TOWARDS SUSTAINABILITY IN MAGNETISM

G. Varvaro

CNR, Istituto di Struttura della Materia, nM^2-Lab, Monterotondo Scalo (Roma), 00015, Italy

nM2 Lab
Nanostructured
Magnetic
Materials

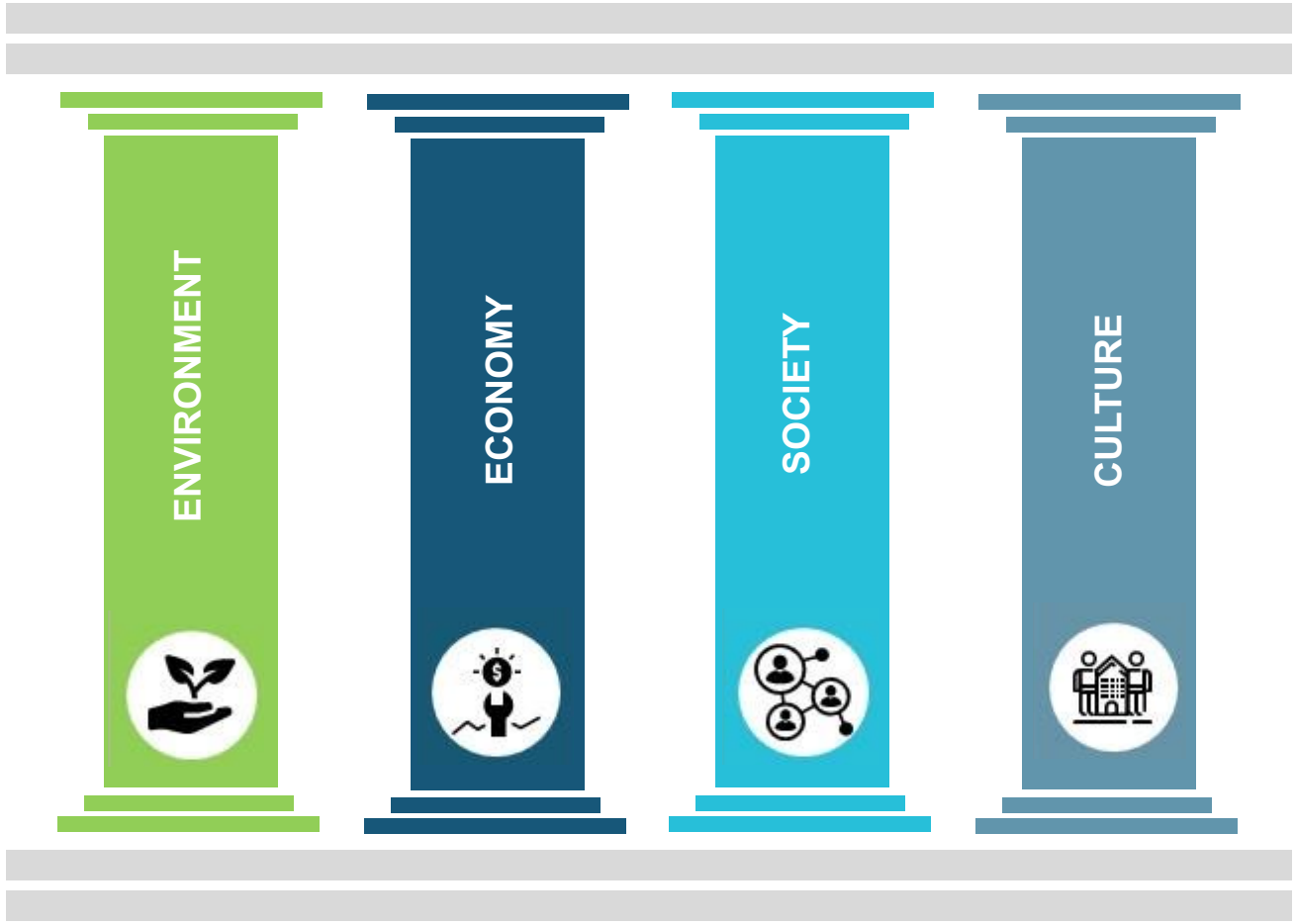
www.nm2lab.com

gaspare.varvaro@cnr.it

LECTURE OVERVIEW

- Introduction to Sustainability
  Four dimensions: ecological, social, economic, and cultural
- Sustainability in Materials Science
  Focus on Critical Raw Materials (CRMs); Challenges in high-performance magnetic materials
- Case Studies in Magnetism
  Permanent magnets, Spintronic devices
- Strategies to Reduce Impact
  Novel materials with reduced or zero CRMs; Recycling; Sustainable synthesis approaches (printing)
- Emerging Tools and Approaches
  Combinatorial materials science; Artificial intelligence
- Life Cycle Assessment
  Evaluating circularity and sustainability

WHAT IS SUSTAINABILITY?



“Meeting the needs of the present without compromising the ability of future generations to meet their own needs”

Ecological Sustainability
Protection of the natural environment

Social Sustainability
Promotion of well-being and social equity

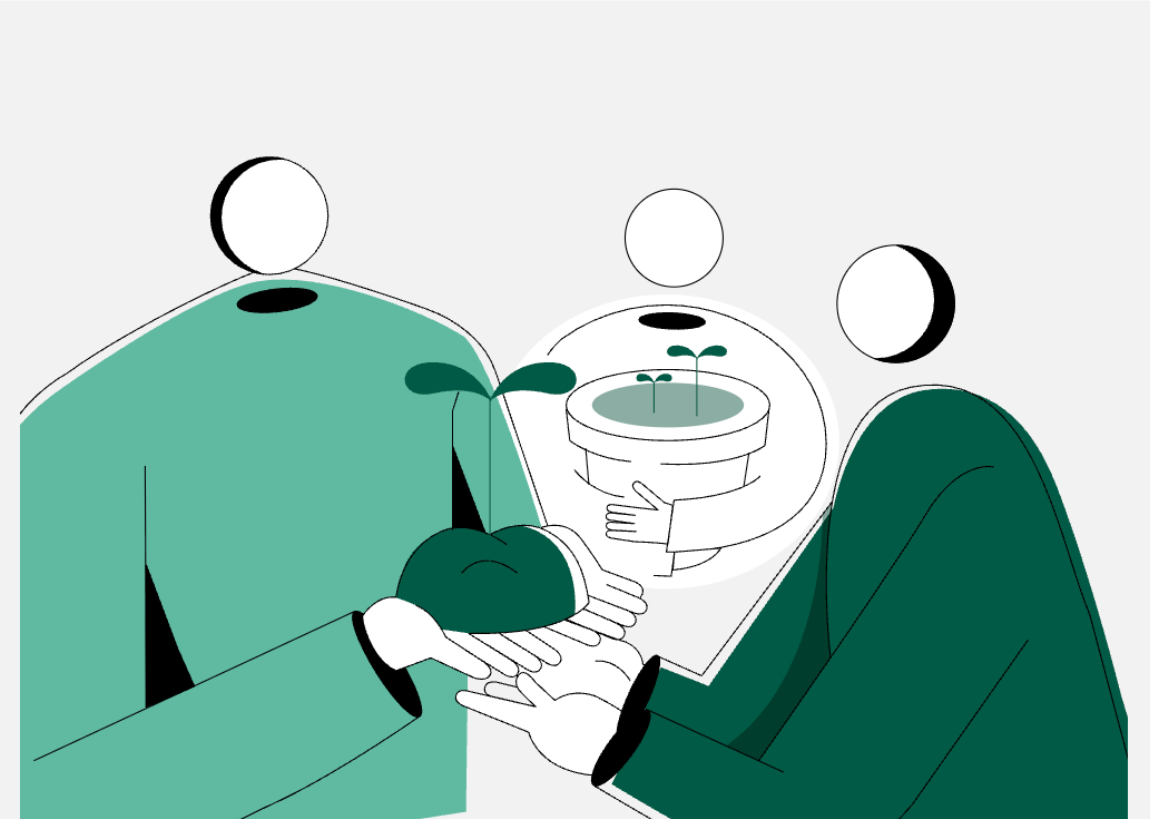
Economical Sustainability
Development of a prosperous and inclusive economy

Cultural Sustainability
Valuing cultural diversity and heritage.

LINK: https://courses.mooc.fi/org/uh-inar/courses/introduction-to-sustainability-2025

WHAT IS SUSTAINABILITY?

Ecological Dimension



To ensure a healthy environment for future generations

Climate change mitigation
Reducing greenhouse gas emissions

Biodiversity conservation
Protecting species and natural habitats

Sustainable resource management
Responsible use of water, energy, and soil

LINK: https://courses.mooc.fi/org/uh-inar/courses/introduction-to-sustainability-2025

WHAT IS SUSTAINABILITY?

Economic Dimension



To promote a stable and prosperous economy in harmony with the other dimensions.

Promote inclusive growth
Development that benefits all segments of society

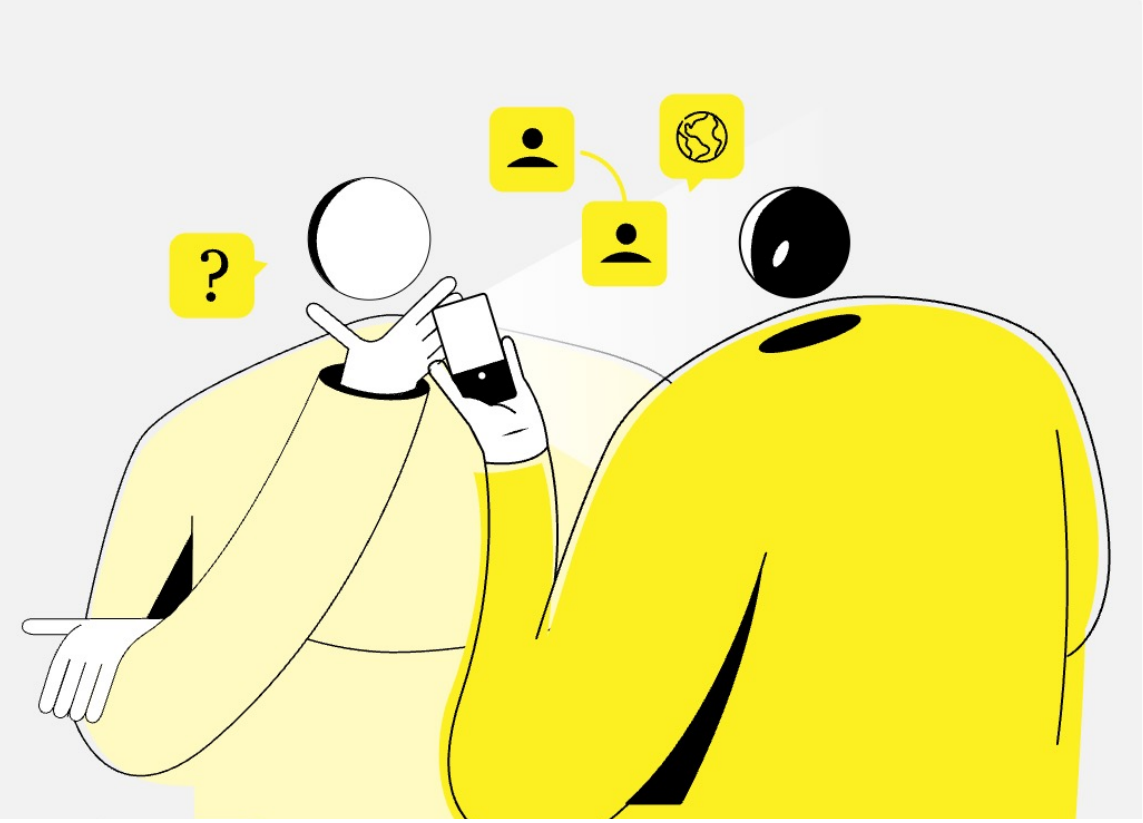
Encourage innovation
Adoption of sustainable technologies and practices

Manage risks
Addresses economic challenges in a resilient manner

LINK: https://courses.mooc.fi/org/uh-inar/courses/introduction-to-sustainability-2025

WHAT IS SUSTAINABILITY?

Social Dimension



To ensure human well-being, equity, and strong communities

Social justice
Equitable access to resources and opportunities

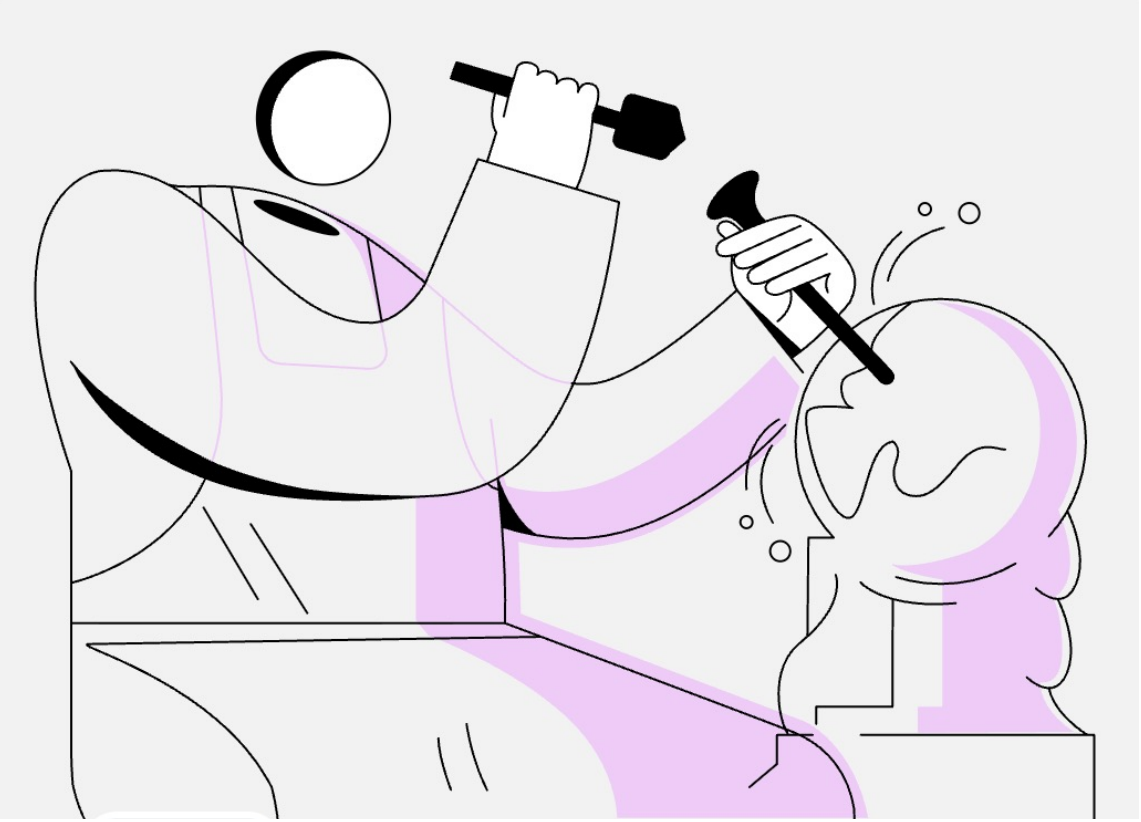
Health and well-being
Promoting physical and mental health

Community participation
Active involvement of citizens in decision-making

LINK: https://courses.mooc.fi/org/uh-inar/courses/introduction-to-sustainability-2025

WHAT IS SUSTAINABILITY?

Cultural Dimension



To preserve cultural heritage, traditions, and diversity

Values cultural diversity
Promotes respect and intercultural understanding

Preserves heritage
Protects traditions and cultural expressions

Fosters inclusion
Ensures that all cultures have a voice in decision-making

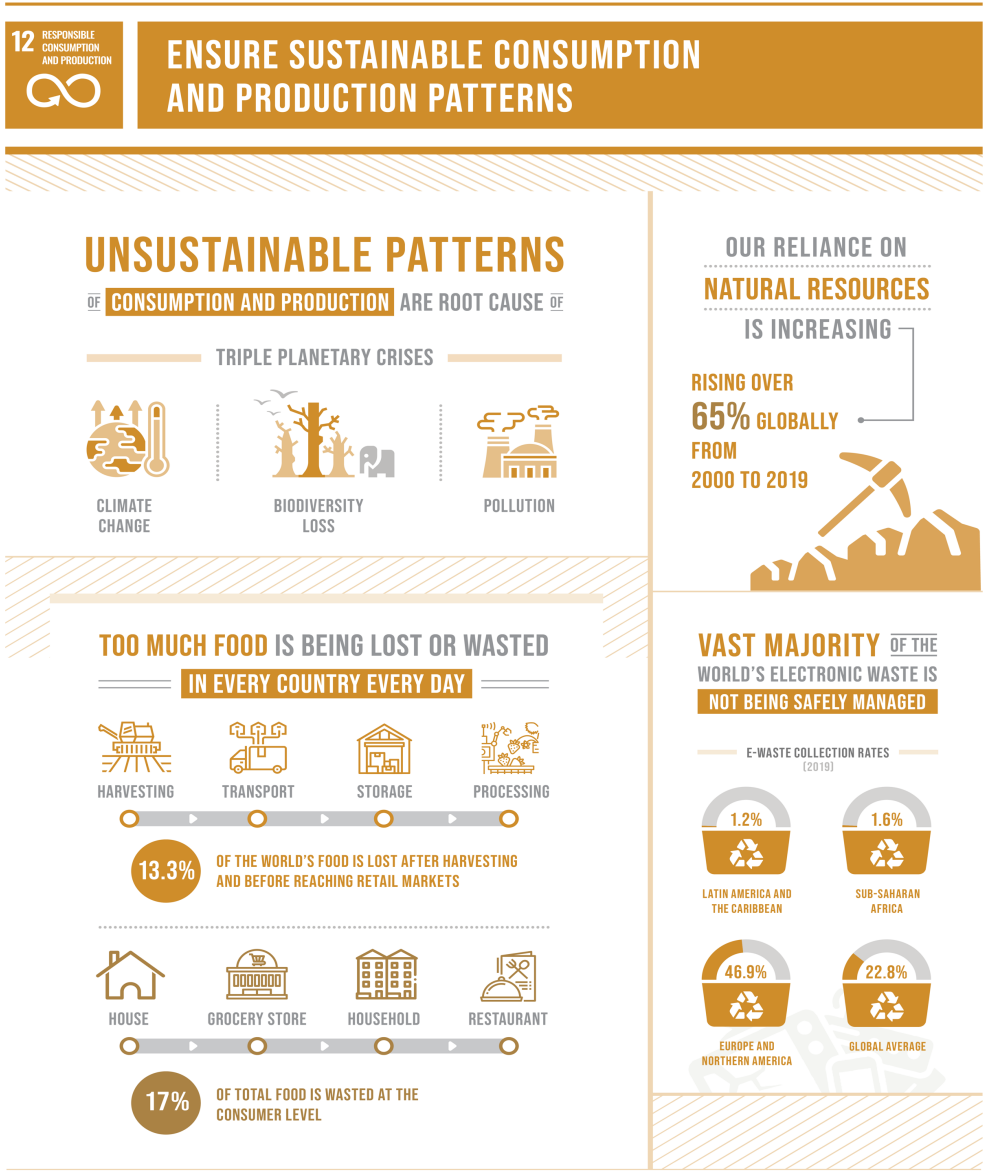
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SUSTAINABILITY

