ENV 501 / GR A3 30

Material Flow Analysis and resource management

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Course room
GR A3 30

Computer lab
CM 1 111

Fall 2024

Course outline

Block	Week	8:15 - 9:00 and 9:15 - 10:00		13:15 - 14:00	14:15 - 15:00
Block I: EW-MFA global / national	W1 - Sep 12	Introduction to the course and general concepts	All	Exercise	Project
	W2 - Sep 19	EW – MFA and EW – MFA in different countries	FMC	Exercise	Project
	W3 – Sep 26	EW – MFA in the Swiss context, Urban Metabolism	External Guest – Florian Kohler	Exercise	Project
	W4 - Oct 03	EW – MFA in the Swiss context: Cantons and Circular Economy	FMC	Exercise	Project
Block II: MFA regional / urban	W5 - Oct 10	The Service-Stock-Flows Nexus	CRB	Exercise	Project
	W6 - Oct 17	Dynamic MFA	External Guest – Stefan Pauliuk	Exercise	Project
	Oct 24	Autumn break			
	W7 - Oct 31	Spatial MFA	FMC	Exercise	Project
	W8 - Nov 07	Input-Output Analysis and Material Flow Cost Accounting	External Guest – Vincent Moreau	Exercise	Project
	W9 - Nov 14	MFA and Uncertainty	External guest – Stefan Pauliuk	Exercise	Project
	W10 - Nov 21	Case studies: Waste management in Indonesia / Critical Raw Materials in the Swiss context	GF & FMC	Exercise	Project
Block III: Social sciences and public policy	W11 - Nov 28	Social Metabolism	CRB	Exercise	Project
	W12 - Dec 05	Agent-based model	CRB, FMC, MAH, SLC	Past exam	Project
	W13 - Dec 12	Group Project Presentation	CRB, FMC, MAH	Project	Project
	W14 - Dec 19	Group Project Presentation	CRB, FMC, MAH	Project	Project

Goals of today's lecture

- Understand the relevance of resources and resource depletion
- Situate material flow analysis (MFA) within a set of tools for resource management
- Get an overview of the course

Binder, Felix Martin del Campo, Hecher, Campfens

Content of lecture

- **Historical** overview of resource use in time and space
- **Key issues** in resource management
- **Industrial Ecology** as key research area of resource management
- **Overview of approaches** for resource management

Material Flow Analysis

WHY IS IT IMPORTANT?

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Material Flow Analysis

Searched first in 2008. MFA term has been searched the most in China and in some African countries during the past 5 -15 years

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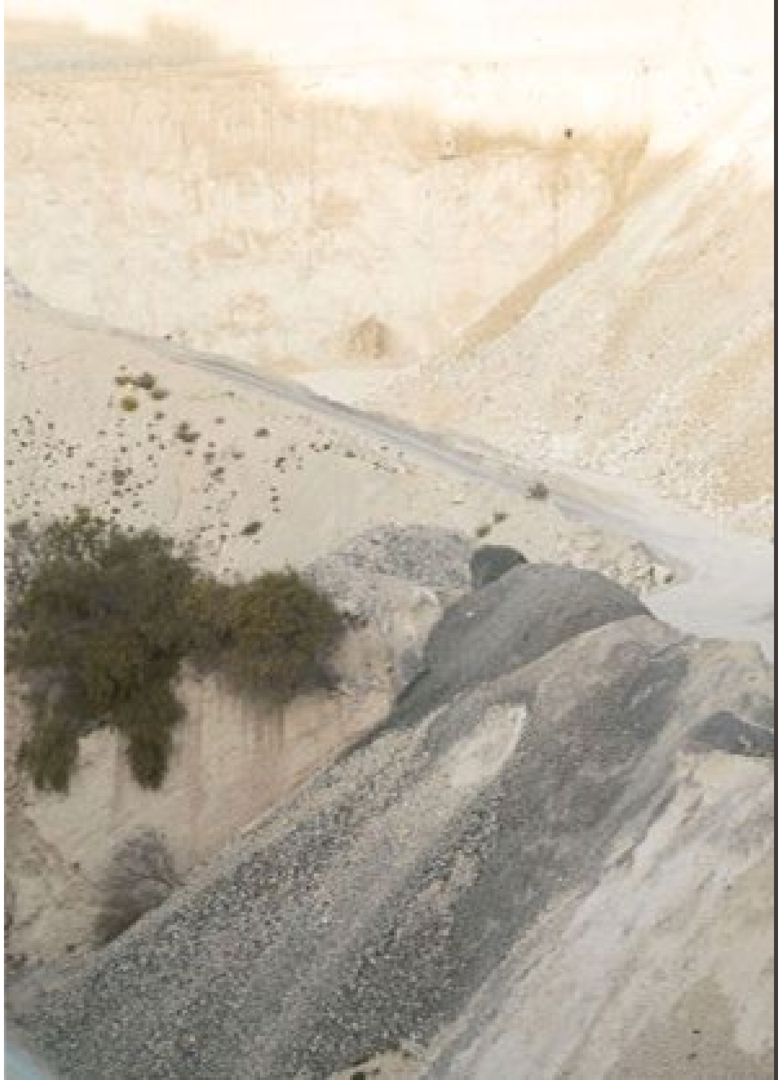
The UNEP triple crises of climate change, biodiversity loss and pollution: Scientific bodies

- **Climate Change**
  - Scientific body: Intergovernmental Panel on Climate Change (IPCC)
- **Nature**
  - Scientific body: Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES)
- **Pollution**
  - Global Environment Outlook (GEO) (also addresses climate change and nature) through its coverage of air/atmosphere, oceans, biodiversity, land, freshwater
- **Resources**
  - Scientific body: International Resource Panel (IRP)

What are the key sustainability issues in relation to resources?

- **Depletion: lack of availability of required/desired resources**
  - Renewable: Sustainable stock; Extraction less than or equal to renewal
  - Non-renewable: Minimum reserve life (Production/Reserves)
- **Environmental damage**
  - Scale of resource use
  - Production and consumption processes and practices
  - Waste management
- **Policies**
  - Depletion: resource efficiency, substitution, circular economy, reduce resource use (sufficiency)
  - Environmental damage: reduce resource use; change production/ consumption/ waste management processes and practices; implications for prices



A historical perspective on resource use

Overview

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Resource: Definition

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A **resource** [rɛˈsʊrsə] (frz. *la ressource* [ʀəˈsuʀs], means, source‘ from lat. *resurgere* ‚rise‘) is a **means to an action or a process**.

Economy: Resources as a production factor - labor, capital, land - new environment

Sociology: Cultural resources

Psychology: Inner potential of the human being

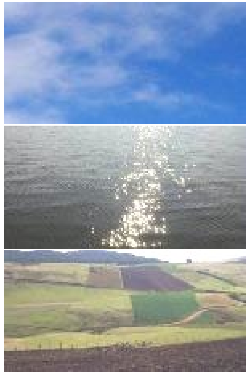
Computer sciences: Network resources

Natural sciences: The largest available stock. Corresponds to the concentration of an ore or another mineral or fossil fraction of the earth crust.

Biological evolution

300‘000 until ca. 30‘000 BC

Binder, 2006



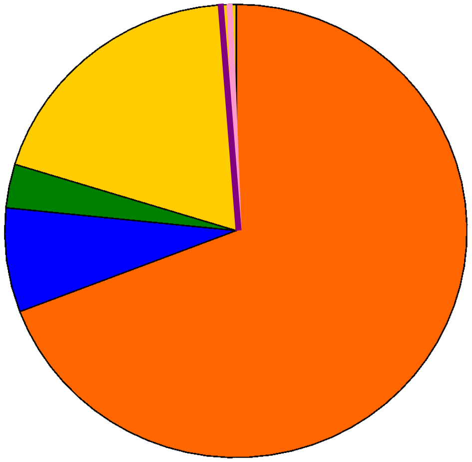
Chronological table
Hunters and gatherers

The first humans

- Preservation of the species
- Equilibrium: use and regeneration of resources

Biological evolution: Chronological table

- Big bang: 1. January 0:00
- World: 15. September
- Flora: 24. September
- Fauna: 18. December
- Humans: 31. December 22:43
- Jesus Christ: 4.6 seconds before midnight



Binder, 2006; adapted from Lindl and Klötzer, 2006

Binder, Felix Martin del Campo, Hecher, Campfens

Cultural evolution

Agricultural & industrial age

Humans in the 20th/21st century
- Changing needs
- Increasing per capita consumption
- Increase of human impact on resource use

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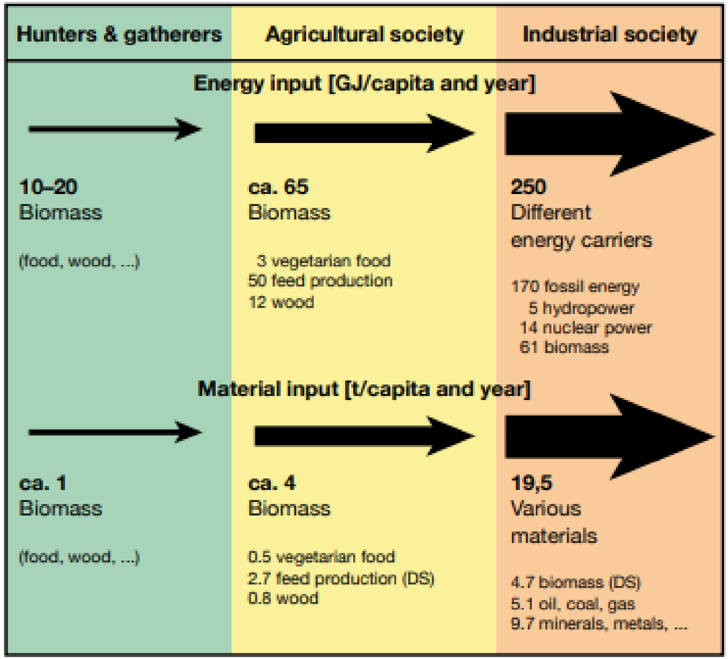
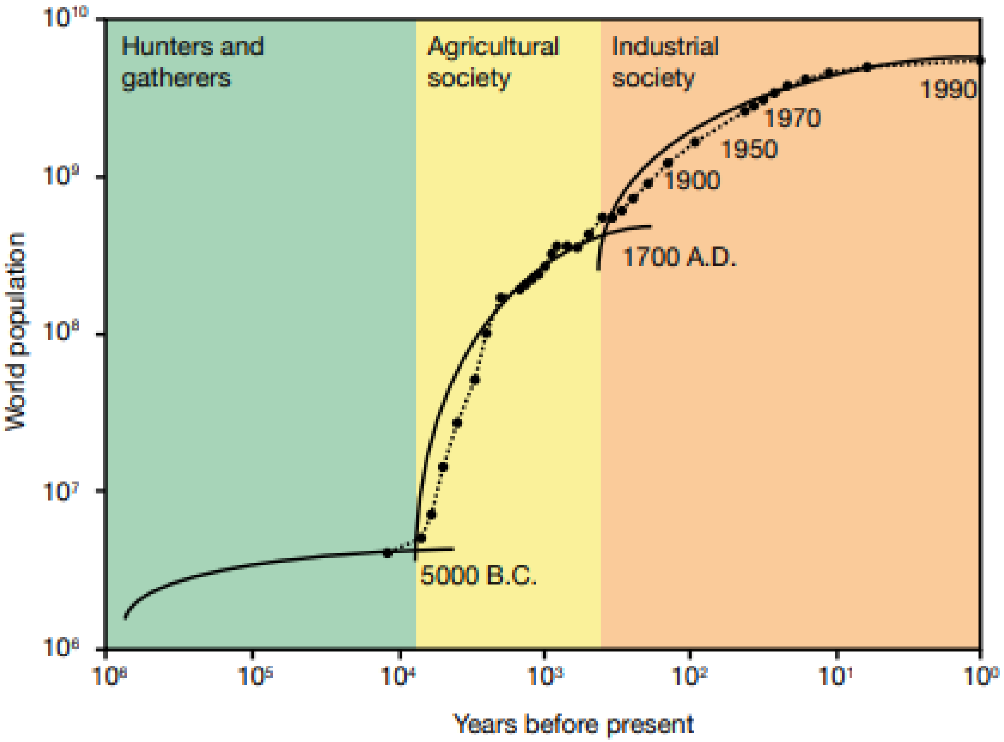
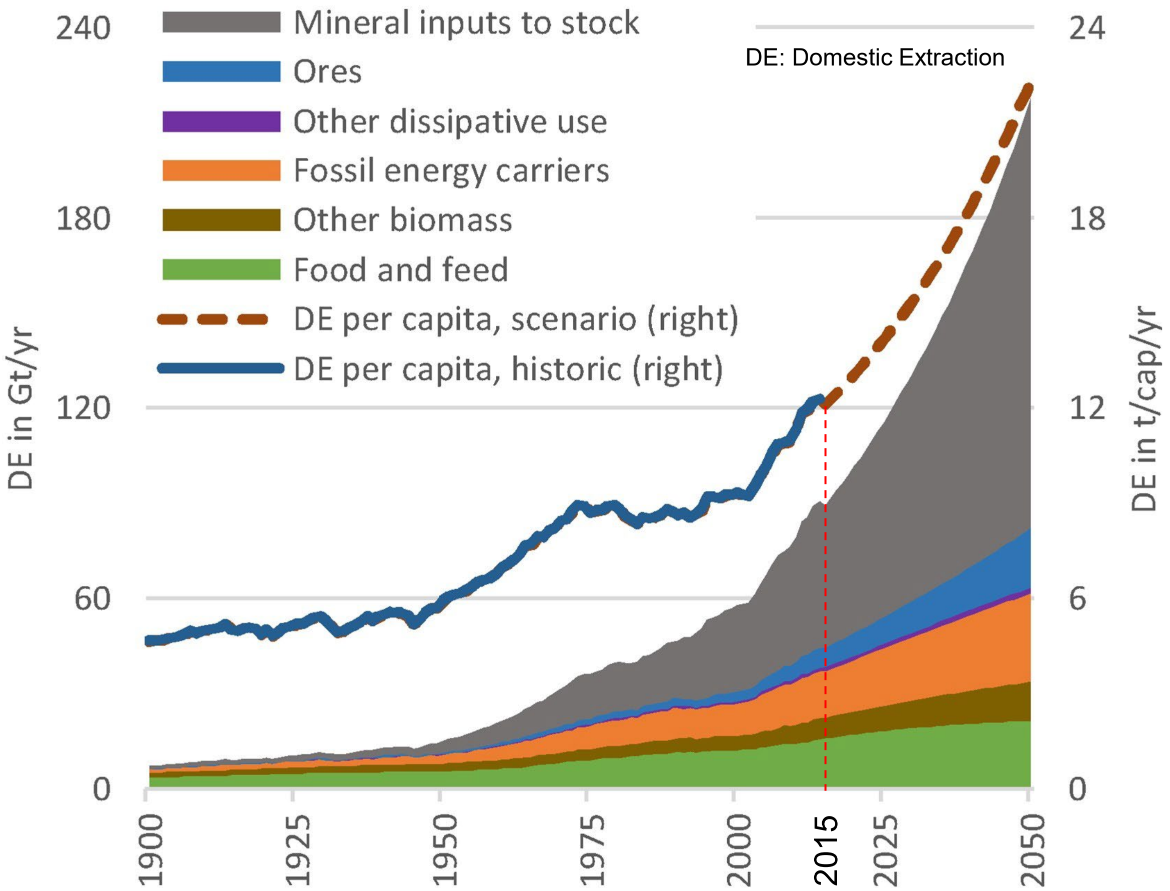
Changes in the the material / energy use





ipo, Hecher, Campfens

Scenarios of global material extraction



Krausmann et al. 2018

Binder, Felix Martin del Campo, Hecher, Campfens

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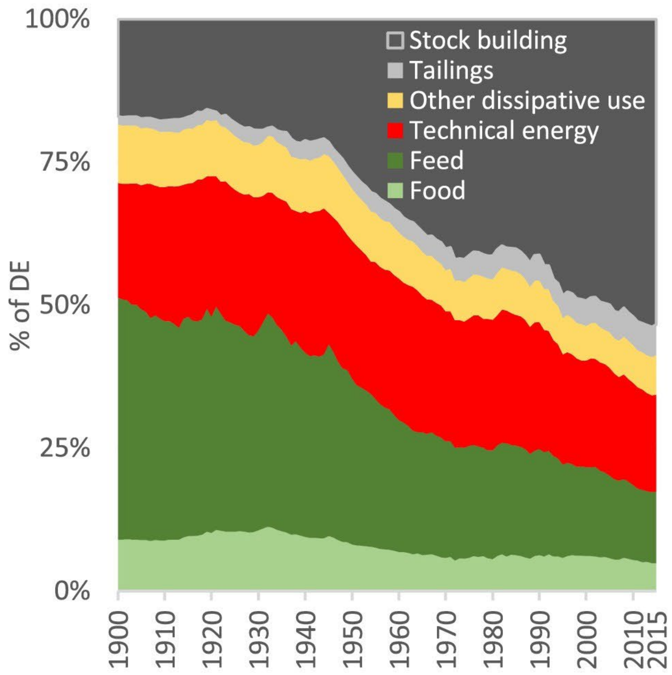
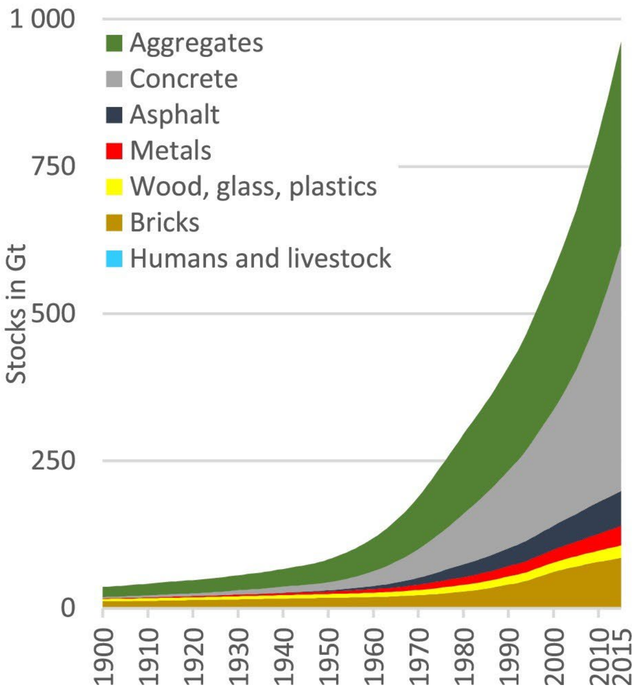
Global material flows from 1900 to 2015.

