

Materials design and selection for circular economy

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Module 1: Materials in circular economy and eco-informed material choice

Gross, Bernardo

Introduction to materials: main features (composition, structure, morphology, structure-properties relationships), main classes (metals/alloys, polymers, ceramics/glasses) their relevance in main specific sectors (plastics, building & construction, metals, apparel & textiles, energy conversion and storage) in a circular economy perspective. Eco-informed material choice. Specific topics:

Basics on circular chemistry.

Embedding sustainability in the design/manufacturing of materials. Sankey diagrams of materials flow.

How to address criticality: material design to reduce CRM content and substitution approaches.

Introduction to material properties charts: development and use. Definition of materials indices: performance of a component according to a combination of properties; selection through charts and indices. Presentation of "pure" selection case studies, with discussion of the characteristic equations and derivation of selection indices. Materials selection with conflicting objectives: trade-off analysis.

Environmental impact monitoring methods. Case studies of graphical materials selection oriented to environmental sustainability (control of energy and carbon footprint) in primary production.

Materials life cycle: definition of boundaries, introductory remarks to LCA, principles of eco-auditing. Updates on environmental sustainability from inclusion of manufacturing step. Presentation and analysis of end-of-life options. Case studies of application of eco-audits: introduction to the CES (Cambridge Engineering Selector) software, comparison between disposable and reusable constructions, material substitution

Case studies on cost/environmental sustainability trade-off

Sustainability by means of material minimization: introduction of shape factors, with case studies.

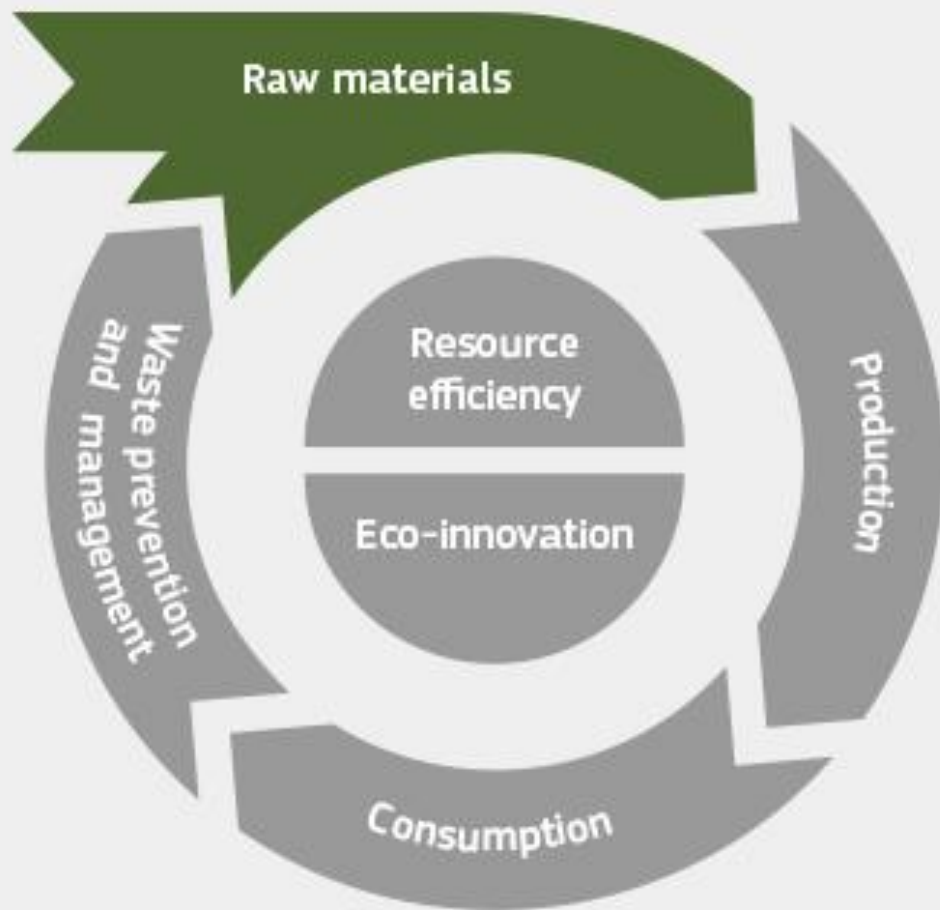


'**Materials**' sometimes refers to primary or **raw materials**, understood as virgin materials extracted from the natural environment. This normally includes biomass, metal ores, non-metallic minerals and fossil energy carriers. On other occasions, it also includes **secondary raw materials** such as recycled steel, plastics and concrete. Furthermore, some policies are directed at specific materials, such as in the case of the EU list of **critical raw materials** (see lecture prof. Ardit).

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS

Roadmap to a Resource Efficient Europe

Raw materials



Raw materials are the **basis of a large number of industrial value chains in the EU**. Specific raw materials are needed to make a wide range of industrial goods such as car engines, mobile phones or wind turbines.

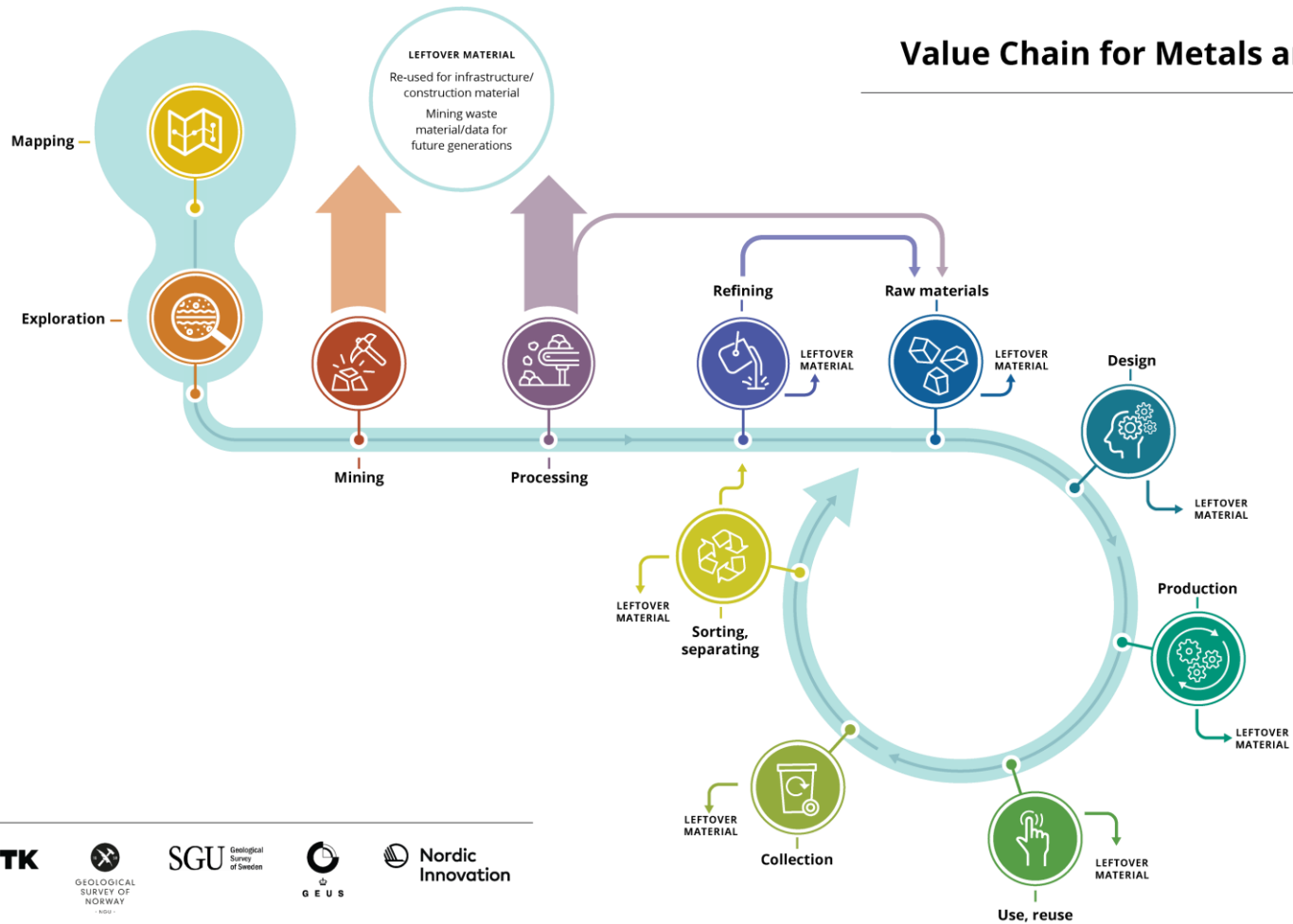
<https://policy.trade.ec.europa.eu/>

Source of the picture: <https://extrudesign.com/classification-of-materials-engineering-material-classification/>

Table 1. Economic and environmental significance of selected materials and products

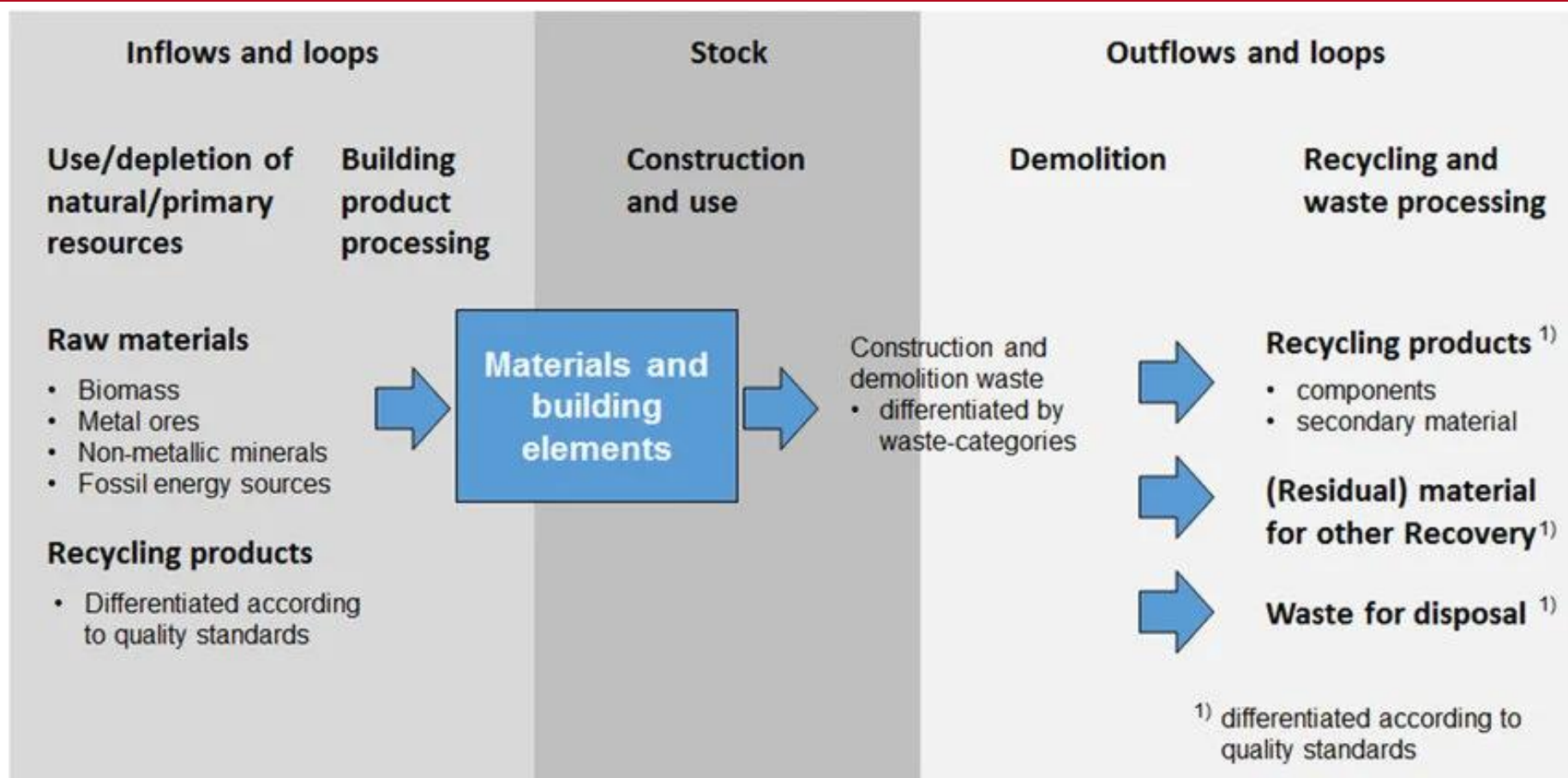
Selected Material/Product	Environmental Significance	Economic Significance
<i>Aluminium</i>	◆ Lightweight (transportation fuel efficiency) ◆ Infinitely recyclable ◆ Energy intensive production (GHG emissions) ◆ Solid waste (red mud)	◆ Widely used esp. in transportation, construction, electricity generation ◆ Increasing global demand ◆ Price volatility ◆ Consumption strongly coupled with economic growth
<i>Copper</i>	◆ Infinitely recyclable ◆ Energy-intensive production ◆ E-waste	◆ Widely used esp. in electrical transmission and construction ◆ Increasing global demand ◆ Price volatility
<i>Iron and Steel</i>	◆ Infinitely recyclable ◆ well-developed scrap markets ◆ Energy-intensive production	◆ Most widely used and traded metal in the world ◆ Increasing global demand ◆ Price volatility
<i>Rare Earth Elements</i>	◆ Used in clean energy and energy efficiency technologies ◆ Recycling extremely challenging ◆ Chemically-intensive processing ◆ E-waste	◆ Used in wide range of high-tech electronics ◆ Lack of substitutes ◆ Increasing global demand, recent supply chain issues ◆ Price volatility
<i>Phosphorus</i>	◆ Eutrophication ◆ Waste (phosphogypsum) and emissions (fluorine) ◆ Recyclable (with losses)	◆ Food security ◆ Supports agricultural production
<i>Paper</i>	◆ Renewable / recyclable (with losses) ◆ Carbon sequestration, habitat (forests) ◆ Potential source of energy (wood biomass) ◆ Energy- and water-intensive production	◆ Demand growing esp. in emerging economies ◆ Wide variety of products

What is a value chain



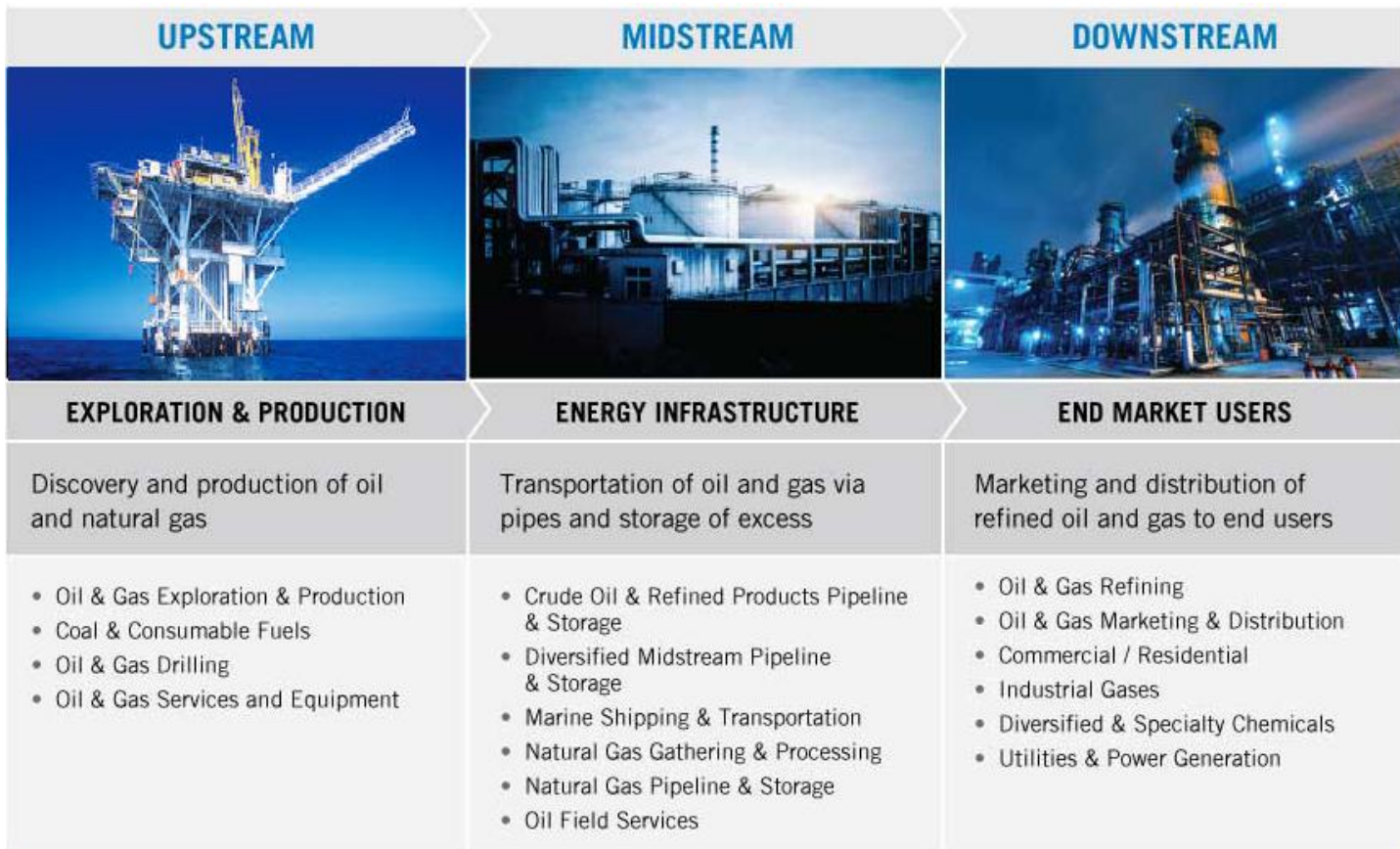
Source of figure: fity.org

What is a value chain



Source of figure: Material Flows In Buildings' Life Cycle And Regions – Material Inventories To Support Planning Towards Circular Economy - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Change-of-material-categories-following-the-value-chain-of-materials-and-products-own_fig3_333932101 [accessed 28 Sept 2026]

Upstream vs. downstream



Source of figure: <http://outperformsrm.com/oil-gas/>

The **upstream supply chain** includes all activities related to the organization's suppliers: those parties that source raw material inputs to send to the manufacturer.

The **downstream supply chain** refers to activities **post-manufacturing**, namely distributing the product to the final customer.

Relevant sources of data and info in the field of materials and resources

Joint Research Centre (JRC)

The Joint Research Centre is the Commission's science and knowledge service.

<https://joint-research-centre.ec.europa.eu/>

EuroStat

Eurostat is the statistical office of the European Union.

<https://ec.europa.eu/eurostat/web/main/about-us/who-we-are>

EIT Raw Materials

It is the largest consortium in the raw materials sector worldwide. Its vision is to develop raw materials into a major strength for Europe.

