01	7,81E-04	2,28E-01	1,98E-04	2,25E-04	
35	Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]	[mc
36	Absolute impact at start of production		2023		1,54E+09	1,13E+13	2,18E+09	1,13E+13	1,76E+10	5,12E+12	4,46E+09	5,06E+09	
37	Absolute impact at end of production			2050	3,09E+09	2,26E+13	4,36E+09	2,26E+13	3,51E+10	1,02E+13	8,91E+09	1,01E+10	
38													
39	**Green house Gas emissions**	**Scenario:**	World Business As Usual (BAU) + 2 x Electricity in 2050					Climate change Total					
40	Equavalent world emssion start	[Gt CO2e]						1,13E+01					
41	Equavalent world emssion end	[Gt CO2e]						2,26E+01					
42	GHG start fraction of UN 1.5 Degree	[%]						27					
43	GHG end fraction of UN 1.5 Degree	[%]						263					
44													

World Business

2,50E+13

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Impacts weighted with electricity technology mix per kWh

$$EF_{average} = \sum_{i=1}^{N} EF_i \cdot f_i$$

Impacts on planet scale

$$E_m = EF_{average} \cdot E$$

Green house gas emission and comparison to planetary boundary

Comparison to planetary boundary given by the Paris Agreement

UN Green House Gas (GHG) emission scenarios

Year	1.5 degree [Gt CO2e]	2.0 degree [Gt CO2e]	Year	World Business As Usual (BAU [Gt CO2e]	World Green [Gt CO2e]	Denmark 2 x electricity in 2050 [Gt CO2e]
2015	54,4	54,4	2023	1,13E+01	1,13E+01	1,66E+01
2020	54,7	55,5	2050	2,26E+01	9,47E+00	3,31E+01
2025	42,2	48,1				
2030	32,8	40,7				
2035	24,6	35,6				
2040	18,0	30,1				
2045	13,3	24,6				
2050	8,6	20,3				

Source : UN Emission Gap Report 2022
https://www.unep.org/resources/emissions-gap-report-2022

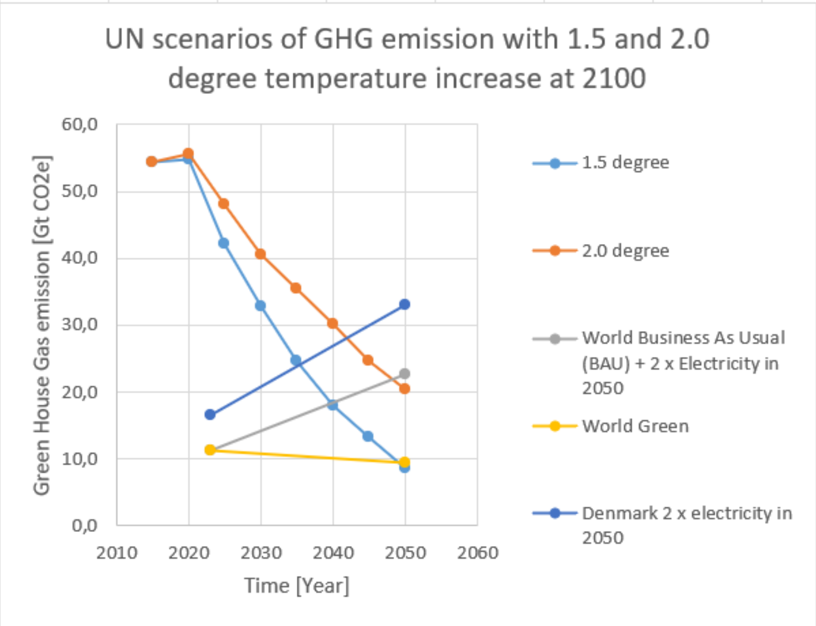


Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Planetary boundary of Global Warming Potential

World business as usual scenario to violate GPW planetary boundary by 263 % in 2050

Scenario : World green mix coal ↓ and onshore wind ↑

	A	B	C	D	E	
1	**World Green**	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$	change biogenic	Clima chan
2			[%]	[%]	[kg CO2-Eq]	[kg C
3	Hard coal	PC, without CCS	39	10	6,87E-05	
4	Hard coal	IGCC, without CCS	0	0	5,38E-05	
5	Hard coal	SC, without CCS	0	0	6,45E-05	
6	Natural gas	NGCC, without CCS	23	23	7,78E-05	
7	Hard coal	PC, with CCS	0	0	1,06E-04	
8	Hard coal	IGCC, with CCS	0	0	7,23E-05	
9	Hard coal	SC, with CCS	0	0	9,90E-05	
10	Natural gas	NGCC, with CCS	0	0	9,39E-05	
11	Hydro	660 MW	0	0	5,32E-05	
12	Hydro	360 MW	15	15	1,80E-05	
13	Nuclear	average	9	9	2,56E-05	
14	Concentrated Solar Power (CSP)	tower	1	1	3,02E-05	
15	Concentrated Solar Power (CSP)	trough	0	0	4,57E-05	
16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5	3,43E-04	
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0	3,34E-04	
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0	8,86E-05	
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0	5,59E-05	
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0	8,58E-05	
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0	5,47E-05	
22	Wind	onshore	7	36	1,37E-05	
23	Wind	offshore, concrete foundation	0	0	1,74E-05	
24	Wind	offshore, steel foundation	1	1	1,87E-05	
25	Total		100	100		
26						Elect

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

27	Start & End year		2023	2050				
28	Start & End production [kWh/year]	World	2,25E+13	4,50E+13				
29	Start & End population [Citicenz]	World	8,00E+09	8,E+09				
30								
31	**LCA impacts**	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
32	Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	[kg CO2-Eq/kWh]	[kg CO2-Eq/kWh]
33	Impact at start per kWh		2023		6,86E-05	5,03E-01	9,70E-05	5,03E-01
34	Impact at end per kWh			2050	5,41E-05	2,11E-01	5,43E-05	2,11E-01
35	Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]
36	Absolute impact at start of production		2023		1,54E+09	1,13E+13	2,18E+09	1,13E+13
37	Absolute impact at end of production			2050	2,44E+09	9,47E+12	2,44E+09	9,47E+12
38								
39	**Green house Gas emissions**	**Scenario:**	World Green					Climate change Total
40	Equavalent world emssion start	[Gt CO2e]						1,13E+01
41	Equavalent world emssion end	[Gt CO2e]						9,47E+00
42	GHG start fraction of UN 1.5 Degree	[%]						27
43	GHG end fraction of UN 1.5 Degree	[%]						110
44								

Planetary CO2 boundary | Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

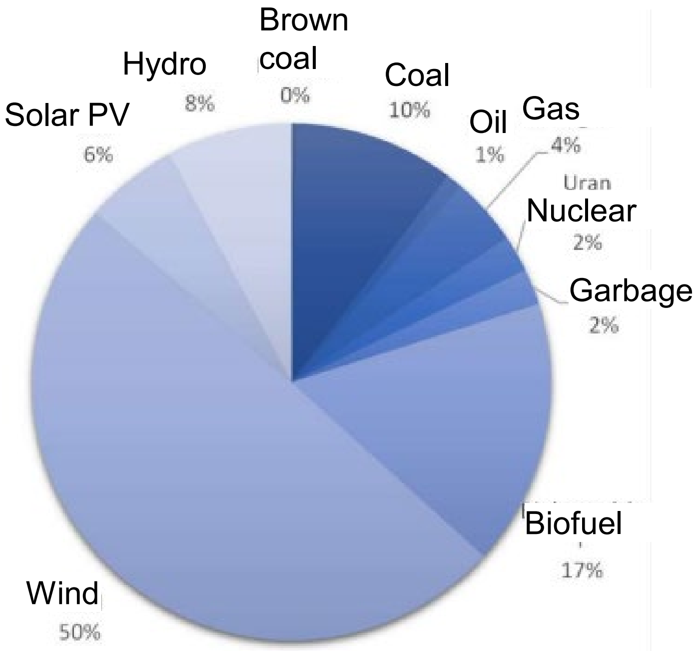
World Green scenario to violate GPW planetary boundary by 110 % in 2050

Region scaled to planet emission : Denmark

	A	B	C	D
1	**Denmark scaled to world**	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$
2			[%]	[%]
3	Hard coal	PC, without CCS	30,0	30,0
4	Hard coal	IGCC, without CCS	0,0	0,0
5	Hard coal	SC, without CCS	0,0	0,0
6	Natural gas	NGCC, without CCS	4,0	4,0
7	Hard coal	PC, with CCS	0,0	0,0
8	Hard coal	IGCC, with CCS	0,0	0,0
9	Hard coal	SC, with CCS	0,0	0,0
10	Natural gas	NGCC, with CCS	0,0	0,0
11	Hydro	660 MW	8,0	8,0
12	Hydro	360 MW	0,0	0,0
13	Nuclear	average	2,0	2,0
14	Concentrated Solar Power (CSP)	tower	0,0	0,0
15	Concentrated Solar Power (CSP)	trough	0,0	0,0
16	Photo Voltaic (PV)	poly-Si, ground-mounted	6,0	6,0
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0,0	0,0
18	Photo Voltaic (PV)	CdTe, ground-mounted	0,0	0,0
19	Photo Voltaic (PV)	CdTe, roof-mounted	0,0	0,0
20	Photo Voltaic (PV)	CIGS, ground-mounted	0,0	0,0
21	Photo Voltaic (PV)	CIGS, roof-mounted	0,0	0,0
22	Wind	onshore	27,5	27,5
23	Wind	offshore, concrete foundation	0,0	0,0
24	Wind	offshore, steel foundation	22,5	22,5
25	Total		100,0	100,0
26				

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

Electricity production : Denmark in 2022

Population of region : Denmark

Population of World

Equivalent World electricity production

	A	B	C	D	E	F	G	H
27	Start & End year		2023	2050				
28	Start & End production [kWh/year]	Denmark	3,55E+10	7,10E+10				
29	Start & End region population [Citicenz]	Denmark	5,90E+06	6,E+06				
30	Start & End world population [Citicenz]	World	8,00E+09	8,E+09				
31	Start & End equivalent World production [kWh/year]	Equivalent world	4,81E+13	9,63E+13				
32								
33	**LCA impacts**	Unit	Start year	End year	Climate change biogenic	Climate change fossil	Climate change land use and land use change	Climate change Total
34	Unit				[kg CO2-Eq / kWh]	[kg CO2-Eq/ kWh]	[kg CO2-Eq/kWh]	[kg CO2-Eq/kWh]
35	Impact at start per kWh		2023		5,84E-05	3,44E-01	8,26E-05	3,44E-01
36	Impact at end per kWh			2050	5,84E-05	3,44E-01	8,26E-05	3,44E-01
37	Unit				[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]	[kg CO2-Eq]
38	Absolute impact at start of production of region		2023		2,07E+06	1,22E+10	2,93E+06	1,22E+10
39	Absolute impact at end of production og region			2050	4,15E+06	2,44E+10	5,87E+06	2,44E+10
40	Absolute impact at start of production eq. World		2023		2,81E+09	1,65E+13	3,98E+09	1,66E+13
41	Absolute impact at end of production eq. World			2050	5,62E+09	3,31E+13	7,95E+09	3,31E+13
42								
43	**Green house Gas emissions**	**Scenario:**	Denmark 2 x electricity in 2050					Climate change Total
44	Region emission start	[Gt CO2e]						1,22E-02
45	Region emission end	[Gt CO2e]						2,44E-02
46	Equavalent world emssion of Region start	[Gt CO2e]						1,66E+01
47	Equavalent world emssion of Region end	[Gt CO2e]						3,31E+01
48	GHG start fraction of UN 1.5 Degree	[%]						39
49	GHG end fraction of UN 1.5 Degree	[%]						385
50								

Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

Denmark scenario scaled to World production to violate GPW planetary boundary by 385 % in 2050

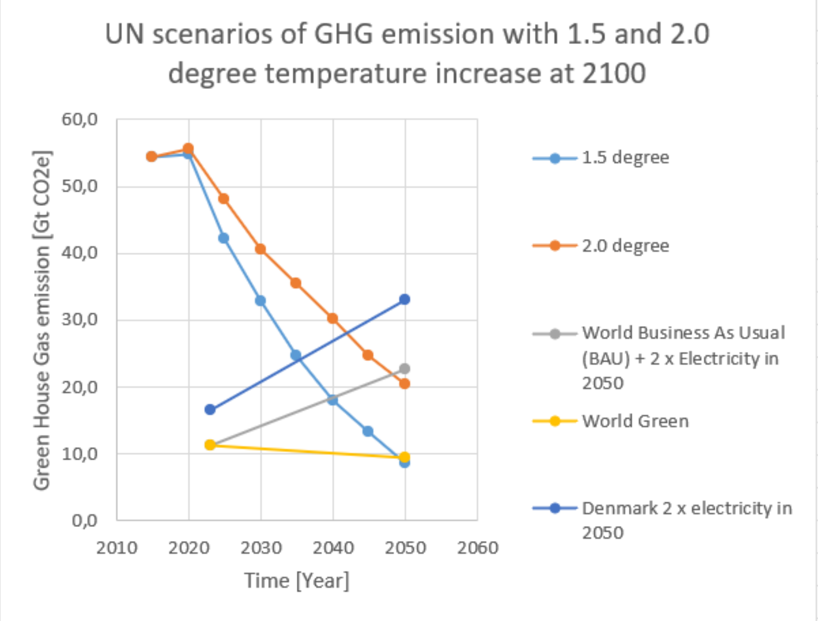
This scenario used the electricity production of Denmark.

Comparison to planetary boundary given by the Paris Agreement of scenarios

UN Green House Gas (GHG) emission scenarios

Year	1.5 degree [Gt CO2e]	2.0 degree [Gt CO2e]		Year	World Business As Usual (BAU [Gt CO2e]	World Green [Gt CO2e]	Denmark 2 x electricity in 2050 [Gt CO2e]
2015	54,4	54,4		2023	1,13E+01	1,13E+01	1,66E+01
2020	54,7	55,5		2050	2,26E+01	9,47E+00	3,31E+01
2025	42,2	48,1					
2030	32,8	40,7					
2035	24,6	35,6					
2040	18,0	30,1					
2045	13,3	24,6					
2050	8,6	20,3					

Source : UN Emission Gap Report 2022
https://www.unep.org/resources/emissions-gap-report-2022



Planetary boundary of Global Warming Potential

Table 14 UN LCA World BAU | Table 14 UN LCA World Green | Table 14 UN LCA Denmark | UN GHG scenarios

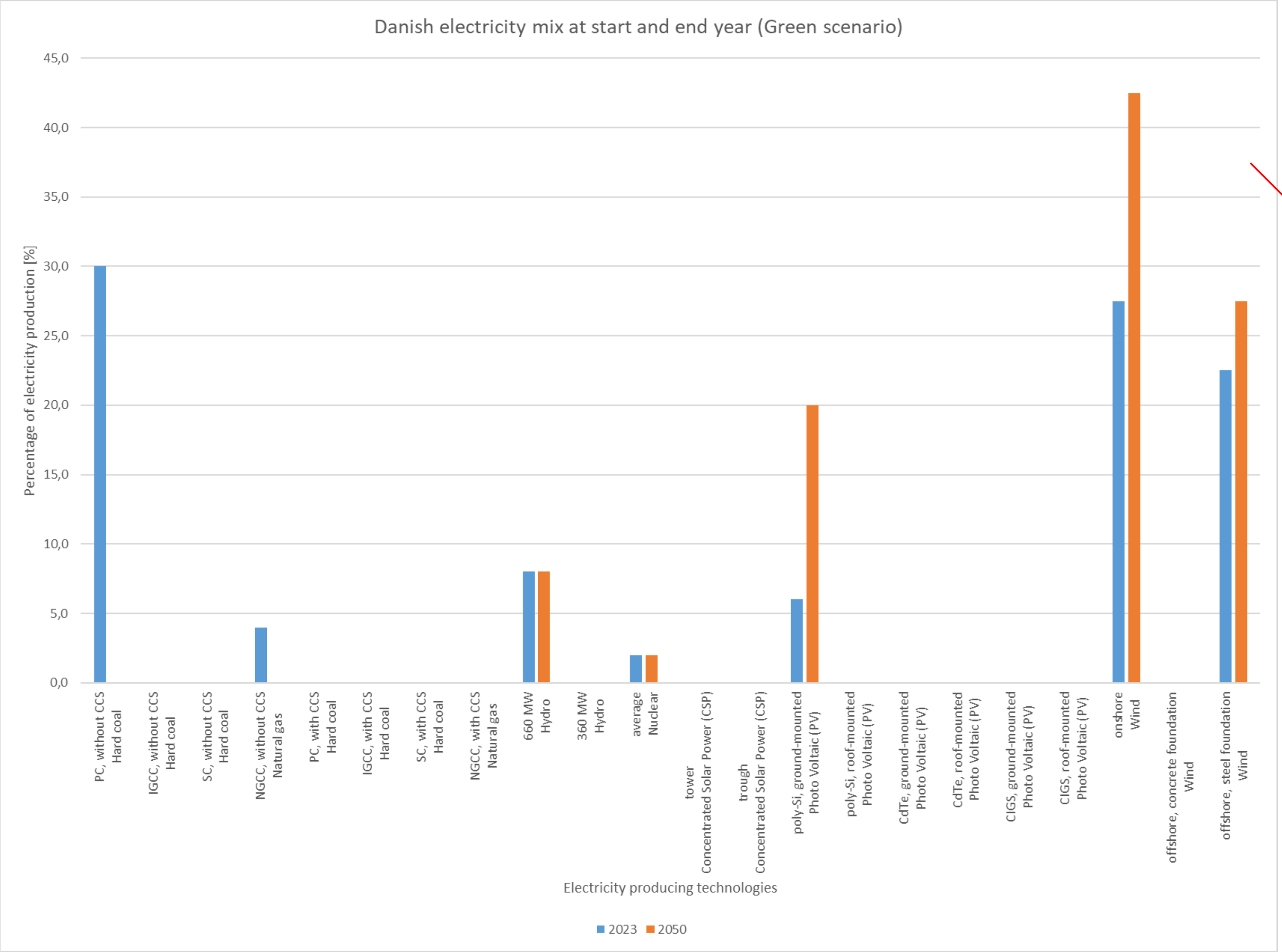
Rather large changes of the electricity systems are needed to comply with GPW planetary boundary in 2050 !

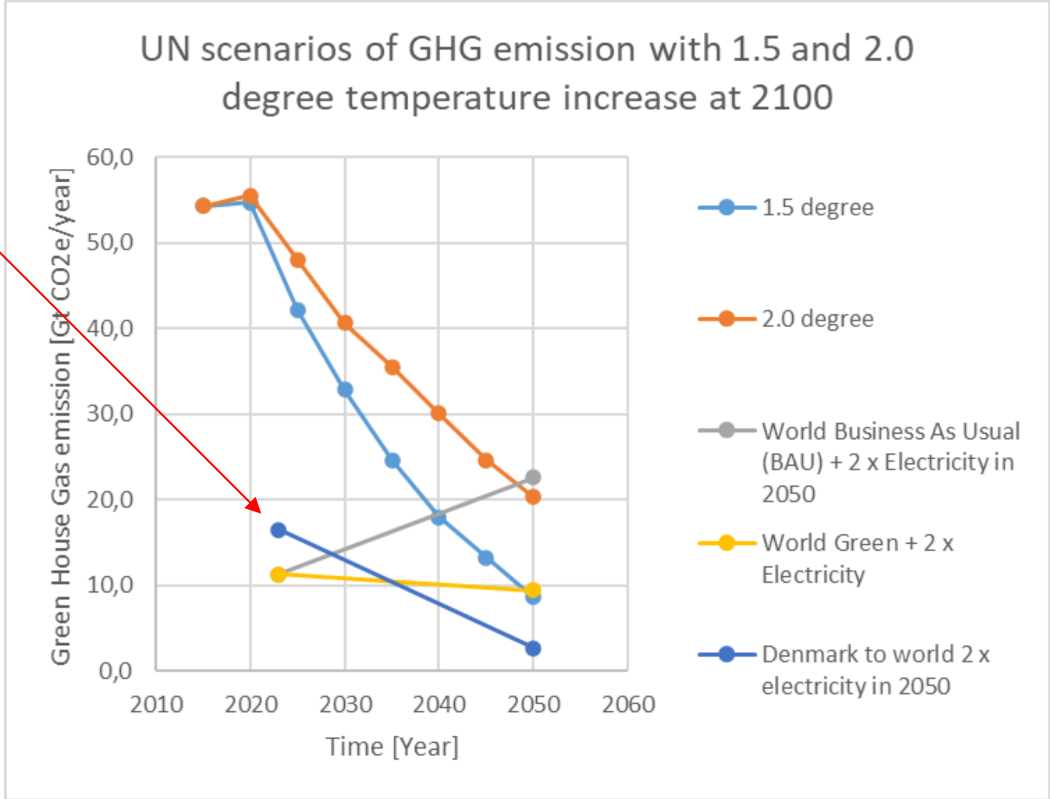
Exercise for all students

- 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?

Result example of green Denmark scaled to planet impact





Scaling up the usage of known renewable electricity producing technologies will help to comply with the Paris agreement in 2050. However the emissions of the Danish scenario above is ~ 28 g CO_{2e} / kWh and is expected to level out at around 5-20 g CO_{2e} / kWh. Thus low carbon material manufacturing will be needed after 2050.

Learning objectives of decarbonizing the energy system

The student should be able to

- **Describe** the main electricity generating technologies used around the world
- **Explain** the origin of CO_2 emissions from electricity producing units
- **Describe** the typical technology mix used for electricity production in different countries

- **Estimate** the resulting CO_2 emission of the electricity mix when producing 1 kWh of electricity

- **Discuss** the expected future CO_2 emission of electricity production and propose strategies of decarbonizing the electricity system
- **Discuss** which additional technologies that might be needed in the electricity system

- **Analyse** expected CO_2 emissions from a specific country or region and
  compare the Global Warming Potential with the UN CO_2 emission scenarios.

- **Evaluate** if the planetary CO_2 boundary is violated by the electricity generation ?

MILJØREDEGØRELSE 2022

Årlig redegørelse for drivhusgasudledninger fra det danske elforbrug og -produktion samt prognose for drivhusgasudledninger fra dansk elproduktion for 2023-2032

Dok. 23/06461-1 Offentlig/Public - Juni 2023

ELSEKTORENS MILJØPÅVIRKNING

Energinet udgiver Miljøredegørelse 2022, en årlig redegørelse for drivhusgasudledninger fra det danske elforbrug samt prognose for drivhusgasudledninger fra dansk elproduktion for 2023-2032. Miljøredegørelsen består af:

- National deklaration
- Miljødeklarationen
- Eldeklarationen
- Miljøberetningen.

National-, Miljø-, og Eldeklarationerne beskriver brændselsfordelingen og de tilhørende miljøpåvirkninger ved forbruget af 1 kWh el i Danmark for 2022 ud fra forskellige antagelser og formål.

Miljødeklaration er en med time-for-time-opgørelse af leveret strøm via elnettet. National deklaration er en samlet målestok for den grønne omstilling med nationale briller. Eldeklarationen (generel deklaration) er en finansiel deklaration baseret på køb og salg af certifikater.

Miljøberetningen beskriver brændselsfordeling og dertilhørende miljøpåvirkninger ud fra dansk elproduktion. Miljøberetningen forholder sig desuden til elsystemets udvikling de næste 10 år, både med hensyn til den generelle udvikling på produktionssiden i elsystemet og tilhørende miljøpåvirkninger og drivhusgasemissioner.

Yderligere information om deklarationerne kan findes på https://energinet.dk/el/gron-el/eldeklarationer/hvor-kommer-strommen-fra/.

Miljøredegørelsen udgives årligt af Energinet og kan findes på https://energinet.dk/Om-publikationer/Publikationer/Miljoeredegoerelse-2022.

LÆSEVEJLEDNING

Miljøredegørelsen 2022 er en samling af Miljø-beretningen og deklarationerne for dansk elforbrug. Miljøredegørelsen er derfor ét samlet produkt, som redegør for miljøpåvirkningerne af det danske elforbrug og -produktion.

Rapporten begynder med Miljøberetning 2022 og efterfølges af National-, Miljø- og Eldeklarationerne 2022. En kort oversigt over de forskellige produkter kan læses i boksene til højre og herunder.

MILJØBERETNING 2022

Miljøberetningen redegør for miljøpåvirkninger i forbindelse med dansk el- og kraftvarmeproduktion i det forgangne år. Dertil indeholder den en tiårig prognose for den forventede udvikling i den samlede danske elsektor samt de tilhørende miljøpåvirkninger.

Miljøberetningen giver desuden et overblik over udviklingen af CO_2-intensiteten ved produktion af 1 kWh el.

NATIONAL DEKLARATION 2022

National deklarationen angiver brændselsfordelingen samt de tilhørende miljøpåvirkninger ved forbrug af 1 kWh el i det forgangne år og er således en god indikator for den grønne omstilling af elsystemet i Danmark.

National deklarationen giver et billede af den teoretiske selvforsyningsgrad, hvor dansk elproduktion og forbrug balanceres time for time, korrigeret for handel med nabolande og nettab.

MILJØDEKLARATION 2022

Miljødeklarationen bruges til bestemmelse af den reelle sammensætning af el i stikkontakten på timebasis opdelt i Danmarks to prisområder: Øst- og Vestdanmark. Her bruges en bruttomodel, det vil sige, at dansk forbrug dækkes af dansk elproduktion og et miks af importeret el i en given time.

Miljødeklarationen kan give incitament til at flytte forbrug til timer med grøn strøm, da en individuel emissionsfaktor baseret på timeforbrug og lokation kan udregnes.

ELDEKLARATION 2022

Eldeklarationen anvendes i forbindelse med udregning af den finansielt leverede el i Danmark. Den generelle eldeklaration viser brændselsfordelingen samt tilhørende miljøpåvirkninger ved almindelig salg af el i Danmark, korrigeret for elsalg til kunder som har købt individuelt deklareret el fx grøn strøm-certifikater.

Den individuelle eldeklaration, der benyttes ved forbrug af certifikatudstedt el, opgøres af elhandlere. Find information om den individuelle eldeklaration her.

ANVENDT REGNSKABSPRAKSIS

Anvendt regnskabspraksis forklarer metodebrug for, hvordan National- og Eldeklaration er udarbejdet for 2022.

Anvendt regnskabspraksis giver desuden et overblik over anvendte kontroller og validering, som sikrer, at datagrundlag og analyse er kvalitetssikret og implementeret korrekt.

Anvendt regnskabspraksis kan findes her

MILJØBERETNING 2022

MILJØBERETNING 2022

Energinet redegør i overensstemmelse med Lov om elforsyning (LBK nr. 984 af 12. maj 2021) for de væsentligste miljøforhold fra dansk el- og kraftvarmeproduktion.

Miljøberetning 2022 indeholder de lovpligtige beskrivelser:

- Statusopgørelse for miljøpåvirkninger fra dansk elproduktion i 2022.
- Prognose 2023-2032 for elproduktion, brændselsforbrug og emissioner til luften*.

Statusopgørelsen for 2022 i miljøberetningen er baseret på miljødeklarationen for el i 2022. Prognosen for årene frem til 2032 er baseret på modelberegninger foretaget i Energinets markedsmodel, SIFRE, som i detaljer simulerer det danske el- og varmesystem.

Data til modelberegninger stammer fra Energistyrelsens Analyseforudsætninger til Energinet 2022 (AF22).

For en yderligere beskrivelse af datagrundlag bag Miljøberetning 2022, herunder Energistyrelsens Analyseforudsætninger til Energinet 2022, henvises til selvstændige dokumenter på hjemmesiden: www.energinet.dk.

*For baggrundsdata for miljøberetningen henvises til https://energinet.dk/Om-publikationer/Publikationer/Miljoeredegoerelse-2022.

SAMMENFATNING

I 2022 steg Danmarks samlede elproduktion til 33 TWh. Det er grøn el, det vil sige vind- og solkraft, som primært har sikret forøgelsen i den danske elproduktion. Derfor ses der et fald i CO_2-udledningen, som i 2022 er faldet med ca. 7 pct. sammenlignet med 2021, til 5,9 mio. ton CO_2.

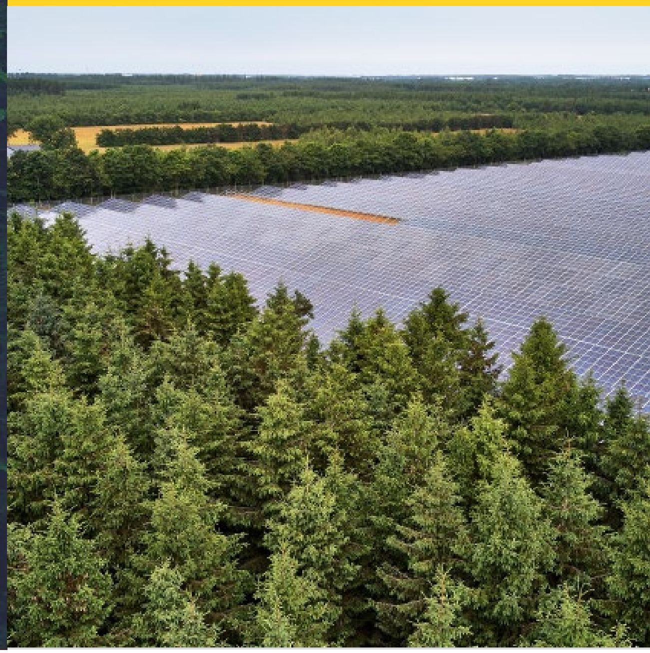
I 2022 er det danske bruttoelforbrug faldet 3 pct. sammenlignet med 2021. Forbruget af kul og affald er uændret, mens forbruget af gas og biobrændsler er faldet. Det bevirker også, at andre luftemissioner og restprodukter fra forbrænding er faldet i større eller mindre grad i 2022. CO_2-udledningen forventes at fortsætte en generel nedadgående tendens den næste tiårige periode.

Samtidig med at den samlede danske elproduktion er steget, er det danske elforbrug faldet i 2022 til 35,6 TWh, hvilket medfører, at nettoimporten er faldet i 2022 sammenlignet med året før. Det forventes, at Danmark i højere grad kan være eksportør af grøn energi efter 2030, ud fra en forventning om, at Danmark vil producerer mere el, end vi forbruger på årsniveau.

SOL OG VIND

Den samlede produktion fra sol og vind er vokset fra 17,3 TWh i 2021 til 21,2 TWh i 2022. I 2022 var sol og vind i stand til at dække ca. 60 pct. af det danske elforbrug.

Produktion af sol steg med 70 pct. i 2022 i forhold til året før, ligesom udbygningen af nye solcelleparker er vokset. Det er dog fortsat vind, som producerer mest el, nemlig 19 TWh i 2022.