Material use



Stocks



Krausmann et al. 2018

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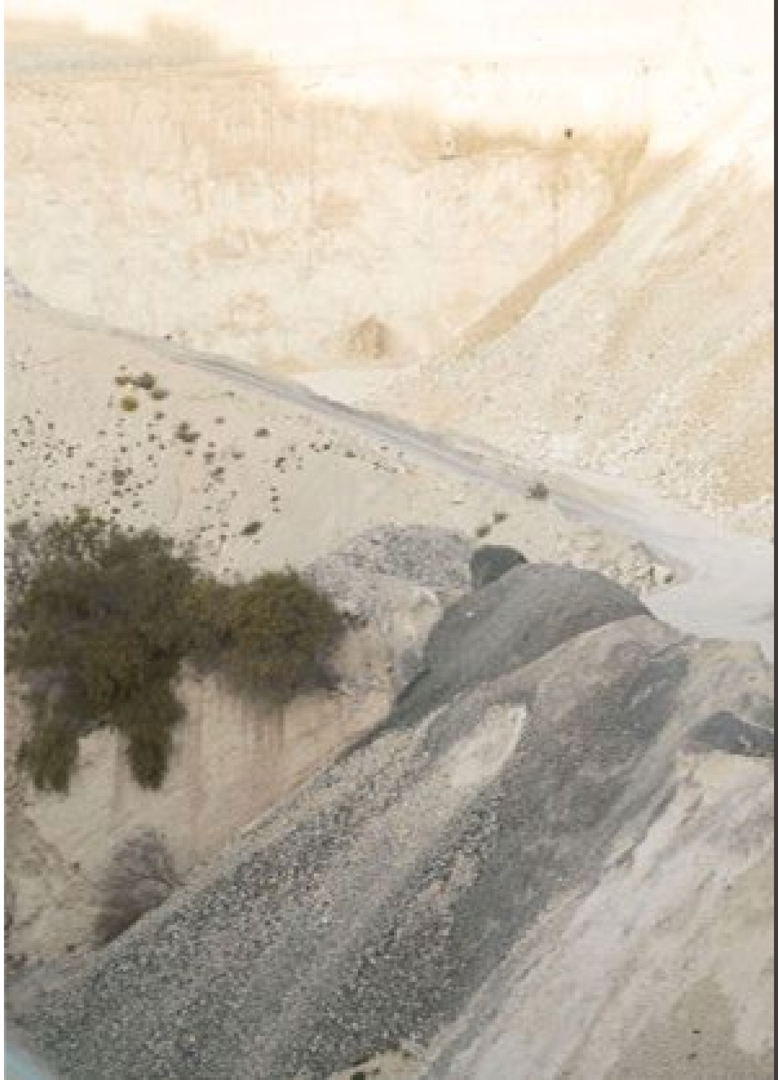

A historical perspective on resource use

Reserves and demand

Resources vs Reserves

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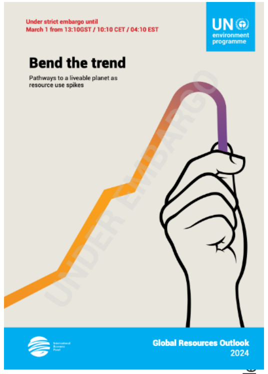
- ***Resources***: the “concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible”
- ***Reserves***: “that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth

Resources vs Materials



***Biomass**: crops for food, energy and bio-based materials, wood for energy and industrial uses*

***Fossil fuels**: covering coal, gas and oil*

***Metals**: such as iron, aluminum, copper, energy transition minerals*

***Non-metallic minerals:** sand, gravel, limestone and minerals used for industrial applications*

Air, Land

Oceans, Freshwater

Materials: *Everything extracted from the Earth*

Includes biodiversity

Resources: *Materials +Air, Land, Oceans and Freshwater*

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[Global Resources Outlook 2024, International Resource Panel, UNEP, 2024]

International Resource Panel

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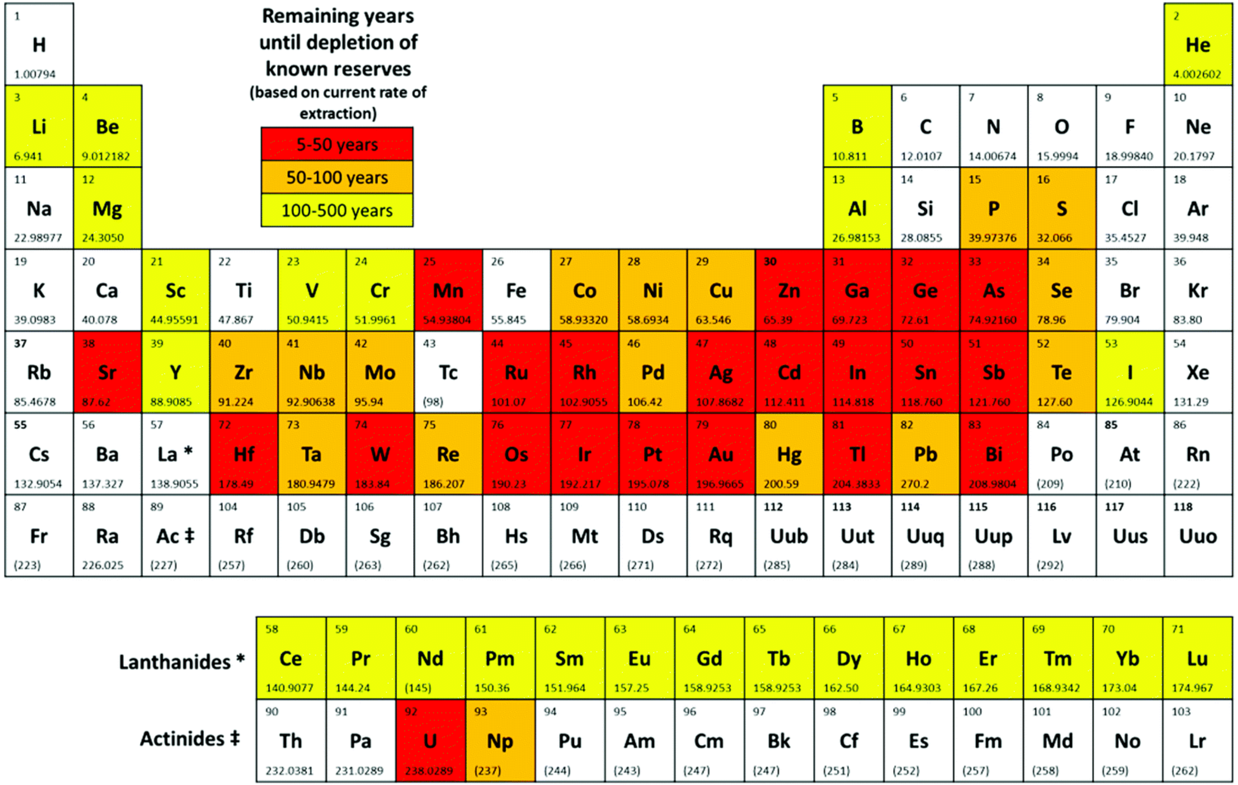
Years until depletion of resource



J. Hunt & S. Matharu, 2015

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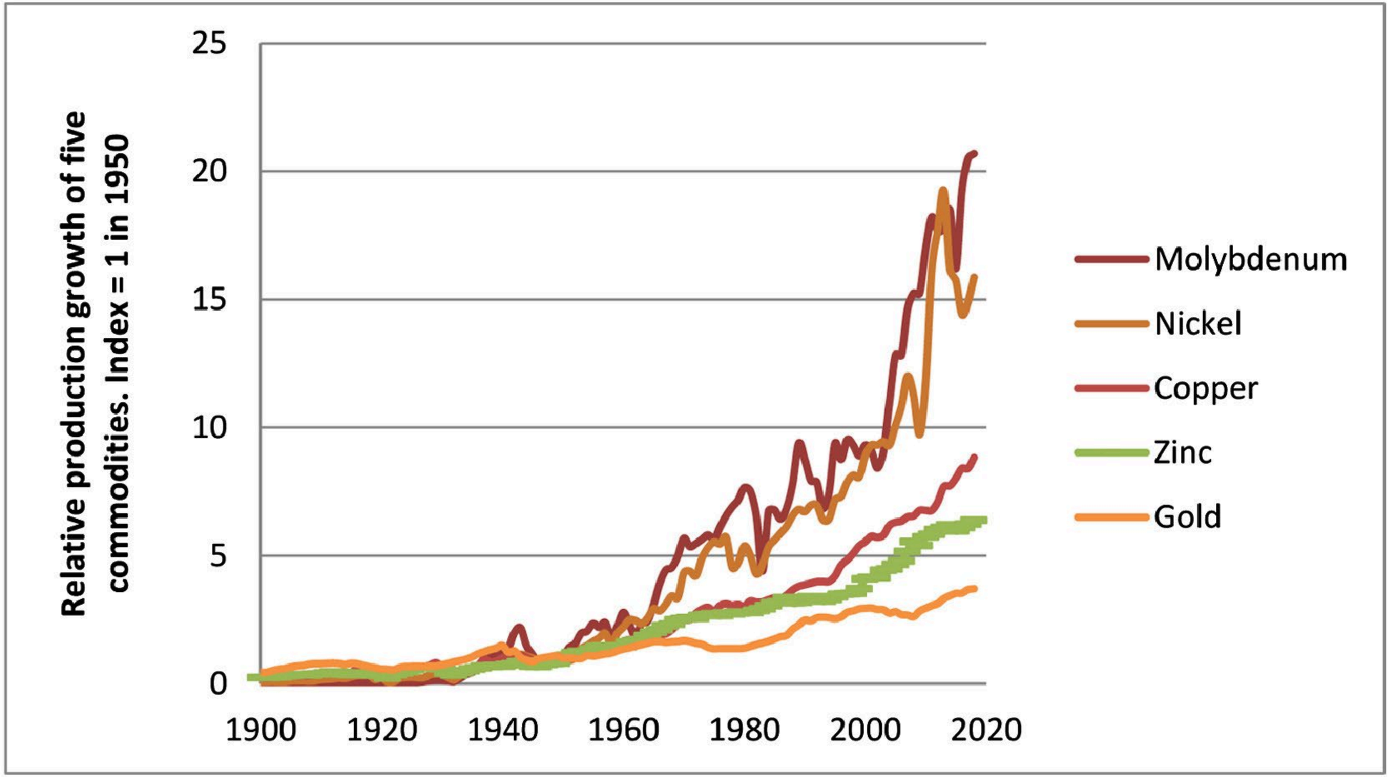
Global production of metals



Heckens, 2021 with US Geological Survey, 2015, 2018, 2019

Elements in an intel circuit board

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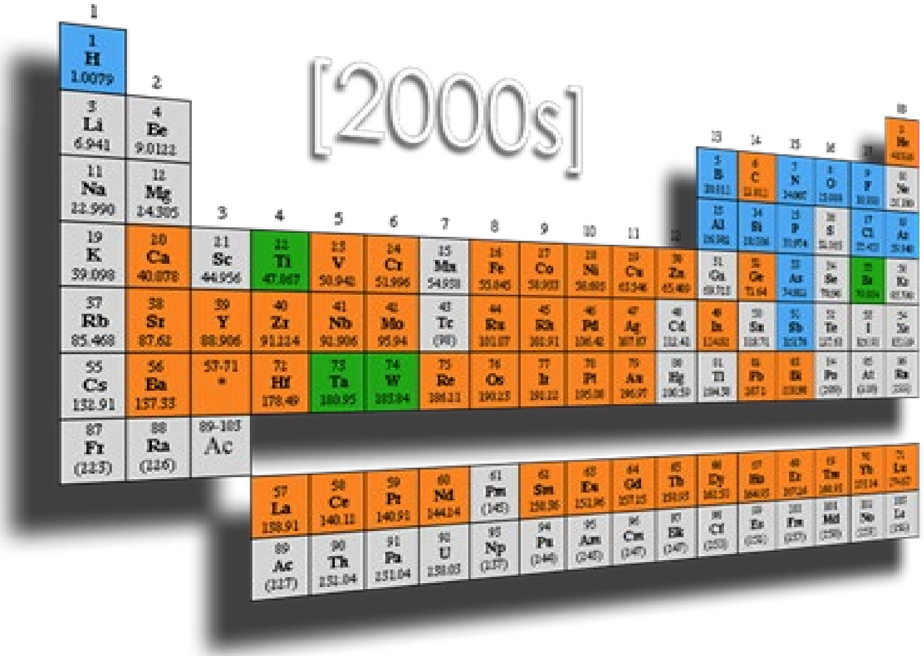
+45 Elements
(Potential)

Before 1980
Today
Future



McManus, Intel Corp., 2006

Elements needed for fueling our technologies

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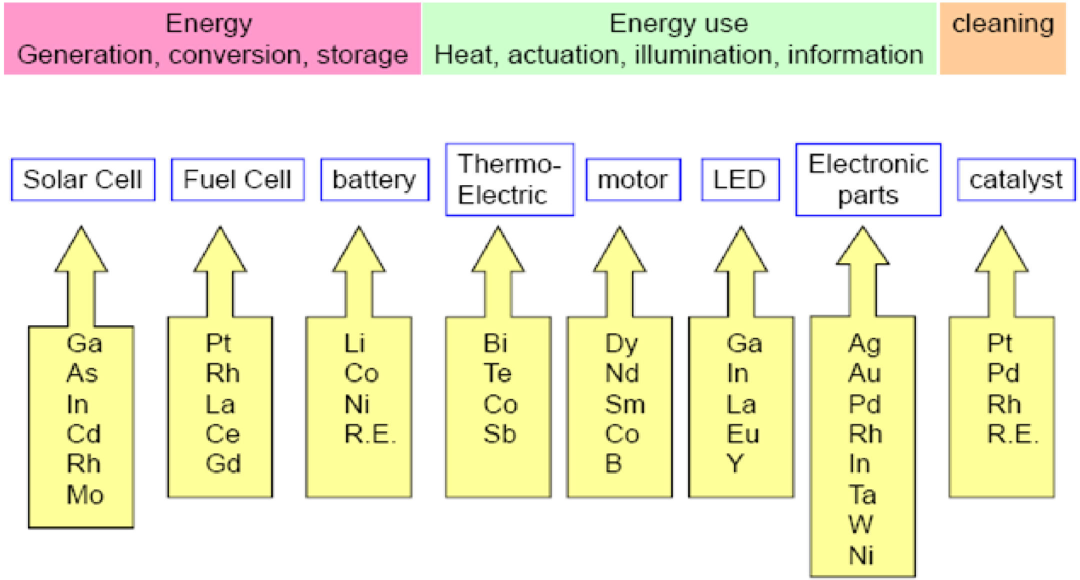
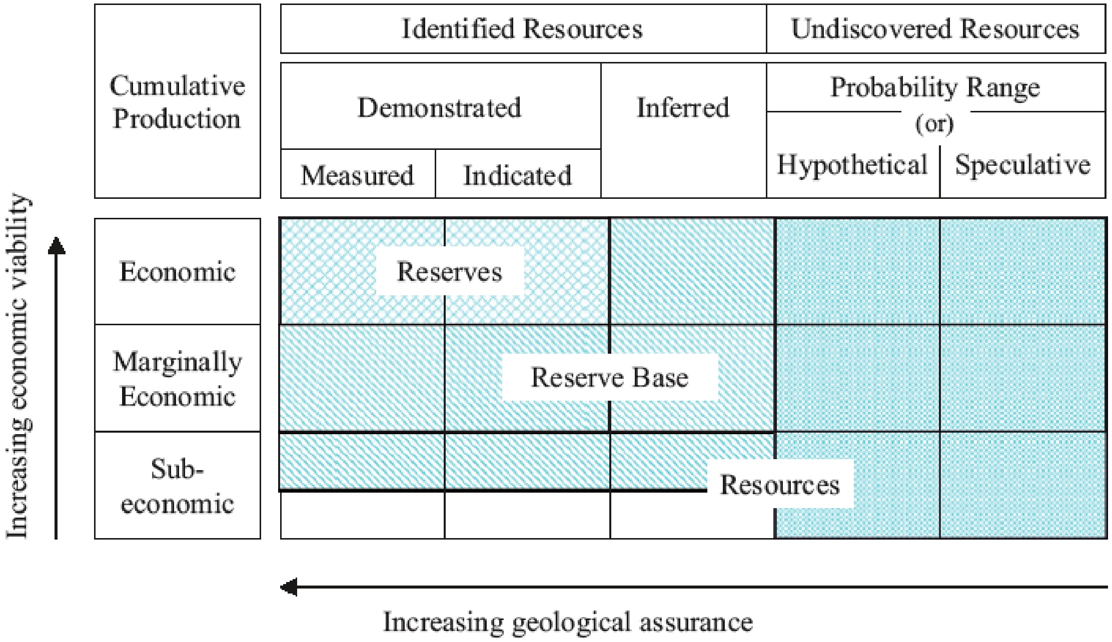


Green technologies increase the demand for scarce resources

The lockdown: Shifting material consumption?

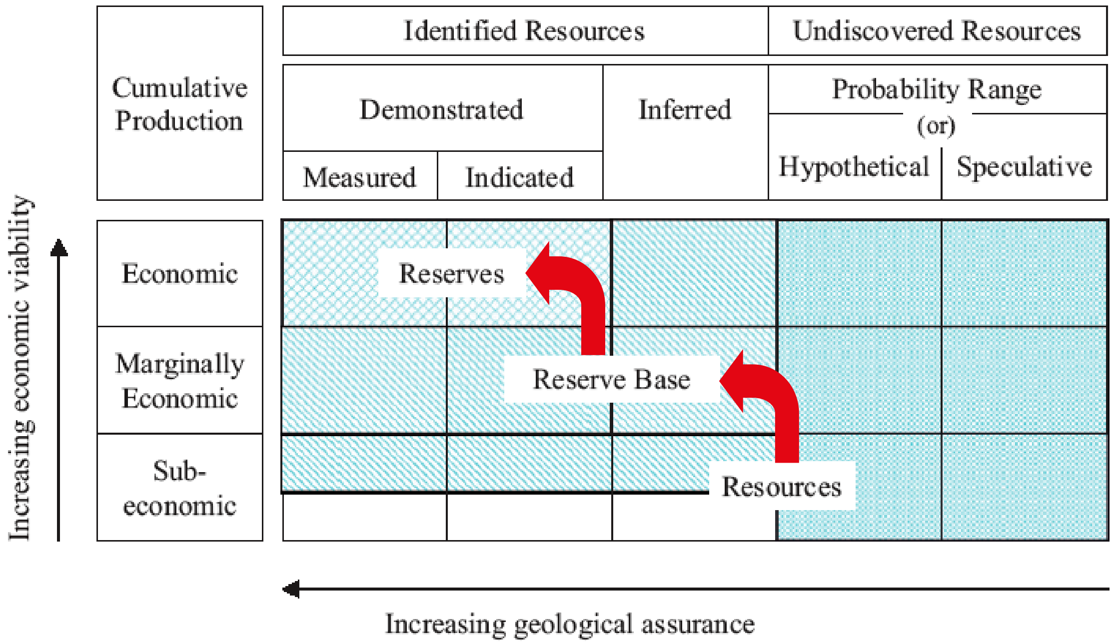
The McKelvey chart



Gordon et al. 2007

The McKelvey chart

Dynamic concept



Gordon et al. 2007

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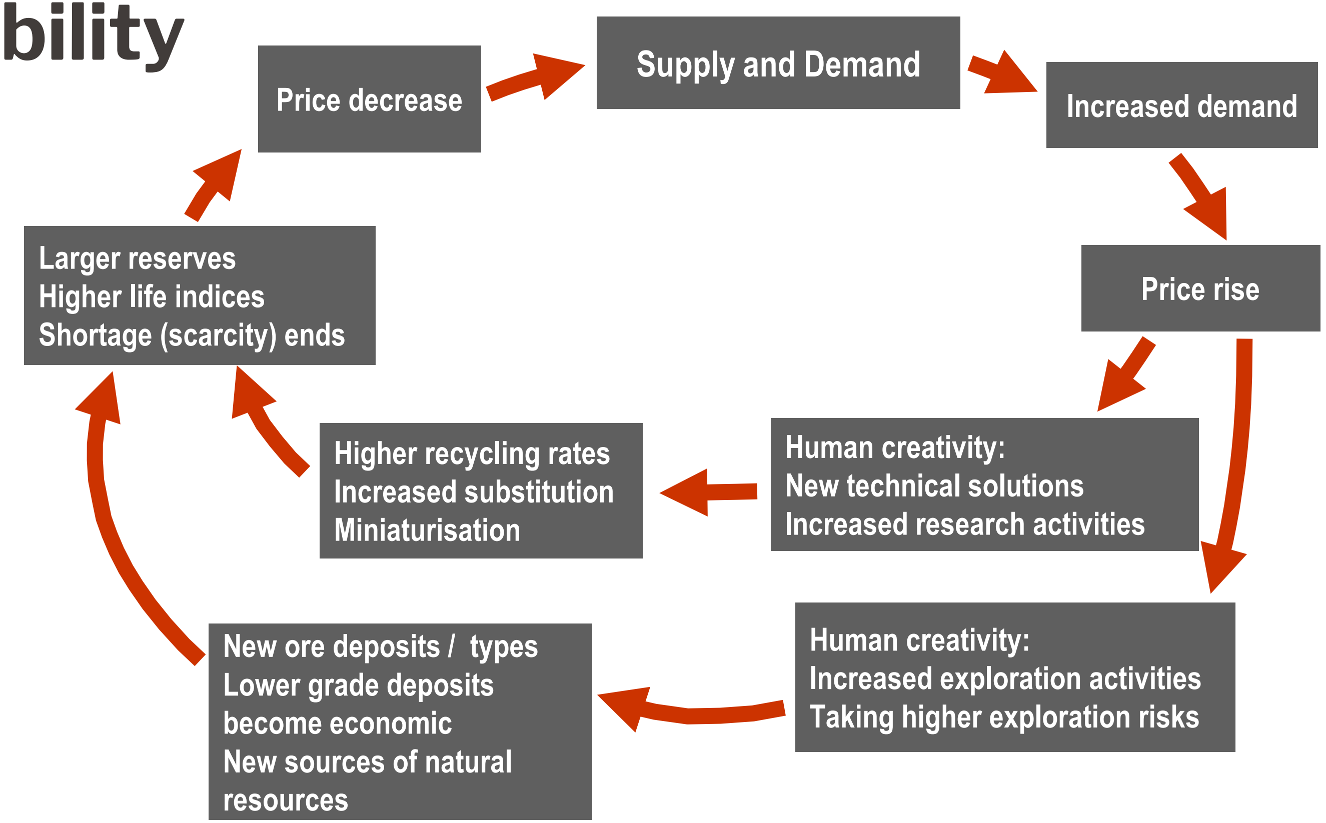
Dynamics of resource availability