<https://eitrawmaterials.eu/>

European Raw Materials Alliance (ERMA)

<https://erma.eu/about-us/>

U.S. Geological Survey

It leads national efforts to map mineral resources and analyze the supply chains needed to drive the U.S. economy and national security

<https://www.usgs.gov/>

Relevant sources of data and info in the field of materials and resources

British Geological Survey

<https://www.bgs.ac.uk/mineralsuk/>

World Mining Data (Austria)

<https://www.world-mining-data.info/>

Screen3

<https://screen.eu/crms-2023/>

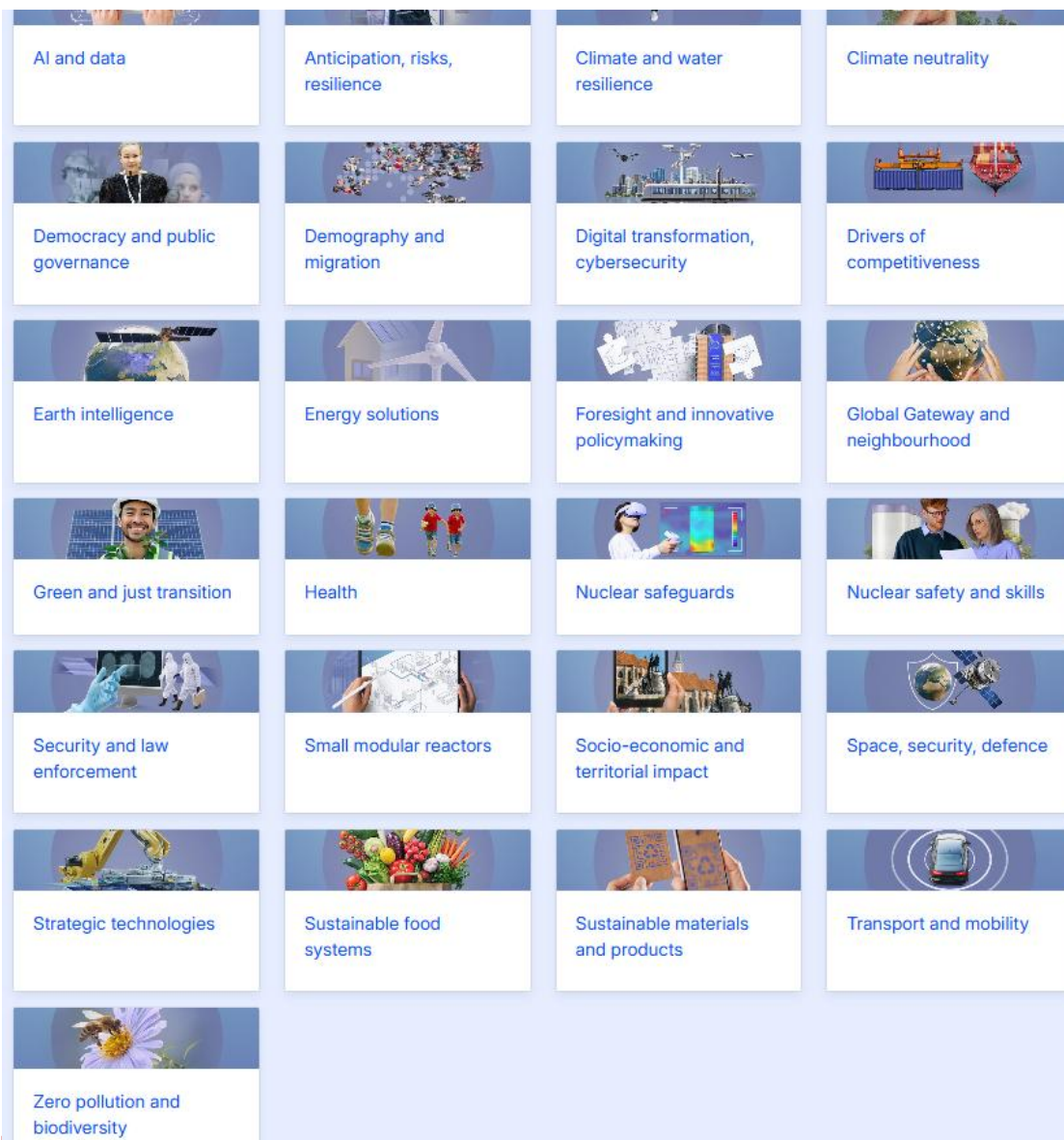
CRM Alliance

<https://www.crmalliance.eu/hrees>

Joint Research Centre (JRC)

Scientists at the **Joint Research Centre (JRC)** carry out research in various fields to provide independent advice to EU policymakers and put science at the heart of European policies. Originally established under the Euratom Treaty, the JRC has longstanding expertise in the nuclear field, but offers scientific competences from a wide range of disciplines to support almost all EU policy areas.

<https://joint-research-centre.ec.europa.eu/>



Resources: the starting points

- Increase of world population
- Increase of materials and resources demand
- Materials depletion and criticality (see lecture Prof. Ardit)
- Planet resources overexploitation

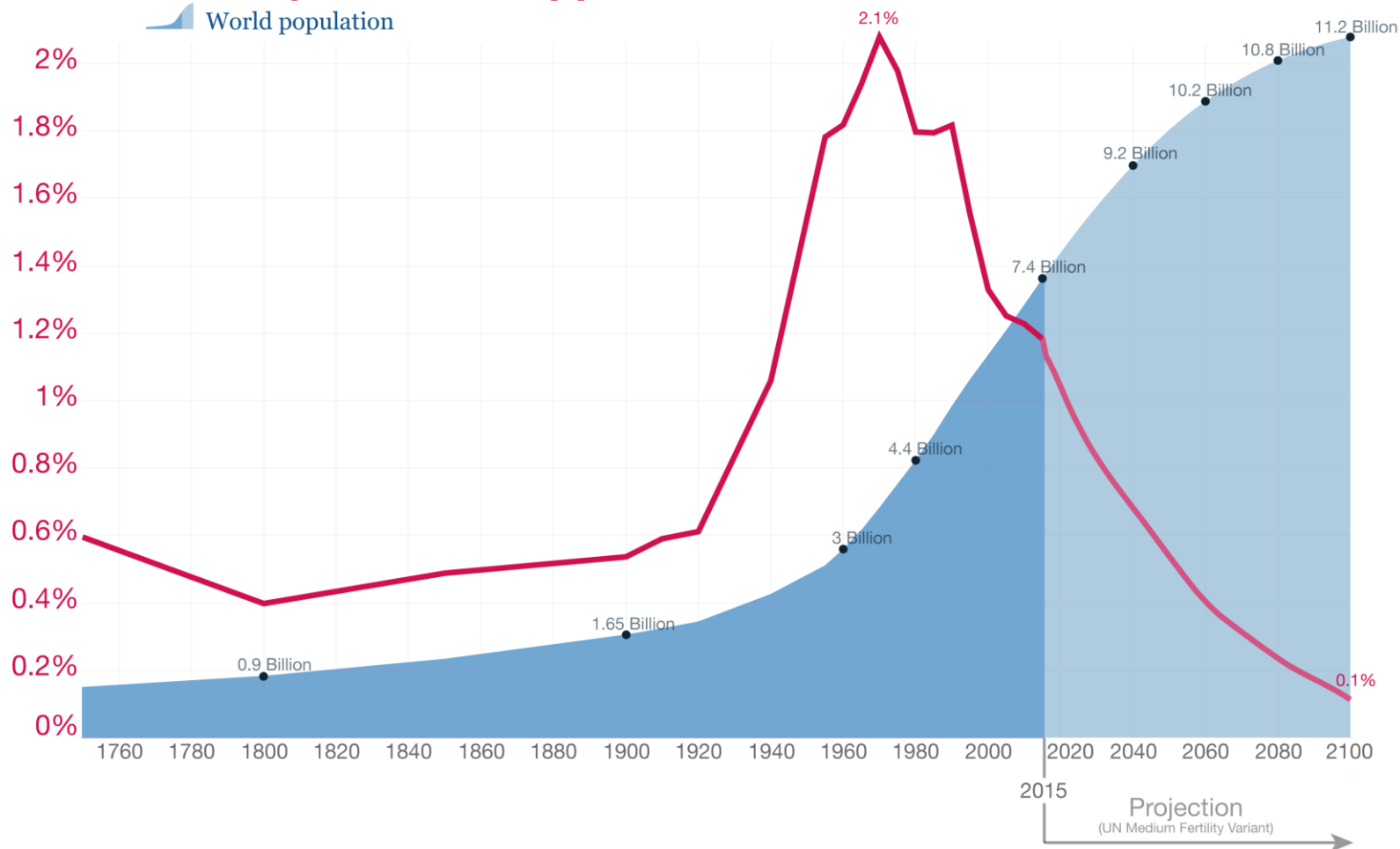
- Increase of world population
- Increase of materials and resources demand
- Materials depletion and criticality (see lecture Prof. Ardit)
- Planet resources overexploitation

The starting points

Our World
in Data

World population growth, 1750-2100

 Annual growth rate of the world population
 World population



Data sources: Up to 2015 OurWorldInData series based on UN and HYDE. Projections for 2015 to 2100: UN Population Division (2015) – Medium Variant. The data visualization is taken from [OurWorldInData.org](https://ourworldindata.org). There you find the raw data and more visualizations on this topic.

Licensed under CC-BY-SA by the author Max Roser.

<https://ourworldindata.org/world-population-growth>

The starting points

- Increase of world population
- Increase of materials and resources demand
- Materials depletion and criticality (see lecture Prof. Ardit)
- Planet resources overexploitation

Basics concepts and definitions

- **Domestic extraction (DE):** total amount of material extracted for further processing in the economy, by resident units from the natural environment. The data originates from Eurostat's dataset 'Material flow accounts (env_ac_mfa)' the production of which is under legal coverage: Regulation (EU) No 691/2011 on European Environmental Economic Accounts - Annex 3: Economy-wide Material Flow Accounts. The module is conceptually related to the international statistical standard System of Environmental-Economic Accounting 2012 (SEEA).
- **Raw material equivalents (RME):** conversion factors to express a unit of product traded into the amount of material extraction needed, anywhere in the world, to produce the traded product. (expressed in tons or kg)
- **Raw material input (RMI):** the amount of material in terms of RME available to the economy for use in production and consumption activities. It is the sum of domestic extraction and imports in RME (calculated at the aggregate product level, by material).
- **Raw material consumption indicator (RMC):** the amount of material in terms of RME needed (or, the amount of extraction, domestic and abroad, required directly and indirectly) to produce the products consumed in the geographical reference area. It is calculated as RMI minus exports in RME (calculated at the aggregate product level, by material).

https://ec.europa.eu/eurostat/cache/metadata/en/env_ac_rme_esms.htm

Basics concepts and definitions

$RMI = \text{domestic extraction} + \text{imports in raw material equivalents}$

$RMC = RMI - \text{exports in raw material equivalents}$

Material flow accounts in raw material equivalents

Eurostat

Basics concepts and definitions

Methods and criteria for material equivalents

MFA indicators

Direct material input (DMI)
= domestic extraction (DE)
+ imports

Physical trade balance (PTB)

= imports – exports

Domestic material
consumption (DMC)
= DE + imports – exports

RME-based indicators

Raw material input (RMI)
= DE + RME of imports
(RIM)

Raw material trade balance
(RTB)
= RIM – RME of exports
(REX)

Raw material consumption
(RMC)
= DE + RIM – REX

Note: MFA = material flow accounting; RME = raw material equivalents.

Calculation model for estimating RME at country level

The calculation model for estimating RME at country level was developed for conducting the **estimation of RME of product flows at country level**.

The aim was to develop an approach which is satisfying the following conditions:

- Comparatively low resource requirement
- Sufficient degree of accuracy
- Compliance with the concepts, methods and data of the EU-level RME model
- Harmonized approach for all member countries.

(PDF available on the Moodle of the course)



**Handbook for estimating
raw material equivalents**

**of imports and exports and RME-
based indicators on the country level
– based on Eurostat's EU RME model**

November 2024

Calculation model for estimating RME at country level

Figure 1: Schematic description of estimation of country-level RME by the "adjusted coefficient approach"

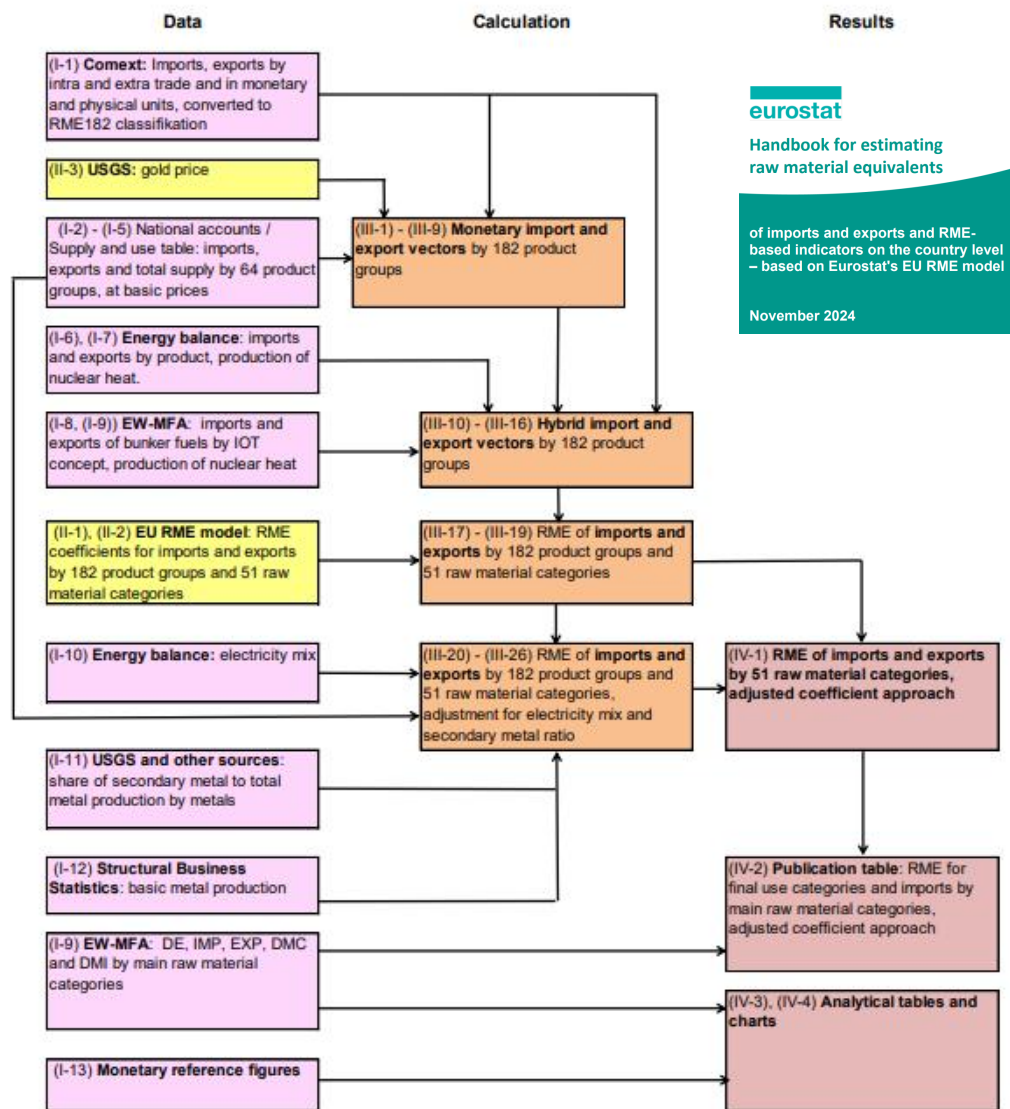


Figure 1 presents a schematic description of the calculation model. The chart shows the data inputs, the major calculation steps and the different types of results. The following data sources are used:

Country-level data: Comext*, National Accounts/Supply and use tables; Energy Balance, economy-wide material flow accounts (EW-MFA), USGS and other sources, Structural Business Statistics, Eurostat (* <https://ec.europa.eu/eurostat/comext/newxtweb>)

Data valid for all countries: Eurostat's RME model (Annual RME coefficient matrices for imports and exports, EU-level), USGS (gold prices). The EU model is applying a hybrid IOT matrix, i.e. **selected sales structures are expressed in physical units and not in monetary units**. Accordingly, also the RME coefficients from that model are based on mixed units for the denominator. The calculation method of the adjusted coefficient approach combines annual EU-level RME coefficient matrices for imports and exports with hybrid country-level import and export vectors. The mix of units of the hybrid trade vectors is fully matching the mix of units for the EU coefficients.

Basics concepts and definitions

Material flow accounts in raw material equivalents (MFA-RME) complement economy-wide material flow accounts (EW-MFA). MFA-RME account for products in terms of the amount of **domestic extraction** necessary to produce them, irrespective of where the material was extracted. Producing those estimates is closely related to input-output techniques, which is one of the elements in the SEEA CF* research agenda. The main MFA-RME indicator, **raw material consumption (RMC)**, is also referred to as a 'material footprint', as it captures the amount of extraction of materials needed to meet the country's consumption and investment demand.

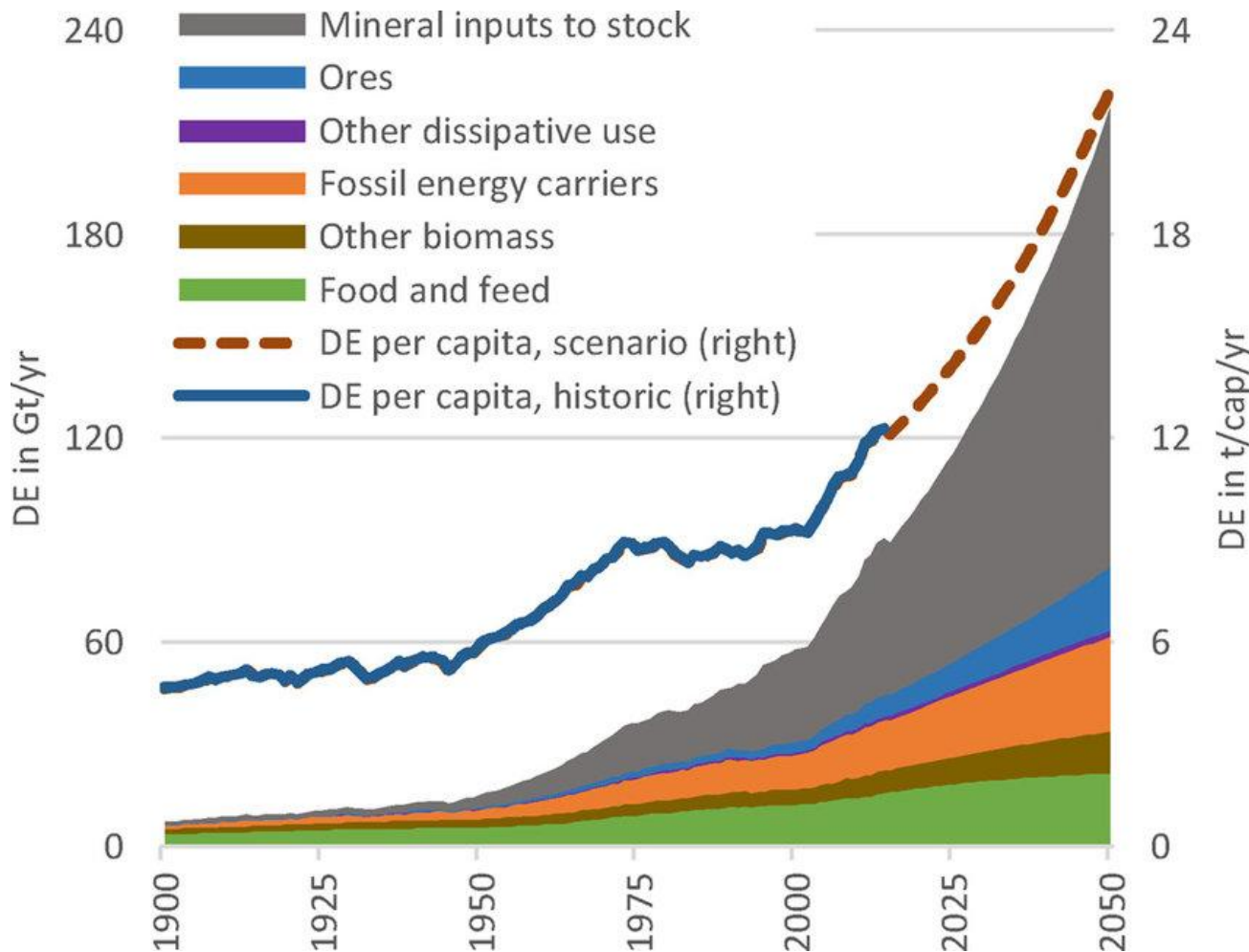
In the European Statistical System the term '**material flow accounts in raw material equivalents (MFA-RME)**' was introduced to emphasise that one may consider a wider accounting framework behind the layman's term 'material footprint'.