TERMISK PRODUKTION

Produktion på termiske el- og kraftvarmeværker er faldet i 2022. Centrale værkers elproduktion er faldet med ca. 20 pct. i 2022 i forhold til 2021. Forbruget af biobrændsler er faldet og udgjorde i 2022 47 pct. af brændselsforbruget til el- og kraftvarmeproduktion.

ELKAPACITET, - PRODUKTION OG FORBRUG I DANMARK

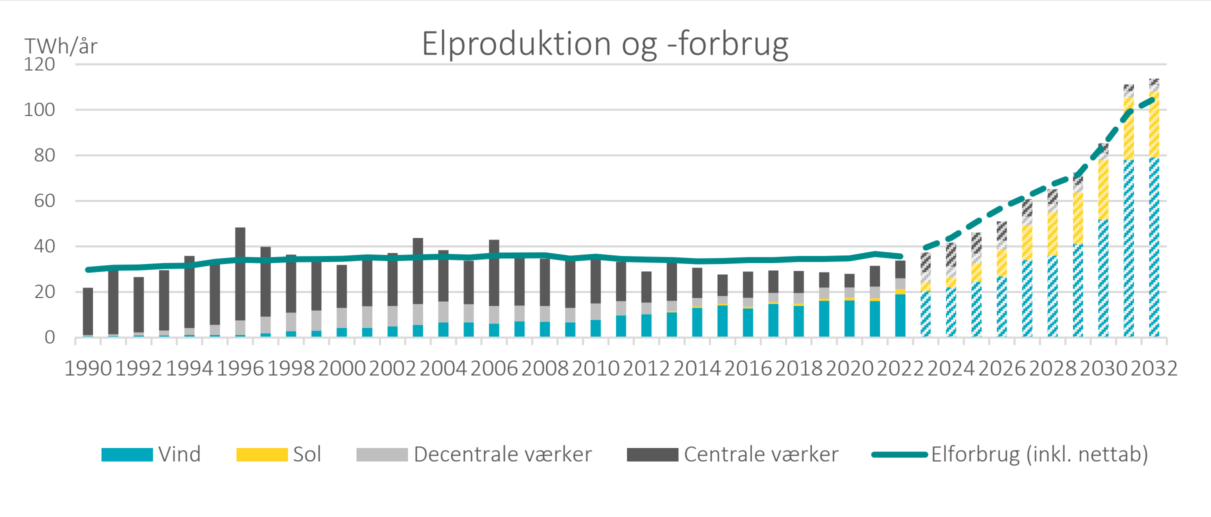
Figuren herunder viser udviklingen i den danske elproduktion og bruttoelforbruget historisk og fremskrevet. Figuren viser, at elforbruget er faldet i 2022 til 35,6 TWh/år. Det forventes, at elproduktion vil stige de kommende 10 år. Dette tilskrives især udbygning med sol og vind, mens elproduktion fra termiske værker forventes at falde. Det forventede forbrug forventes dog også at stige på grund af et øget elforbrug fra nye forbrugere såsom Power-to-X-anlæg, elkedler og varmepumper til fjernvarme.

Tabel 1.1 viser en række nøgletal for elproduktionen i Danmark, og hvordan disse har udviklet sig fra 2021 til 2022. Her fremgår det, den danske elproduktion er steget, mens det danske elforbrug er faldet. Samlet set medførte det, at den danske nettoimport af el faldt med 68,7 pct. Udviklingen i elproduktionen og nettoimporten kan især tilskrives høje energipriser i Europa samt danskernes ændring i forbrugsvaner.

Tabel 1.2 viser udviklingen i installeret eleffekt opdelt efter anlægstype. Ændringen på 295 MW i de centrale værkers eleffekt skyldes, at Kyndbyværket Blok 21 og Studstrupværket Blok 4, som ellers begge var godkendt til konservering, er midlertidig driftsklare frem til sommeren 2024. Dette er en ekstraordinær foranstaltning, som skal sikre dansk og europæisk forsyningssikkerhed under de store omvæltninger i det europæiske energisystem, som har fundet sted.

I løbet af 2022 er der registreret 1.368 MW sol i systemet og 171 MW yderligere vind. I samme periode er der lukket 19 MW decentrale termiske anlæg. Det giver samlet set en forøgelse i den installerede eleffekt på 1.815 MW i 2022, hvor installerede solcelleanlæg står for 75 pct. af ny installeret eleffekt.

*Data til modelberegninger for prognose stammer fra AF22



Tabel 1.1: Nøgletal for elproduktionen i Danmark	2021	2022	Ændring
	GWh	GWh	%
Nettoelproduktion	31.905	34.098	6,9%
Nettoimport	4.859	1.523	-68,7%
Elforbrug (inklusiv nettab)	36.764	35.621	-3,1%
Opdeling af elproduktion	GWh	GWh	%
El fra centrale værker	9.999	7.798	-22,0%
El fra decentrale værker	4.552	4.772	4,8%
El fra vindmøller	16.029	19.024	18,7%
El fra solceller	1.309	2.203	68,3%
El fra vandkraft	16	15	-6,3%

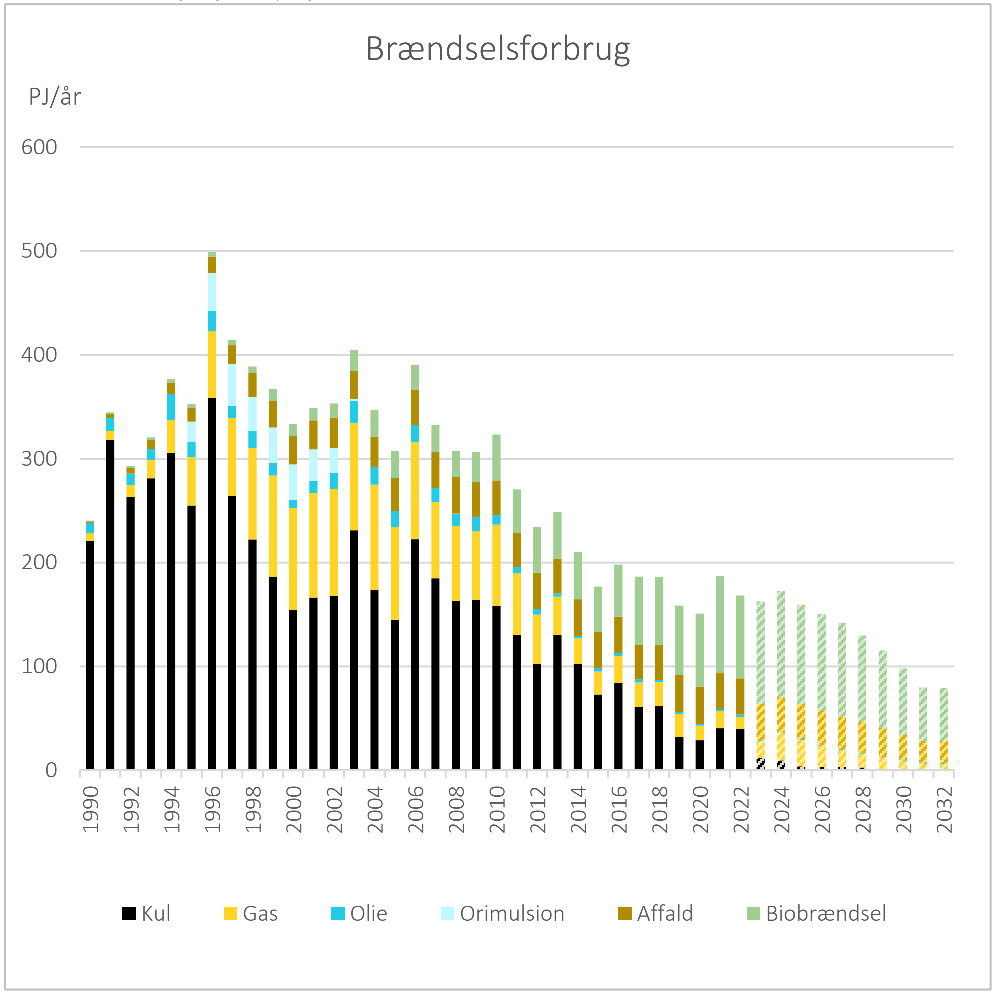
Tabel 1.2: Eleffekt opdelt efter anlægstype, installeret	Primo 2022	Ultimo 2022	Ændring
	MW	MW	MW
Vind	6.997	7.168	171
Sol	1.824	3.192	1.368
Vand	7	7	0
Centrale værker	3.538	3.833	295
Decentrale værker	2.320	2.302	-19
Total	14.686	16.501	1.815

Kilde: Energiproducenttælling (EPT) og Energinets Energi Data Service.

BRÆNDSELSFORBRUG

Brændselsforbruget til dansk el- og kraftvarmeproduktion i 2022 bærer præg af den europæiske energisituation og afspejler også, at der generelt er installeret mere VE i Danmark. Gasforbruget og forbruget af biobrændsler er faldet, mens forbruget af affald og kul er på ca. samme niveau som i 2021. Brændselsforbruget til dansk el- og kraftvarmeproduktion fra 1990 til 2032 fremgår af nedenstående figur, hvor de ikkeskraverede søjler viser det historiske brændselsforbrug, og de skraverede søjler angiver prognosen for de næstkommende 10 år baseret på modelberegninger.

*Data til modelberegninger for prognose stammer fra AF22



FORHØJET OLIEFORBRUG I 2022

Forbruget af olie er steget til 2,3 PJ, svarende til en stigning på 67 pct. i 2022 i forhold til året før. Forbruget af olie udgør dog stadig kun ca. 1 pct af det samlede brændselsforbrug til dansk el- og kraftvarmeproduktion i 2022.

Det forventes, at forbruget af olie falder til ca. 0,7 PJ i 2032. Til sammenligning forventes kul helt at udfases fra 2029.

FORBRUG AF GAS UDFASES FORTSAT

Gasforbruget til de danske el- og kraftvarmeværker faldt i 2022 med 31 pct. i forhold til året før. Faldet skyldes primært energikrisens høje gaspriser som følge af stoppet af russisk gas. Det har medført besparelser og konverteringer til andre brændsler. Derudover udfases naturgas også gradvist i den danske el- og kraftvarmesektor over de næste 10 år.

FALD I FORBRUG AF BIOBRÆNDSLER

De seneste mange år er forbruget af biobrændsler steget. I år 2022 faldt det dog fra 93PJ til 80 PJ, et fald på mere end 10 pct. i forhold til året før.

I år 2022 udgjorde biobrændsel 47 pct. af det samlede brændselsforbrug til el- og kraftvarmeproduktion.

UÆNDRET AFFALDSFORBRUG

Affaldsforbruget til danske el- og kraftvarmeværker var i 2022 på 35 PJ, hvilket er samme niveau som de seneste tre år.

Forbrug af affald forventes at falde til 22 PJ i år 2032.

FALD I CO_2-UDLEDNINGEN

I 2022 blev der udledt 5.9 mio. ton CO_2 fra dansk el- og kraftvarmeproduktion, og den gennemsnitlige CO_2-intensitet var 119 g/kWh. Det er et fald for den gennemsnitlige CO_2-intensitet på 13 pct. sammenlignet med 2021.

CO_2-udledningen fra den danske el- og kraftvarmeproduktion har generelt fulgt en nedadgående trend historisk. Dette kan også aflæses i figuren til højre, der viser udledningen af CO_2 samt CO_2-intensiteten historisk og fremskrevet.

I 2021 steg elproduktionen fra termiske værker, hvilket medførte en stigning i CO_2-udledningen fra dansk el- og kraftvarmeproduktion. I 2022 er CO_2-udledningen samt CO_2-intensiteten faldet ca. 7 pct. til et niveau, der svarer til CO_2-intensiteten i 2019.

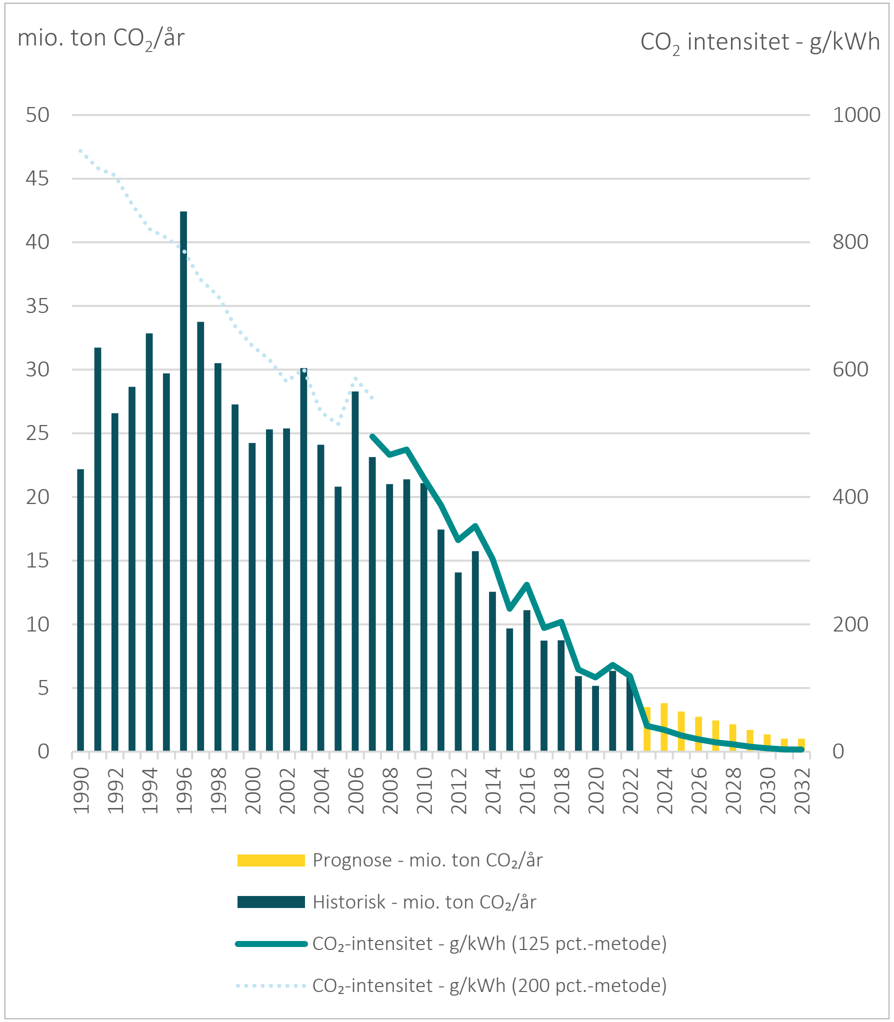
FALD I CO_2-UDLEDNINGEN PÅ LANGT SIGT

På langt sigt ventes CO_2-udledningen ligesom tidligere år at falde frem mod 2032. Prognosen, som ses til højre, viser, at CO_2-udledningen i 2032 forventes at falde til omkring 1,0 mio. ton, som primært stammer fra forbrug af gas. CO_2-intensiteten falder til 3,5 g/kWh i 2032.

Note til figur: Fra 2008 skiftede Miljøberetningen til 125 pct.-metoden for fordeling af brændselsforbruget og dermed miljøpåvirkningerne mellem el- og varmeproduktion på kraftvarmeværker.

*Data til modelberegninger for prognose stammer fra AF22

UDLEDNING AF CO_2 FRA EL- OG KRAFTVARMEPRODUKTION



ØVRIGE MILJØPÅVIRKNINGER FRA DANSK EL- OG KRAFTVARMEPRODUKTION

Øvrige miljøpåvirkninger fra el- og kraftvarmeproduktion inkluderer både øvrige udledninger til atmosfæren og diverse affaldsprodukter fra el- og kraftvarmeproduktionen i 2022. Figurerne nedenfor viser den historiske udvikling i udledning af luftemissioner og den fremskrevne prognose fra 2023-2032 baseret på modelberegninger. Fremskrivningen er vist med stiplede linjer.

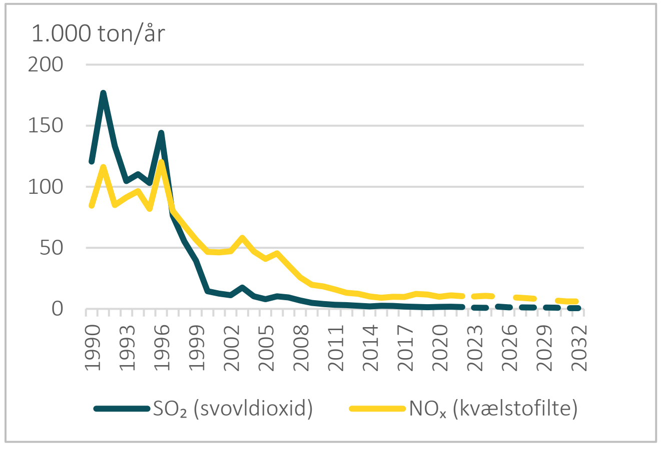
Figuren til venstre viser udledningen af svovldioxid (SO_2) og kvælstofilte (NO_x). Begge har primært været faldende i perioden fra 1990, og også i 2022 er udledning fra både svovldioxid og kvælstofilte faldet i forhold til året før. I 2022 var udledningen fra svolvdioxid og kvælstofilte helholdsvis 1,5 kton og 10,4 kton. Det forventes, at udledningerne fortsat vil reduceres i takt med et mere grønt elproduktionsmiks, og udledningerne fra svovldioxid og kvælstofilte vil ca. halveres i løbet af de næste 10 år.

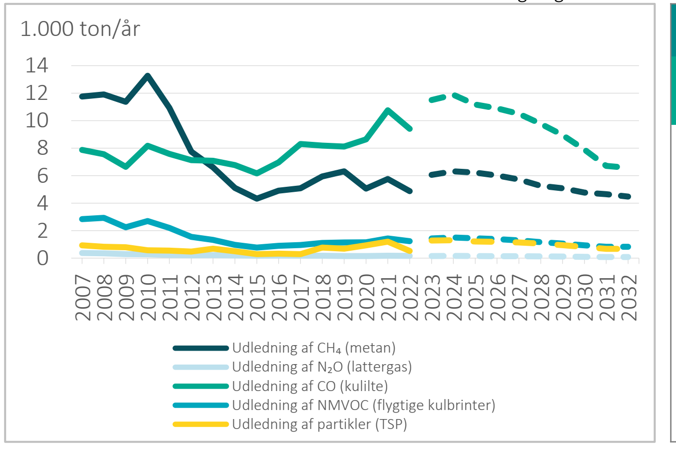
Figuren i midten viser en række øvrige luftemissioner; metan(CH_4), lattergas(N_2O), kulilte(CO), flygtige kulbrinter (NMVOC) og partikler (TSP). Fra 2007 til 2015 har der generelt været et fald i disse udledninger, men udviklingen er efterfølgende stagneret eller vendt. Dette skyldes især et større forbrug af biobrændsler i den danske el- og kraftvarmeproduktion, som generelt udleder flere af disse stoffer i forhold til brændslernes energiindhold.

Udledningen af samtlige øvrige luftemissioner er ligesom svovldioxid og kvælstofilte også faldet fra 2021 til 2022. I forhold til klimapåvirkning er det især værd at bemærke metan (CH_4) og lattergas (N_2O), som begge er stærke drivhusgasser. Set i et 100-årigt perspektiv, er drivhuseffekten af metan 28 gange værre end CO_2, mens lattergas er 265 gange værre end CO_2. I 2022 er metan-udledningerne faldet til 4,8 kton, et fald på ca. 15 pct. i forhold til året før. Udledninger vedrørende lattergas er i 2022 ca. 0,2 kton, hvilket er et niveau, der har været stabilt siden 2011. Prognosen for udledningerne af øvrige luftemissioner starter generelt på et højere niveau i 2023 sammenlignet med 2022 på grund af en forventning om højere brændselsforbrug af biobrændsler og gas, men over de næste 10 år ses dog fortsat et fald i samtlige udledninger.

I tabellen til højre kan det ses, at restprodukter i forbindelse med afbrænding af kul, det vil sige kulslagge, kulflyveaske og afsvovlingsprodukter, kun er faldet en anelse i 2022. Det skyldes, at kulforbruget til el- og kraftvarmeproduktion i 2022 kun var en anelse lavere end i 2022. Tilsvarende er mængden af bioaske faldet, da der i 2022 blev brugt mindre biobrændsel. Der er forbrændt ca. lige meget affald i 2021 og i 2022, hvilket forklarer, hvorfor der er udledt samme mængde slagge som år 2021 fra den danske el- og kraftvarme-produktion.

*Data til modelberegninger stammer fra AF22





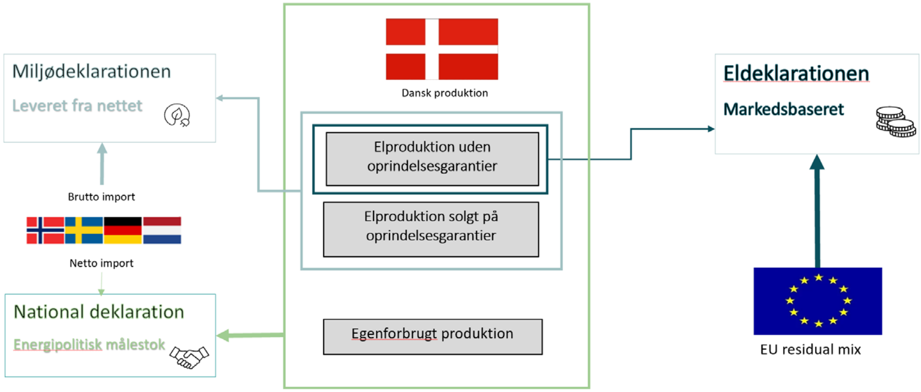
Nøgletal for Danmark	2019	2020	2021	2022
Restprodukter fra el- og kraftvarmeproduktion	Ton	Ton	Ton	Ton
Kulslagge	24.534	22.282	31.283	30.720
Kulflyveaske	142.545	129.461	181.758	178.488
Afsvovlingsprodukter	51.826	47.069	66.083	64.894
Bioaske	78.941	82.607	112.957	96.007
Slagge (Affaldsforbrænding)	614.167	618.447	600.514	600.229
RGA (Røggasaffald)	93.031	93.679	90.963	90.919

DEKLARATIONER PÅ FORBRUG 2022

DEKLARATIONER PÅ FORBRUG, 2022

En deklaration angiver i denne sammenhæng brændselsfordelingen samt de tilhørende miljøpåvirkninger ved forbrug af 1 kWh el. Energinet udsender tre deklarationer, der tjener hver sit formål. Fælles for deklarationer på forbrug er, at de på forskellige måder tager højde for udvekslingen med udlandet, og derfor ikke kun er baseret på dansk elproduktion. Fx indgår atomkraft derfor i alle tre deklarationer.

- **Miljødeklarationen** er en med time-for-time-opgørelse af leveret strøm via elnettet.
- **National deklaration** er en samlet målestok for den grønne omstilling med nationale briller.
- **Eldeklarationen** (generel deklaration) Finansiel deklaration baseret på køb og salg af certifikater.



ANVENDELSE I GRØNNE REGNSKABER

I helhold til GHG (Greenhouse Gas) protokollen beregnes CO_2-udledning både som "location based" (miljødeklarationen) og en "market based" (eldeklarationen).

Den nationale deklaration anvendes ikke til grønne regnskaber.

MILJØDEKLARATIONEN

Miljødeklarationen anvendes som deklaration af den el, der leveres fra stikkontakterne. I beregningerne ligestilles import med produktion, og derfor er deklarationen tættere på faktisk drift og tættere på vilkårene i elmarkedet. Egetforbrugt elproduktion er ikke inkluderet, da den ikke er leveret til nettet.

NATIONAL DEKLARATION

Den nationale deklaration er en målestok for den grønne omstilling af elsystemet, hvor dansk produktion holdes op imod dansk forbrug baseret på balancen hver time. National indpasning af VE indgår således i deklarationen, og der udveksles kun med udlandet i det omfang, der er nødvendigt.

Den nationale deklaration følger principper i den tidligere miljødeklaration.

ELDEKLARATIONEN

Eldeklarationen omhandler den finansielt leverede el. EU stiller krav om, at alle elkunder kan få oplyst en eldeklaration fra deres forsyningsselskab eller elhandler. I Danmark varetages dette krav med Elmærkningsbekendtgørelsen. Energinets eldeklaration omfatter den el, der ikke er dækket ind af oprindelsesgarantier.

NATIONAL DEKLARATION 2022

Den nye nationale deklaration følger beregningsprincipperne i den tidligere miljødeklaration, og laves udelukkende som et benchmark for hvor langt Danmark er kommet med den grønne omstilling af elsystemet.

I den nationale deklaration tilstræbes det at anvende dansk elproduktion i Danmark, og det opgøres time for time, i hvilken grad det er nødvendigt at importere og eksportere til udlandet for at opretholde balancen imellem forbrug og produktion.

Deklarationen kan ikke anvendes til grønne regnskaber, da den rummer produktion, der ikke er leveret til nettet.

I 2022 er elforbruget faldet i forhold til 2021, hvilket kan skyldes de meget høje elpriser i 2022. Elproduktion baseret på naturgas har haft en markant nedgang, hvorimod forbruget af olie er steget i både Danmark og igennem importen.

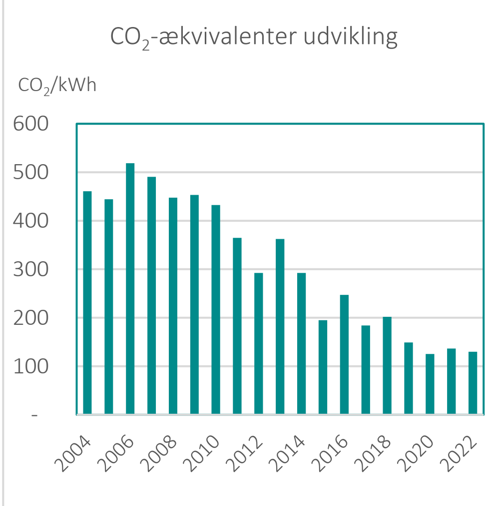
Kul udgør forsat en meget stor andel af den samlede elforsyning, særligt naturligvis i de timer, hvor vind og sol ikke producerer el. Kul udgør også den største andel af CO_2-udledningen fra elproduktionen.

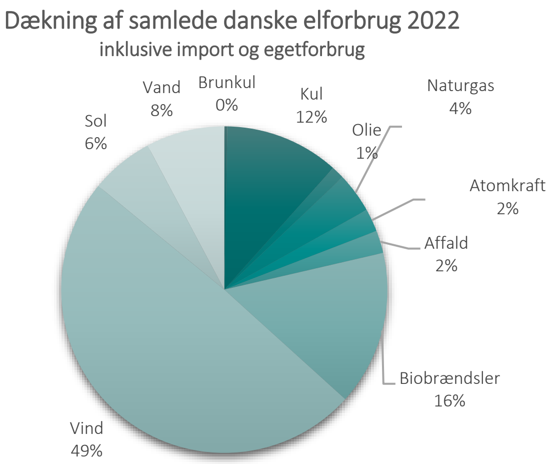
CO_2 på det samlede danske forbrug er igen faldende; fra 136 g/kWh i 2021 til 130 g/kWh i 2022.

	125 % metode	200 % metode
Emissioner på transmissionsniveau		
CO2, g/KWh	127	145
CH4 Metan	0.08	0.10
NO2 Lattergas	0.003	0.003
CO2-ækvivalenter i alt	*130*	*149*

	Co2 ækvivalenter
CH4	28
NO2	265

Diverse nøgletal	CO2/kWh 125%	VE andel
Dk nationalt forbrug	123.3	79%
Dk produktion	117.8	82%
Anvendt DK produktion	123.3	81%
Eksport	73.2	89%
Import	123.3	69%
Dansk VE produktion i forhold til dansk forbrug		78.6%





2022 opgørelse efter nettoudveksling (GWh)

		Dansk produktion			Dansk forbrug		
	Elproduktion fra Brændsler	**Leveret via net**	**Egetforbrug**	**I alt DK**	**Heraf anvendt i DK**	**Import**	**Dækning af forbrug i alt**
Ikke VE	Kul	4045	0	4045	3759	152	3911
Ikke VE	Olie	144	32	176	166	274	440
Ikke VE	Naturgas	1182	4	1186	1114	263	1376
Ikke VE	Uran (atomkraft)	0	0	0	0	784	784
Ikke VE	Brunkul	0	0	0	0	104	104
Ikke VE	Affald (ikke VE 45 %)	712	105	817	761	12	774
VE	Affald (VE 55 %)	871	128	998	930	15	946
VE	Biobrændsler	5.618	53	5.671	5.250	46	5.296
VE	Vind	19.024	-	19.024	16.350	666	17.016
VE	Sol	2.065	138	2.203	2.069	93	2.161
VE	Vand	15	-	15	14	2.681	2.695
	I alt	**33.676**	**458**	**34.134**	**30.413**	**5.090**	**35.503**
							Usikkerhed 0,2 %
CO2 indhold gram/kWh		116	215	118	123	123	123
VE andel		82%	69%	82%	81%	69%	79,2%

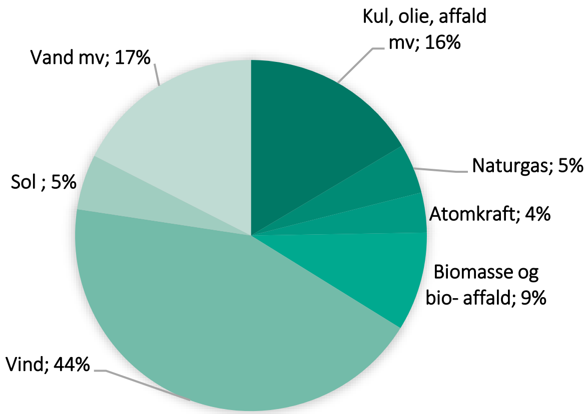
MILJØDEKLARATIONERNE 2022

Miljødeklaration udgives pr. time opdelt på Vestdanmark (DK1) og Østdanmark (DK2), og der er taget højde for udveksling over Storebælt. Værdierne vist her er gennemsnitsværdier vægtet efter forbruget i området. I miljødeklarationen sidestilles import med dansk produktion, og derfor fylder import relativt mere, end det er tilfældet i den nationale deklarationen. Det slår også igennem på fordelingen på brændsler, da fx atomkraft i 2022 dækker 11 pct. af forbruget i DK2 på grund af importen fra Sverige; hvorimod kul mv. dækker 16 pct. af forbruget i DK1 på grund af import fra Holland og Tyskland.