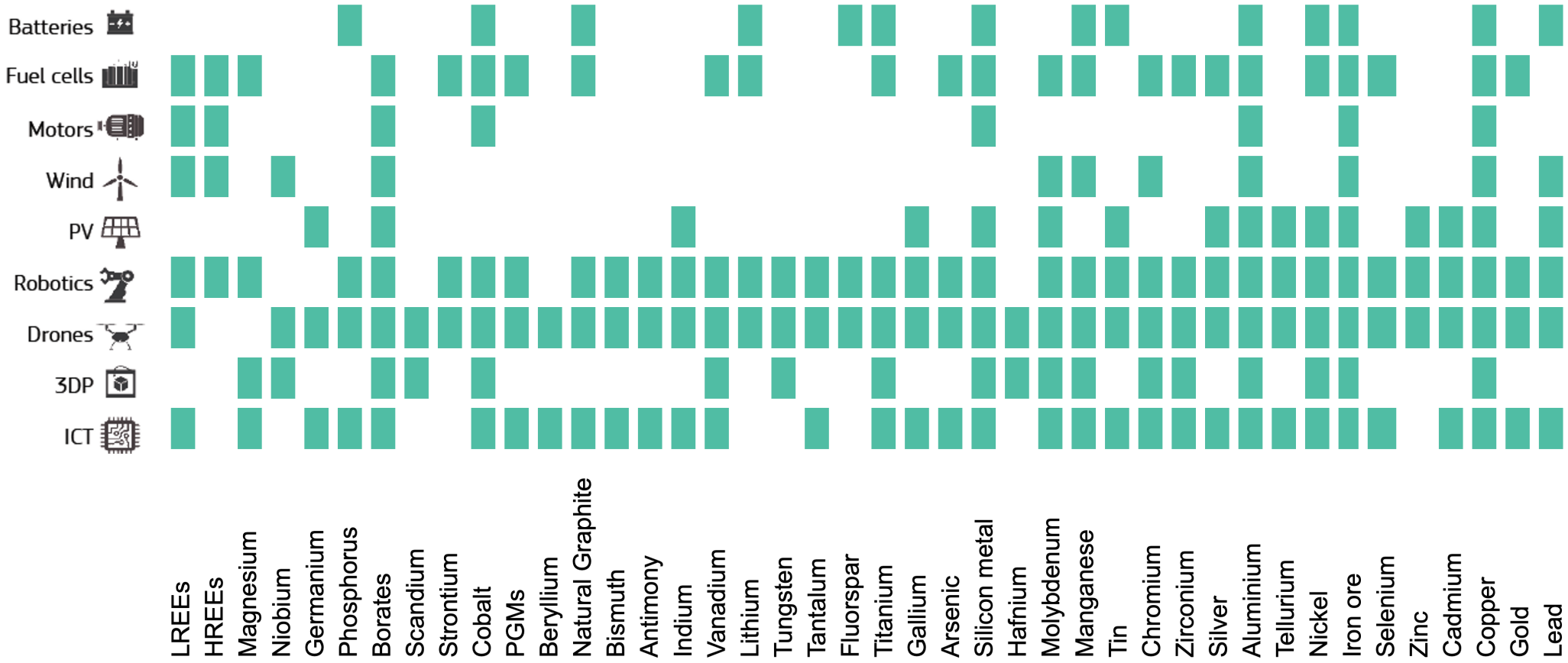


SUSTAINABILITY





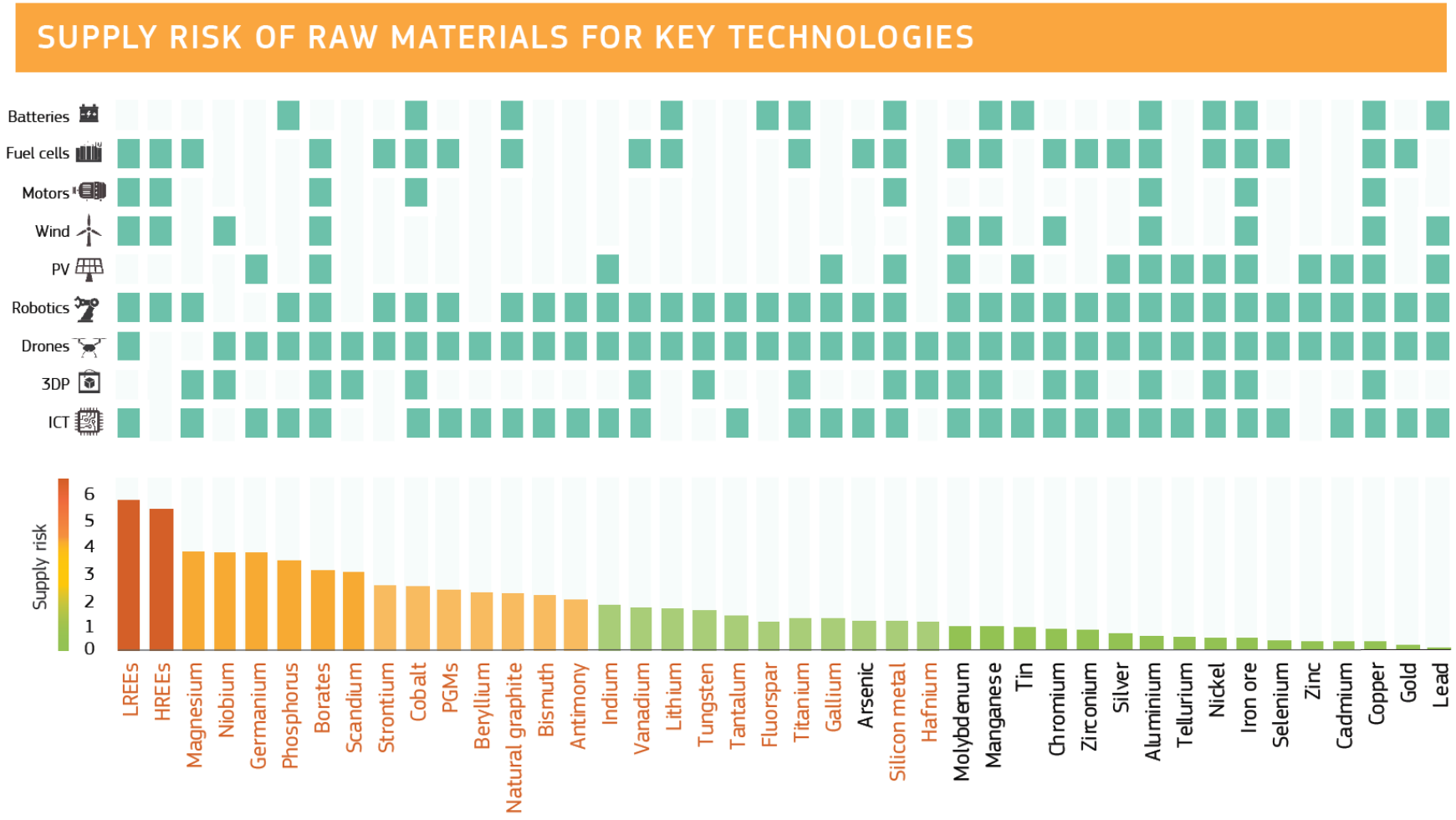
SUSTAINABILITY IN MATERIALS SCIENCE



Source: EU Commission - Critical Raw Materials for Strategic Technologies and Sectors in the EU A Foresight Study

SUSTAINABILITY IN MATERIALS SCIENCE

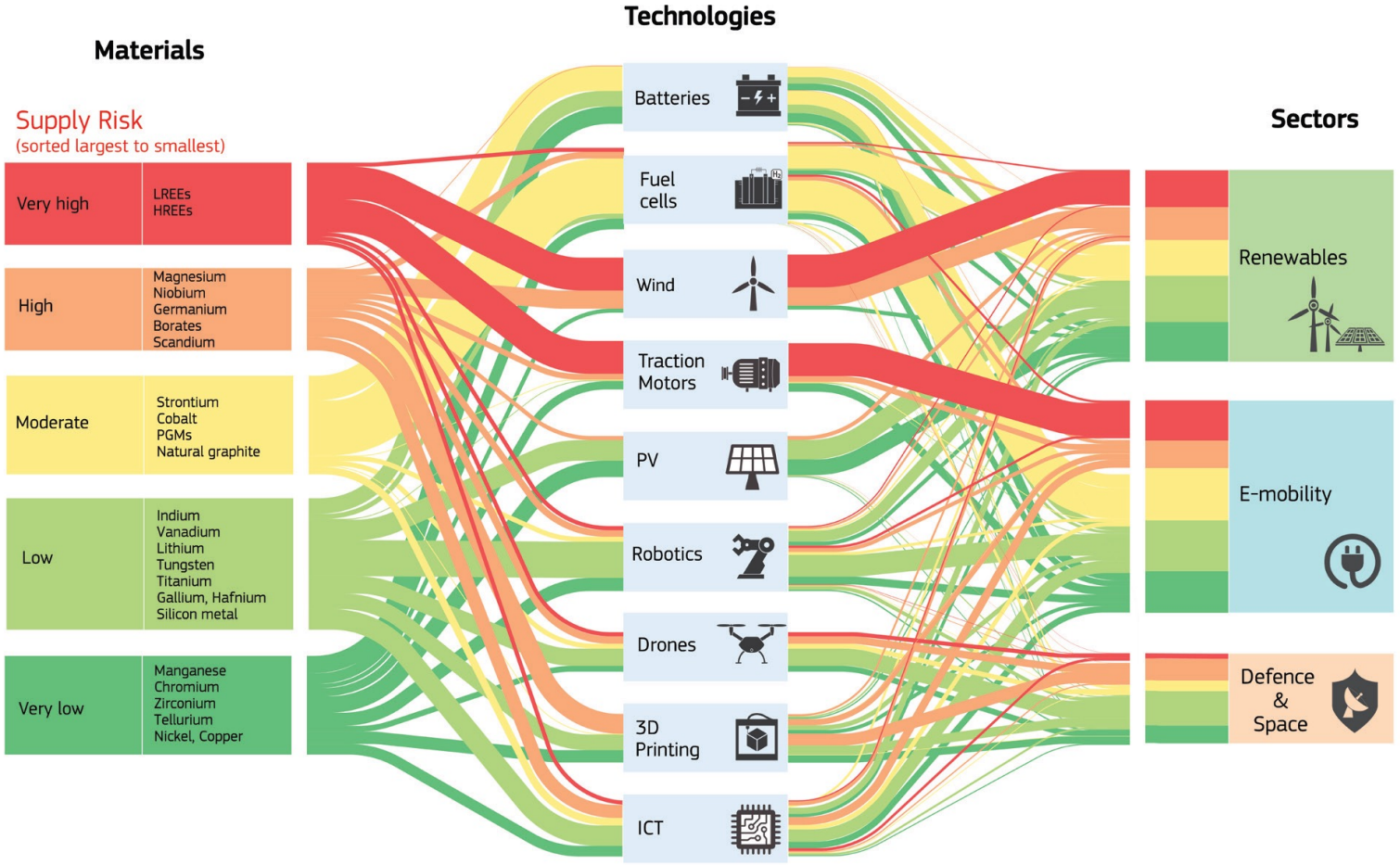
Critical Raw Materials (CRMs) | Economic & Geopolitical Challenges



Source: EU Commission - Critical Raw Materials for Strategic Technologies and Sectors in the EU A Foresight Study

SUSTAINABILITY IN MATERIALS SCIENCE

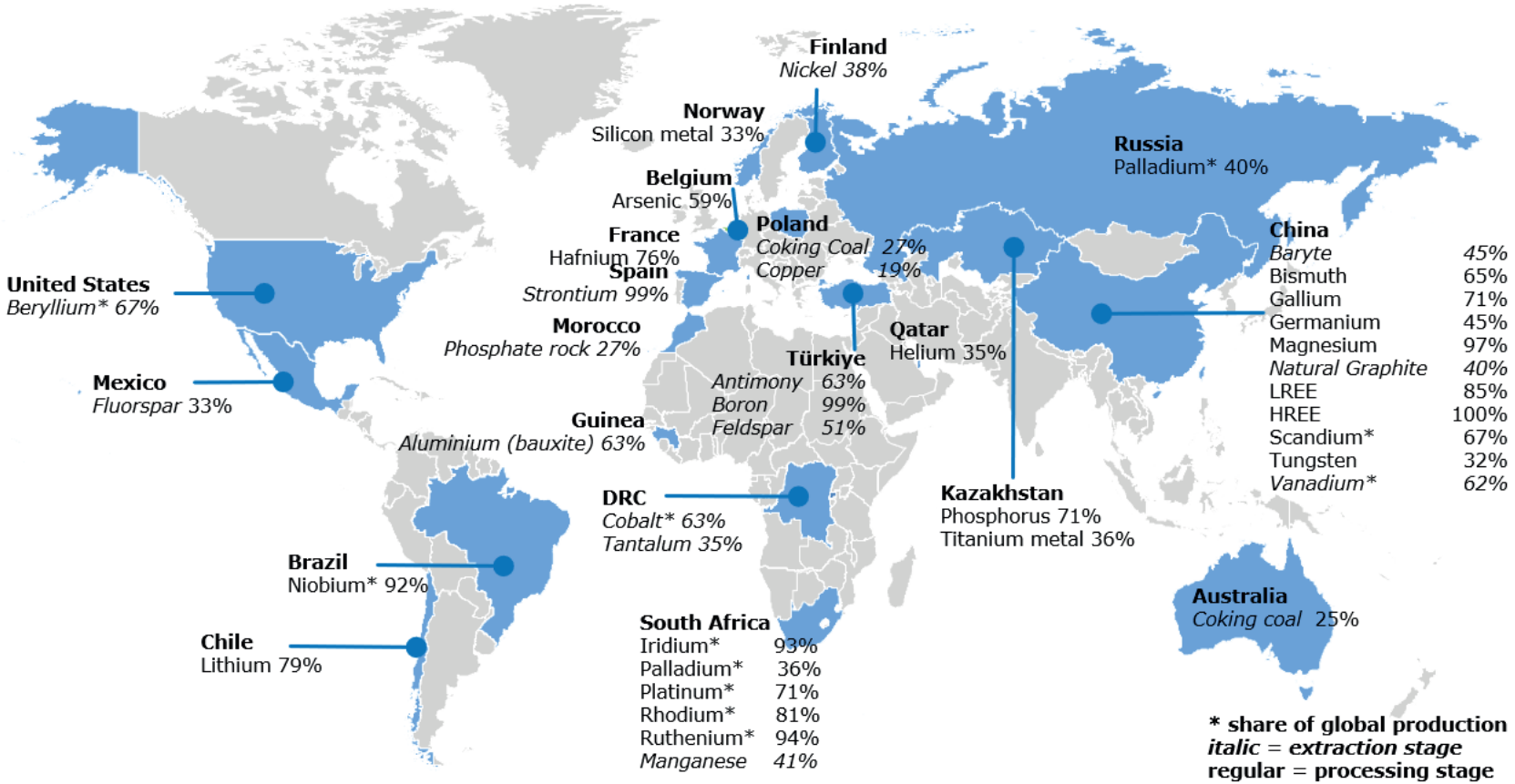
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Source: EU Commission - Critical Raw Materials for Strategic Technologies and Sectors in the EU A Foresight Study

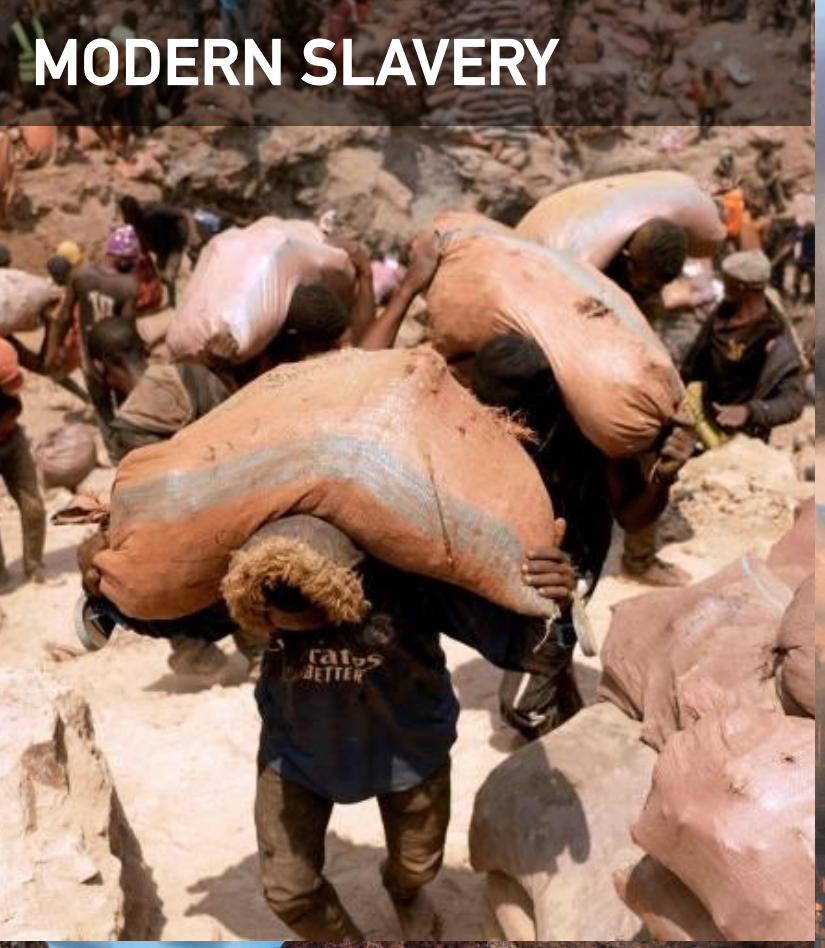
SUSTAINABILITY IN MATERIALS SCIENCE

Critical Raw Materials (CRMs) | Economic & Geopolitical Challenges



Source: "European Commission, Study on the Critical Raw Materials for the EU 2023– Final Report"

Extremely low number of extraction sites and the high geographical concentration outside Europe