The rationale of MFA-RME is to express the final use of products in equivalents of material extractions (=raw material equivalents). This means **the material extraction worldwide** (domestically and in the rest of the world) that was necessary to produce and make available the respective products to final use in a national economy.

Material flow accounts in raw material equivalents

*System of Environmental Economic Accounting
Central Framework

Global material resource extraction (DE)

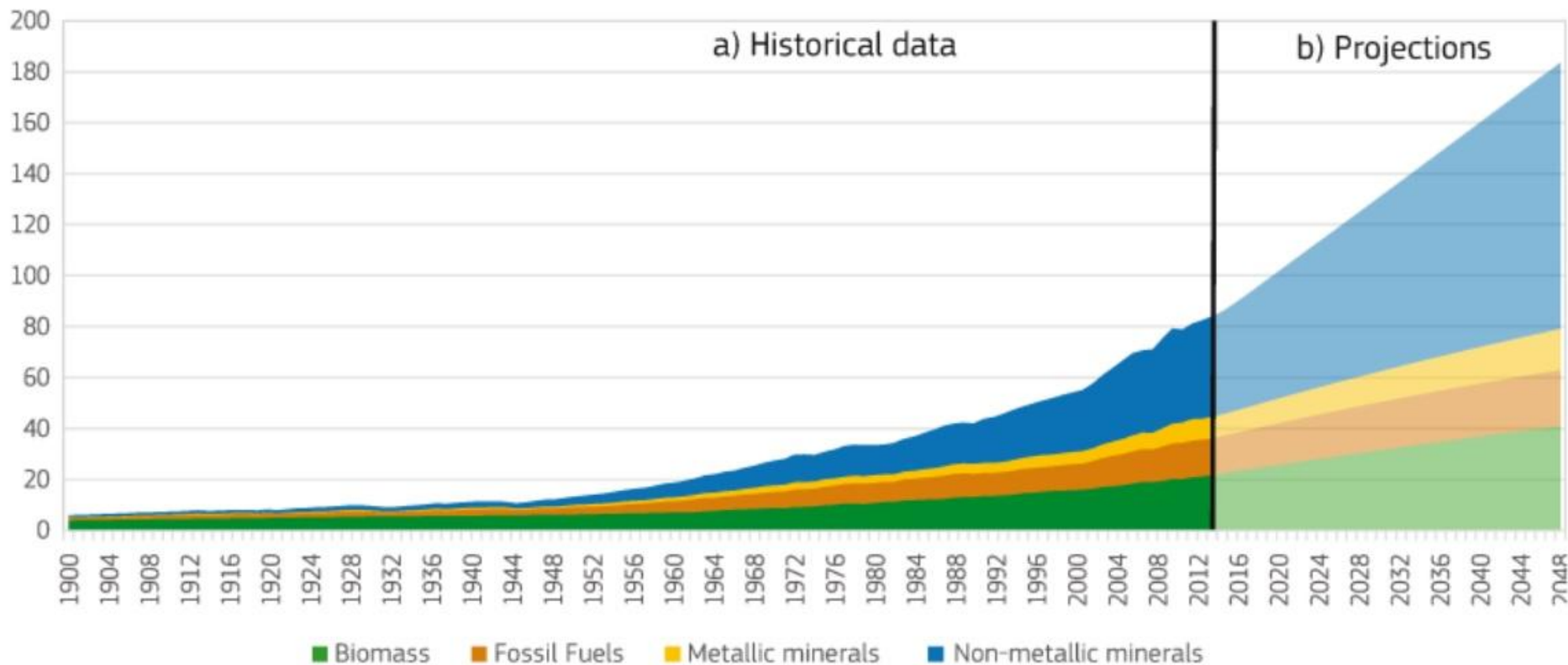


DE = global (domestic) extraction (total amount of material extracted for further processing in the economy, by resident units from the natural environment)

A **resident (institutional) unit** is an institutional unit that is resident because it has a centre of economic interest in the economic territory of a country (or a grouping like the [European Union \(EU\)](#) or the [euro area](#)).

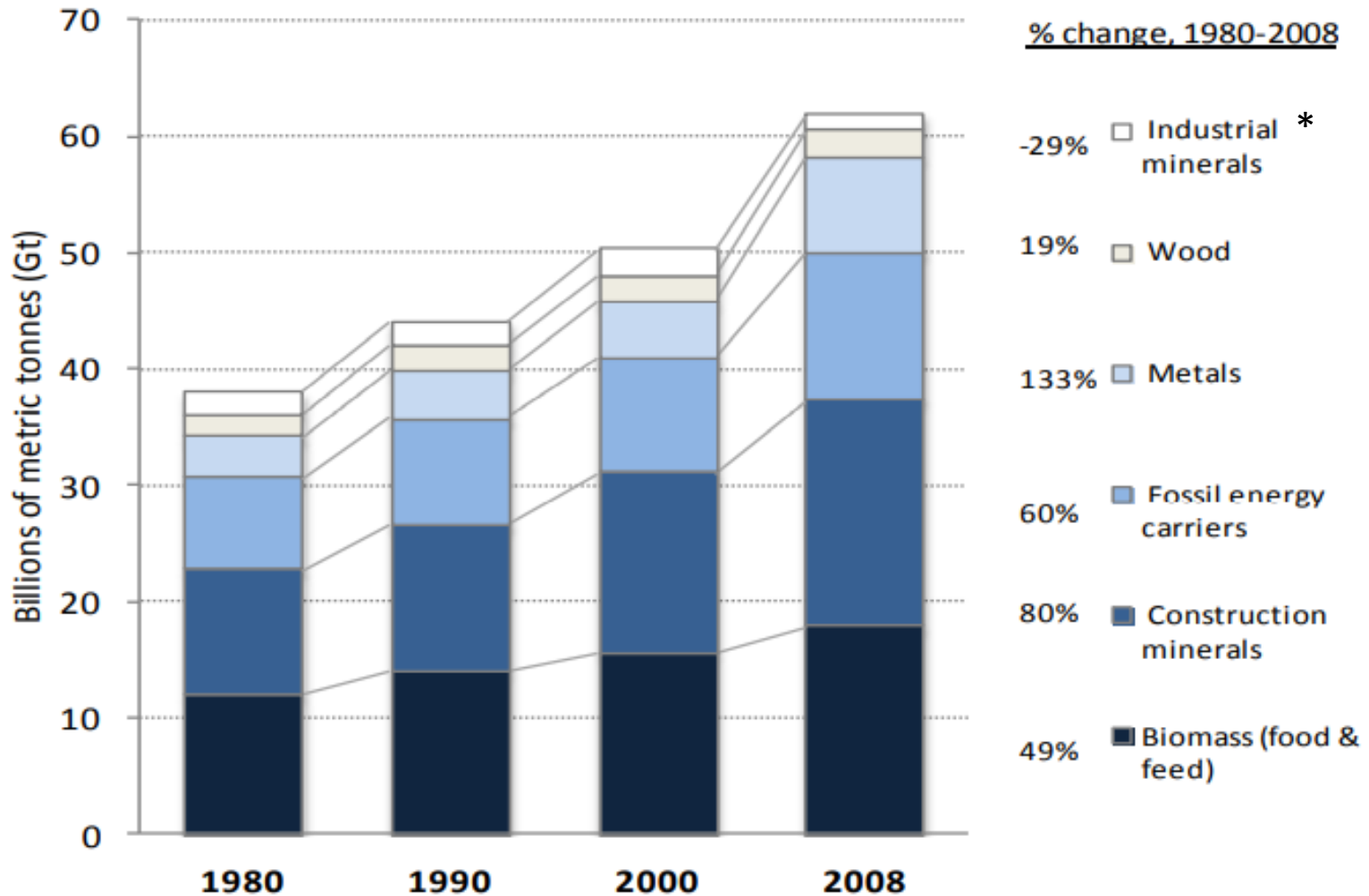
Krausmann, Fridolin & Lauk, Christian & Haas, Willi & Wiedenhofer, Dominik. (2018). From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Global Environmental Change*. 52. 131-140. 10.1016/j.gloenvcha.2018.07.003.

Global material resource extraction (DE)



Source: https://knowledge4policy.ec.europa.eu/foresight/topic/aggravating-resource-scarcity/global-materials-extraction-resource-type_en

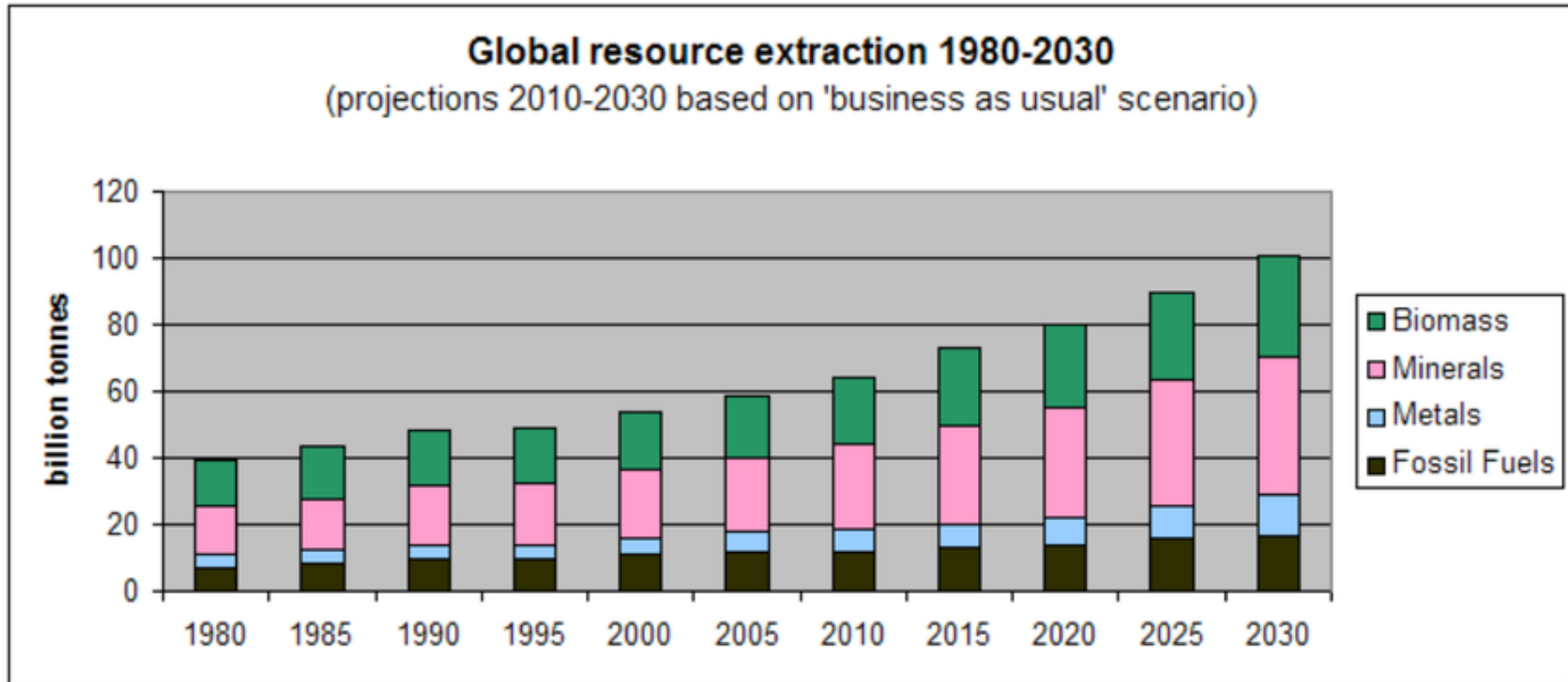
Global material resource extraction



Source: SERI (Sustainable Europe Resource Institute) material flows database.

*limestone, clays, sand, gravel, diatomite, kaolin, bentonite, silica, barite, gypsum, and talc

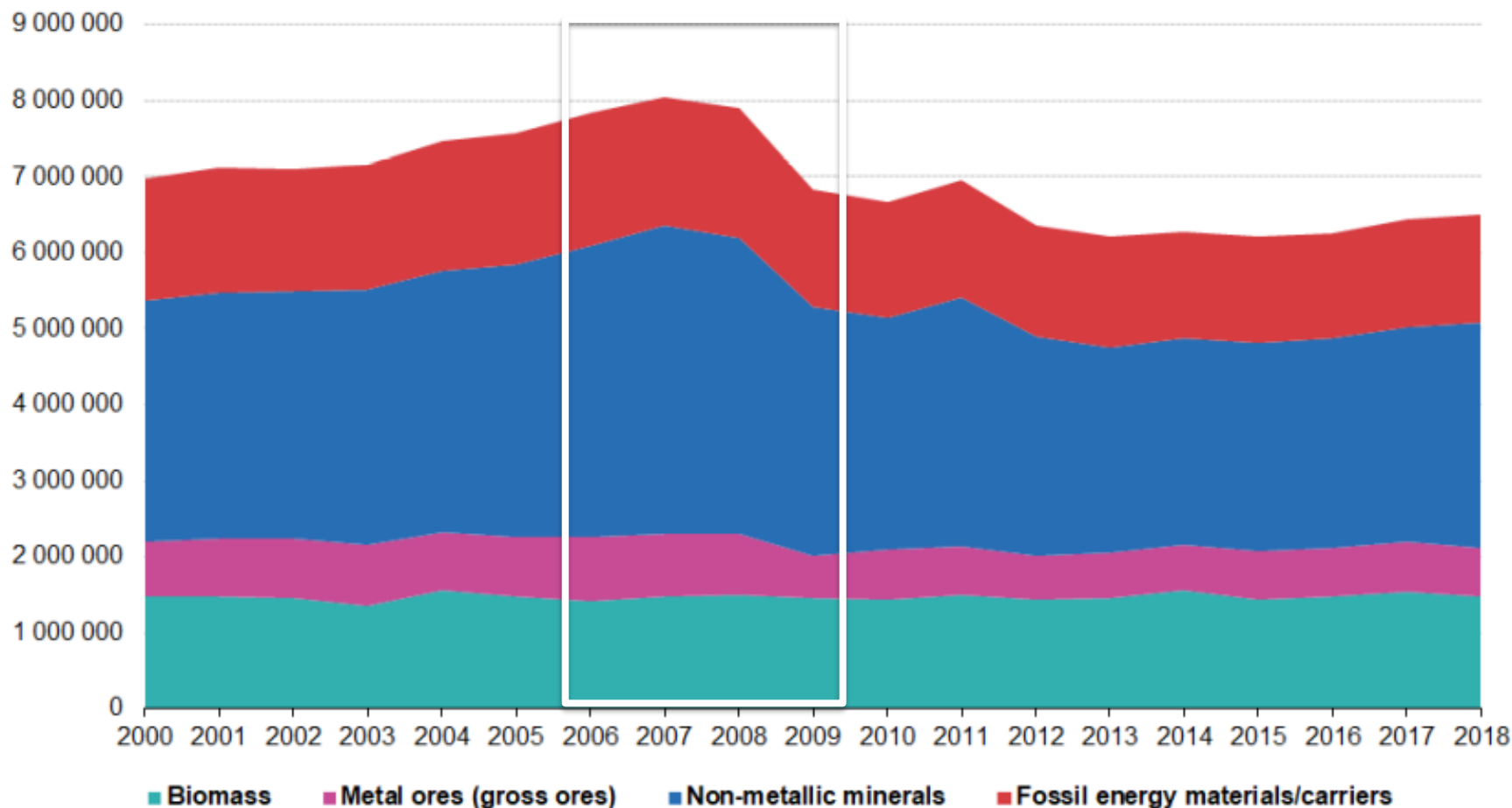
Global material resource extraction



Bleischwitz, Raimund. (2010). International economics of resource productivity – Relevance, measurement, empirical trends, innovation, resource policies. International Economics and Economic Policy. 7. 227-244. 10.1007/s10368-010-0170-z.