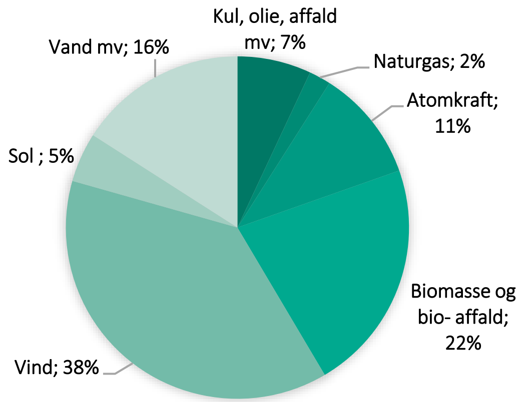
CO_2-indholdet i den leverede el varierer fra 12 til 544 g/kWh i DK1 og fra 15 til 328 g/kWh i DK2.

Det gennemsnitlige CO_2-indhold i DK2 for 2022 er næsten nede på det halve af DK1, 66,3 imod 148,5 g/kWh, hvilket primært skyldes den høje andel af kulkraft i DK1. Der produceres stort set ikke længere el, som er baseret på kul i DK2.

DÆKNING AF FORBRUG: JYLLAND OG FYN (DK1)



DÆKNING AF FORBRUG: SJÆLLAND, LOLLAND-FALSTER OG BORNHOLM (DK2)



Emissioner leveret til distribution, g/kWh		
	125 pct. metode	200 pct. metode
CO_2, g/KWh	148,5	162,5
CH4 Metan	0,07	0,09
N2O Lattergas	0,002	0,003
CO2-ækvivalenter i alt	151,1	165,7
Usikkerhed +- 1 gram/kWh		
Gennemsnitlig justering for tab i distribtution		4,2%

Emissioner leveret til distribution, g/kWh		
	125 pct. metode	200 pct. metode
CO_2, g/KWh	66.3	77.1
CH4		
Metan	0.04	0.05
N2O Lattergas	0.002	0.003
CO2-ækvivalenter i alt	68.1	79.3
Usikkerhed +- 1 gram/kWh		
Gennemsnitlig justering for tab i distribtution		4.3%

GENEREL ELDEKLARATION 2022

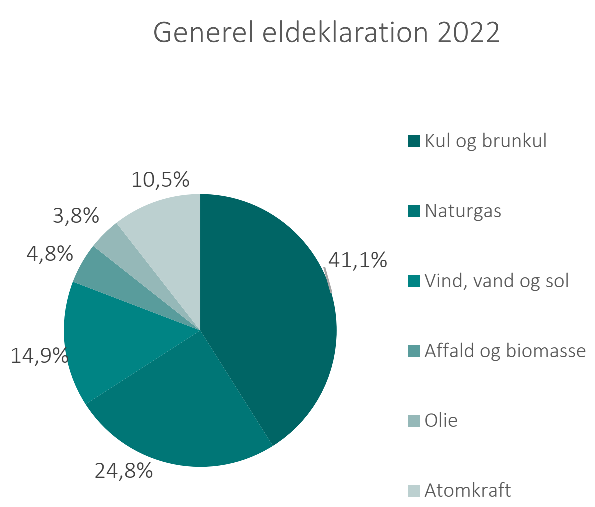
Ved opgørelsen af eldeklarationerne er fokus overvejende på køb og salg af oprindelsesgarantier og mindre på den nationale produktion. Eldeklarationerne har derfor ikke meget at gøre med det fysiske elsystem eller det fysiske flow af energi.

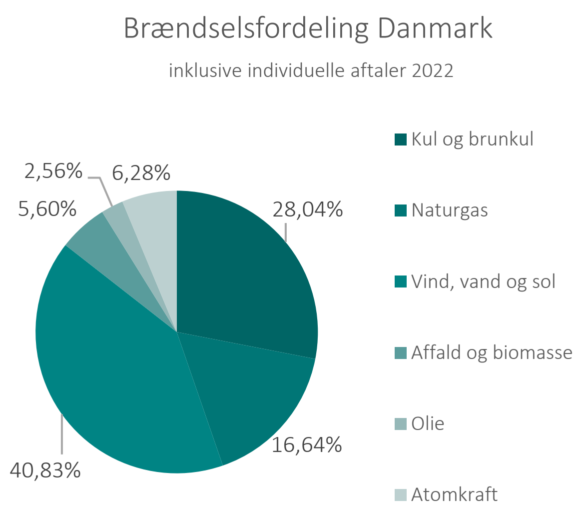
Der udstedes oprindelsesgarantier for 93 pct. (23,2 TWh) af den danske VE produktion, og denne del af den danske produktion er derved realt eksporteret og sat til salg igennem markedet for certifikater. Danske elhandlere har opkøbt 11,8 TWh, som er solgt til de danske elkunder i form af grøn strøm. Samlet set "mister" Danmark således 11,8 TWh grøn strøm igennem handlen med certifikater.

Den danske generelle eldeklaration består af 8,8 TWh dansk fortrinsvis fossil produktion (særligt kul og naturgas, som der ikke udstedes certifikater på), samt 14,4 TWh importeret igennem EU attribute mix, der består af overskudsproduktion fra andre EU-lande. Den generelle eldeklaration består af godt 62 pct. "importeret" strøm, og derfor udgør særligt kul en relativt stor andel.

Den samlede brændselsfordeling for Danmark er baseret på den samlede balance i køb og salg af oprindelsesgarantier. Den er således ikke begrænset af de fysiske forhold i elnettet og kan ikke sammenlignes med fysiske opgørelser af Danmarks elforsyning, fx National deklaration eller miljødeklarationerne.

Emissioner per kWh	Generel deklaration
Emissioner til luften	**g/kWh**
CO_2 (Kuldioxid - drivhusgas)	422
CH_4 (Metan - drivhusgas)	0,30
N_2O (Lattergas - drivhusgas)	0,005
Drivhusgasser (CO_2 ækv.)	432
SO_2 (Svovldioxid)	0,06
NO_x (Kvælstofilte)	0,33
CO (Kulilte)	0,11
NMVOC (Uforbrændte kulbrinte	0,06
Partikler	0,01
Restprodukter	
Kulflyveaske	14,6
Kulslagge	2,5
Afsvovlingsprodukter	5,3
Slagge (affaldsforbrænding)	3,7
RGA (røggasaffald)	0,6
Bioaske	0,04
Radioaktivt affald (mg)	0,3
MWh omfattet:	23.228.153





ORDLISTE

Analyseforudsætninger udarbejdes af Energistyrelsen årligt og angiver et sandsynligt udviklingsforløb for det danske el- og gassystem frem mod 2050

Biogas er en gas, hvis primære indhold er metan (CH_4) og kuldioxid (CO_2), som er dannet ud fra biologisk nedbrydning af eksempelvis gylle, rester af afgrøder og slagteriaffald. Regnes som CO_2-neutralt. **Opgraderet biogas/bionaturgas** er biogas, hvor kuldioxiden (CO_2) er fjernet eller beriget med brint, og der derfor kun er metan (CH_4) tilbage.

Biomasse er en fællesbetegnelse for halm og træ (træpiller eller træflis). Regnes som CO_2-neutralt, idet biomassen menes at have optaget den samme mængde CO_2 under vækst, som udledes under forbrændingen.

Biobrændsler bruges som samlebetegnelse for brændsler som biogas og biomasse, der regnes som CO_2-neutrale.

Brint/hydrogen (H_2) kan laves via elektrolyse og bruges i industrielle processer til opgradering af biogas eller til at fremstille syntetiske brændsler til eksempelvis tung transport. Se også opgraderet biogas .

Centrale kraftværker/kraftvarmeværker er kraftværker/kraftvarmeværker placeret på områder, der er udpeget som "centrale pladser". Har traditionelt været de største værker målt på eleffekt.

CO_2 (kuldioxid) dannes ved forbrænding af kulstofholdige brændsler. Både fossile brændsler som kul, naturgas og olie samt VE-brændsler indeholder kulstof og danner derfor CO_2 ved forbrænding. CO_2 fra VE brændsler regnes traditionelt som klimaneutrale.

CO_2-intensitet er et mål for hvor meget CO_2, der udledes ved en aktivitet i forhold til 'det der kommer ud af aktiviteten'. I Miljøredegørelsen måles CO_2-intensiteten i g/kWh.

Decentrale kraftværker/kraftvarmeværker er alle termiske værker, der ikke er definerede som centrale. Er ofte mindre (lavere eleffekt) i forhold til centrale værker.

Eleffekt og -kapacitet er et mål for den effekt eller kapacitet, som et kraftværk kan producere elektricitet med og måles i Watt (W). En produktion på 1 MW (megawatt) i en time vil resultere i produktionen af en MWh (megawatt time).

Elektrificering henviser til øget elproduktion og/eller forbrug som evt. fortrænger fossile eller biobaserede brændsler. Dette kan eks. ske ved installation af vindmøller eller varmepumper.

Emissioner/emissionsfaktor henviser til udledningen af stoffer og restprodukter til vand, jord, luft, deponi mm. Emissionsfaktoren er et nøgletal for disse udledninger.

Fossile brændsler er brændsler, som er baseret på organisk materiale, der har ligget i undergrunden i millioner af år. Eksempler er kul, olie og naturgas, men affald har også en del, der regnes som fossilt brændsel.

Nettab er det tab, som opstår, når elektricitet transporteres igennem elnettet, da den elektriske modstand i ledninger og kabler medfører, at en del af elektriciteten omdannes til varme. Nettabet er typisk 7-9 pct. fra producent til forbruger.

NO_x er en fællesbetegnelse for kvælstofoxiderne NO og NO_2, der begge er forsurende gasser (syreregn) og bidrager til smog-dannelse (fotokemisk ozondannelse i den nederste del af atmosfæren). NO_x dannes ved forbrændingen af brændsler på termiske værker.

Power-to-X/ PtX /P2X er en teknologi, der kan omdanne el til syntetiske brændsler, f.eks. brint via elektrolyse.

SO_2 kaldes svovldioxid og er en forsurende gas ligesom NO_x og kan derfor give anledning til syreregn. Forskellige brændselstyper har forskelligt indhold af svovl og giver derfor anledning til større eller mindre udledning af SO_2 .

Termisk/Termisk elproduktion er produktionen fra et traditionelt kraftværk/kraftvarmeværk, hvor afbrændingen af et brændsel opvarmer og fordamper vand i en kedel. Denne damp kan herefter omdannes til elektricitet ved hjælp af en turbine. Det resterende energiindhold kan eventuelt omdannes til varme (fjernvarme) ved hjælp af varmevekslere.

Tørår er år med meget lidt nedbør i Norge og Sverige, hvorfor vandmagasinerne ved vandkraftværkerne ikke bliver så fyldte. Dermed er det ikke muligt at producere så meget elektricitet baseret på vandkraft, hvilket får priserne på elektricitet til at stige. Se også vådår.

Varmevirkningsgrader (125 pct. eller 200 pct.) er relevante allokeringsmetoder til at udregne miljøudledninger ved samproduktion af el og varme. Beregningsopstilling ved 125 pct.-metoden:

$$Brændsel_{Varme}[GJ] = \frac{Produktion_{Varme}[GJ]}{125\%}$$

VE er en forkortelse for vedvarende energi. Eksempler er elektricitet produceret fra vindmøller og solceller eller traditionel termisk produktion baseret på biomasse.

Vindindeks er et mål for, hvor meget vindenergi der har været til rådighed i en given periode i forhold til normen, der indekseres med 100.

Vådår er år med meget nedbør i Norge og Sverige, hvilket betyder, at vandmagasinerne ved vandkraftværkerne fyldes helt op. Det er derfor muligt at producere meget elektricitet baseret på vandkraft, hvilket er med til at presse prisen ned på elektricitet.

Instruction of Exercise: Planetary boundary of Global Warming Potential of electricity mix

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Introduction

This document describes the instructions for the "Exercise: Planetary boundary of Global Warming Potential of electricity mix" of the course Quantitative Sustainability (12105&12106) and is conducted as part of the lecture "Module 11 - Energy systems and transition/decarbonization".

The exercise will allow the students of the course to explore the global warming potential or the CO_2 emissions resulting from an electricity system with a certain mix of electricity-producing technologies as specified in the recent UN report "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Source" (2021). The CO_2 emissions are first calculated with the present electricity mix of the world and then also for a future 2050 scenario, where the demand for electricity is expected to double, because the heating of houses and transportation are expected to be supplied by electricity instead of fossil fuels. The global CO_2 emissions are estimated from the electricity demand and mix of the planet and are then compared to the planetary boundary of CO_2 emissions of the Paris Agreement of 1.5 degree global warming. The students are then asked to propose a future electricity mix of the world that will not violate the planetary boundary of the CO_2 emission corresponding to the 1.5 degree global warming at the end of the century.

Preparation for the exercise:

1) Download the Excel sheet "PlanetaryCO2Boundary_ElectricityTechnologyMix_v3_Abrahamsen" of the exercise of the module "Module 11 - Energy systems and transition/decarbonization" to your personal computer (see figure 1 for example).
2) Check that the Excel sheet is working by changing the electricity mix percentage of the "World Business As Usual(BAU)" sub-sheet and see if the global emissions result plot is changing in the "UN GHG scenarios" sub-sheet.
3) The third video or the slides of the "Module 11 - Energy systems and transition/decarbonization" show how to use the Excel sheet. The first video and slides explain the input data of the Excel sheet.

Activities in class

1) The exercise is best performed in a group, where the students can discuss the results. The groups will be asked to present their proposal on a future electricity mix at the end of the lecture.
2) Visit the web-page “Our world in data” (https://ourworldindata.org/) and find the menu “Energy” and then “Electricity Mix” (https://ourworldindata.org/electricity-mix). Scroll down and find the plot “Share of electricity production by source, World”.
3) Discuss what has happened to the electricity mix over the last two years of the graph.
4) Check if the Excel sheet should be updated on the current electricity mix. This should be done in all sheets of the world.
5) The sub-sheet “Table 14 UN LCA World BAU” will now show the electricity mix and the resulting global CO_2 emission for 2050 when using the “Business As Usual (BAU)” scenario, where the electricity demand in 2050 is doubled. Discuss if you agree with the global CO_2 emission in 2050.
6) The sub-sheet “UN GHG scenarios” shows the resulting CO_2 emissions now and in 2050 for the “World Business As Usual(BAU)” as the gray line on the plot and you have to evaluate if this is violating the planetary boundary of CO_2 emission in order to comply with a 1.5 degree global warming by the end of the century”. Is the planetary CO_2 boundary violated?
7) The sub-sheet “Table 14 UN LCA World Green” is showing a scenario of the world going green and you can now specify the student proposal of the electricity mix of the green world in 2050 in this sheet. Discuss if you agree with the global CO_2 emission and look at the results plot on the sub-sheet “UN GHG scenarios”. The first proposal on making the world greener is to decrease the amount of coal used for making electricity and increase the amount of onshore wind. The results is shown as the results plot as the yellow curve called “world green + 2 x Electricity”.
8) The students can now discuss in the groups how you will propose to change the electricity system with a lower CO_2 emission and then to check if the planetary boundary of CO_2 emission for a 1.5 degree global warming target is violated by entering your proposal in the sub-sheet “Table 14 UN LCA World Green”. Try out different proposals and create a finite proposal of the group. Make a screen shot of the electricity mix table and of the result plot and be ready to show and explain your proposal in the discussion session of the exercise.

After the session then the student are encouraged to take a look at the “Self-assessment quiz of the Decarbonizing the Energy System module” in the module in order to examine if the learning objectives have been obtained. The solutions to the quiz questions are provided at the end of the document.

Voluntary task of the exercise

If time allows, then you can also investigate what CO_2 emissions, that will result from all the people of the planet living like the Danes. This question is investigated using the sub-sheet “Table 14 UN LCA Denmark”:

1) The second part of the exercise is to investigate the electricity mix of the Danish electricity system as shown in the sub-sheet “Table 14 UN LCA Denmark”. The initial input electricity mix is copied to

2050 and the electricity demand of 2050 is also assumed to be doubled by 2050 due to electrification. In the result plot "UN GHG scenarios" then the blue line is showing emission if the world lives like the Danes. Do you agree with the emission numbers?

2) The student groups can now propose a future version of the Danish electricity mix and investigate if that will violate the planetary boundary of CO_2 emission according to the 1.5 degree Paris Agreement. The groups can discuss the Danish analysis with the TA during the session.

1	**World Green**	Type	Electricity mix start $f_{s,i}$	Electricity mix end $f_{e,i}$
2			[%]	[%]
3	Hard coal	PC, without CCS	39	10
4	Hard coal	IGCC, without CCS	0	0
5	Hard coal	SC, without CCS	0	0
6	Natural gas	NGCC, without CCS	23	23
7	Hard coal	PC, with CCS	0	0
8	Hard coal	IGCC, with CCS	0	0
9	Hard coal	SC, with CCS	0	0
10	Natural gas	NGCC, with CCS	0	0
11	Hydro	660 MW	0	0
12	Hydro	360 MW	15	15
13	Nuclear	average	9	9
14	Concentrated Solar Power (CSP)	tower	1	1
15	Concentrated Solar Power (CSP)	trough	0	0
16	Photo Voltaic (PV)	poly-Si, ground-mounted	5	5
17	Photo Voltaic (PV)	poly-Si, roof-mounted	0	0
18	Photo Voltaic (PV)	CdTe, ground-mounted	0	0
19	Photo Voltaic (PV)	CdTe, roof-mounted	0	0
20	Photo Voltaic (PV)	CIGS, ground-mounted	0	0
21	Photo Voltaic (PV)	CIGS, roof-mounted	0	0
22	Wind	onshore	7	36
23	Wind	offshore, concrete foundation	0	0
24	Wind	offshore, steel foundation	1	1
25	Total		100	100
26				
27	Start & End year		2023	2050
28	Start & End production [kWh/year]	World	2,25E+13	4,50E+13
29	Start & End population [Citicenz]	World	8,00E+09	8,E+09

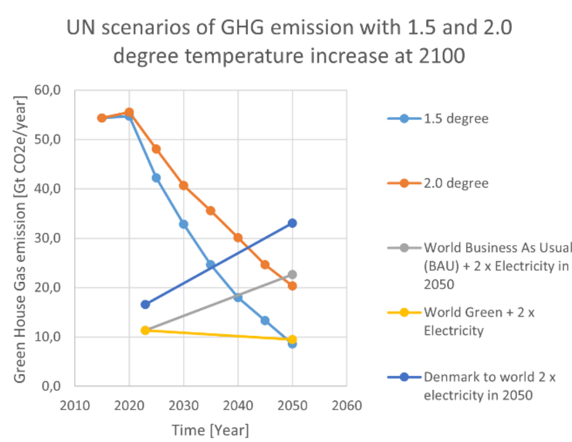


Figure 1. Illustration of the input of a green mix of electricity-producing technologies in 2050 of the analysis Excel sheet (Left) and the determined Global Warming Potential (CO_2 emission) compared to the 1.5 Degree global warming planetary boundary of the Paris Agreement (Right). As can be seen then the green electricity mix proposal shown for the world is just violating the planetary boundary in 2050. The students are encourage to propose other scenarios for 2050 and investigate if the planetary CO_2 boundary is violated.

Interpretation and decision making

Sustainability transitions

Stig Irving Olsen

Associate professor

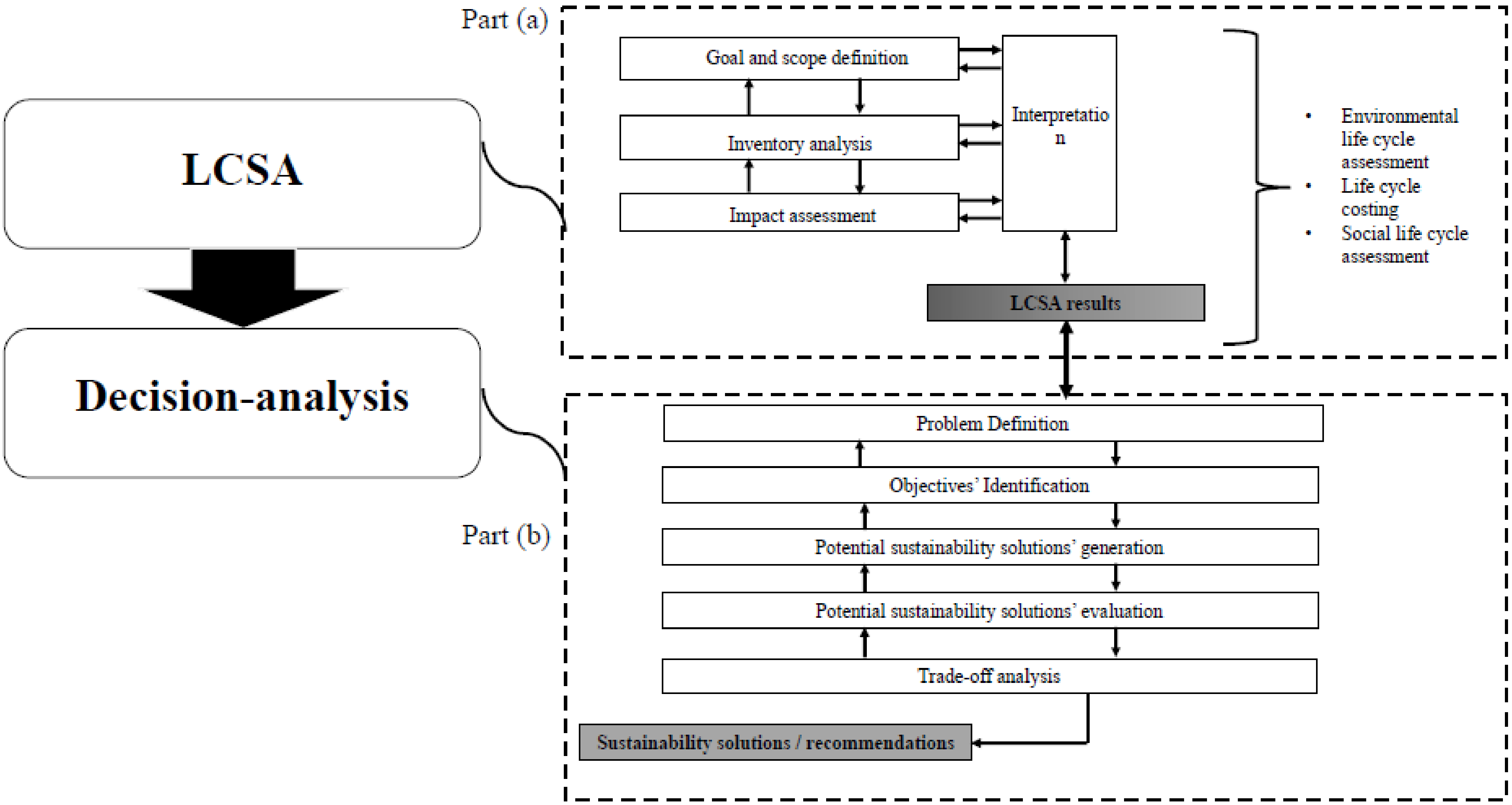
DTU Sustain

Interpretation and decision making

- Concepts
- Multicriteria decision analysis (Mathematical)
- Visual

Main take aways

- Evaluate assumptions, uncertainty and completeness
- Based on the types of data acquired and goal and scope of study, consider which types of decision support are adequate
- MCDA methods have strengths in the guidance
- Visualizations have strenghts in providing overview
- Trade-off are inherent



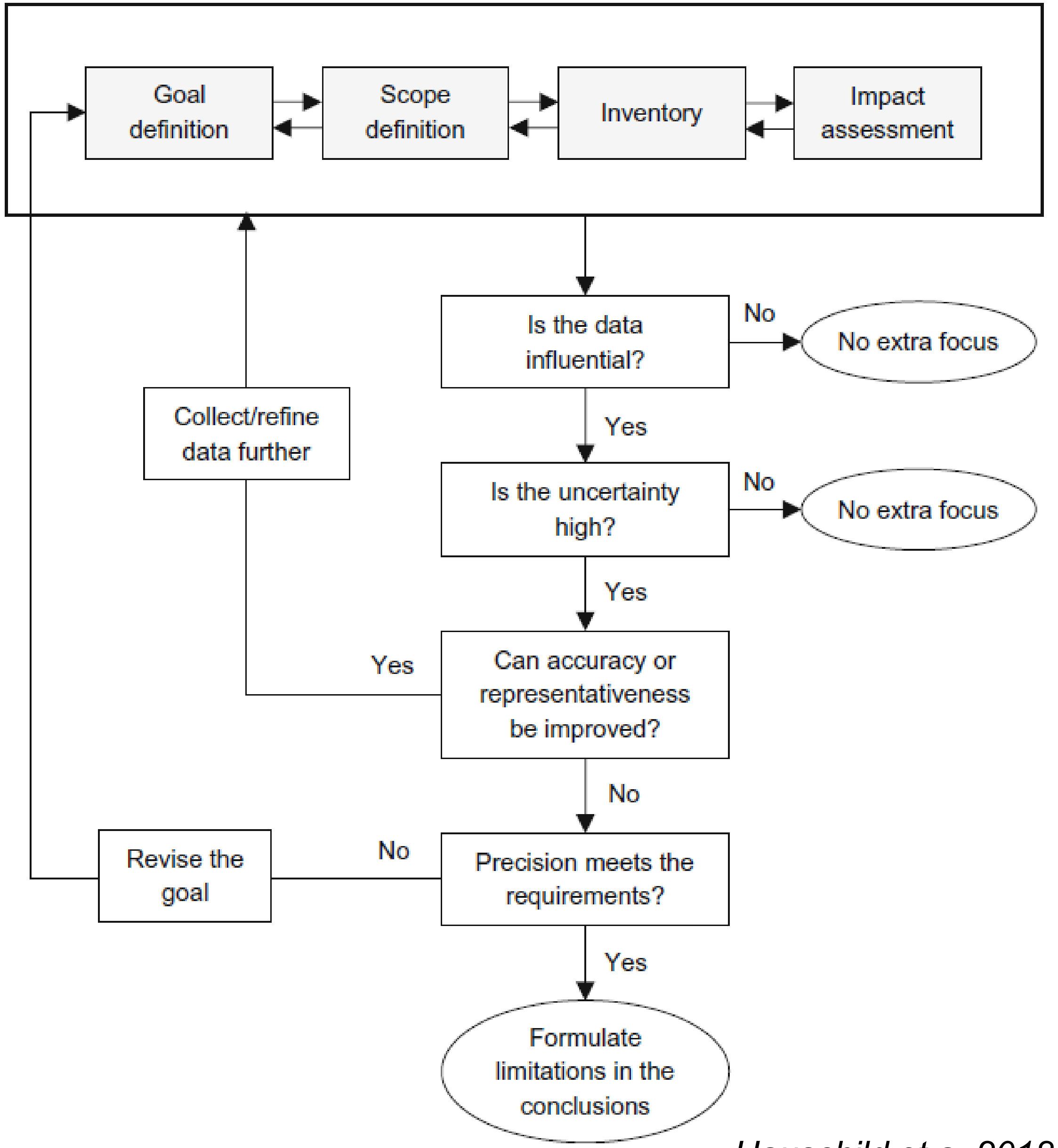
Sustainability ***2018****, 10, 3863; doi:10.3390/su10113863*

Quantitative Sustainability framework contain many different indicators

	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

Results must be interpreted and evaluated

- Consider your assumptions and main uncertainties
  - Which assumption are most sensitive and uncertain?
  - Which data do you consider being most uncertain? Can you improve?
- Completeness
  - Which parts of the life cycle did you not include? Potential influence?
  - Do you consider all dimensions and aspects? Or can you reasonably argue for the omissions



Hauschild et a, 2018, DOI 10.1007/978-3-319-56475-3

Ecolabels provide visual decision support
EPDs provide more in depth information

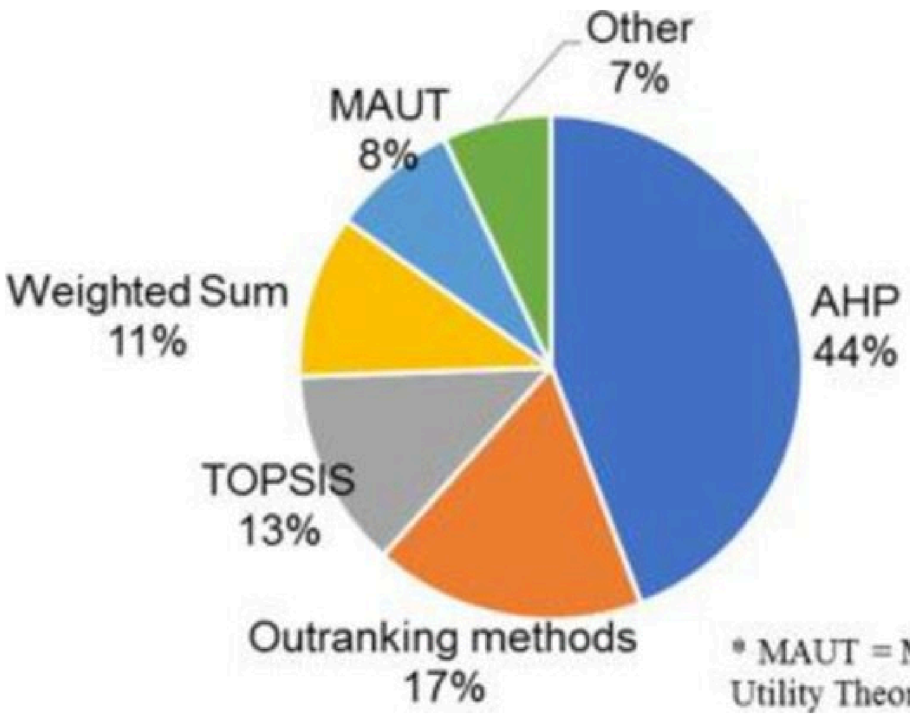
POTENTIAL ENVIRONMENTAL IMPACTS data referred to 1 kg of product		UPSTREAM: Raw material production	UPSTREAM: Packaging and auxiliary materials production	CORE: Production	DOWNSTREAM: Distribution up to shelf	DOWNSTREAM: Primary packaging end of life	TOTAL
GLOBAL WARMING POTENTIAL - GWP ($g\ CO_2$ eq)	Fossil	1.33E+03	2.59E+02	2.90E+02	1.44E+02	2.03E+01	2.05E+03
	Biogenic	4.55E+02	5.47E-01	2.60E-01	2.52E+01	6.10E-04	4.81E+02
	Land use and land transformation	3.55E+02	4.54E+00	3.75E-03	1.69E-02	3.95E-05	3.60E+02
	Total	2.14E+03	2.65E+02	2.90E+02	1.70E+02	2.03E+01	2.89E+03
Acidification Potential - $g\ SO_2$ eq.		2.98E+01	9.16E-01	4.72E-01	5.52E-01	2.62E-03	3.17E+01
Eutrophication Potential - $g\ PO_4^{---}$ eq.		1.45E+01	2.52E-01	7.37E-02	8.95E-02	7.29E-04	1.49E+01
Photochemical Oxidant Formation Potential - gNMVOC eq		7.91E+00	8.53E-01	5.37E-01	6.30E-01	3.73E-03	9.94E+00
Abiotic Depletion Potential - Elements g Sb eq.		1.54E-03	7.15E-05	3.33E-06	6.33E-06	6.89E-08	1.62E-03
Abiotic Depletion Potential - Fossil fuels - MJ. net calorific value		1.18E+01	5.99E+00	4.92E+00	2.01E+00	2.27E-03	2.47E+01
Water scarcity potential. m^3 eq.		7.64E-01	7.89E-02	6.00E-04	1.45E-03	2.78E-05	8.45E-01

WASTE PRODUCTION* data referred to 1 kg of product	UPSTREAM: Raw material production	UPSTREAM: Packaging and auxiliary materials production	CORE: Production	DOWNSTREAM: Distribution up to shelf	DOWNSTREAM: Primary packaging end of life	TOTAL
Hazardous waste disposed (g)	2.02E-03	3.11E-03	0.00E+00	0.00E+00	0.00E+00	5.1E-03
Non-Hazardous waste disposed (g)	9.91E+00	1.99E+01	0.00E+00	0.00E+00	0.00E+00	3.0E+01
Radioactive waste disposed (g)	5.69E-01	4.05E-01	5.28E-02	1.53E-01	7.05E-05	1.2E+00

The biogenic contribution to Global Warming Potential refers only to biogenic methane.
The contribution given by biogenic CO_2 is equal to zero, since the absorbed amount is equal to the emitted biogenic CO_2 within the reference 100 years period.