MODERN SLAVERY




GHGs EMISSION


LAND MODIFICATION

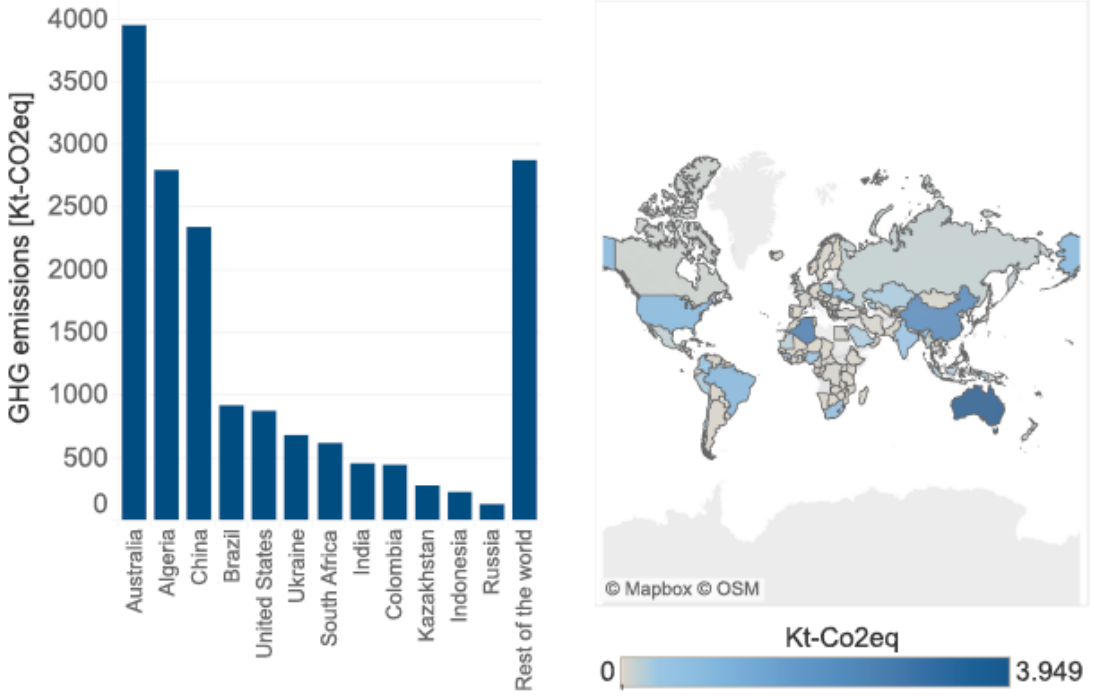

WATER POLLUTION


WATER CONSUMPTION

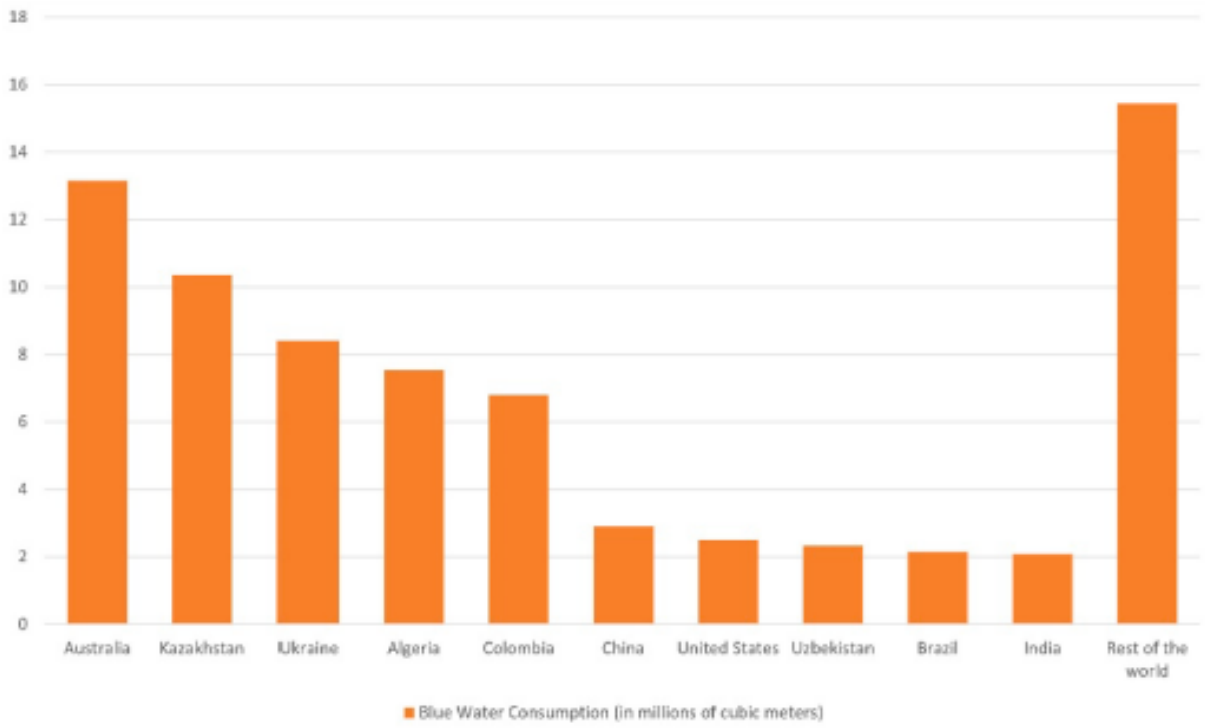
SUSTAINABILITY IN MATERIALS SCIENCE

Critical Raw Materials (CRMs) | Environmental & Social Challenges

Projections for 2040



Projections for 2040



2019 → 2040

2 kt-CO_2eq → **14** kt-CO_2eq

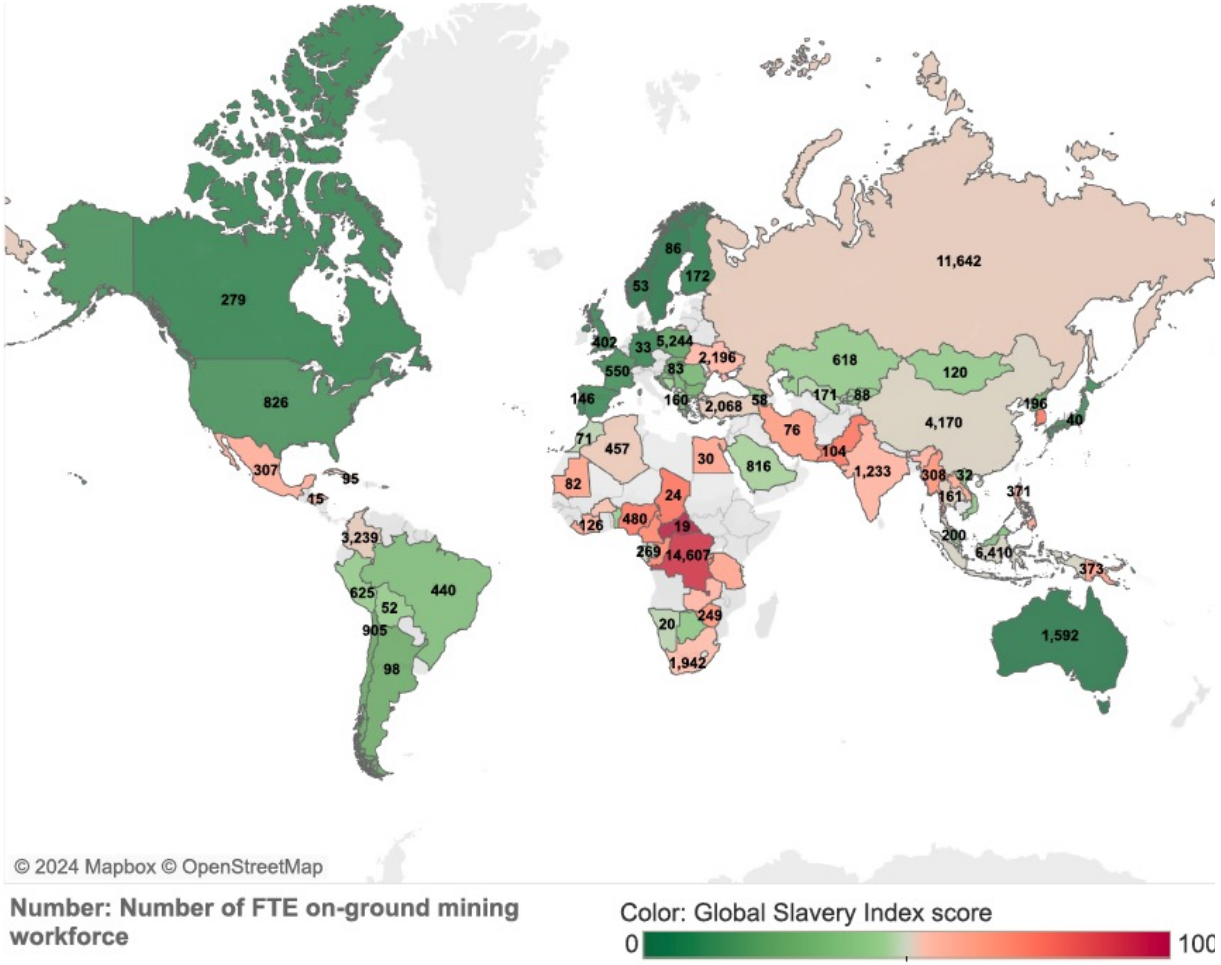
2019 → 2040

15 milions of m^3 → **70** milions of m^3

E. Berthet et al., Global Environmental Change 86 (2024) 102841

SUSTAINABILITY IN MATERIALS SCIENCE

Critical Raw Materials (CRMs) | Environmental & Social Challenges

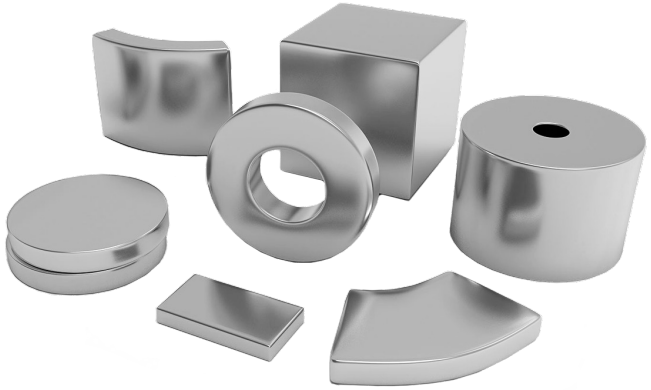


E. Berthet et al., Global Environmental Change 86 (2024) 102841

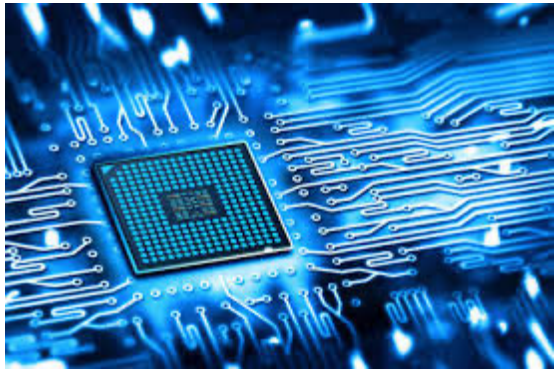
SUSTAINABILITY IN MATERIALS SCIENCE

CRMs in Magnetic Materials for Strategic (Green) Technologies

PERMANENT MAGNETS



MATERIALS for SPIN-BASED ELECTRONICS



RENEWABLE ENERGY (Wind Turbines)

MOTORS

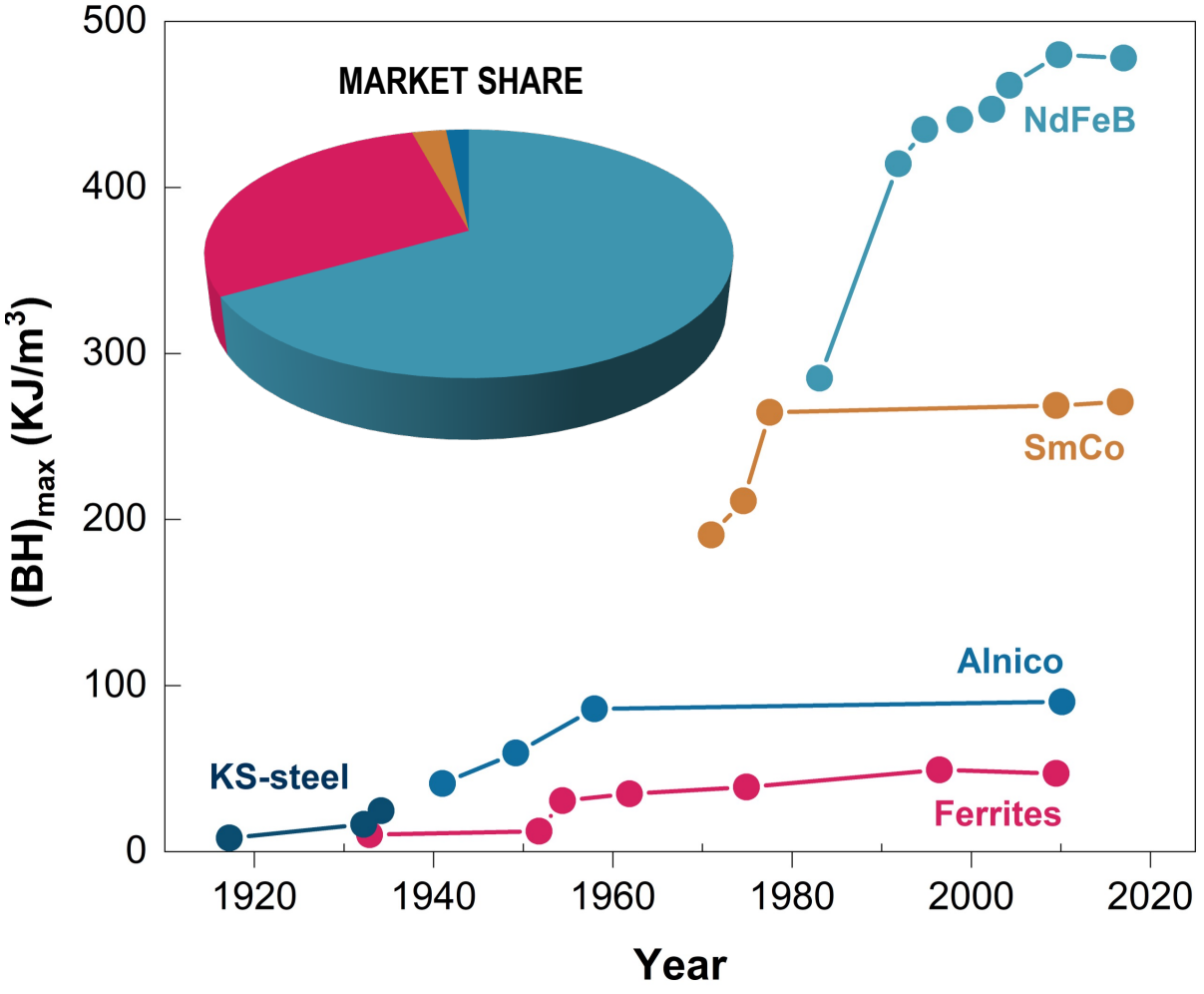
e-MOBILITY

ROBOTICS

DIGITAL TECHNOLOGIES

DEFENSE

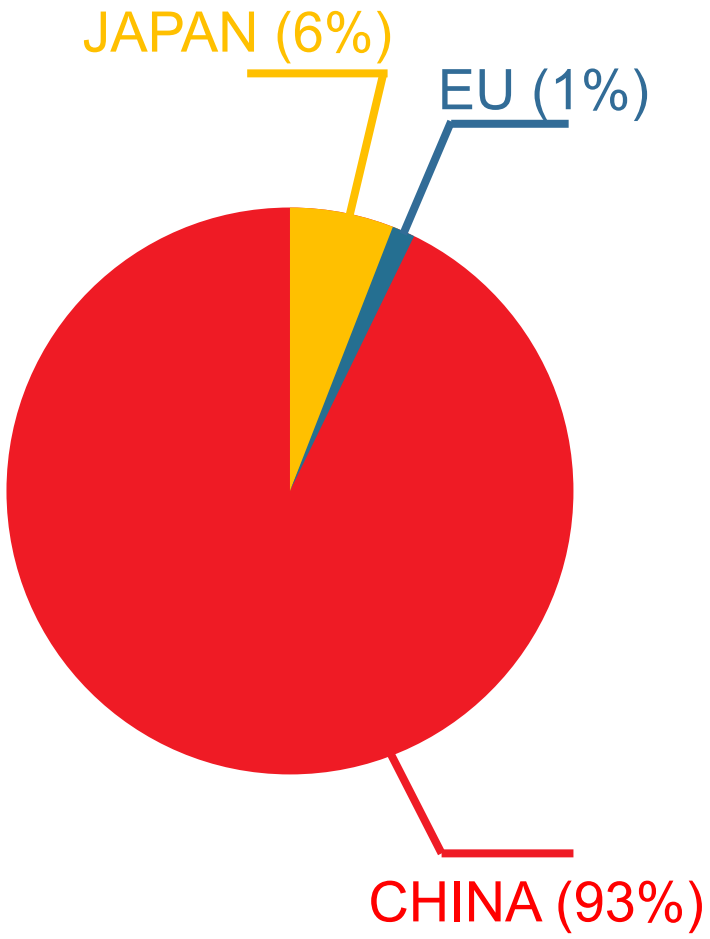
PERMANENT MAGNETS

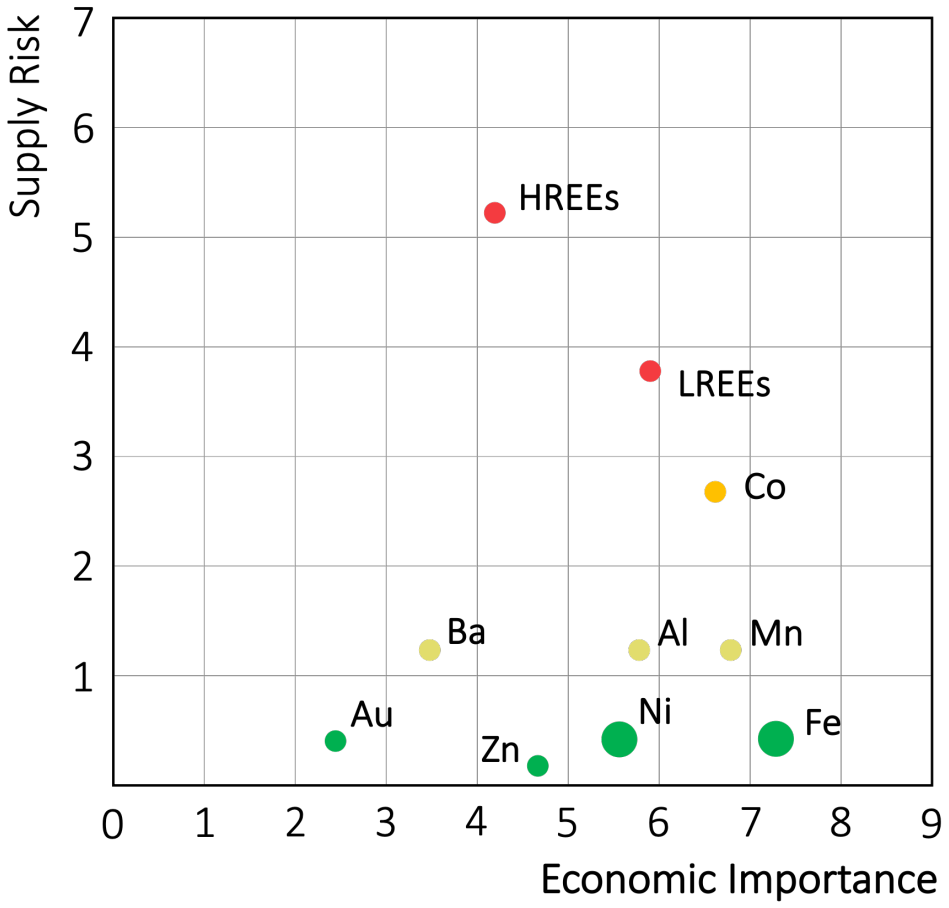


T. Hasegawa, Electron. Commun. Japan 104 (2021) 1–8
J. M. D. Coey, Engineering 6 (2020) 119

PERMANENT MAGNETS

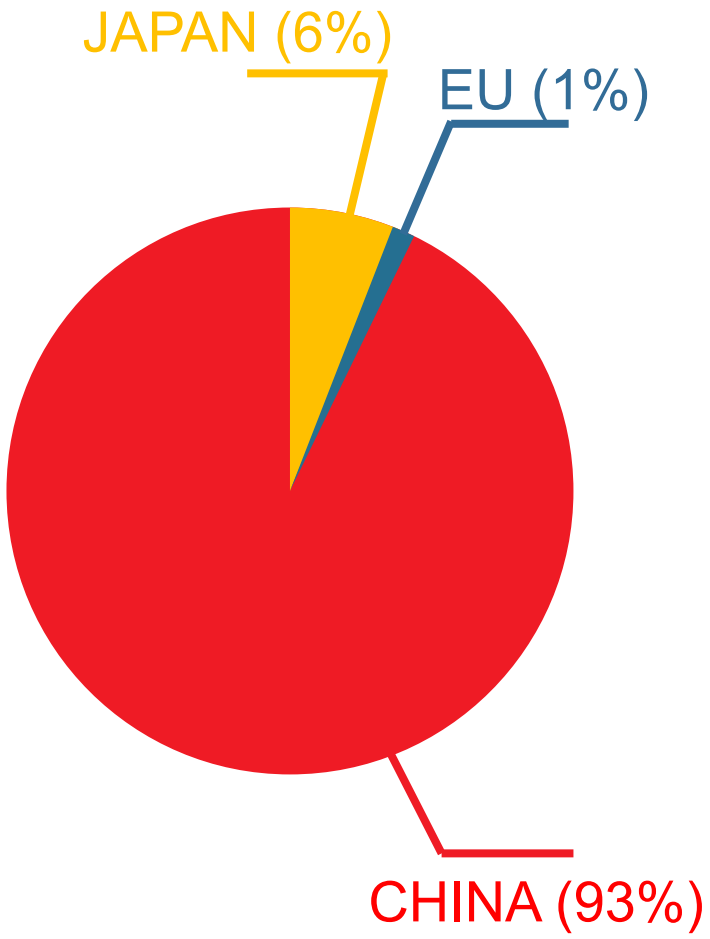
Economic & Geopolitical Challenges

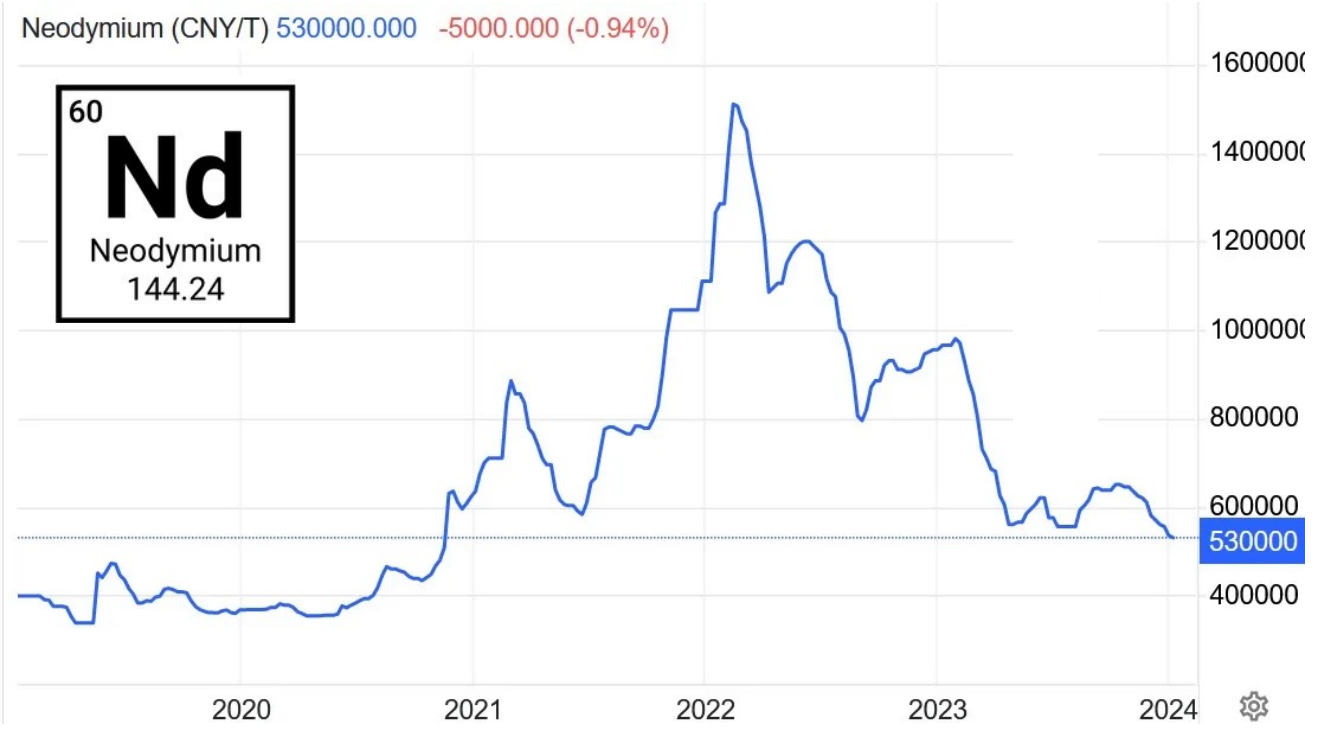




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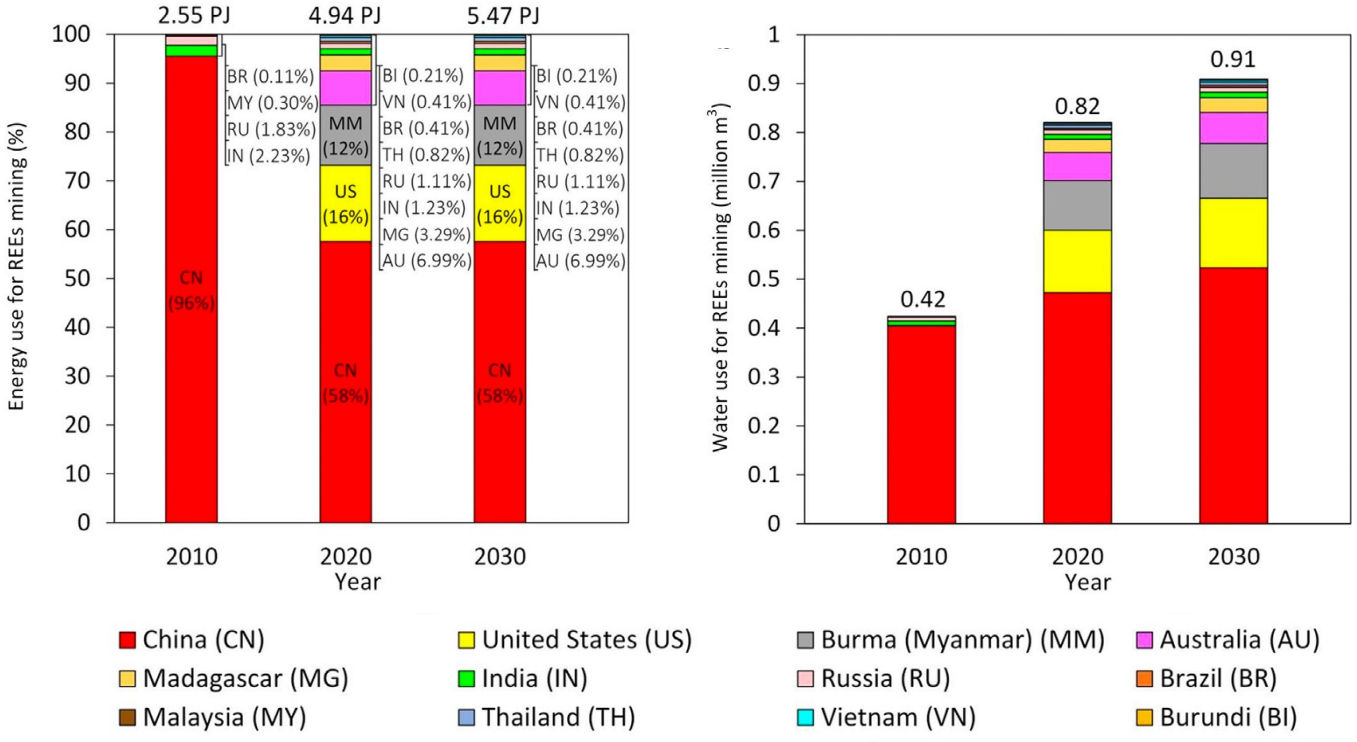
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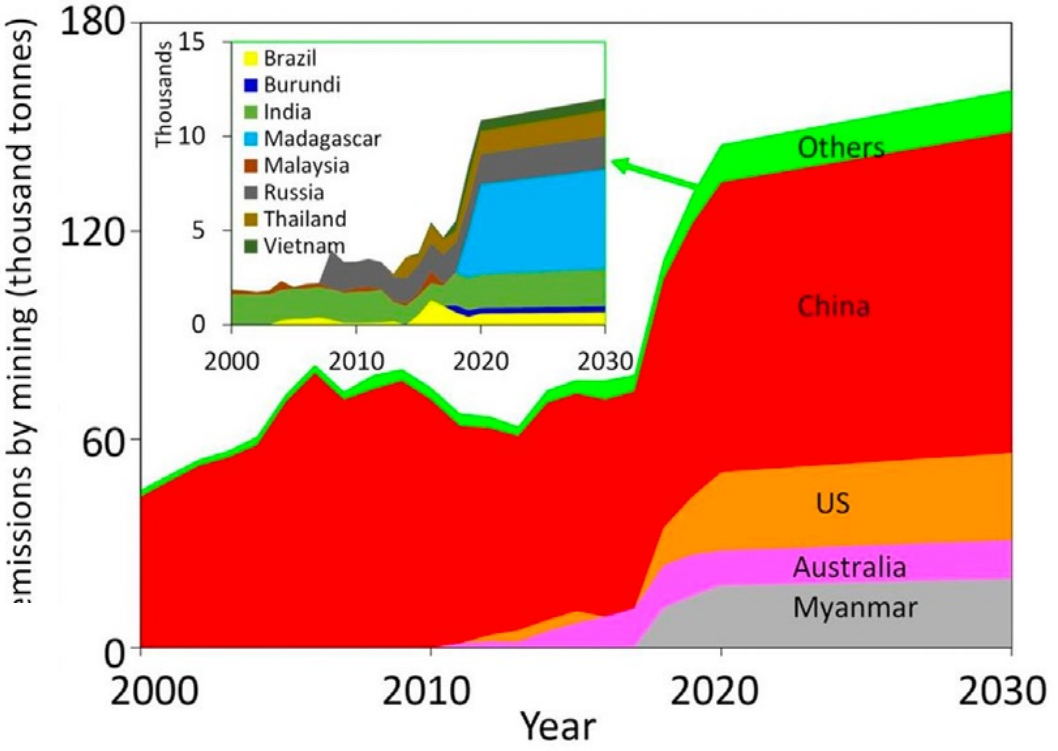