As the prices increase, the available stock increases



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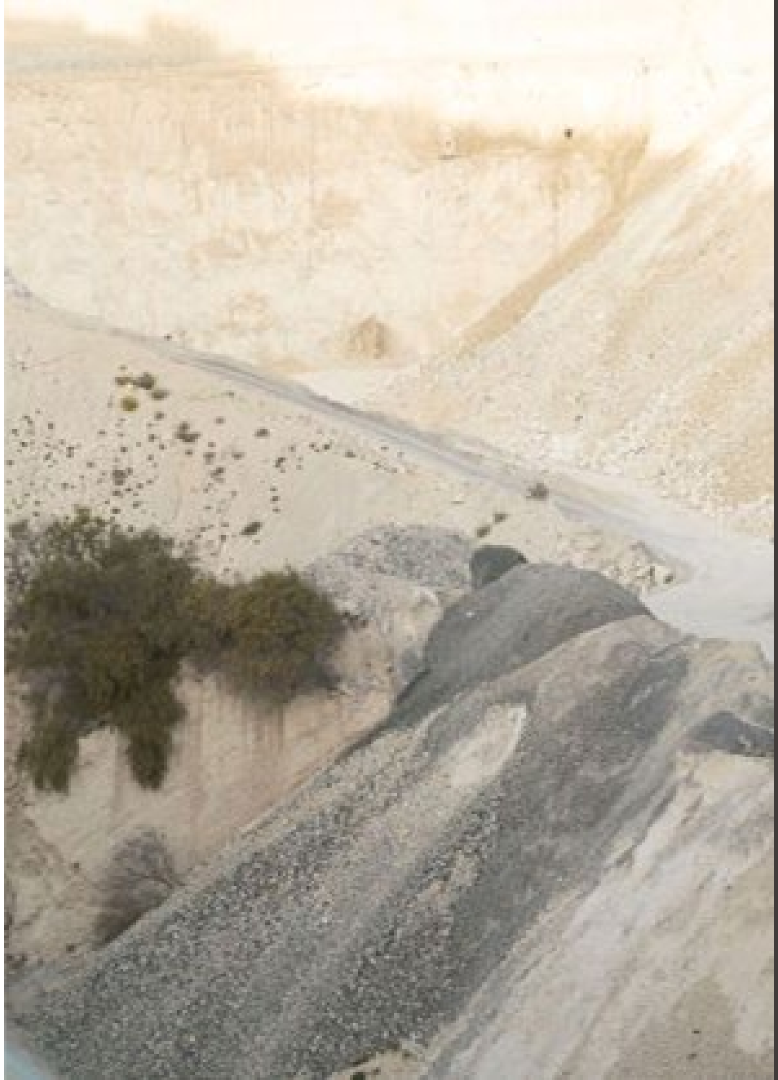
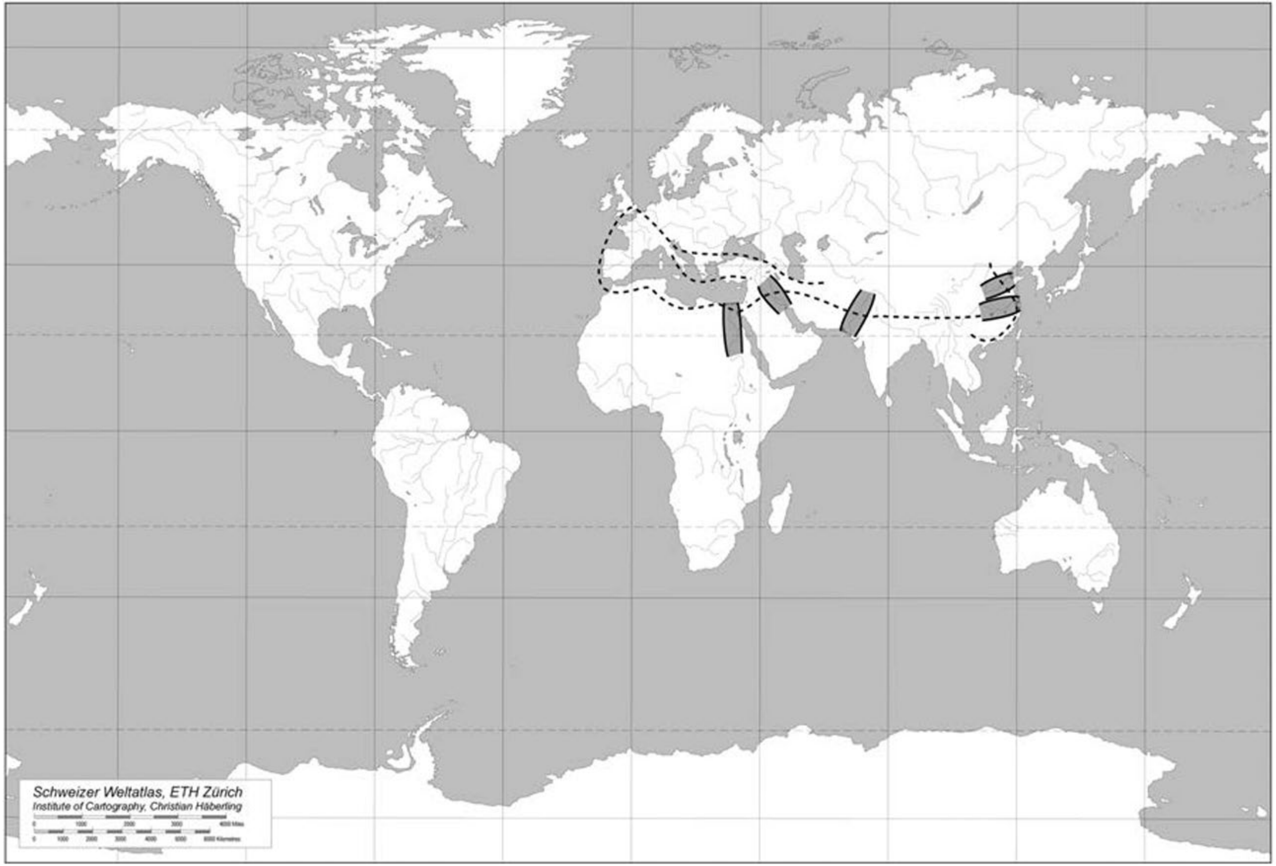


A historical perspective on resource use

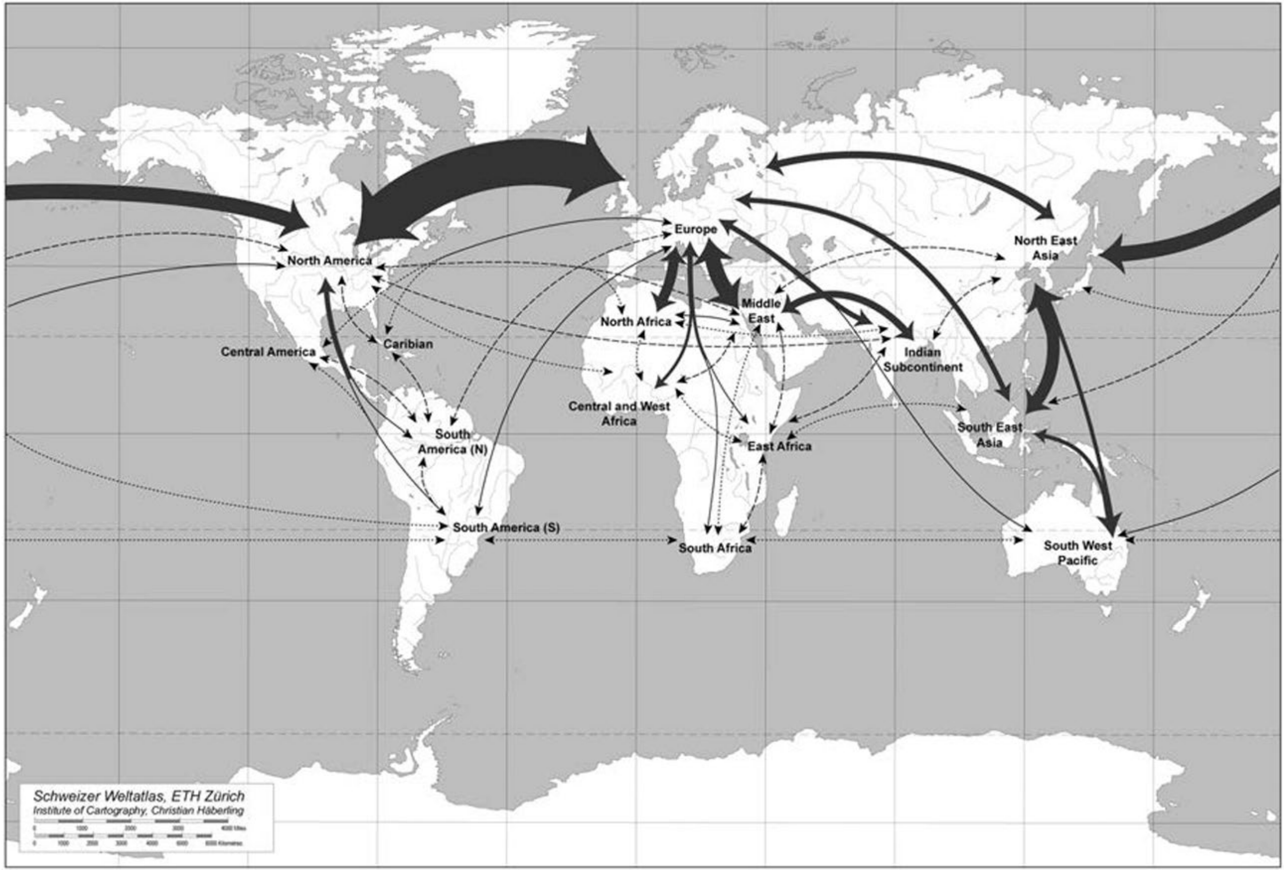
Resource use and space

First anthropogenic trade routes (400 BC)



[Baccini and Brunner, 2012]

Today‘s anthropogenic trade routes



Baccini and Brunner, 2012

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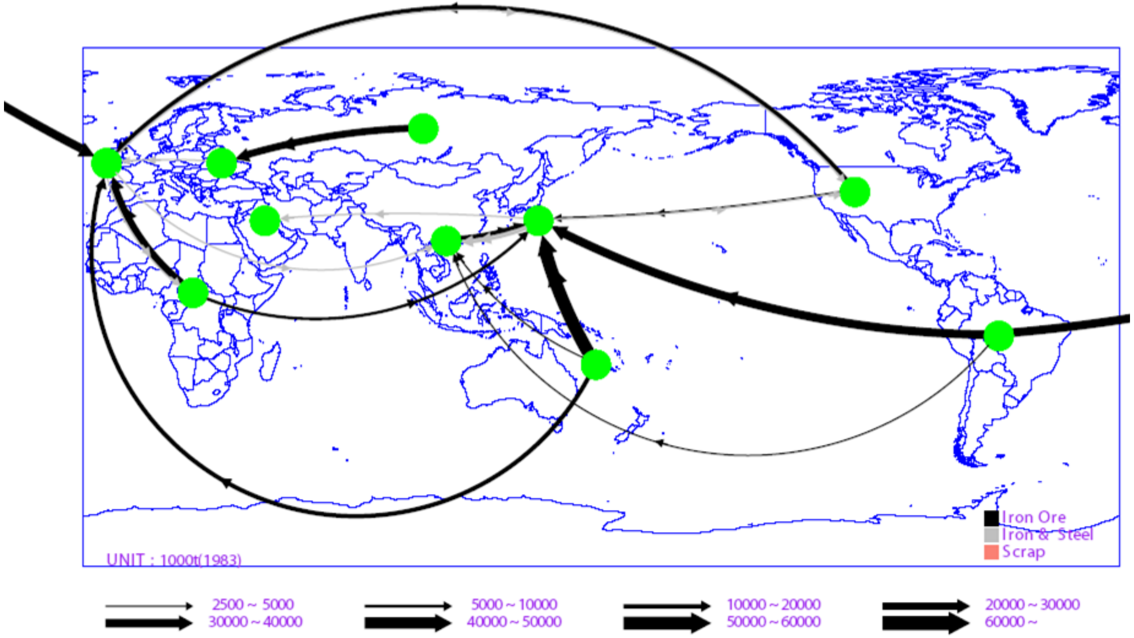
Example: Iron 1983

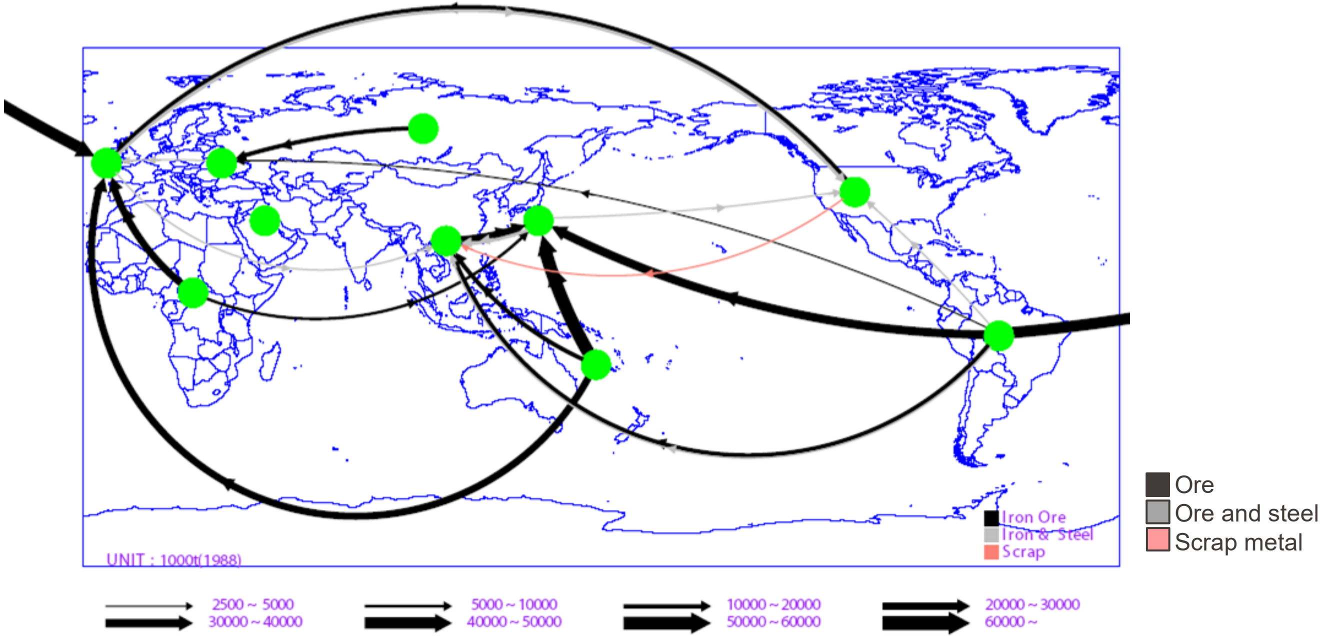


Ore
Ore and steel
Scrap metal

Trade Flow of the Iron in the World[1983]

Source: NIES

Example: Iron 1988



Trade Flow of the Iron in the World[1988]

Source: NIES

Example: Iron 1993

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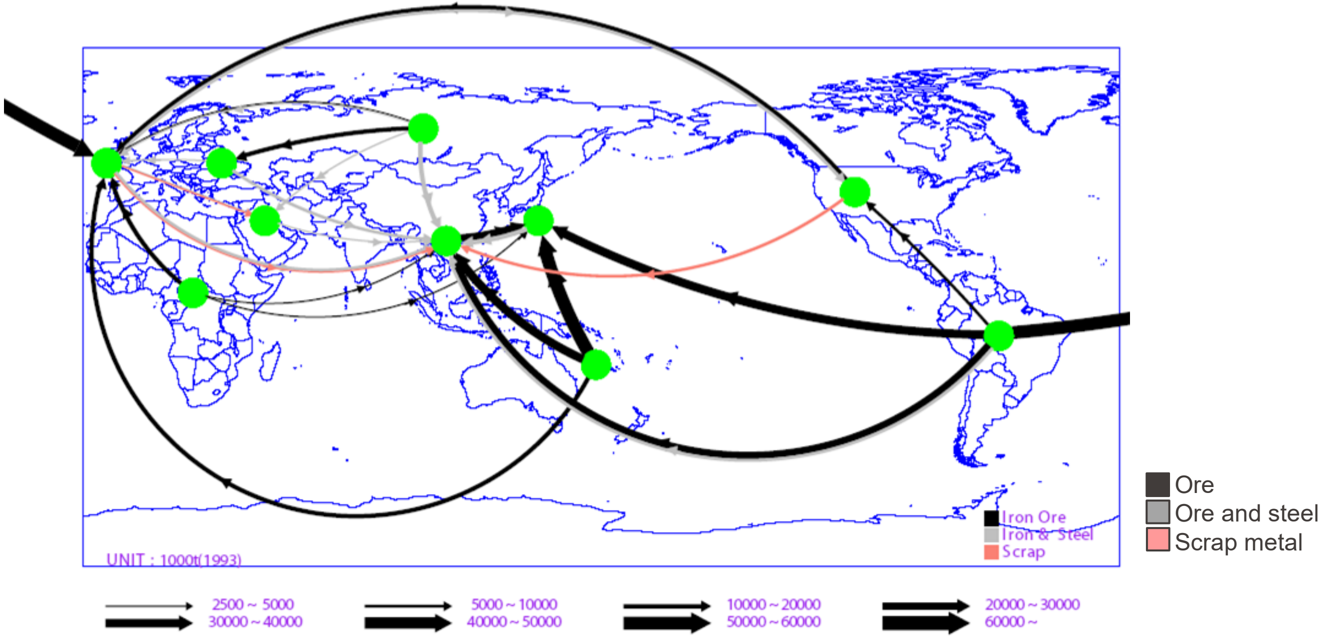
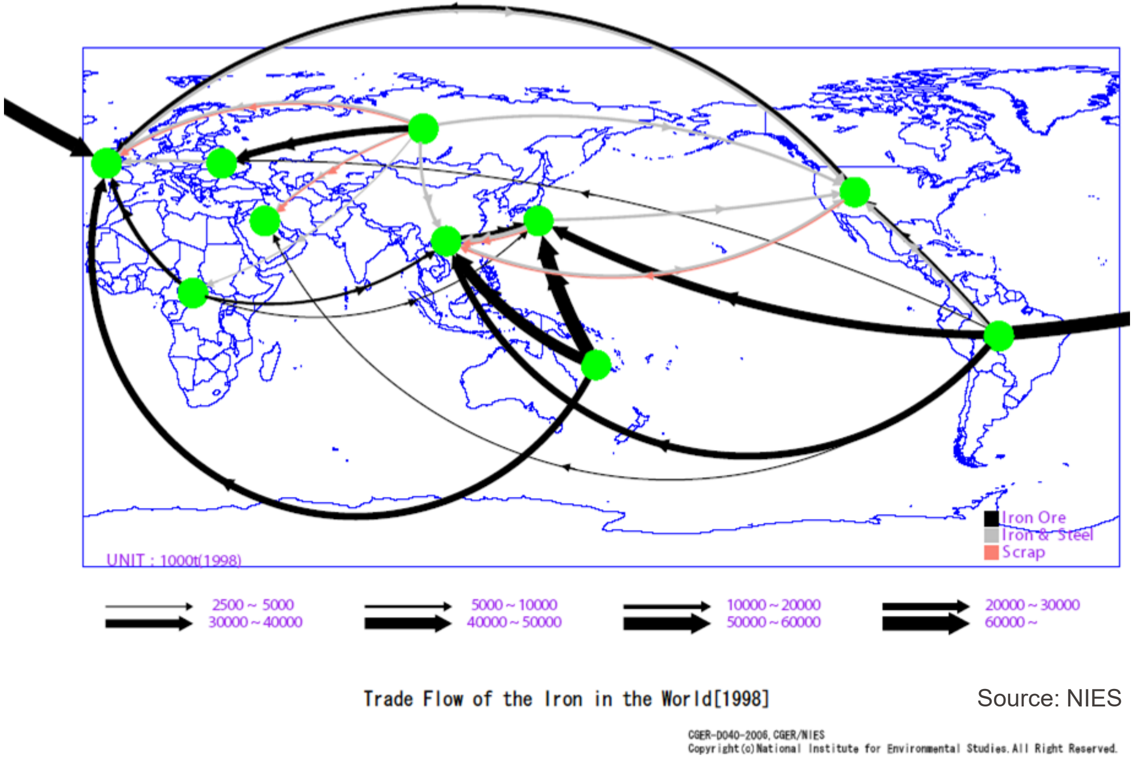


Trade Flow of the Iron in the World[1993]

