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# Introduction

MSE-433 Towards Sustainable Materials

Yves Leterrier, Martyn Wakeman
Spring 2025

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# Life is a journey … learning and sharing

**BAe**

- Apprenticeship
- Technical & commercial

**University of Nottingham**

- PP composites
- BEng, PhD, CEng, MIMechE
- Sponsored by Ford / Jaguar

**EPFL**

- Post Doc
- Group Leader
- Advanced composites
- Teaching, research
- Cost modelling, LCA/LCC
- 80+ publications

**DuPont**

- Composites expert
- Material & process
- Marketing / TCM / LCA
- OEM & Tier 1, VP
- M&A strategy
- R&D work, 30 patents

**WCC**

- Consulting …

UNIVERSITY OF CAMBRIDGE
INSTITUTE FOR SUSTAINABILITY LEADERSHIP

**EPFL**

- ASFOR AFP/3D printing, functionalized composites
- Innosuisse Flagship: Towards NetZero Plastics
- E4S: NetZero CF scenario modelling
- Sustainability & circular economy
- Lecturer

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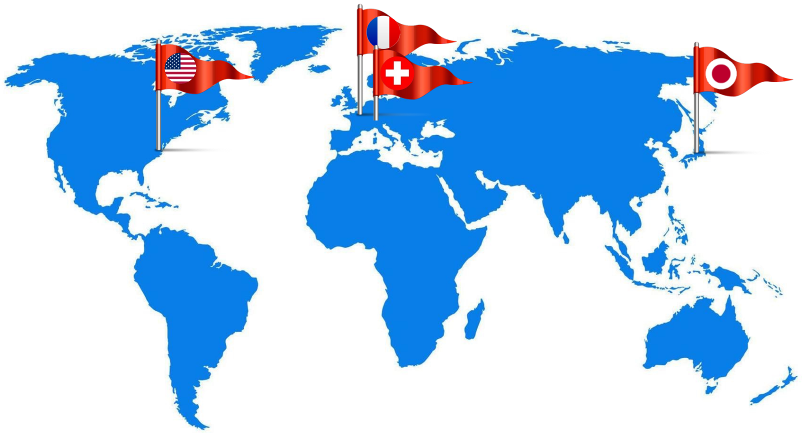
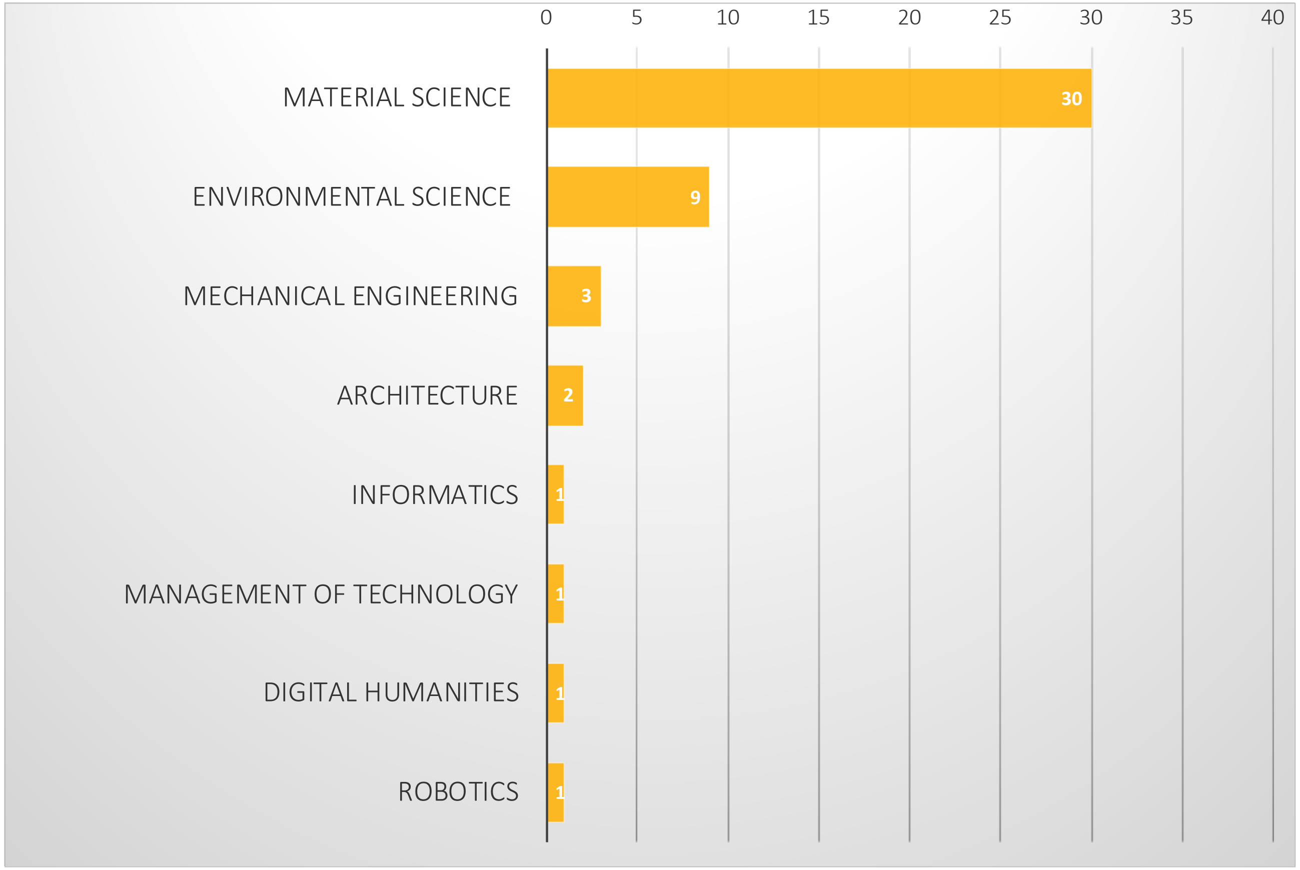
# Yves Leterrier

- 1987 MS in Materials Science and Engineering (*ESSTIN & Ecole des Mines de Nancy, France)*
- 1991 PhD in processing of composites (*Ecole des Mines de Nancy, France)*
- 1992 Post-doc on polymer physics (*NIST, USA*)
- 1993 Senior scientist and lecturer (*Institute of Materials, LTC & LPAC-EPFL*)
- 1994-2024 'Sustainable materials and processes' courses (*EPFL, CH, EU, Korea*)
- 2021 Coordinator of the EPFL minor 'Engineering for Sustainability'
- 2022 Collaboration with the University of Tokyo



# You are 48 students in 8 different sections ☺️

*(as of Feb. 16, 2025)*



# UN’s 17 sustainable development goals



Leterrier / Wakeman

SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD


Materials are central, especially 6,7,9,11,12,13

# UN’s 17 sustainable development goals

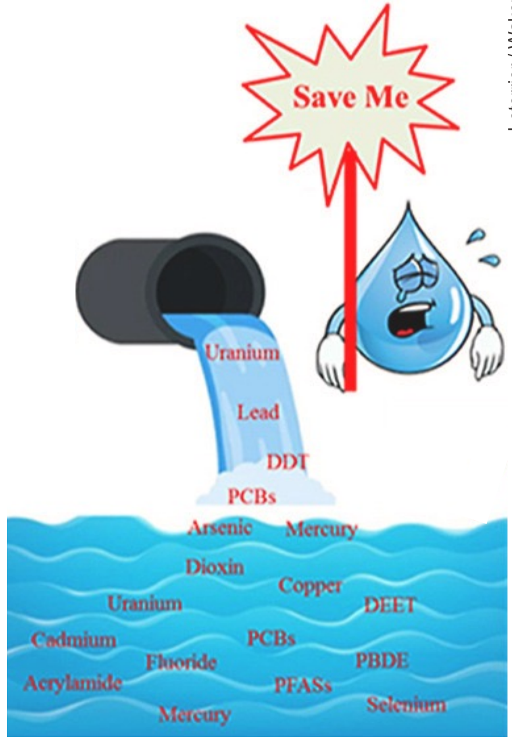





THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2023: SPECIAL EDITION- UNSTATS.UN.ORG/SDGS/REPORT/2023/

*Contamination of water in industrial processes*


Alagan et al., *Chemosphere* 335 (2023): 139178




Long-term exposure to the above harmful substances can result in respiratory, immunological, and neurological illnesses, cancer, and problems during pregnancy.

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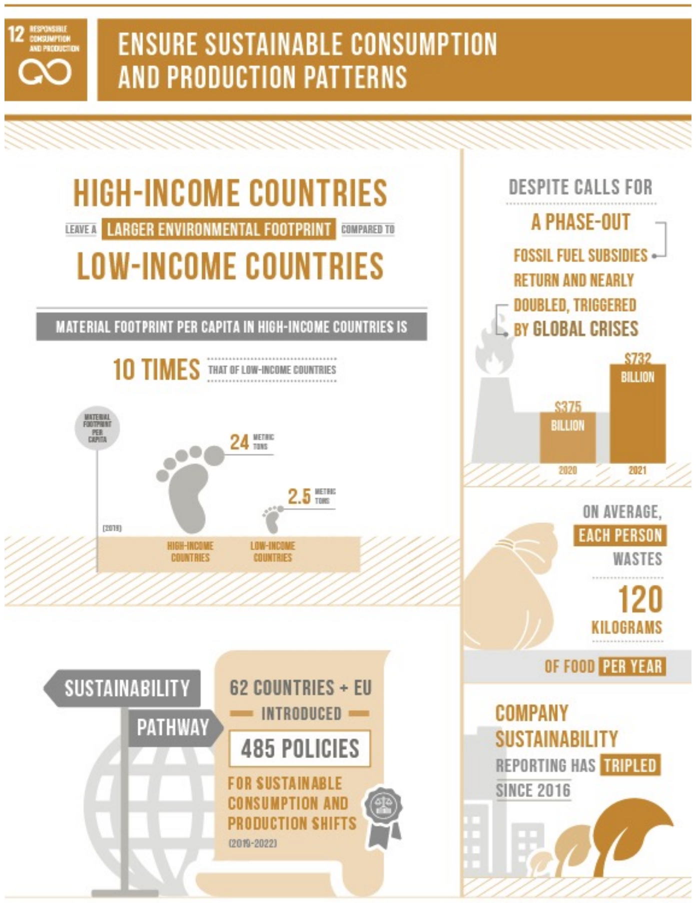
# UN's 17 sustainable development goals

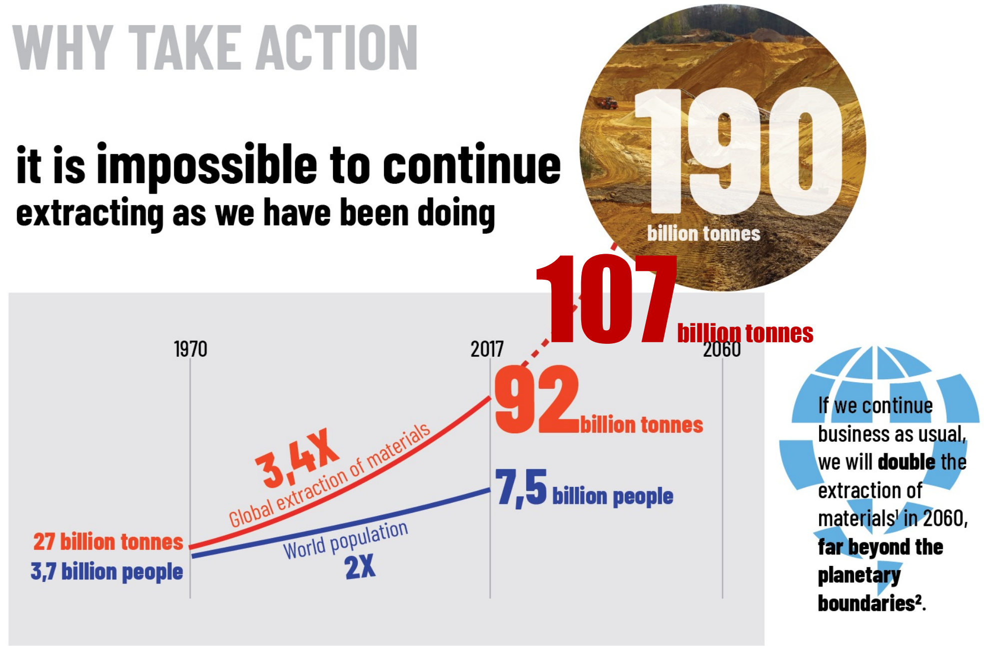







THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2023: SPECIAL EDITION- UNSTATS.UN.ORG/SDGS/REPORT/2023/

We extracted 107 billion tonnes of raw materials from our planet in 2024, still increasing at 2.3%/yr