PERMANENT MAGNETS

Environmental & Social Challenges

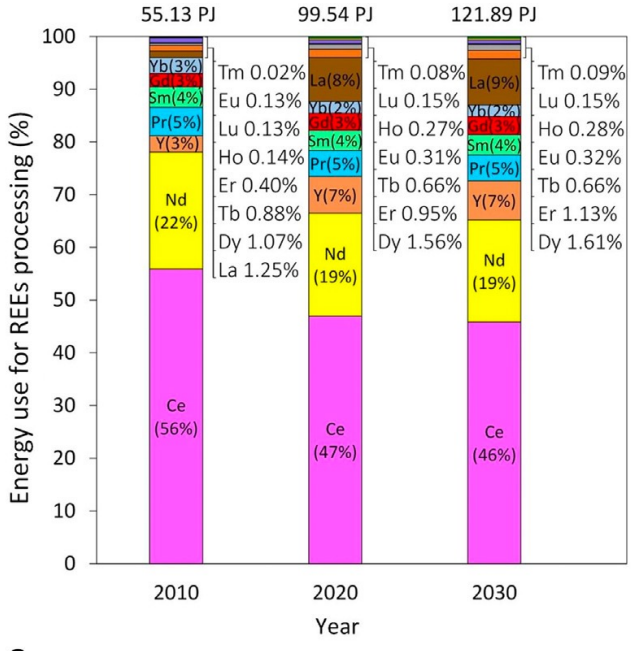


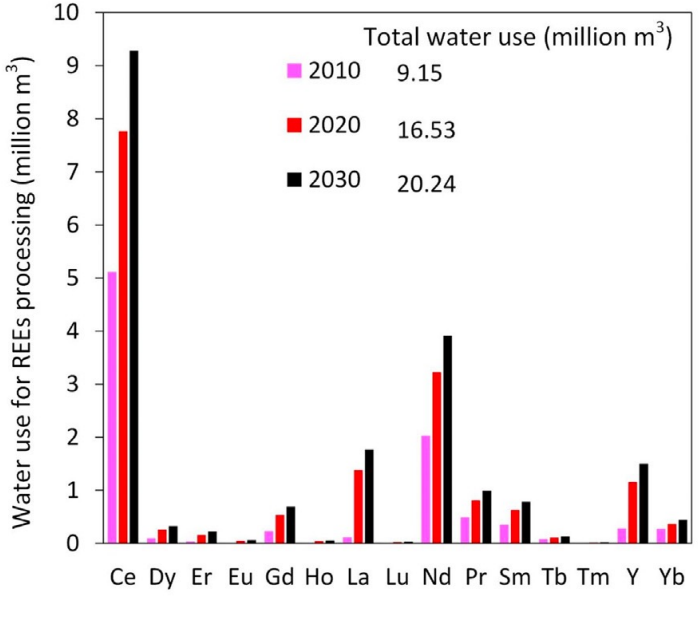


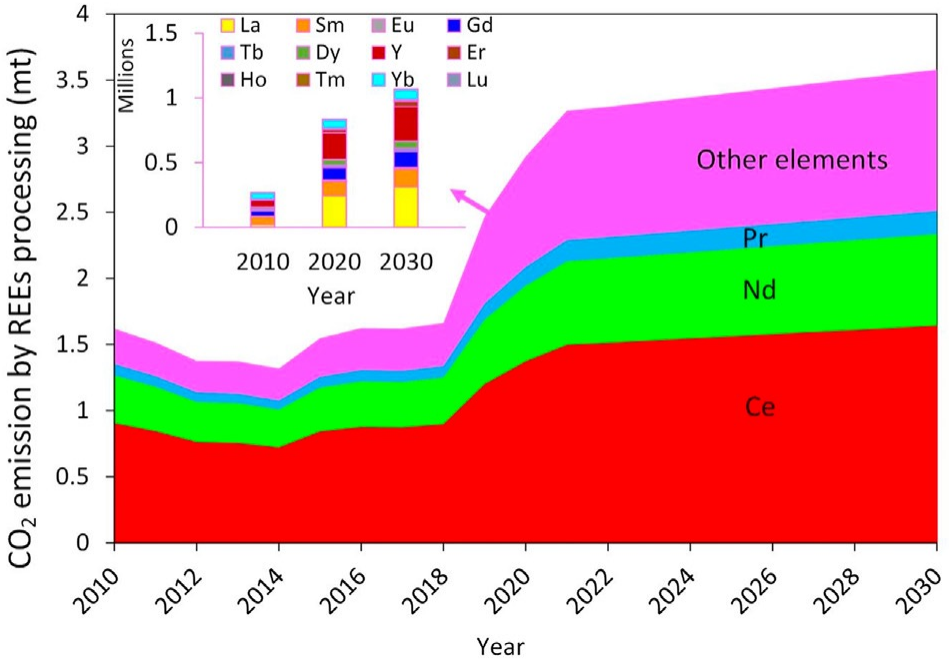
S.R. Golroudbary et al., Science of the Total Environment 832 (2022) 155022

PERMANENT MAGNETS

Environmental & Social Challenges







S.R. Golroudbary et al., Science of the Total Environment 832 (2022) 155022

PERMANENT MAGNETS



THE **ECOLOGICAL TRANSITION** AND THE GLOBAL INCREASE IN **LIVING STANDARDS** WILL CONTRIBUTE TO THE **INCREASE IN DEMAND** FOR PERMANENT MAGNETS AND RARE EARTH ELEMENTS.

PERMANENT MAGNETS

Mitigation Actions

OPTIMIZATION OF EXISTING MATERIALS

J.M.D. Coey, Engineering. 6 (2020) 119
C. De Julián Fernández et al., J. Phys. D. Appl. Phys. 54 (2021) 153001
A. Kovacs et al,, Engineering. 6 (2020) 148
P. Maltoni et al. J. Phys. D. Appl. Phys. 54 (2021) 124004 (1–10).
J.M.D. Coey,, Scr. Mater. 67 (2012) 524–529.
H. Tahanian et al., IEEE Trans. Magn. 56 (2020) 900120

RECYCLING/REUSE OF END-OF-LIFE MAGNETS

Z. Li et al., EPJ Appl. Phys. 86 (2019) 20901
A. Lixandru, et al., Waste Manag. 68 (2017) 482
J.R. Peeters et al. J. Clean. Prod. 175 (2018) 96
U. Rösel and D. Drummer, Magnetism 2 (2022) 251

DEVELOPMENT OF NEW HARD MAGNETIC PHASES FREE OF REEs

J. Cui et al., Acta Mater. 158 (2018) 118
D. Goll et al., J. Phys. Condens. Matter. 26 (2014) 064208

PERMANENT MAGNETS

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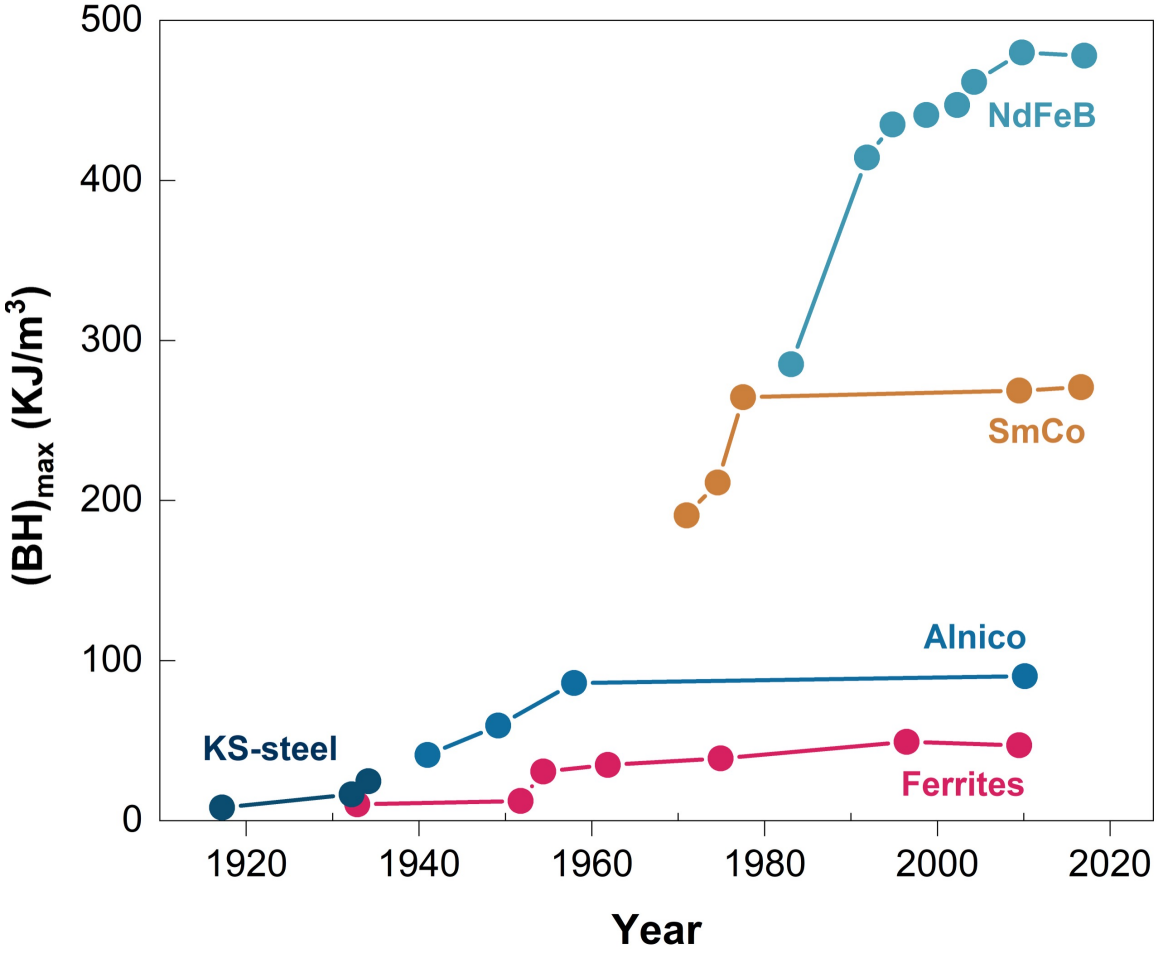
Z. Li et al., EPJ Appl. Phys. 86 (2019) 20901
A. Lixandru, et al., Waste Manag. 68 (2017) 482
J.R. Peeters et al. J. Clean. Prod. 175 (2018) 96
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PERMANENT MAGNETS

Mitigation Actions | **Optimization of Existing Materials**



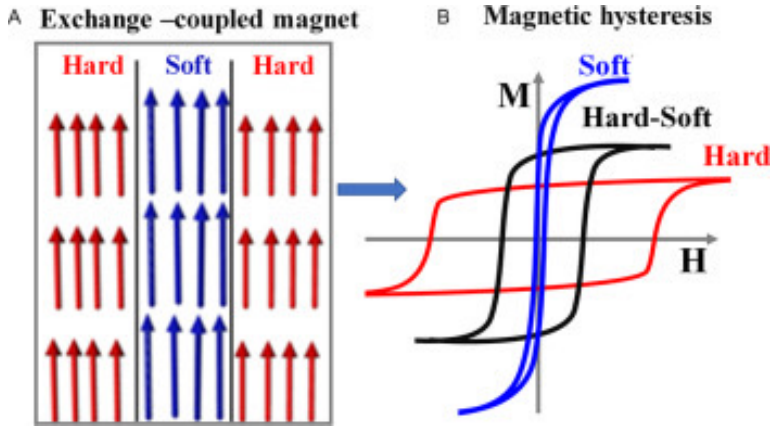
REDUCING RE CONTENT IN Nd–Fe–B MAGNETS WITHOUT AFFECTING PERFORMANCE

A. Microstructure Engineering

- Grain-Boundary Engineering
- Grain-Size Refinement and Texture Control

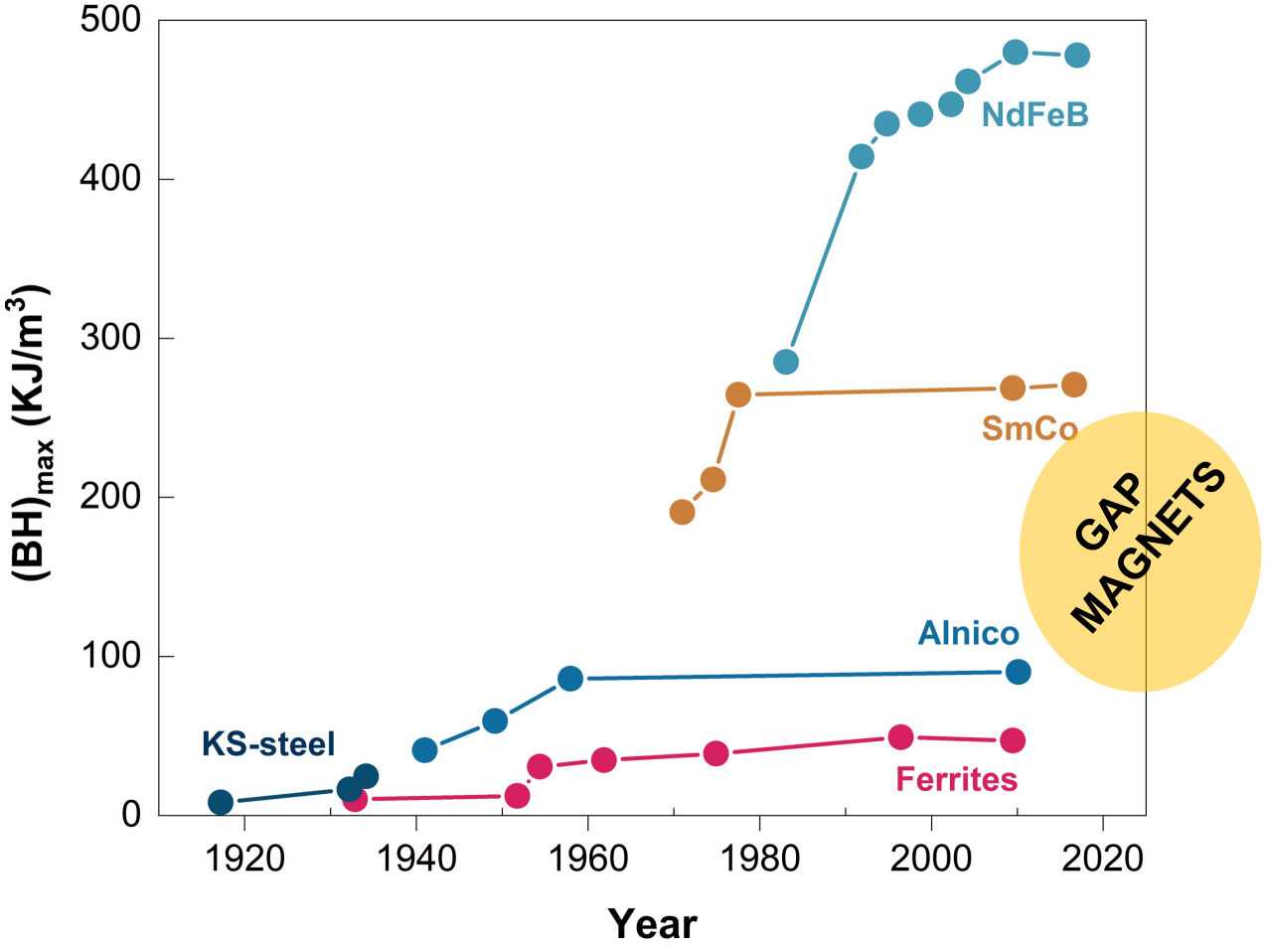
B. Exchange-Spring / Hard–Soft Nanocomposites

Combine a high-coercivity hard Nd-Fe_1-B magnetic phase with a high-saturation soft magnetic phase (e.g., Fe, FeCo)



PERMANENT MAGNETS

Mitigation Actions | **Optimization of Existing Materials**



IMPROVING THE PERFORMANCE OF LOW-COST FERRITES ("GAP MAGNETS")

A. Reducing Particle Size to the Nanoscale

B. Controlled Doping

C. Hard/Soft Composites

P. Maltoni, GV et al., Acta Materialia 282 (2025) 120491
P. Maltoni, GV et al., Small 20 (2024) 2304152
C. de Julián Fernández et al. J. Phys. D: Appl. Phys. 54 (2021) 153001