Zero values indicate that – even if some waste are produced and disposed – their impact is evaluated within the system boundaries.

Many different Multi criteria decision analysis methods exists

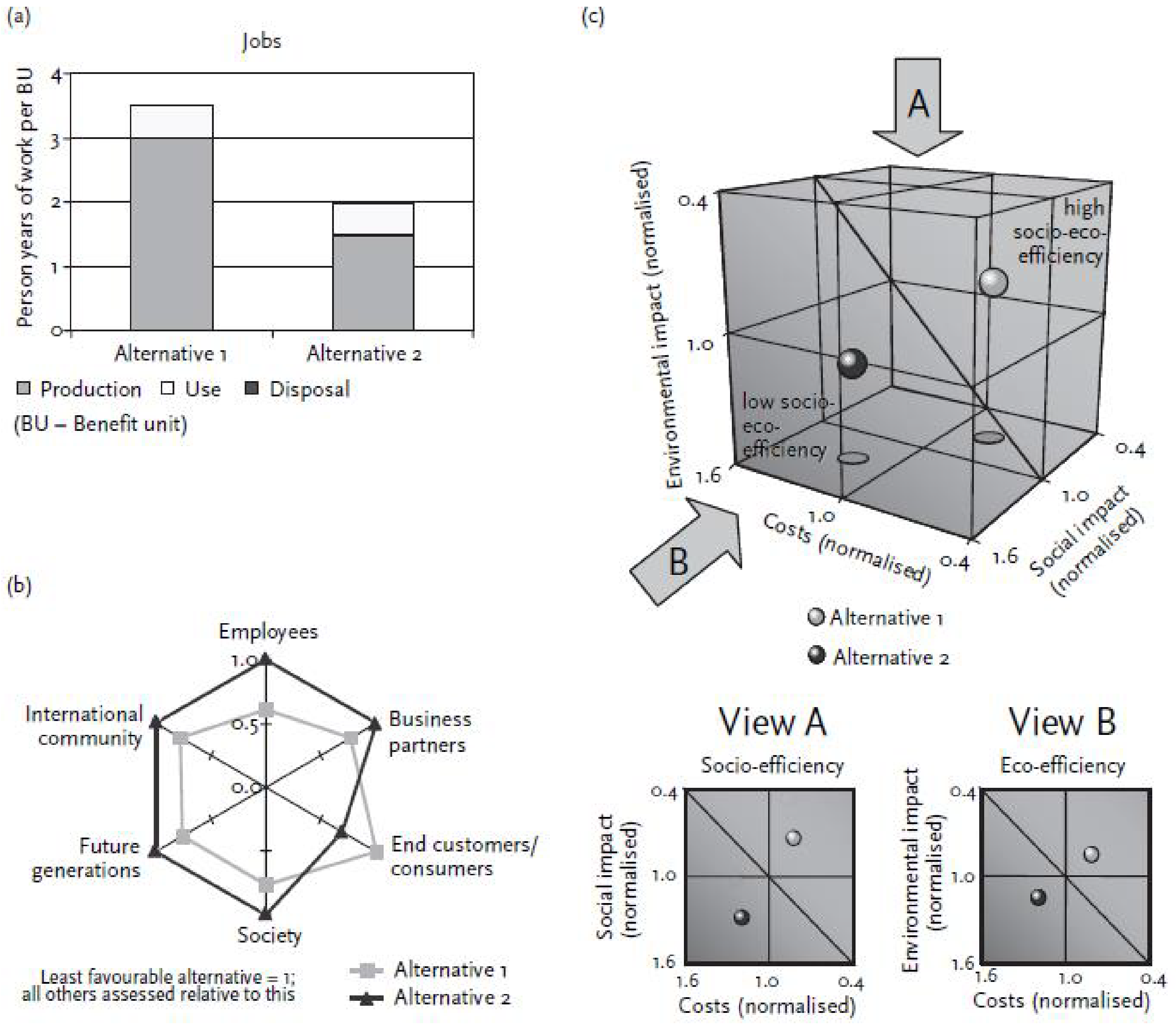


* MAUT = Multi-attribute Utility Theory

	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)	Can use qualitative 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

DOI: 10.13140/RG.2.2.36610.96960

Visualizations can provide overview



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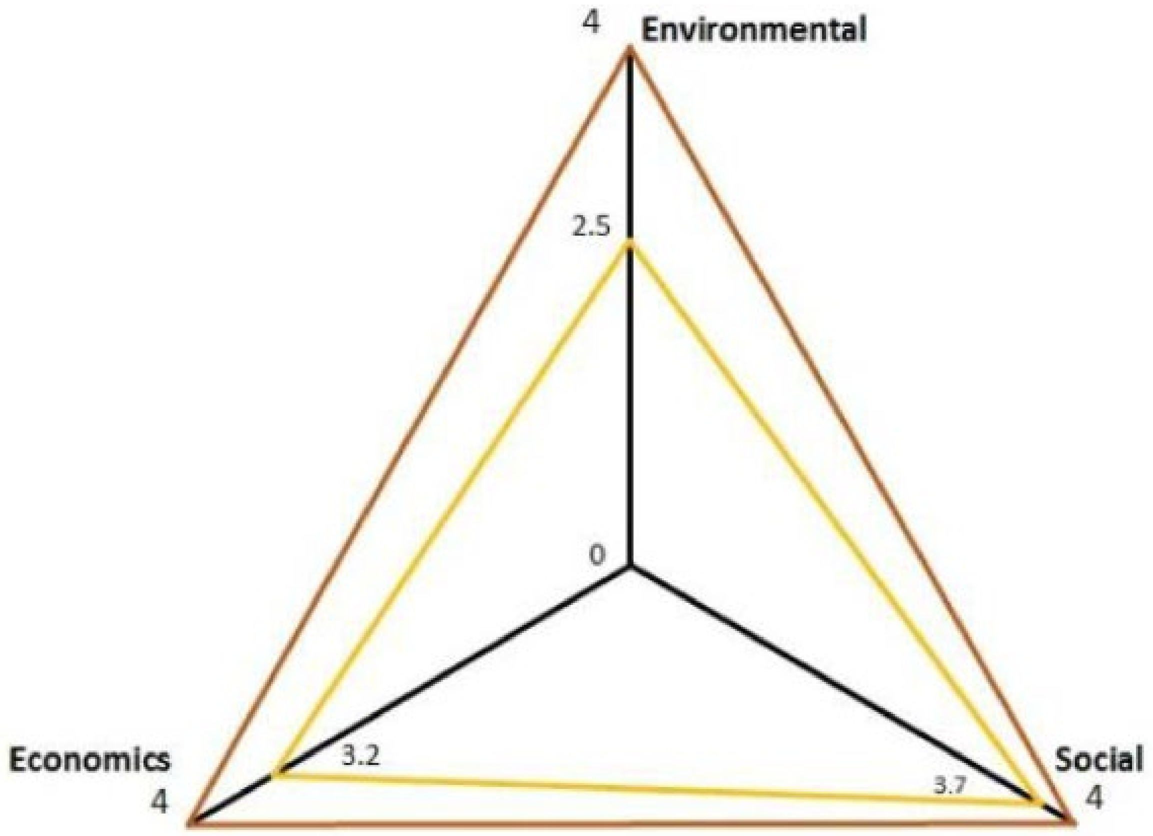
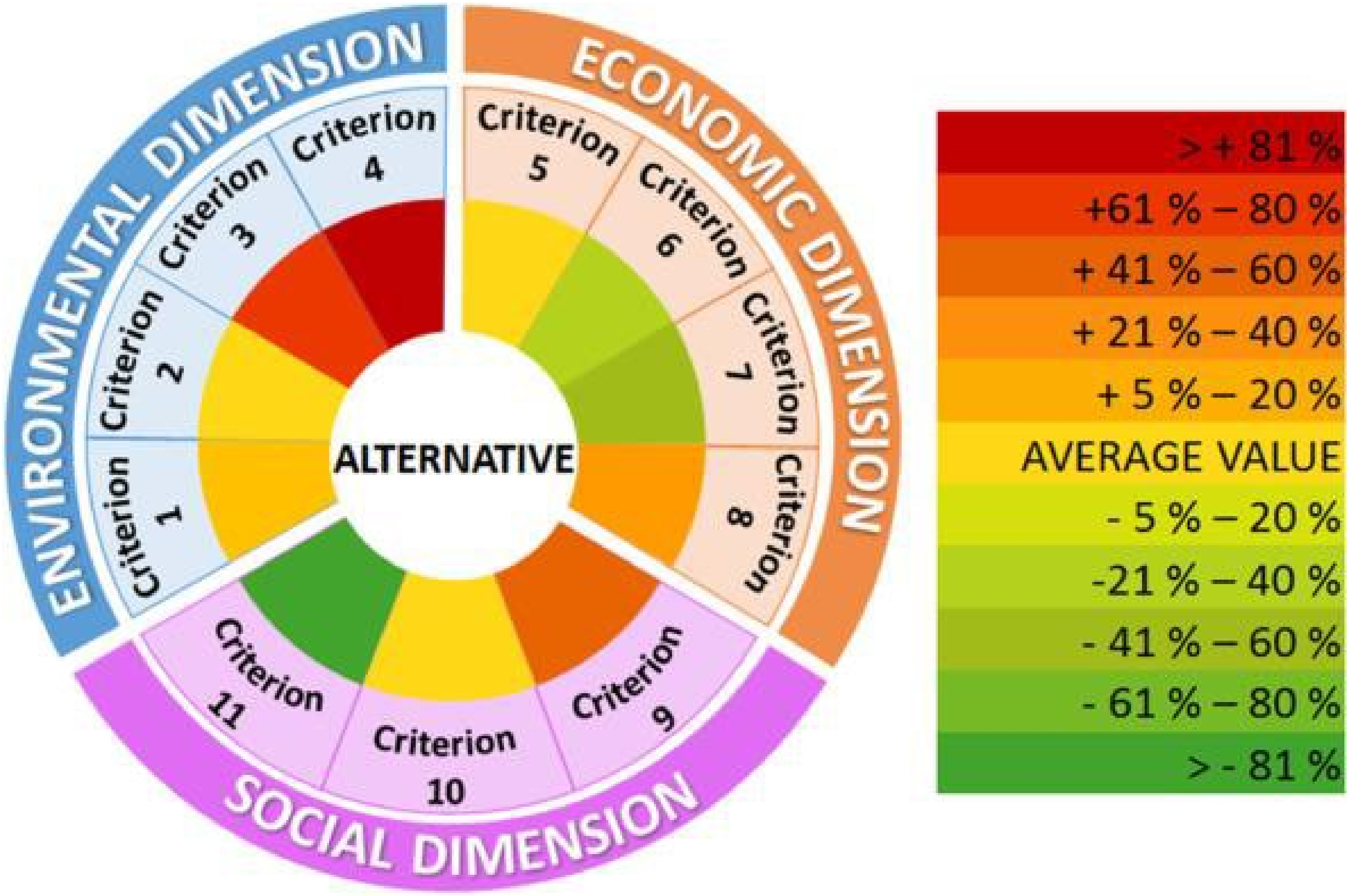
Three sided triangle still requires aggregation within each dimension

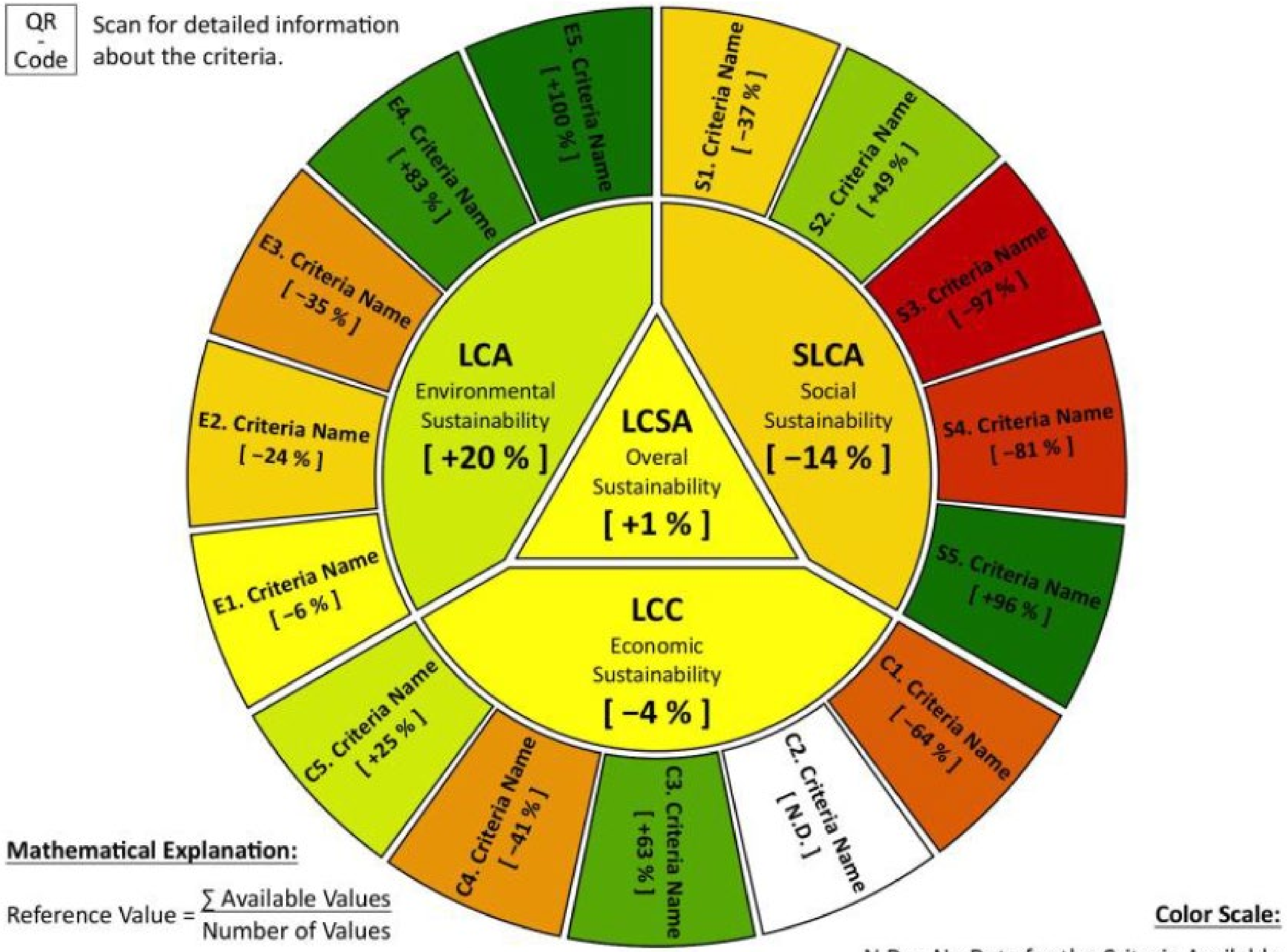


Sustainability crowns compare several indicators within each dimension



Sustainability ***2023****, 15, 10658. https://doi.org/10.3390/su151310658*

LCSA wheel fulfils all comparison criteria



Mathematical Explanation:

$$\text{Reference Value} = \frac{\sum \text{Available Values}}{\text{Number of Values}}$$

$$\text{Single Criteria Result} = \pm \frac{\text{Criteria Value} - \text{Reference Value}}{\text{Reference Value}}$$

$$\text{LCSA Dimension Result} = \frac{\sum \text{Single Criteria Result}}{\text{Number of Criteria}}$$

$$\text{LCSA Result} = \frac{\sum \text{Dimension Result}}{\text{Number of Dimensions}}$$

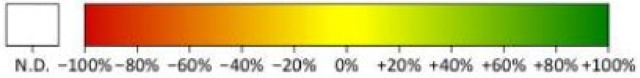
Color Scale:

N.D. = No Data for the Criteria Available

Criteria is Neglected in Calculations

Positive Result (+) = Above the Reference Value

Negative Result (−) = Below the Reference Value



Summary

- Visualizations have strenghts in providing overview
- MCDA methods have strengths in the guidance
- Evaluate assumptions, uncertainty and completeness
- Based on the types of data acquired and goal and scope of study, consider which types of decision support are adequate

Pathways and interventions

Sustainability transitions

Stig Irving Olsen & David Lusseau

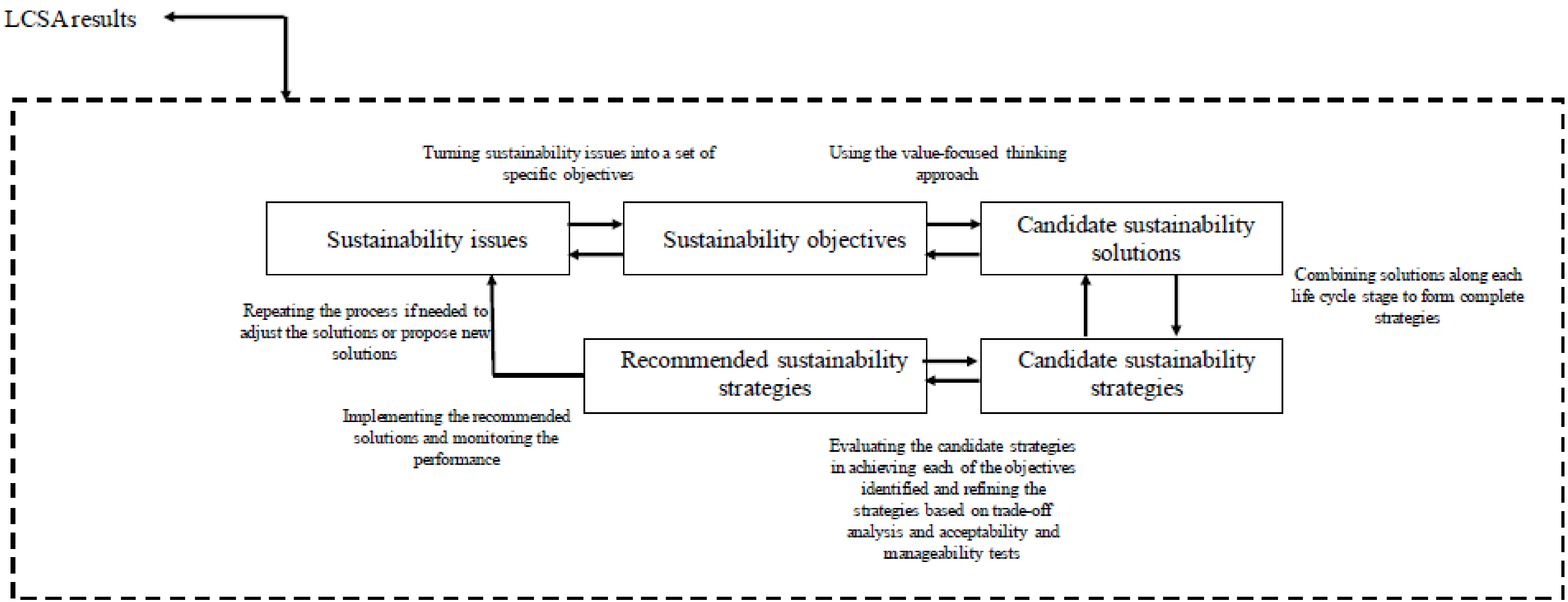
Content

Interpretation

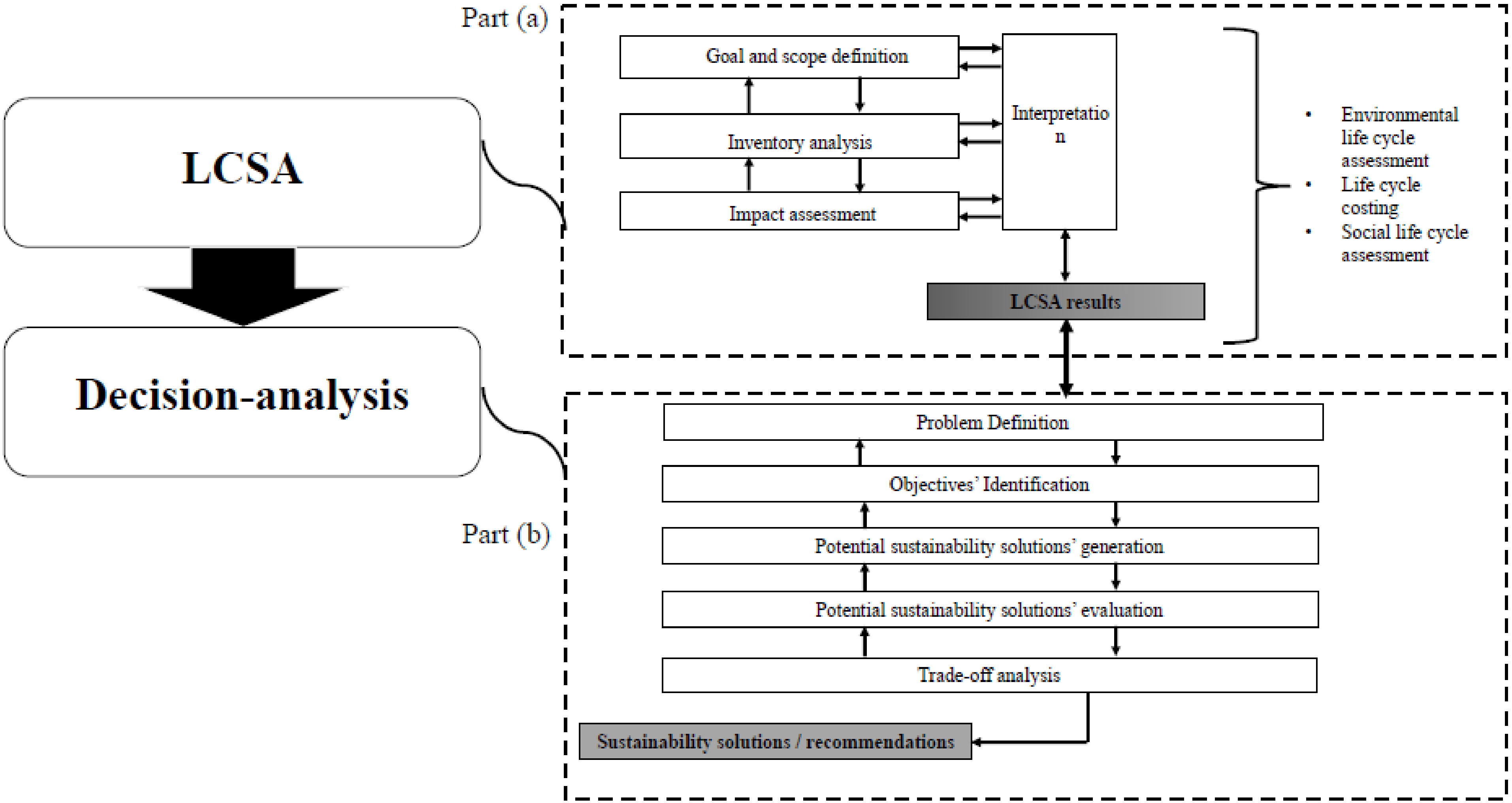
- Concepts
- Mathematical
- Visual

System dynamics

- Concepts
  - System states
  - Hysteresis and early warning signals
- Interventions
  - Economic, behavioural, and governance
- Tools to identify sustainability transitions
  - Focus on agent-based models



Sustainability ***2018****, 10, 3863; doi:10.3390/su10113863*



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Quantitative Sustainability framework

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Transition					Interpretation System dynamics	9, ASAB 10, DAVLU, SIOL

How to interpret the results

- Consider your assumptions and main uncertainties
  – Which assumption are most sensitive and uncertain?
  – Which data do you consider being most uncertain? Can you improve?
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  – Which parts of the life cycle did you not include? Potential influence?
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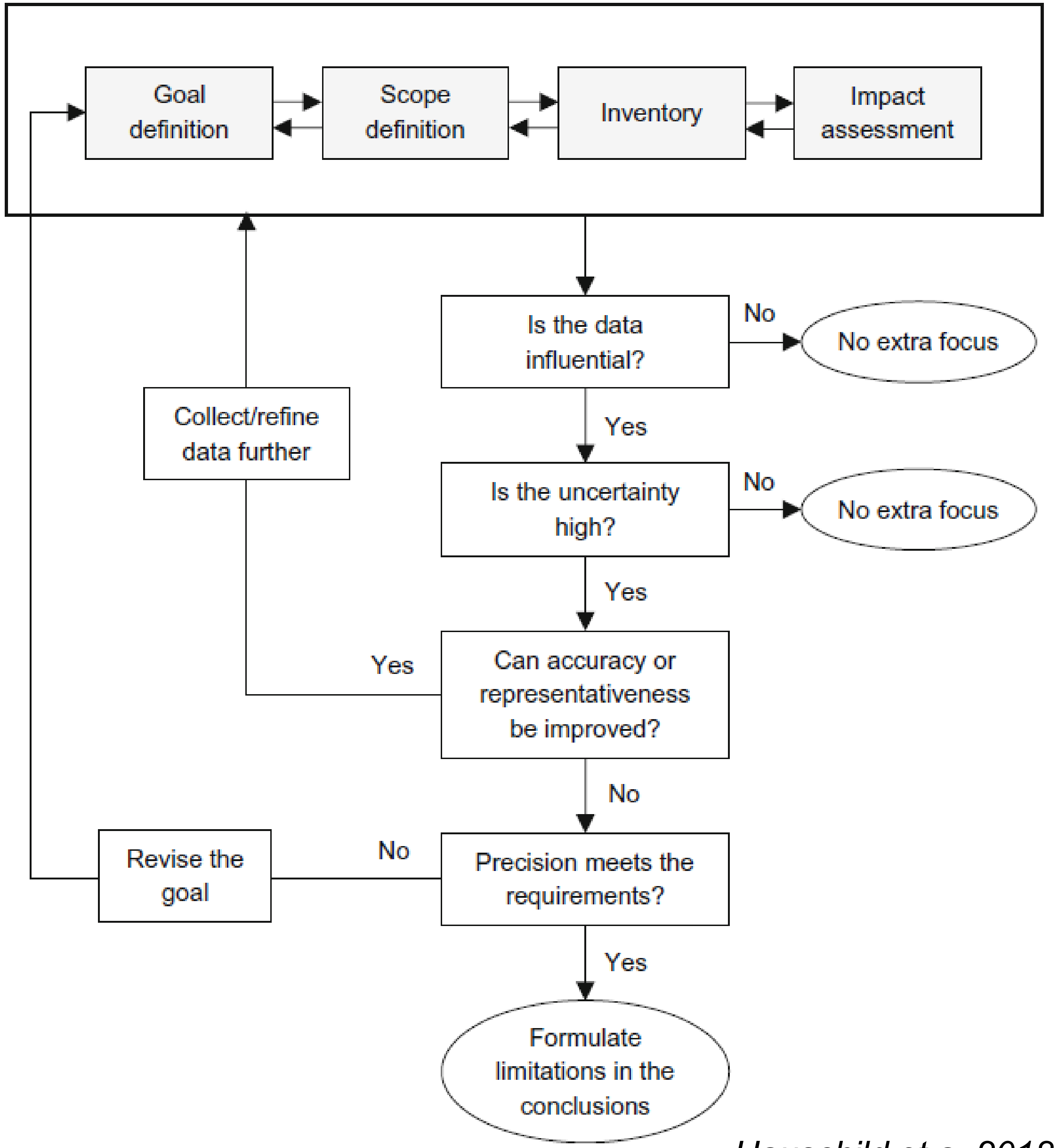
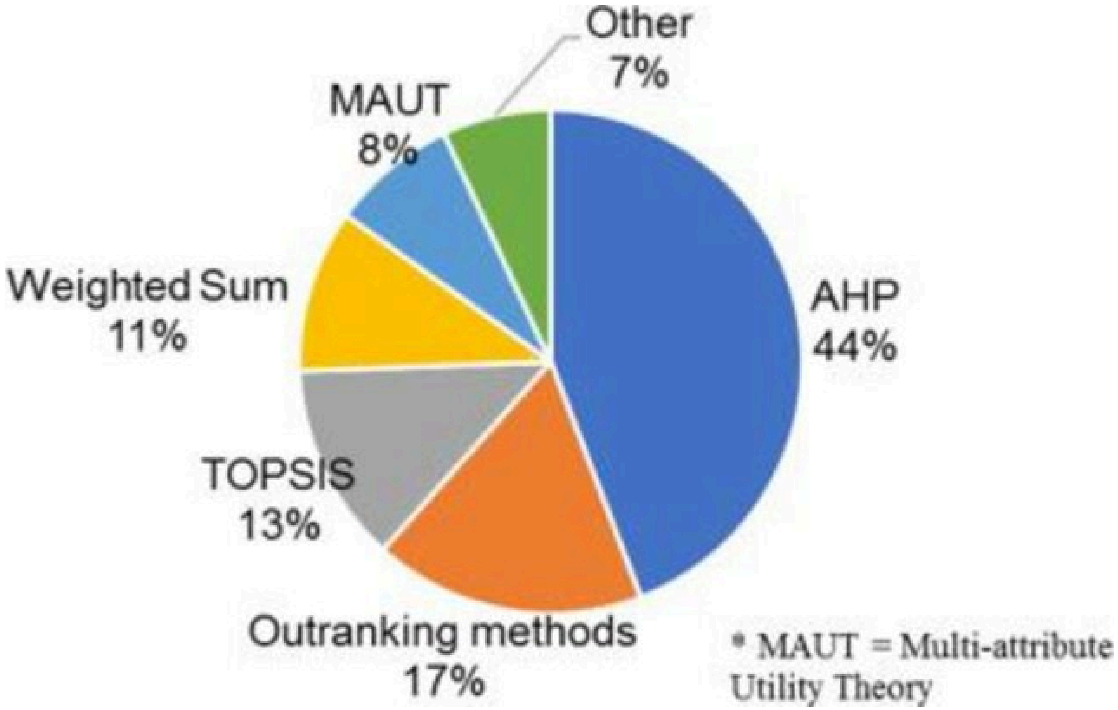