Source: IRP (2019): Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya
1: "Materials" include biomass, fossil fuels, metals and non-metallic minerals, being are a subset of natural resources which encompasses all material plus water and land.
2: For more information: https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

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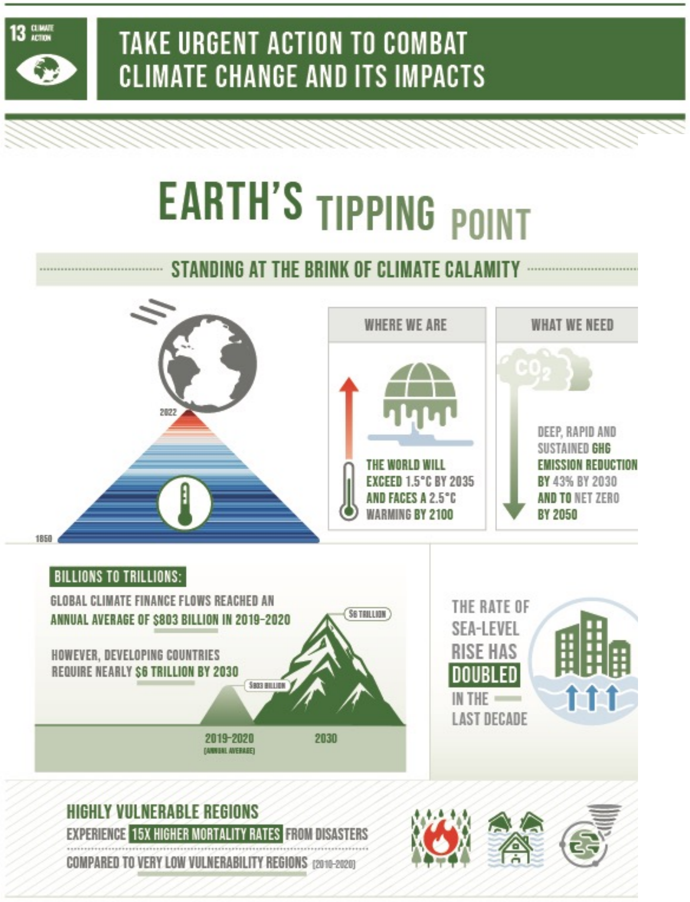
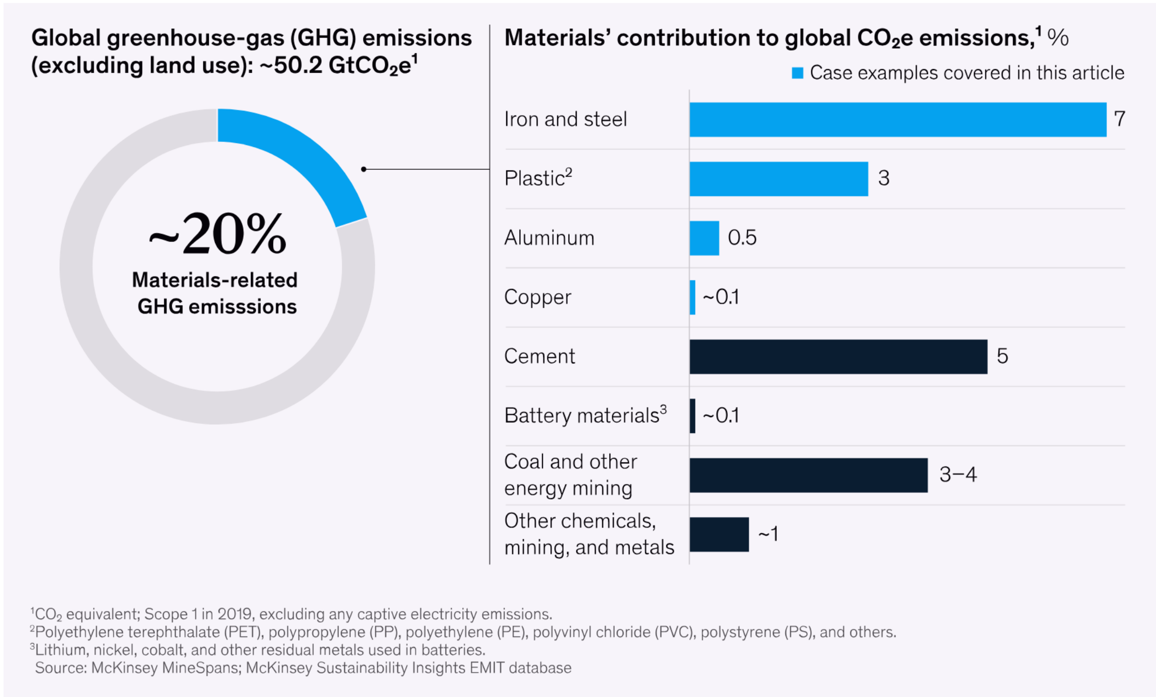
# UN's 17 sustainable development goals




THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2023: SPECIAL EDITION- UNSTATS.UN.ORG/SDGS/REPORT/2023/

## Material value chains lead to 20% of the global carbon footprint, generated by a few commodities




McKinsey & Company

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# UN's 17 sustainable development goals

## Progress not fast enough - not fair enough

"Future of Spaceship Earth"

Likelihood of meeting the 17 Sustainable Development Goals in five world regions:

- Green: Goal likely to be reached (i.e target fulfilment of more than 95%)
- Orange: Goal not likely to be reached, but more than 50% of gap between today's status and the goal is likely closed
- Red: Goal not likely to be reached, and less than 50% of gap between today's status and the goal is likely closed

| | ROW | BRISE | CHINA | OECD | USA |
|---|---|---|---|---|---|
| 1. No poverty | red | orange | orange | orange | orange |
| 2. Zero hunger | red | red | green | green | green |
| 3. Good health and well-being | orange | orange | green | green | green |
| 4. Quality education | red | orange | green | green | green |
| 5. Gender equality | red | red | red | orange | orange |
| 6. Clean water and sanitation | red | orange | orange | green | green |
| 7. Affordable and clean energy | orange | orange | green | orange | orange |
| 8. Decent work and economic growth | orange | orange | orange | red | red |
| 9. Industry, innovation and infrastructure | orange | orange | green | green | green |
| 10. Reduced inequalities | red | red | red | red | red |
| 11. Sustainable cities and communities | red | orange | red | green | green |
| 12. Responsible consumption and production | olive | red | red | red | red |
| 13. Climate action | red | red | red | red | red |
| 14. Life below water | red | red | red | orange | orange |
| 15. Life on land | red | red | orange | orange | orange |
| 16. Peace, justice and strong institutions | red | red | orange | orange | orange |
| 17. Partnerships for the goals | Not enough data to assess | | | | |

DNV GL 2016

COVID-19 pandemic, escalating conflicts, geopolitical tensions, and growing climate chaos are hitting SDG progress hard.

To meet the 2030 targets:

- First, we need peace
- Second, we need solidarity
- Third, we need a surge in implementation
- And fourth we need gender equality.

*António Guterres, Secretary-General of the United Nations (2024)*

# Global trends and drivers in sustainability

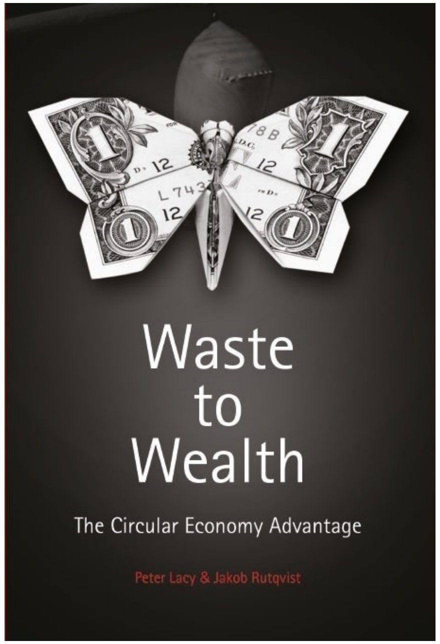
**Net zero: The race moves forward**
Carbon-neutral goods and services may be worth $10.3 trillion to the global economy by 2050.[1]

**Sustainability reporting: Accountability on the record**
More than 80% of companies now create new roles and responsibilities.[2]

**Circular economy: When waste is a resource**
Transitioning to a circular economy could generate $4.5 trillion in economic benefits by 2030.[3]

**Biodiversity: Embracing nature-positive**
Similar to "carbon neutral" in the context of emissions, nature positive refers to stopping, avoiding and reversing environmental destruction.

**Sustainable technology: New ways to do more**
AI & ML can help optimize energy consumption, reduce emissions and support decision-making processes in sustainability strategy development.




https://www.ibm.com/think/insights/sustainability-trends
(1) https://www.arup.com/news/green-transition-creates-$10t-opportunity-for-the-global-economy-by-2050-a-new-report-finds/
(2) Deloitte Sustainability action report: Survey findings on ESG disclosure and preparedness (December 2022)
(3) https://newsroom.accenture.com/news/2015/the-circular-economy-could-unlock-4-5-trillion-of-economic-growth-finds-new-book-by-accenture

# Course and learning objectives





**Course objectives**

- Address and model key sustainability issues through an engineering lens
- Examine emerging materials, hard to abate, and critical materials used to manufacture items in our economy during the transition to NetZero targets
- Investigate and model the environmental, societal, and human impacts of material life cycles

**By the end of the course, you will:**

- Understand key sustainability models and concepts including the NetZero transition
- Learn the impact and importance of key material classes
- Discuss this from an environmental, technological and economic perspective
- Equipped to use modelling tools: Material Circularity Indicator, TCM, MFA, LCA
- Develop transversal skills to assess a product across multiple requirements
  - Materials selection, manufacturing process choice, supply chain effect,
  - State main environmental and societal burdens and how their approach mitigates these
- Generate SMART* sustainability initiatives quantified by the studies and a stakeholder engagement plan

(*) Specific, Measurable, Attainable, Relevant, Time Oriented

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# Key blocks of the course





- **11 course sessions with 3 lectures followed by a debate**
  - Global perspectives (SDGs, linear vs circular economy, impact of materials …)
  - Methodologies (Circularity metrics, Life Cycle Assessment, Life Cycle Costing …)
  - Core materials (hard to abate materials, biobased materials, critical materials …)
  - 14 lectures by invited guests from EPFL, IMD, companies and NGOs
  - Numerous case studies

- **9 debates (45 min) on predefined questions** (e.g., *How can we reduce the impingement of materials on the novel entities planetary boundary and human health?*)

- **A group project!**
  - 1 full course session for group project feedback (April 7, 2025)
  - 1 full course session for group project presentations (May 19, 2025)