Raw material consumption in the EU-27

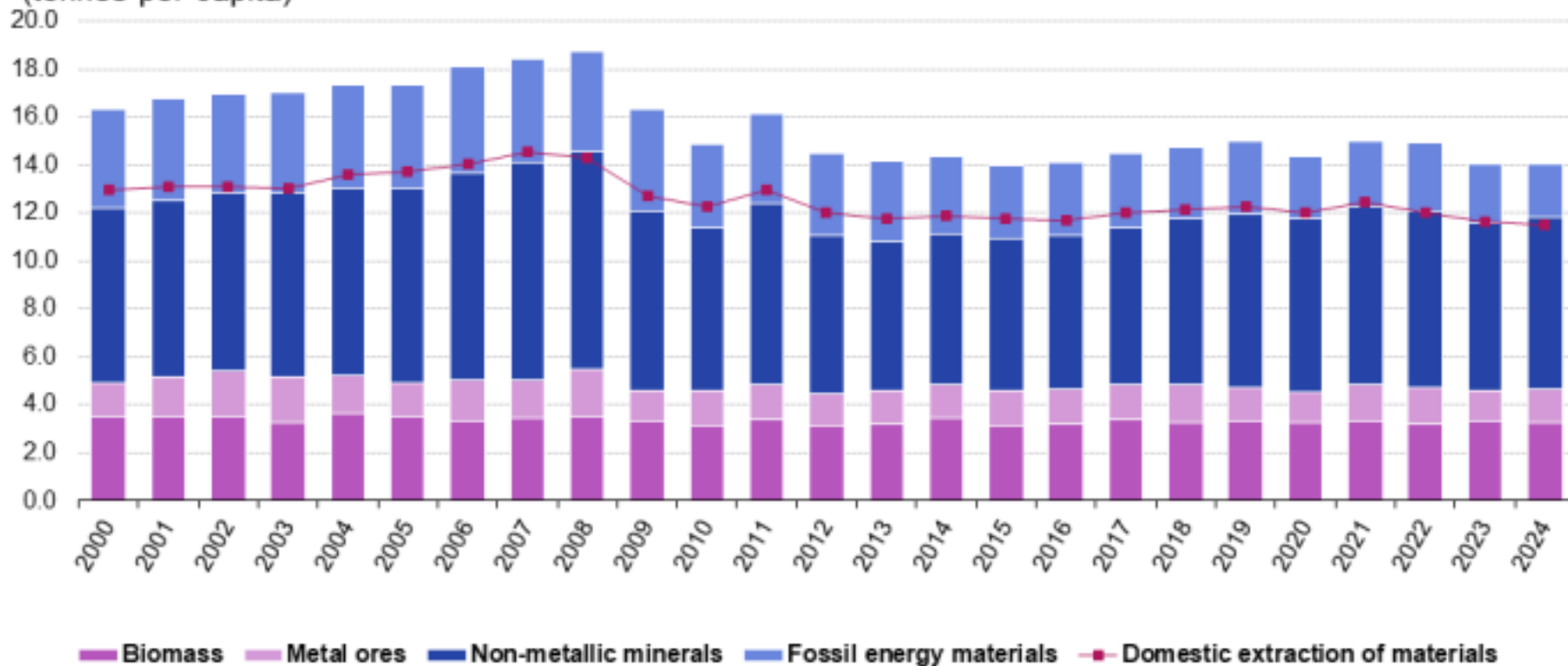
(thousand tonnes)



Source: Eurostat (online data code: env_ac_rme)

Raw material consumption (RMC) by main material categories, EU, 2000-2024

(tonnes per capita)

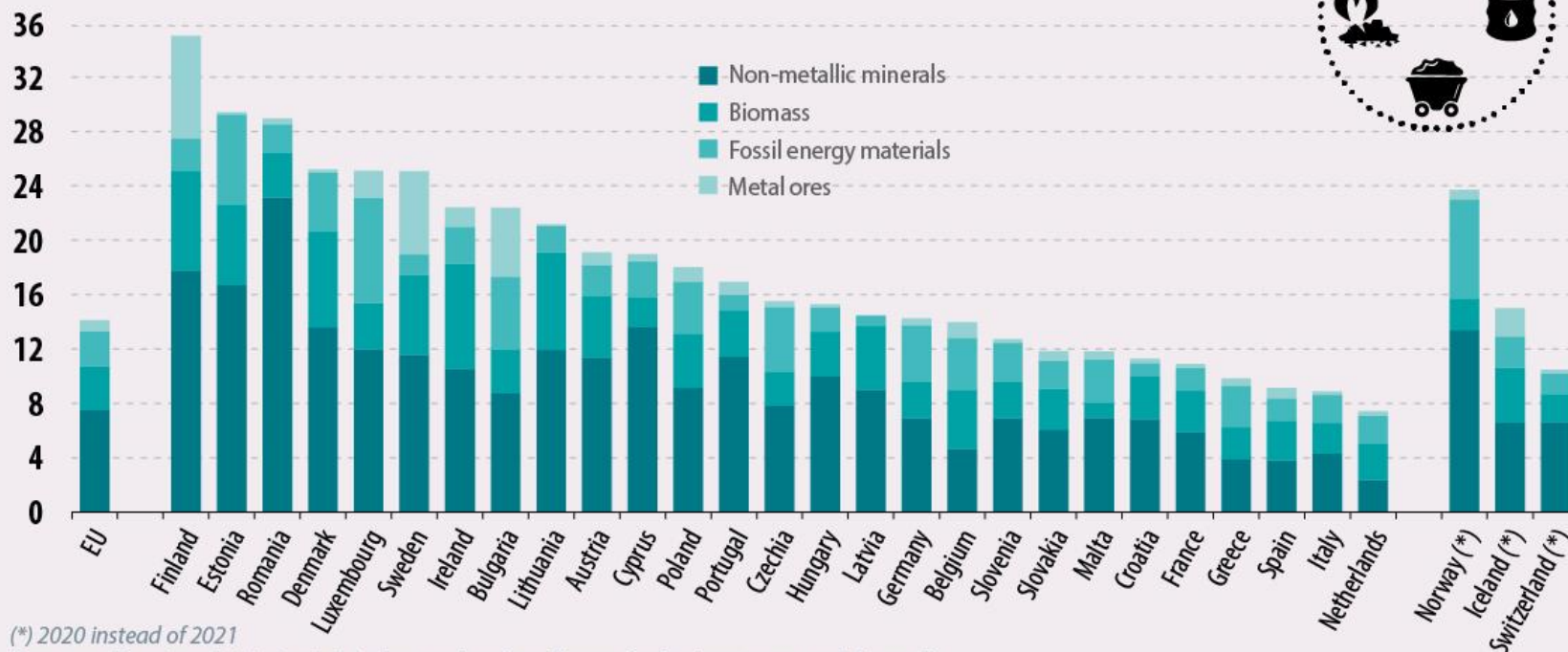


Source: Eurostat (online data code: env_ac_rme)

eurostat 

Raw materials consumption (pro capita)

Domestic material consumption by main material category, 2021
(tonnes per person)



(*) 2020 instead of 2021

'Non-metallic minerals' also include 'other products' and 'waste for final treatment and disposal'.

ec.europa.eu/eurostat

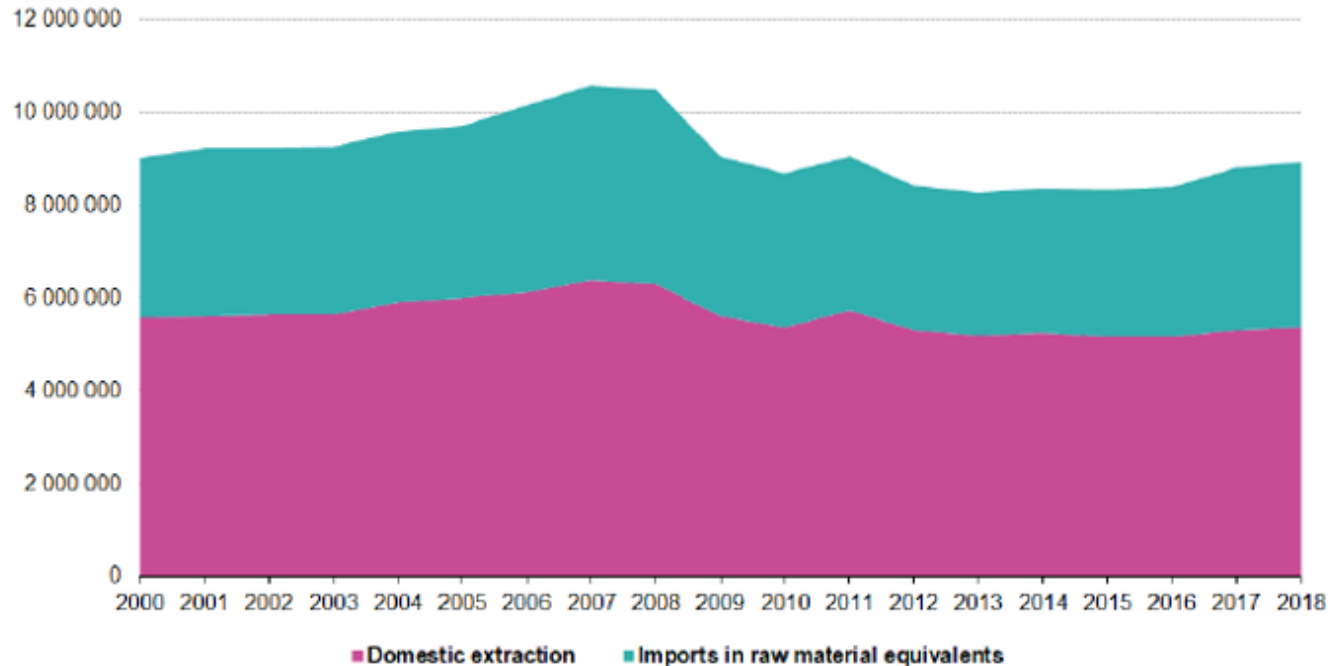
Consumption of the main material categories also varied across EU Member States.

In 2021, consumption of non-metallic minerals ranged from 2 tonnes per person in the Netherlands to 23 tonnes per person in Romania. Cross-country differences can be a result of **varied levels of construction activities (investments), population densities and sizes of transport infrastructures**, such as road networks. Biomass consumption varied from a tonne per person in Malta to 8 tonnes per person in Ireland. Economies with high biomass consumption are often specialised in timber production (Finland) or certain livestock production (Ireland, Denmark).

Consumption of fossil energy material varied from a tonne per person in Latvia to 8 tonnes per person in Luxembourg.

Raw material input for EU27 according to material flow accounts in raw material equivalents

(thousand tonnes)

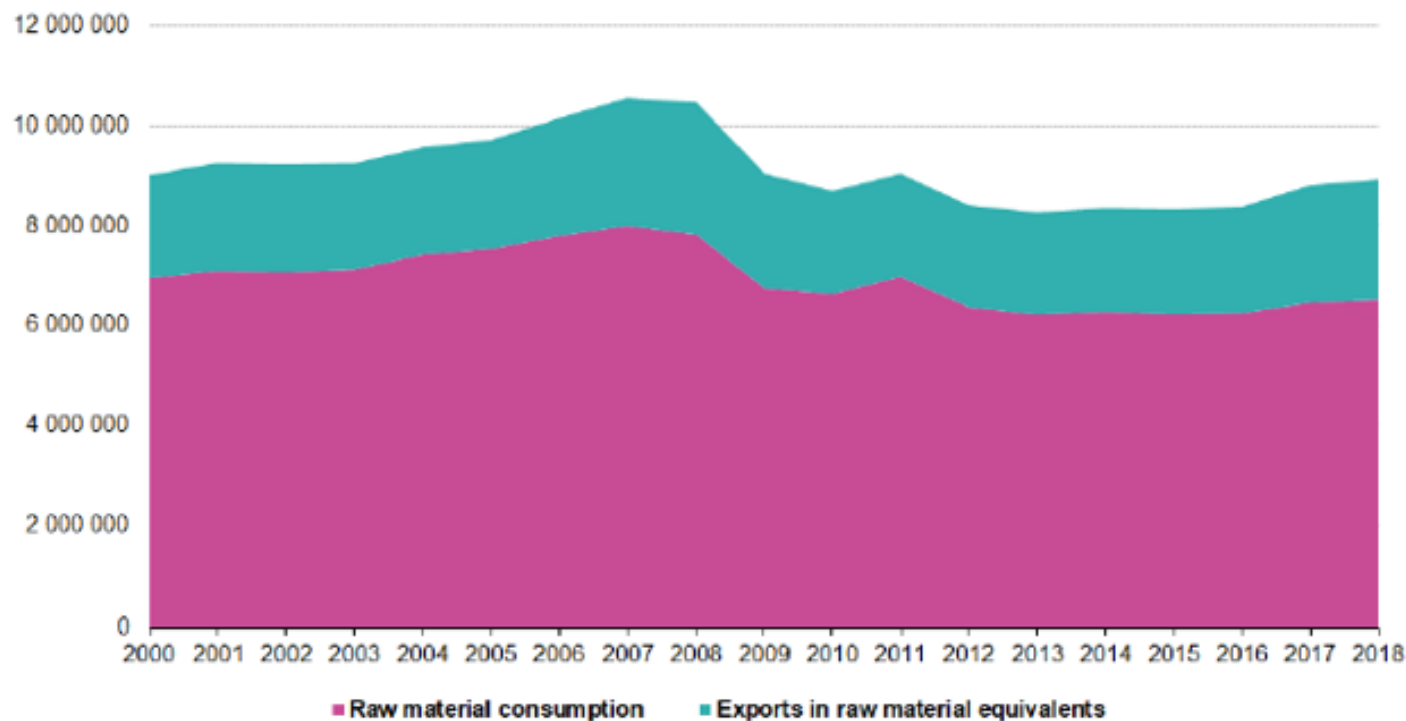


Reminder: Raw material equivalents (RME): conversion factors to express a unit of product traded into the amount of material extraction needed, anywhere in the world, to produce the traded product. The conversion factors for the EU are obtained from a hybrid input-output model.

Source: Producing environmental accounts with environmentally extended inputs outputs analysis, **Eurostat, 2021**

Raw material consumption and exports for EU27 according to material flow accounts in raw material equivalents

(thousand tonnes)



Source: Eurostat (online data code: env_ac_rme)

eurostat 

Source: Producing environmental accounts with environmentally extended inputs outputs analysis, **Eurostat, 2021**

The starting points: the EU industry environment

- The European industry dominated by **manufacturing industry** (i.e. the manufacture of end products and applications) and also the **refining industry** (metallurgy, etc.)
- The value chain of CRMs is not fully and homogeneously covered by the European industry (see Lecture Prof. Ardit).
- Pronounced imbalance exists between the **upstream steps** (extraction/harvesting) and the **downstream steps** (manufacturing and use).
- Considering the **very limited supply of CRMs from secondary sources**, the need for **access to primary sources**, including ores, concentrates, processed or refined materials is huge and crucial for the wealth – and even the survival – of European industries and their associated jobs and economic benefits. (see Critical Raw Materials Act, Proff. Palermo and Cortese)

The starting points

- Increase of world population
- Increase of materials and resources demand
- **Materials depletion and criticality (see lecture Prof. Ardit)**
- Planet resources overexploitation

Materials resources depletion

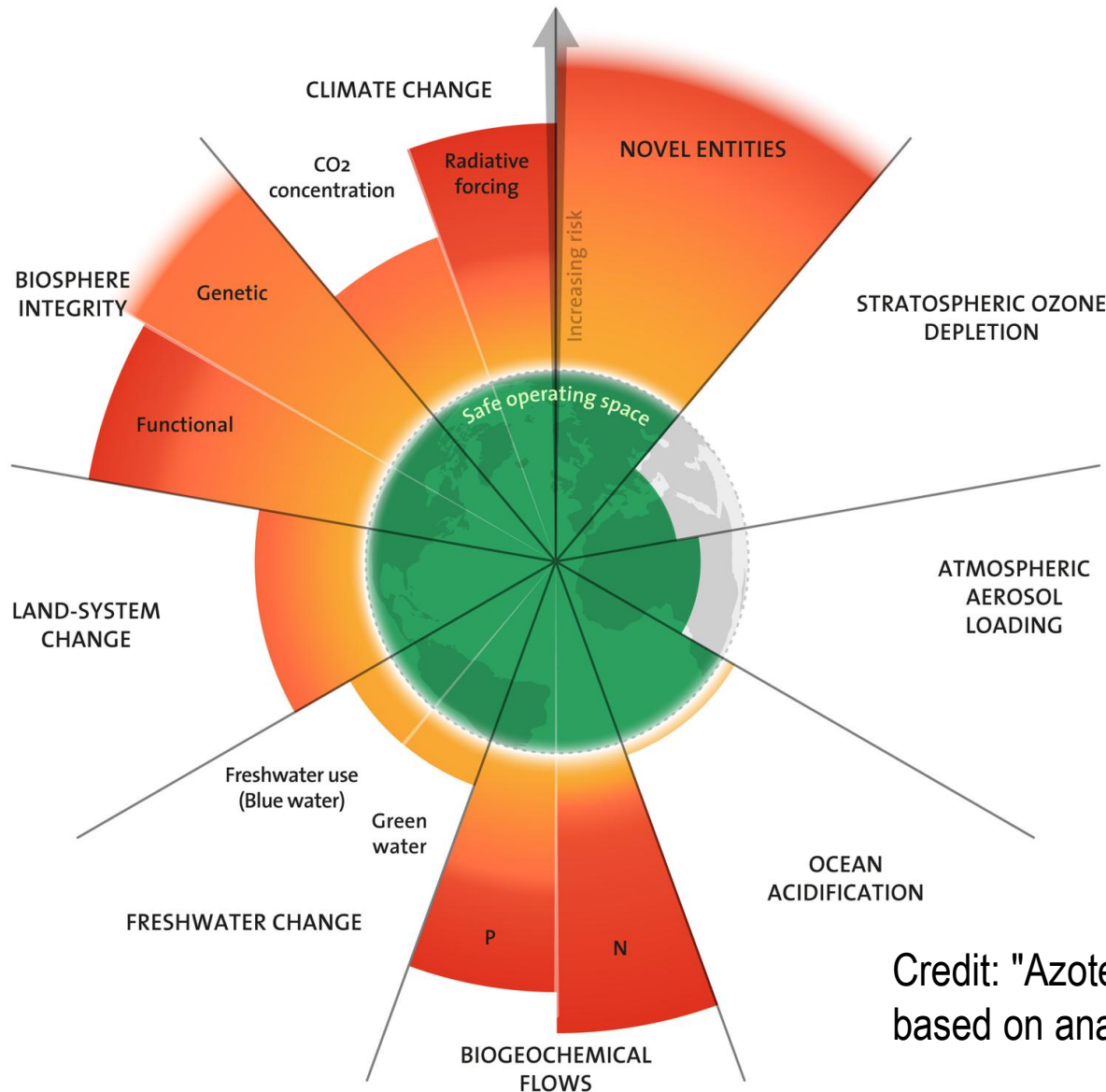
The use of **materials from natural resources** in production and consumption processes has many environmental, economic and social consequences that extend beyond borders and affect future generations.

It has consequences on:

- The rates of extraction and depletion of renewable and non-renewable natural resource stocks, and the extent of harvest and natural productivity of renewable resource stocks.
- The **environmental pressures** associated with the extraction, processing, transport, use and disposal of materials (e.g. pollution, waste, habitat disruption); (to be deepened if we have time)
- Its effect on environmental quality (e.g. air, climate, water, soil, biodiversity, landscape) and ecosystem services and human health.
- International trade and market prices of raw materials and other goods, and the productivity and competitiveness of the economy.

The way natural resources and materials are managed through their life-cycle affects all of these activities (see **planet boundaries framework**)

What are planetary boundaries?

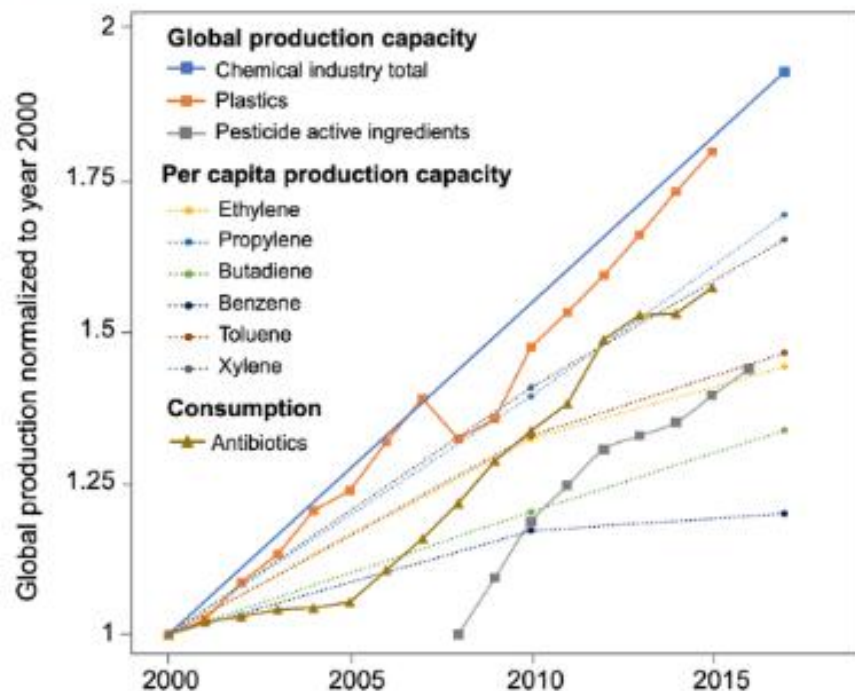


The Planetary Boundaries Framework presents a set of quantitative boundaries and thresholds for nine Earth systems, to guide sustainable human development on a rapidly changing planet. Control variables for the nine planetary boundaries are set so as to remain at a safe space from thresholds for each earth system, the crossing of which would increase the risk of large-scale abrupt or irreversible environmental changes.

Credit: "Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2025

What are novel entities?