Hauschild et a, 2018, DOI 10.1007/978-3-319-56475-3

Multi criteria decision making

- Many different MCDA methods exists



	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)	Can use qualitative inputs as such (without transformation to semi-quantitative inputs)
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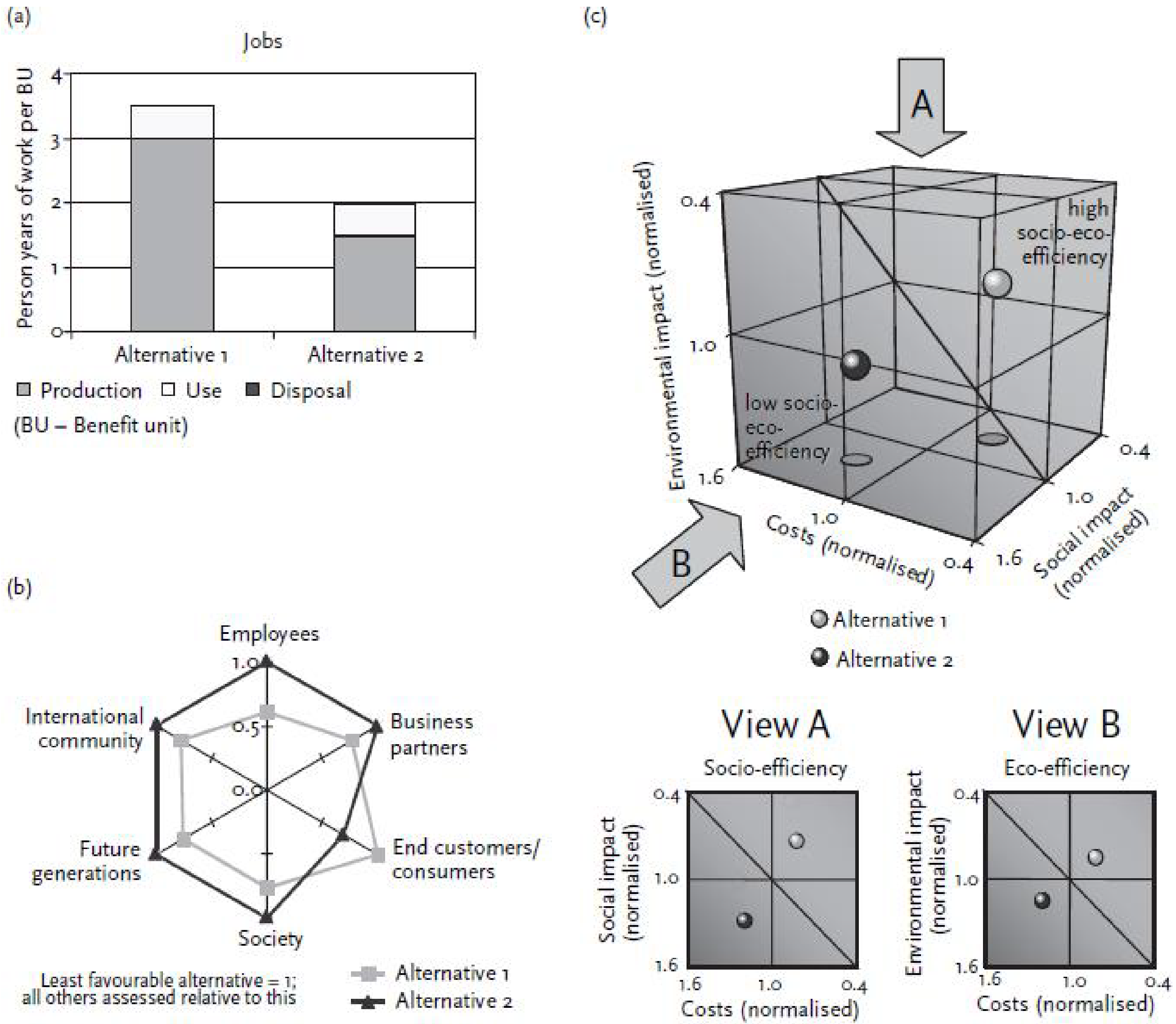
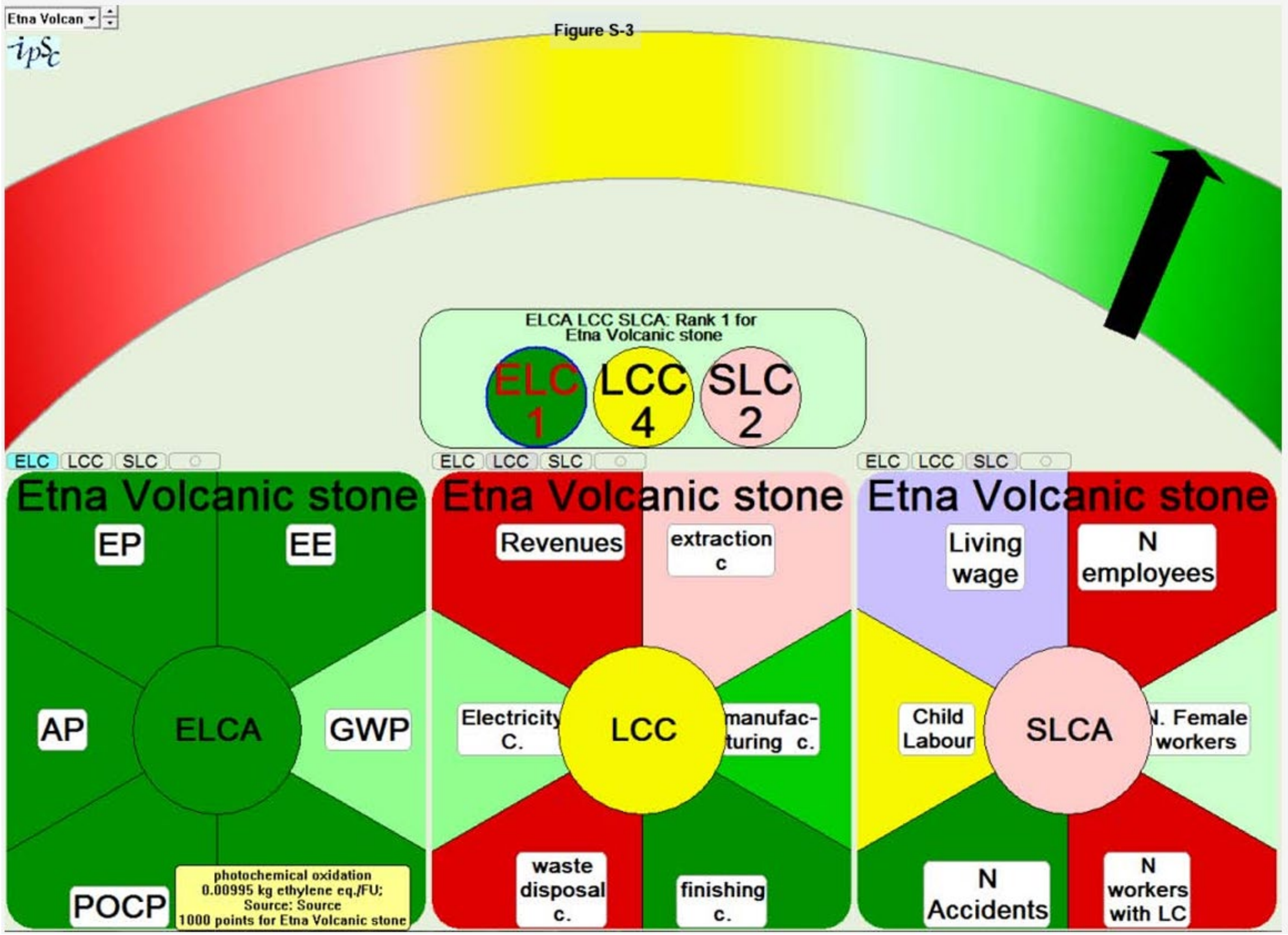
PEF normalization and weighting	weak	yes	yes	no
Distance to target weighting	weak	yes	yes	no
Monetary weighting	weak	yes	yes	yes

DOI: 10.13140/RG.2.2.36610.96960

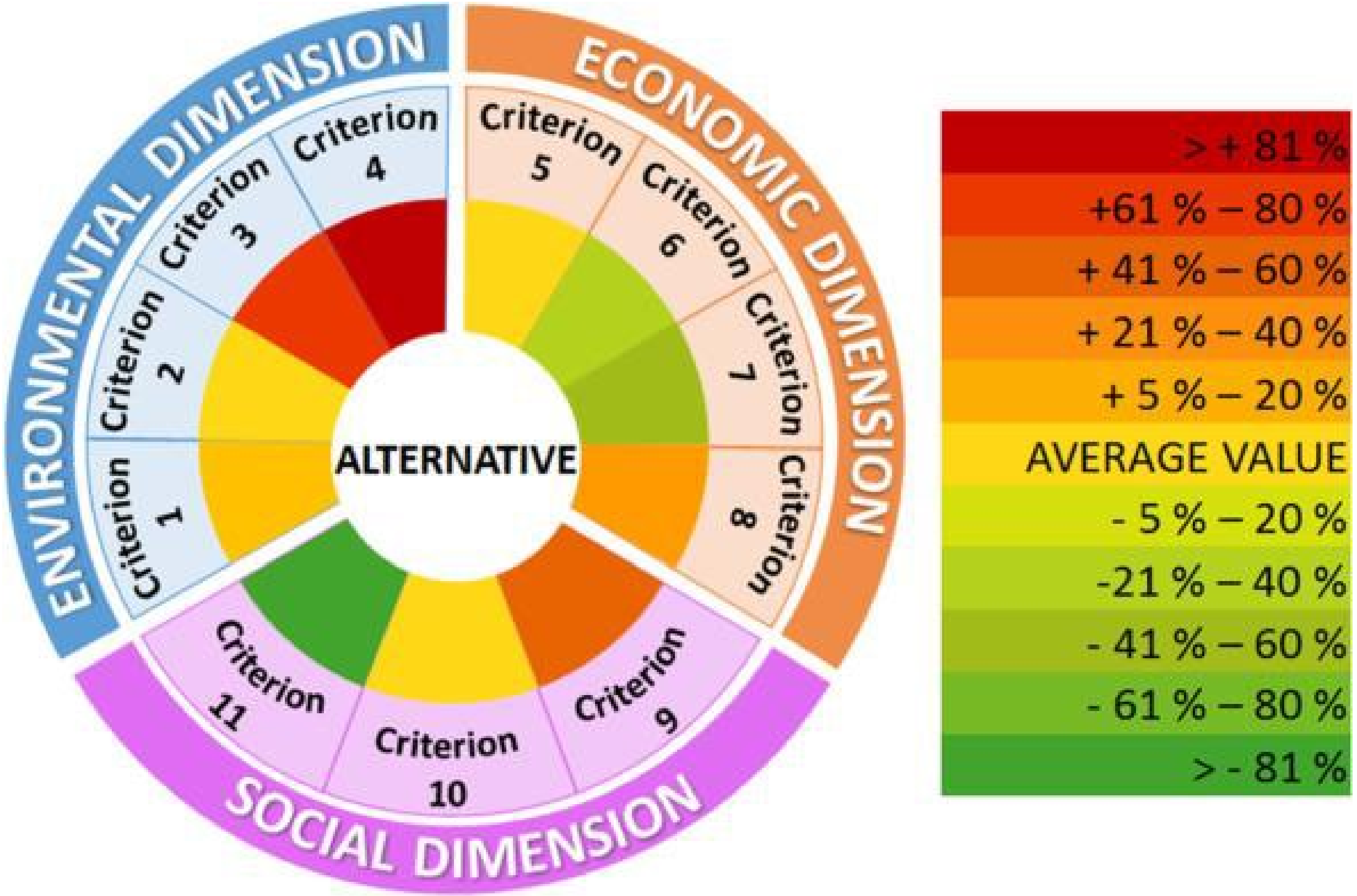
Visualisations



Life Cycle Sustainability dashboard



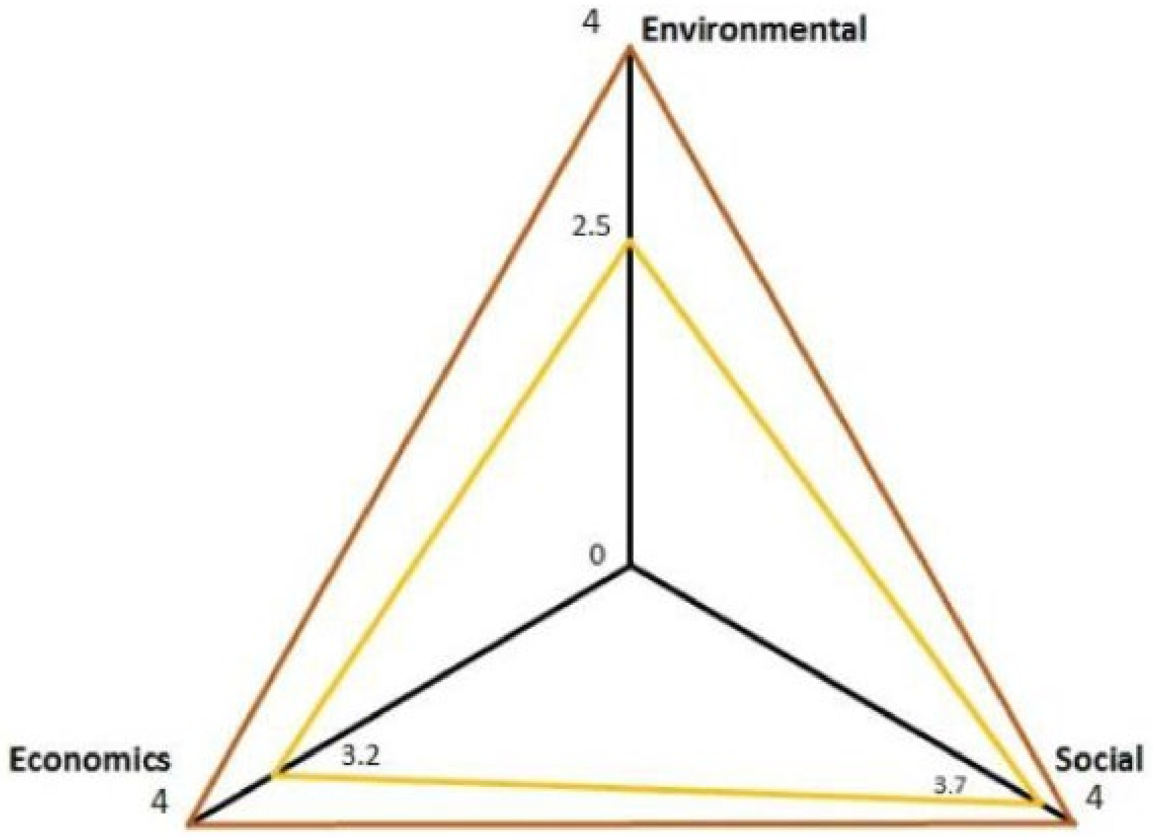
Sustainability crowns



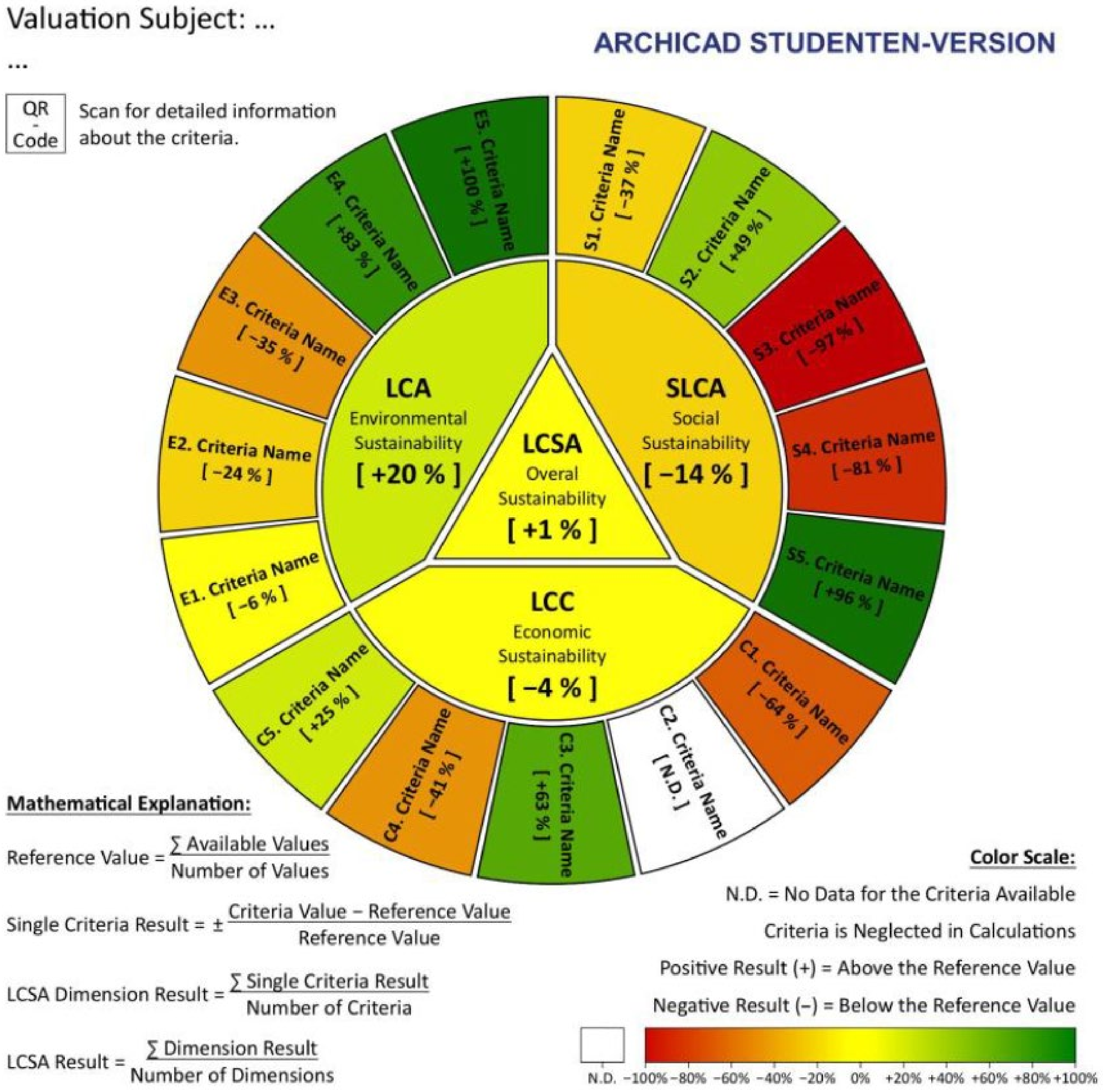
Sustainability ***2023****, 15, 10658. https://doi.org/10.3390/su151310658*

Doughnut inspired model

Three sided triangle



LCSA wheel



Valuation Subject: ...
...
ARCHICAD STUDENTEN-VERSION
QR - Code
Scan for detailed information about the criteria.
LCSA
Overal Sustainability
[+1 %]
LCA
Environmental Sustainability
[+20 %]
SLCA
Social Sustainability
[–14 %]
LCC
Economic Sustainability
[–4 %]
E1. Criteria Name [–6 %]
E2. Criteria Name [–24 %]
E3. Criteria Name [–35 %]
E4. Criteria Name [+83 %]
E5. Criteria Name [+100 %]
S1. Criteria Name [–37 %]
S2. Criteria Name [+49 %]
S3. Criteria Name [–97 %]
S4. Criteria Name [–81 %]
S5. Criteria Name [+96 %]
C1. Criteria Name [–64 %]
C2. Criteria Name [N.D.]
C3. Criteria Name [+63 %]
C4. Criteria Name [–41 %]
C5. Criteria Name [+25 %]
Mathematical Explanation:
Reference Value = ∑ Available Values / Number of Values
Single Criteria Result = ± (Criteria Value – Reference Value) / Reference Value
LCSA Dimension Result = ∑ Single Criteria Result / Number of Criteria
LCSA Result = ∑ Dimension Result / Number of Dimensions
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Criteria is Neglected in Calculations
Positive Result (+) = Above the Reference Value
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N.D. –100% –80% –60% –40% –20% 0% +20% +40% +60% +80% +100%

Summary

- Evaluate assumptions, uncertainty and completeness
- Based on the types of data acquired and goal and scope of study, consider which types of decision support are adequate
- MCDA methods have strengths in the guidance
- Visualizations have strenghts in providing overview

Content

System dynamics

- Concepts
  - System states
  - Hysteresis and early warning signals

- Interventions
  - Economic, behavioural, and governance

- Tools to identify sustainability transitions
  - Focus on agent-based models

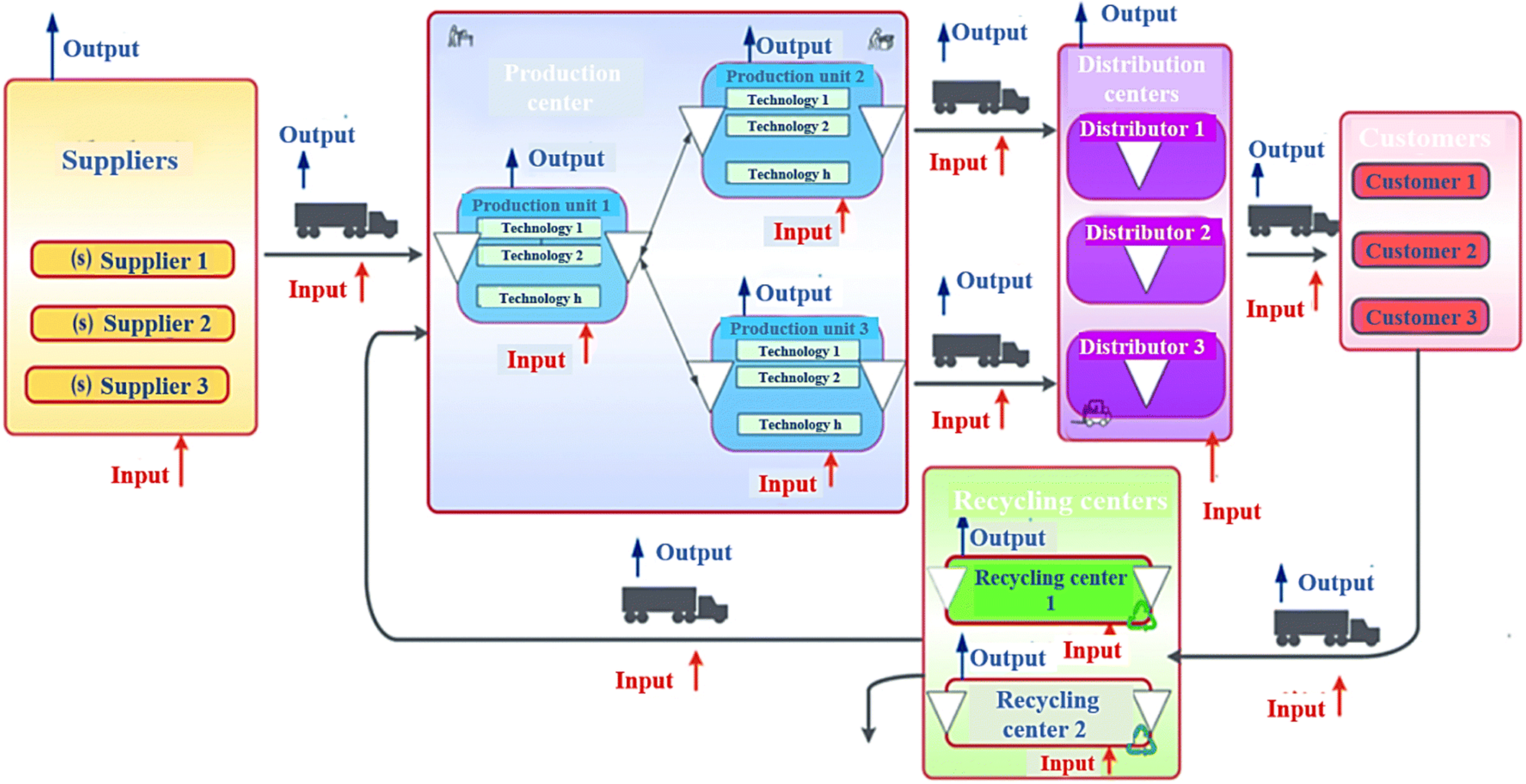
Concepts

What does sustainability transition mean?

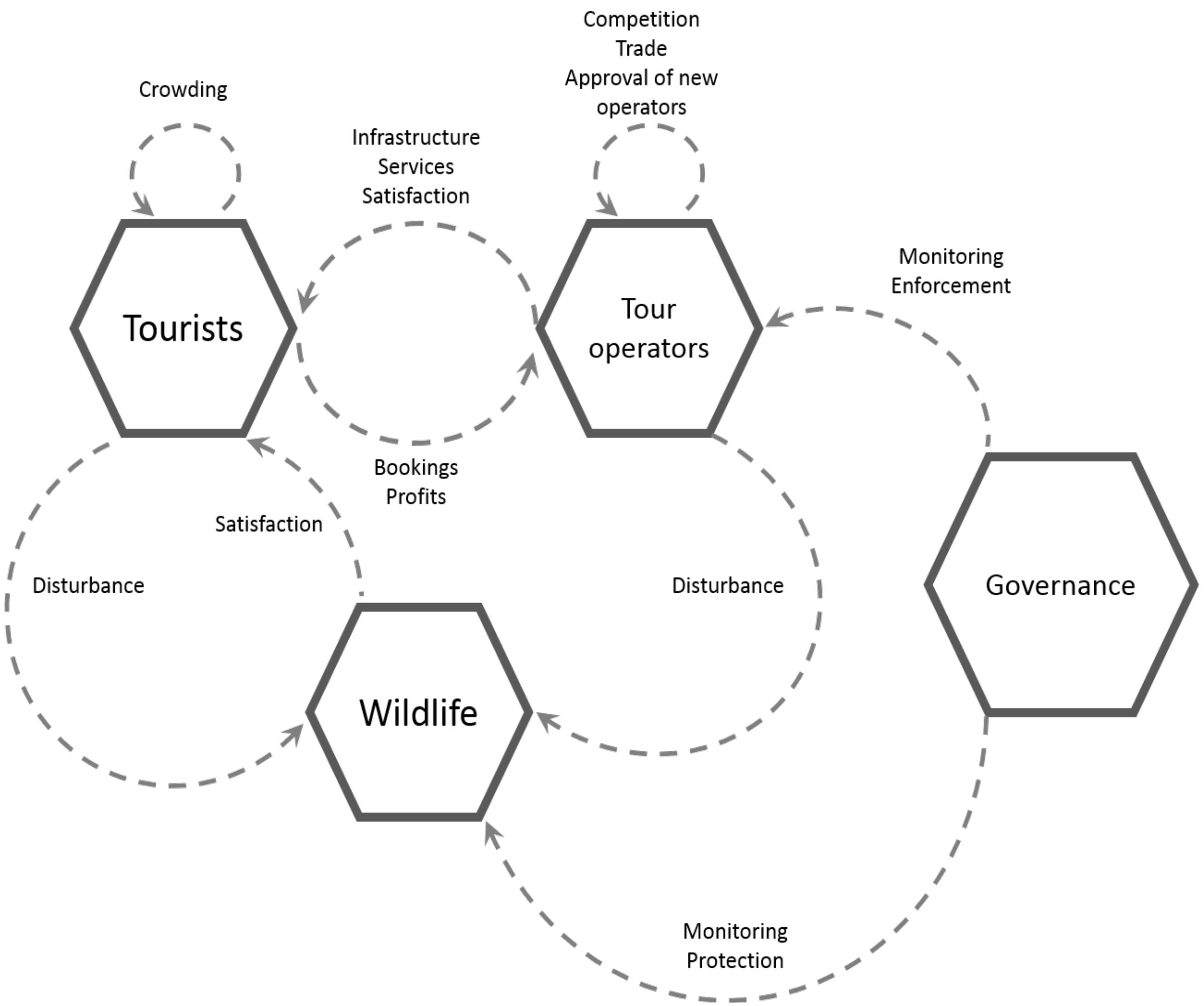
- Systemic interventions to
  - Sustain acceptable outcomes on the three dimensions of sustainability
  - Change the system currently in unacceptable state

- Applies to all scales:
  - Manufacturing system
  - Resource exploitation system
  - Socioecological system