- **A written test** (May 26, 2025)

- **A best group project prize!**

# Key blocks of the course

| | | |
|---|---|---|
| I – Global perspectives | 1 | Course introduction and sustainability frameworks |
| | 2 | Introduction to sustainable materials |
| II – Methodologies | 3 | Addressing the impacts of materials |
| | 4 | Life cycle analysis |
| | 5 | Monetary and mass flows |
| III – Core materials | 6 | Hard to abate (polymeric) materials |
| | 7 | Bio-based materials and Direct Air Carbon Capture |
| | 8 | Group project feeback session |
| | 9 | Hard to abate (cement / concrete) materials |
| | | Vacation easter |
| | 10 | Mobility, composites, and the energy transition |
| | 11 | Critical materials & precious metals |
| | 12 | Hard to abate (metallic) materials |
| Exam | 13 | Group project presentations |
| | 14 | Written test |

# The Experts





| Date | Guest Speaker | Affiliation | Title of the Talk |
|---|---|---|---|
| 24th February 2025 |  Robin Quartier | VBSA ASED ASIR | The economics of waste management |
| 3rd March 2025 |  Nicholas Myers | OMNIS INSTITUTE Omnis Institute | Impacts on Global South of climate change & raw materials extraction |
| 17th March 2025 |  Prof. Claudia Binder | HERUS Laboratory on Human-Environment Relations in Urban Systems, EPFL | Material flow analysis |
| 24th March 2025 |  Jonathan Sterne | INEOS | Industrial initiatives: polymeric materials |
| 31st March 2025 |  Prof. Tiffany Abitbol | SML SUSTAINABLE MATERIALS LAB Sustainable Materials Laboratory (SML-EPFL) | Bio-based materials |
| |  Prof. Kumar Agrawal | Laboratory of Advanced Separations (Gaznat Chair, EPFL) | Technoeconomics challenges of carbon capture |
| |  Lars Lundquist | Nestlé | Industrial initiatives: packaging PC to bio-mass |

# The Experts

| Date | Guest Speaker | Affiliation | Title of the Talk |
|---|---|---|---|
| 14th April 2025 |  Prof. Corentin Fivet | STRUCTURAL XPLORATION LAB EPFL | Materials in built environment |
| |  Prof. Karen Scrivener | Laboratory of Construction Materials (LMC-EPFL) | Low carbon cement and concrete |
| |  Christophe Levy | HOLCIM | Industrial initiatives: concrete |
| 28th April 2025 |  Jon Meegan | SYENSQO | Industrial initiatives: composites |
| 5th May 2025 |  Matthew Kilgarriff | RICHEMONT | Industrial initiatives: precious metals' stakeholder engagement across supply chains |
| 12th May 2025 |  Prof. Roland Logé | Laboratory of Thermomechanical Metallurgy (LMTM-EPFL) | Additive Manufacturing for improved sustainability? |
| |  Prof. Karl Schmedders | IMD Real learning Real impact | Winning the sustainability investment argument with CFOs |

slido

Please download and install the Slido app on all computers you use

# What is the degree of circularity of the present global economy?

ⓘ Start presenting to display the poll results on this slide.

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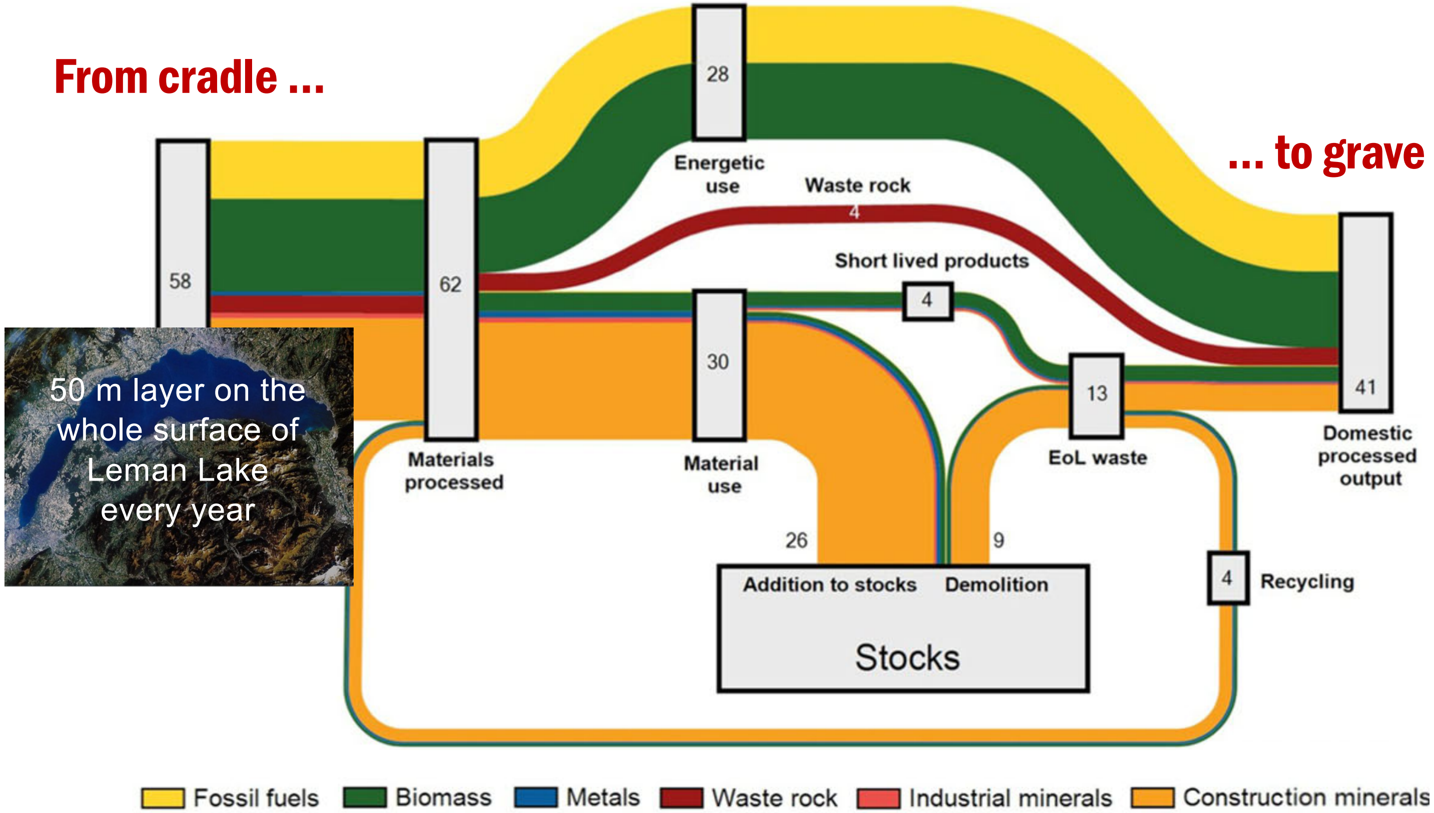
# Global materials flows [Gt/yr]





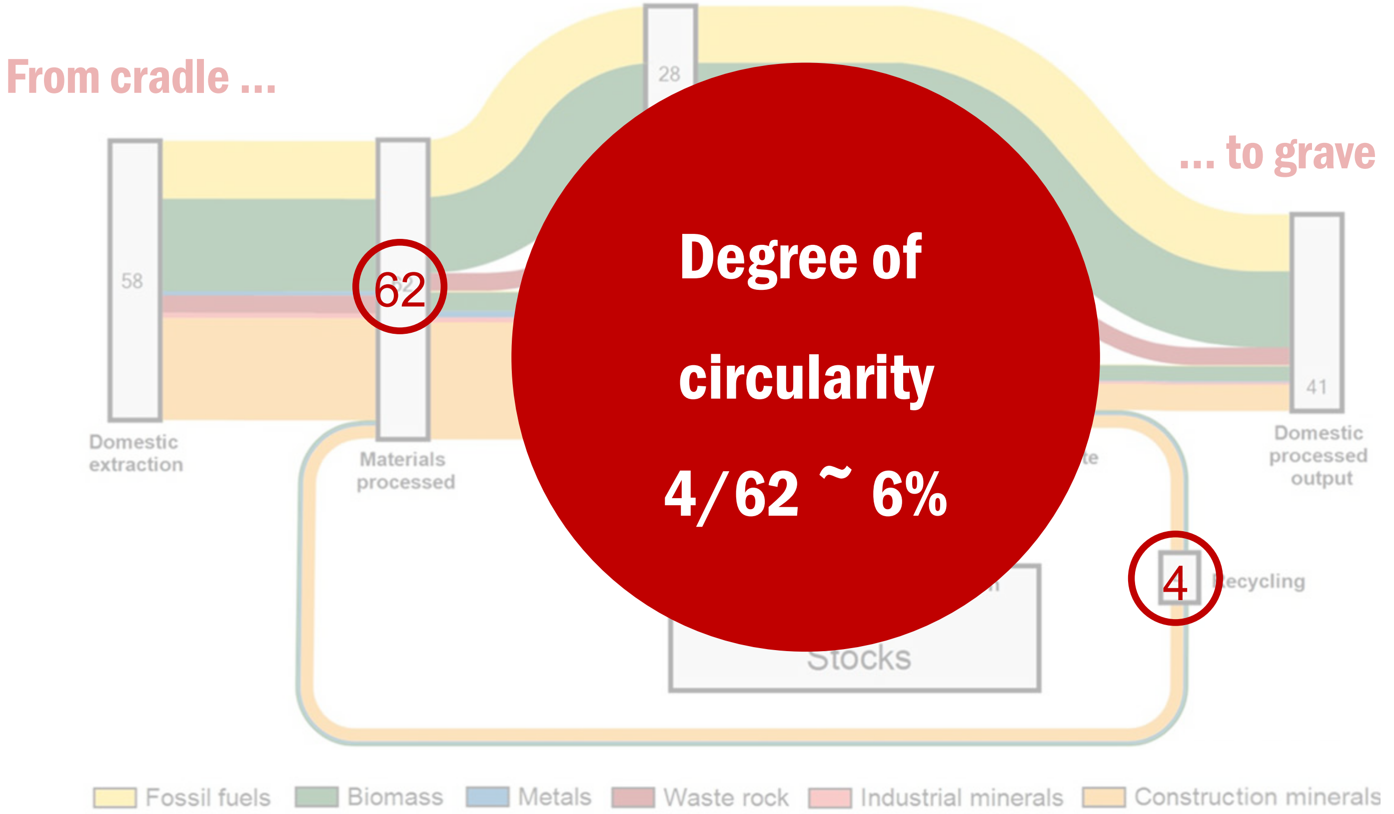





- Haas, Krausmann, Wiedenhofer, Heinz, Journal of Industrial Ecology, 2015 (2005 data)