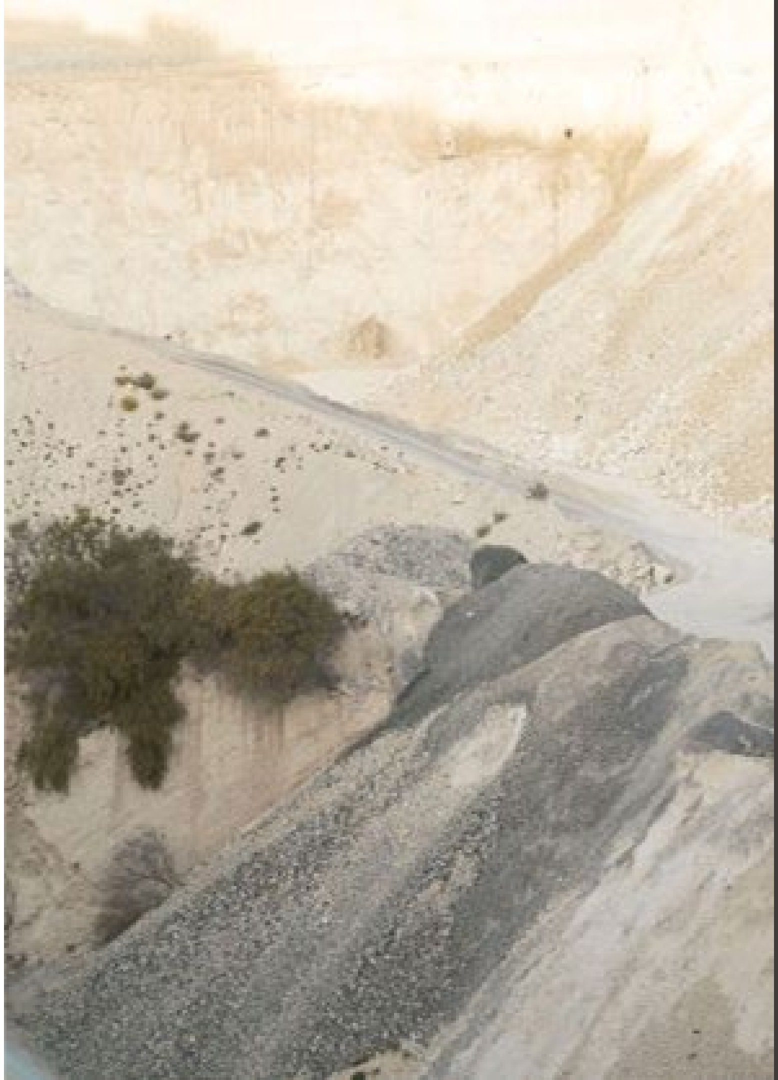
Source: NIES

Example: Iron 1998



Ore
Ore and steel
Scrap metal

Source: NIES



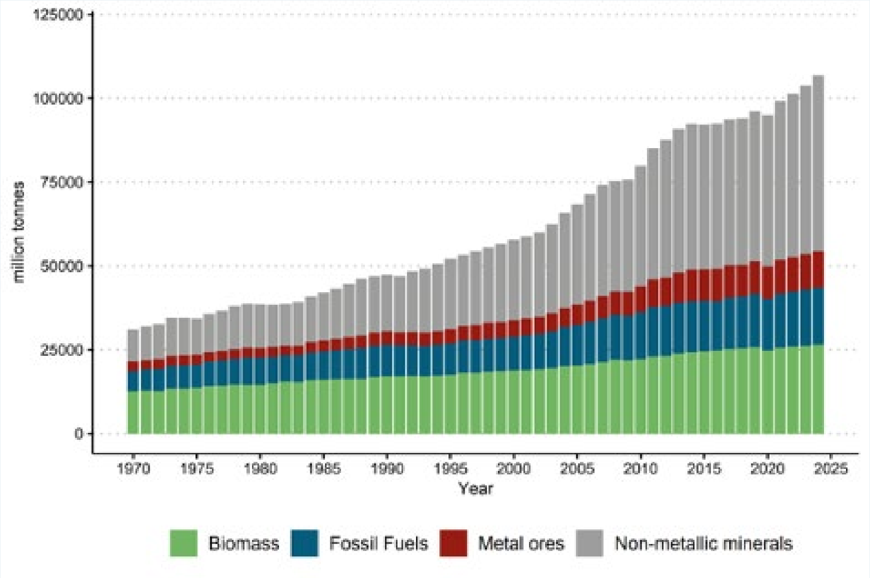
A historical perspective on resource use

Trends and drivers

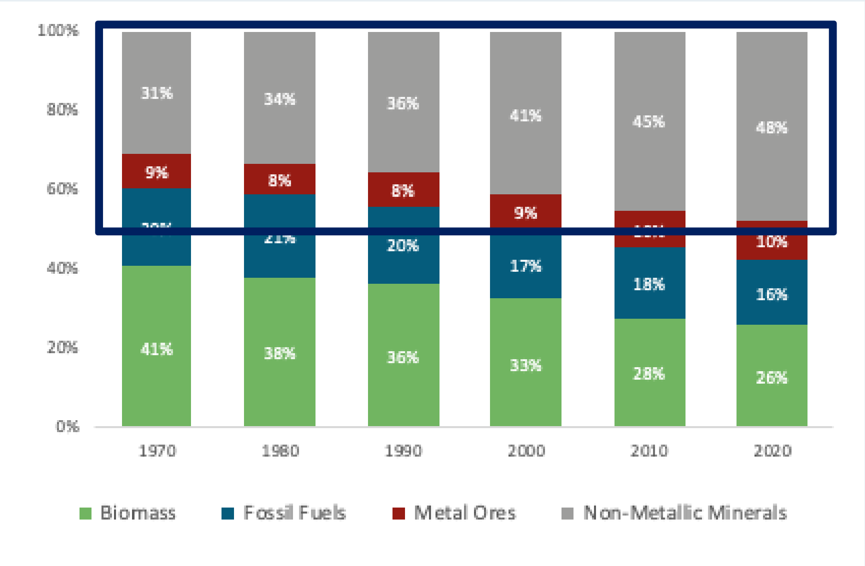
Trends: Global Material Use and Share in 1970-2023

Global Material Use has increased for more than a factor of 3 since 1970 due to urbanisation and industrialisation (and population growth) - 2.3% per year

… which is increasing also the share of Non-Metallic Minerals in Global Material Use

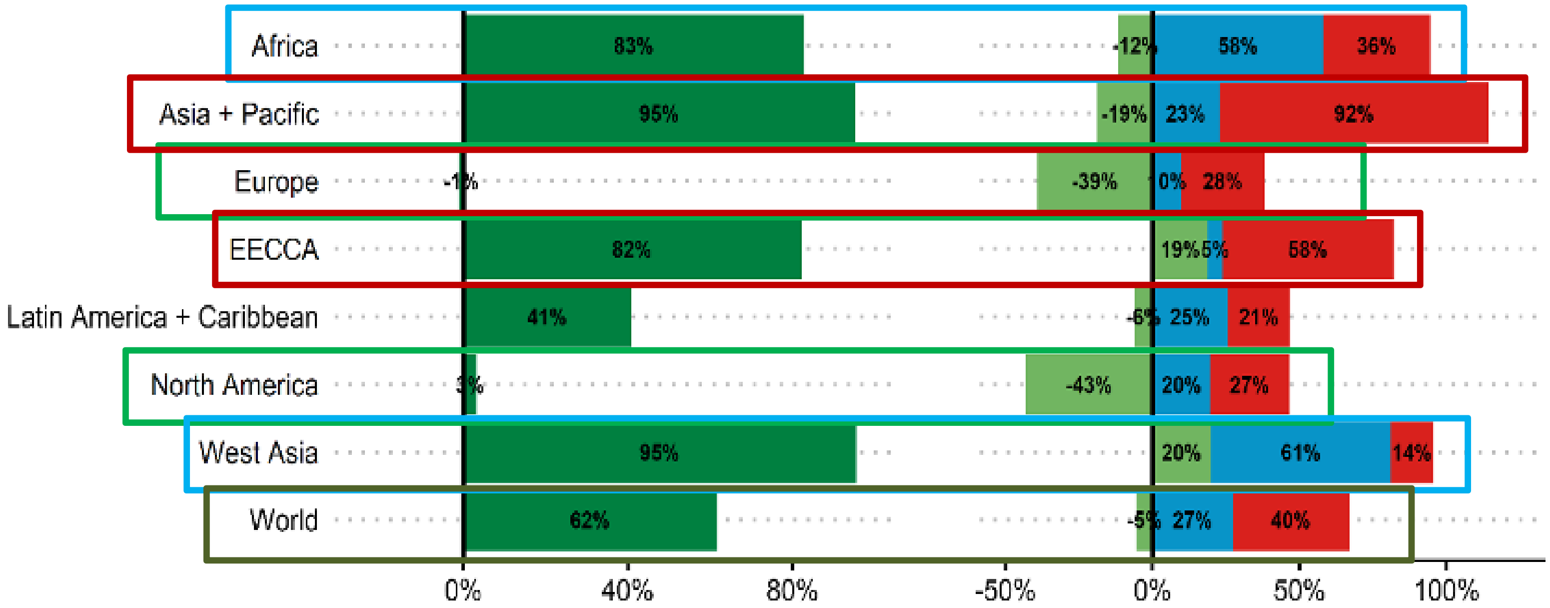


Global material extraction, four main material categories, 1970 – 2024, million tones.



Global material extraction, four main material categories, 1970-2020, shares

Trends: Drivers of Material Footprint 2000-2022, % by world regions

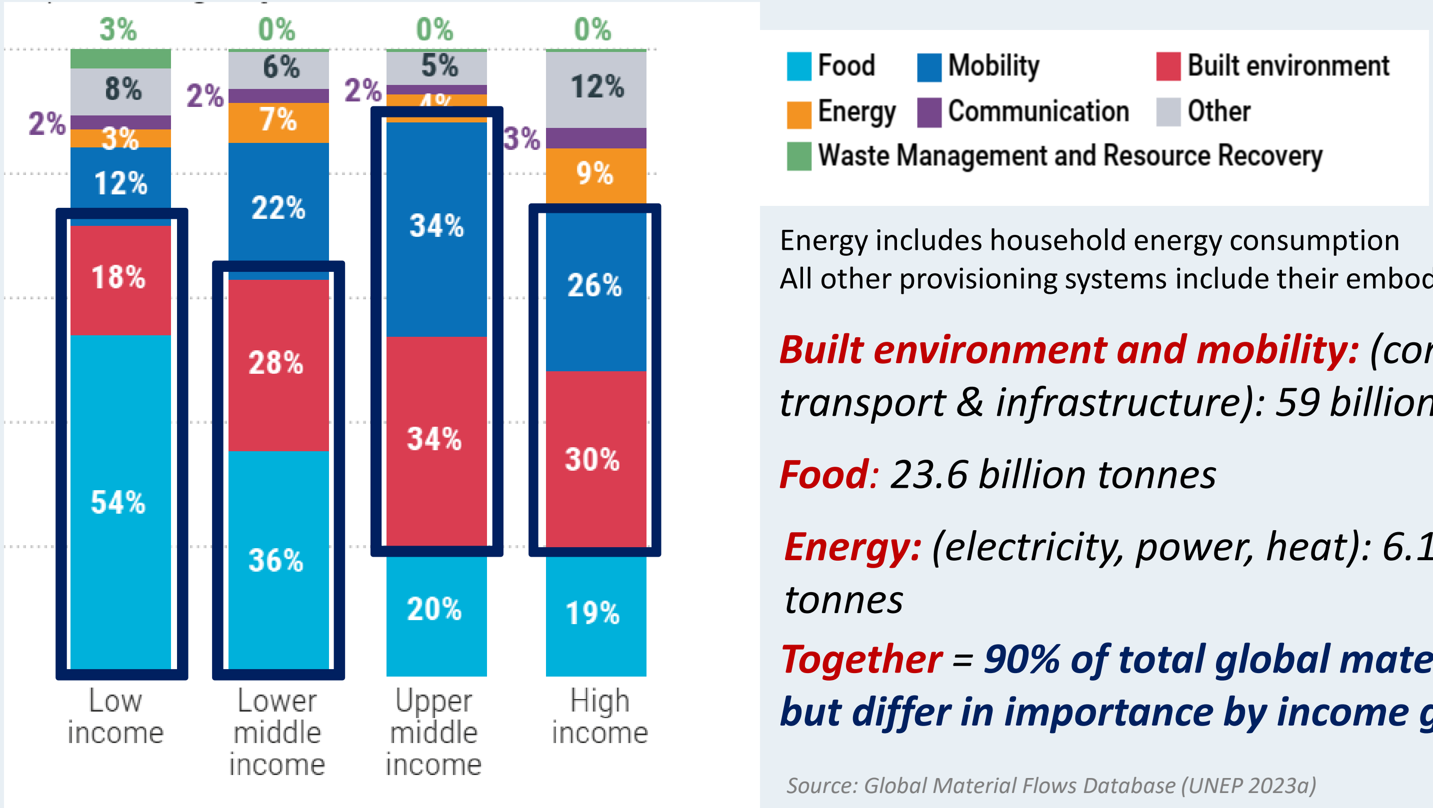


Tons per capita - 2020
5
13
17
18
12
30
13
13

EECCA: Eastern Europe, Caucasus and Central Asia region

Net change % DE   Affluence   Population   Technology

Drivers: The material needs for provisioning systems (built environment, mobility, energy and food) by country income groups (2020)



Energy includes household energy consumption
All other provisioning systems include their embodied energy

Built environment and mobility: *(construction, transport & infrastructure): 59 billion tonnes*

Food*: 23.6 billion tonnes*

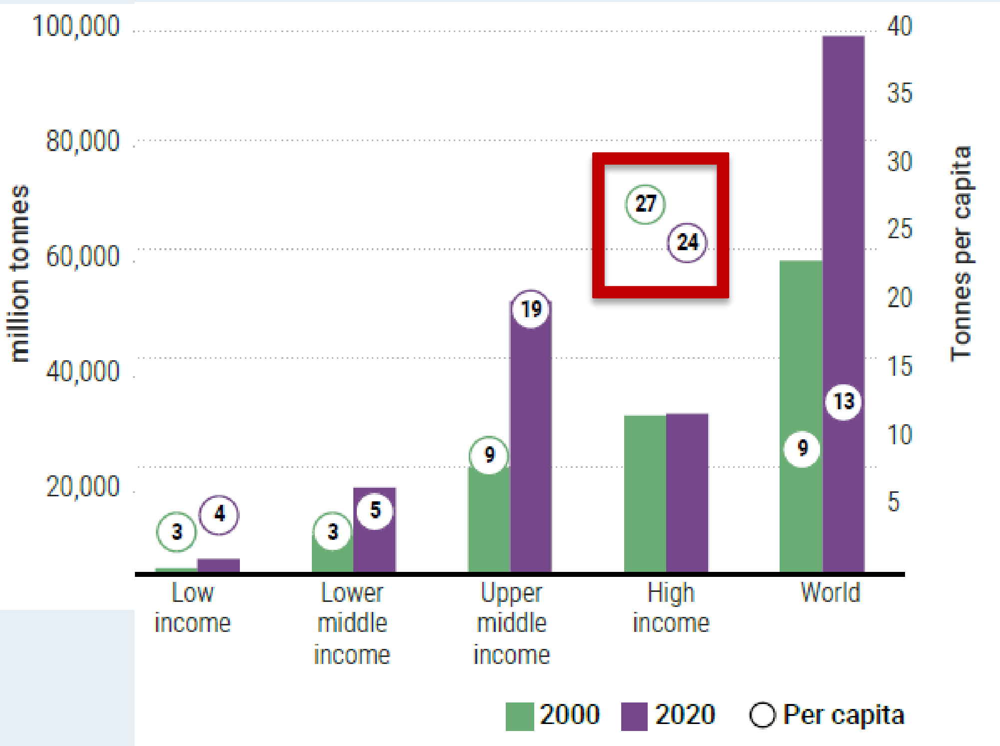
Energy: *(electricity, power, heat): 6.1 billion tonnes*

Together = 90% of total global material demand, but differ in importance by income group

Source: Global Material Flows Database (UNEP 2023a)

Trends: High-income countries use six times more materials per capita and are responsible for ten times more climate impacts per capita than low-income countries.

Material footprint (total and per capita) by income group



Since 2000 …

- *High-income: Highest material footprint of all groups, relatively constant. Climate impact per capita = 10 x low-income group.*
- *Middle-income: material footprint more than doubled, approaching high-income levels. Climate impact per capita = roughly 50% of high-income group; 6 x low-income group.*
- *Low-income: Remain comparatively low, and mostly unchanged.*

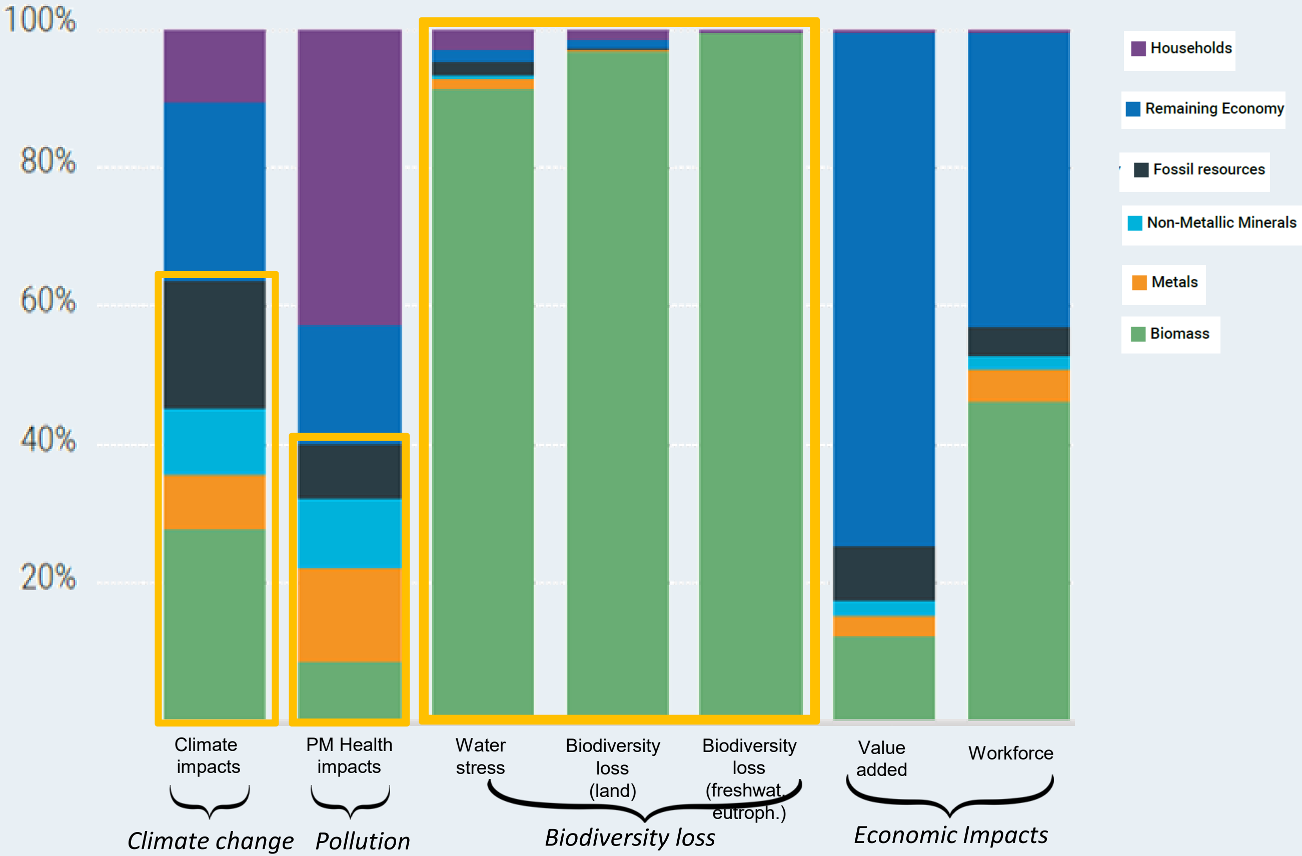
Impacts: *Extraction and Processing of Natural Resources Drives all Aspects of the Triple Planetary Crisis*

Environmental impacts of materials in the value chain in extraction and processing phase

60% of global climate change impacts including land use change

40% of air pollution health impacts

More than 90% of water stress and global land and water eutrophication related biodiversity loss