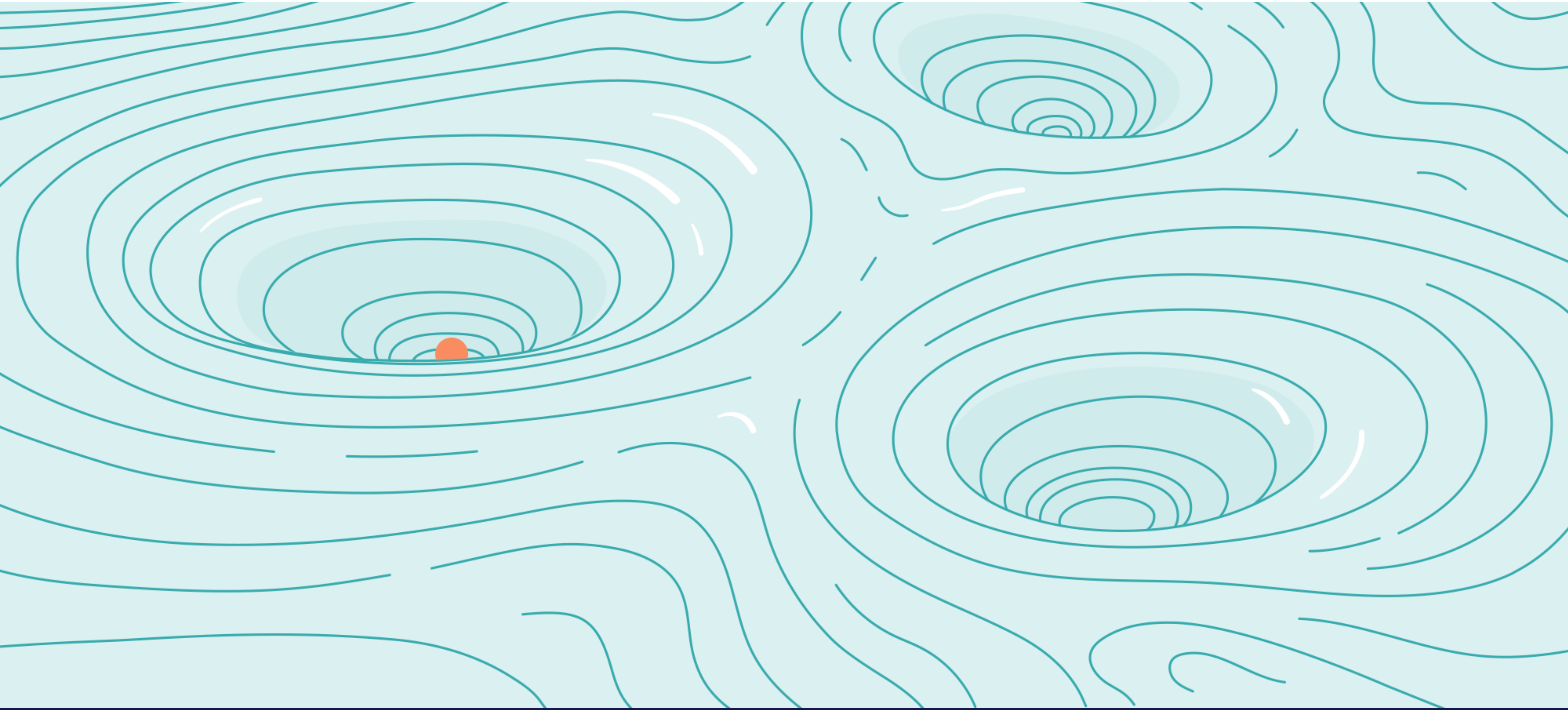
system perspectives



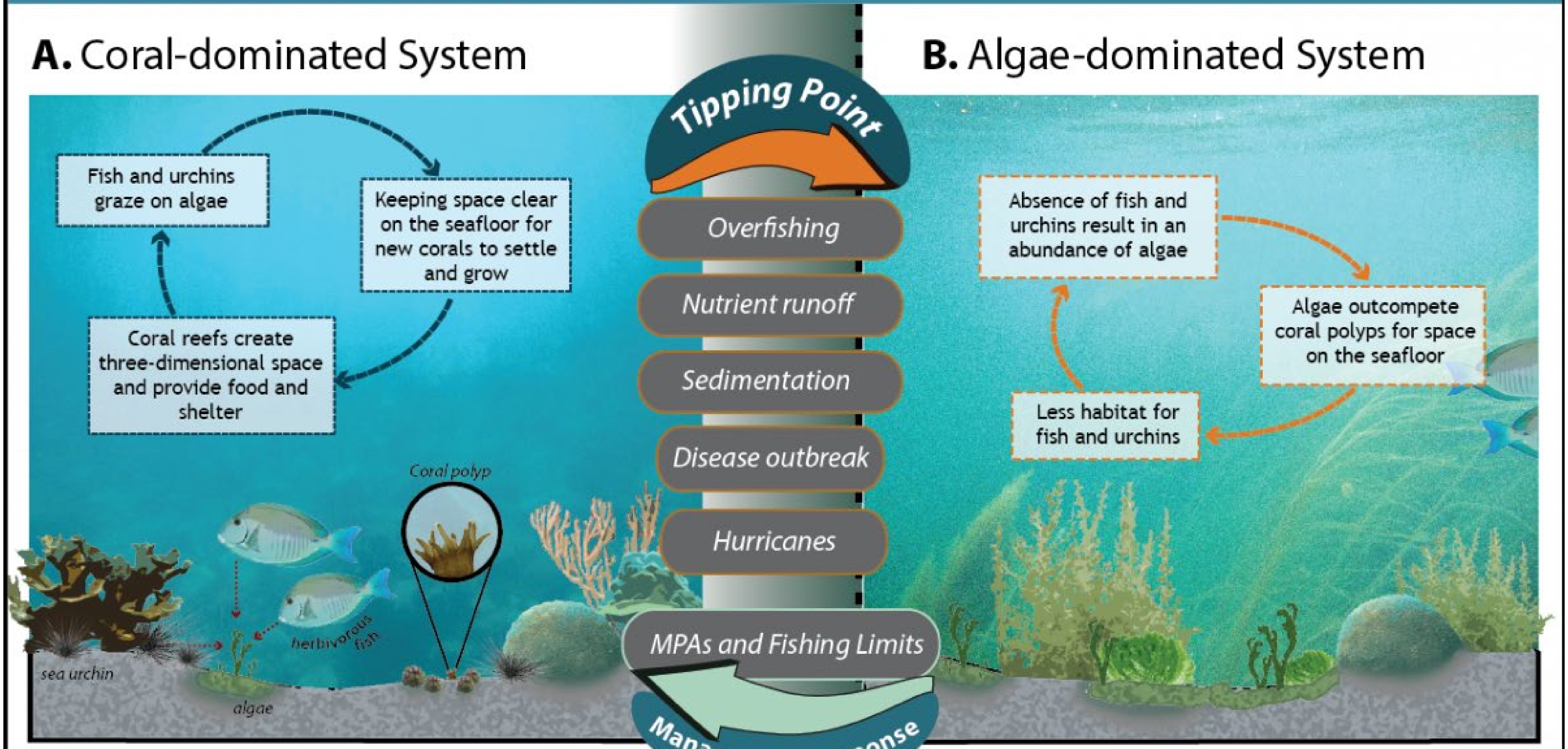
Socioecological system perspectives



Multi-state dynamics



DISCOVERY BAY, JAMAICA



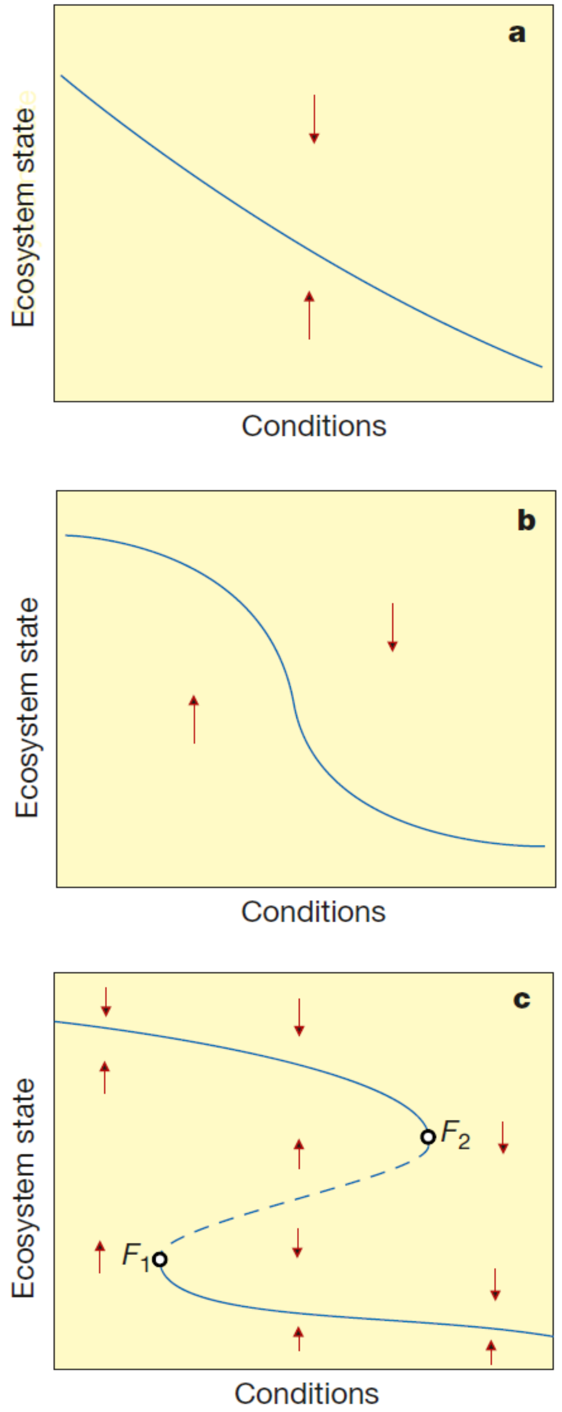
Herbivorous fish and urchins help to maintain healthy coral reefs, which support valuable commerial fisheries and tourism

Overfishing and disease reduced herbivores severely. When a hurricane killed much of the coral, algae was able to take over the reef and prevent coral recovery

Dependence of system state on its history

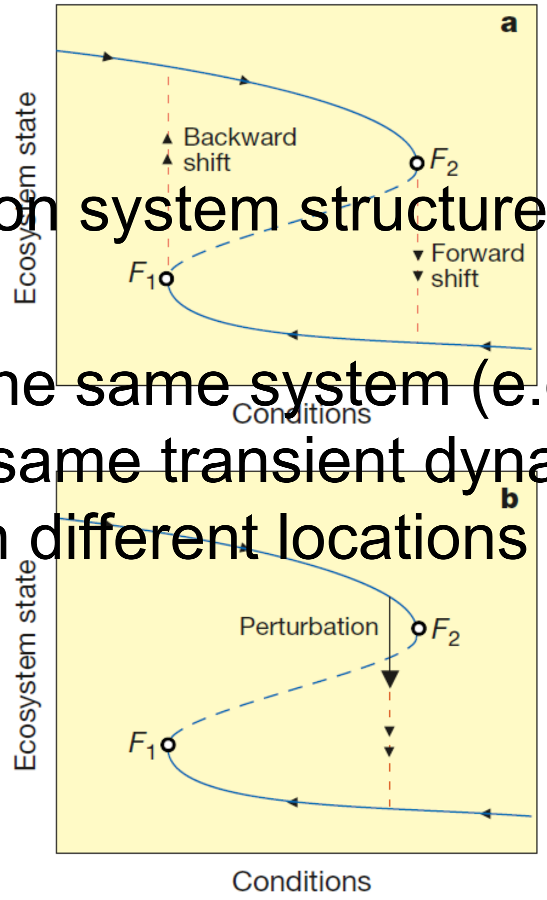
hysteresis

Discontinuity in state shift



It depends on system structure and parameter values

Even with the same system (e.g., coral reef) we cannot expect the same transient dynamics and regime shift dynamics in different locations

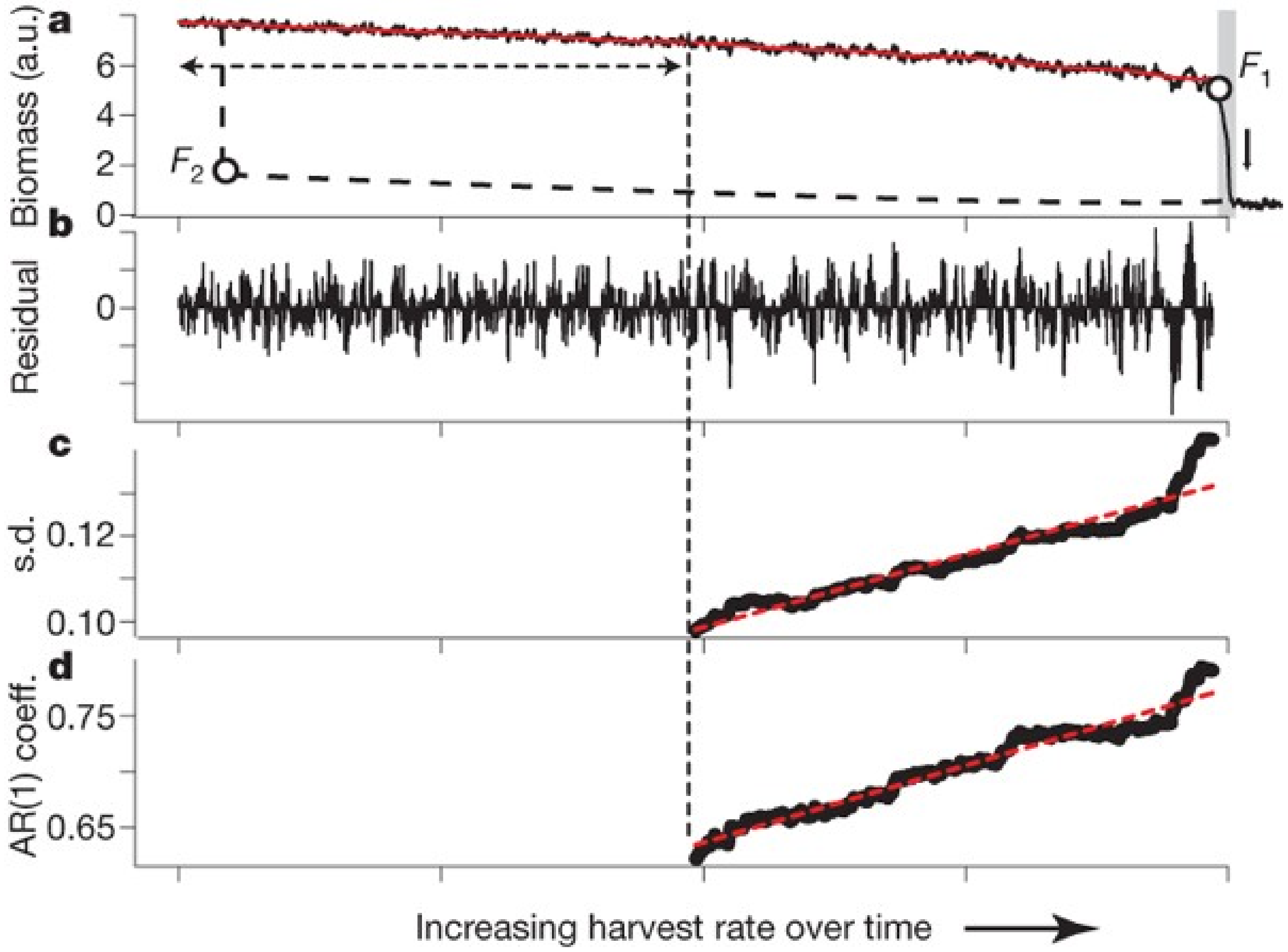


Scheffer et al 2001 Nature; Scheffer & Carpenter 2003 TREE

Early warning signals

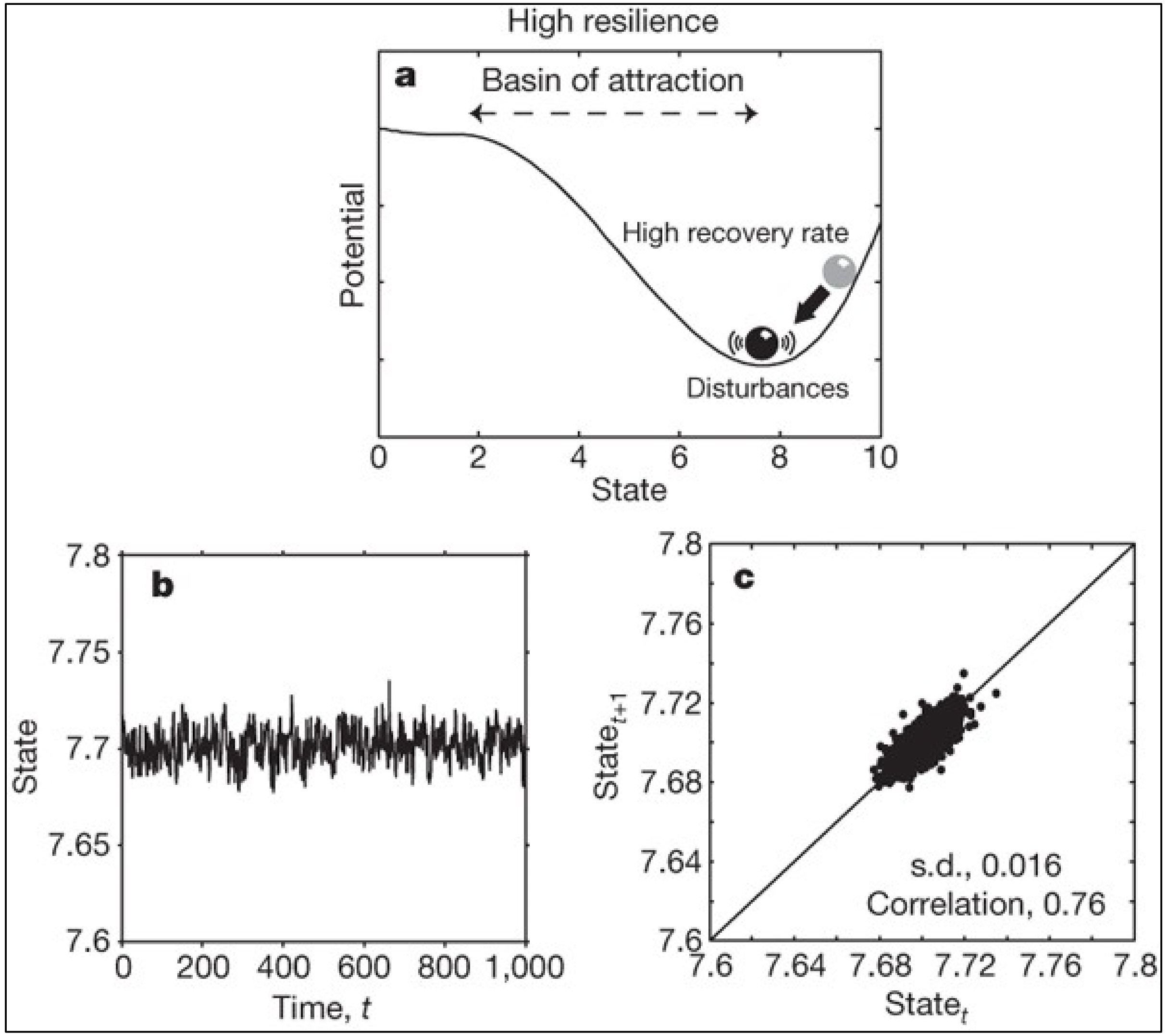
Behaviour as system approaches critical transition

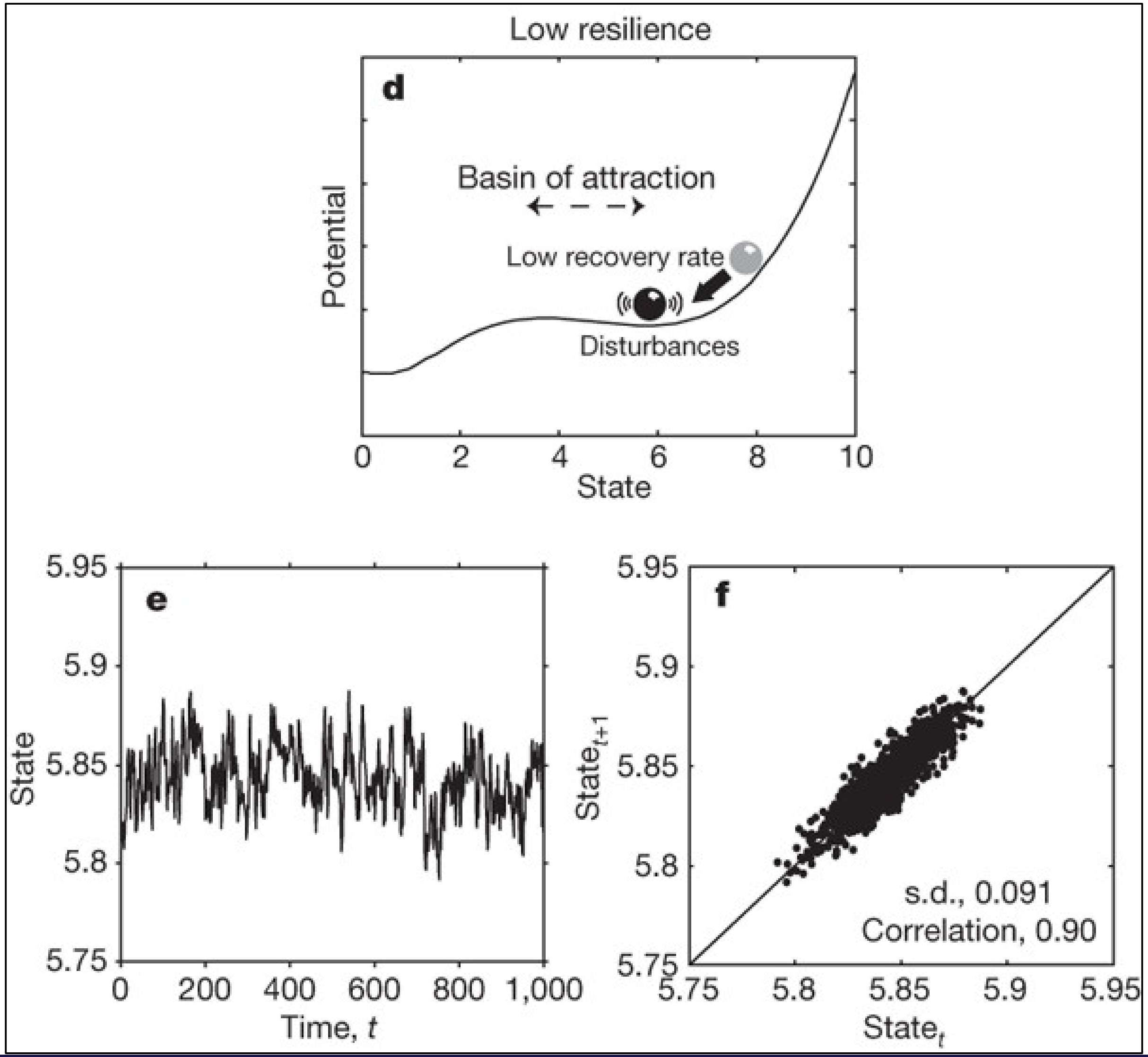
- The system becomes less resilient to perturbations (a small change is more likely to tip it into another state)
- If it is less resilient the system is therefore more 'wobbly', do we see more variance?



van Nes et al. 2008 Ecology; Dakos et al. 2008 PNAS; Scheffer et al. 2009 Nature

Behaviour as system approaches critical transition





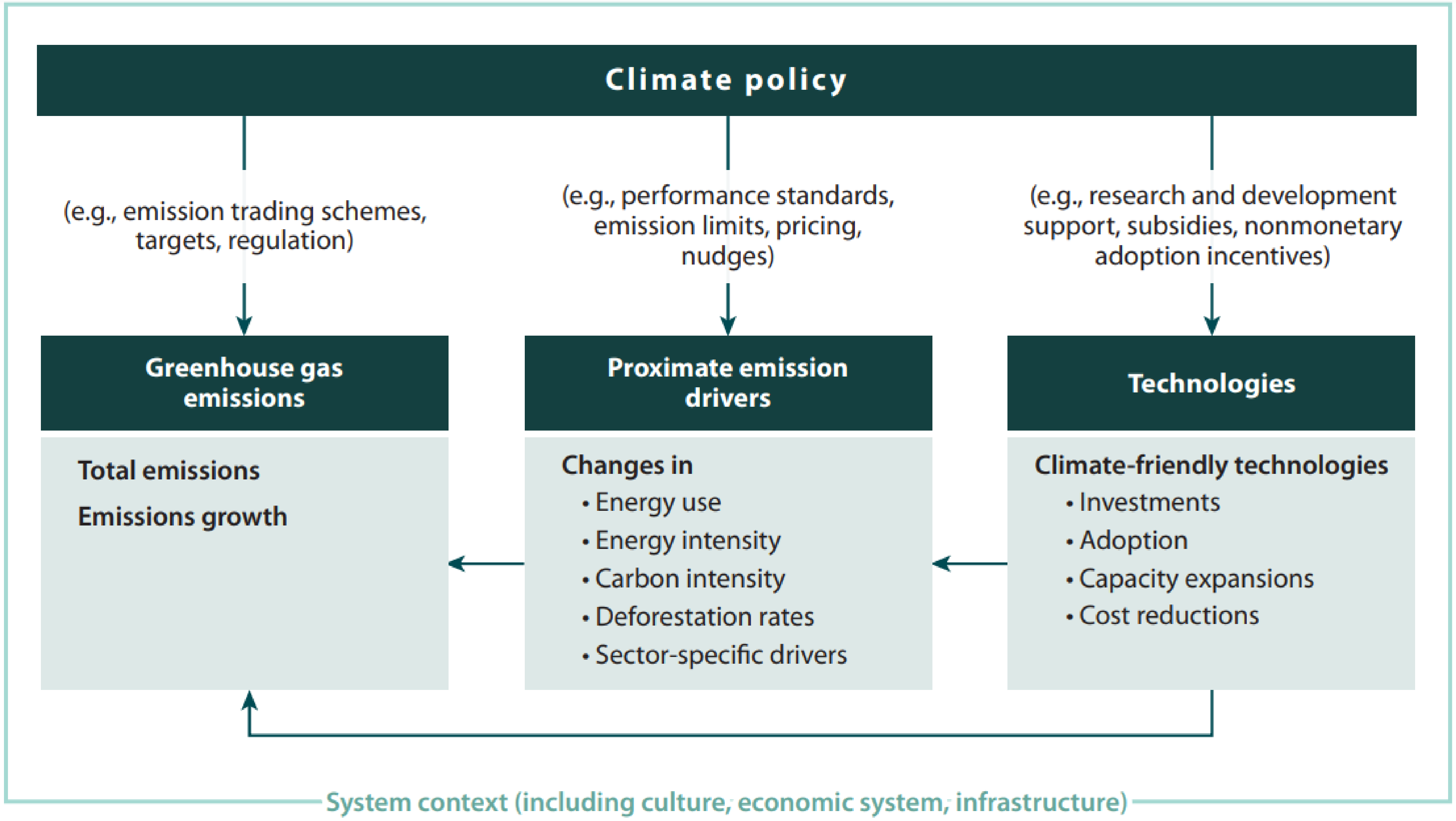
Scheffer et al. 2009 Nature

interventions

Systemic interventions

Tapering

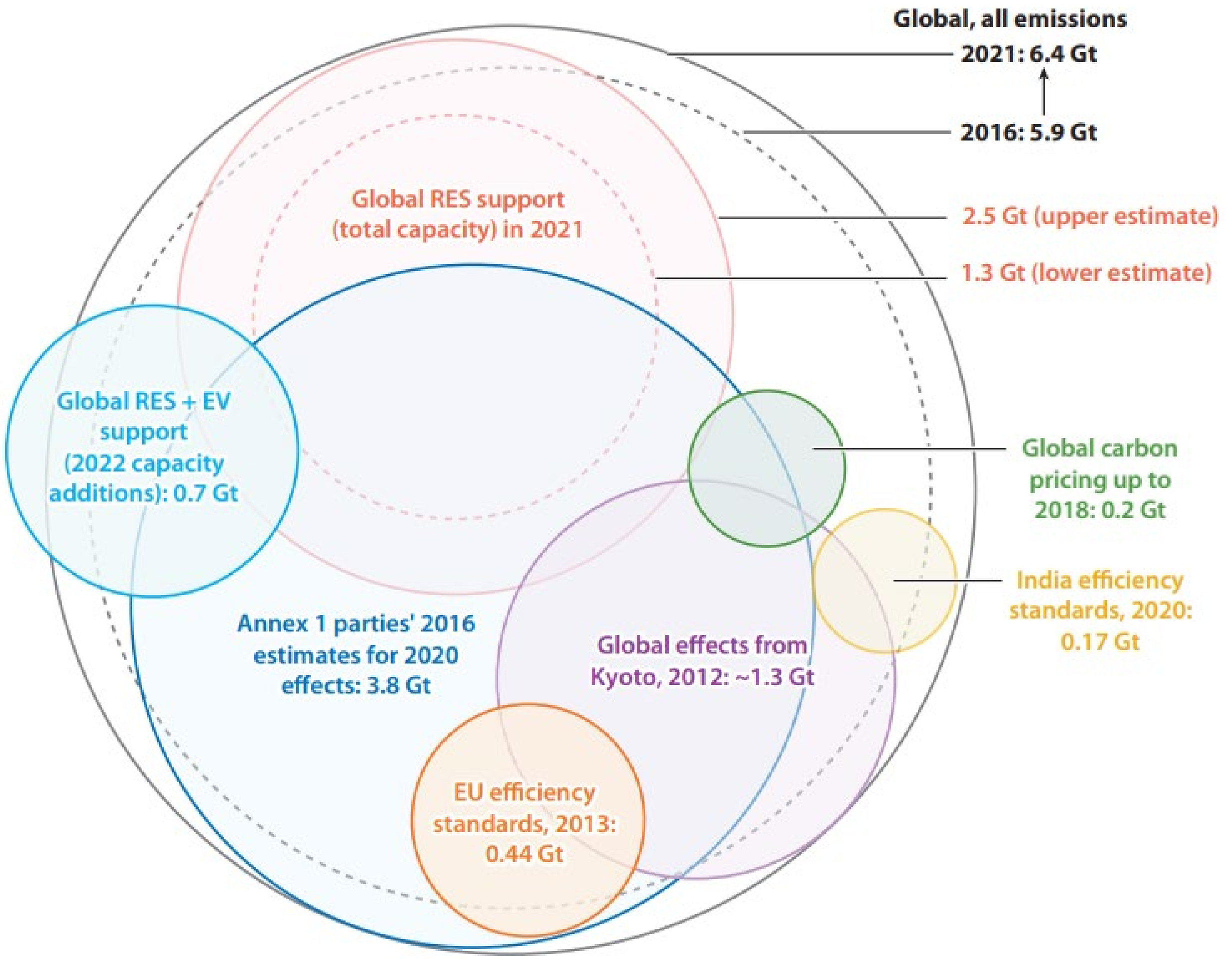
Climate – is it all doom and gloom?



Hoppe et al. 2023 Ann Rev Env & Res

Climate – is it all doom and gloom?