# Global materials flows [Gt/yr]





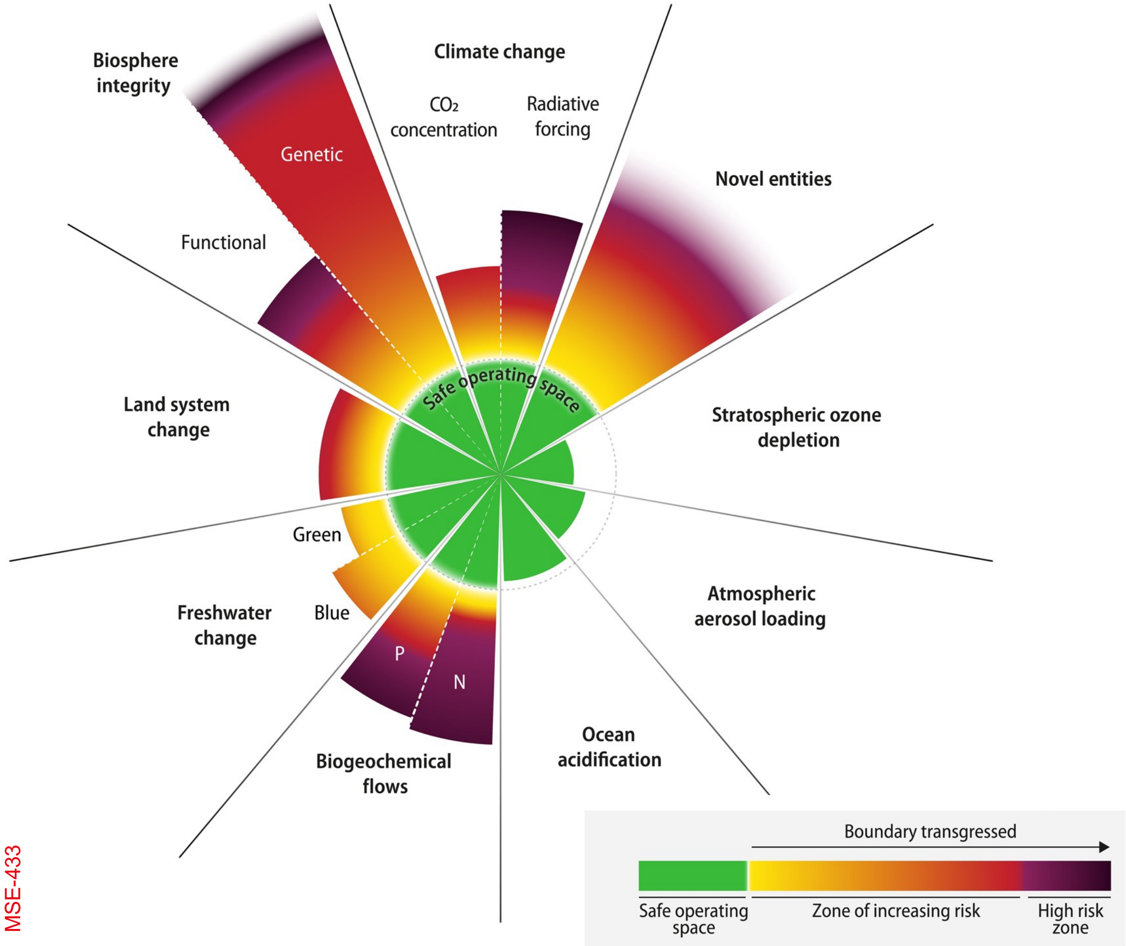



- Haas, Krausmann, Wiedenhofer, Heinz, Journal of Industrial Ecology, 2015 (2005 data)

# Challenges!

- Earth beyond six of nine planetary boundaries
- Linear Economy vs. Circular Economy
- Degree of circularity
- Dematerialization
- Construction materials
- Critical materials
- Hard-to-abate multimaterial systems
- Water
- Logistics
- Recycling
- Global South
- … and more!

# Earth beyond six of nine planetary boundaries!




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

1️⃣ nine major processes facilitate and regulate the Earth's system as it has existed for approximately 10,000 years (*Holocene*);

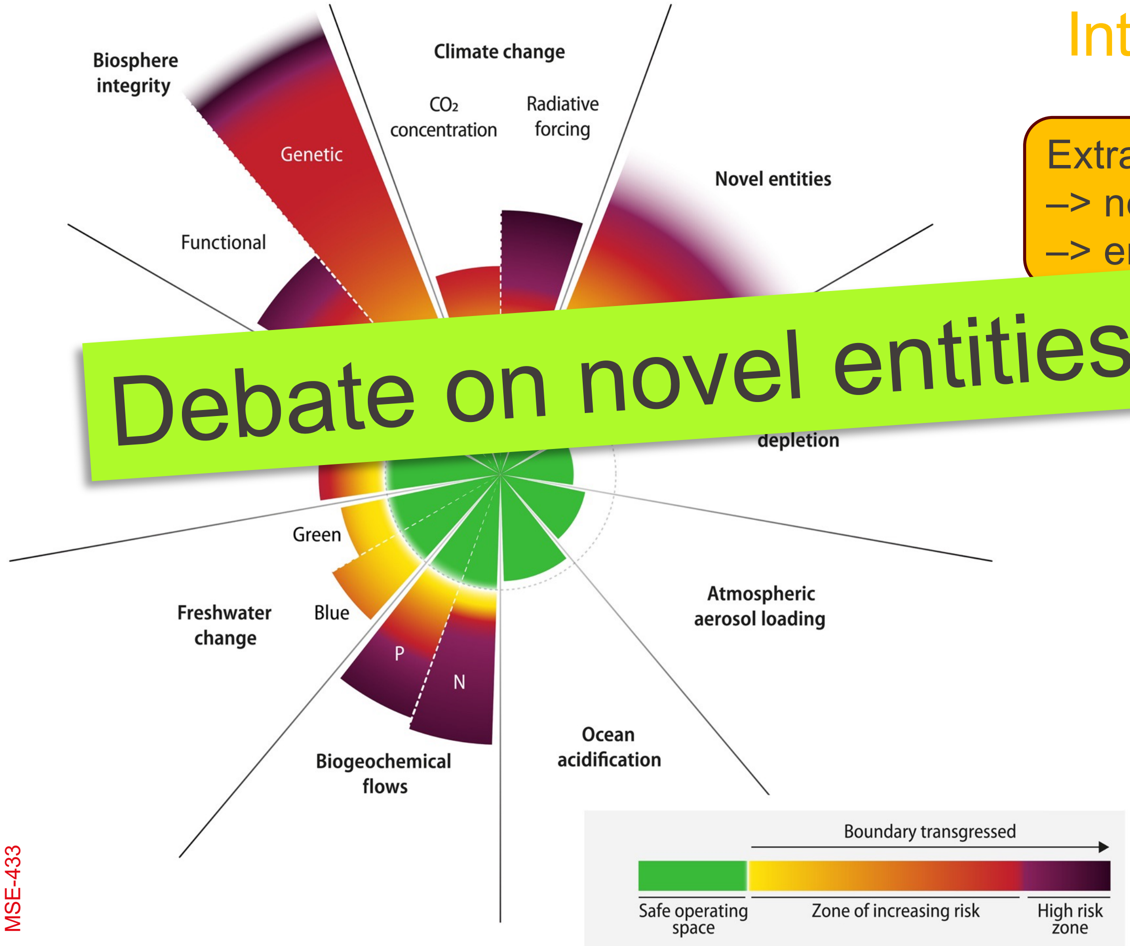
2️⃣ these processes are today impacted by human activities;

3️⃣ there exists for each of these a limit beyond which the process will no longer produce the usual effects and lead to radical imbalances.

Prof. Johan Rockström

EPFL

# Earth beyond six of nine planetary boundaries!




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

## Interactions at all levels within PB

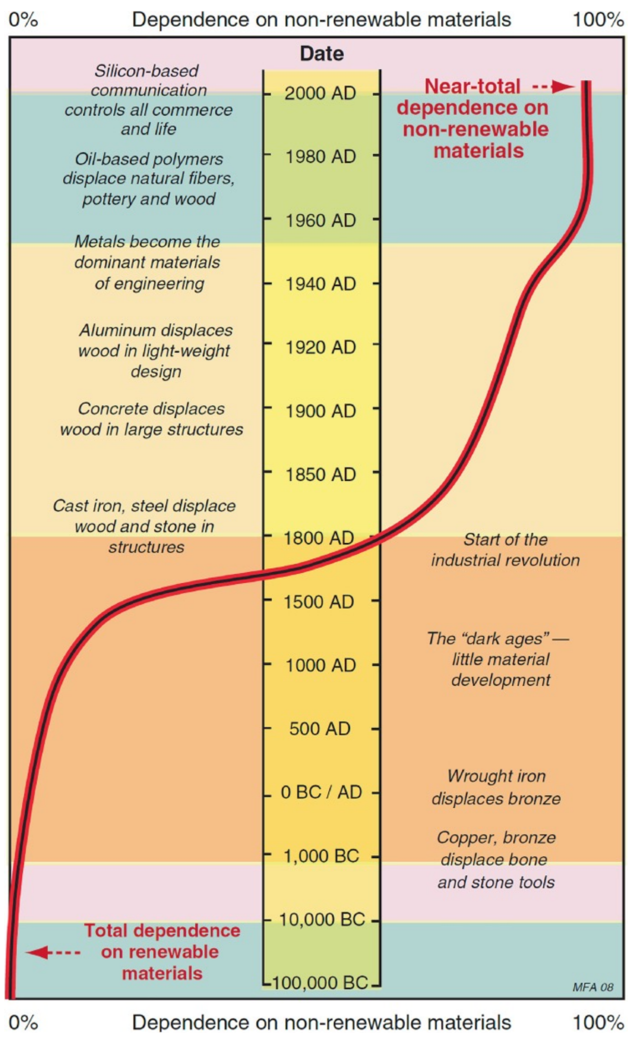
Extraction of raw materials
–> needs energy
–> emits $CO_2$
Economy

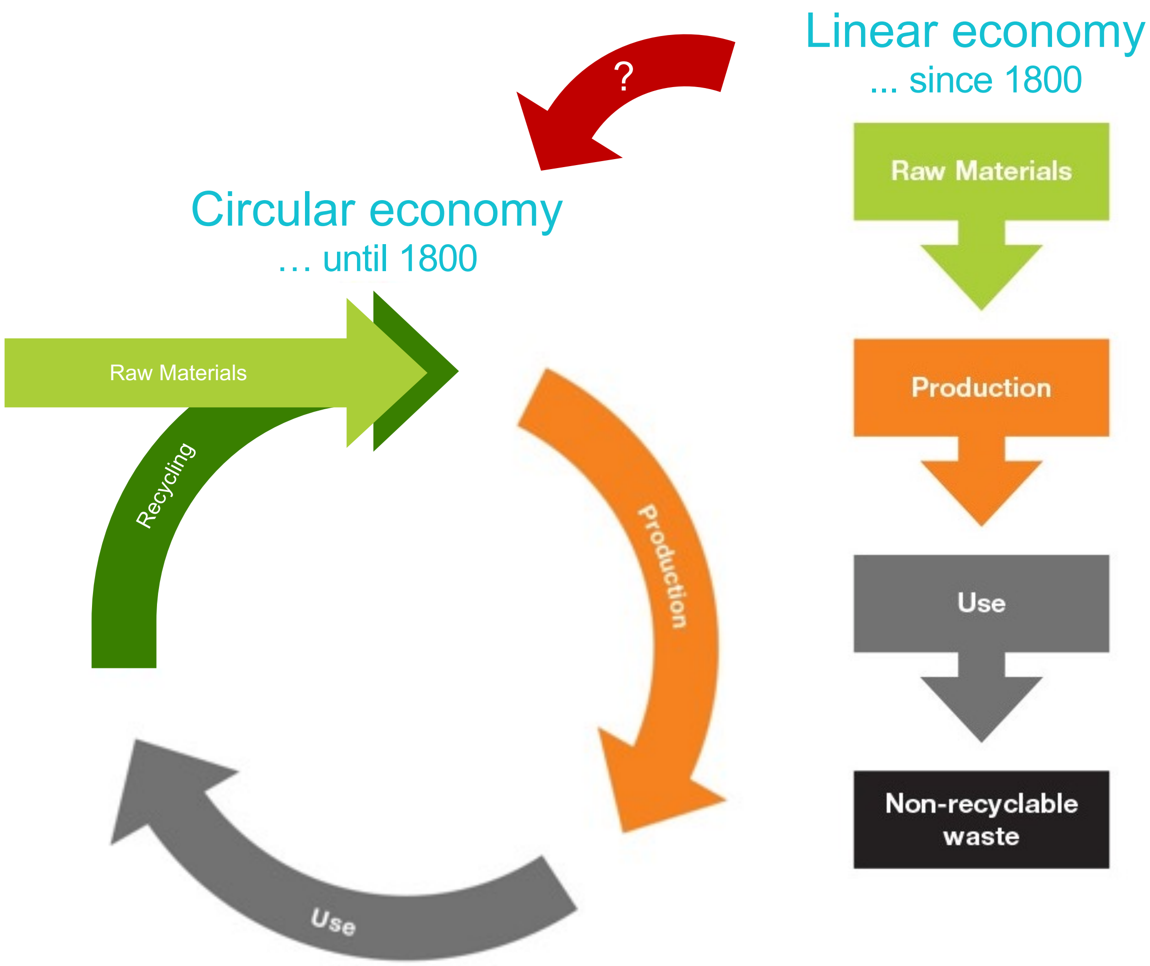
Global warming impacts
–> Sustainable forest management
–> Stable ocean ecosystems
Environment