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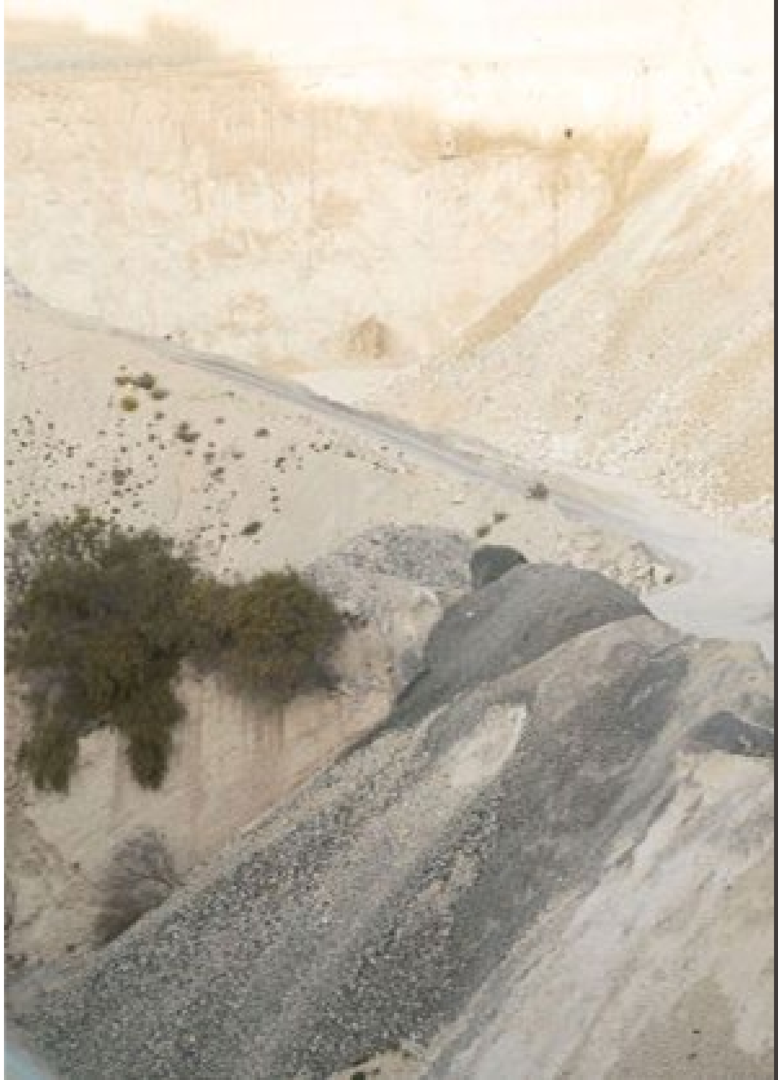

A historical perspective on resource use

Summary

Summary

The transition to the industrial age involved changes in human-environment relations

- Higher material flows
- Disequilibrium between use and regeneration of resources and the production and the decomposition of wastes
- Changes in the impact of human action in time and space

Binder, Felix Martin del Campo, Hecher, Campfens

Summary

To address the coupled climate, energy, biodiversity crises there is a necessity to manage the human-environment (resource) relations (more) sustainably

- Understanding the key material and energy flows and their development over time
- Understanding the link between economic flows and material and energy flows
- Understanding policy needs and regulatory mechanism of the human-resource relations

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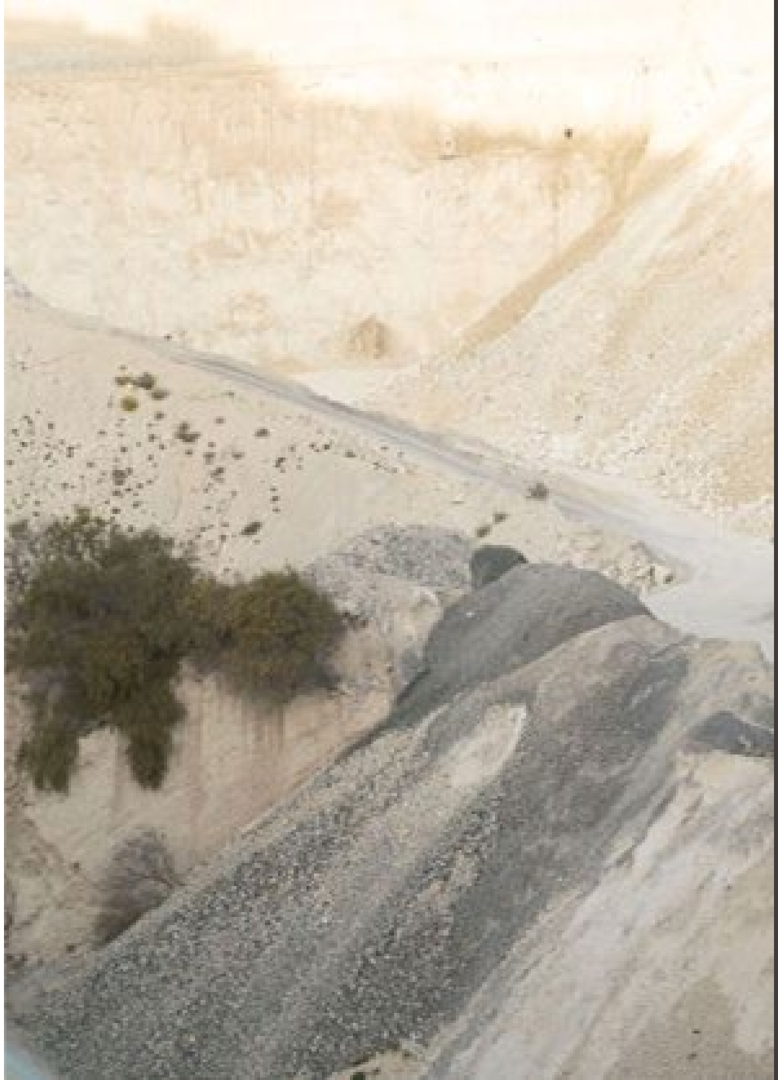

Industrial Ecology (IE)

The research field for sustainable resource management

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IE: Definition

- **Ecology**: Science of ecosystems
- **Industrial**: All economic activities taking place within the industrial system

- **Industrial Ecosystem**: "An industrial system in which the use of energies and materials is optimized, wastes and pollution are minimized, and there is an economically viable role for every product of a manufacturing process"

IE: Definition

- … the study of the **technological organisms***, their **use of resources**, their potential environmental **impact** and the way in which their **interactions** with the natural world could be **restructured** to enable global **sustainability** (Graedel & Allenby 2010).

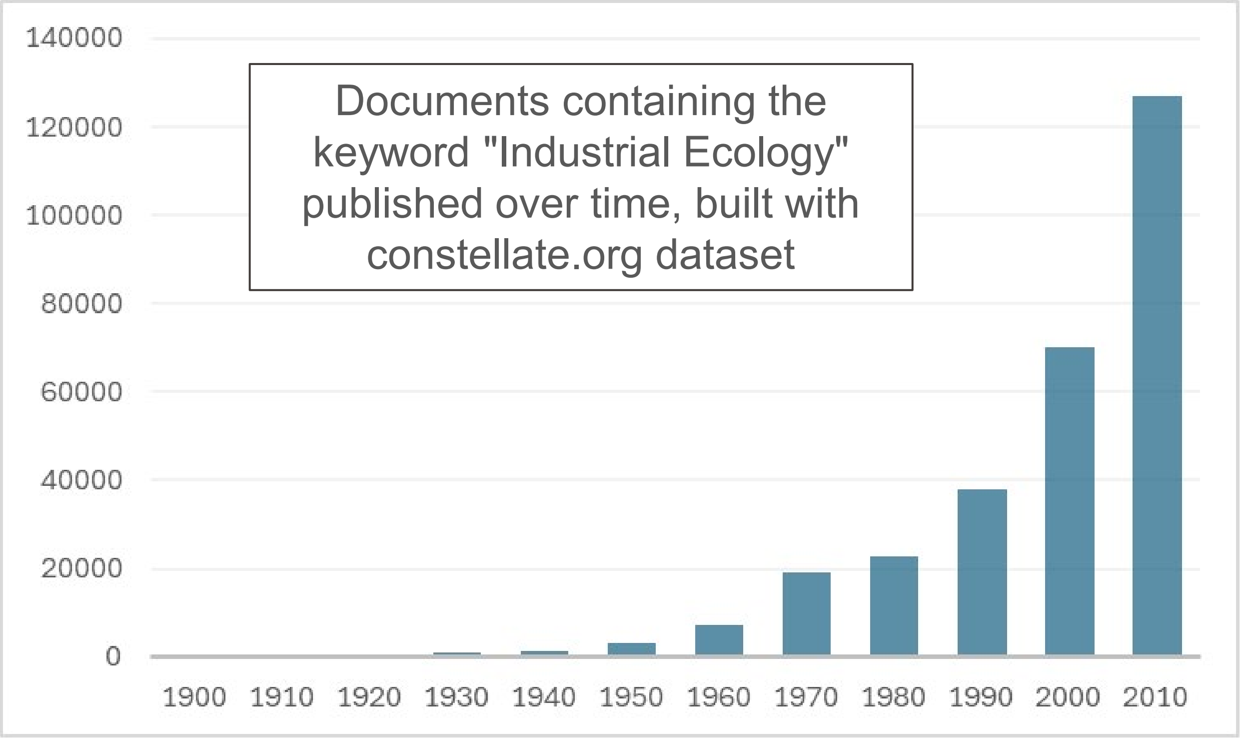
- … the study of the **flows of materials and energy** in industrial and consumer activities, of the **effects of these flows** on the environment, and of the **influences** of economic, political, regulatory, and social factors on the flow, use, and **transformation of resources** (White, 1994).

* Technological organism is an overarching name for manmade systems such as cities, industrial production systems, agricultural production systems, transport systems.

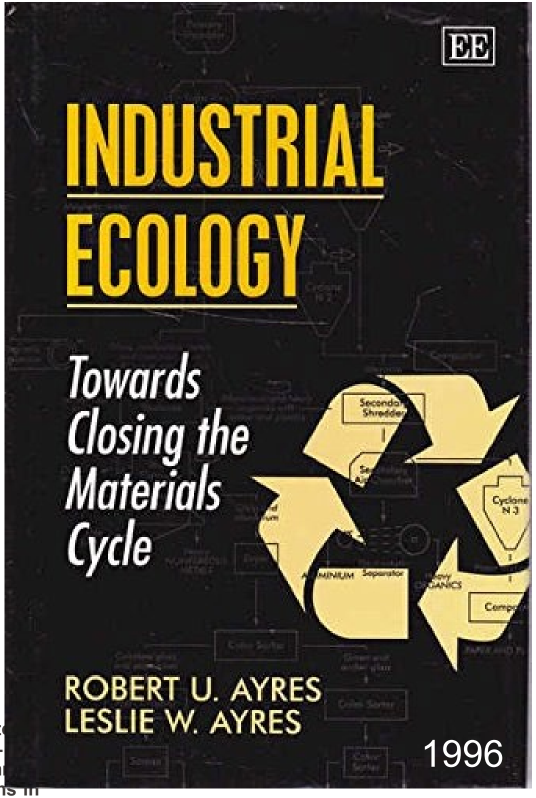
IE: Definition

The term "industrial ecology" first gained significant search interest on Google in 2004, reaching its peak popularity around 2005-2006.

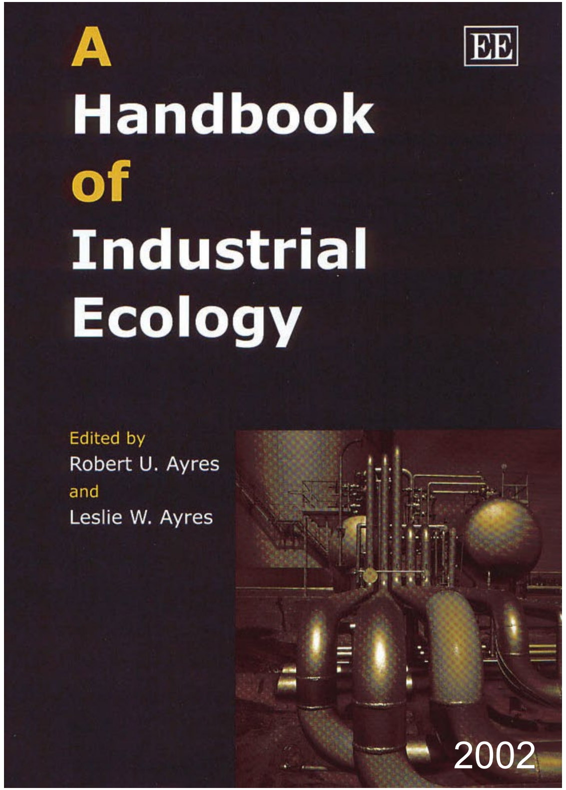
Since then, its global usage has gradually declined, making way for other emerging concepts like circular economy to take center stage.



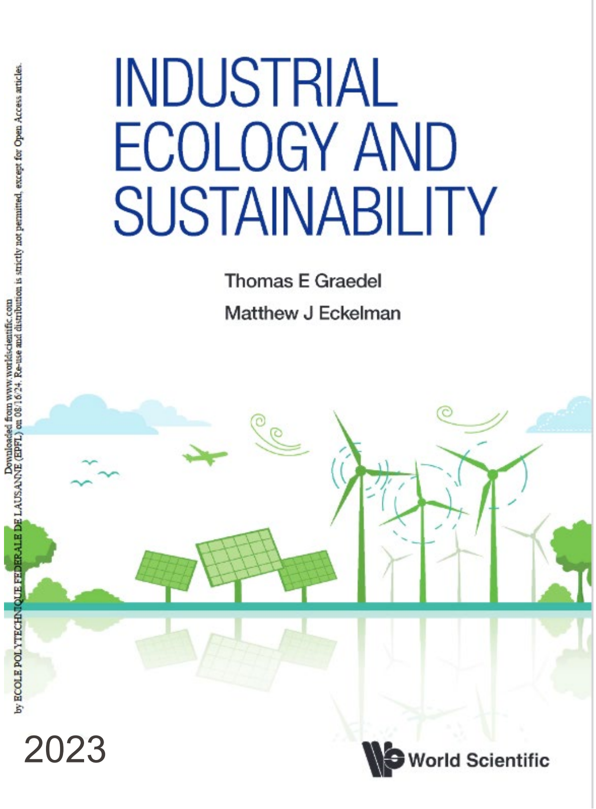
IE: Definition



1996



2002



2023

- Laborat
Human-
Environ
Relations in
Urban Systems

Core elements of IE

- Biological analogy
- Use of systems perspective
- Role of technological change
- Dematerialization and eco-efficiency
- Forward-looking research and practice

Lifeset and Graedel in Ayres and Ayres, 2001

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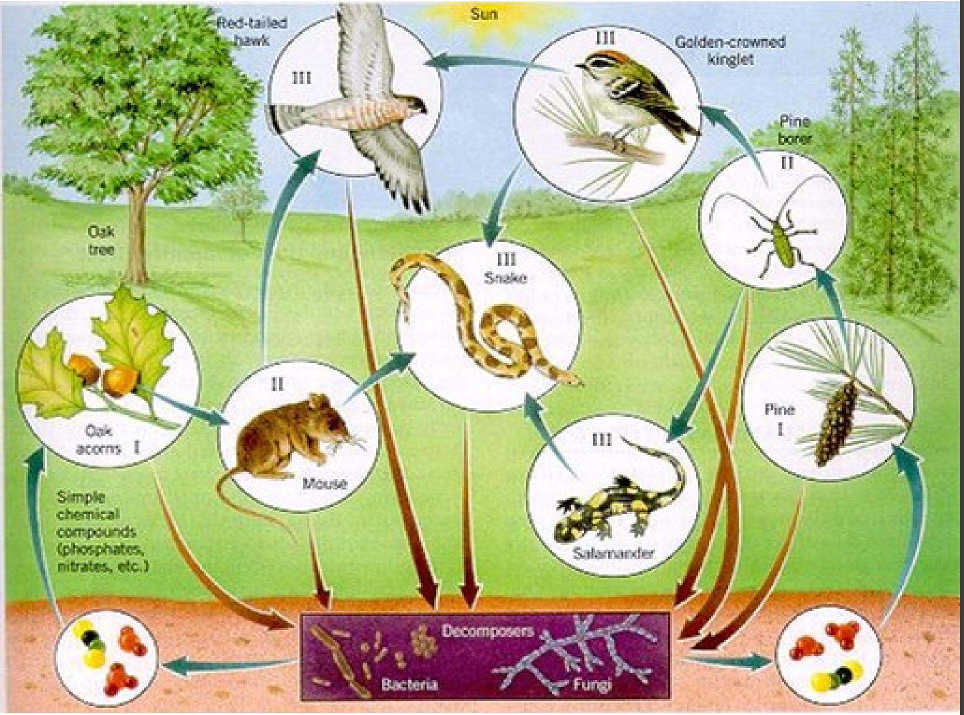

Core element: The biological analogy

The biological analogy: Metabolism

“ to sustain the processes of life, a typical cell carries out thousands of biochemical reactions each second. The sum of all biological reaction constitutes metabolism. What is the purpose of these reactions – of metabolism? Metabolic reaction convert raw material, obtained from the environment, into the building blocks of proteins and other compounds unique to organisms. Living things must maintain themselves, replacing lost material with new ones; they also grow and reproduce, two main activities requiring the continued formation of macromolecules”.

Fischer-Kowalski in Ayres and Ayres, 2001

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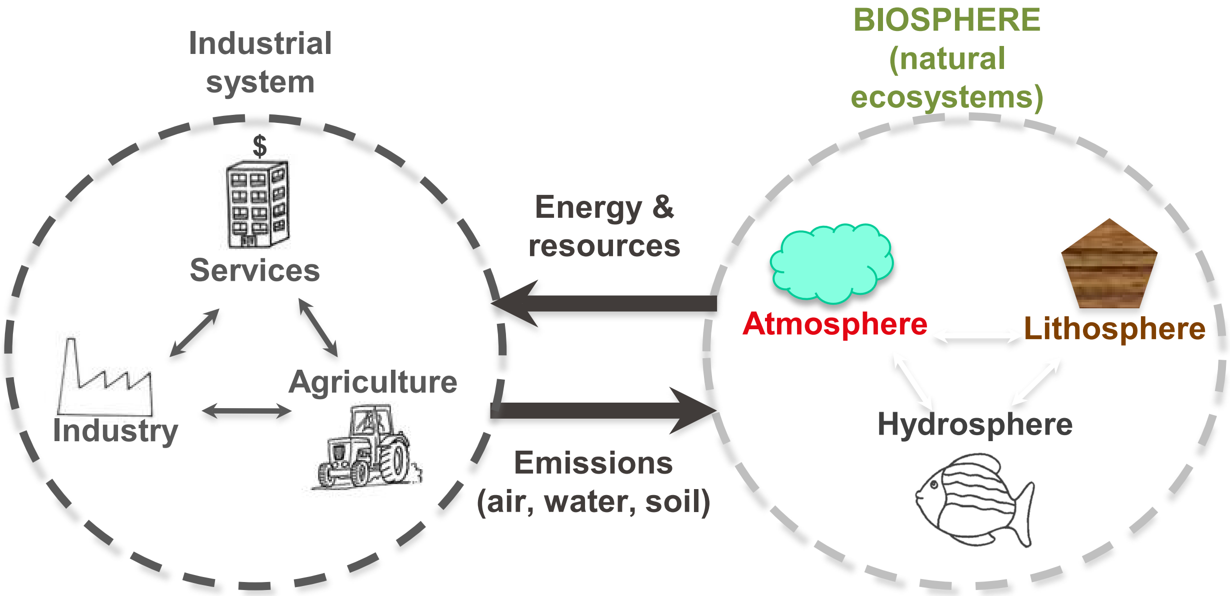
Ecosystems as models for facilities, districts, cities, regions



Source: Université de Lausanne

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Typology of ecosystems

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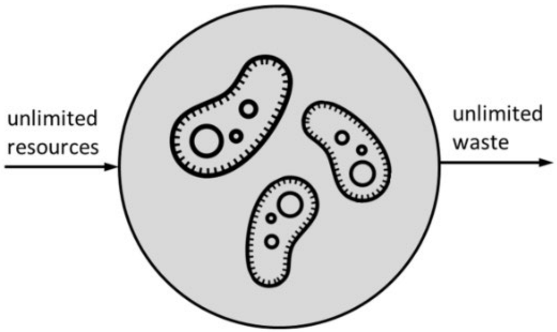
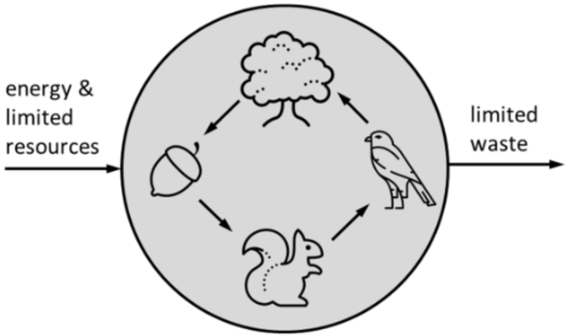
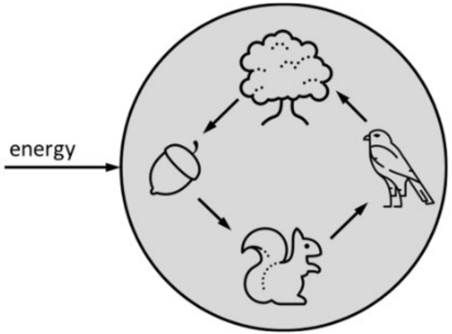


Linear materials flows in Type I biological ecology.



Quasi-cyclic materials flows in Type II biological ecology.