The definition of this boundary is now restricted to truly novel anthropogenic introductions to Earth system. These include synthetic chemicals and substances (e.g., microplastics, endocrine disruptors, and organic pollutants); anthropogenically mobilized radioactive materials, including nuclear waste and nuclear weapons; and human modification of evolution, genetically modified organisms and other direct human interventions in evolutionary processes



ENVIRONMENTAL
Science & Technology

pubs.acs.org/est

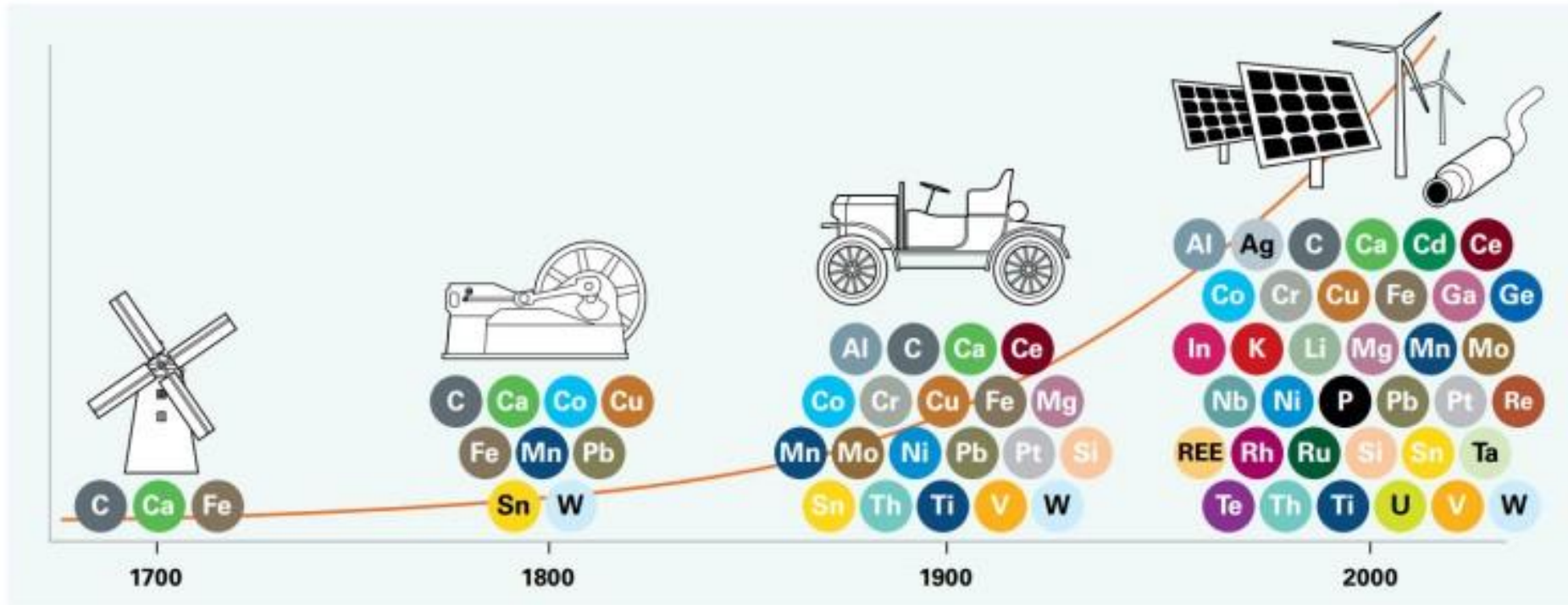


Policy Analysis

Outside the Safe Operating Space of the Planetary Boundary for Novel Entities

Linn Persson,* Bethanie M. Carney Almroth, Christopher D. Collins, Sarah Cornell, Cynthia A. de Wit,* Miriam L. Diamond, Peter Fantke, Martin Hassellöv, Matthew MacLeod, Morten W. Ryberg, Peter Sogaard Jorgensen, Patricia Villarrubia-Gómez, Zhanyun Wang, and Michael Zwicky Hauschild

Neede resources: metals



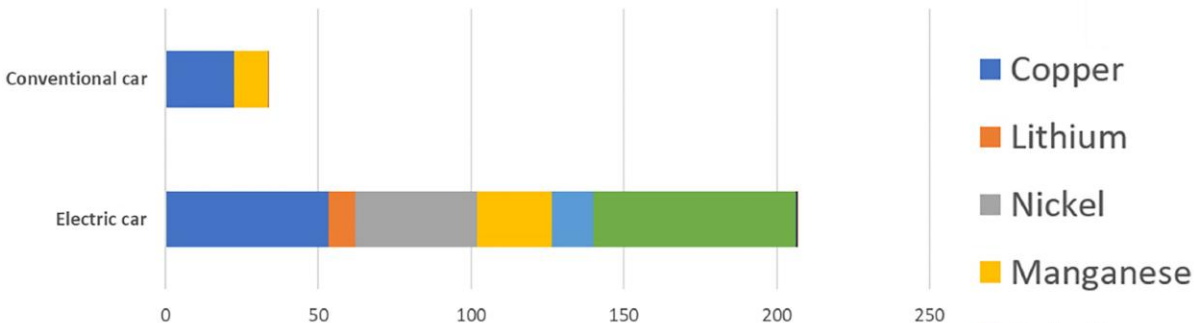
Elements widely used in energy pathways

Achzet et al., Materials critical to the energy industry, Augsburg, 2011

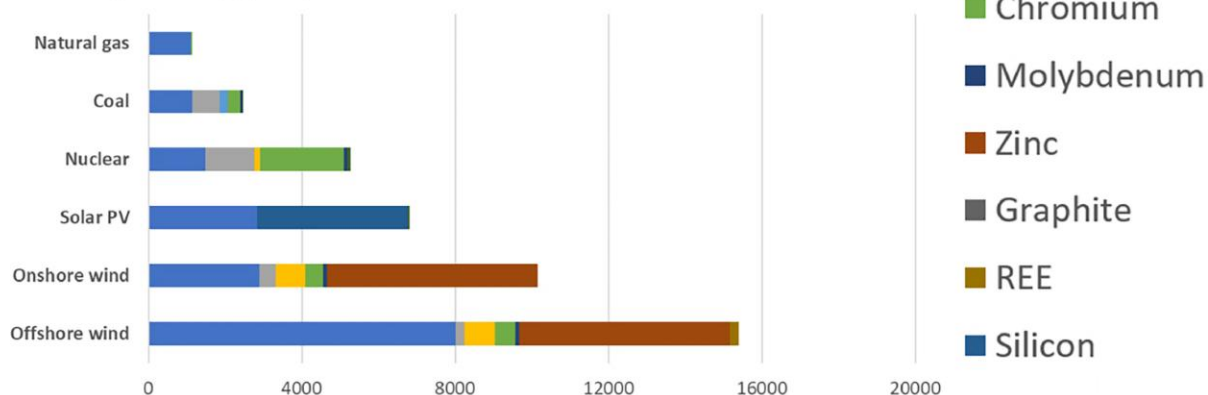
See lectures Prof. Ardit

Energy transition is a materials transition

Transport (kg/vehicle)



Power generation (kg/MW)



Gas vehicle	Material	Electric vehicle
0 kg	Graphite	66.3 kg
0 kg	Cobalt	13.3 kg
0 kg	Lithium	8.9 kg
0.4 kg	Rare Earths	2.3 kg

Source of the figure:



Sustainability of the use of critical raw materials in electric vehicle batteries: A transdisciplinary review

Hanna Lehtimäki^{a,*}, Marjaana Karhu^b, Juha M. Kotilainen^c, Rauno Sairinen^c, Ari Jokilaakso^d, Ulla Lassi^e, Elina Huttunen-Saarivirta^b



Energy transition is a materials transition

The **energy transition is a materials transition**. A clean energy system is much more minerals- and metals-intensive than a conventional fossil fuel energy system, and even with increased circularity, the implications for the extraction of raw materials, and for global competition to secure access to them, are enormous.

*Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, Á., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D., Christou, M., **Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study**, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889*



Li-ion batteries



Wind turbines



Heat pumps



Data storage and servers



Robotics



Fuel cells



Traction motors



Hydrogen direct reduced iron and electric arc furnaces (H2-DRI)



Smartphones, tablets and laptops



Drones



Electrolysers



Solar photovoltaics (PV)



Data transmission networks



Additive manufacturing (AM)



Space launchers and satellites

Source: JRC elaboration based on flaticon.com

**Strategic technologies
for the European Union**

Critical raw materials (CRM)



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Email: fabrice.mathieux@ec.europa.eu

Tel.: +39 332789238

JRC Science Hub

<https://ec.europa.eu/jrc>

JRC108710

See lectures Prof. Ardit

EUR 28832 EN

JRC SCIENCE FOR POLICY REPORT

Critical raw materials and the circular economy

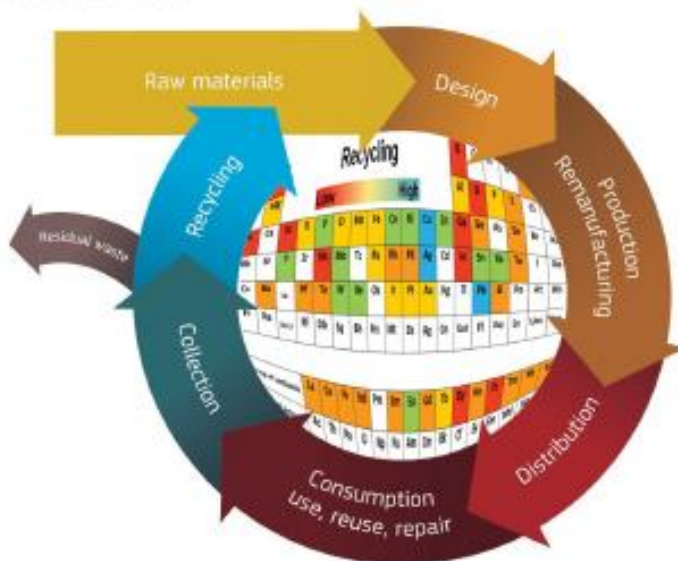
Background report

Fabrice Mathieux, Fulvio Ardente, Silvia Bobba, Philip Nuss, Gian Andrea Blengini, Patricia Alves Dias, Darina Blagoeva, Cristina Torres de Matos, Dominic Wittmer, Claudiu Pavel, Tamas Hamor, Hans Saveyn, Bernd Gawlik, Glenn Orveillon, Dries Huygens, Elena Garbarino, Evangelos Tzimas, Fayçal Bouraoui, Slavko Solar

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Print	ISBN 978-92-79-74283-5	ISSN 1018-5593

Luxembourg: Publications Office of the European Union, 2017

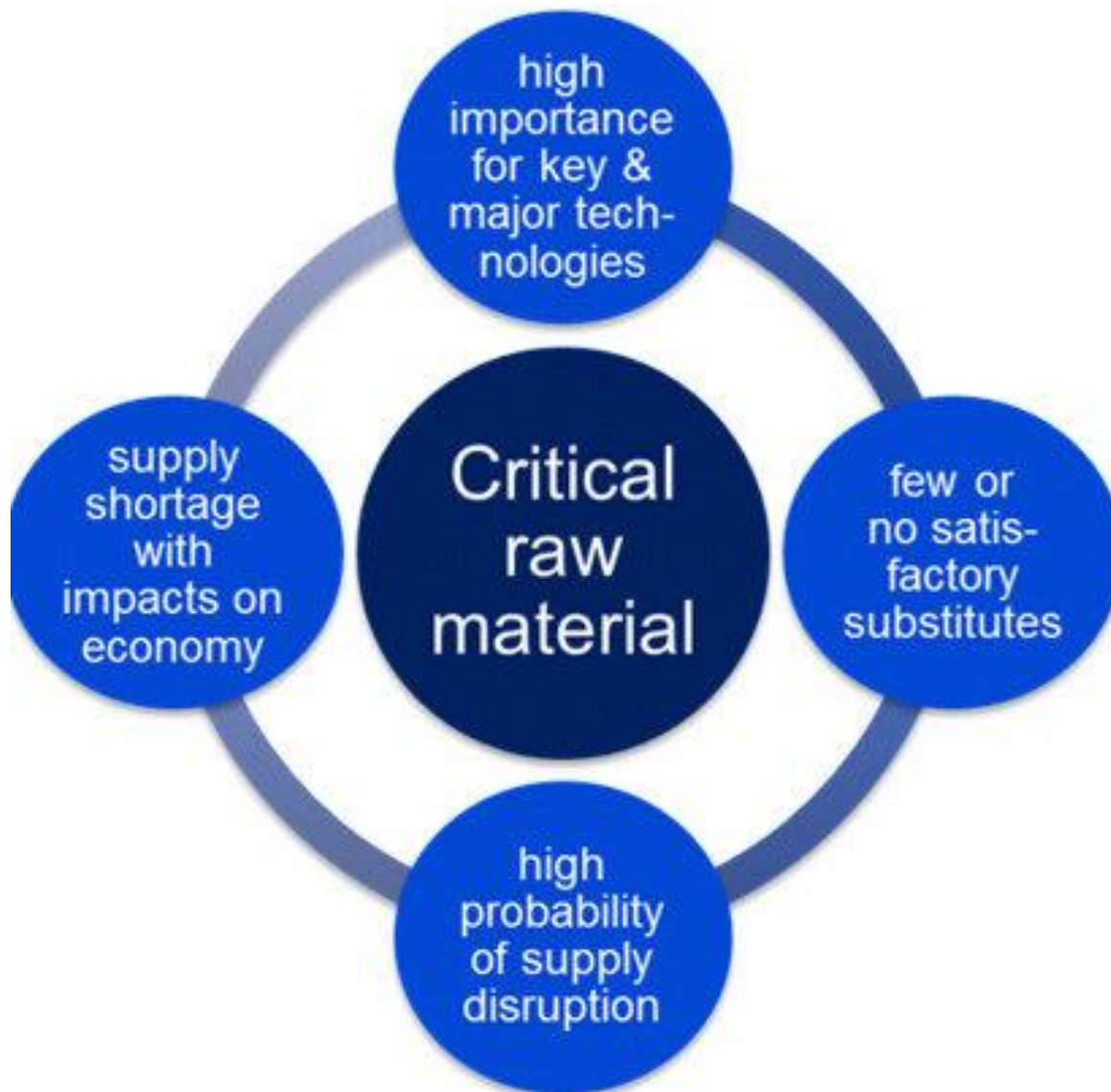
© European Union, 2017



Criticality identified by the EU according to two main dimensions:

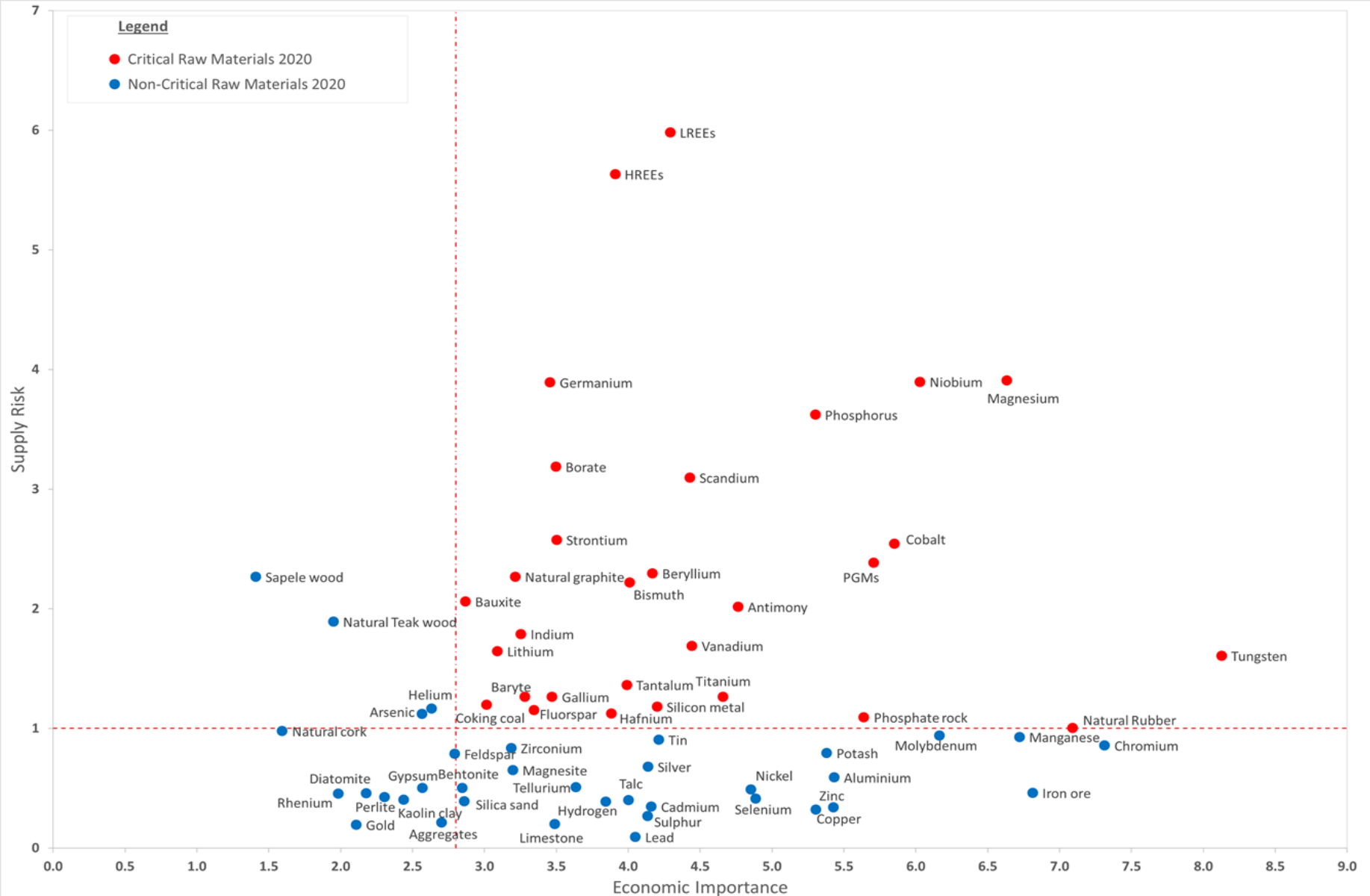
- 1) economic importance
- 2) risk of supply disruption

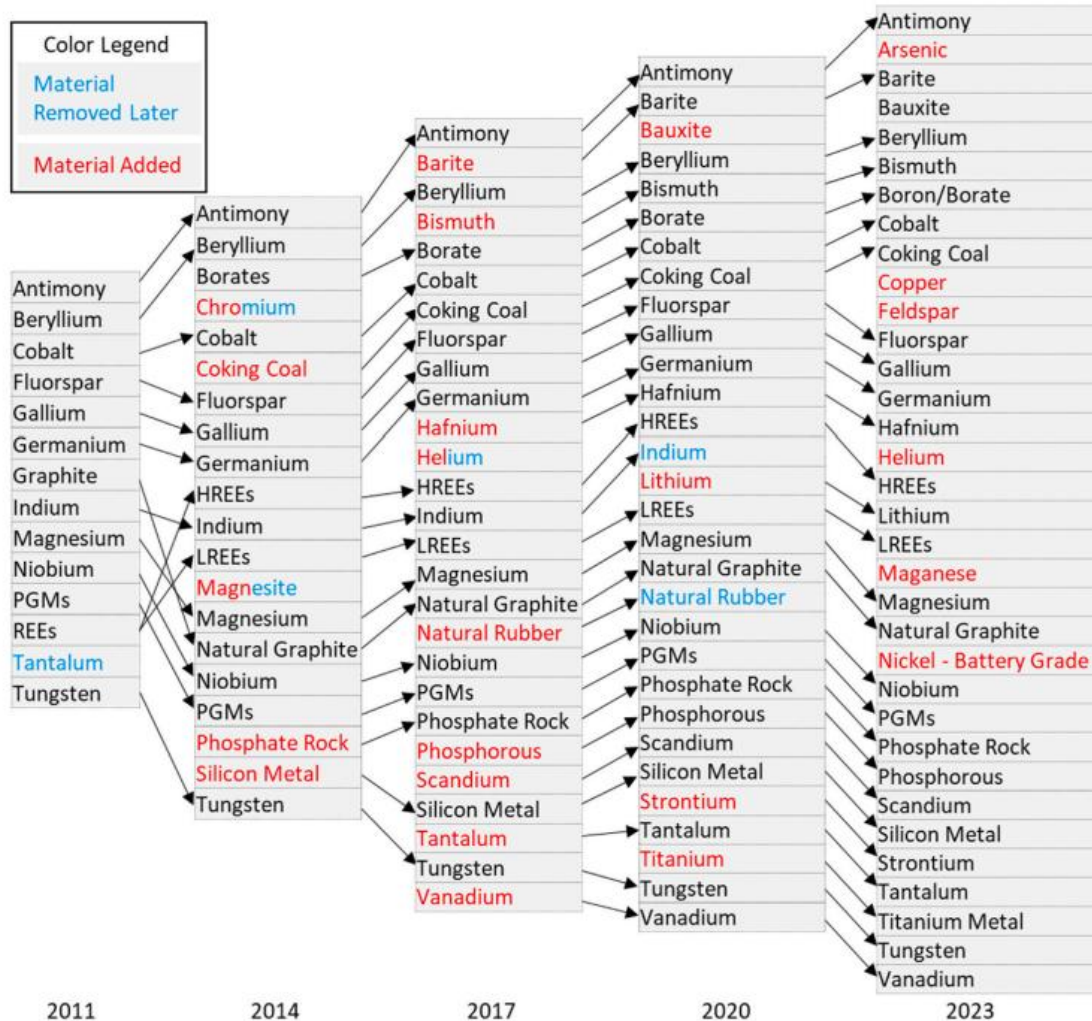
Critical raw materials (CRM)



See lectures on
substitution materials

Critical raw materials (CRM)





Changes in the list of CRMs from 2011 to 2023 as defined by the European Commission.