PERMANENT MAGNETS

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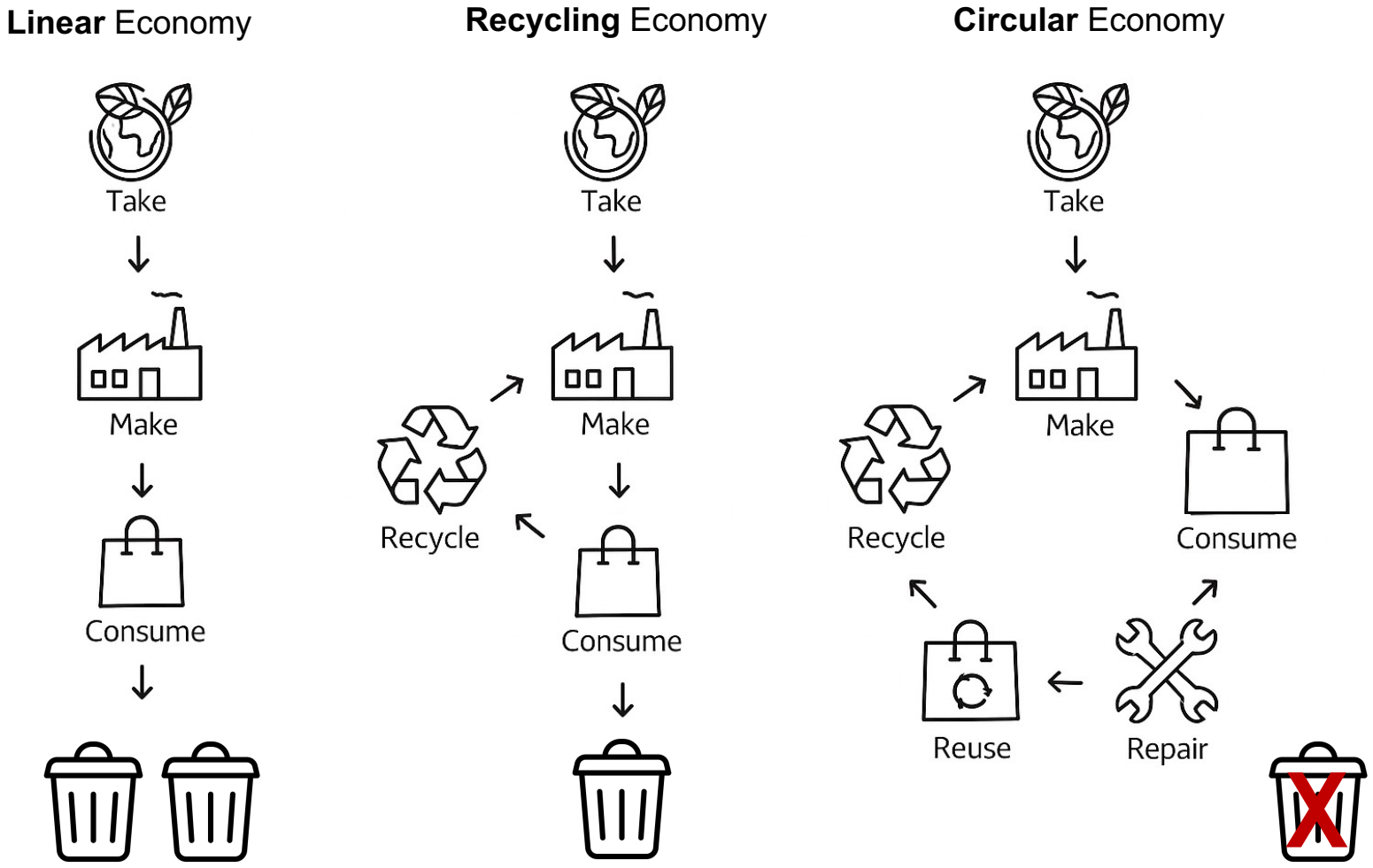
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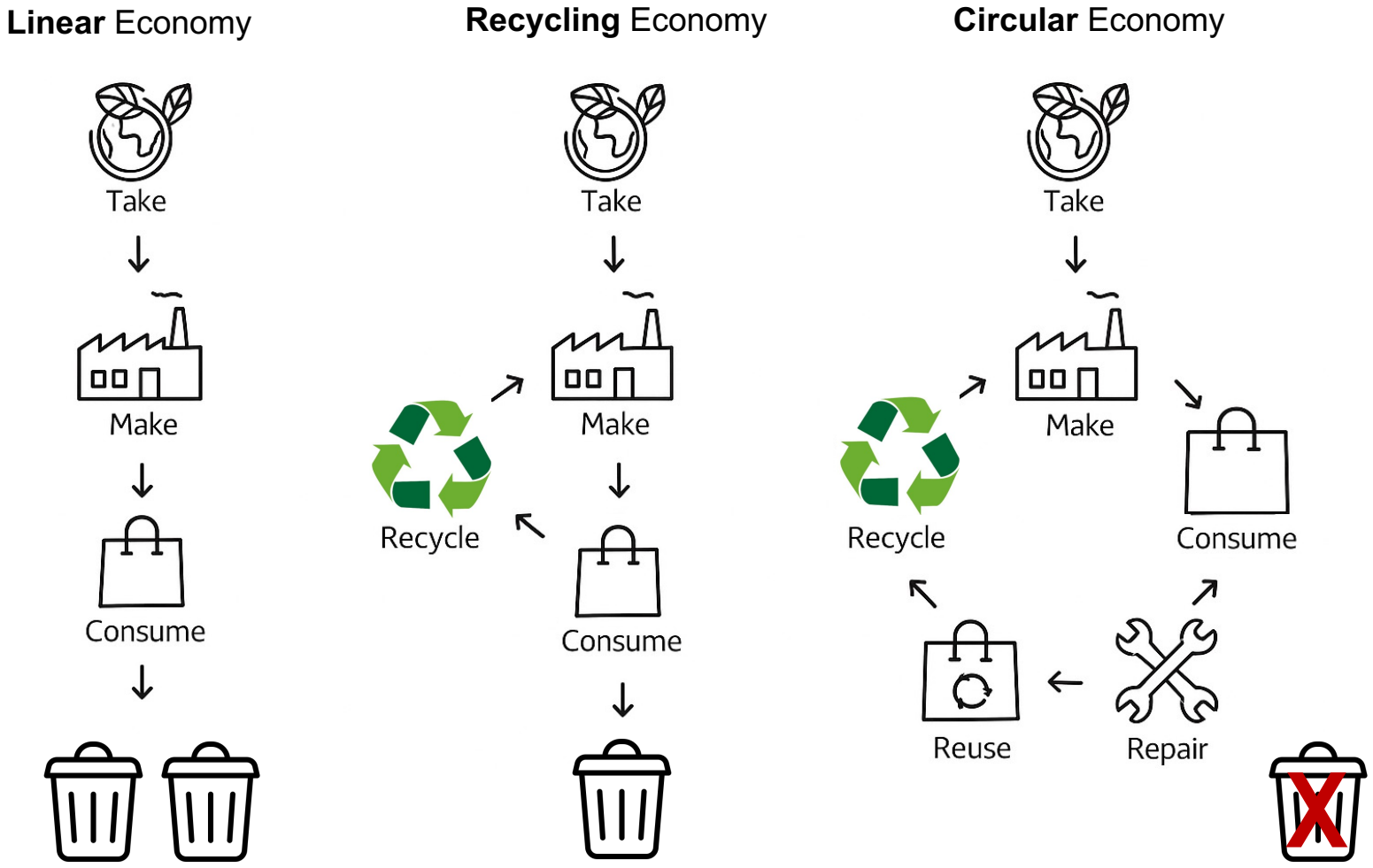
PERMANENT MAGNETS

Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**



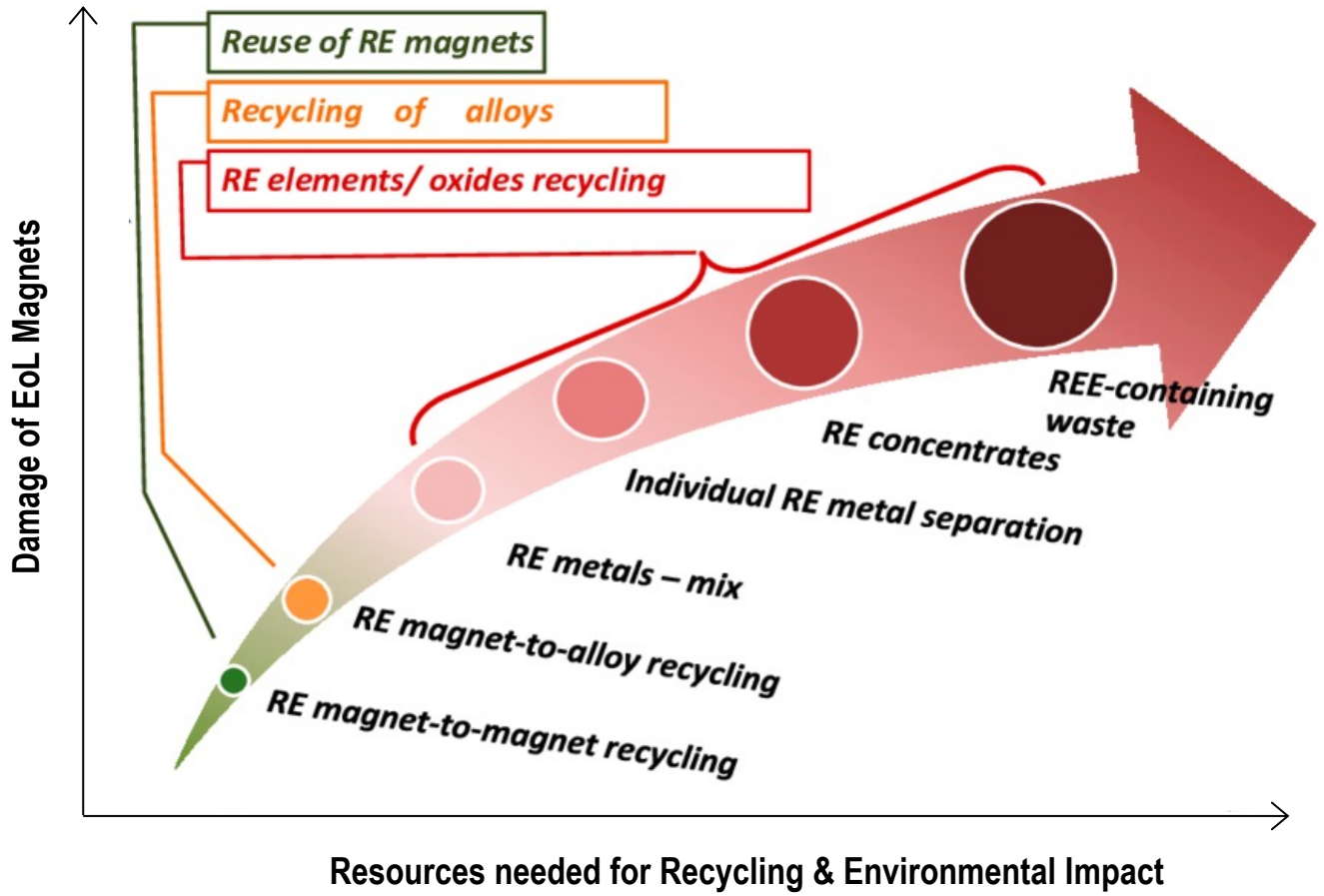
PERMANENT MAGNETS

Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**



PERMANENT MAGNETS

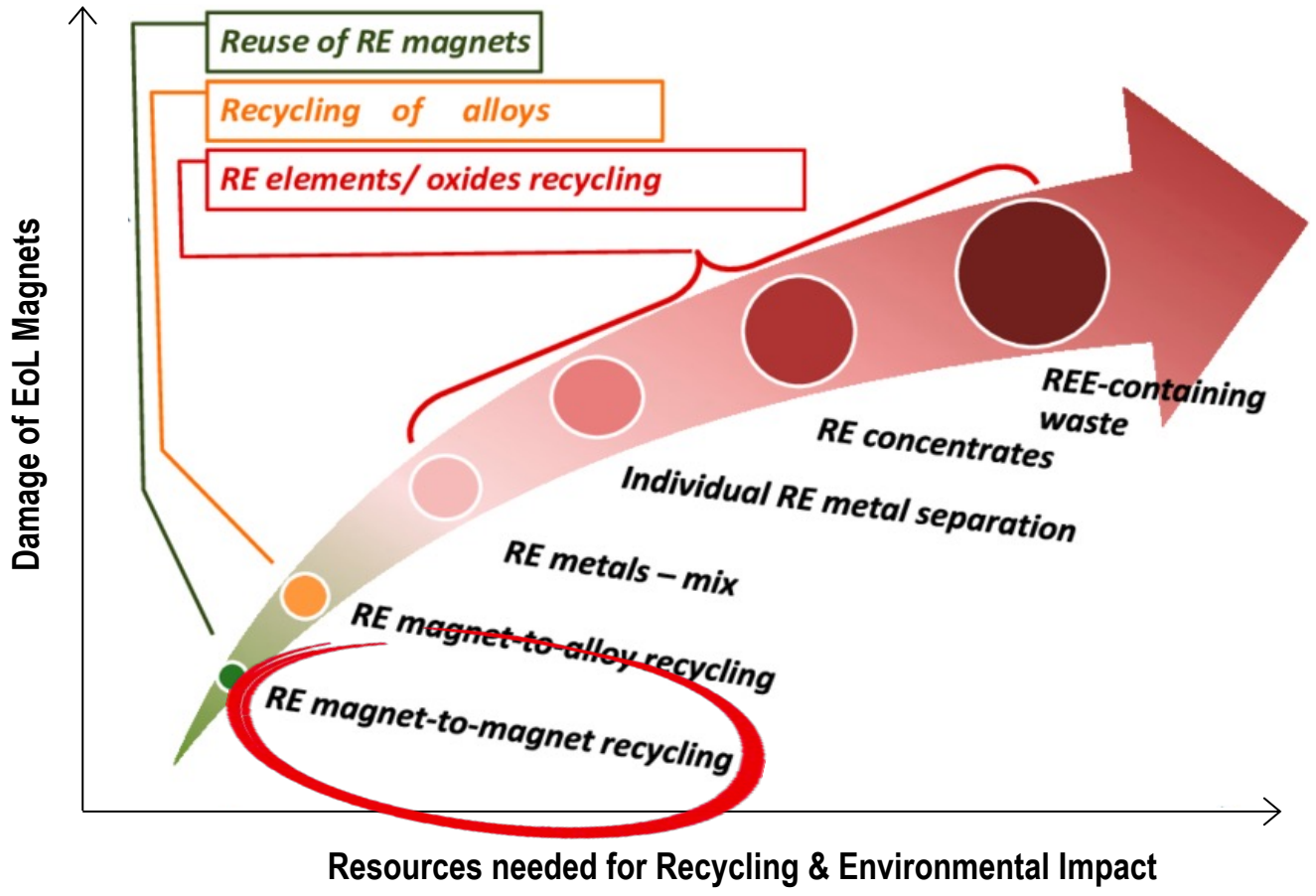
Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**



Z. Cherkezova-Zheleva et al., Metals 14 (2024) 658

PERMANENT MAGNETS

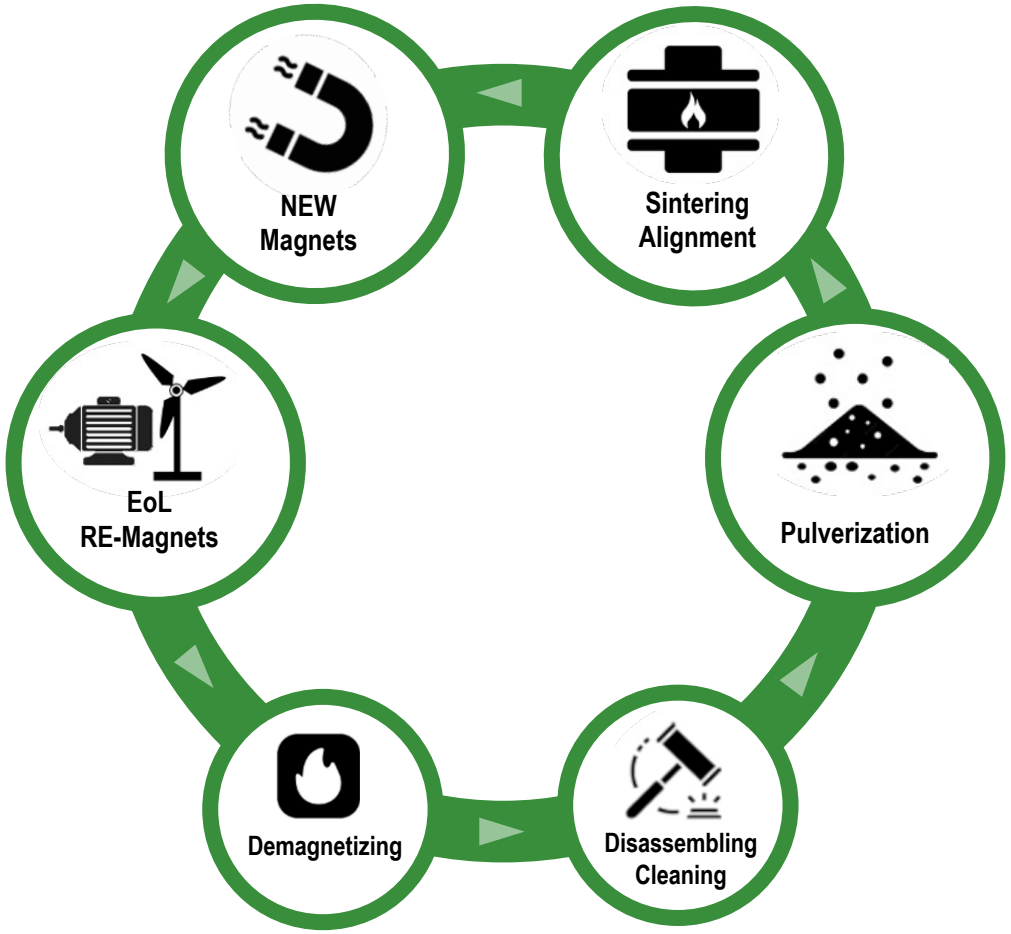
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Z. Cherkezova-Zheleva et al., Metals 14 (2024) 658

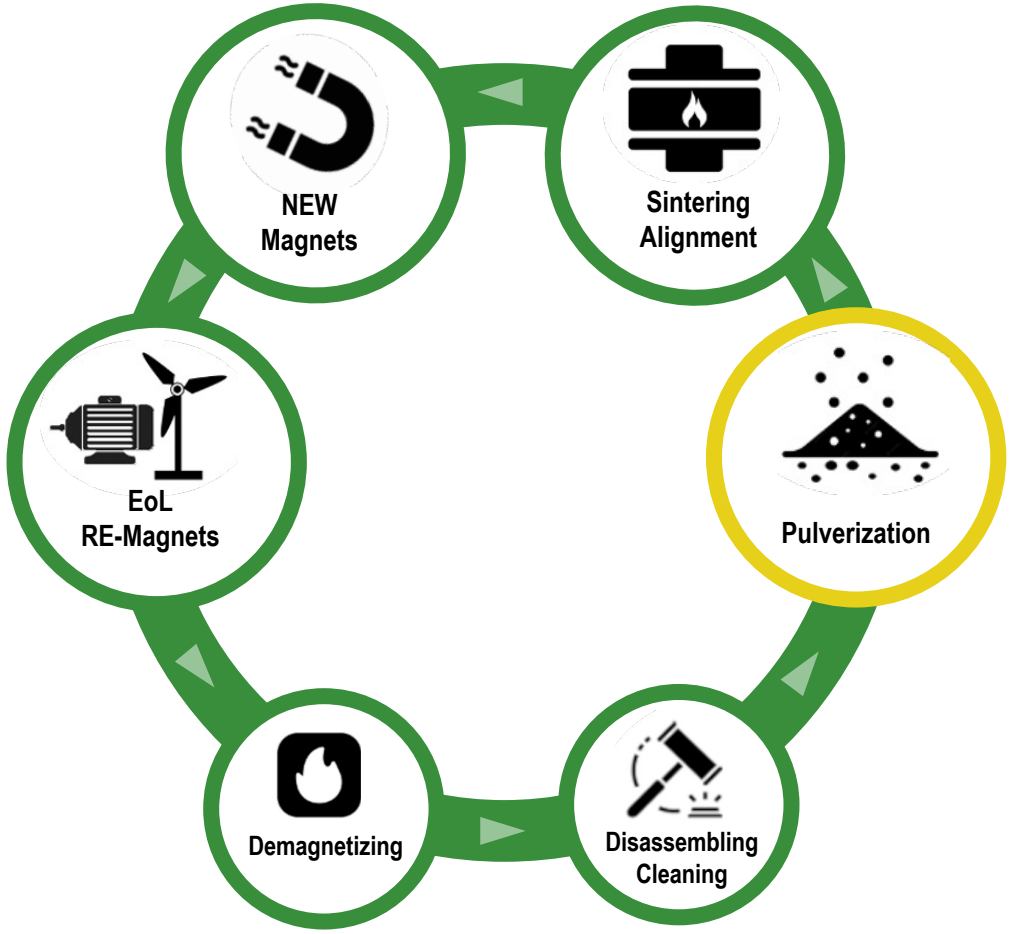
PERMANENT MAGNETS

Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**



PERMANENT MAGNETS

Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**



- **Hydrogen Decrepitation (HD)**

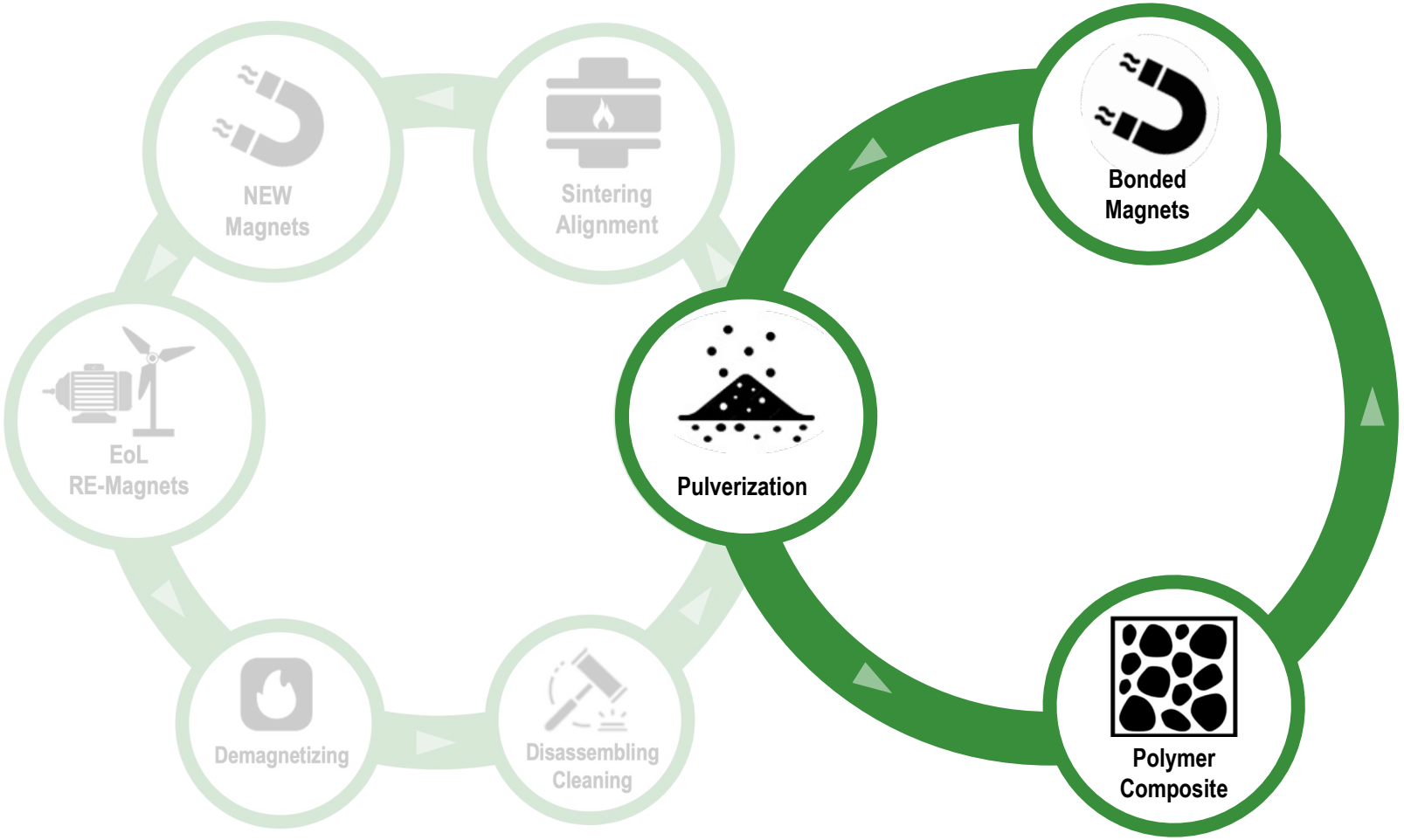
  Hydrogen Disproportionation–Desorption–Recombination (HDDR)