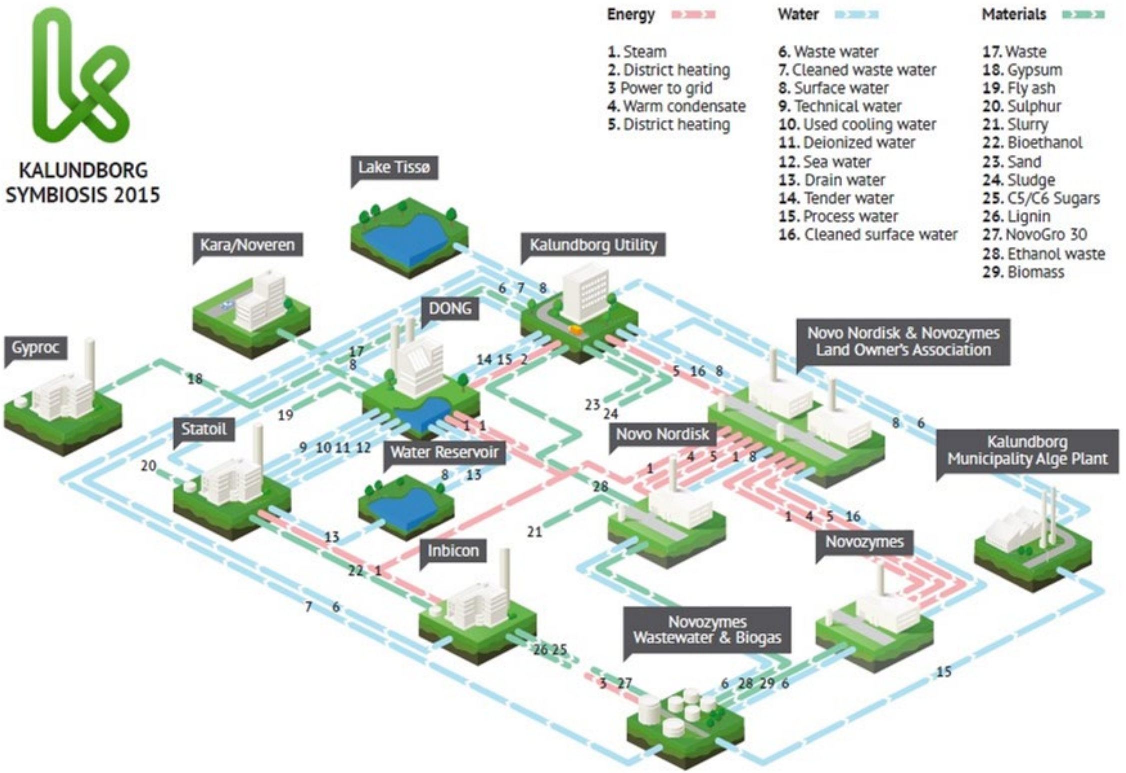
Cyclic materials flows in Type III biological ecology.

Graedel, 2020

Type III: Kalundborg in DK

1972. World's first industrial symbiosis with a circular approach to production.

- Residual flow in one company becomes a resource in another,
- The symbiosis creates growth in the local community and supports the green transition.



Source: http://www.symbiosis.dk/

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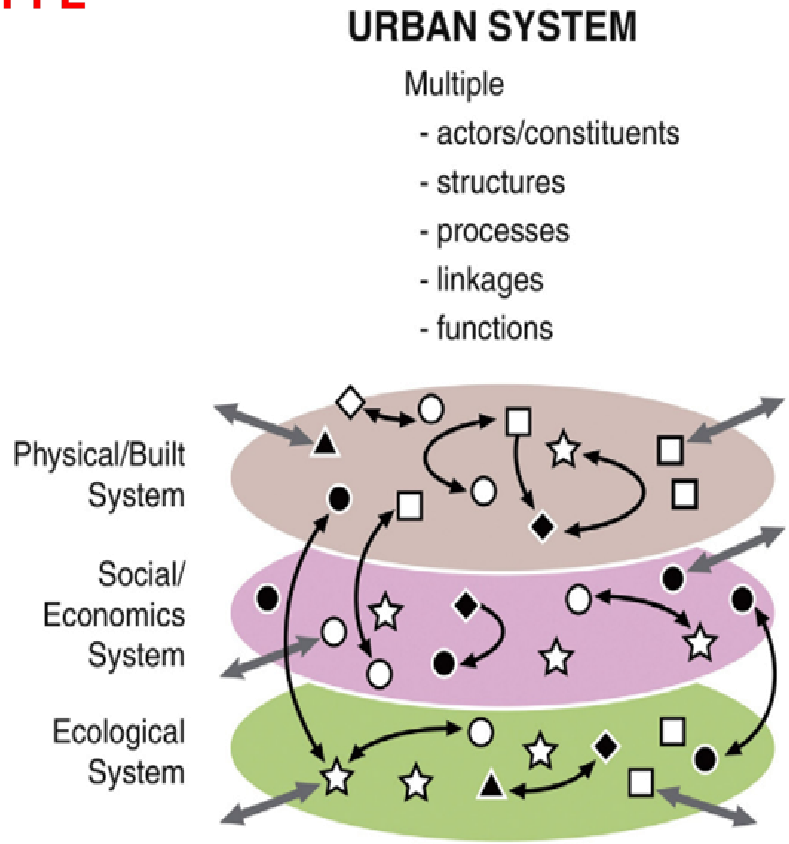

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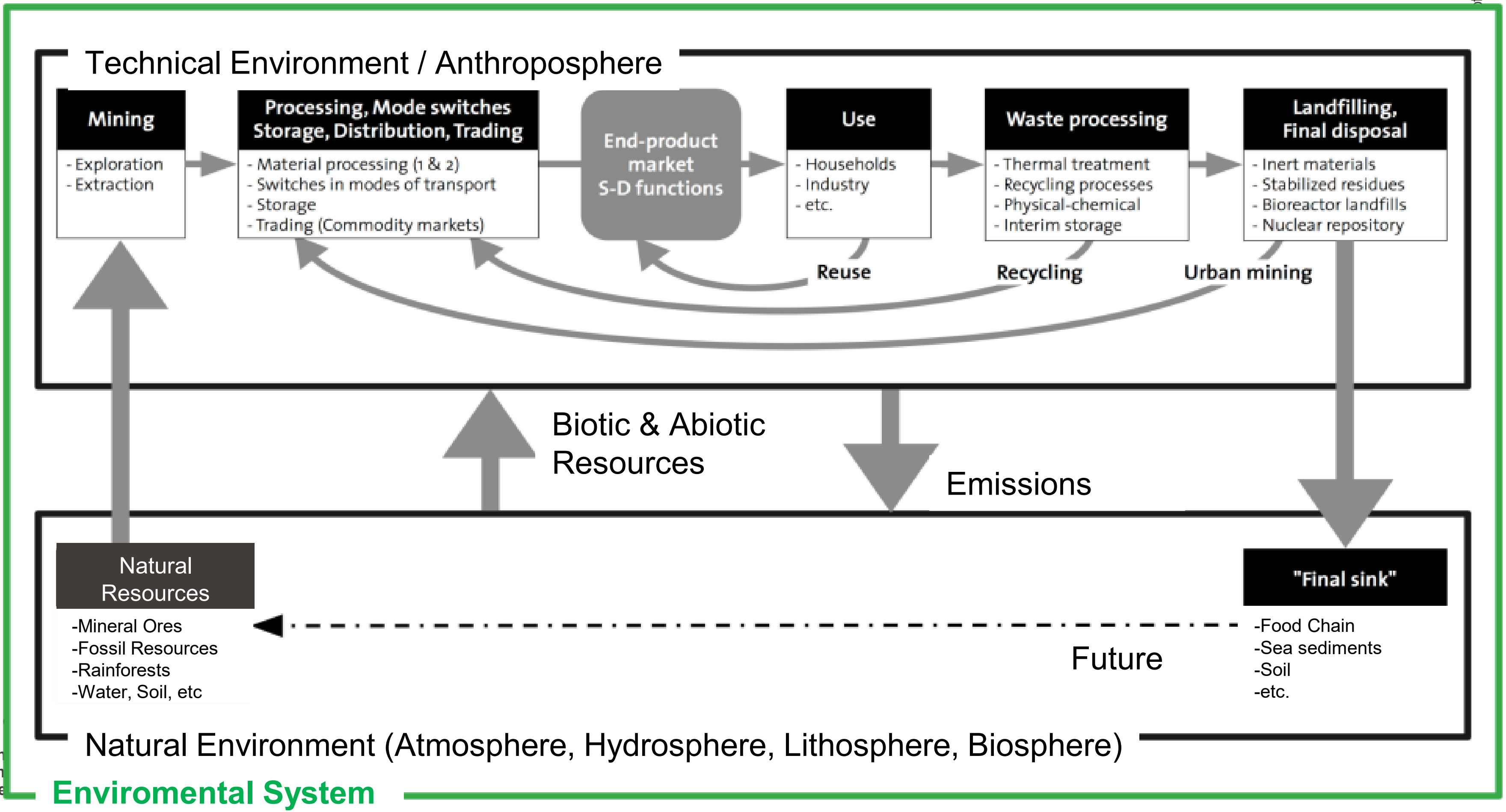
Core element: Use of systems perspective

The systems perspective

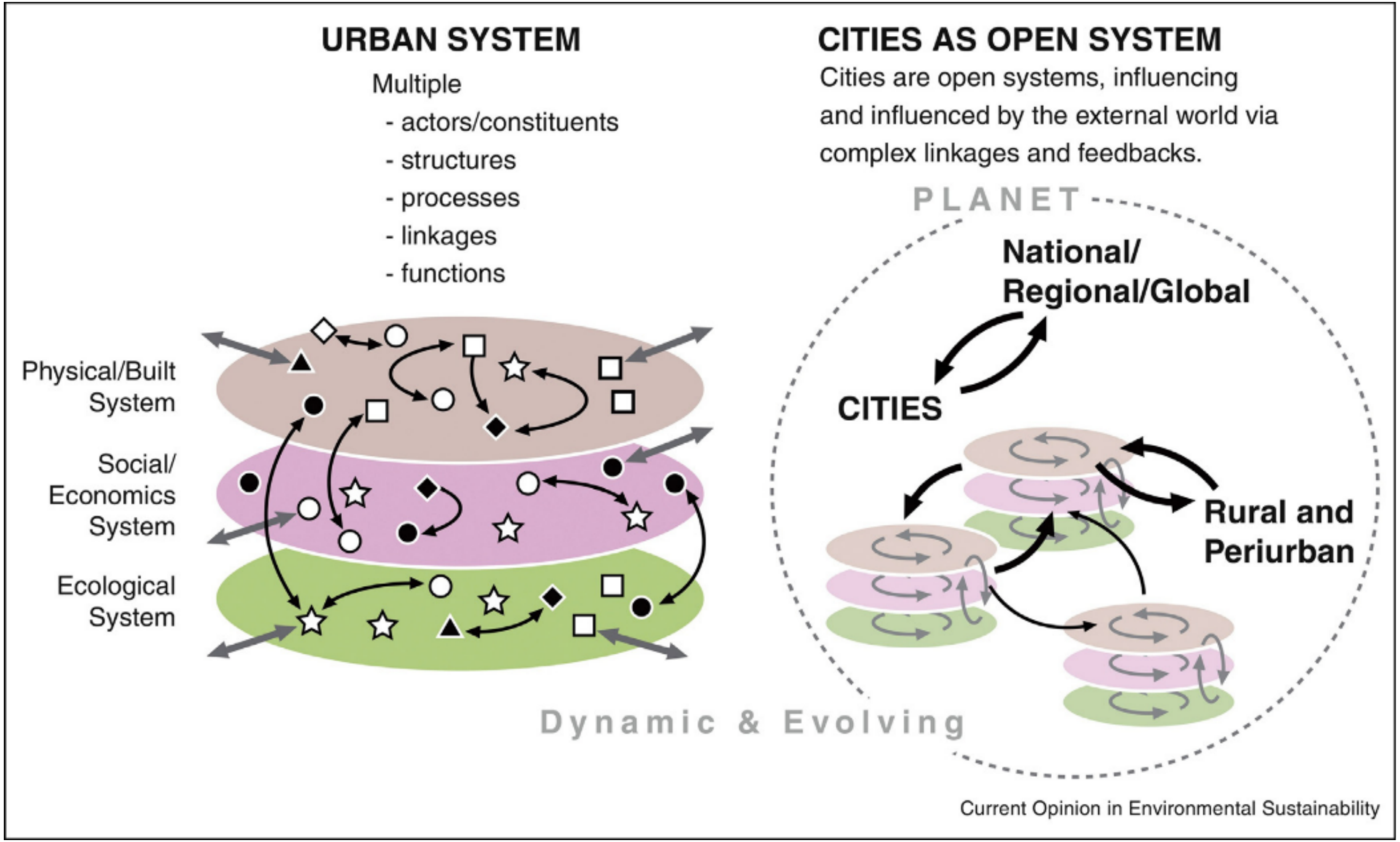
- **Goal**: Avoid narrow, partial analyses that can overlook important variables and lead to unintended consequences.

- **Holistic thinking**: Solving problems must involve understanding the connections that exist between sub-systems, multiple factors cannot be analyzed in isolation.
- **Example**: A city can be divided into commercial areas, residential areas, offices, services, infrastructures, …. all sub-systems of the bigger picture. Problems can emerge in one sub-system, but the solution has to be global.
- **Life cycle thinking**: All environmental impacts caused by a product, system, or project during its life cycle are taken into account. From raw material extraction, material processing, manufacture, use, maintenance, disposal

The life cycle of resources



Cities as systems



Bai et al., 2016

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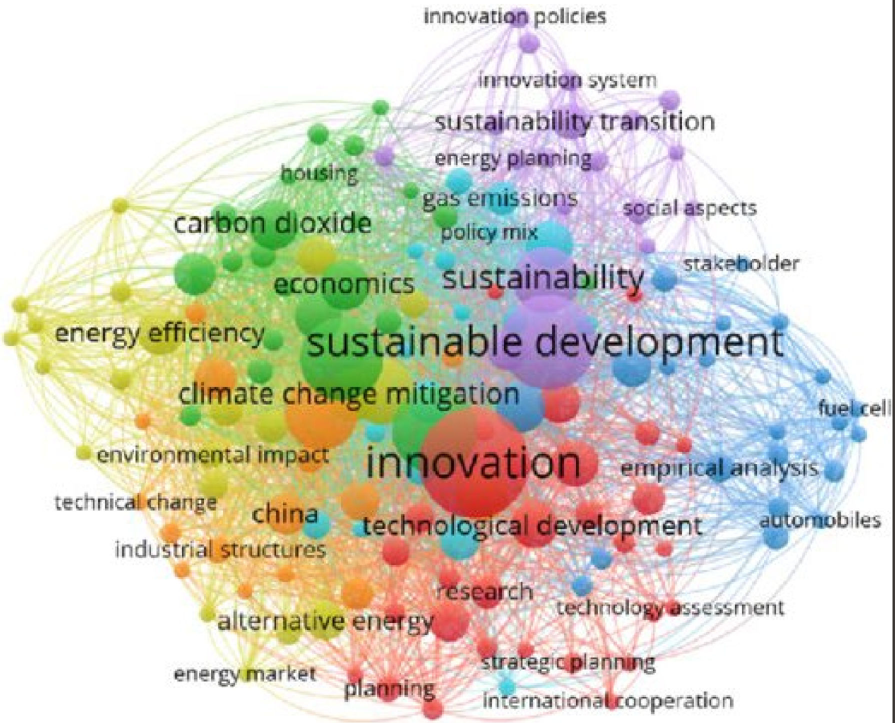

Matos et al., 2022

Core element: Technological change

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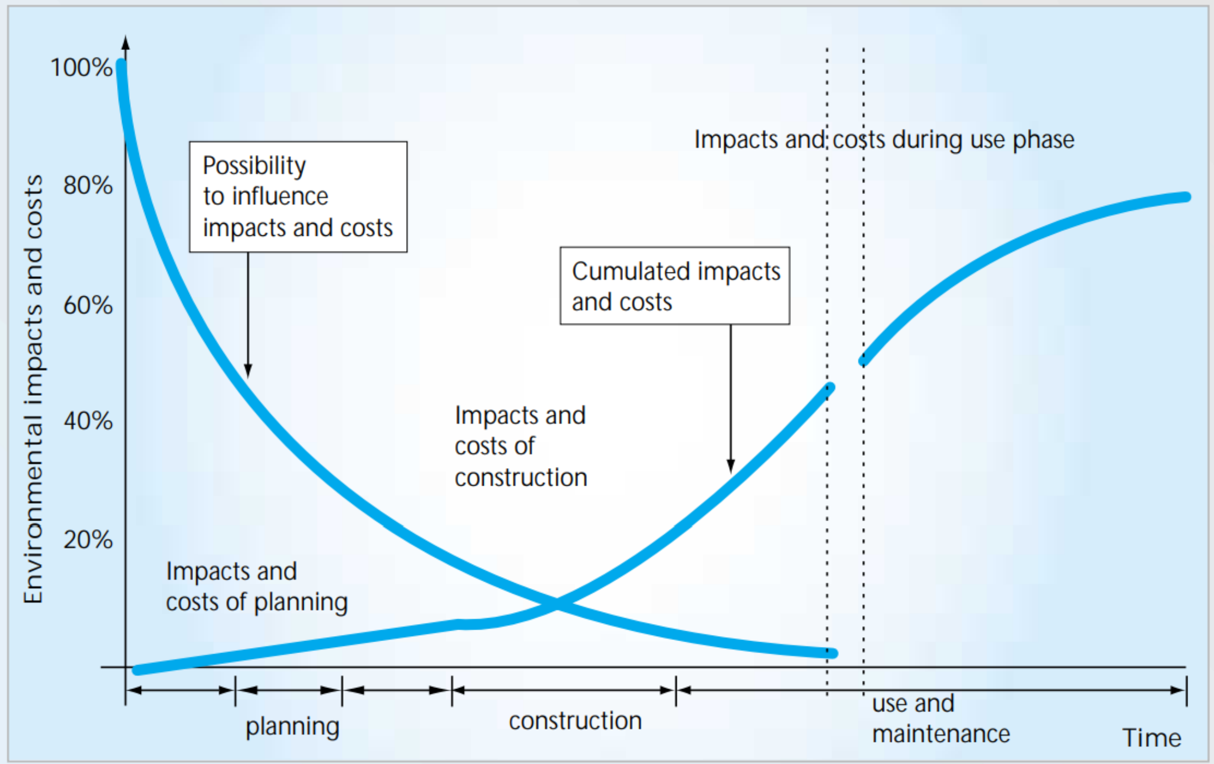
Technological change

Technological innovation as a central means to solve environmental problems

Binder, Felix Martin del Campo, Hecher, Campfens

Influence of design decisions on life cycle impacts and costs

Binder, Felix Martin del Campo, Hecher, Campfens



Braganca et al. 2014

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Core element: Dematerialization and eco-efficiency

Dematerialization and eco-efficiency

- **Dematerialization**: absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output' (Cleveland and Ruth 1998, p. 16
- **Eco-efficiency**: conceptualization and development of materials or structures to reduce the consumption of virgin materials and provide a utility.

Dematerialization and eco-efficiency

Market Business News

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Dematerialization and eco-efficiency

Dematerialization (world, nation level)

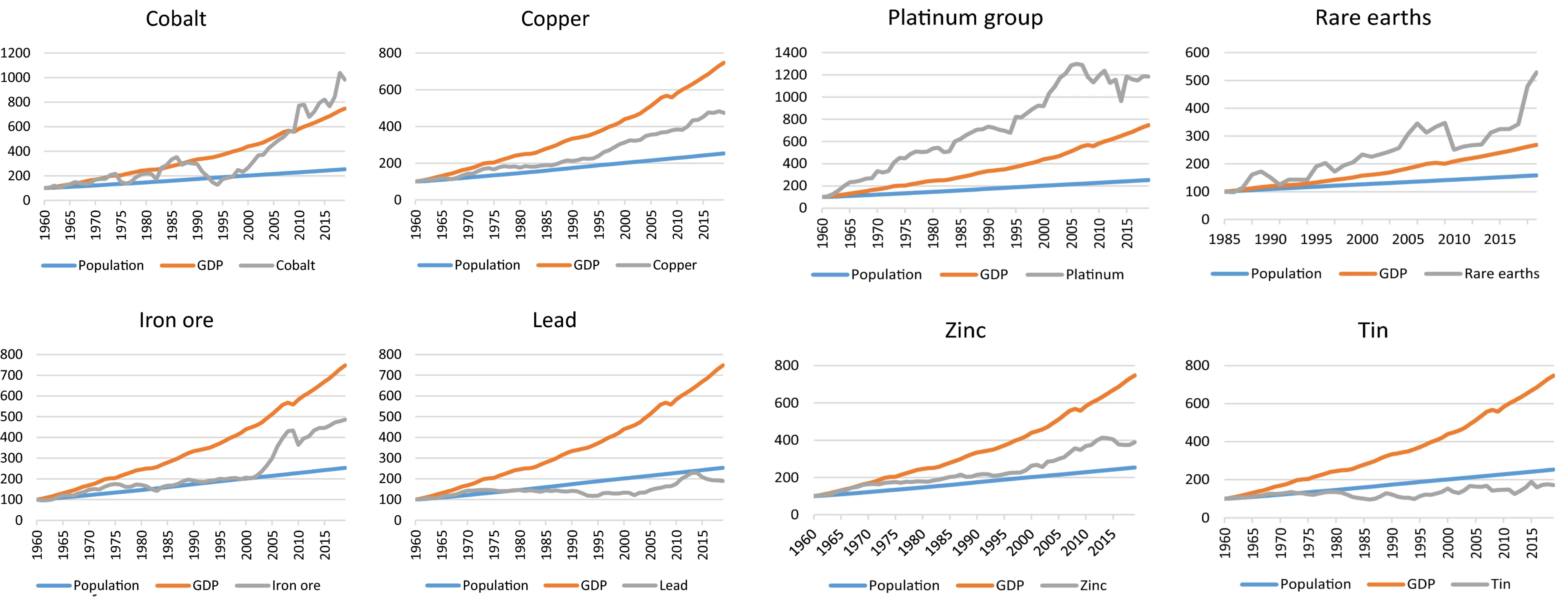
- Reduction in quantity of materials used to accomplish a task
- Offer the possibility to **decouple resource use** and environmental impact (CO2 emissions, i.e. decarbonization) from **economic growth**

Eco-efficiency (firm level)

- How can companies produce the same level of output (or service) with reduced use of environmental resources?
- Indicator: output / environmental resources
- Problem of **rebound effect**

Link to technological change, industrial symbiosis, eco-design etc.