European Commission (2011, 2014, 2017, 2020, 2023)

European Commission, **2011**. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Tackling the Challenges in Commodity Markets and on Raw Materials. COM(2011). European Commission, Brussels, p. 25 (Final).

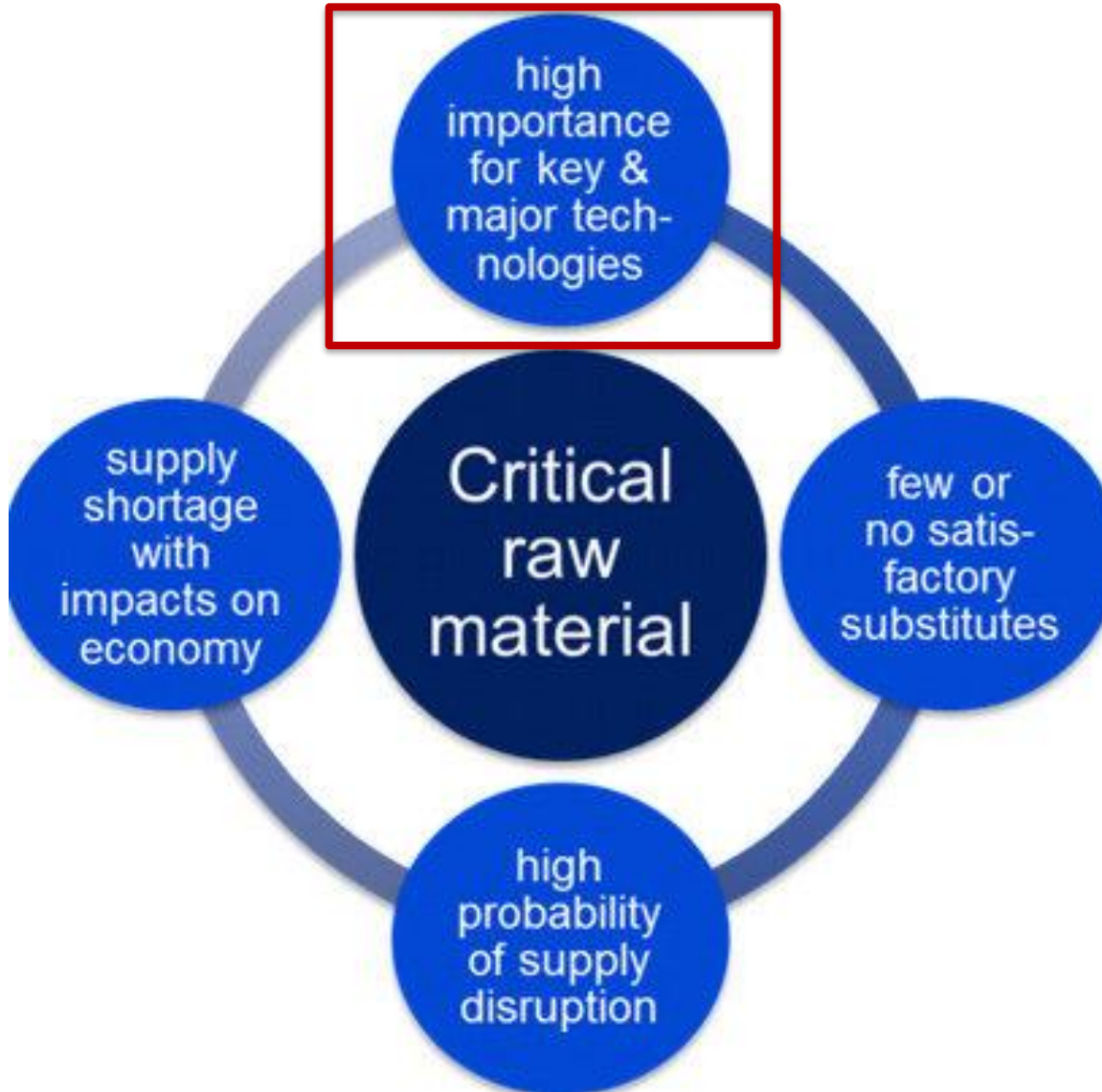
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European Commission, **2020**. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability. COM(2020).

European Commission, **2023**. European Commission, 2023b. Regulation of the European Parliament and of the Council: Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. COM(2023). European Commission, Brussels, p. 160 (Final)

Critical raw materials (CRM)



See lectures on
substitution materials

Technology-related materials & energy criticalities



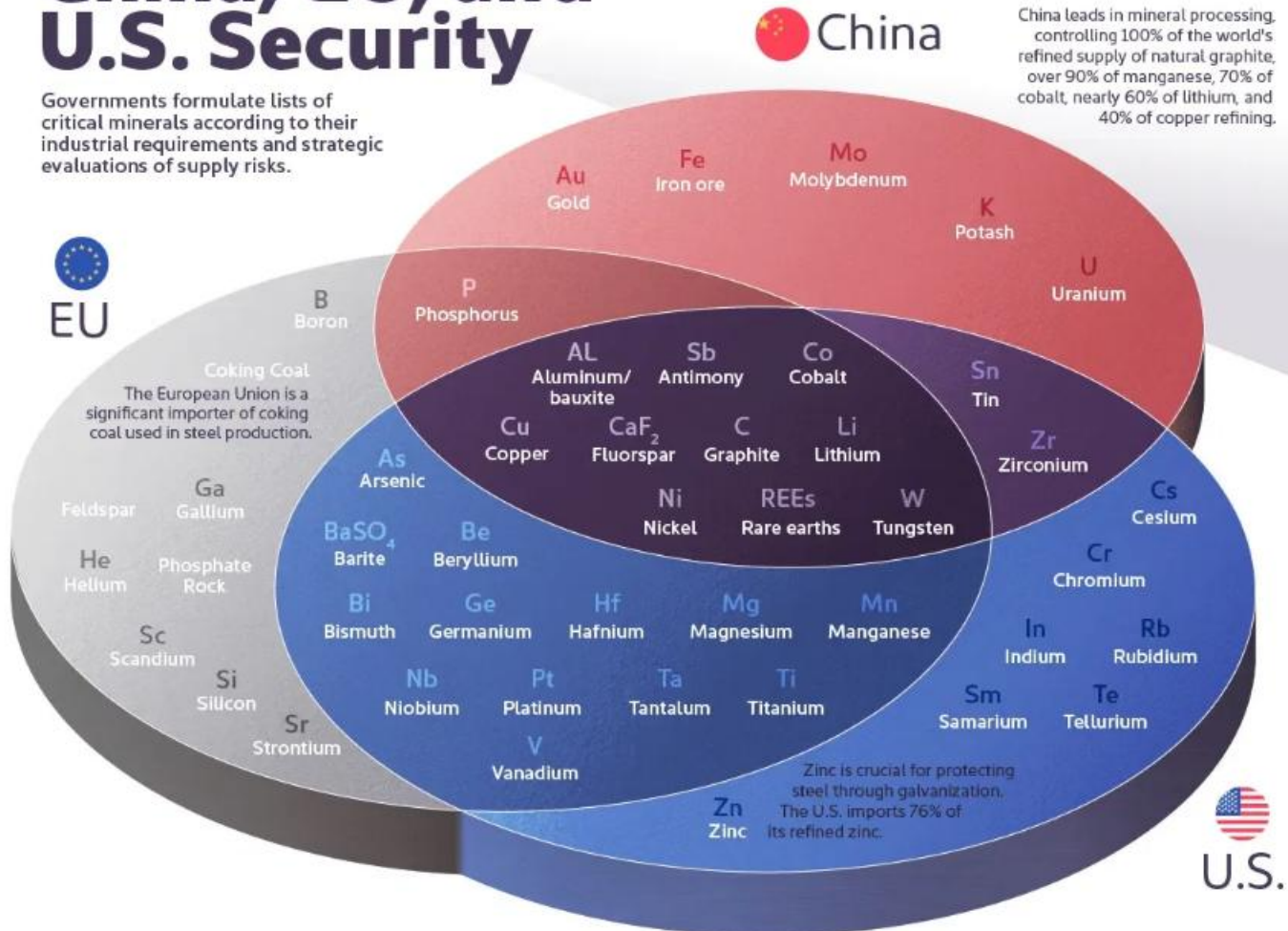
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Critical metals in EU, US, China

The Critical Minerals to China, EU, and U.S. Security

Governments formulate lists of critical minerals according to their industrial requirements and strategic evaluations of supply risks.



China leads in mineral processing, controlling 100% of the world's refined supply of natural graphite, over 90% of manganese, 70% of cobalt, nearly 60% of lithium, and 40% of copper refining.

Source:
<https://www.voronoiapp.com/natural-resources/Critical-Materials-Where-China-the-EU-and-the-US-Overlap-474>

The starting points

- Increase of world population
- Increase of materials and resources demand
- Materials depletion and criticality (see lecture Prof. Ardit)
- Planet resources overexploitation

The starting points



Earth Overshoot Day marks the date when humanity's demand for ecological resources and services in a given year exceeds what Earth can regenerate in that year. In 2024, it was on August, 1st

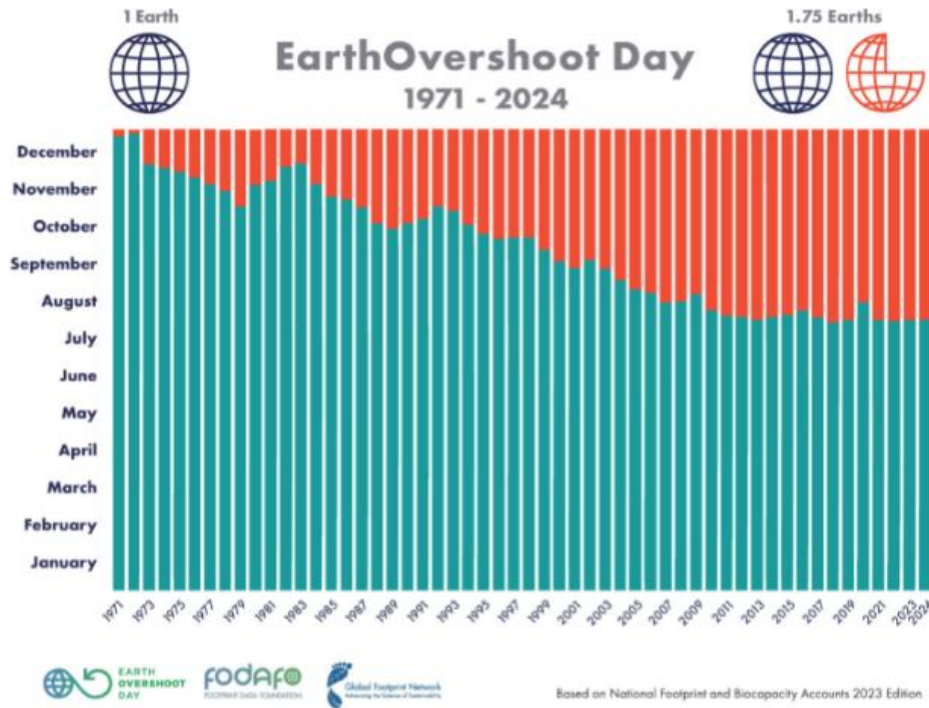
<https://www.overshootday.org/>

The starting points

Earth Overshoot Day marks the date when humanity's demand for ecological resources (fish and forests, for instance) and services in a given year **exceeds what Earth can regenerate in that year**. We maintain this deficit by liquidating stocks of resources and accumulating waste, primarily carbon dioxide in the atmosphere. Andrew Simms originally conceived the concept of Earth Overshoot Day while working at the UK think tank New Economics Foundation.

<https://www.overshootday.org/>

The starting points



<https://overshoot.footprintnetwork.org/>

The remainder of the year corresponds to global overshoot. Earth Overshoot Day is computed by dividing the planet's biocapacity (the amount of ecological resources Earth is able to generate that year), by humanity's Ecological Footprint (humanity's demand for that year), and multiplying by 365, the number of days in a year:

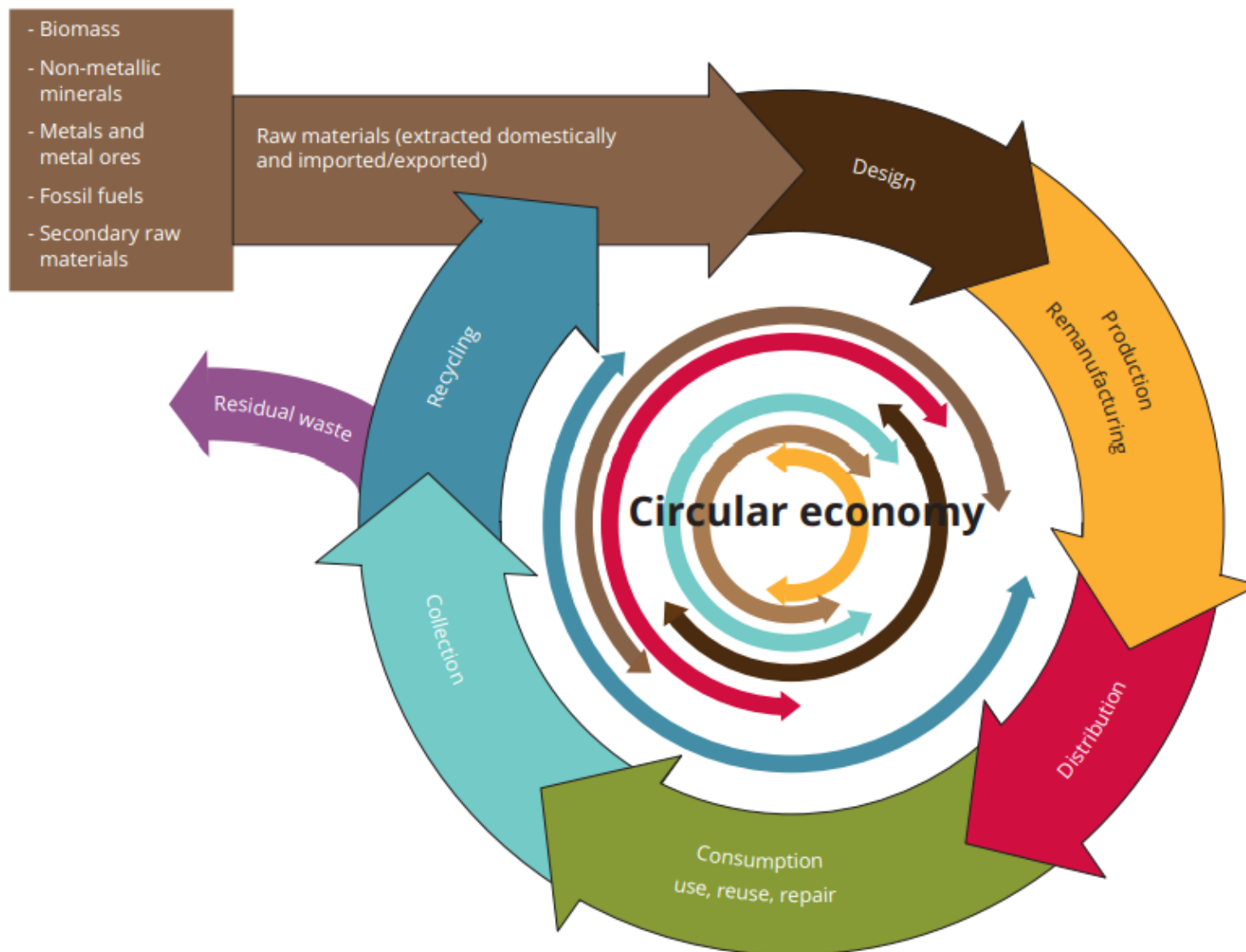
$(\text{Earth's Biocapacity} / \text{Humanity's Ecological Footprint}) \times 365 = \text{Earth Overshoot Day}$

<https://www.overshootday.org/>

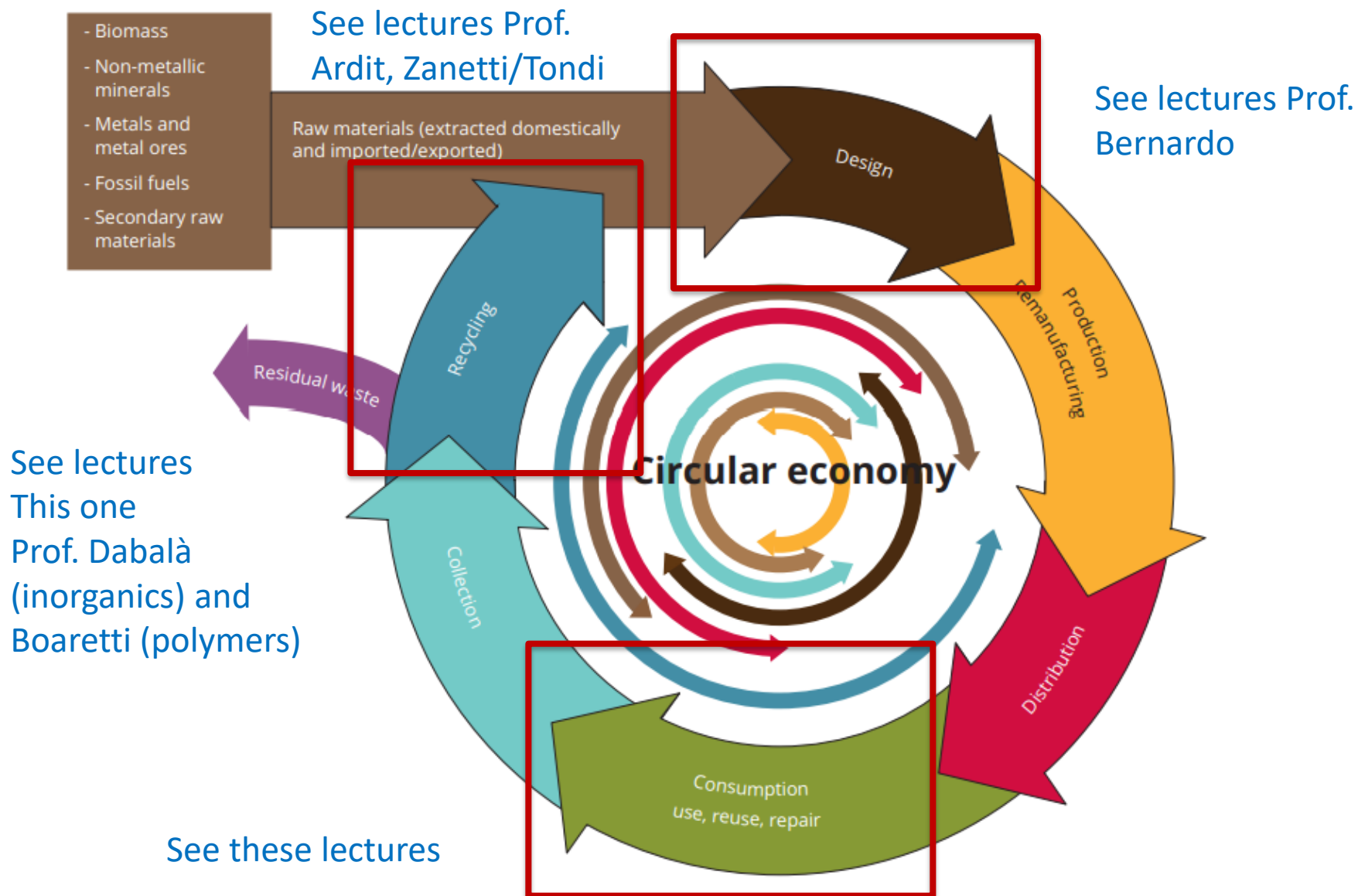
- Increase of world population
- Increase of materials and resources demand
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- Planet resources overexploitation

Solutions?