- **Milling (Ball Milling o Jet Milling)**

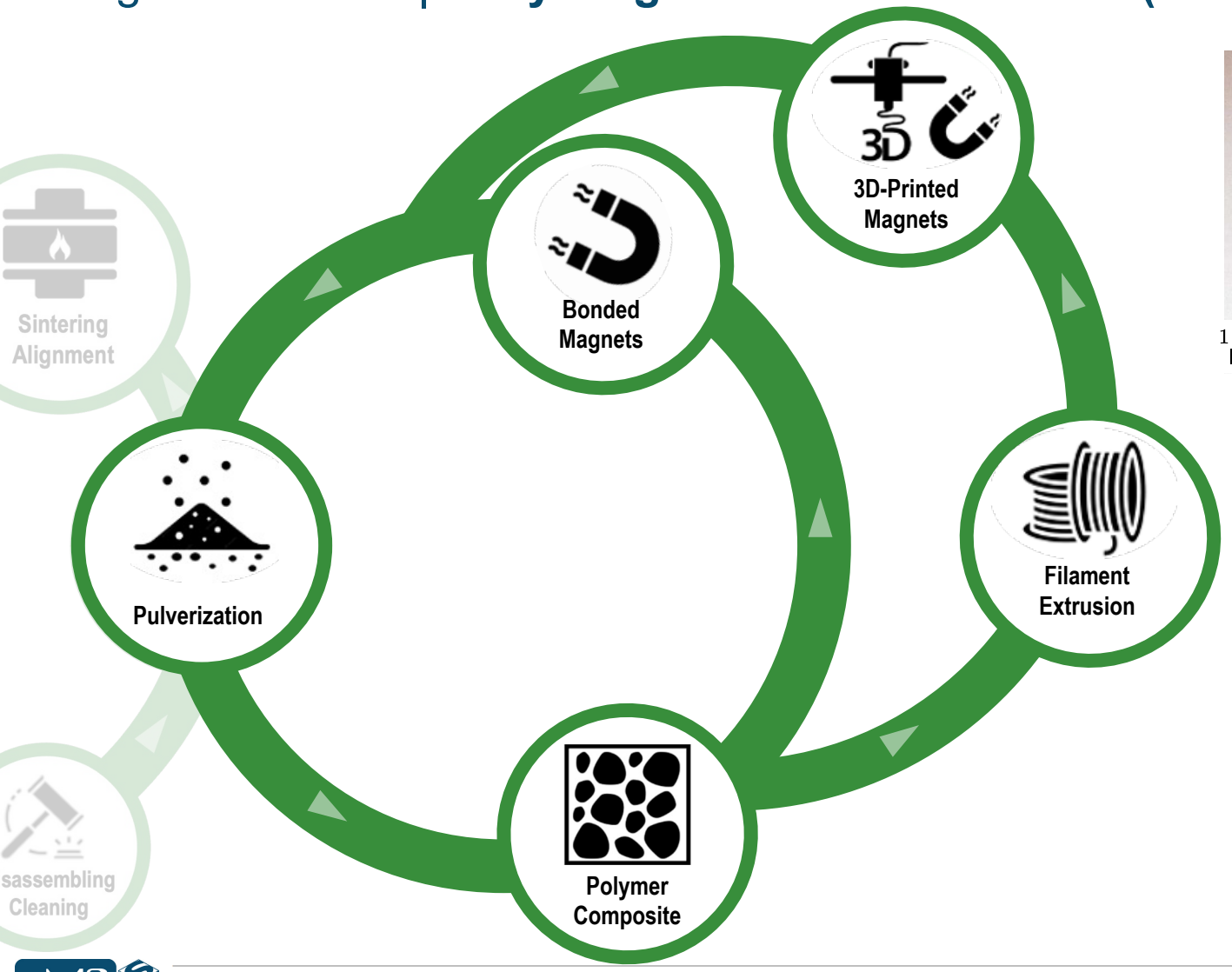
PERMANENT MAGNETS

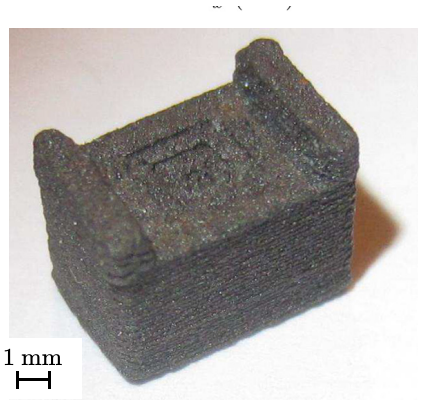
Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**

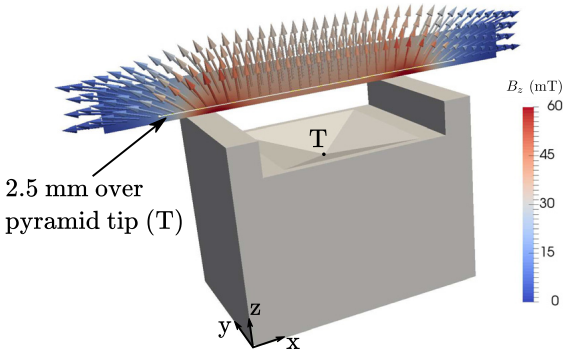


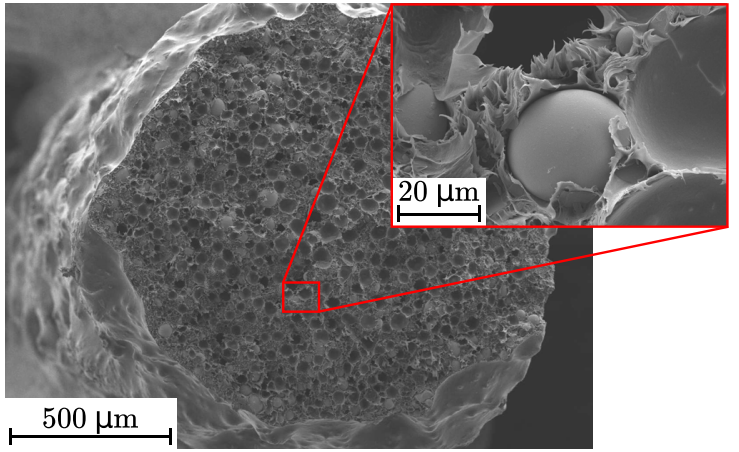
PERMANENT MAGNETS

Mitigation Actions | **Recycling/Reuse of End-of-Life (EoL) Magnets**





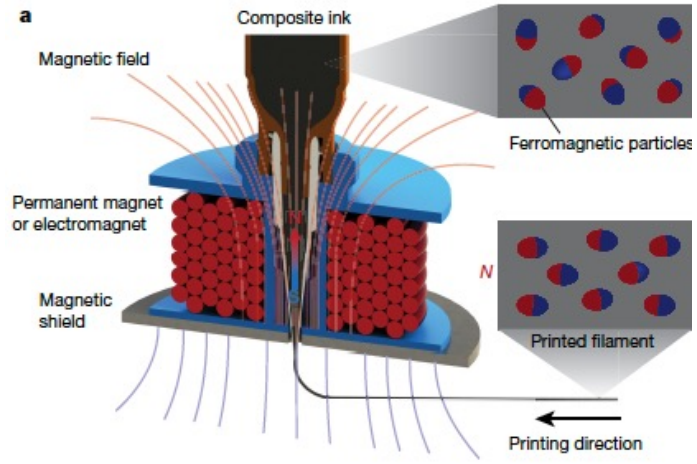




C. Huber et al., Appl. Phys. Lett. 109 (2016) 162401

PERMANENT MAGNETS

From Waste to Value-Added Smart Objects



Printing ferromagnetic domains for untethered fast-transforming soft materials

Yoonho Kim[1,2*], Hyunwoo Yuk[1*], Ruike Zhao[1*], Shawn A. Chester[3], Xuanhe Zhao[1,4]

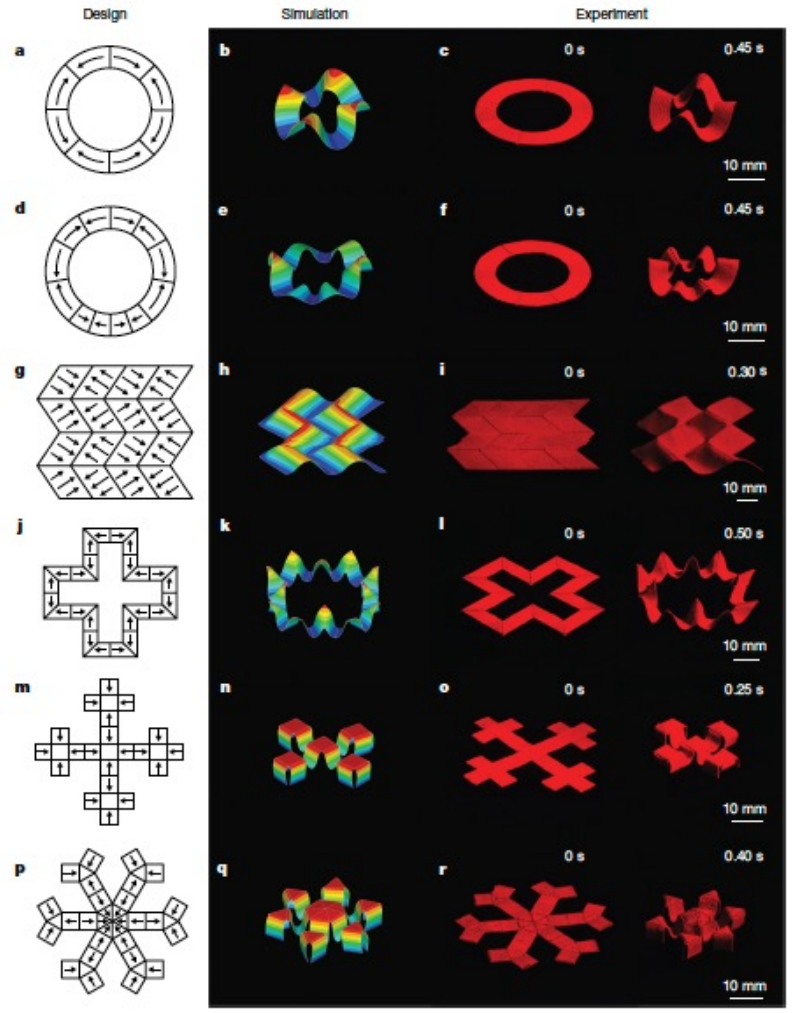
[1]Soft Active Materials Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology
[2]Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology
[3]Department of Mechanical and Industrial Engineering, New Jersey Institute of Technology
[4]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology

*These authors contributed equally to the current work
Correspondence should be addressed to Xuanhe Zhao (zhaox@mit.edu)

Massachusetts Institute of Technology

Rolling-based locomotion and delivery of a drug pill of the hexapedal structure under a rotating magnetic field

SAMs Lab



H. Zhai et al., Composites Part B 298 (2025) 112387

Y. Kim et al., Nature 558 (2018) 274

PERMANENT MAGNETS

Mitigation Actions

OPTIMIZATION OF EXISTING MATERIALS

J.M.D. Coey, Engineering. 6 (2020) 119
C. De Julián Fernández et al., J. Phys. D. Appl. Phys. 54 (2021) 153001
A. Kovacs et al,, Engineering. 6 (2020) 148
P. Maltoni et al. J. Phys. D. Appl. Phys. 54 (2021) 124004 (1–10).
J.M.D. Coey,, Scr. Mater. 67 (2012) 524–529.
H. Tahanian et al., IEEE Trans. Magn. 56 (2020) 900120

RECYCLING/REUSE OF END-OF-LIFE MAGNETS

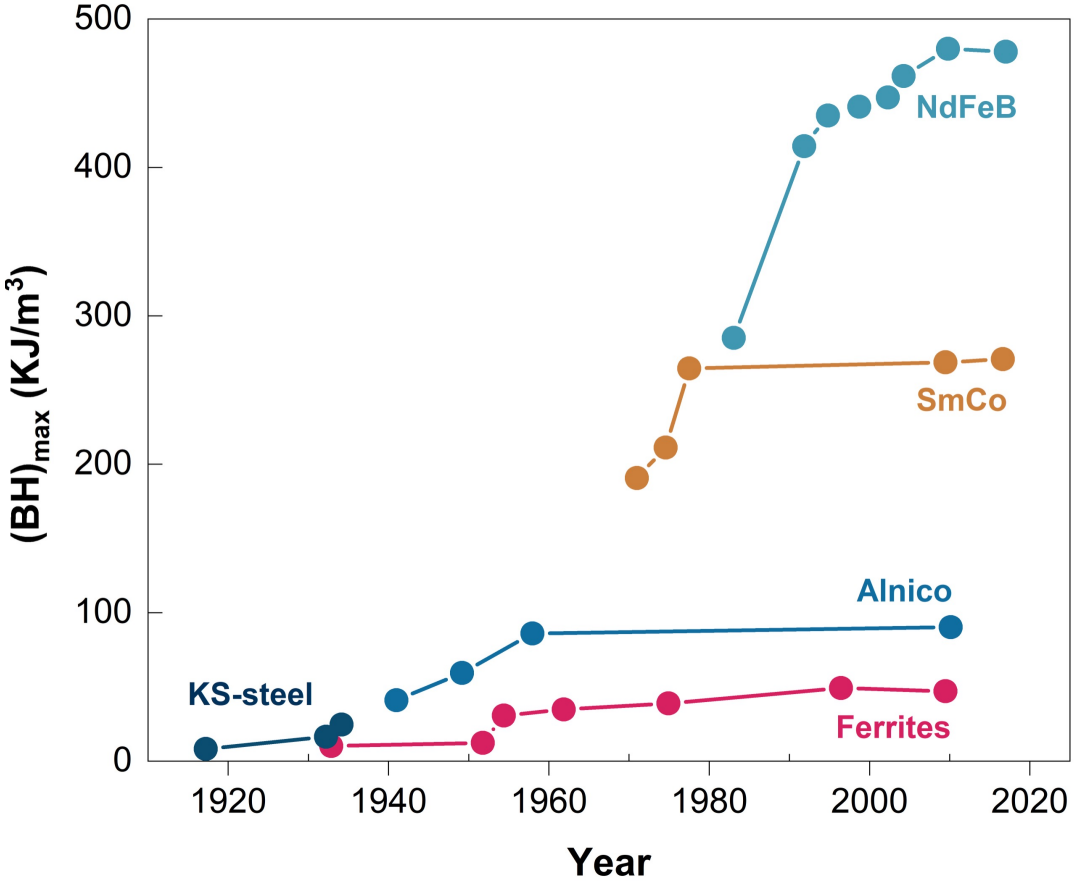
Z. Li et al., EPJ Appl. Phys. 86 (2019) 20901
A. Lixandru, et al., Waste Manag. 68 (2017) 482
J.R. Peeters et al. J. Clean. Prod. 175 (2018) 96
U. Rösel and D. Drummer, Magnetism 2 (2022) 251