- Policy support for renewable development and uptake has been relatively most impactful to date

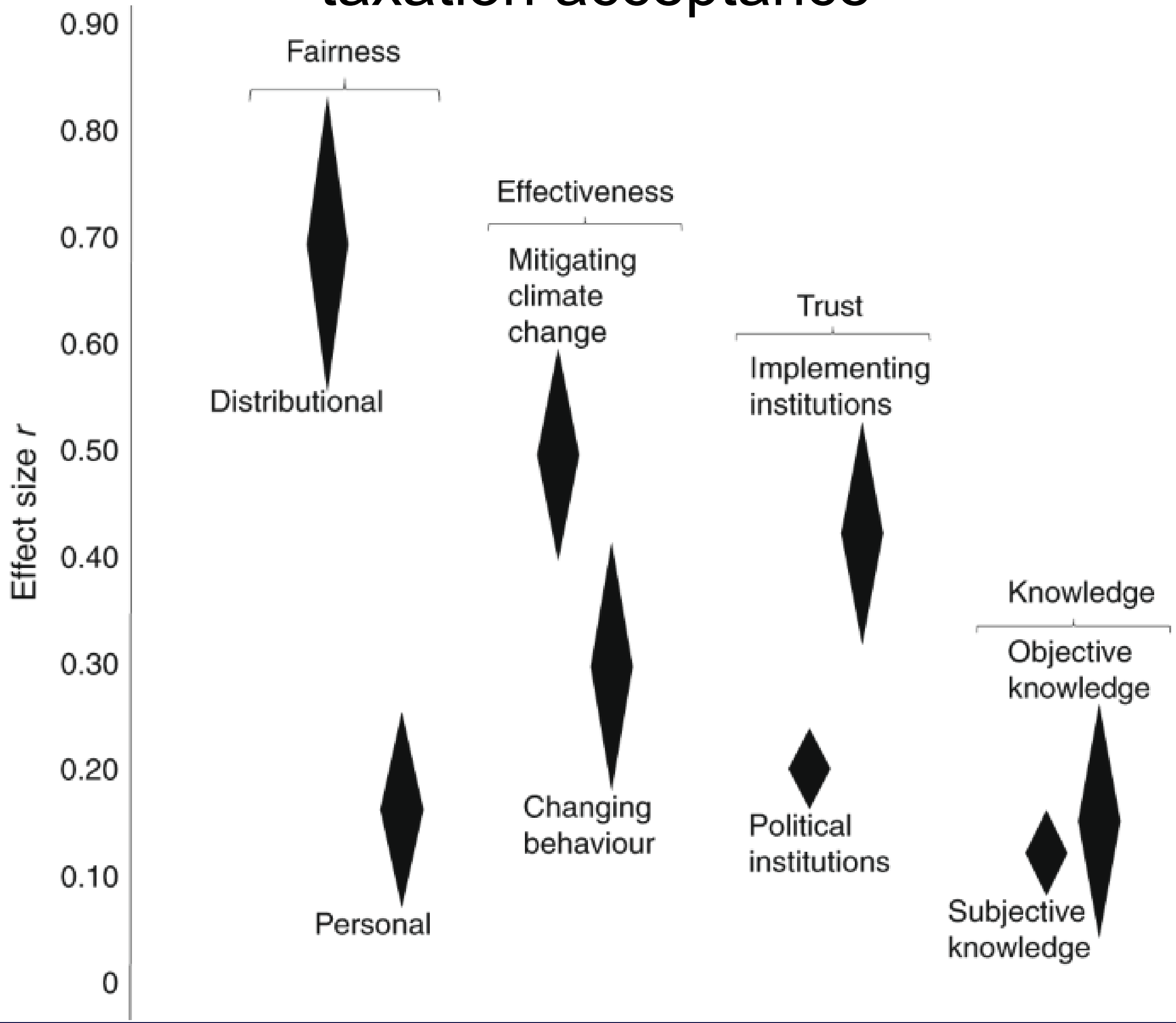


Hoppe et al. 2023 Ann Rev Env & Res

The carrot and the stick

- Economic interventions: pricing, taxation, subsidies
- Internalise in price of goods & services their socioecological costs

Drivers of “sustainability-oriented” taxation acceptance



Bergquist et al 2022 [meta analysis] Nat Clim Ch

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

Behavioural interventions

- All of this works if people are interested in the new goods and services or can change habits

- The concept of nudging, as a public policy tool, has been proposed as a way to change the average behaviour of population to increase sustainability.

Nudging and plastic bags

- 5 pence levy fee introduced in Scotland in 2015
  - About 80% reduction in bags used (replicated in England, Wales and Northern Ireland)

- 2021: levy increased to 10p (partly to ‘re-shock’ the system)
  - There is a dampening of the effect over time

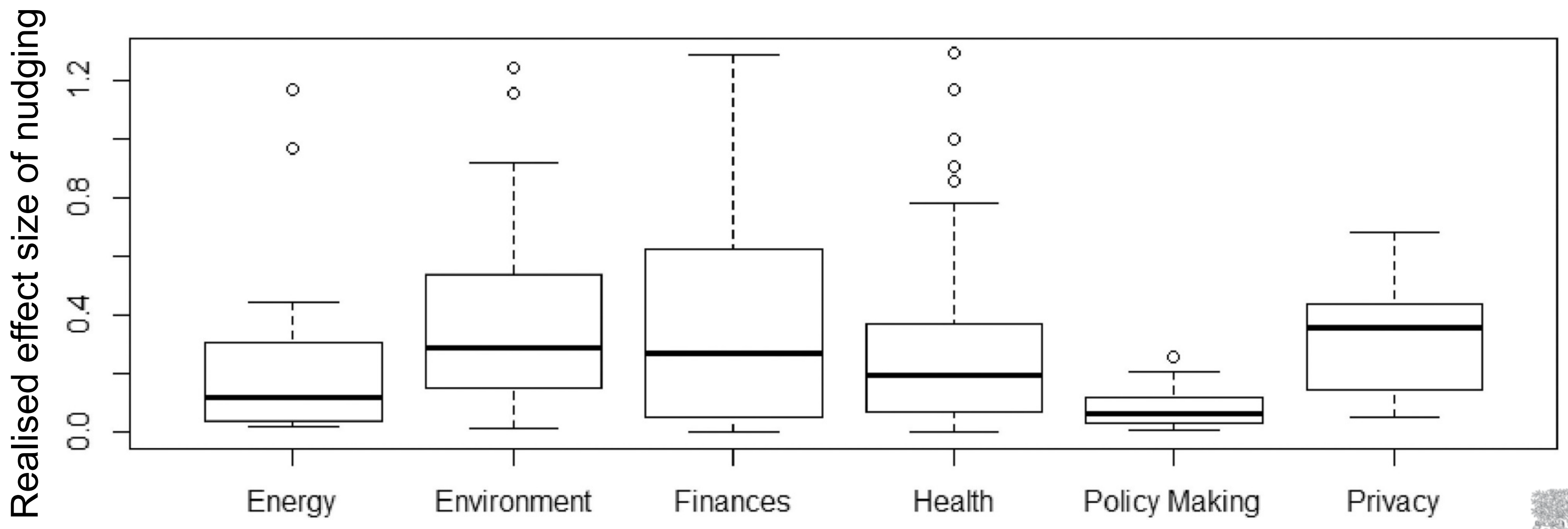
Review | Open Access | Published: 09 March 2021

Effectiveness of intervention on behaviour change against use of non-biodegradable plastic bags: a systematic review

Gbadebo Collins Adeyanju, Teslin Maria Augustine, Stefan Volkmann, Usman Adetunji Oyebamiji, Sonia Ran, Oluyomi A. Osobajo & Afolabi Otitoju

Discover Sustainability **2**, Article number: 13 (2021) | Cite this article

meta-analysis of effects




ELSEVIER
Journal of Behavioral and Experimental Economics
Volume 80, June 2019, Pages 47-58

How effective is nudging? A quantitative review on the effect sizes and limits of empirical nudging studies

Dennis Hummel, Alexander Maedche

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PNAS

ARTICLES FRONT MATTER AUTHORS TOPICS + SIGN IN

LETTER | PSYCHOLOGICAL AND COGNITIVE SCIENCES |

No evidence for nudging after adjusting for publication bias

Maximilian Maier, František Bartoš, T. D. Stanley, +2, and Eric-Jan Wagenmakers Authors Info & Affiliations

July 19, 2022 | 119 (31) e2200300119 | https://doi.org/10.1073/pnas.2200300119

VIEW THE ORIGINAL ARTICLE + THIS ARTICLE HAS A REPLY +

Thaler and Sunstein's "nudge" (1) has spawned a revolution in behavioral science research.

Despite its popularity, the "nudge approach" has been criticized for having a "limited evidence

estimation

Methods - summary

- From a SES map to understanding its state, transient dynamics, and drivers of dynamics

- System dynamics (a branch of Ergodic theory)
  - Deterministic approach:
    - Coupled ODEs (and PDEs)
    - Qualitative approach: causal loop analysis / Bayesian Belief Network

  - Stochastic approach:
    - Simulations: agent-based models / multi-agent models

Agent-based models – what does this mean?

- Systems of interest are often composed of many interacting components and can exist in multiple states
  - Tractability challenge

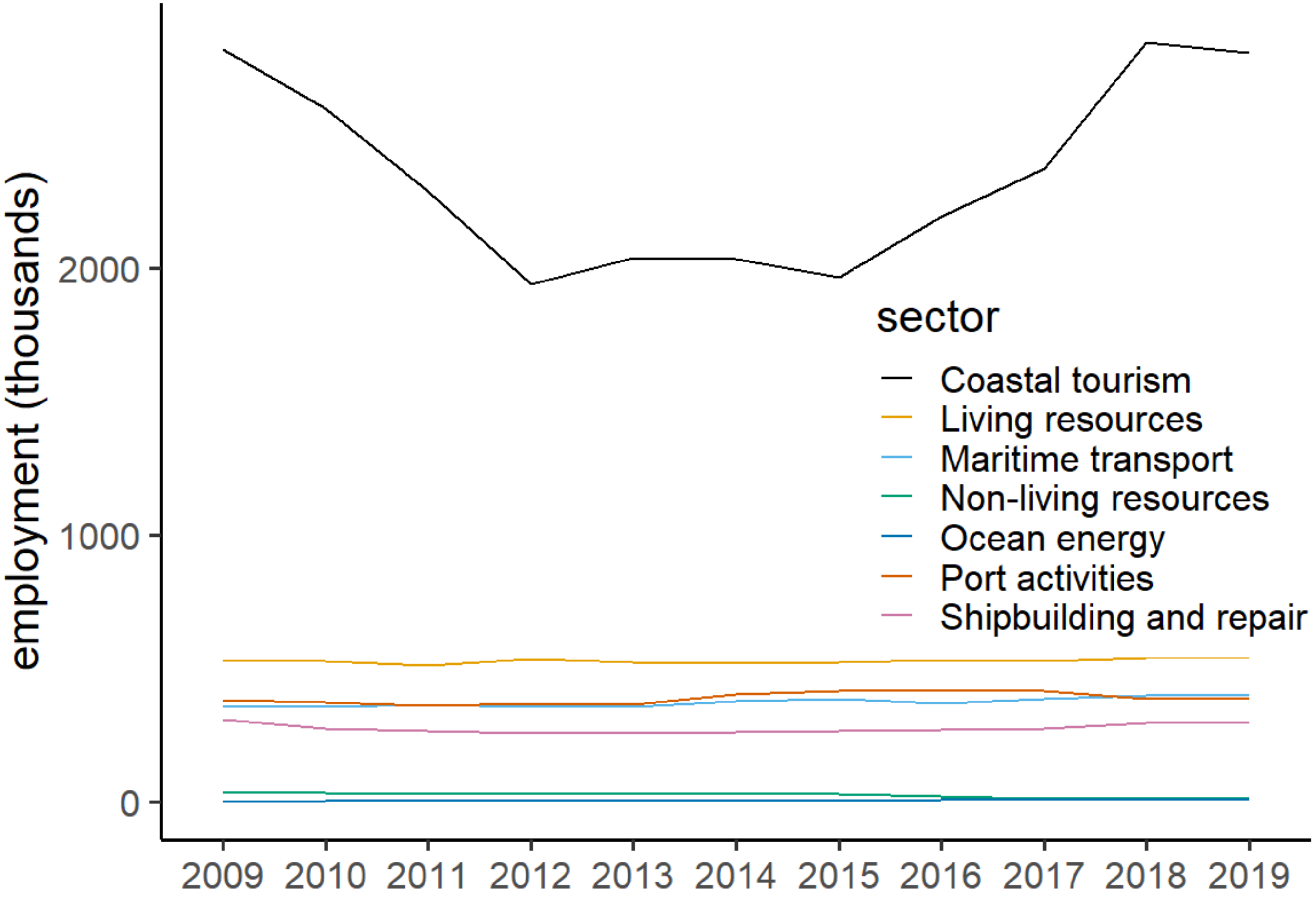
- Their dynamics and emergent properties (sustainability is often an emergent property) are often near impossible to estimate deterministically or statistically

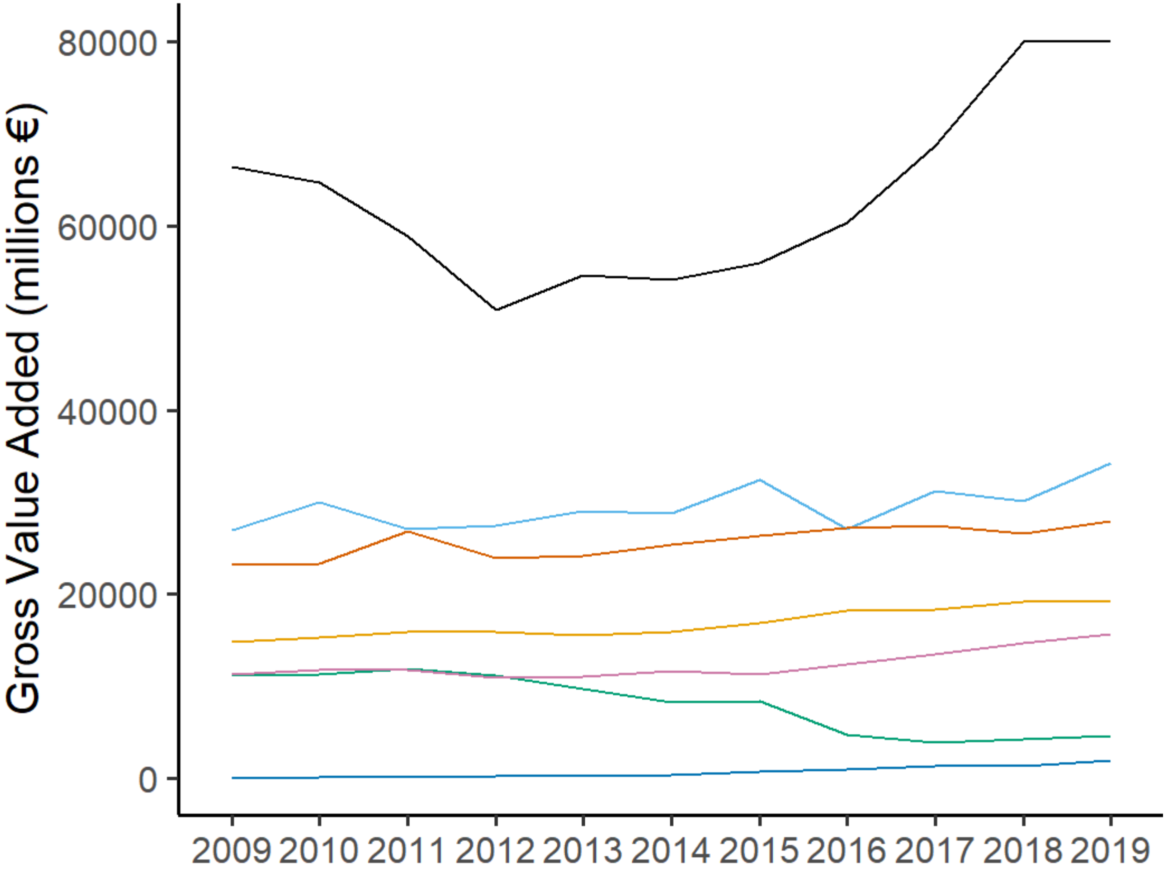
- Stochasticity plays a non-trivial role in system dynamics

- We can replicate a model of the interacting components to assess when to simulate their behaviour and estimate parameters of interest

Socioecological models of sustainable wildlife tourism

EU Coastal tourism – dominant sector of the Blue Economy





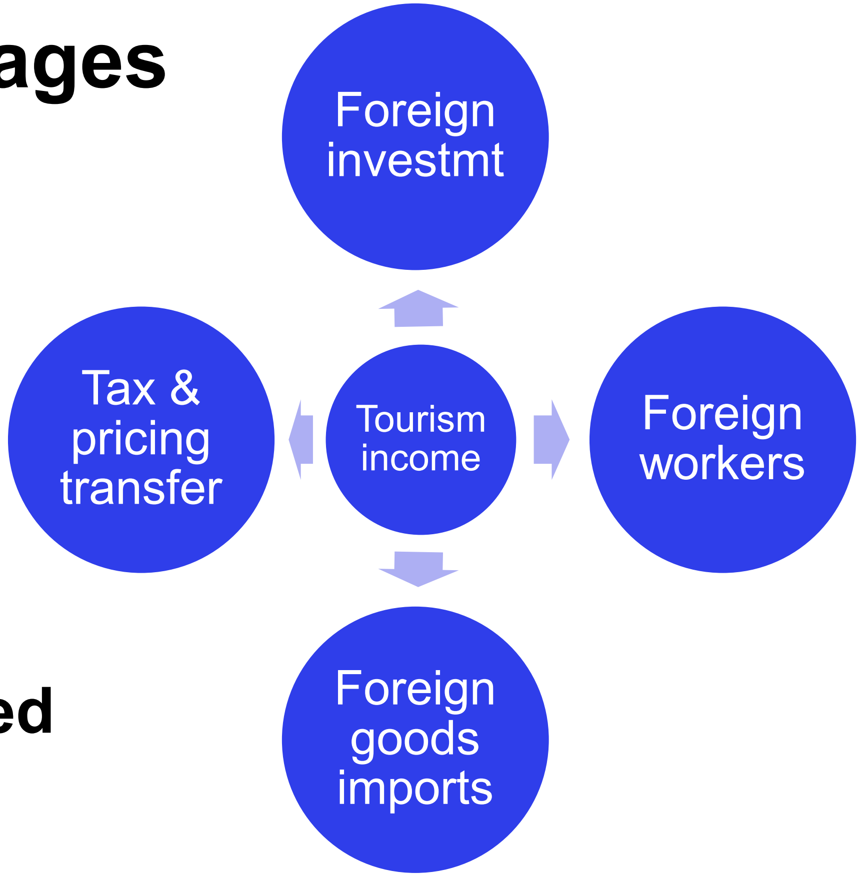
European Commission (2022). *The EU Blue Economy Report. 2022*

Tourism & Recreation Biodiversity Footprint

RED LIST
v. 2022-1

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%

Tourism & recreation economic leakages



1 € spent on tourism generate the following value added

country	Inbound tourism	Domestic tourism
Spain	**0.97**	**1.22**
Portugal	0.78	0.55
Italy	**1.20**	**1.14**
Germany	~0.63	~0.63
UK	0.67	0.51

Figini 2019 EU report GRO-SME-17-C-091a/C

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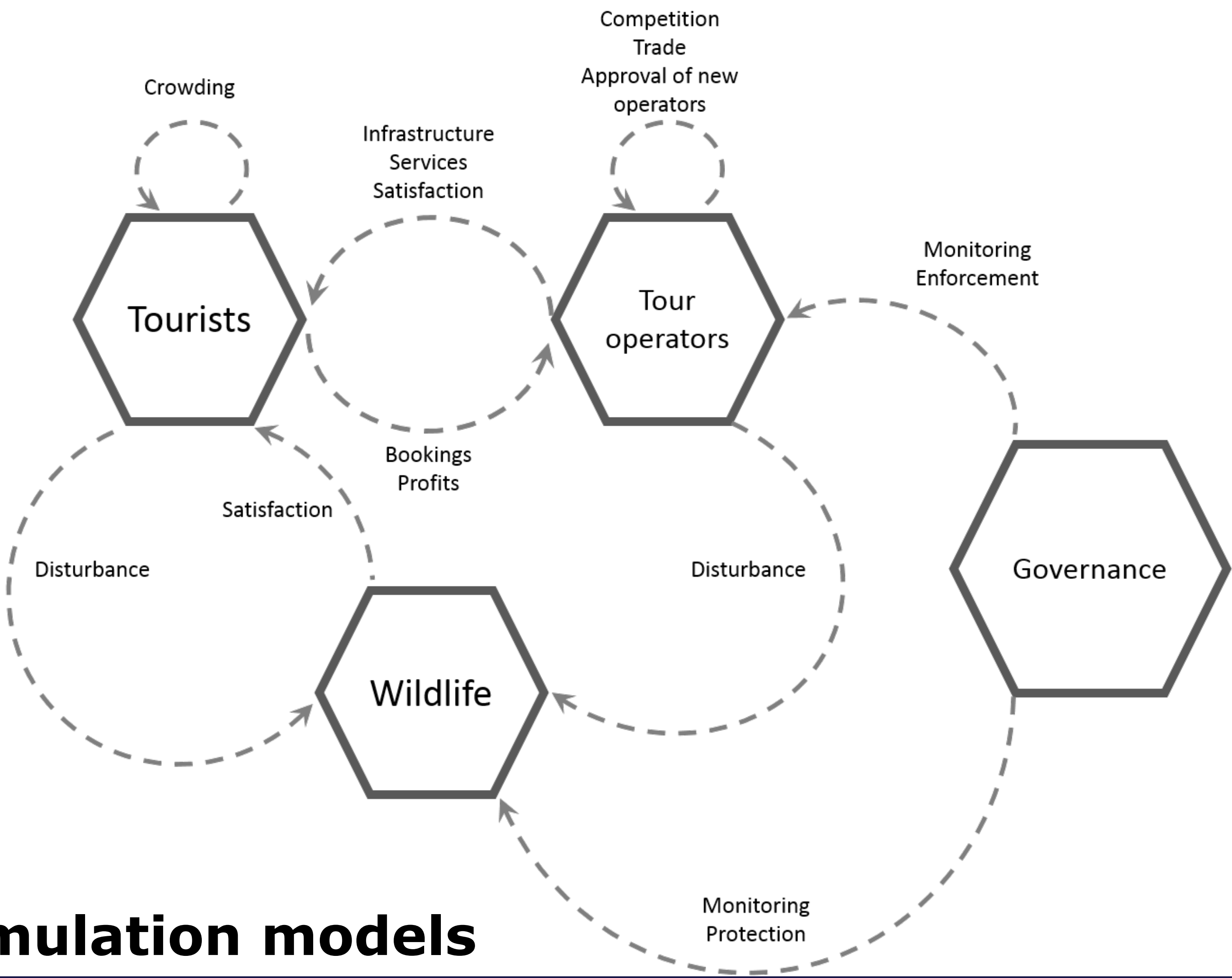
Navigating towards Sustainability?

Integrative modelling of resource management actions in coupled nature-human systems

Governance structure most likely to yield sustainability?

Triple win:

- Economic prosperity
- Environmental quality
- Social justice
  - But still economic target (lack of monopolisation)



Multi-agent simulation models

Pirotta & Lusseau 2015 Eco Appl; Mancini, Coghill & Lusseau 2017 Envtal Sc & Policy; Mancini et al. 2021 Tour Man

Governance models

- Structures
  - Free market
  - Regulations
  - Hybrids (eg Cap and Trade/co-management)

- Accounting for
  - Responsibility assignment
  - Uncertainties (mngnt & monitoring)
  - Operator & customer behaviour

Tour operator component

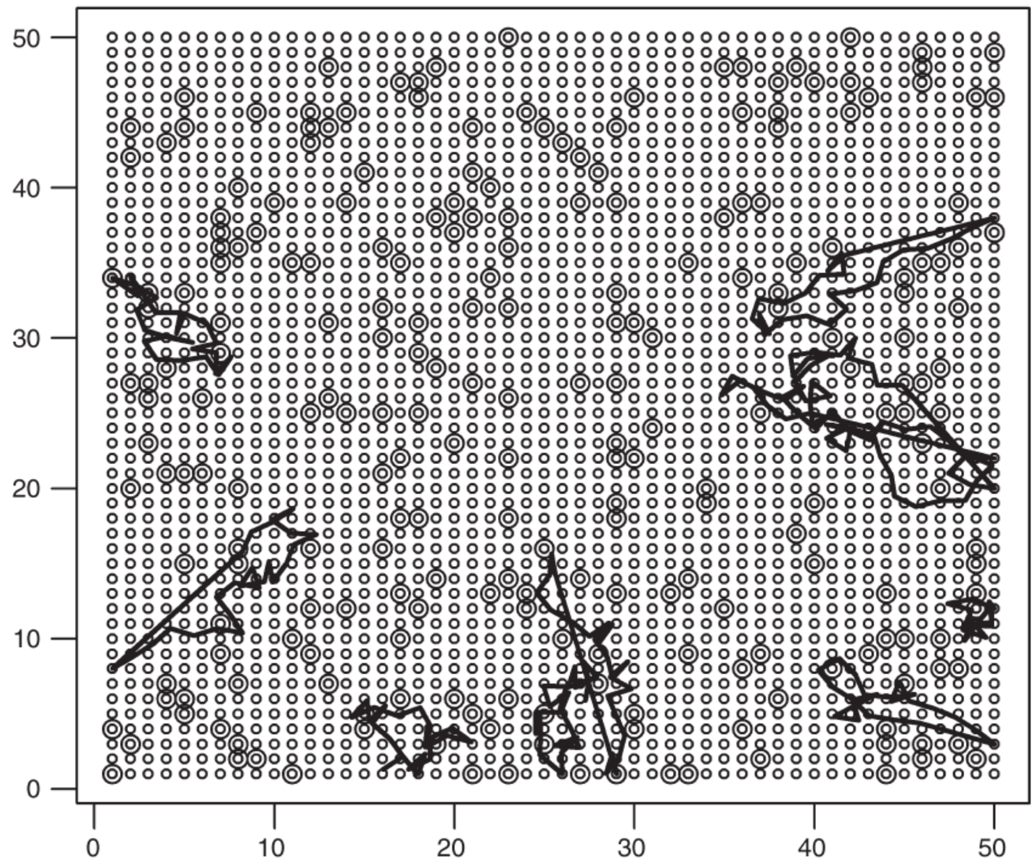
- At each tour, correlated random walk in the ‘study area’
- Discrete grid: encounter overlap wildlife/operator
- Encounter duration: Weibull distribution

- 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

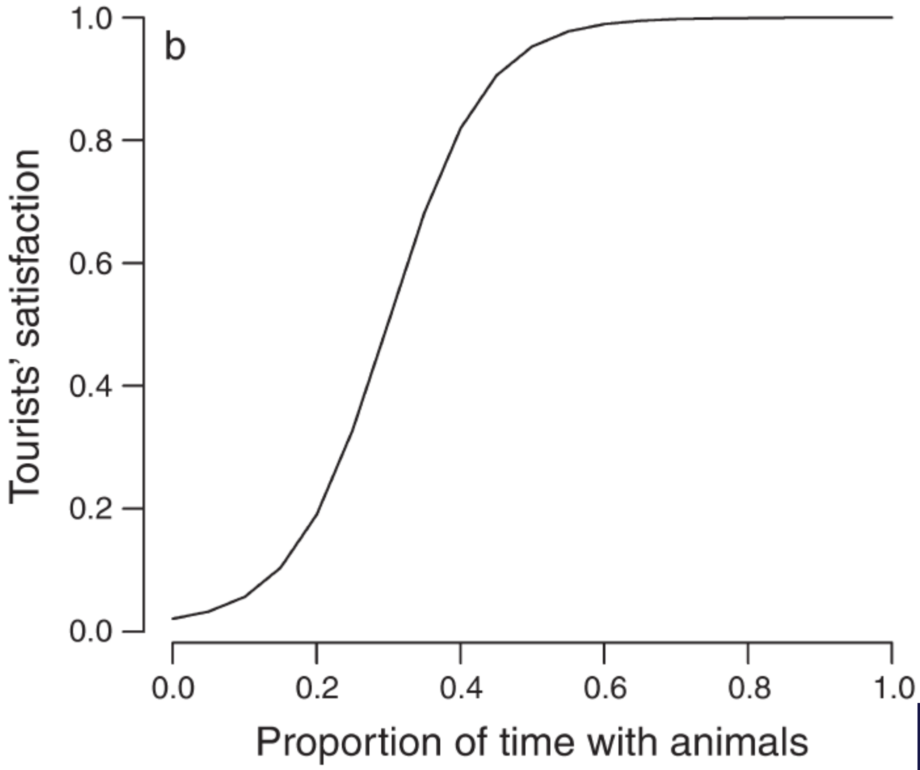
- Tradeable Wildlife Allowance – TWA: When a tour operator at the end of the day has spent all the time they were allowed with the animals, they will try to buy some extra TWA from tour operators that did not spend much of their allowed time.

- If a defecting tour operator is detected, 1000 money units are subtracted from their profits
  - A ticket is about 30 units).