Materials resource efficiency implies circular economy



Materials resource efficiency implies circular economy



Materials in this Master (and their circular options)

DABALA'

- Steel
- Copper
- Zinc
- Silicon
- Aluminum

ARDIT

- PGM
- REE
- Li
- Uranium

MOVILLI/BOARETTI

- Polymers
- Biopolymers

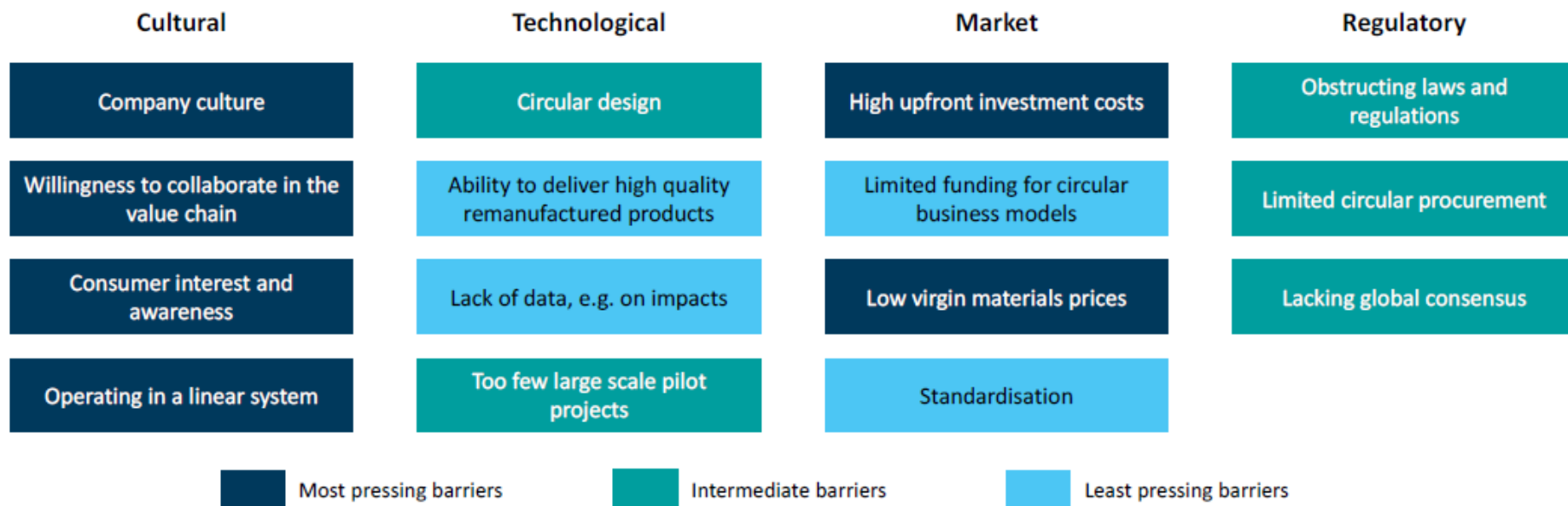
GROSS/BERNARDO

- Concrete cement
- Textiles
- Nanocomposites
- Refractory materials/ceramics
- Glass
- Nanomaterials

ZANETTI/TONDI

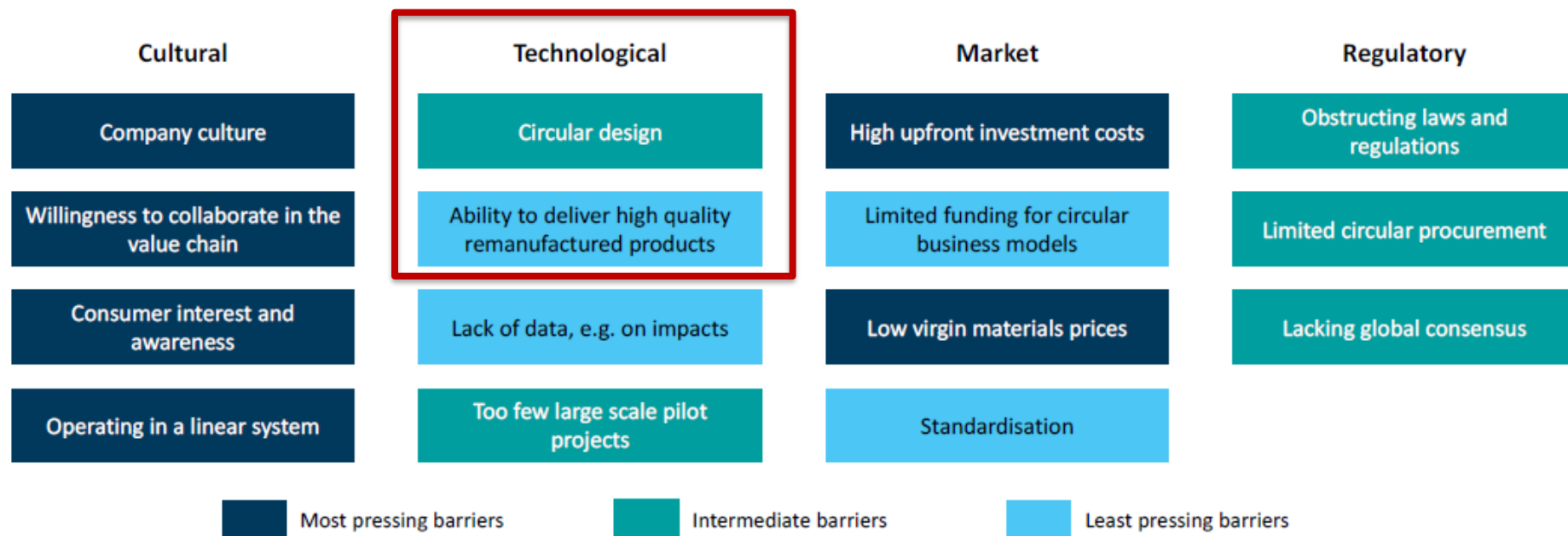
- Cellulose
- Paper
- Biomass

Barriers to CE from a stakeholders perspective



Source: Kirchher et al. (2017) and Barclays Research

Barriers to CE from a stakeholders perspective



the role of materials and materials design

Source: Kirchher et al. (2017) and Barclays Research

Elements of policy agenda to accelerate circular economy

	1. SET THE DIRECTION	2. CREATE ENABLERS	3. LEVEL THE PLAYING FIELD	4. TAKE GOVERNMENT ACTION
MATERIALS RECIRCULATION	- Targets for high value recycling - Improved transparency and statistics for waste and recycling	- Support for innovation and technology development - Standards for secondary materials - Waste regulations and landfill bans - Regulation of long-term destructive practices (e.g. copper, additives)	- Carbon pricing - Extended producer responsibility - Quotas or other support for demand - Improved end-of-life handling (e.g. shredding, demolition) - Product design (e.g. Ecodesign directive)	- Public procurement - Waste regulation systems
PRODUCT MATERIALS EFFICIENCY	- Targets for efficient materials use and re-use in key sectors - Materials passports and documentation	- Information systems and platforms (e.g. BIM) - Labelling schemes for materials efficiency in construction etc. - Fund innovation and technology development	- Waste charges - Support for design for disassembly	- Stimulate re-use and recycling markets - Require high materials efficiency (re-use, design for disassembly etc.) in public procurement
CIRCULAR BUSINESS MODELS	- Improved evidence base and conviction about benefits of shared mobility and buildings - Endorse shared mobility systems as target vision	- Create supportive city regulations (e.g. parking for shared cars) - Revise barriers in existing regulations (e.g., insurance) - Adapt data regulations to support in new business models	- Pricing or regulation of congestion, air pollution and other externalities - Include efficient materials use or labelling in building standards	- City plans for longevity and adaptability of buildings - Integrate car sharing with public transport systems

See lectures
Prof. Bernardo

Building Information Modeling (also known as Building Information Management, abbreviated as BIM) is a process concerning generating and managing data of certain structures throughout their life-cycles.

Source: Materials Economics

Elements of policy agenda to accelerate circular economy

1. SET THE DIRECTION

2. CREATE ENABLERS

3. LEVEL THE PLAYING FIELD

4. TAKE GOVERNMENT ACTION

MATERIALS RECIRCULATION

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- Extended producer responsibility
- Quotas or other support for demand
- Improved end-of-life handling (e.g. shredding, demolition)
- Product design (e.g. Ecodesign directive)

- Public procurement
- Waste regulation systems

See lectures
Prof. Bernardo

PRODUCT MATERIALS EFFICIENCY

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CIRCULAR BUSINESS MODELS

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- City plans for longevity and adaptability of buildings
- Integrate car sharing with public transport systems

Source: Materials Economics

Abatement potential across materials

ABATEMENT OPPORTUNITY

KEY MEASURES AND ENABLERS

CO₂ ABATEMENT



STEEL

As the EU steel stock saturates, there is potential to meet demand to a large extent through secondary steel production. In combination with low-carbon electricity, this makes possible deep cuts to emissions.

Enable high-quality secondary production through more advanced scrap markets
Avoiding contamination of steel by copper
Increase collection of post consumer scrap
Reduce fabrication scrap

41 Mt



PLASTICS

Plastics recycling is very low, despite high technical potential. Secondary plastics production driven by intrinsic materials value could see more than half of total plastics recycled.

Product design that facilitates recycling
Large-scale and specialised recycling operations and regional integration of markets
Technology development for sorting, automation, and chemical recycling

117 Mt



ALUMINIUM

Aluminium recycling can be increased further by reducing losses of aluminium, process scrap, and by avoiding the downgrading of aluminium through the mixing of different qualities of metal.

Reduce collection losses
Increase alloy separation in scrap recycling to avoid downgrading and thereby increase the usefulness of secondary aluminium
Reduce scrap forming during production

26 Mt



CEMENT

Cement recycling is at an early stage, but both re-grinding and re-use of building structural segments are now being trialled.

Increased development of smart crushers and increased use of recovered concrete in construction
Development of local markets for re-use of structural segments

25 Mt



PASSENGER CARS

Materials in cars have the potential to be more efficiently used when cars are shared and more intensively used.

Increased lifetime and more durable materials will be keys to the economic logic of the sharing model
Vehicle size customized for the number of people riding saves materials as cars can be smaller

19 Mt



BUILDINGS

Material use for buildings can decrease by 30% as they are used more efficiently.

Material savings during construction by reduction of waste
Through engineering for light-weighting can less material be used
Development of local markets for re-use of building components
Increased sharing of space to reduce total floor space

55 Mt



OTHERS

Similar CO₂ abatement opportunities for other product groups, such as rest of transportation, machinery etc.

Light-weighting to reduce materials per product
Development of local markets for re-use of building components
Prolonged lifetime
Leasing models to increase utilisation

13 Mt

Source: Materials Economics
The Circular Economy

Global and EU context for materials resource

The global context



The 2030 Agenda for Sustainable Development, adopted by all UN Member States in 2015

Sustainability 17 development goals



SUSTAINABLE DEVELOPMENT GOALS

- Goal 1.** End poverty in all its forms everywhere
- Goal 2.** End hunger, achieve food security and improved nutrition and promote sustainable agriculture
- Goal 3.** Ensure healthy lives and promote well-being for all at all ages
- Goal 4.** Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
- Goal 5.** Achieve gender equality and empower all women and girls
- Goal 6.** Ensure availability and sustainable management of water and sanitation for all
- Goal 7.** Ensure access to affordable, reliable, sustainable and modern energy for all
- Goal 8.** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- Goal 9.** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- Goal 10.** Reduce inequality within and among countries
- Goal 11.** Make cities and human settlements inclusive, safe, resilient and sustainable
- Goal 12.** Ensure sustainable consumption and production patterns
- Goal 13.** Take urgent action to combat climate change and its impacts
- Goal 14.** Conserve and sustainably use the oceans, seas and marine resources for sustainable development
- Goal 15.** Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
- Goal 16.** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
- Goal 17.** Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development



SUSTAINABLE DEVELOPMENT GOALS

TARGET 8.4

Improve progressively, through 2030, **global resource efficiency in consumption and production** and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead

8 GOOD JOBS AND
ECONOMIC GROWTH



TARGET 12.2

By 2030, achieve the **sustainable management and efficient use of natural resources**

12 RESPONSIBLE
CONSUMPTION
AND PRODUCTION



A Green Deal for Europe (2020)

The European Green Deal is about improving the well-being of people. **Making Europe climate-neutral** and protecting our natural habitat will be good for people, planet and economy.

No one will be left behind.



https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu_en

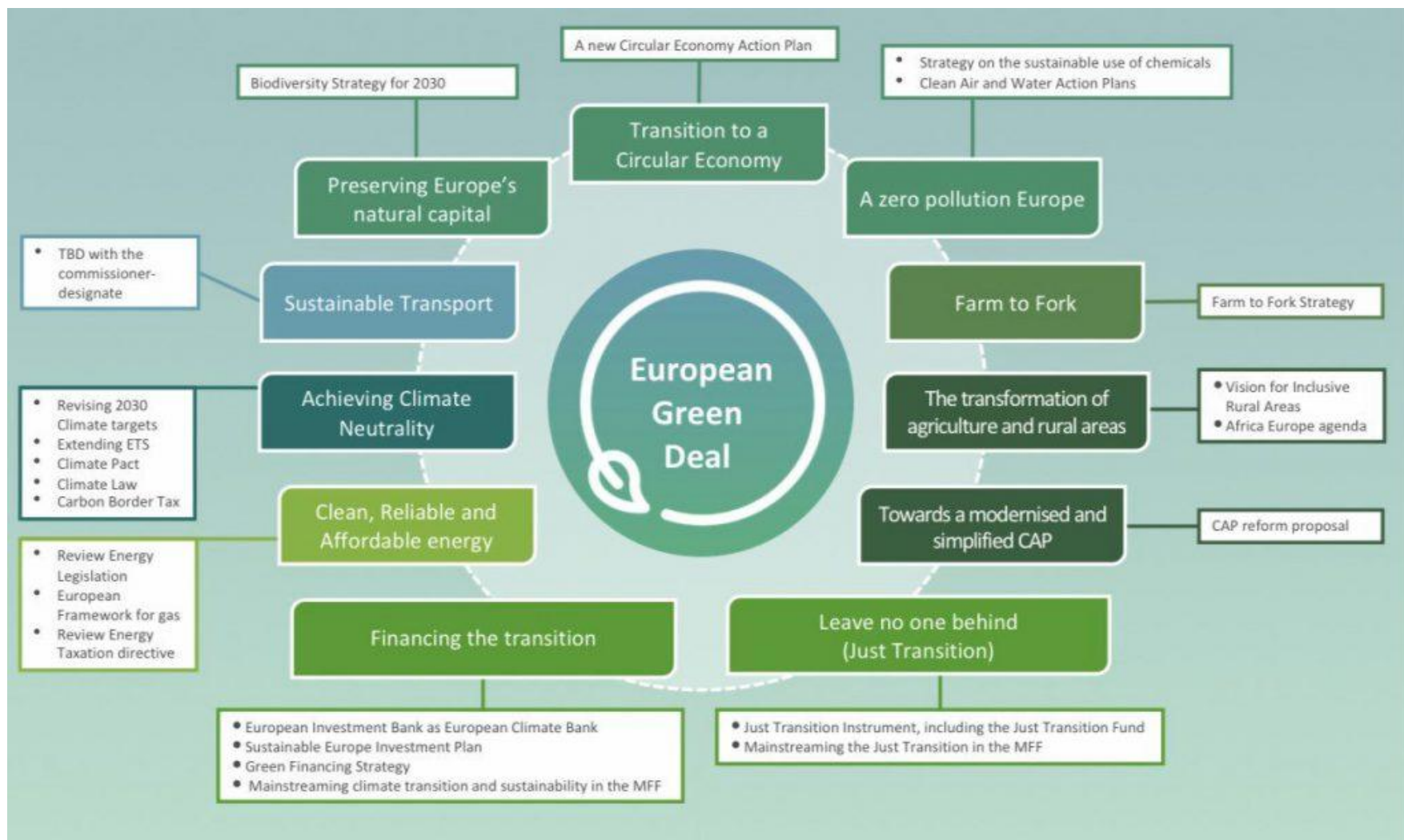
The EU relevant context



[...] We will be a world leader in **circular economy** and clean technologies. We will work to decarbonise energy-intensive industries. [...]