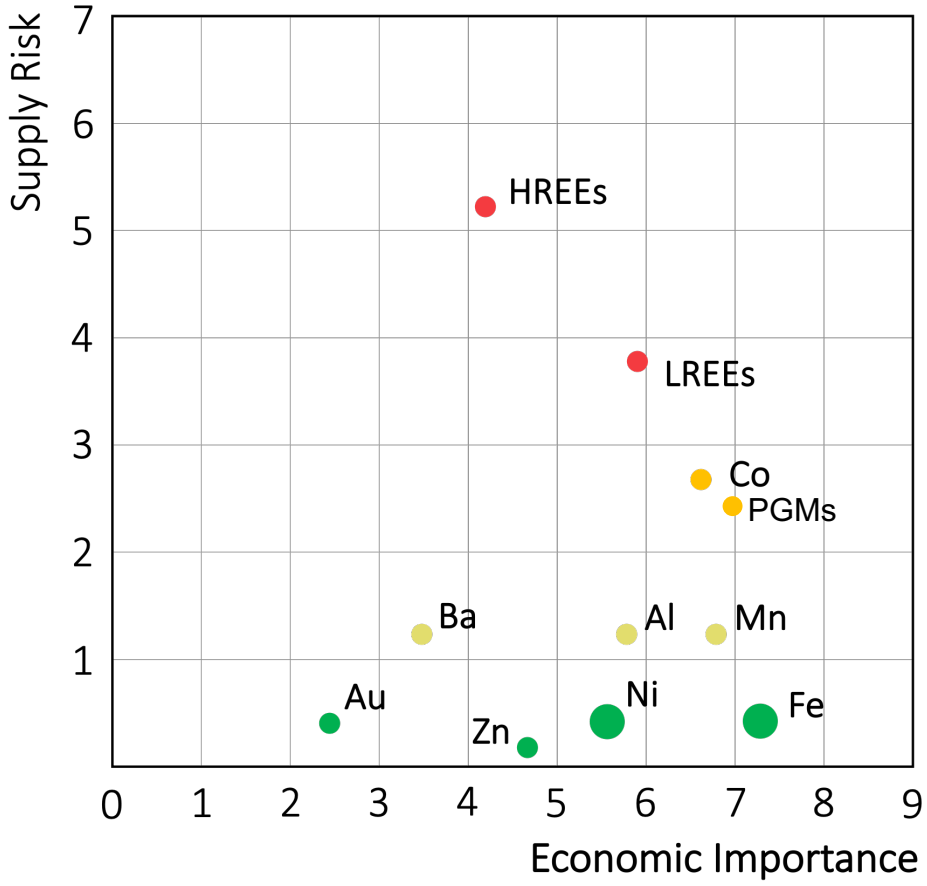
DEVELOPMENT OF NEW HARD MAGNETIC PHASES FREE OF REEs

J. Cui et al., Acta Mater. 158 (2018) 118
D. Goll et al., J. Phys. Condens. Matter. 26 (2014) 064208

PERMANENT MAGNETS

Mitigation Actions | **Development of new hard magnetic phases FREE of REEs**

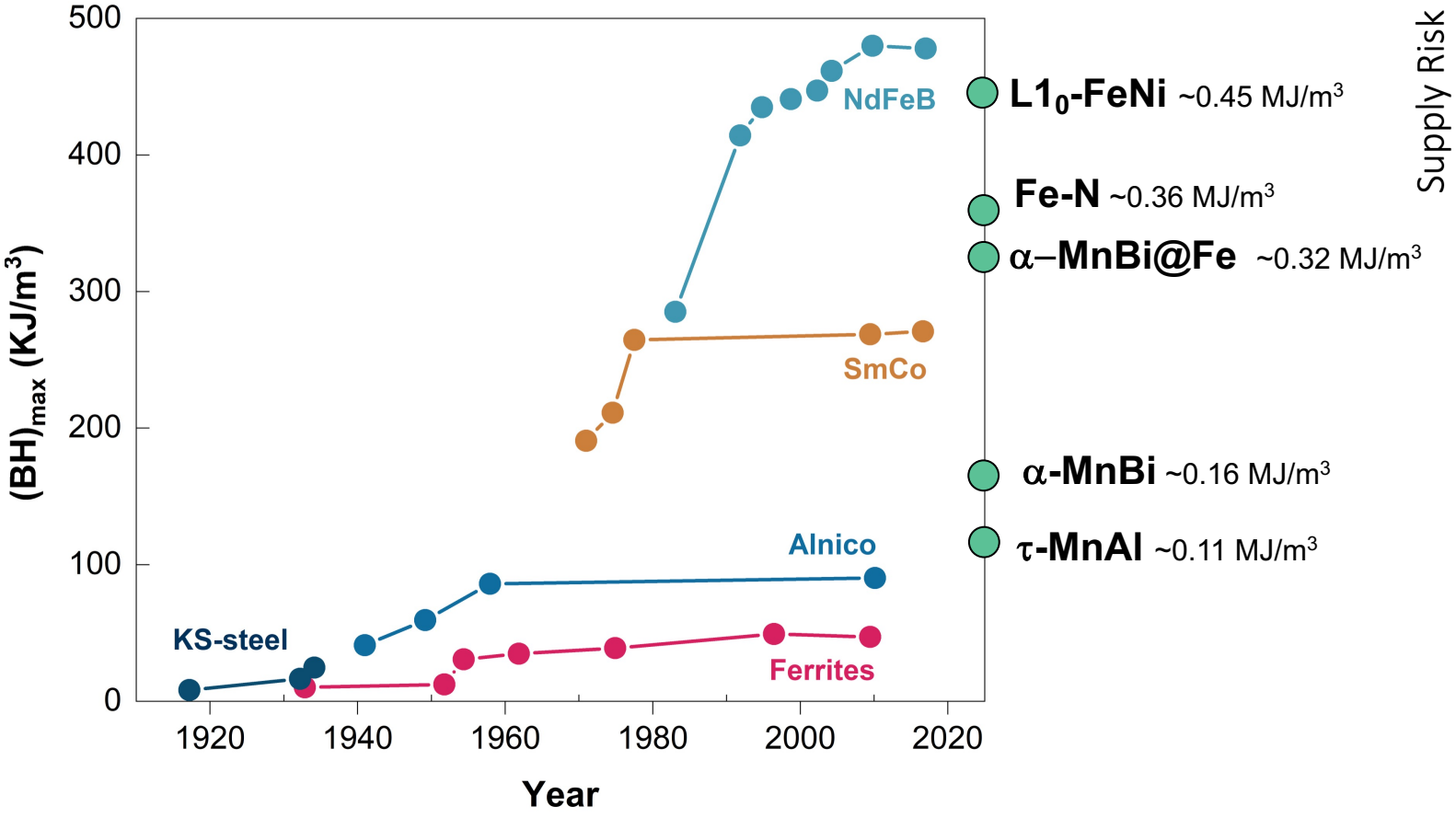


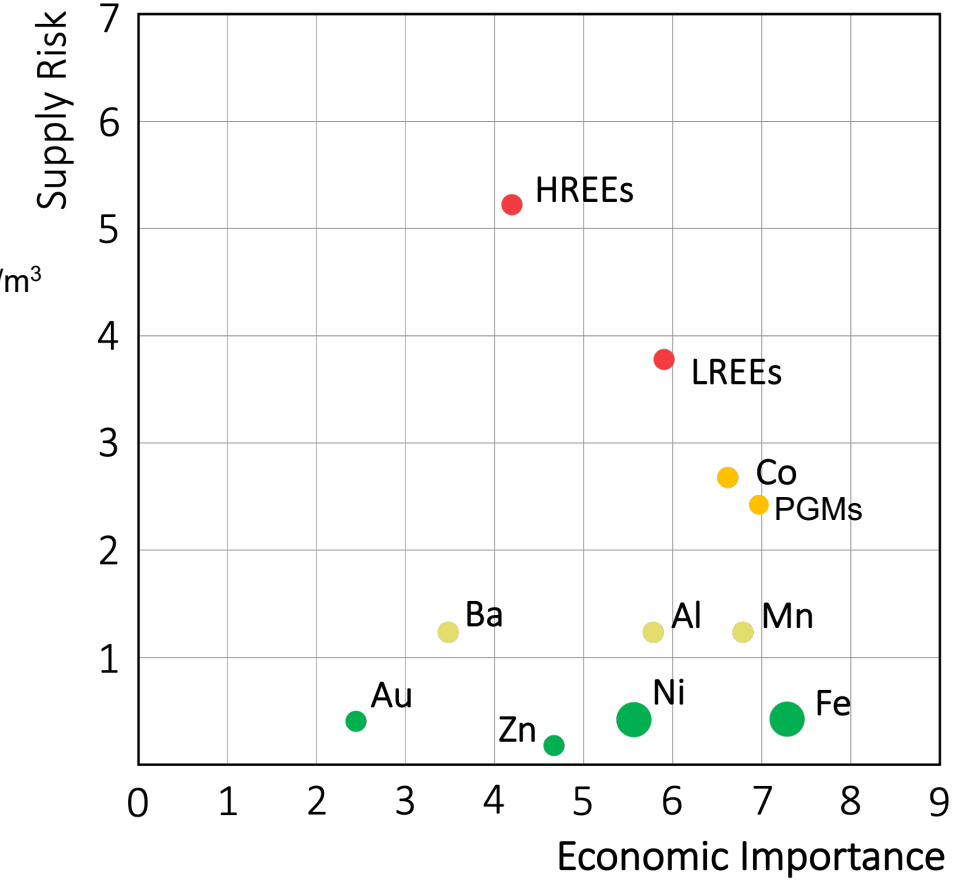


J. Cui et al., Acta Mater. 158 (2018) 118
D. Goll et al., J. Phys. Condens. Matter. 26 (2014) 064208

PERMANENT MAGNETS

Mitigation Actions | **Development of new hard magnetic phases FREE of REEs**

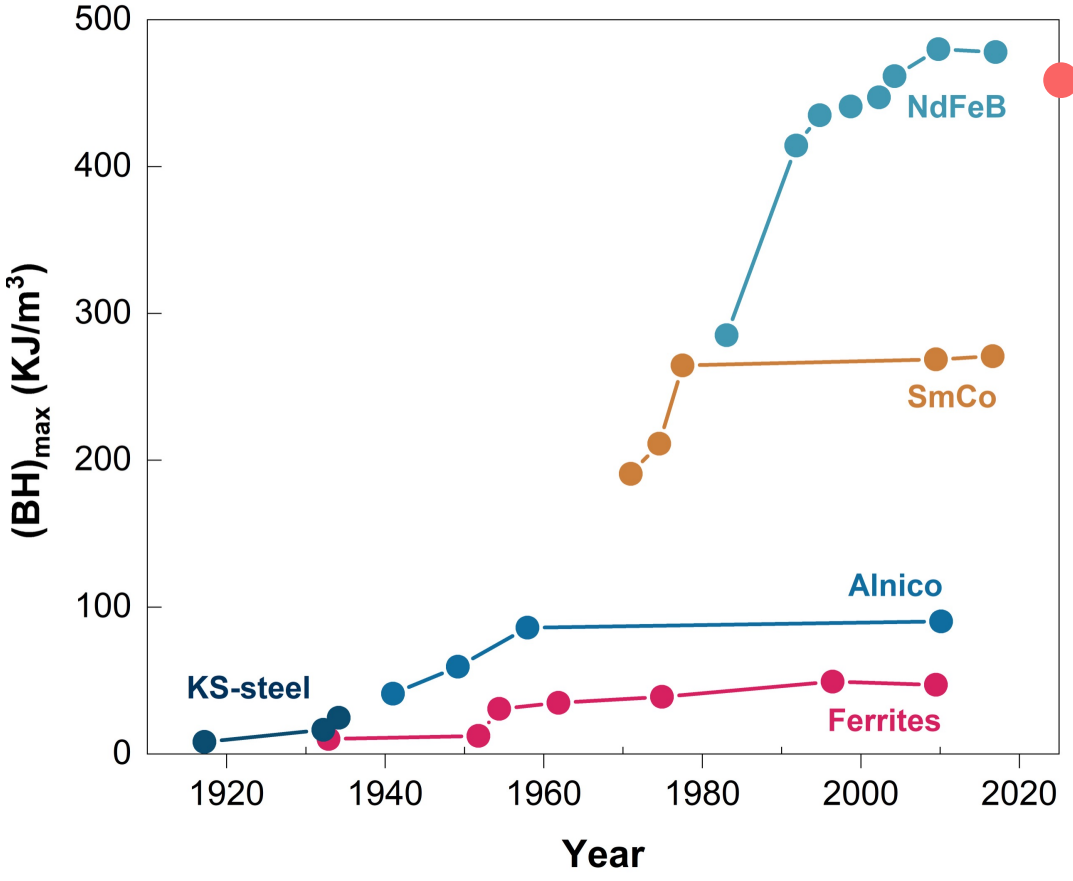




J. Cui et al., Acta Mater. 158 (2018) 118
D. Goll et al., J. Phys. Condens. Matter. 26 (2014) 064208

PERMANENT MAGNETS

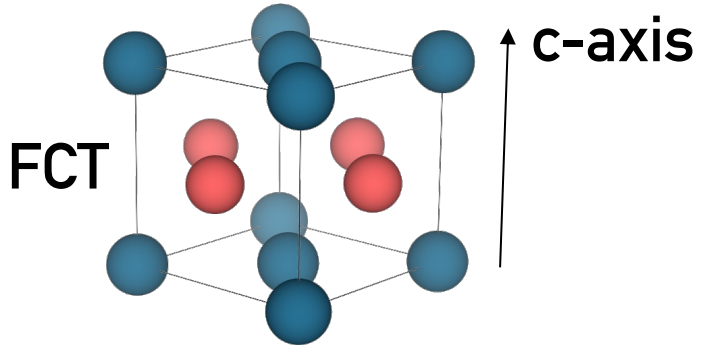
Mitigation Actions | **Development of new hard magnetic phases FREE of REEs | $L1_0$-FeNi**



$L1_0$ FeNi

Ms ~ 1.6 T; K ~ 10^6 J/m^3

→ $(BH)_{max}$ ~0.45MJ/m^3

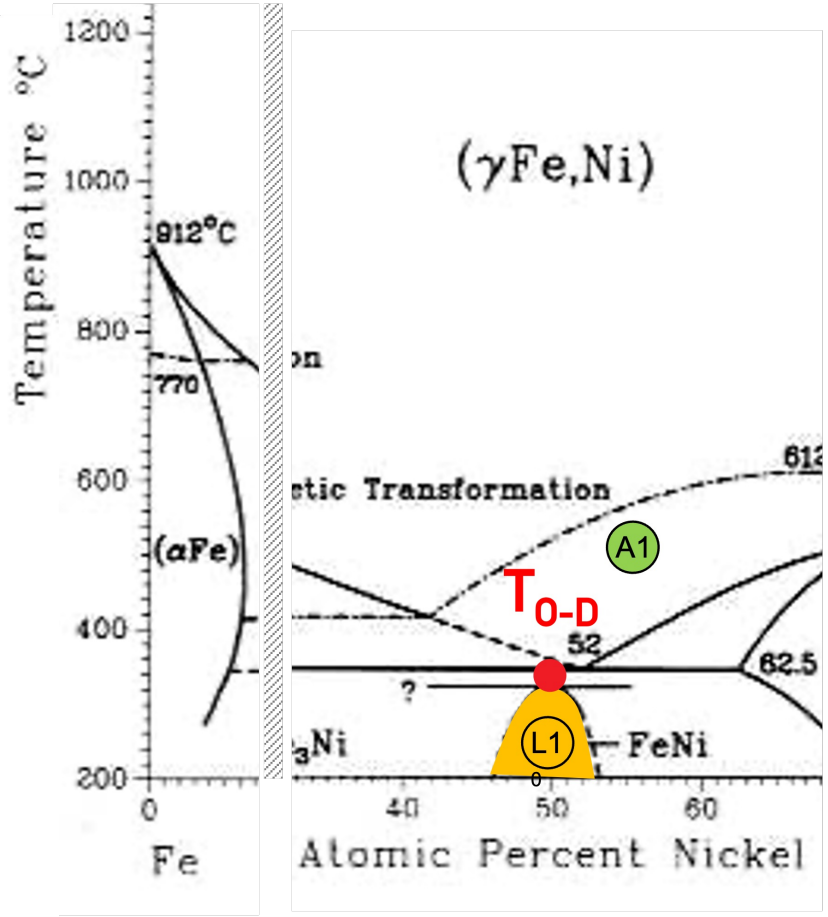


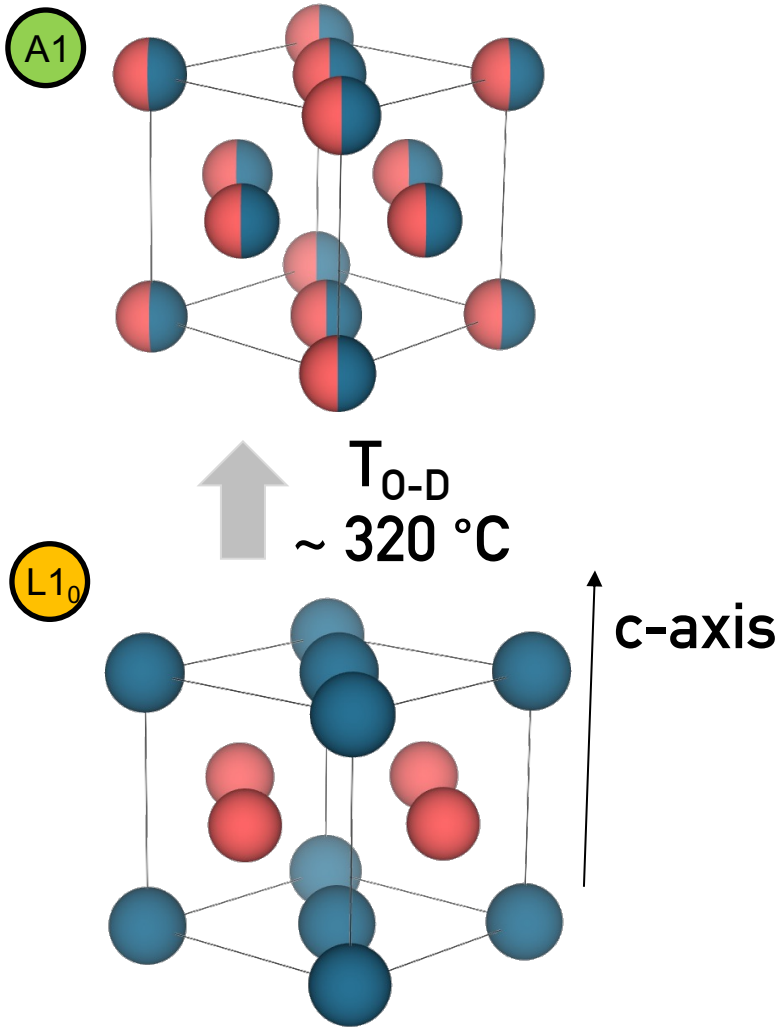
J. Cui et al., Acta Mater. 158 (2018) 118

S. Mandal et al., Crit. Rev. Solid State Mater. Sci. 2022

PERMANENT MAGNETS

Mitigation Actions | **Development of new hard magnetic phases FREE of REEs | $L1_0$-FeNi**

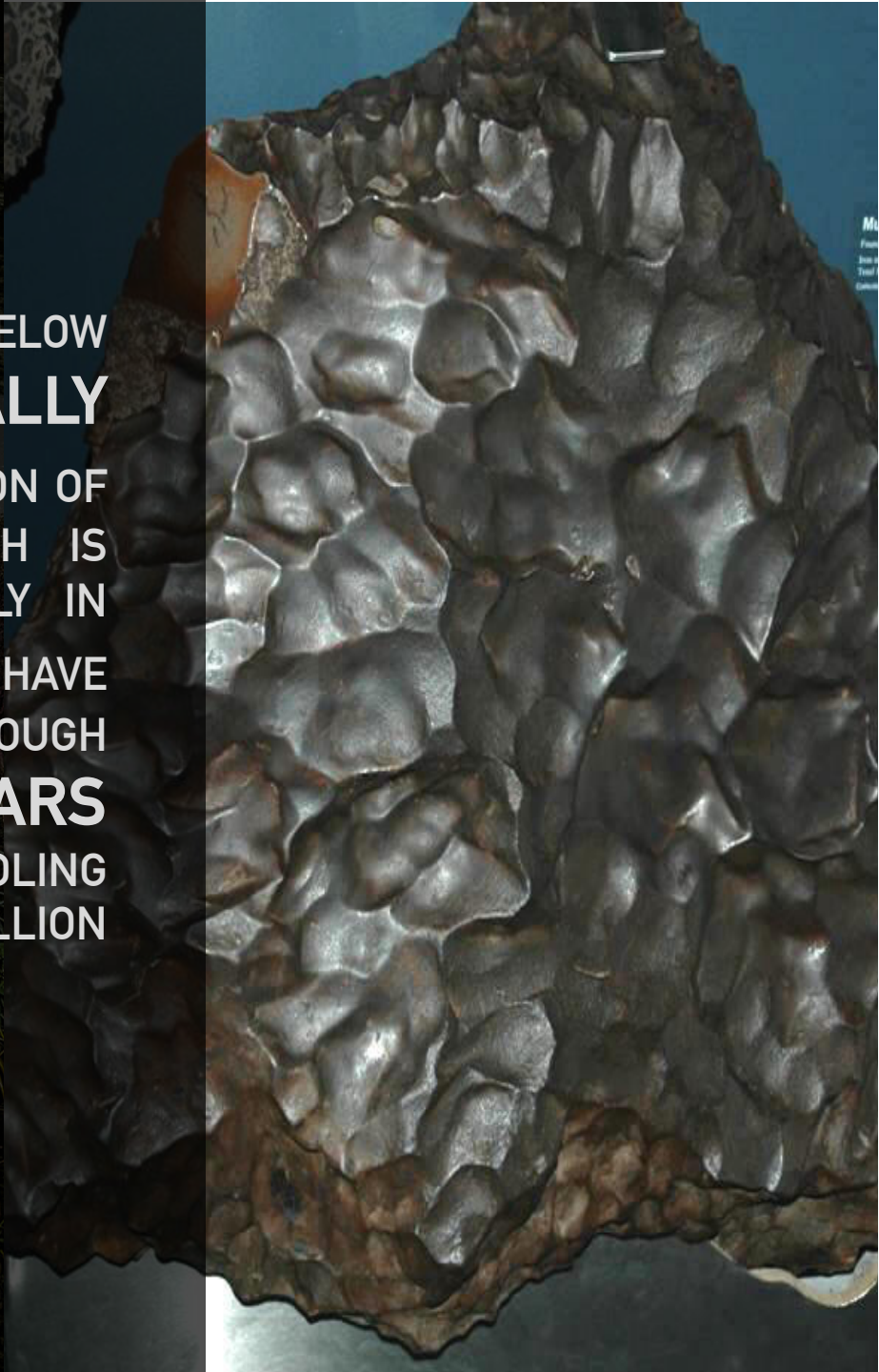




N. Bordeaux et al., Acta Mater. 103 (2016) 608
E. Poirier et al., J. Appl. Phys. 117 (2015) 17E318



LOW ATOMIC MOBILITY BELOW T_{O-D} **KINETICALLY LIMITS** THE FORMATION OF THE $L1_0$ PHASE, WHICH IS NATURALLY FOUND ONLY IN **METEORITES** THAT HAVE COOLED THROUGH **BILLIONS OF YEARS** AT EXTREMELY LOW COOLING RATES (1 K EVERY MILLION YEARS).



PERMANENT MAGNETS

Mitigation Actions | **Development of new hard magnetic phases FREE of REEs | $L1_0$-FeNi**

Neutron irradiation (fluence 2.1×10^{23} m^2 for >1 MeV) of $Fe_{50}Ni_{50}$ disc, 9.3 mm diam., 1.1 mm thick[3,26]	$Fe_{50}Ni_{50}$	high	30 nm[e]
Irradiation with 1 MeV electrons[10]	Fe–(29–49)Ni	<10%	10 nm
Irradiation with 70 keV Ne ions[11]	$Fe_{50}Ni_{50}$	—	within 100 nm thin film
Cyclic oxidation and reduction of Ni-coated Fe particles over 5 h at 623 K[15]	$Fe_{50}Ni_{50}$	19%	≤2 μm
Alternate monolayer deposition using molecular beam epitaxy[8,34]	$Fe_{50}Ni_{50}$	—	thin film 18 nm thick
Reverse martensitic transformation in Fe-(31.4)Ni steel[17]	Fe-(40–50)Ni	<5%	plates, 15 nm thick
High-pressure torsion & annealing (for up to 40 days) of Fe–Ni–Co alloys[12]	$Fe_{50}Ni_{50}$	"very low"	≈100 nm
Crystallization of Fe–Ni–Si—B–P–Cu glassy ribbons annealed (673 K, 288 h; 773 K, 1 h; or 813 K, 1 h)[18,19]	$Fe_{50}Ni_{50}$	8–13%	30–50 nm
$Fe_{54}Ni_{46}$ and $Fe_{52}Ni_{46}Ti_2$ plates 2 mm thick, cold-rolled to 86% reduction in thickness. Melt-spun ribbons of $Fe_{52}Ni_{46}Ti_2$ cryo-milled for 9 h. Deformed samples then annealed at 563 K for 6 weeks[9]	—[f]	—[f]	—[f]
Nitriding (573 K, 50 h) and denitriding (523 K, 2 h)[16]	$Fe_{50}Ni_{50}$	100%	nanopowder 90 nm
Cyclic oxidation and reduction (593 K, 5 h, or 10 h) of FeNi nanopowder[24]	$Fe_{50}Ni_{50}$	≈10%	nanopowder 100 nm

[a] Of the tetrataenite itself, not the overall sample; [b] There are many observations. The ranges of values quoted here are from the early review by Wasilewski[22] and the papers cited therein; [c] Estimated from the solvus line given in ref. [29]; [d] Within the decomposed taenite; [e] Diameter of the ordered crystallites in the bulk sample;[26] [f] No details given, but X-ray and neutron diffractometry show the presence of $L1_0$ with $c/a = 1.003$.