Decouple resource use from economic growth



Hannesson, 2021

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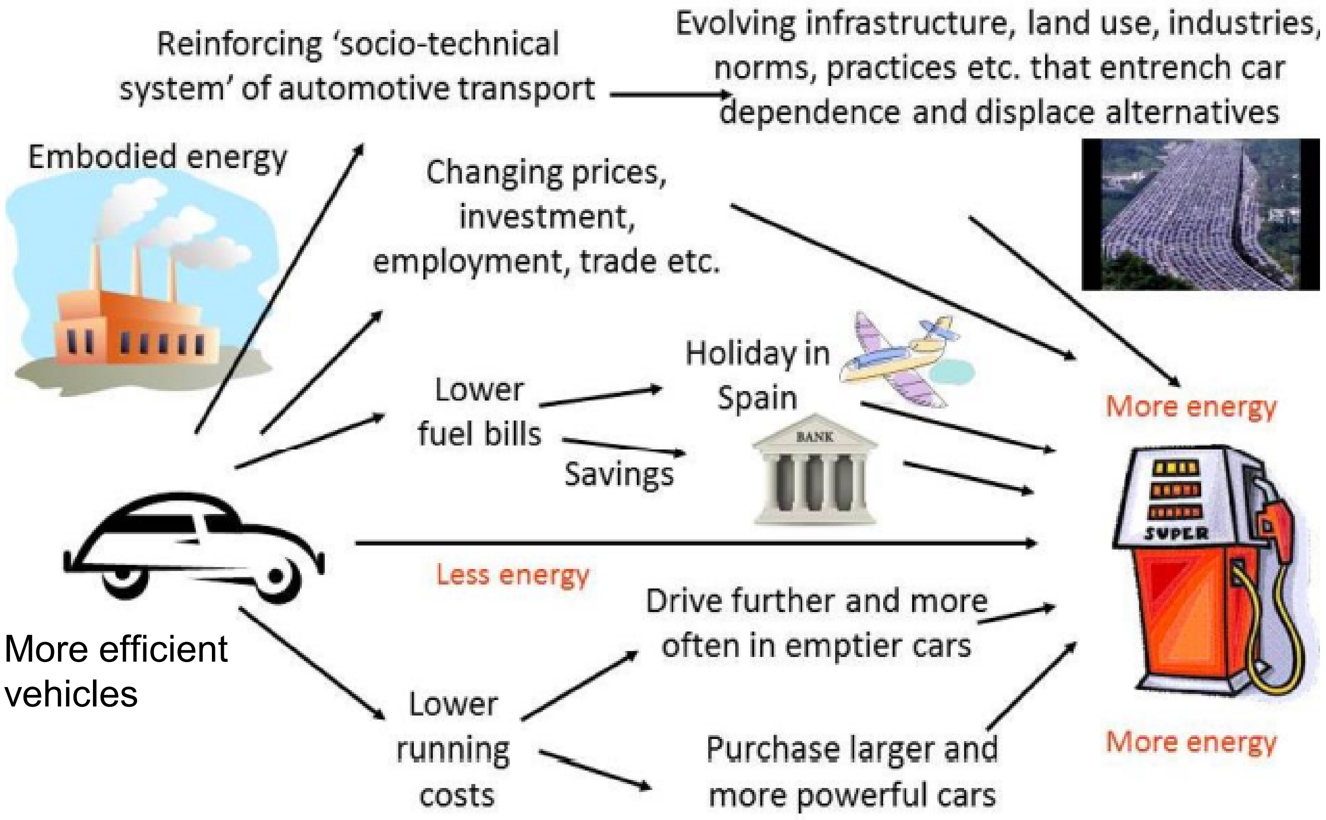
Ecoefficiency and Rebound effects



More efficient vehicles

ECEE et al. 2018

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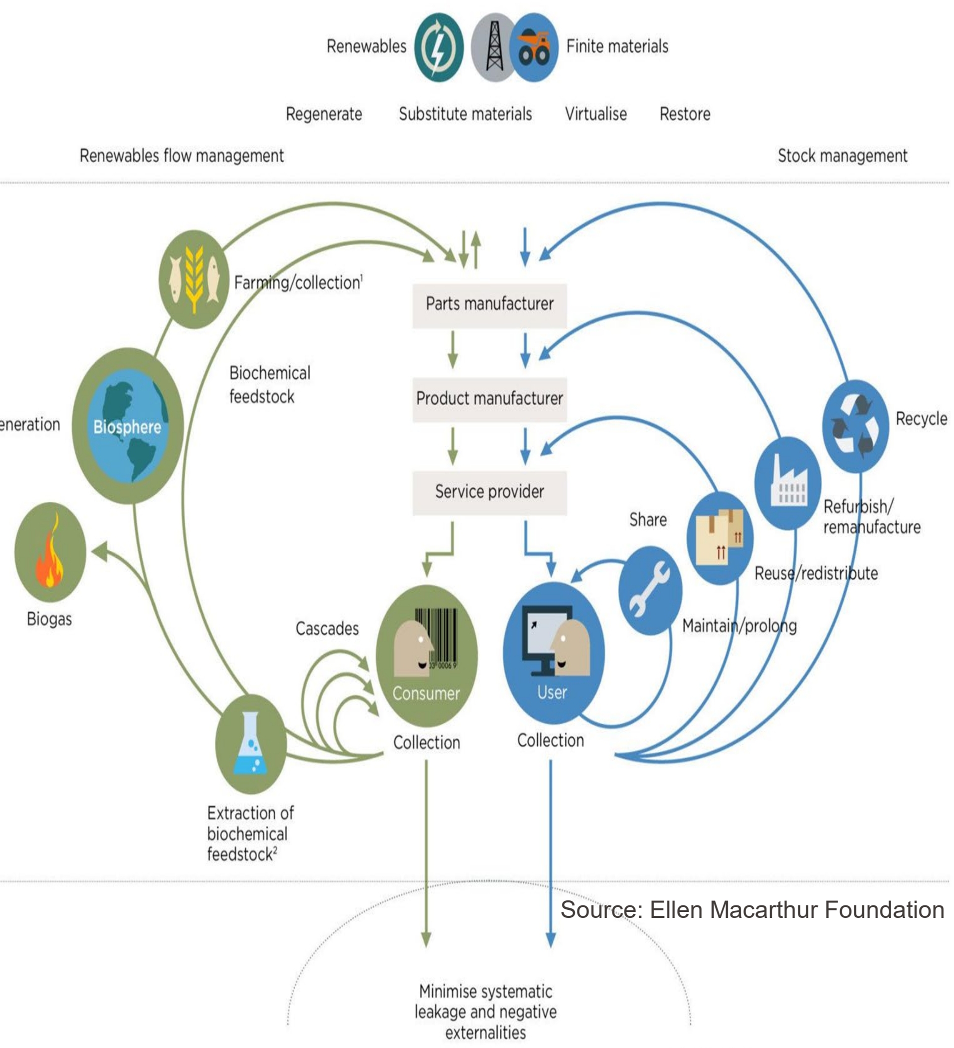


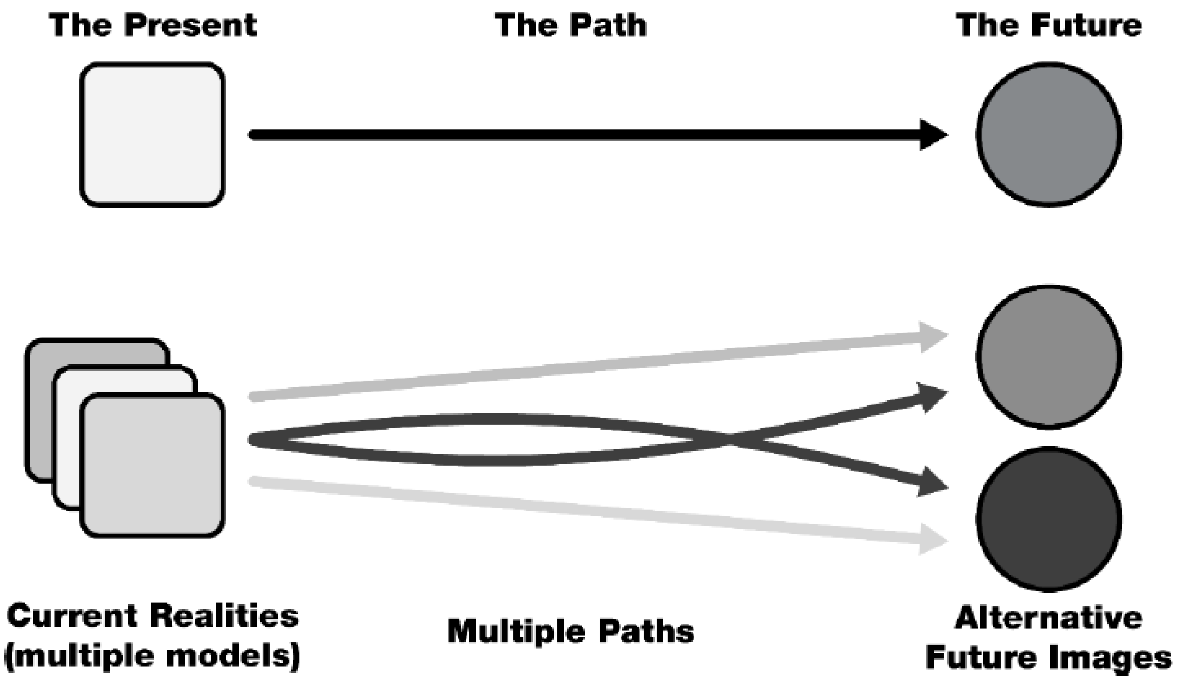
Source: Ellen Macarthur Foundation

Core element: Forward-looking research and practice

Predictions versus scenarios

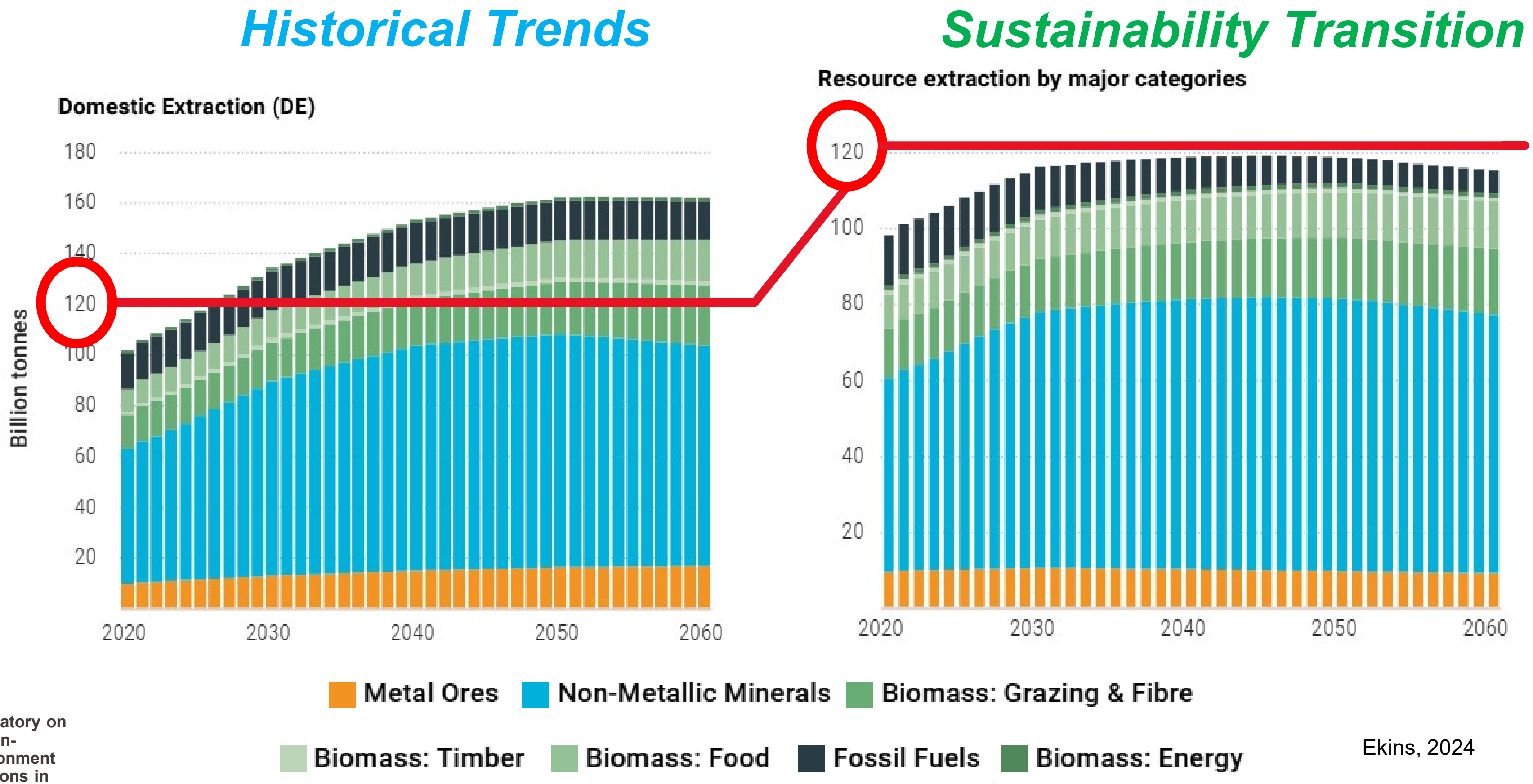
A **prediction** assesses the present, sketches the transitions, and presents its presumption of the future

A **scenario** looks at the present from different perspectives, imagining several possible transitions to a future state



Graedel & Eckelmann, 2023

Impacts: Outlook of Material Extraction under two scenarios



Ekins, 2024

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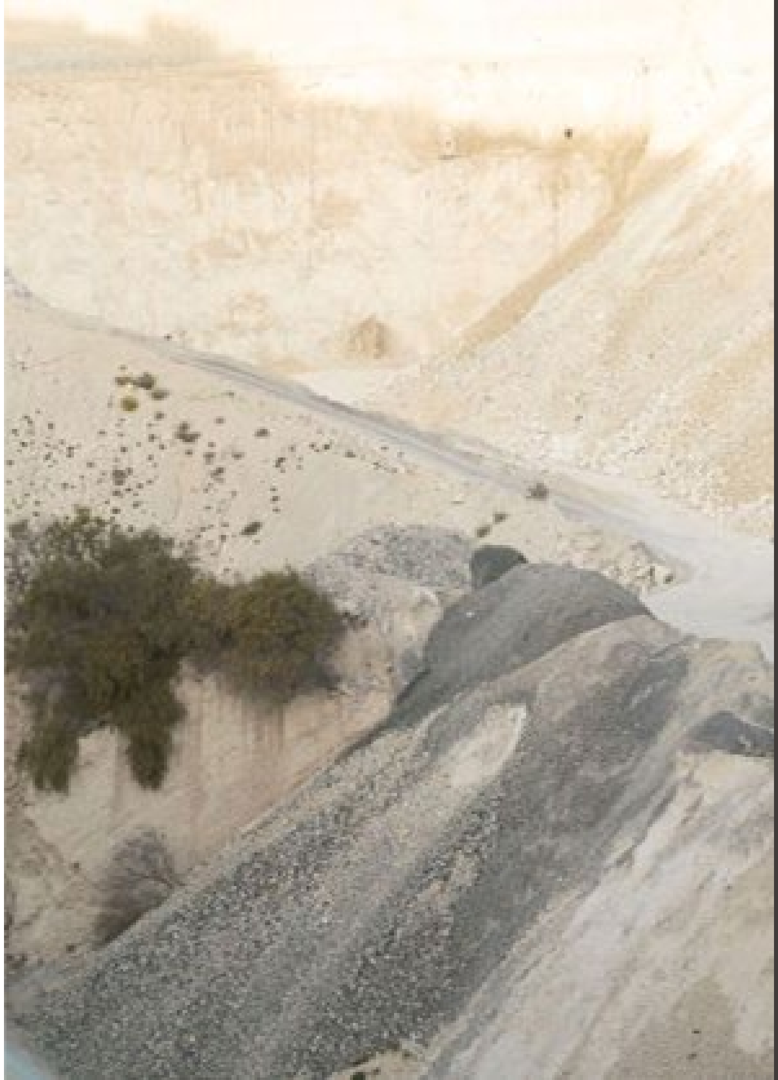
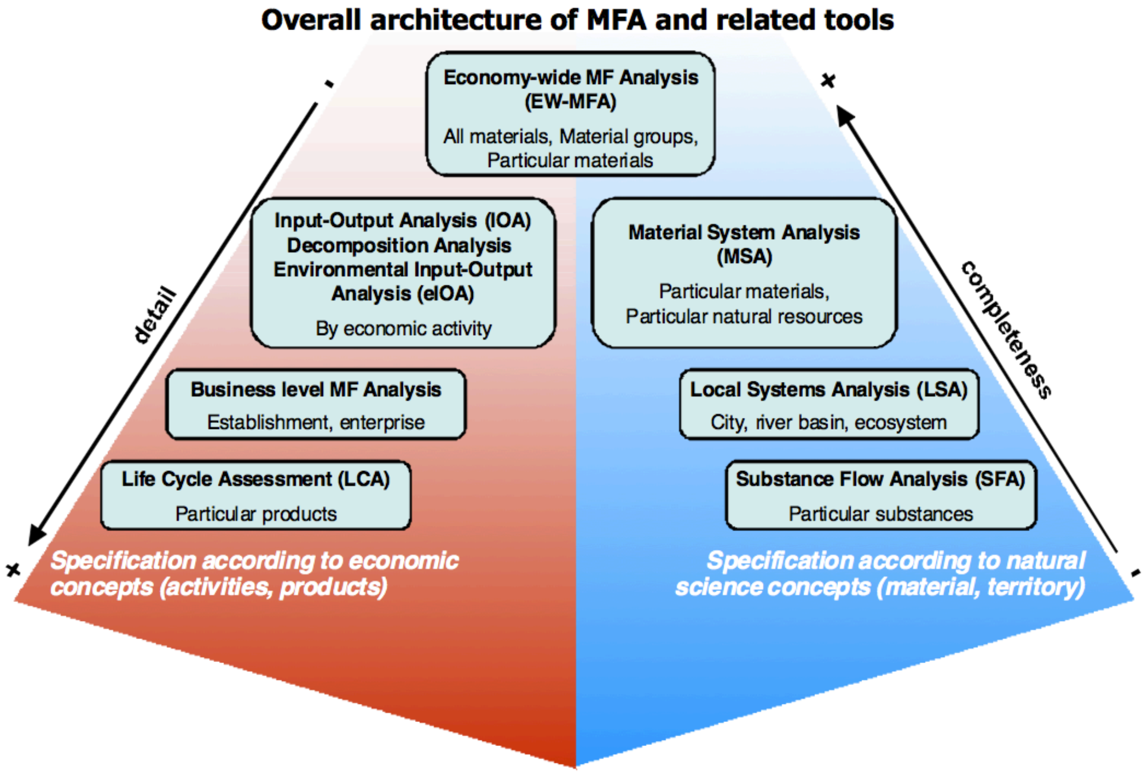


Industrial Ecology tools

Hierarchy of MFA tools



OECD, 2008

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MFA approaches

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Scale of the system
f.e. regions, industrial plants, private households, whole economy, specific parts of economy…

Materials
f.e. substances, materials, products…

Data sources
f.e. national or international econometric statistics, physical substance flows…