Supply chains, trade and political environments
–> Community rights
–> Corruption / transparency
Society

Debate on novel entities, March 31, 2025

# Linear Economy vs. Circular Economy!



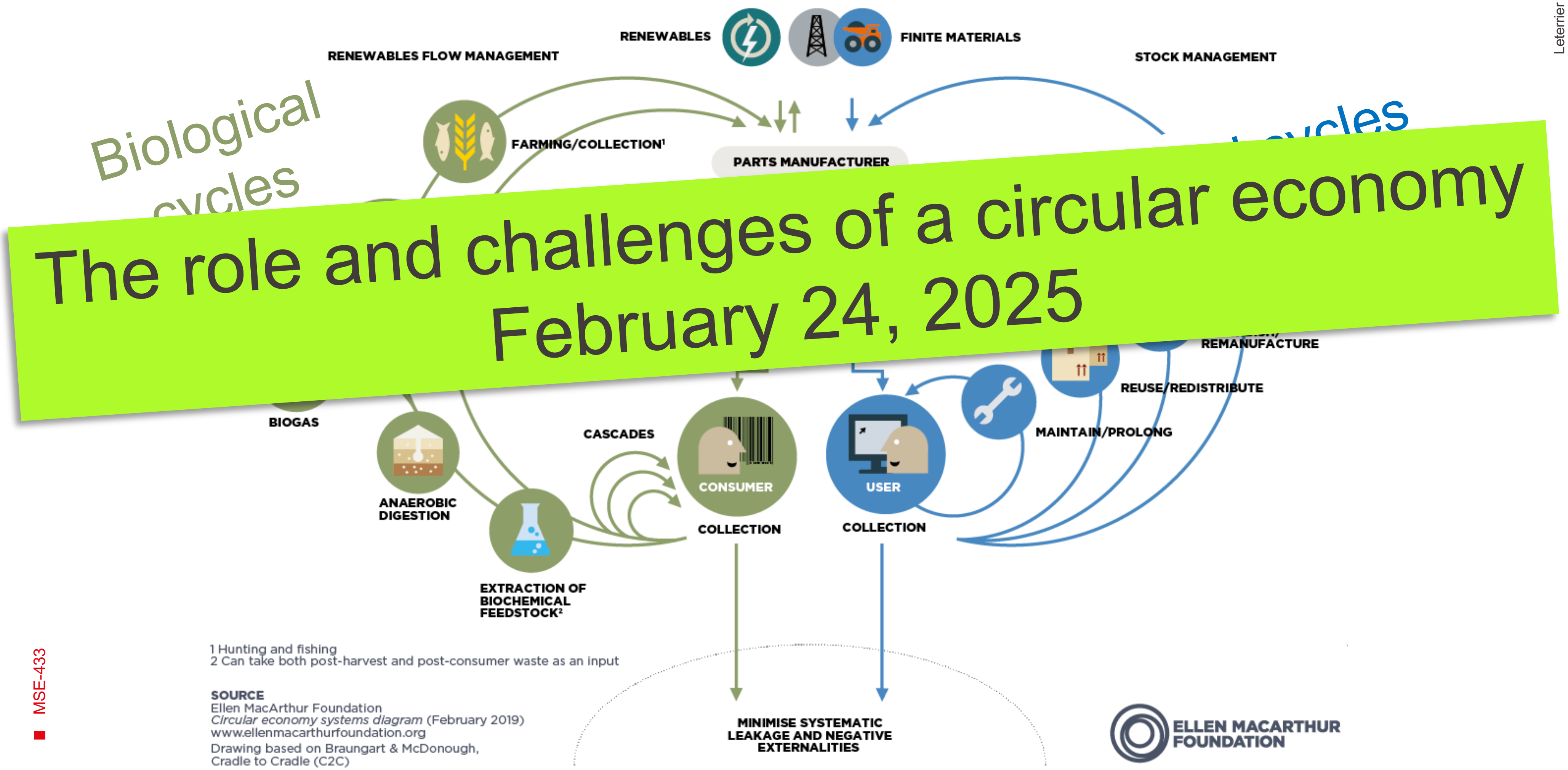




Gutowski et al., Phil Trans Roy Soc A, 2013, 371, 20120003
Ashby, *Materials and the environment: eco-informed material choice, 2nd Ed.* 2012: Butterworth-Heinemann, Oxford

# Linear Economy vs. Circular Economy!








The role and challenges of a circular economy

February 24, 2025

1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

**SOURCE**
Ellen MacArthur Foundation
*Circular economy systems diagram* (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

# Degree of circularity!




- Material circularity indicator (MCI, Ellen MacArthur Foundation)
- Circular Transition Indicators (CTI, WBCSD)
- Circularity Gap (Circle Economy)
- Circular Footprint Formula (CFF, European Commission)
- Circularity Check, Ecopreneur.eu

ELLEN MACARTHUR FOUNDATION
GRANTA MATERIAL INTELLIGENCE
World Business Council for Sustainable Development
CIRCLE ECONOMY
European Commission
ecopreneur.eu

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# Degree of circularity!

- Material circularity indicator (MCI, Ellen MacArthur Foundation)
- Circular Transition Indicators (CTI, WBCSD)
- Circularity Gap (Circle Econo…
- …ommission)
- Circularity Check, Ecopreneur.eu

Material circularity indicator, March 3rd, 2025

More metrics:

- Dependence on renewable materials
- PBs
- Distance to NetZero …


Ashby MF (2012) Materials and the environment: eco-informed material choice, 2nd Ed. Elsevier

# Dematerialization!

Dematerialization is the absolute or relative decline over time in the quantities of materials used, or the quantity of wastes generated, or both, in the production of a unit of economic output.

A widely used measure of dematerialization is intensity of use (IU), IU=$X_i$/GDP, where $X_i$ is the annual consumption of a specific material, i, in terms of mass or volume, and GDP is the *per capita* gross domestic product. Progressive decrease in materials IU over time is called weak dematerialization while progressive decrease in the total materials use in absolute terms is called strong dematerialization.

Is this dematerialization?

- Yes if based on weight only
- Probably no if based on material intensity!

Dematerialization is different from miniaturization!

Kem-Laurin Kramer, ‘User Experience in the Age of Sustainability. A Practitioner's Blueprint’, Elsevier 2012’
https://www.sciencedirect.com/book/9780123877956/user-experience-in-the-age-of-sustainability

# Dematerialization!



| Dematerialization pros & cons | |
|---|---|
| + Technological developments (improved design and quality control, increased recycling) | – population growth (and increase in the number of goods and services) |
| + Materials substitution (light-weighting of vehicles via substitution of steel by aluminum and composites) | – increased goods productivity and increasing demand …‘the rebound effect’ (e.g., display devices in households, clothing) |
| + Replace goods by services (car sharing …) | – “less” from a materials perspective may not always be “less” from an environmental perspective, e.g., the substitution of aluminum for steel and plastic for timber |
| + Legislation (ban on substances, e.g. lead, increased recycling rates) | |

# Comparison of the environmental impact of paper books vs e-books

Casagrande Kulcke M., Dupont G., Jaccard G., Köhler T., Massonnet G., Micaleff A.

## Motivation

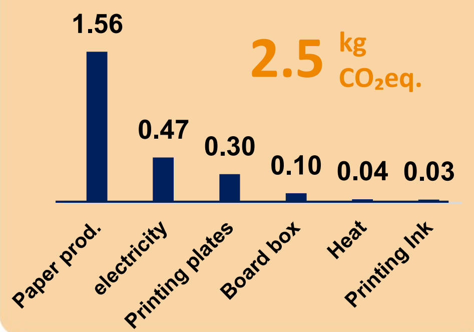
- Cultural transformation towards electronics devices: USA (2012) **E-books: 28% of total book sales** [1]
- **Question**: What is the environmental impact of **our reading choice**?

## Survey

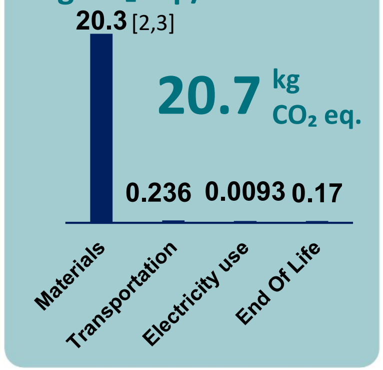
- **53%** of people think that paper books are more sustainable than e-readers
- **10 books** read on average **per year**

33% Buy paper books
67% Rent/borrow

## kg $CO_2$ eq./1 paper book




## kg $CO_2$ eq./1st e-book



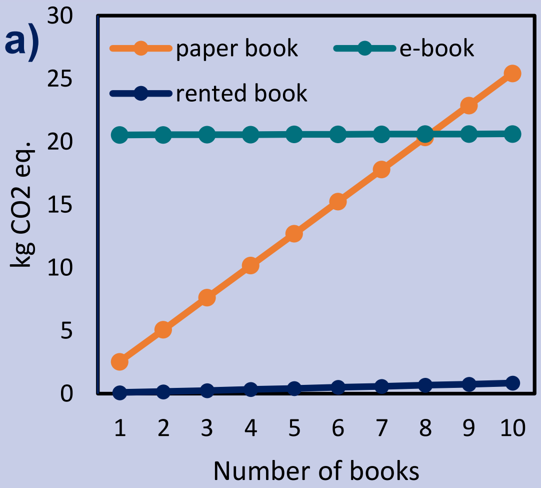

## Scenarios and results

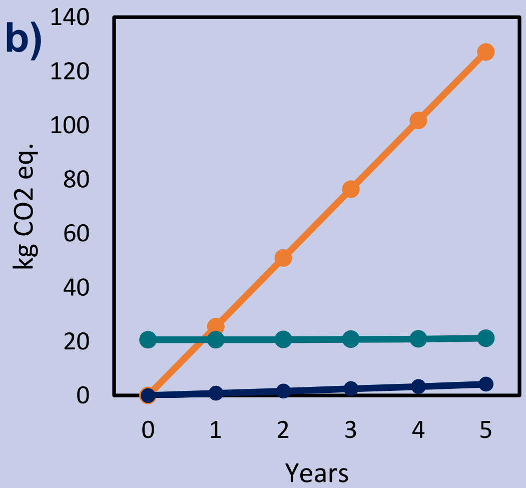
**a)** Global warming potential of **books read in 1 year**

Functional Unit:
kg $CO_2$ eq. for # of books read

**b)** GWP of books over **5 years** (lifetime of a kindle)

Functional Unit:
kg $CO_2$ eq. of 10 books per year for 5 years




## Conclusions

- A **Kindle emits less $CO_2$** than 8 new paper books
- **Renting books** in the library emits **far less $CO_2$** than both new paper books and e-books


**References**

[1] Tahara K, Shimizu H, Nakazawa K, Nakamura H, Yamagishi K. Life-cycle greenhouse gas emissions of e-books vs. paper books: A Japanese case study. J Clean Prod. 2018 Jul 10;189:59–66
[2] Dowd-Hinkle, D. J. Kindle vs. Printed Book An Environmental Analysis (2012). Thesis. Rochester Institute of Technology.
[3] Hedgehog Company B. V. What has a lower environmental impact? Digital versus traditional reading: a comparative LCA. 2021 16 July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# Construction materials!