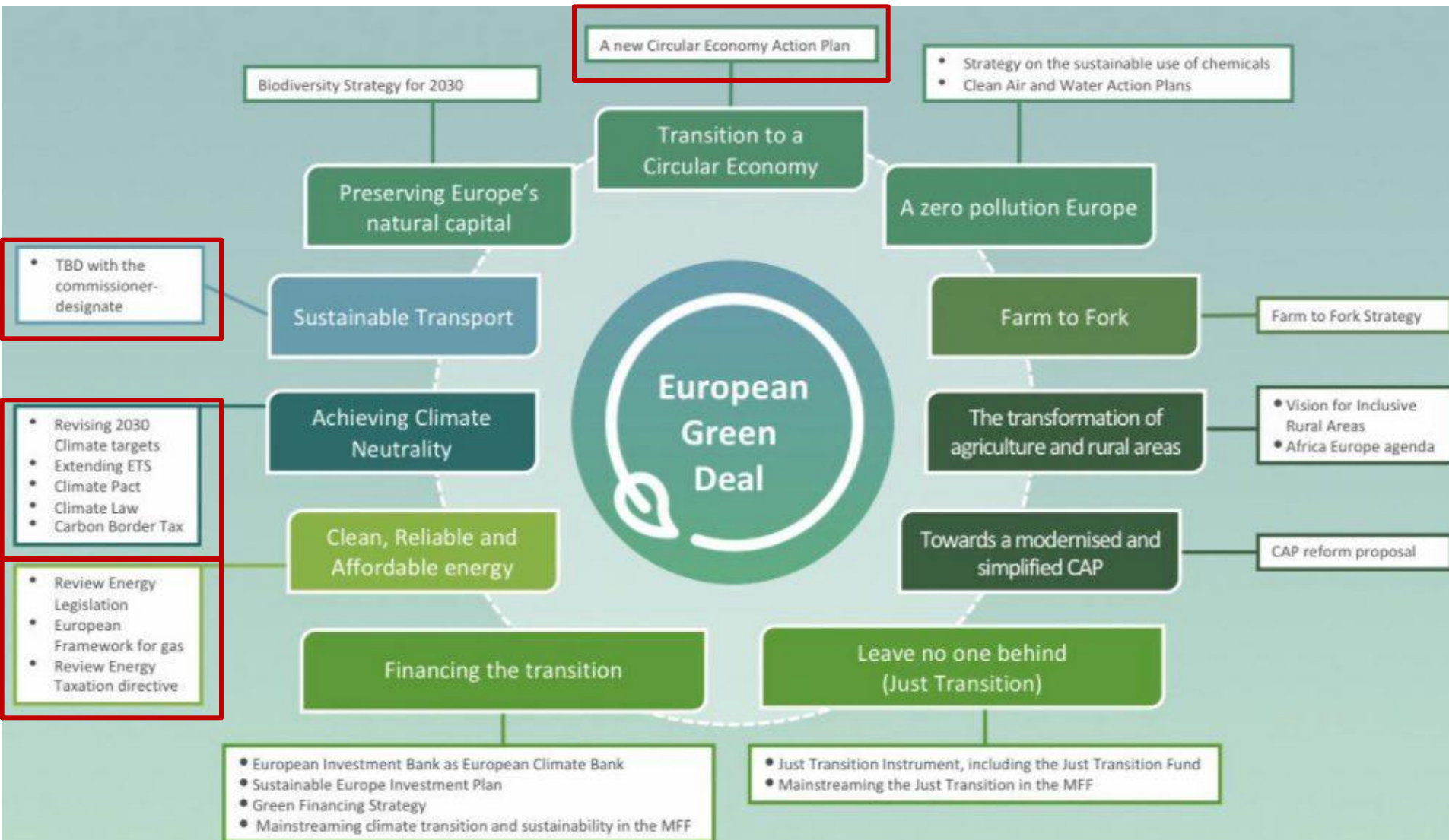
Ursula Gertrud von der Leyen, President of the EU Commission, term 2019-2024

The EU Green Deal



https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu_en

The EU Green Deal



The EU relevant context

*To achieve climate-neutrality by 2050, to preserve our natural environment, and to strengthen our economic competitiveness, requires a fully circular economy. Today, our economy is still mostly linear, with only 12% of secondary materials and resources being brought back into the economy. **Many products break down too easily, cannot be reused, repaired or recycled, or are made for single use only.** There is a huge potential to be exploited both for businesses and consumers. With today's plan we launch action to **transform the way products are made and empower consumers to make sustainable choices for their own benefit and that of the environment.***

Executive Vice-President for the European Green Deal, Frans Timmermans



EUROPEAN COMMISSION

Brussels, 20.9.2011
COM(2011) 571 final

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS**

Roadmap to a Resource Efficient Europe

<https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0571&from=EN>

The Vision: By 2050 the EU's economy has grown in a way that respects resource constraints and planetary boundaries, thus contributing to global economic transformation. Our economy is competitive, inclusive and provides a high standard of living with much lower environmental impacts. **All resources are sustainably managed, from raw materials to energy, water, air, land and soil.** Climate change milestones have been reached, while biodiversity and the ecosystem services it underpins have been protected, valued and substantially restored.

Roadmap to a Resource Efficient Europe

https://ec.europa.eu/clima/policies/strategies/2050_en

The EU relevant context

- **Ecodesign Framework Directive** (2005, revised 2009) framing energy savings at production stage and during lifetime for 40 products groups responsible for ca. 40% GHG emission at EU level
- The **Waste Framework Directive** (2008) aimed at preventing and reducing the adverse impact of waste generation and management on environment and human health
- **REACH** (2006) [Registration, Evaluation, Authorisation of Chemicals) covering and regulating the production, use and distribution of chemicals and formulations
- **Net-Zero Industry Act: Accelerating the transition to climate neutrality** (2023): NZIA will help strengthen the European manufacturing capacity of net-zero technologies and overcome barriers to scaling up the manufacturing capacity in Europe
- **Critical Raw Materials Act** (2023): The Regulation and Communication on critical raw materials adopted on 16th March leverage the strengths and opportunities of the Single Market and the EU's external partnerships to diversify and enhance the resilience of EU critical raw material supply chains

https://ec.europa.eu/clima/policies/strategies/2050_en

Table 1.1 Examples of EU policies related to material use and resource efficiency

Theme	Examples
Energy	• Energy 2020: A strategy for competitive, secure and sustainable energy • A policy framework for climate and energy for 2020–2030 • Energy Roadmap 2050 • European Energy Security Strategy
Waste and recycling	• Waste Framework Directive • Landfill Directive • Packaging and Packaging Waste Directive • Thematic Strategy on the prevention and recycling of waste
Sustainable management of natural resources	• Sixth Environment Action Programme (6EAP) • Thematic Strategy on the sustainable use of natural resources • EU Forest Strategy
Sustainable consumption and production, and business-oriented initiatives	• Sustainable Consumption and Production and Sustainable Industrial Policy (SCP/SIP) Action Plan • Eco-innovation Action Plan • Industrial Policy for the Globalisation Era and Innovation Union • Single Market for Green Products • The Green Action Plan for Small and Medium Enterprises (SMEs)
Raw materials	• Raw Materials Initiative • Strategy on commodity markets and raw materials • European Innovation Partnership on Raw Materials • EU list of critical raw materials
Resource efficiency	• Europe 2020 strategy for smart, sustainable and inclusive growth • Flagship initiative for a resource-efficient Europe • Roadmap to a Resource Efficient Europe • Seventh Environment Action Programme (7EAP)
Circular economy	• Towards a circular economy: A zero waste programme for Europe (2014) • Flanking communications on sustainable buildings, green employment, SMEs • Closing the loop: An EU action plan for the Circular Economy (2015)

The scope of materials, resources and resource efficiency in EU policies

There is no uniform definition or even implicit understanding of key terms such as **materials, raw materials or resources** in EU policy documents that deal with resource efficiency and raw materials.

- **'Materials'** sometimes refers to primary or raw materials, understood as virgin materials extracted from the natural environment. This normally includes biomass, metal ores, non-metallic minerals and fossil energy carriers. On other occasions, it also includes secondary raw materials such as recycled steel, plastics and concrete. Furthermore, some policies are directed at specific materials, such as in the case of the EU list of critical raw materials.
- The **2005 EU Thematic Strategy on the sustainable use of natural resources** defines **'natural resources'** rather broadly and includes raw materials such as minerals, biomass and biological resources; environmental media such as air, water and soil; flow resources such as wind, geothermal, tidal and solar energy; and space (land area).
- The **2011 Flagship initiative for a resource-efficient Europe** has an even broader scope, setting out to support '... policy agendas for climate change, energy, transport, industry, raw materials, agriculture, fisheries, biodiversity and regional development'.
- The **2011 Roadmap to a Resource Efficient Europe** offers a slightly different scope, in which 'all resources are sustainably managed, from raw materials to energy, water, air, land and soil. Climate change milestones have been reached, while biodiversity and the ecosystem services it underpins have been protected, valued and substantially restored'. The Roadmap addresses the following specific resources: ecosystem services, biodiversity, minerals and metals, water, air, land and soils, and marine resources.
- **Energy** is frequently singled out from other resources because the topic is subject to its own regulatory framework, while climate is sometimes considered as part of resources, as stated, for example, in the **Roadmap to a Resource Efficient Europe**: 'climate is a key resource: specific challenges of progressing to a low-carbon economy are addressed in detail in the Commission's Roadmap for moving to a competitive low-carbon economy and the forthcoming Energy Roadmap 2050'.
- The **European Commission's December 2015 Circular Economy Package — Closing the loop: An EU action plan for the Circular Economy** — does not explicitly discuss the scope of materials or resources, but outlines targeted action in areas such as 'chemicals, plastics, food waste, construction, critical raw materials, industrial and mining waste, consumption and public procurement'. Fertilisers and water reuse will be addressed as the next step. The term **'resource efficiency'** denotes the political goal of **'allowing the economy to create more with less, delivering greater value with less input, using resources in a sustainable way and minimising their impacts on the environment'**. The December 2015 EU Action Plan aims to support a circular economy in which 'the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimised'. (Circular economy package updated in 2020, 2021)

Circular Economy Action Plan (2015, update 2020)



The actions under the action plan contributed to accelerate Europe's transition by helping "close the loop" of product lifecycles through greater recycling and re-use, and brought benefits for both the environment and the economy.

https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu_en

European Commission's December 2015 Circular Economy Package — Closing the loop: An EU action plan for the Circular Economy

EU Circular Economy Action Plan – quantitative targets in place prior to the 2021 update

EU quantitative circularity targets

Minimum share of municipal waste to be recycled by 2035	65%
Minimum share of packaging waste to be recycled by 2030	70%
Paper and cardboard	85%
Ferrous metals	80%
Aluminium	60%
Glass	75%
Plastic	55%
Wood	30%
Maximum share of municipal waste to be processed to landfill by 2035	10%
Share of plastics packaging that must be reusable or recyclable in a cost-effective manner	100%

Source: Circular Economy: the next frontiers to decarbonise industrials – Barclays Research

EU regulatory agenda for boosting circular economy (1)

CEAP implementation timeline

A sustainable product policy framework

Legislative proposal for a sustainable product policy initiative	2021
Legislative proposal empowering consumers in the green transition	2021
Legislative and non-legislative measures establishing a new right to repair	2021
Legislative proposal on substantiating green claims	2021
Mandatory green public procurement criteria and targets in sectoral legislation and phasing-in mandatory reporting	2021
Review of the Industrial Emissions Directive, including the integration of Circular Economy practices	Ongoing
Launch of an industry-led industrial symbiosis reporting and certification system	2022

Key product value chains

Circular electronics initiative, common charger solution and reward systems to return old devices	2021
Review of the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment	2021
Proposal of a new regulatory framework for batteries	Done
Review of the rules on end-of-life for vehicles	2021
Review of the rules on proper treatment of waste oils	2022
Review to reinforce the essential requirements for packaging and reduce over-packaging and packaging waste	2021
Mandatory requirements on recycled plastic content and plastic waste reduction (packaging, construction materials and vehicles)	2021/22
Restriction of intentionally added microplastics and measures on unintentional release of microplastics	2021
Policy framework for bio-based plastics and biodegradable or compostable plastics	2021
EU strategy for textiles	2021
Strategy for a sustainable built environment	2021
Initiative to substitute single-use packaging, tableware and cutlery by reusable products in food services	2021

Source: Circular Economy: the next frontiers to decarbonise industrials – Barclays Research

EU regulatory agenda for boosting circular economy (2)

Less waste, more value

Waste reduction targets for specific streams and other measures on waste prevention	2022
EU-wide harmonised model for separate collection of waste and labelling to facilitate separate collection	2022
Methodologies to track and minimise the presence of substances of concern in recycled materials and articles made thereof	2021
Harmonised information systems for the presence of substances of concern	2021
Scoping the development of further EU-wide end-of-waste and by-product criteria	2021
Revision of the rules on waste shipments	2021

Making the Circular Economy work for people, regions and cities

Supporting the Circular Economy transition through the skills agenda, the forthcoming action plan for Social Economy and the ESF+	Ongoing
Supporting the Circular Economy transition through Cohesion Policy funds, the Just Transition Mechanism and urban initiatives	Ongoing

Crosscutting actions

Improving measurement, modelling and policy tools to capture synergies between Circular Economy and climate change	Ongoing
Regulatory framework for the certification of carbon removals	2023
Reflecting Circular Economy objectives in the revision of the guidelines on state aid in the field of environment and energy	2021
Mainstreaming circularity objectives in the context of the rules on non-financial reporting and sustainable corporate governance	2021/22

Leading efforts at the global level

Leading efforts towards a global agreement on plastics	Ongoing
Proposing a global Circular Economy alliance and initiating discussions on an international management of natural resources	Ongoing
Mainstreaming circularity objectives in free trade agreements, bilateral, regional and multilateral agreements and EU external policy	Ongoing

Monitoring progress

Updating the Circular Economy Monitoring Framework to reflect new priorities and develop further indicators	2021
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Circular Economy Act, 2025

EU AIMS TO DOUBLE CIRCULARITY RATE BY 2030 WITH NEW CIRCULAR ECONOMY ACT

To hasten the EU's shift from a linear to a circular economy,
the new law scheduled for adoption in 2026



WHY IS THE CIRCULAR ECONOMY ACT CRITICAL FOR THE EU'S FUTURE?

The Act aims to change how businesses handle waste and resources by solving resource usage inefficiencies and establishing a single market for secondary raw materials.



WHAT ARE THE CORE PILLARS OF THE CIRCULAR ECONOMY ACT?

Improve collection, recycling, and demand for secondary raw elements & to establish a functional single market for waste and recycled materials



Due for adoption in late 2026, the Circular Economy Act aims to establish a **Single Market for secondary raw materials**, increase the supply of high-quality recycled materials and stimulate demand for these materials within the EU. It will contribute to the ambition laid out in the [Competitiveness Compass](#) to make the EU the world leader in the circular economy by 2030.

The **circularity rate** is one way to measure how circular our economy is. This number shows how much of the materials we use are recycled or reused instead of being thrown away. Right now, Europe's circularity rate is about 12%, but the goal is to **double it to 24% by 2030**. This target is part of the EU's [Clean Industrial Deal](#).

Source: https://environment.ec.europa.eu/news/commission-launches-consultation-upcoming-circular-economy-act-2025-08-01_en

Commission launches consultation and call for evidence for upcoming Circular Economy Act

The feedback period is open until 6 November 2025.



https://environment.ec.europa.eu/news/commission-launches-consultation-upcoming-circular-economy-act-2025-08-01_en

A comparison: China legislative actions

China's legislative actions in favour of the Circular Economy

Legislation	Date	Main aspects
Law for the Promotion of the Circular Economy	2008	- Defining the requirements for circularity (viable technology, economically practical, resource-saving, protecting the environment) - Any new government law must comply with Circular Economy criteria - Obligation for industrials to implement systems that reduce resource use and waste Policy shift from resource efficiency to recycling heavy industrial resources
The 12th Five-Year Plan	2011-2015	- Increasing the re-use of industrial waste to 72% by 2015 and raising resource output efficiency by 15% - Various recycling initiatives for industrial waste and the conversion of industrial parks - Objective of 50% of national industrial parks and 30% of provincial ones to undergo a complete Circular Economy transition by 2015 Introducing various targets for 2015 and 2020
The Circular Economy Development Strategies Action Plan	2013	2015 goals: re-using 72% of industrial waste, having a modern system for recovering at least 70% of waste products, raising energy productivity by 18.5%, water productivity by 43%, aiding the recycling industry to reach USD276bn of output, re-using 70% of the most heavily polluting minerals 2020 goals: advancing industrial innovation to efficiently re-use and recycle materials - General environmental goals on water quality, resource productivity, new environmental protection tax and compensation framework
The 13th Five-Year Plan	2016-2020	Circularity goals: able to use 90% of polluted soil by 2020 (from 70.6% in 2015); over 75% of national industrial parks to be practicing circular strategies by 2020; reaching an output value of USD450bn by 2020 for the recycling industry

Source: Circular Economy: the next frontiers to decarbonise industrials – Barclays Research

International Resource Panel (IRP)

The International Resource Panel (IRP) was launched by the United Nations Environment Programme (UNEP) in 2007 to build and share the knowledge needed to improve our use of resources worldwide.

<https://www.resourcepanel.org/about-us>



**International
Resource
Panel**

Resources depletion related issues



Multi-dimensional aspects of resource issues

- Bio-physical impacts of resource use.
- The distributional and social justice dimension.
- Economic efficiency.
- Institutional feasibility.
- Behavioral or cultural issues, including the changes needed.
- Successful and ineffective ways to manage change in different societies

<https://www.resourcepanel.org/about-us> (UN Environment Programme)

The global context

Relationship between the International Resource Panel (IRP) scientific assessment and the SDGs

<https://www.resourcepanel.org/about-us>

In the context of the Sustainable Development Goals (SDGs), **natural resource use connects essential material needs for food, water, energy and shelter** (represented by SDGs 2, 6, 7, 9 and 11) and natural and social capital (represented by SDGs 13, 14, 15, and 17) that underpin all life and earth system functions.

Therefore, as recognized by the Sustainable Development Goals 8.4, 12.1 and 12.2, **decoupling resource use from well-being and adverse social and environmental impacts is the key to achieving sustainable development.**



Marine Resources

Governance to Reduce the Effects of Land-Based Activities on Coastal Resources and Support the Transition to a Sustainable Blue Economy (2020)

Policy Options to Reduce Additional Pollution by Marine Plastic Litter by 2050 (2020)



Land and Biodiversity

Land Restoration for Achieving the Sustainable Development Goals (2019)

Unlocking the Sustainable Potential of Land Resources (2016)

Assessing Global Land Use (2014)

Building Natural Capital: How REDD+ Can Support a Green Economy (2014)



Policy Coherence and Partnership

Policy Coherence of the Sustainable Development Goals (2015)



Food Systems

Food Systems and Natural Resources (2016)



Resource Efficiency and Climate Change

Resource Efficiency and Climate Change (2020)

Green Technology Choices (2017)

Green Energy Choices (2016)

10 Key Messages on Climate Change (2015)



Sustainable Cities

The Weight of Cities (2018)

City-Level Decoupling (2013)



Water Resources

Options for Decoupling Economic Growth from Water Use and Water Pollution (2015)

Measuring Water Use in a Green Economy (2012)



Biofuels

Assessing Biofuels Towards Sustainable Production and Use of Resources (2009)



Target 12.1: Implement the 10-year framework of programmes on sustainable consumption and production...
Target 12.2: By 2030, achieve the sustainable management and efficient use of natural resources.



Target 8.4: Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation...

Minerals and Metals

Mineral Resource Governance in the 21st Century (2019)

Metal Recycling: Opportunities, Limits, Infrastructure (2013)

Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles (2013)

Recycling Rates of Metals (2011)

Metal Stocks in Society (2010)

Decoupling and Resource Efficiency

Resource Efficiency for Sustainable Development (2018)

Resource Efficiency: Potential and Economic Implications (2017)

Decoupling: Technologies Opportunities and Policy Options (2014)

Responsible Resource Management for a Sustainable World (2012)

Decoupling Natural Resource Use and Environmental Impacts from Economic Growth (2011)

Assessing the Environmental Impacts of Decoupling and Resource Efficiency (2010)

Global Resource Use

The Global Resources Outlook 2019 (2019)

Natural Resource Use in the Group of 20 (2019)

Assessing Global Resource Use (2017)

Material Flow Analysis and Trade

Sustainable Trade in Resources (2020)

Re-defining Value—The Manufacturing Revolution (2018)

Global Material Flows and Resource Productivity (20z16)

International Trade in Resources (2015)