Main objective	Substances	Materials	Products, Goods and Services		Businesses		Economic activities	Countries, Regions
	e.g., chemical elements or compounds (Cd, Cl, Pb, Zn, Hg, N, [illegible] CO_2, CFC)	e.g., raw materials and semi-finished goods, energy carriers, metals (ferrous and nonferrous), sand and gravel, timber, plastics	e.g., batteries, transportation, packaging		e.g., offices, plants, small and medium sized entreprises, multi-national entreprises		e.g., mining, construction, chemical industry, iron and steel industry	e.g., aggregated mass of materials and related mixed or selected materials
Type of analysis	Substance Flow Analysis	Material Flow Analysis	Life Cycle Assessment		Business level Material Flow Analysis		Input–Output Analysis	Economy-wide Material Flow Analysis
Type of analytical tools	Substance Flow Accounts	Material Flow Accounts, Industrial, Urban or Regional Metabolism	Life-Cycle Inventory, Impact Assessment (ISO 14040)	Lif-Cycle Costing	Material Flow Cost Accounting (ISO 14051)	Business Material Flow Accounting	Physical Input-Output Tables, NAMEA approaches	Economy-wide Material Flow Accounts

Source: Moreau and Massard, 2017

IE approaches in this course

Main objective	Substances	Materials	Products, Goods and Services	Businesses	Economic activities	Countries, Regions
	e.g., chemical elements or compounds (Cd, Cl, Pb, Zn, Hg, N, P, C, CO_2, CFC)	e.g., raw materials and semi-finished goods, energy carriers, metals (ferrous and nonferrous), sand and gravel, timber, plastics	e.g., batteries, transportation, packaging	e.g., offices, plants, small and medium sized entreprises, multi-national entreprises	e.g., mining, construction, chemical industry, iron and steel industry	e.g., aggregated mass of materials and related mixed or selected materials
Type of analysis	**Substance Flow Analysis**	**Material Flow Analysis**	**Life Cycle Assessment**	**Business level Material Flow Analysis**	**Input–Output Analysis**	**Economy-wide Material Flow Analysis**
Type of analytical tools	Substance Flow Accounts	Material Flow Accounts, Industrial, Urban or Regional Metabolism	Life-Cycle Inventory, Impact Assessment (ISO 14040) Lif-Cycle Costing	Material Flow Cost Accounting (ISO 14051) Business Material Flow Accounting	Physical Input-Output Tables, NAMEA approaches	Economy-wide Material Flow Accounts

Source: Moreau and Massard, 2017

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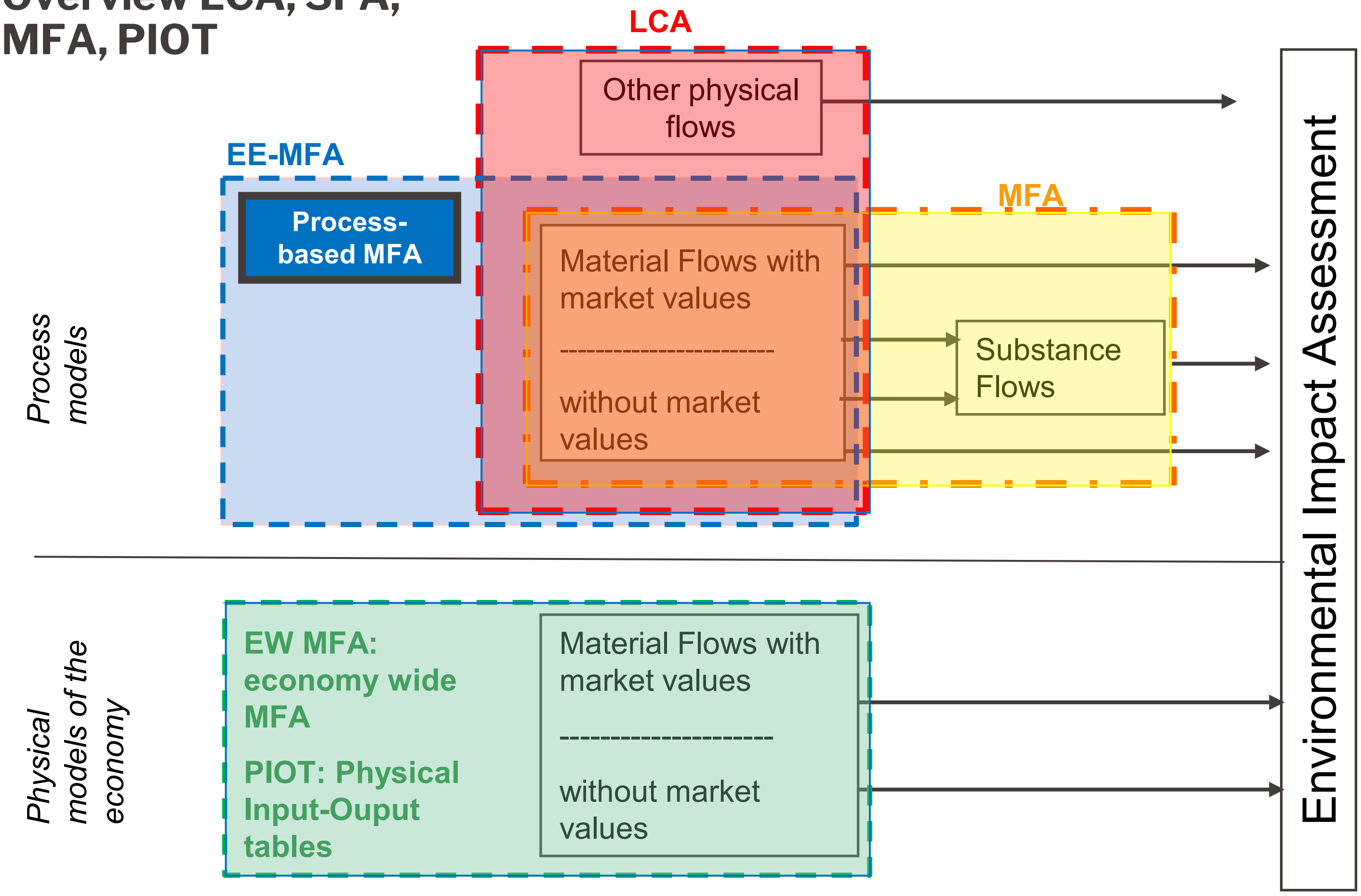
Overview LCA, SFA, MFA, PIOT



Source: Kytzia and Nathani, 2004

Overview of MFA tools

- Material Flow Analysis (MFA)
- Substance Flow analisis (SFA)
- Life-cycle assessment (LCA)
- Material Flow Cost accounting (MFCA)
- Input-Output Analysis (IOA)
- Economy-wide MFA (EW-MFA)

Definition: Material Flow Analysis (MFA)

- Material Flow Analysis (MFA) is the study of **physical flows of natural resources and materials** into, through and out of a given system (usually the economy).
- It is based on accounts in **physical units,** and uses the principle of mass balancing to analyze the **relationships between material flows** (including energy), **human activities** (including economic and trade developments) and **environmental changes.**

Source: OECD, 2008

MFA in practice supports policy and decision making in…

“You can’t manage what you can’t measure.”

Brunner, 2012

- Urban planning
- Energy planning
- Economic and environmental performance
- Development of industrial symbiosis and eco-industrial parks
- Closing material loops and circular economy
- Pollution control
- Material and energy supply security

4 Steps of MFA

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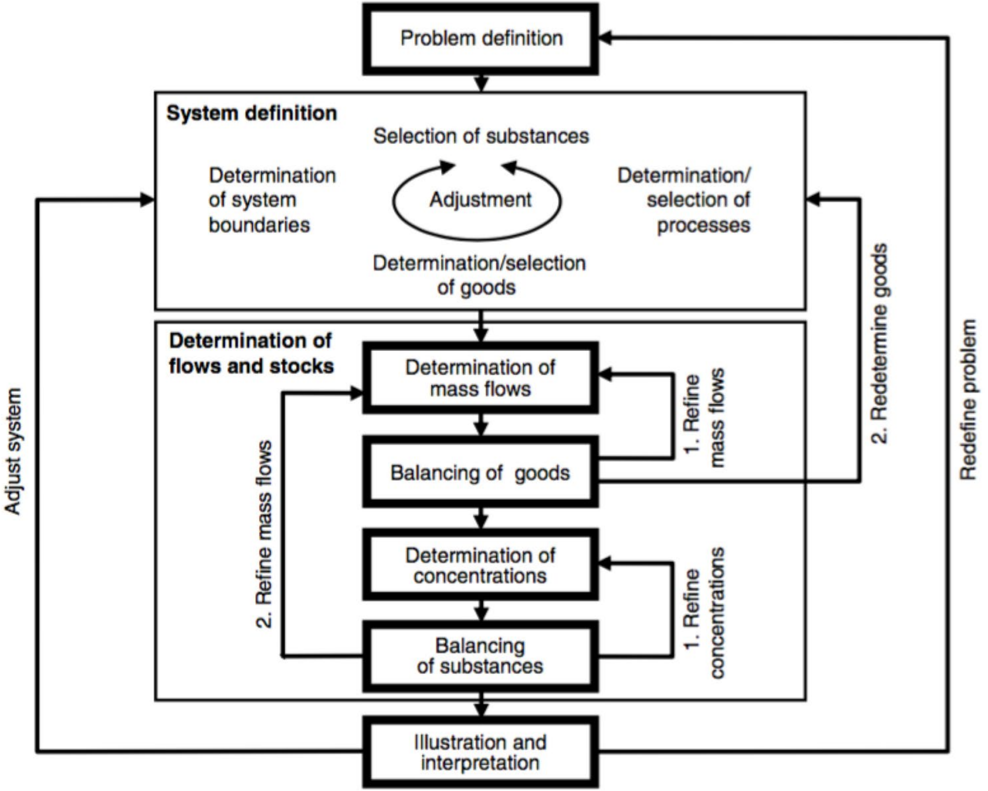
- System definition
- Data acquisition
- Calculation
- Representation and interpretation



Source: Brunner & Rechberger, 2004

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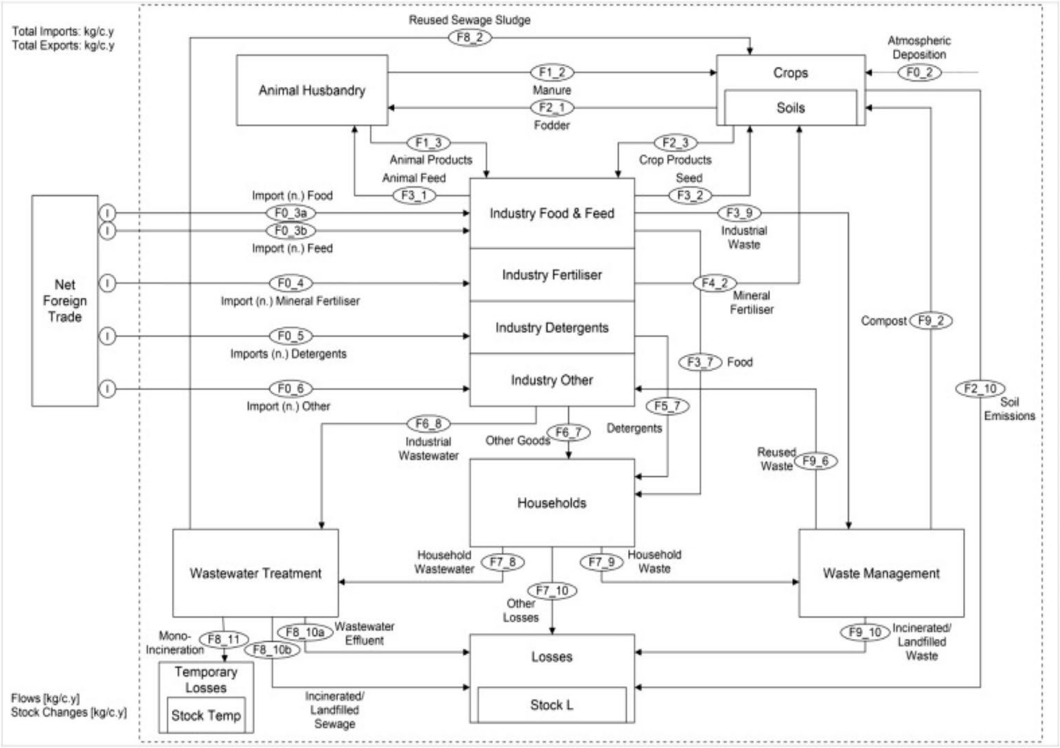
Substance Flow Analysis (SFA)

- MFA for **specific substance** (f.e. phosphorus, iron, zinc, copper…)
- Provide information on **resource management** and **environmental impacts** for specific (limited) substance

Phosphorus stocks and flows in CH



Source: Jedelhauser & Binder 2015

Campo, Hecher, Campfens

Life Cycle Assessment (LCA)

- Addresses **environmental impacts** throughout a **product's life cycle** starting from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)
- **Environmental impacts** f.e. climate change, human health, ecosystem quality, resource depletion
- Comprehensive approach which **identifies impact shifting** from **one phase** of the product life cycle **to another**

Source: https://www.nist.gov/systems-integration-division/lifecycle-graphic

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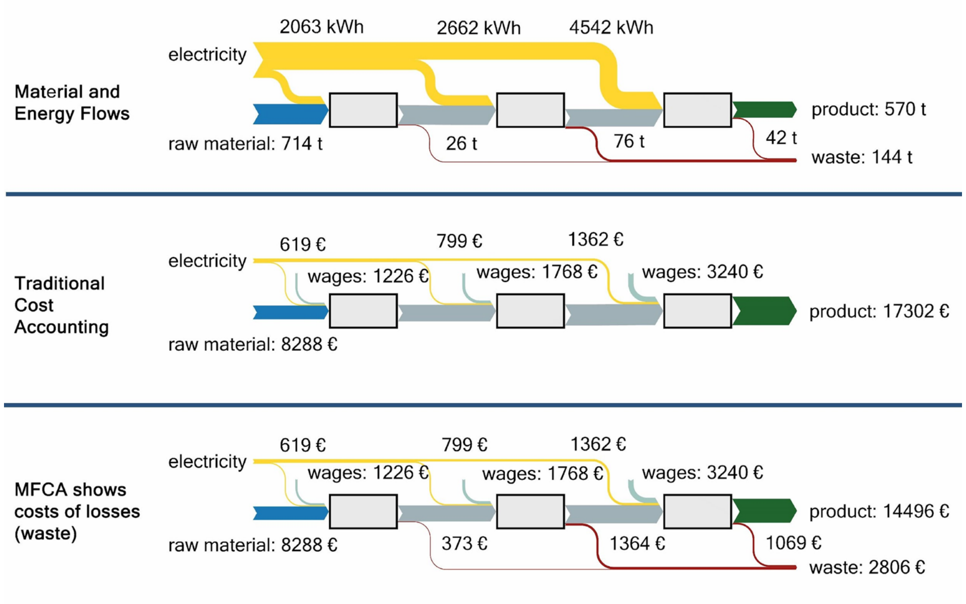
Material Flow Cost Accounting (MFCA)

- Assessing **materials flows in physical and monetary terms along the value chain** / production processes, from purchase to disposal
- **Companies** understand better the environmental and financial consequences of their material and energy use for improvements



Source: https://www.ifu.com/de/materialflusskostenrechnung/

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Material Flow Cost Accounting (MFCA)

- MFCA links monetary and material flows at the activity level

- Costs: **Monetary value of resources** used to perform activities
- Cost allocation: **Indirect** attribution of a **cost** between different objects, such as a product or process, by using an appropriate share basis
- Cost assignment: **Direct** attribution of a **cost** to a specific object, such as a product or process

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Input-Output Analysis (IOA)

- Details the **supply and use of products sector by sector**, including imports and exports and final consumption categories (f.e. households)
- Understand the interactions between economic sectors
- **Environmental extended IOA (EE-IOA)** typically includes energy intensity and carbon emissions by sector

Table 2

Purchases by / Sales of	Industry 1	Industry 2	Industry n	Total sales
Industry 1	x_{11}	x_{12}	x_{1n}	$X_1 = \sum_j x_{1j}$
Industry 2	x_{21}	x_{22}	x_{2n}	$X_2 = \sum_j x_{2j}$
...	...	...	...	...
Industry n	x_{n1}	x_{n2}	x_{nn}	$X_n = \sum_j x_{nj}$
Total purchases	X_1	X_2	X_n	

Table 1: Inter-Industry Transactions

Industries	Inputs to agriculture	Inputs to manufacturing	Final demand	Total outputs
Agriculture	25	175	50	250
Manufacturing	40	20	60	120
Labour services	10	40	0	50

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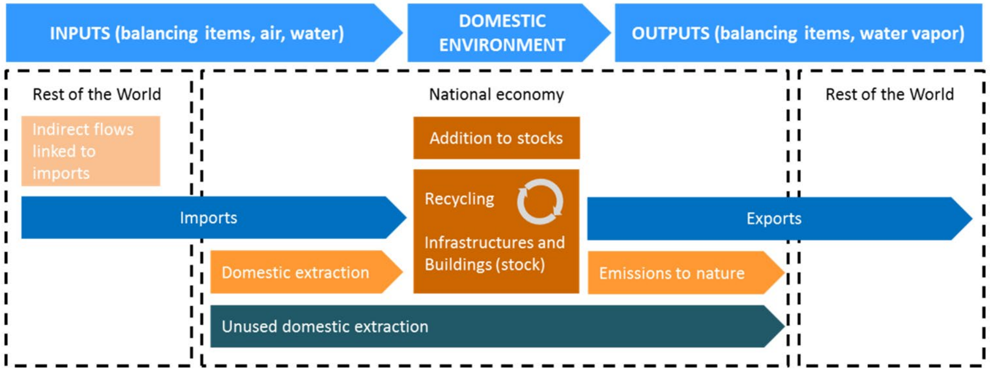
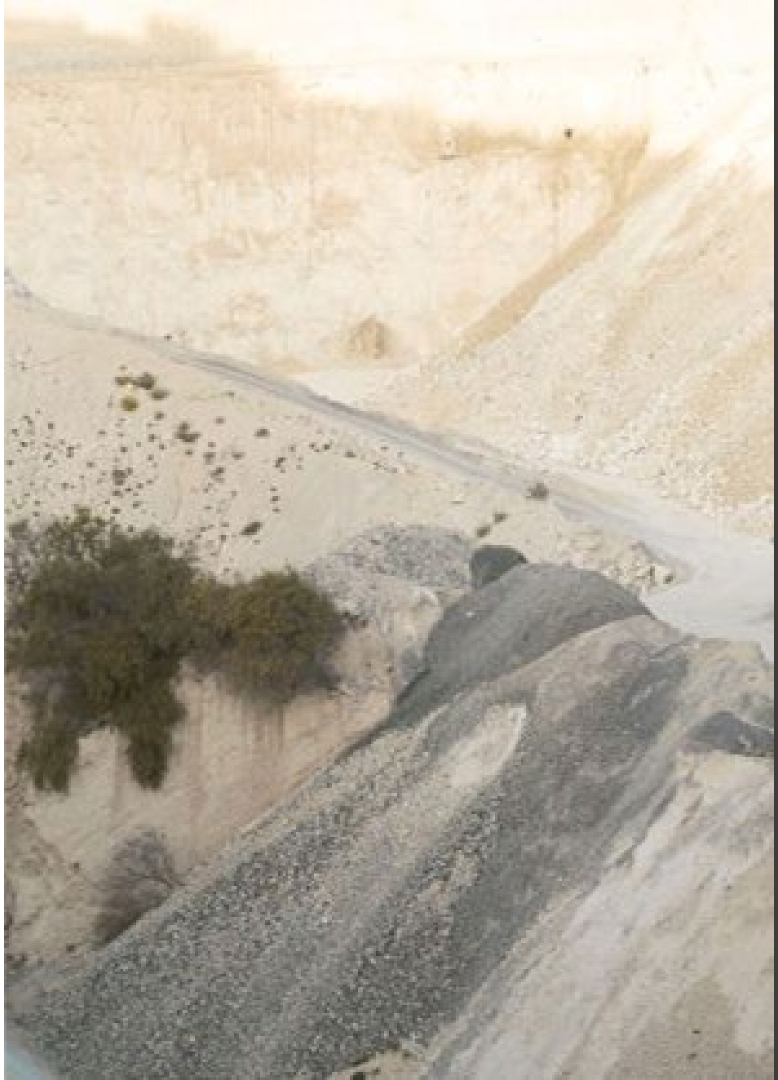
Economy-wide Material Flow Analysis (EW-MFA)

- Quantification of **material flows** (biomass, fossil fuels, metals, mineral ores) **into and out of a whole economy**
- Material flows are **extracted domestically or imported directly and indirectly** through finished and semi-finished goods
- Describes **interaction** of domestic **economy** with the natural **environment** and the **rest of the world economy**





Thank you for your attention!

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