- Bulk minerals such as sand, gravel, stone, or clay, represent 95% of global material extraction
- Buildings are responsible for more than 40 percent of global energy use and one third of global greenhouse gas emissions
- The recycling rate of minerals is quite high (33%) but essentially into downgraded
- The consumption of

Hard to abate (cement / concrete) materials
Fivet, Scrivener, Levy, April 14, 2025



Buildings and Climate Change. Summary for Decision-Makers, UNEP-SBCI (2009)
Haas, Krausmann, Wiedenhofer, Heinz, Journal of Industrial Ecology, 2015

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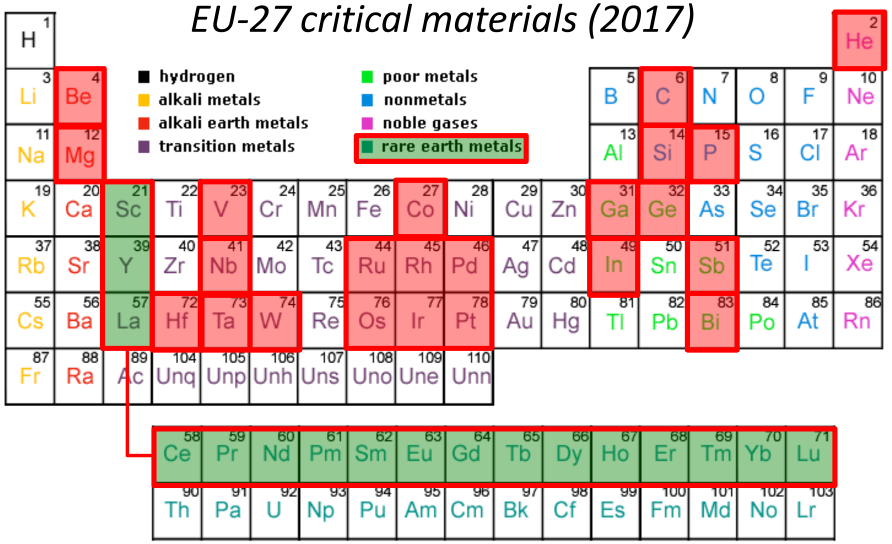
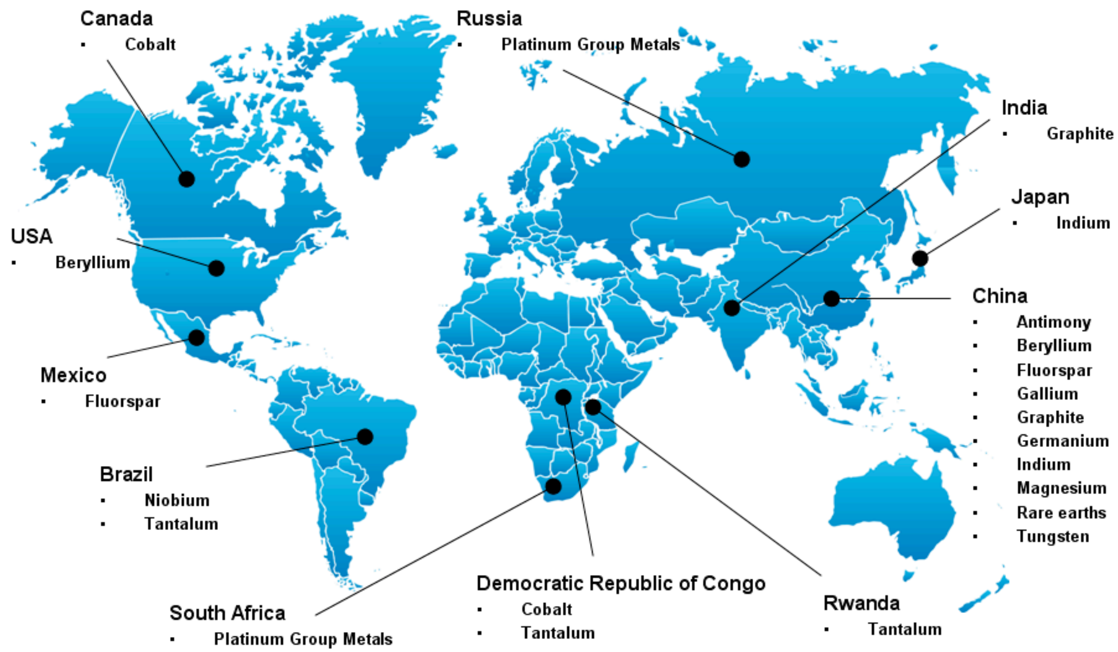
# Critical materials!

"The 21st century vitamins"

*EU-27 critical materials (2017)*




*Production concentration of critical raw mineral materials*




http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm

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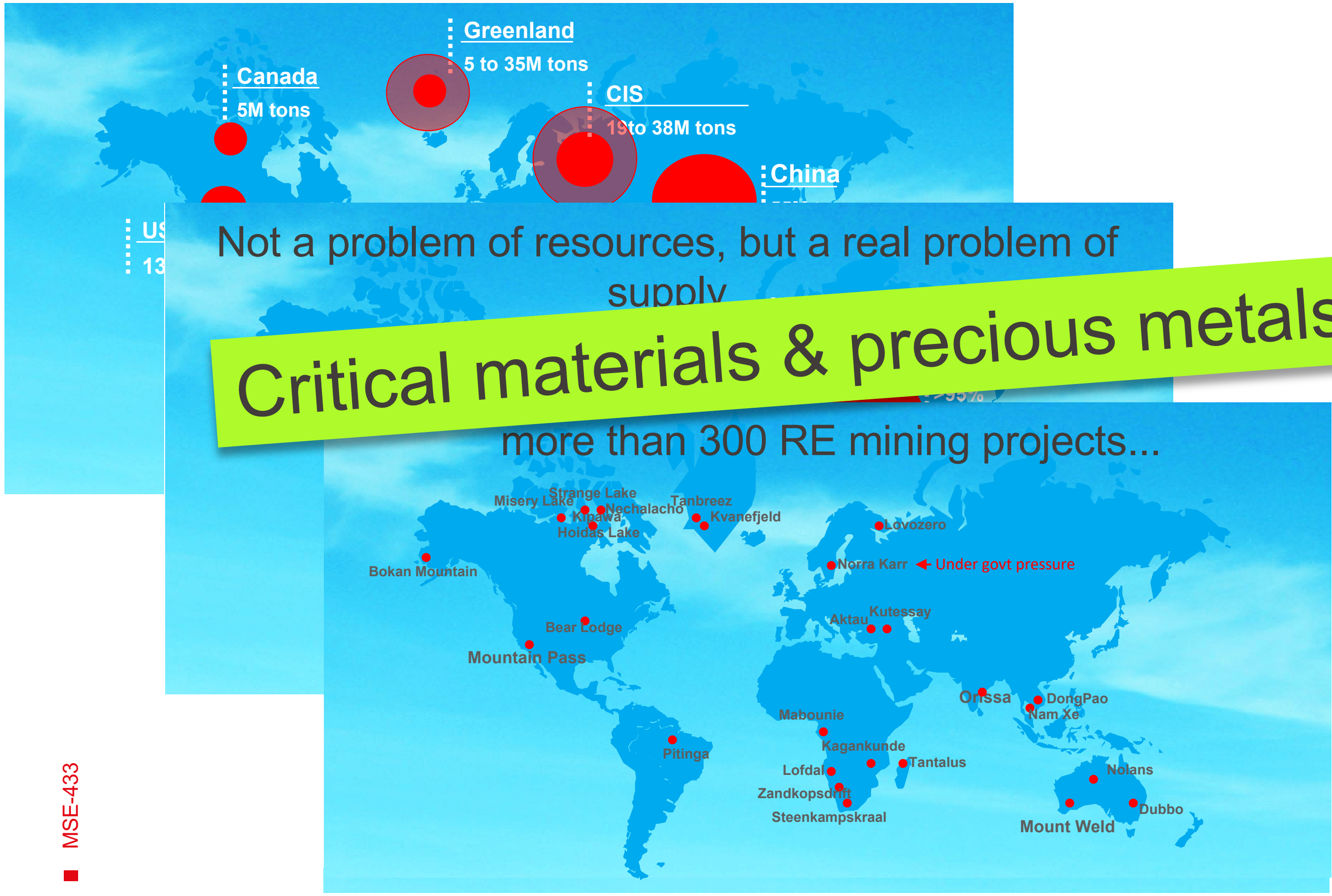
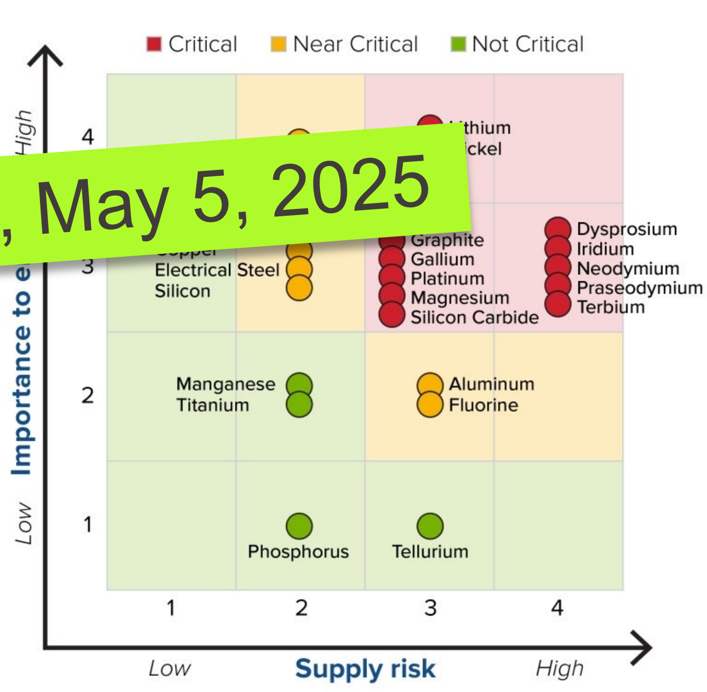
# Critical materials!