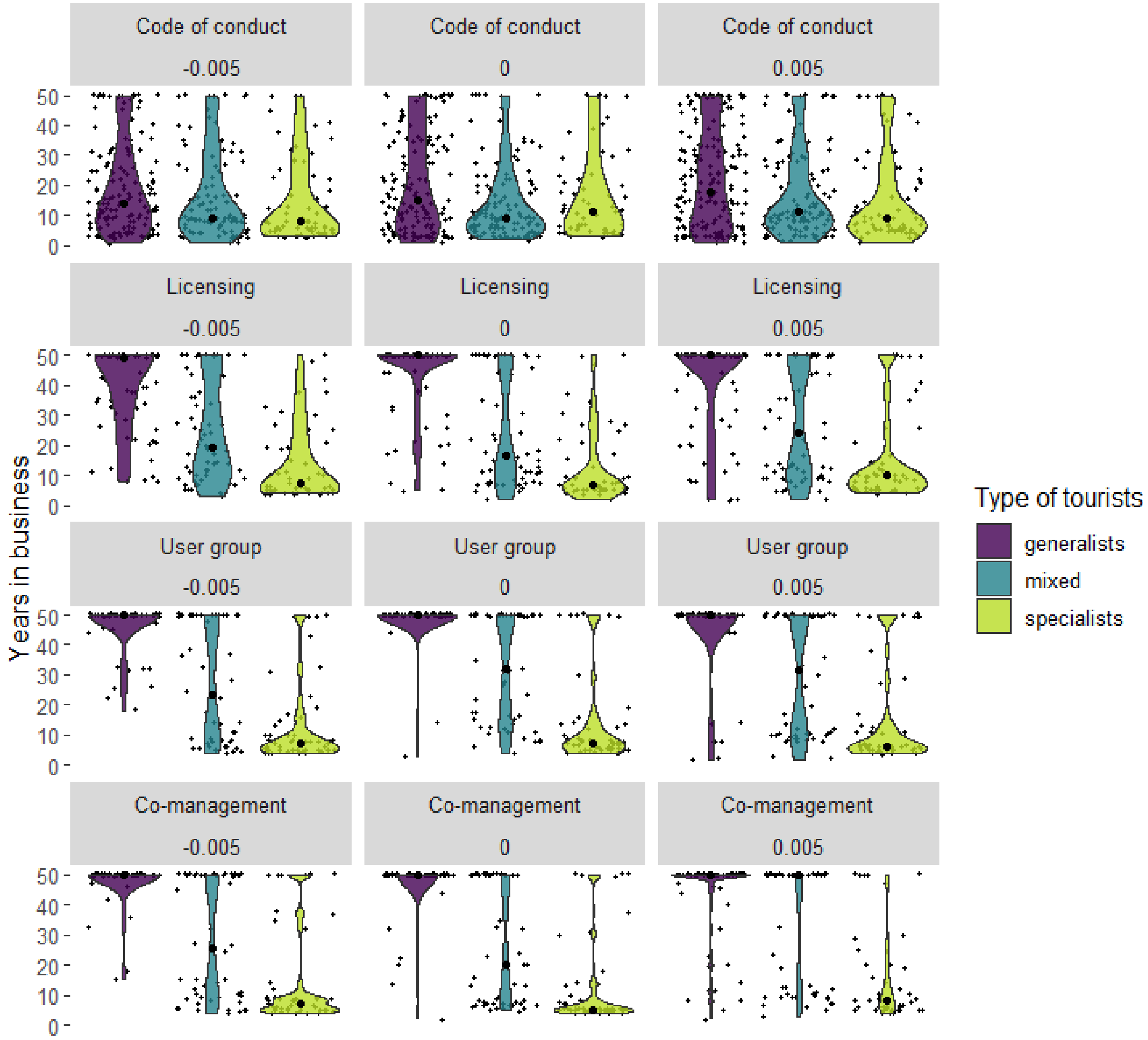
- At the end of the year
  - the tour operators also decide on investments for the next year.
    - infrastructure or services
  - Update ticket price – function of demand:supply ratio.
  - If profits= for 3 years the operator retires.
  - New tour operators can start every year or every 6 years (scenarios)

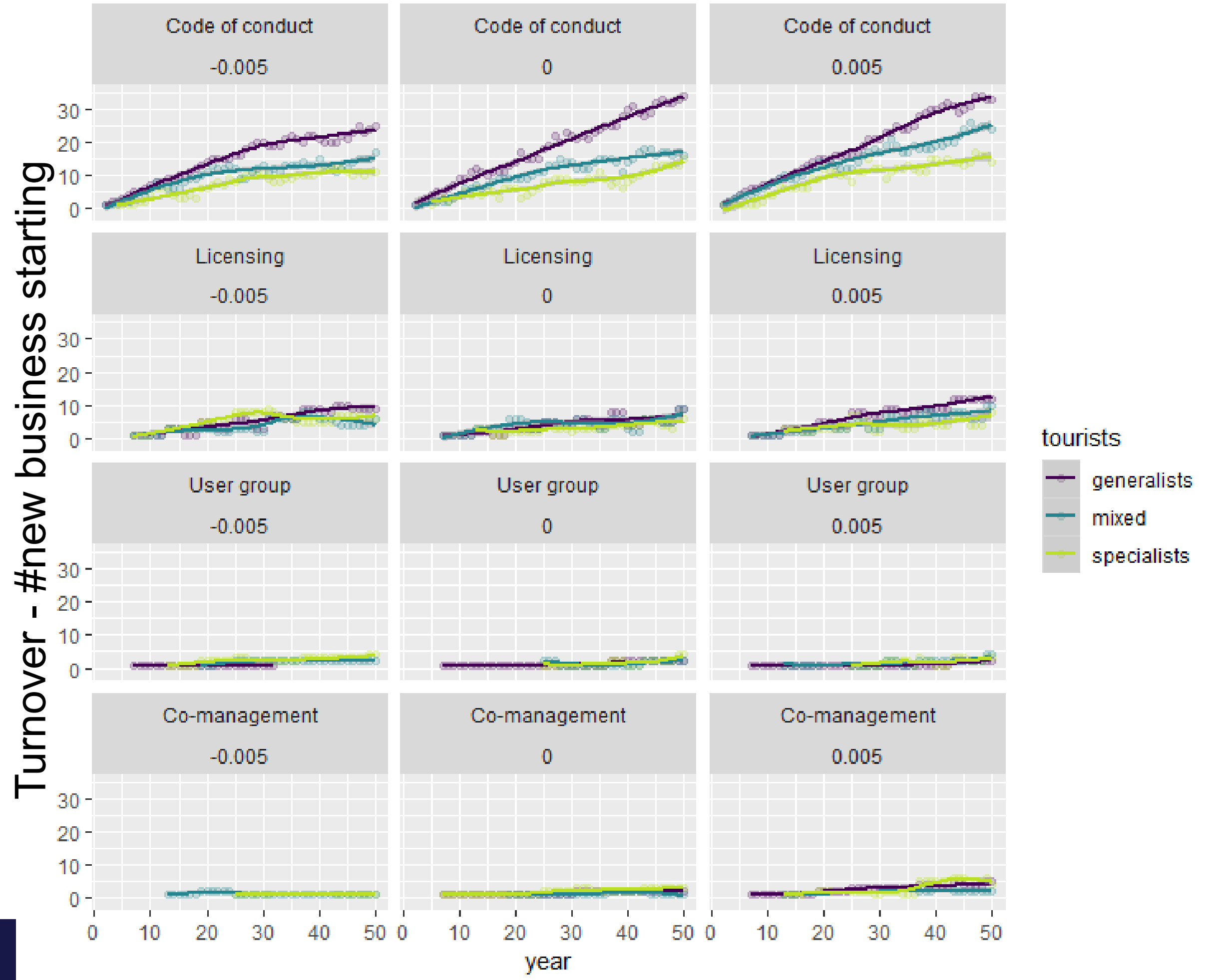
Tourists component

- 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

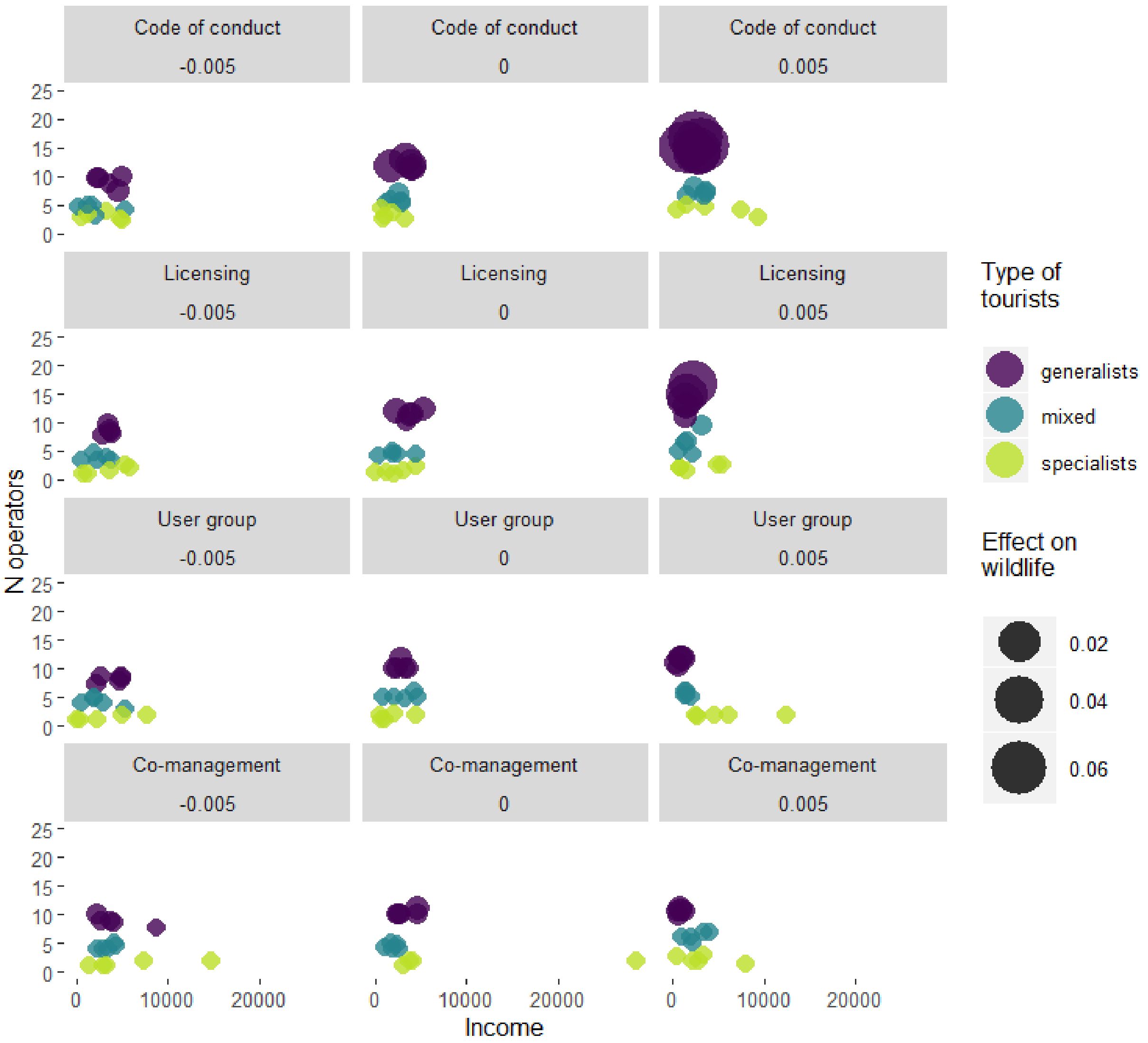


Companies lifespan





monopolisation



Mancini et al. 2020 Tour Man

Outcomes: sustainable governance space

Community-led public-private partnerships

offer the wider sustainable space (over management error & defection rate)

Adaptive management

Changes with destination maturation phases

Tourist typology

Tourist behaviour & typology drives sustainability too

Mancini, Coghill & Lusseau 2017 Envtal Sc & Policy; Pirotta & Lusseau 2015 Eco Appl; Mancini et al. 2021 Tour Man

summary

- We have a toolkit of systemic interventions that can change functional relationships in the way people use the planet
- We have the mathematical tools to understand whether and how system can change state and identify factors that can drive this change
- Systemic changes to improve ‘sustainability’ are possible but contextual (the same change will not necessarily provide the same systemic outcomes across systems)

Sustainability transitions: system dynamics exercises

12 Apr 2024

Preamble

We can estimate system topology using a wide range of approaches. We can use expert and stakeholder knowledge elicitation methods to qualitatively map relationships between different agents (nodes) of the system. We can even, for example using either knowledge elicitation and quantitative data, precise the sign of those relationship and even the shape of the functional relationship. And then of course we can use a wide range of statistical modelling approaches to fully quantify associations in the system or even causal relationship.

We have the mathematical tools needed to make inference about system dynamics from all these different ways to define a system. I have placed a couple of examples in the further reading section for you to have a look. Particularly, you will see that we have there a couple of papers asking the same question (tourism sustainability) from a system defined qualitatively and from the same system defined quantitatively. You will see interestingly from these two papers that the overall conclusions about system dynamics and sustainability are the same! This is not an isolated example.

Those approaches though require some coding in various languages. Here we are going to have an interactive approach to assess the factors influencing the sustainability of two example socioecological systems. To do so we are going to use https://www.insightmaker.com. Why this site? Just because of convenience: it is a flexible and practical tool to build systems quickly and explore their behaviour.

The limitation of using this approach is that we are limited to a deterministic formulation of relationships in the system. We are not able to introduce stochasticity in the behaviour of agents in the agent populations defined.

Before starting

You will need to make an account with insightmaker, go to website and follow the create free account directions.

Once you have an account you will need to add the pre-fabricated systems to your account so that you can manipulate them. to do this you need to **clone** the models from my account.

Go to:

https://insightmaker.com/insight/1S5jZTsFH8G9TBK4XHB2ws/Clone-of-Stage-4-Sustainable-Fishing-Model

you will see that this model is already a clone from a pre-existing model (which I modified for our needs). Then click on “clone insight” (top right, see below) and confirm the cloning on the next page. The model is then added to your account and you can step in it by clicking it from your homepage.

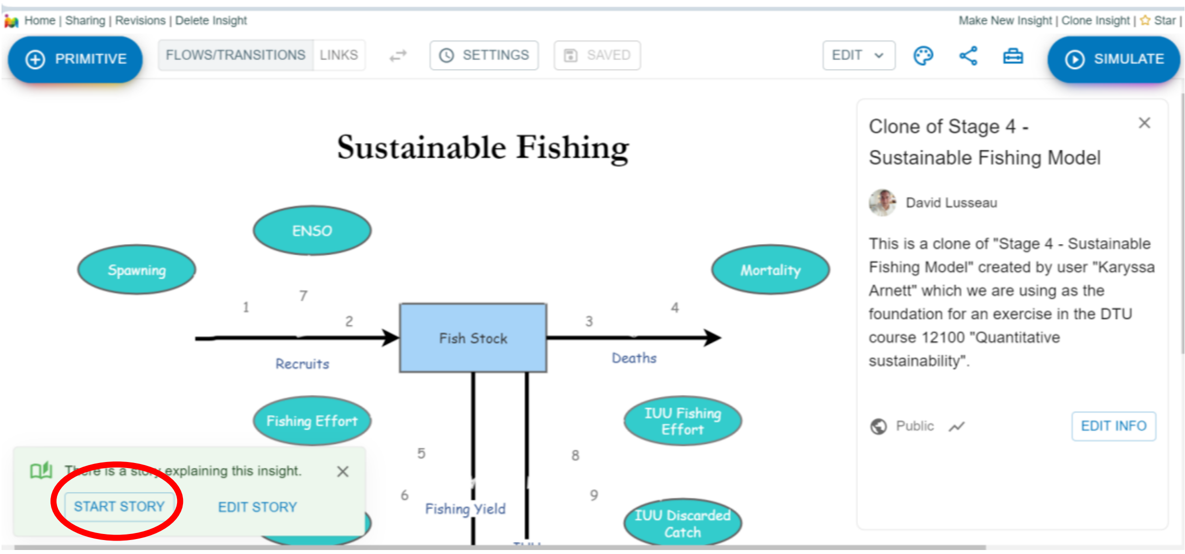
Once that is done, repeat the process for the second exercise:

https://insightmaker.com/insight/7oXIbG6ANRnJNEo2NIdqzr/Clone-of-Fast-Fashion-ISCI-360-Solutions-Final-Edit

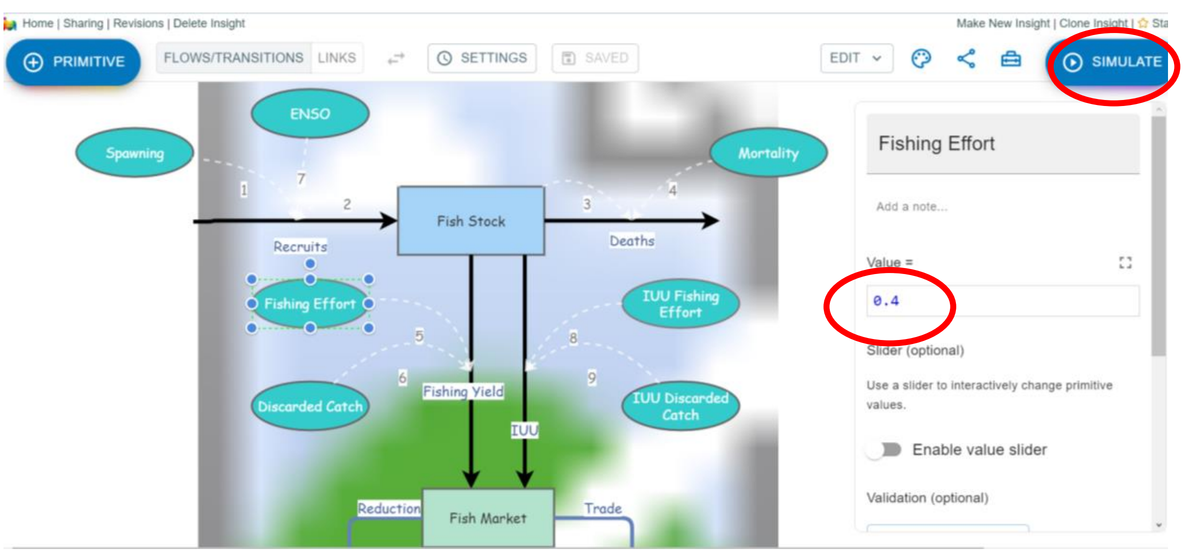
Sustainable fishing

Let's start with an example with which we are familiar from the Resource Management module.

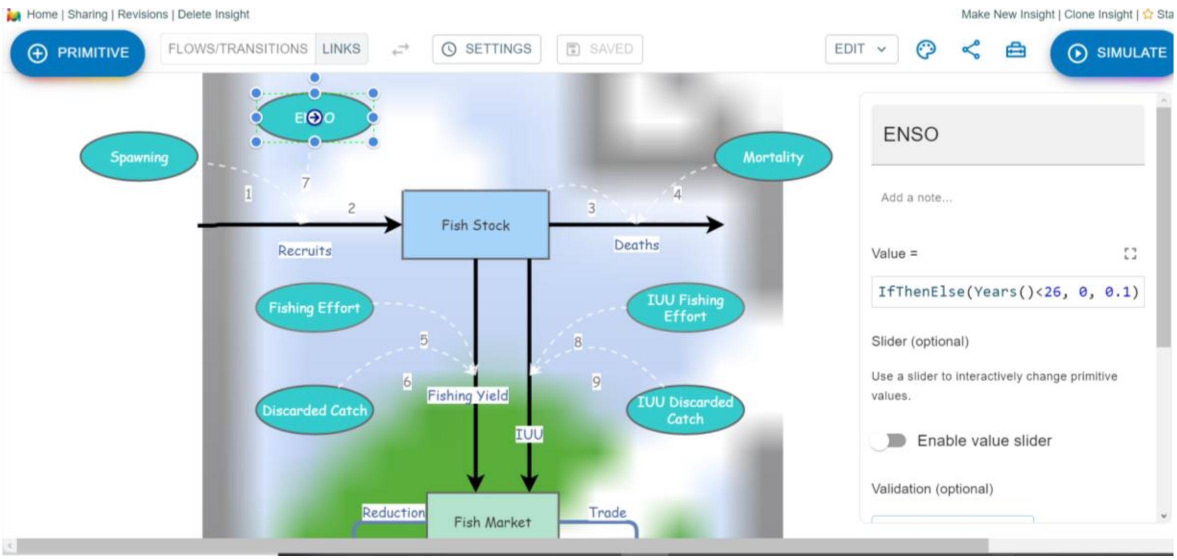
Please go through the story developed by the original model architect by clicking on "start story" (see below) and clicking through the pages (see the outcome of simulations for each stage showing as graphical outputs)



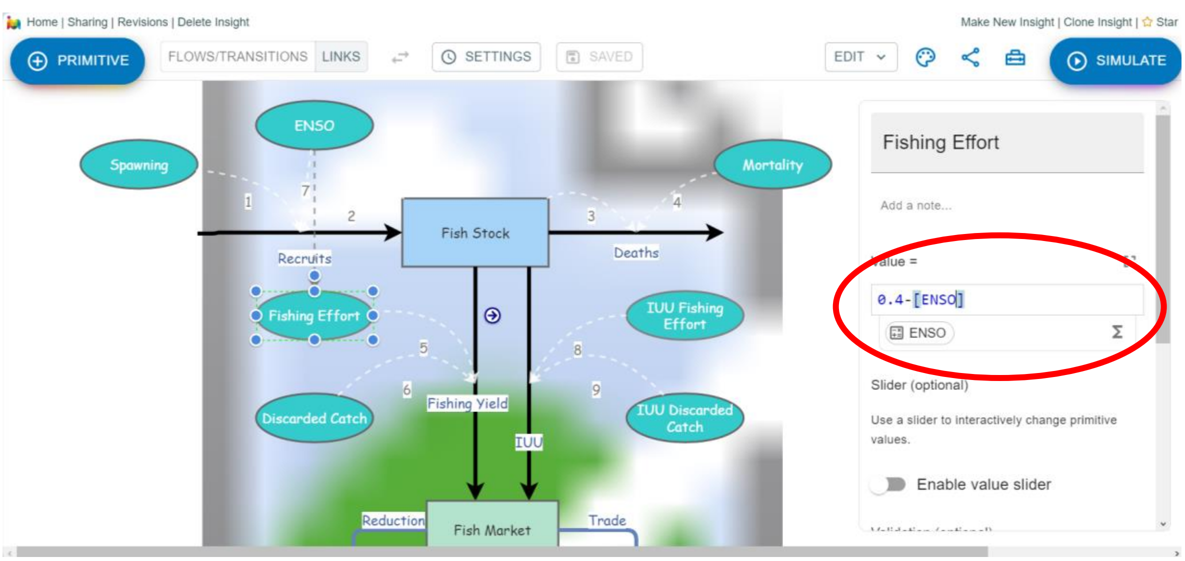
If you click on an element of the model you can see how it is define and you can also change values. For example Fishing effort is a constant and I can change it to any value between 0 and 1by changing the blue value (below). If I then click simulate I will receive the same graphical outputs but updated to account for whatever change I made to it.



I can also make more complicated changes. I can for example assume that fishing effort depends on ENSO (the presence of El Nino effect). To do that I first create a link between ENSO and Fishing Effort by clicking on ENSO. You will see when you click a little arrow appear inside the variable ENSO (below)



Now click and drag that arrow to the Fishing effort variable and a link is created. With that link created, you can now incorporate ENSO as an effect on fishing effort by typing that relationship in the Value box (below):

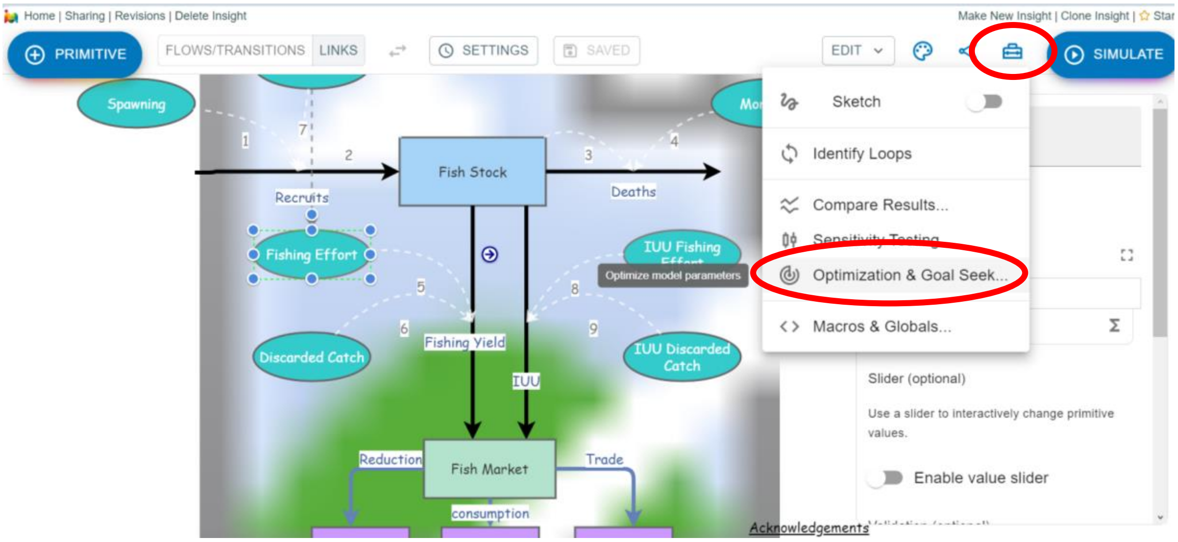


Click simulate again and the outcome will be simulated with this new effect. You can select and delete the link anytime you want. You can use the EDIT drop down menu to undo edits too.

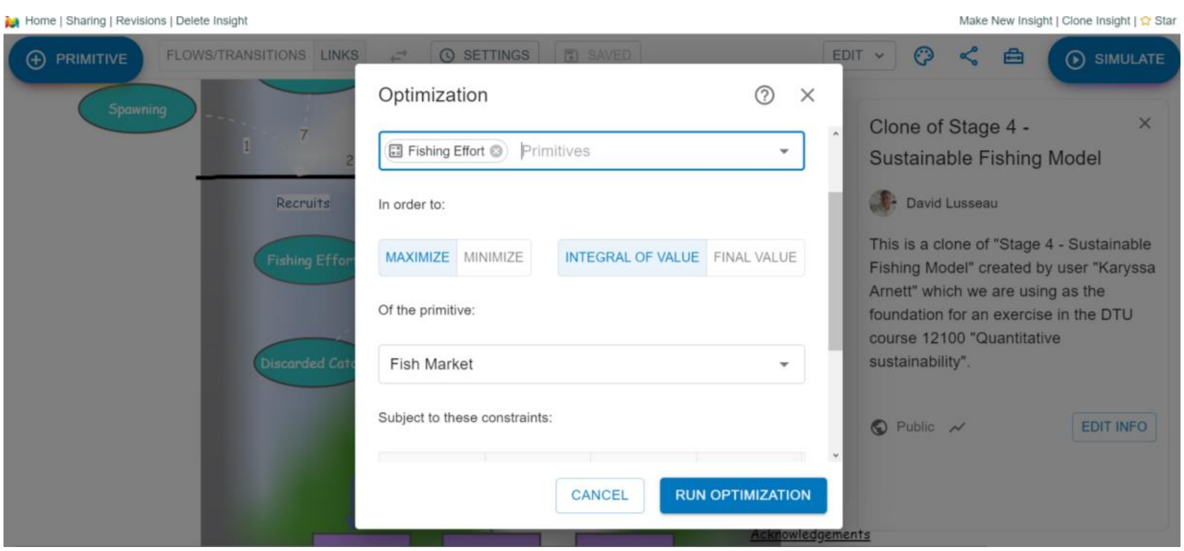
Exploring sustainability

We will try a simple approach with this example: we are trying to maintain exploitation of the stock and at the same time maintain food security.

We can try to optimize the parameters for particular goals to do so click on the toolbox icon and then in the menu that appears on "optimization and Goal seek" (below)



First assess what Fishing Effort value is required to maximise the cumulative annual fish market yield (below)



Questions

You can see that one unrealistic assumption in the fish stock model provided is that spawning and death are not density dependent, this means that the population of herring will grow exponentially indefinitely and therefore of course, a low fishing effort will always have massive rewards. That is also because also the catch per unit effort is not physically constrained in the model, however simply net and vessel size will theoretically constrain the amount of fish that can be caught per unit of effort.

To bring some realism we are going to bring some density dependence on the recruitment rate: it will decrease as the population approaches carrying capacity (here, for mathematical convenience, 1 million tons):

Recruits become: ([Spawning]*[Fish Stock])*(1-[Fish Stock]/1000000)-([ENSO]*[Fish Stock])

We are also going to start the population at 50% of its carrying capacity

Now:

Selection optimization of fishing effort in order to maximise the integral value of the primitive "Fish Market". Then run optimization. Once the optimization has run the value for fishing effort has been changed to the optimized value, you can therefore run again the simulation (click the simulate button) to see the outcome for yield and stock).

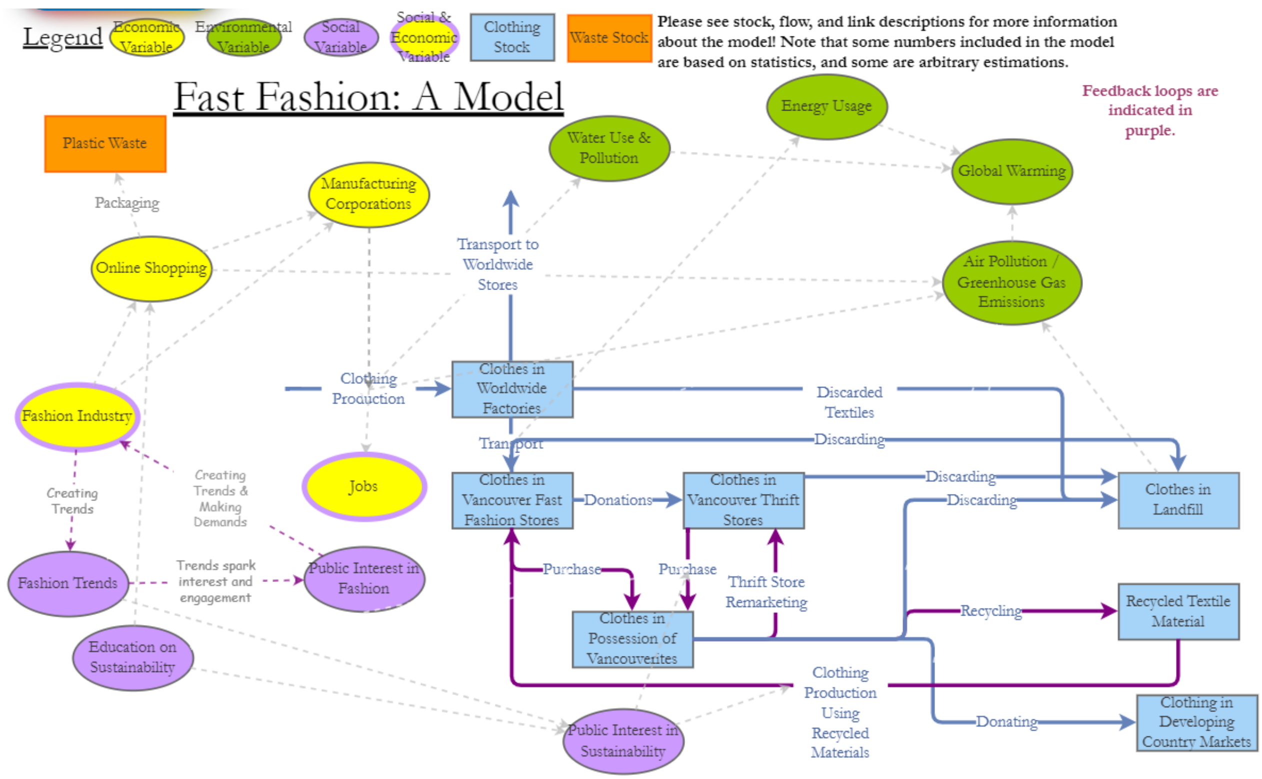
- What happens to the fish stock?
- Repeat the procedure but now optimize for the final value of "fish market". What's the difference?
- What is the temporal pattern of Fish Market? What could be the consequences of it? Could there be a way to mitigate for these effects?

Fast fashion

Fast fashion, or the consumption of clothes and apparels which have a very small lifespan, is yielding a range of sustainability challenges across all dimensions: i) resources are captured to make those clothes which rapidly end up as unused waste, ii) low prices are often achieved by engaging with poor working condition practices during manufacturing, and iii) the waste created puts pressure on waste management where the clothes are consumed.

To mitigate some of those effects, loops can be created in the supply chain of those clothes to increase circularity. We are going to work with the following socioecological system model of fast fashion which introduces a range of variables which can affect the environmental dimension of the sustainability challenge.

https://insightmaker.com/insight/7oXIbG6ANRnJNEo2NIdqzr/Clone-of-Fast-Fashion-ISCI-360-Solutions-Final-Edit



The intervention here is based on the reusing of the clothes by introducing a second-hand market (Thrift stores). The model aims to assess how social interventions (purple variables) can decrease the environmental footprint (green variables) of fast fashion.

First spend some time exploring the relationships between all components in the system

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?

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.

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?