Large and well distributed REO reserves ( ~ 100 Mt)




## Critical materials & precious metals, May 5, 2025

Criticality Matrix



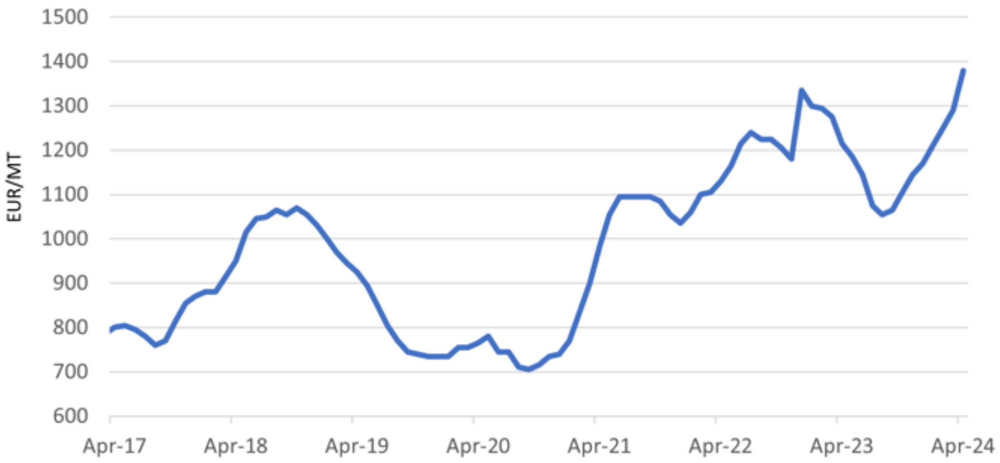

Rowan, Critical Mineral Resources: National Policy and Critical Minerals List, US Congressional Research Service (2024)

# Price volatility!

Leterrier / Wakeman

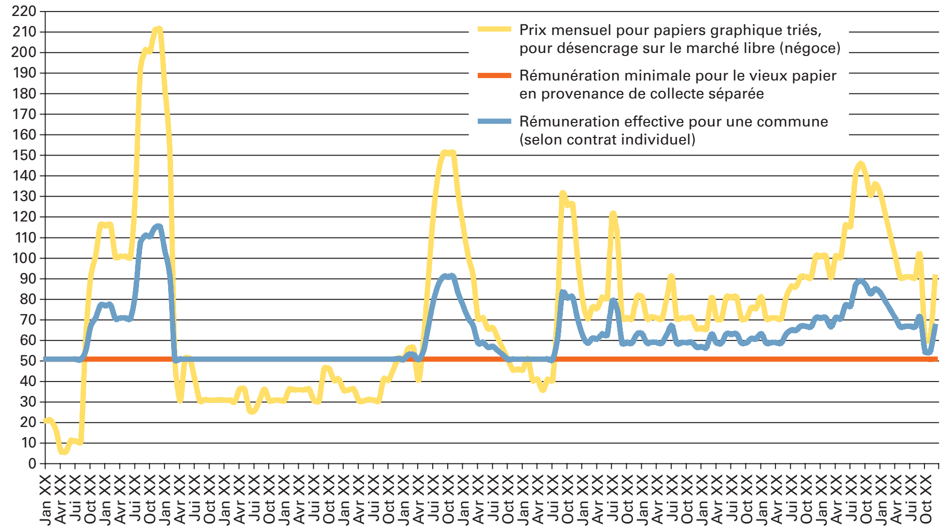
## *Price of pulp*

*Northern Bleached Softwood Kraft*




www.mintecglobal.com

## *Revenues with old paper in Switzerland over 15 years*




www.recycling.ch

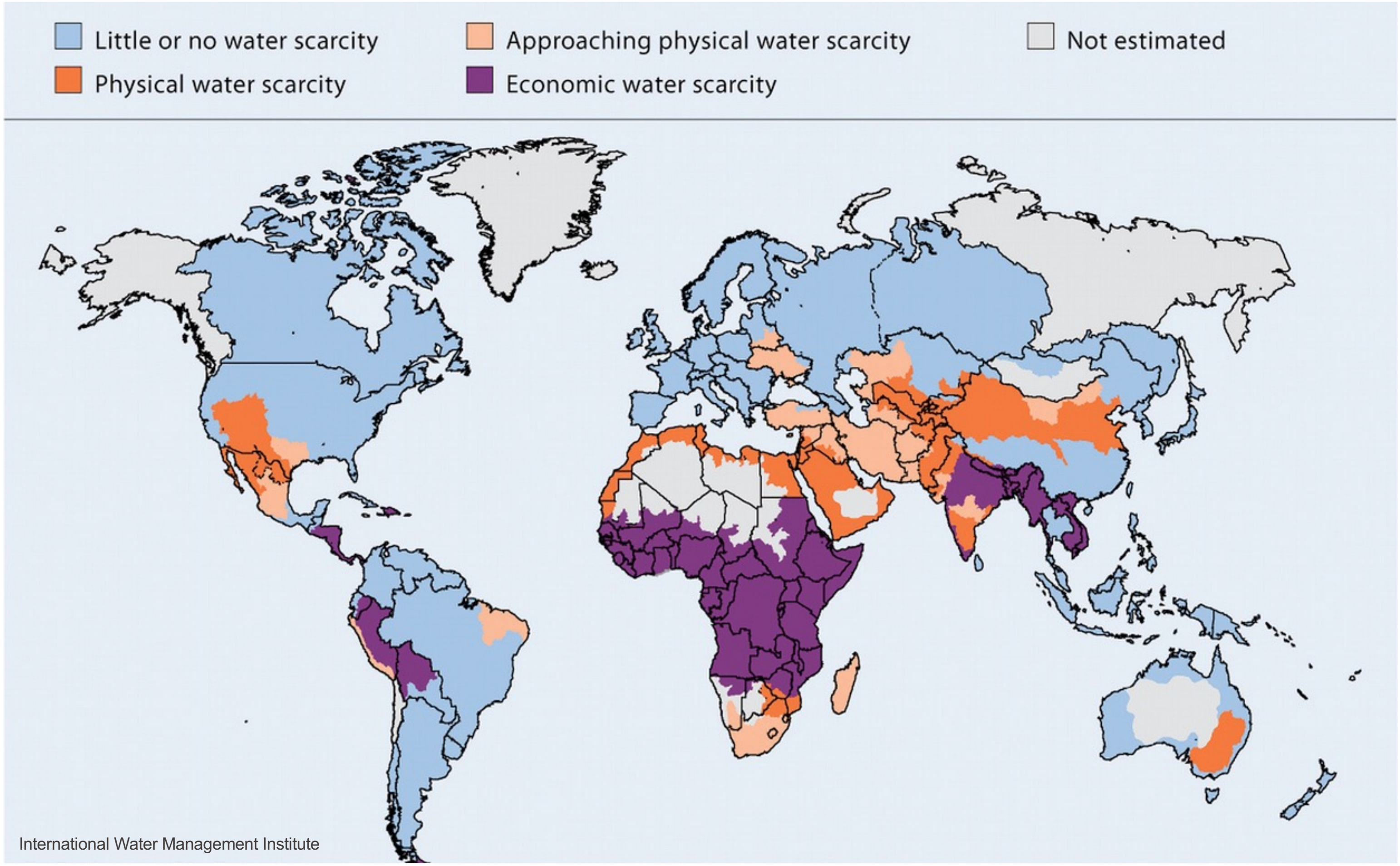
# Price volatility!



# Hard-to-abate multimaterial systems!

Hard-to-abate materials, March 24, April 14, May 12, 2025

# Water!


Little or no water scarcity
Physical water scarcity
Approaching physical water scarcity
Economic water scarcity
Not estimated
International Water Management Institute

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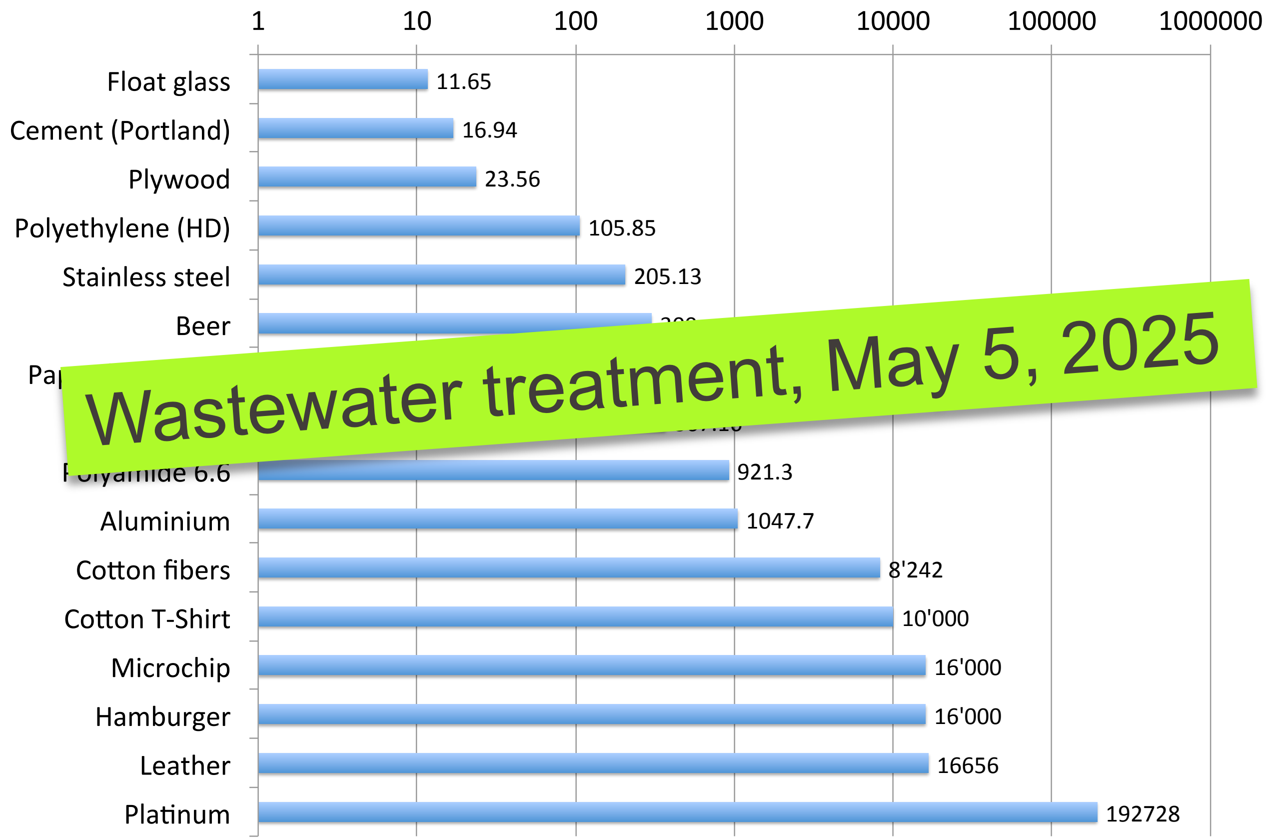
# Water!

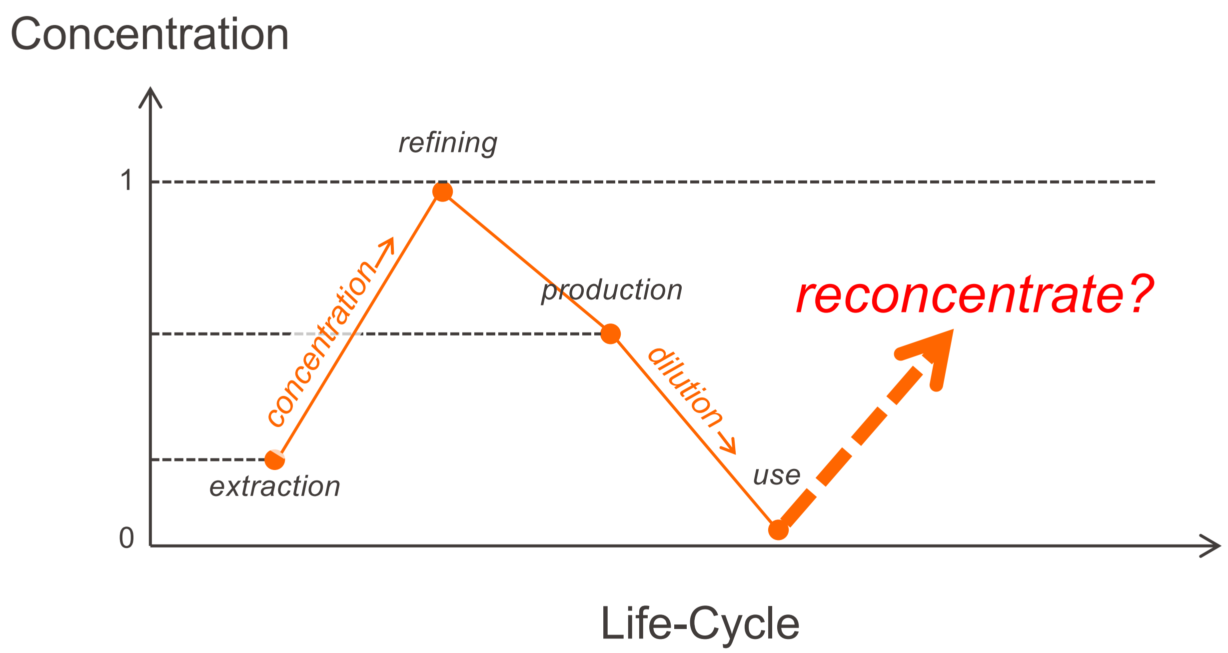
Water Consumption in Industrial Processes
[kg water / kg material]




Wastewater treatment, May 5, 2025

Wuppertal Institute for Climate, Environment and Energy
Hoekstra and Chapagain, Water Resource Management (2006)

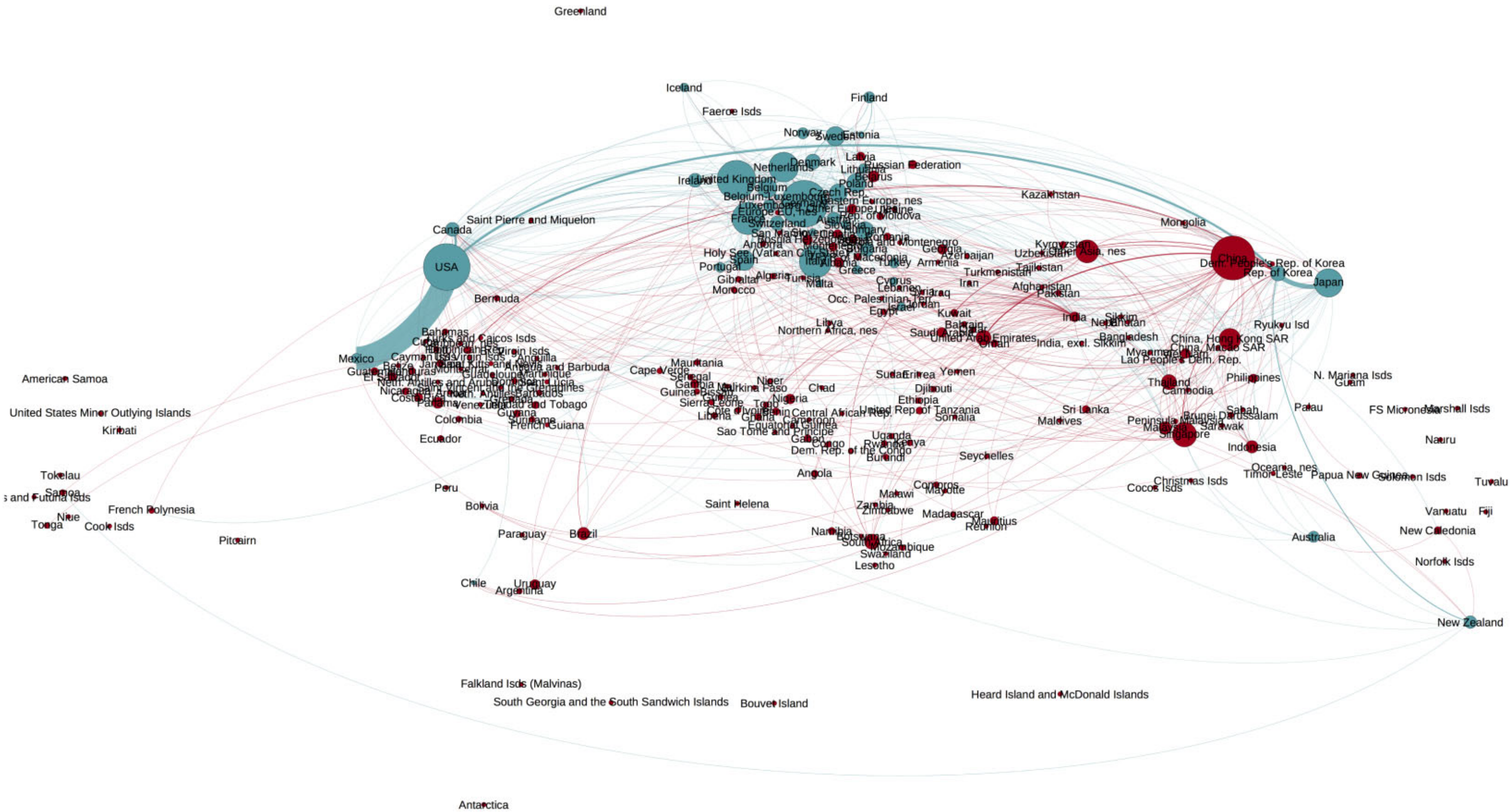
# Logistics!


Concentration
1
0
refining
production
reconcentrate?
concentration
dilution
extraction
use
Life-Cycle

# Logistics!



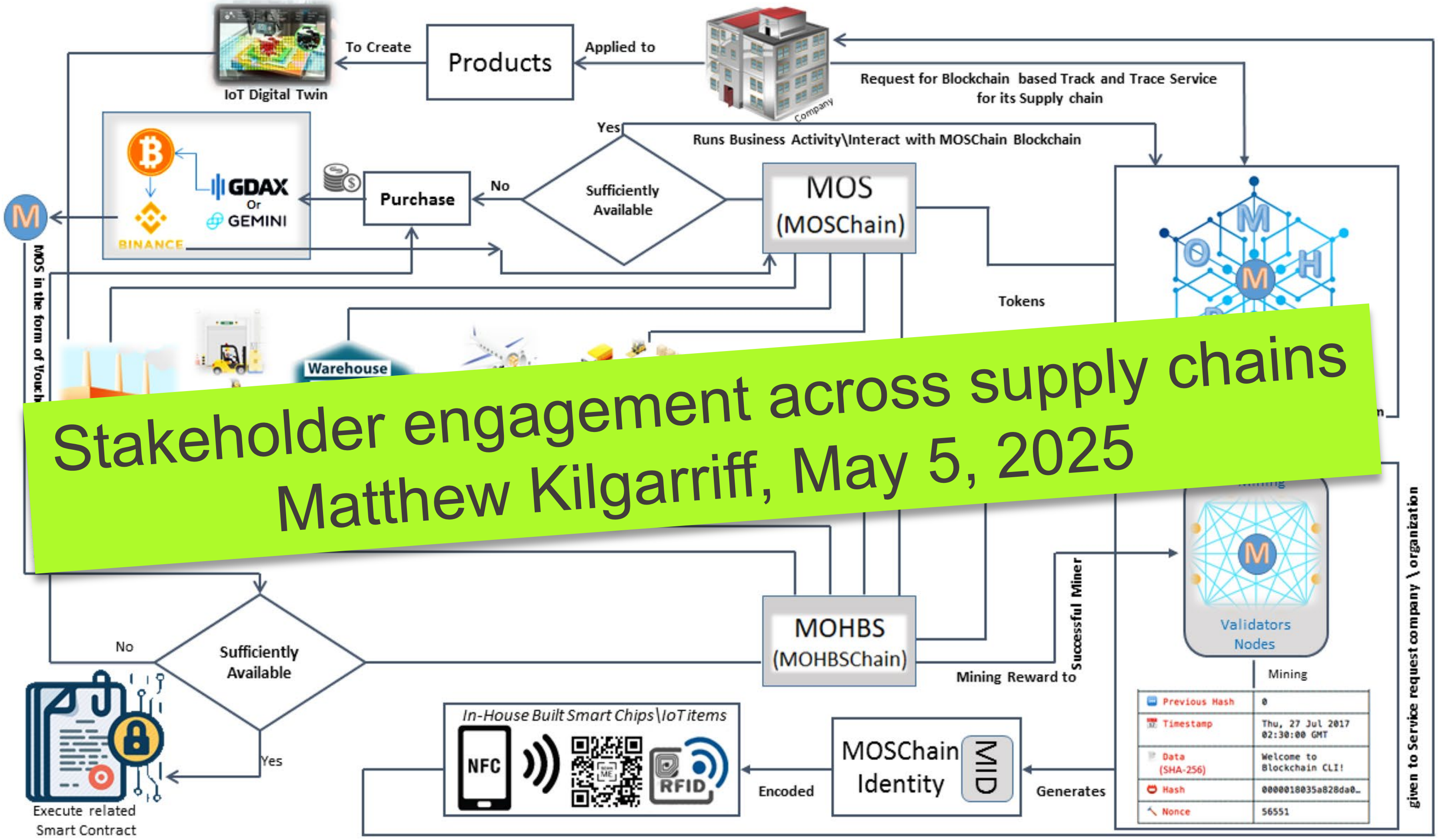
*Global e-waste trade network, 2012*






Lepawsky, The Geographical Journal, 181 (2015)

# Logistics!




Stakeholder engagement across supply chains
Matthew Kilgarriff, May 5, 2025

Jabbar et al., Multimedia Systems (2021) 27:787–806

# Recycling!

# Recycling!



x 40

Primary gold ore ~ 5 g/ton

Secondary gold ore ~ 200 g/ton

Kalgoorlie, Australia


Recycling (gold, plastics), March 24 & May 5, 2025

x 3.6

*Production ~ 3’600 t/yr*

*Production ~ 13’000 t/yr*

# Global South!

Rockwood lit…

Impacts on global south of climate change & raw materials extraction (Nicholas Myers, March 3, 2025)

## The Global South's double burden

The energy transition will require huge quantities of metals and minerals, such as lithium, copper, and other rare earths.

Electromobility in 2040 as an example:

- 40X increase for lithium
- 2X increase for copper

Currently known resources do not cover the needs! (50% for Li, 80% for Cu)

… the

… nvironmental

… largely without protection.

Over the coming decades, the importance of recycling and closed raw material cycles must increase because of resource scarcity and climate impacts. This is the only way of ensuring that climate protection in Western industrialized countries does not take place on the backs of disadvantaged groups and ecosystems in Latin America and other parts of the world.

Adapted from Becker, *IPS Journal, 12.11.2021*
https://www.ips-journal.eu/topics/economy-and-ecology/the-global-souths-double-burden-5539/

# More challenges!

- Circularity vs environmental footprint metrics (March 3 & 10)
- Biobased materials vs $CO_2$ sequestration (March 31)
- Hard to abate materials – steel, aluminium, copper, concrete, plastics (March 24, May 12)
- Modeling uncertainty (April 28)

# Summary: materials are relevant to sustainability!





| Pillar | Definition | Relevance for materials |
|---|---|---|
| Economically sustainable system | • Produce goods and services on a continuous basis | • Dematerialization<br>• Price volatility<br>• Critical materials |
| Environmentally sustainable system | • Maintenance of a stable resource base | • Increase circularity (limit extraction, develop recycling)<br>• Biobased materials<br>• New entities (toxic waste, microplastics) |
| Socially sustainable system | • Able to achieve distributional equity and adequate provision of social services | • No pollution<br>• Food and water quality<br>• No waste |



Muthu S. (Ed) Sustainability in the Textile Industry, Springer (2016)
J.M. Harris, in Dimensions of Sustainable Development - Volume I, Kamaljit S. Bawa, Reinmar Seidler (Eds), EOLSS Publications (2009)