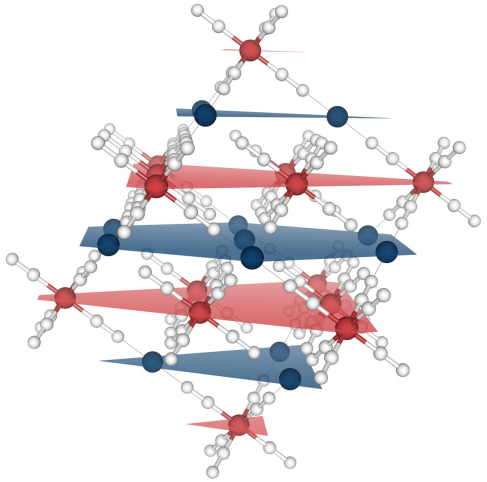
Y. P. Ivanov et al.,, *Adv. Sci.* 10 (2023) 2204315
S. Mandal et al., Crit. Rev. Solid State Mater. Sci. 2022

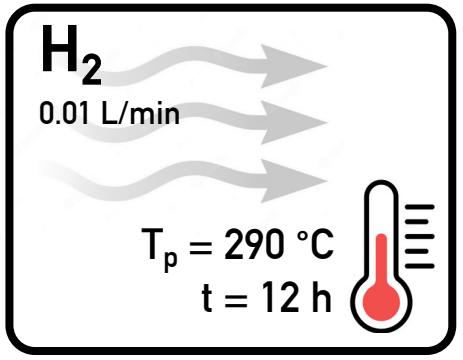
PERMANENT MAGNETS

Mitigation Actions | **Development of new hard magnetic phases FREE of REEs | $L1_0$-FeNi**

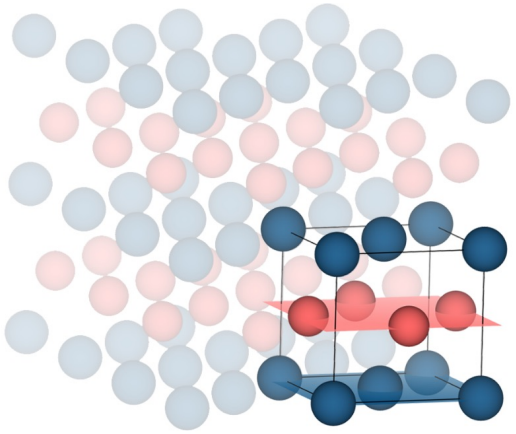
Crystal Complex

$NiFe(CN)_5NO \bullet xH_2O$





$L1_0$-FeNi Alloy

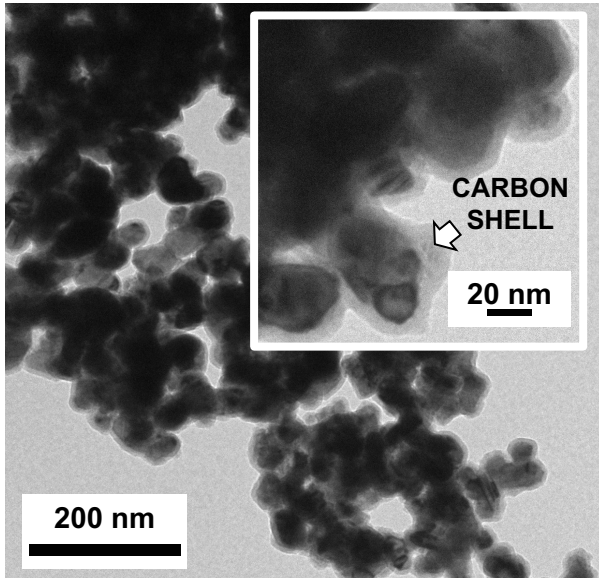


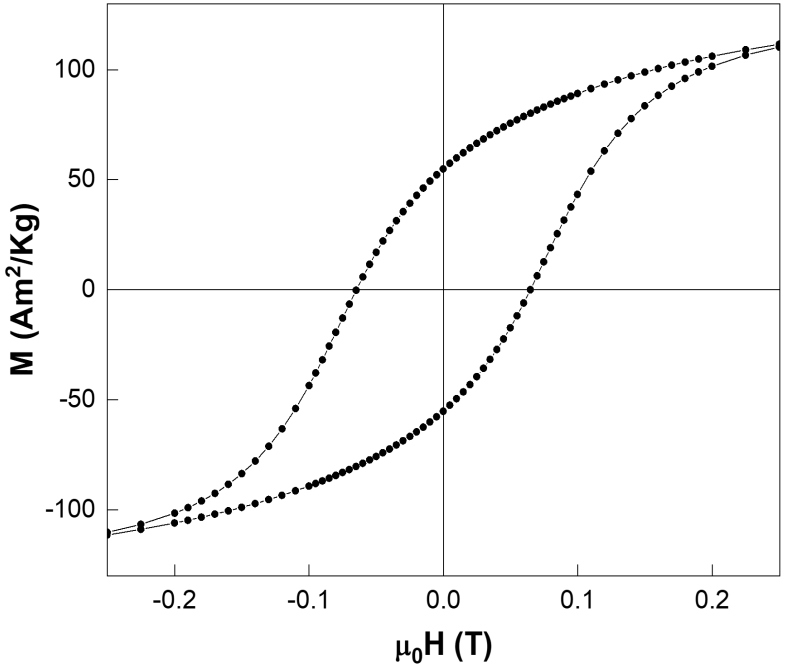
GV et al., Scripta Materialia 238 (2024) 115754

A. Capobianchi, GV et al., Patent Application Filed PCT/IB2023/062068 (2023)

PERMANENT MAGNETS

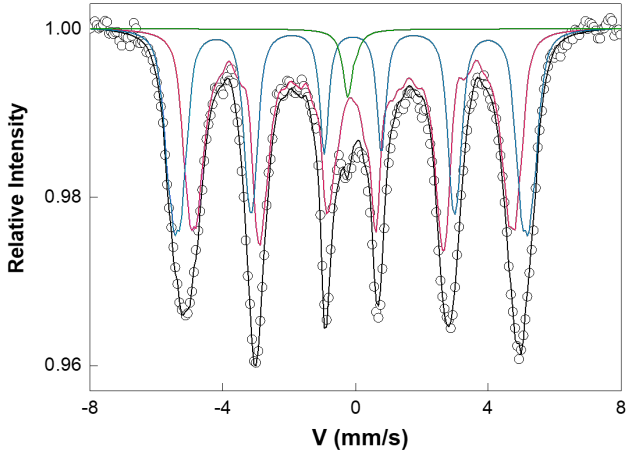
Mitigation Actions | **Development of new hard magnetic phases FREE of REEs | $L1_0$-FeNi**

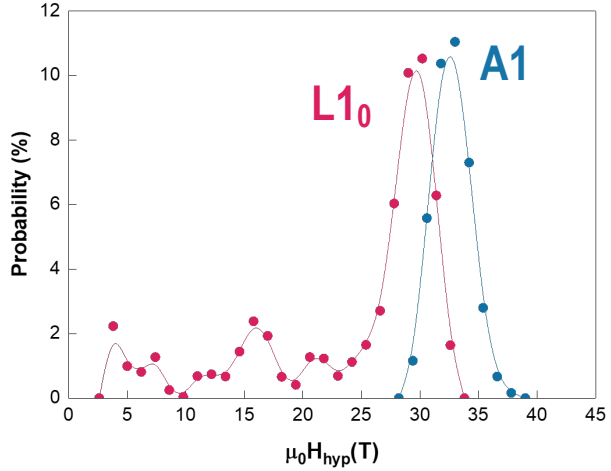




H_c ~ 56 mT

M_s ~140 Am²/Kg
($M_{s,bulk}$ = 154 Am²/Kg)



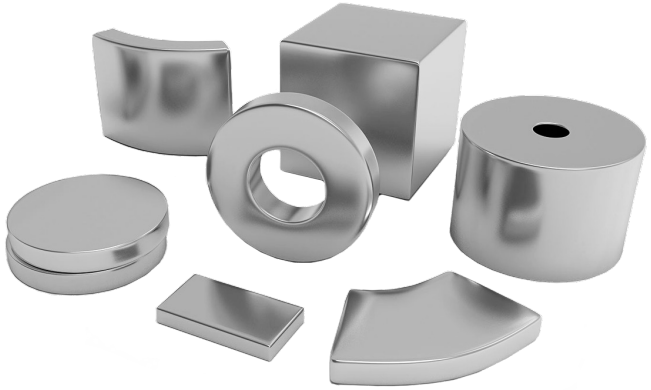


GV et al., Scripta Materialia 238 (2024) 115754
A. Capobianchi, GV et al., Patent Application Filed PCT/IB2023/062068 (2023)

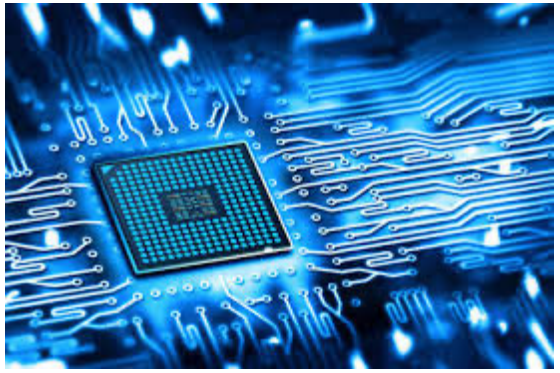
SUSTAINABILITY IN MATERIALS SCIENCE

CRMs in Magnetic Materials for Strategic (Green) Technologies

PERMANENT MAGNETS

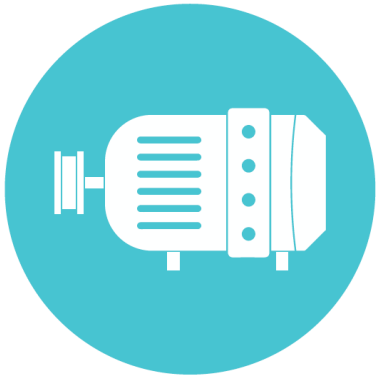


SPIN-BASED ELECTRONICS





RENEWABLE ENERGY (Wind Turbines)



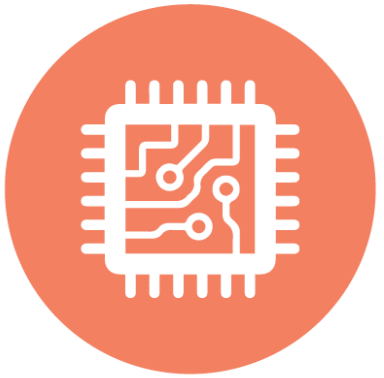
MOTORS



e-MOBILITY



ROBOTICS



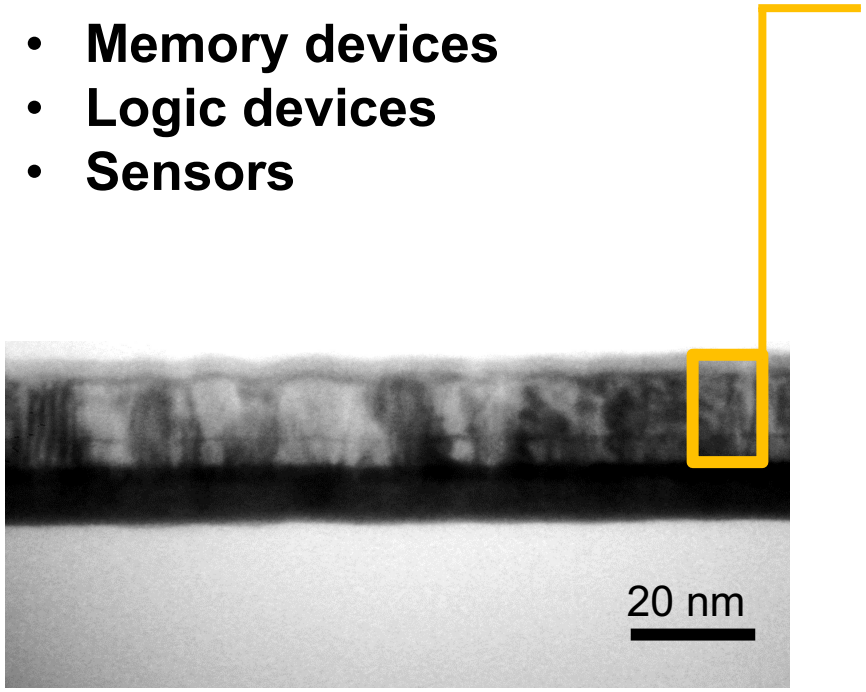
DIGITAL TECHNOLOGIES

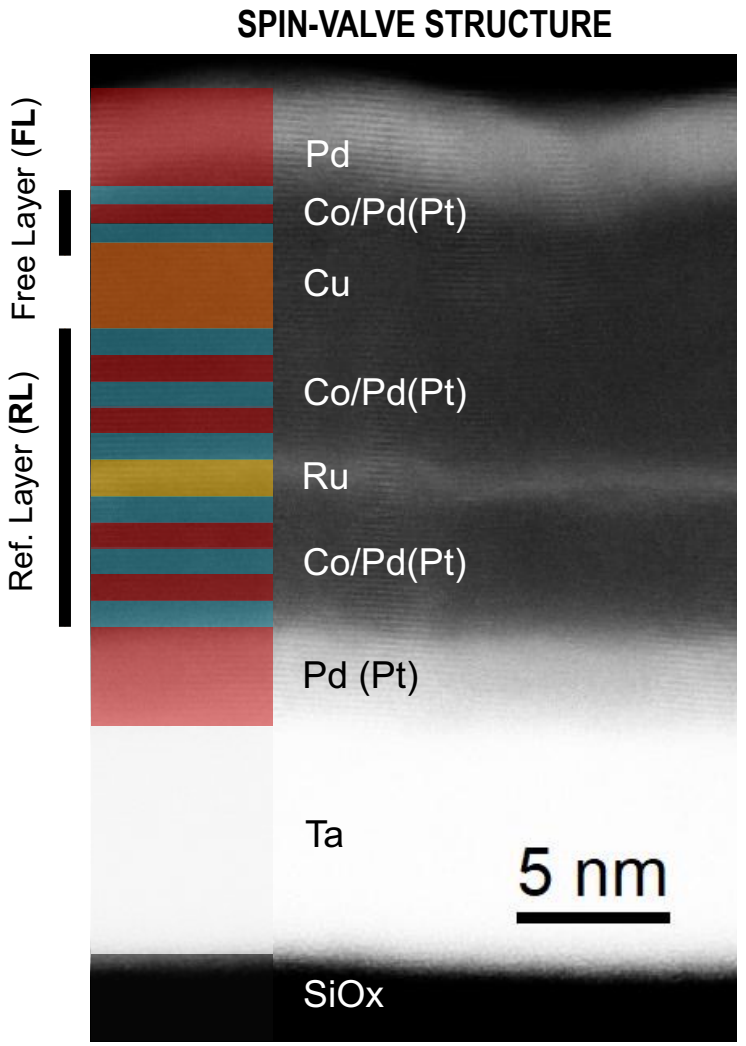


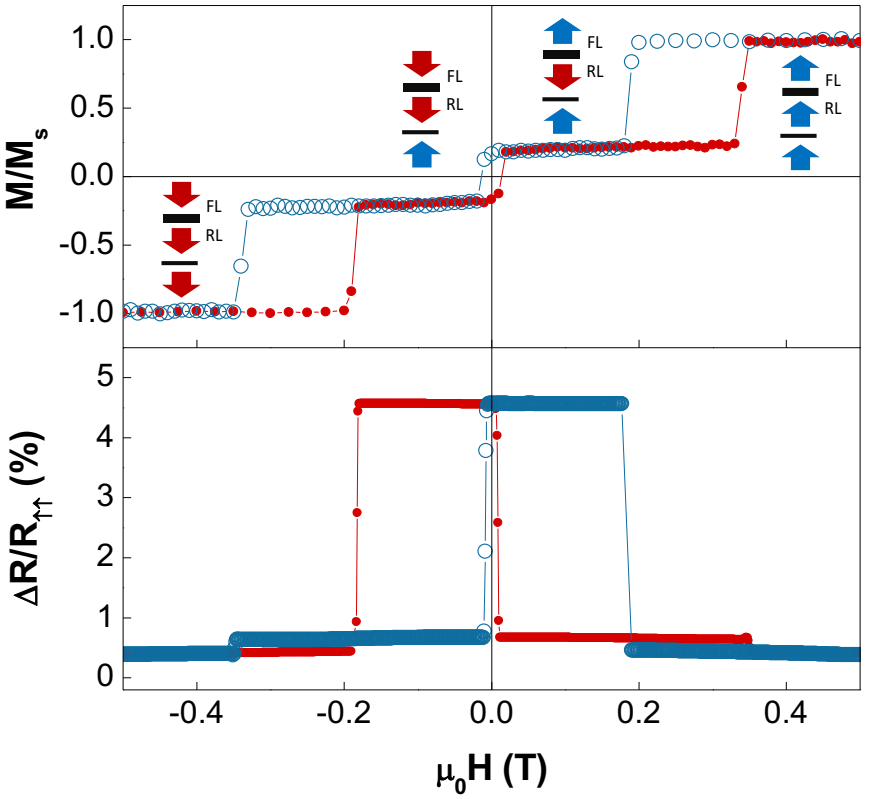
DEFENSE

MATERIALS FOR SPINTRONIC DEVICES

- **Memory devices**
- **Logic devices**
- **Sensors**

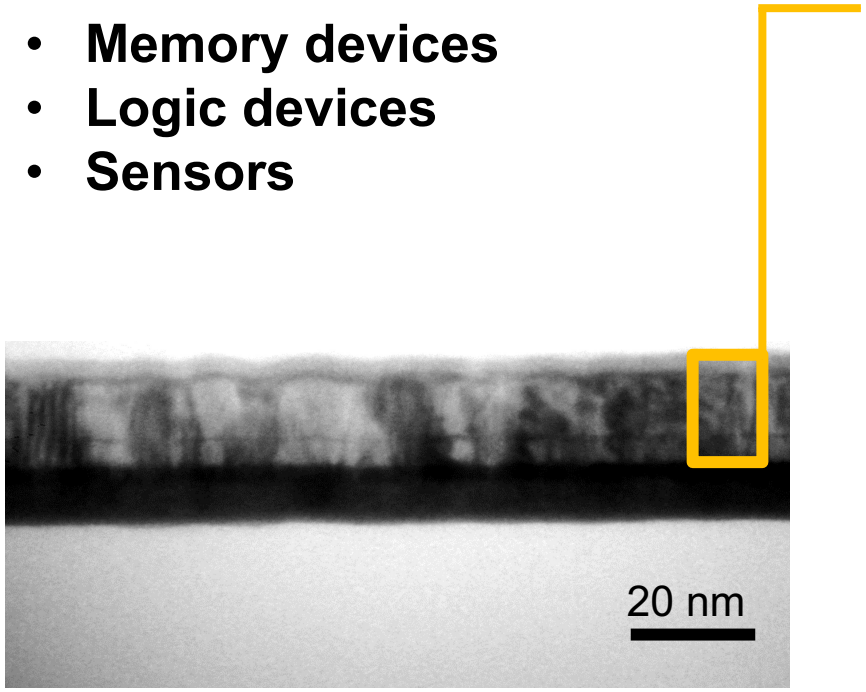


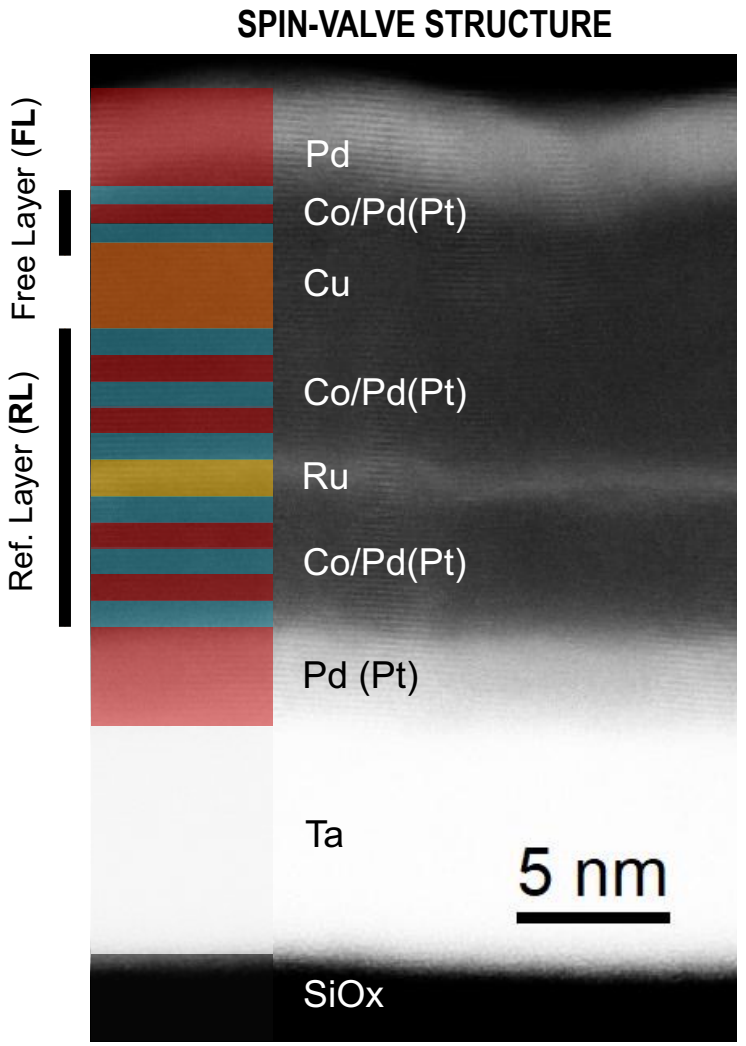


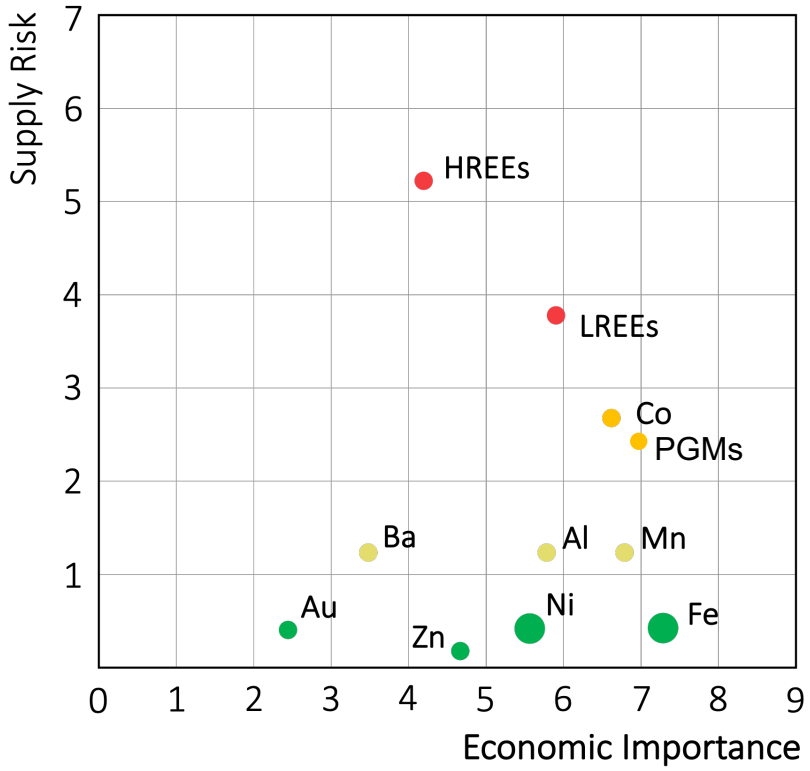


MATERIALS FOR SPINTRONIC DEVICES

- **Memory devices**
- **Logic devices**
- **Sensors**

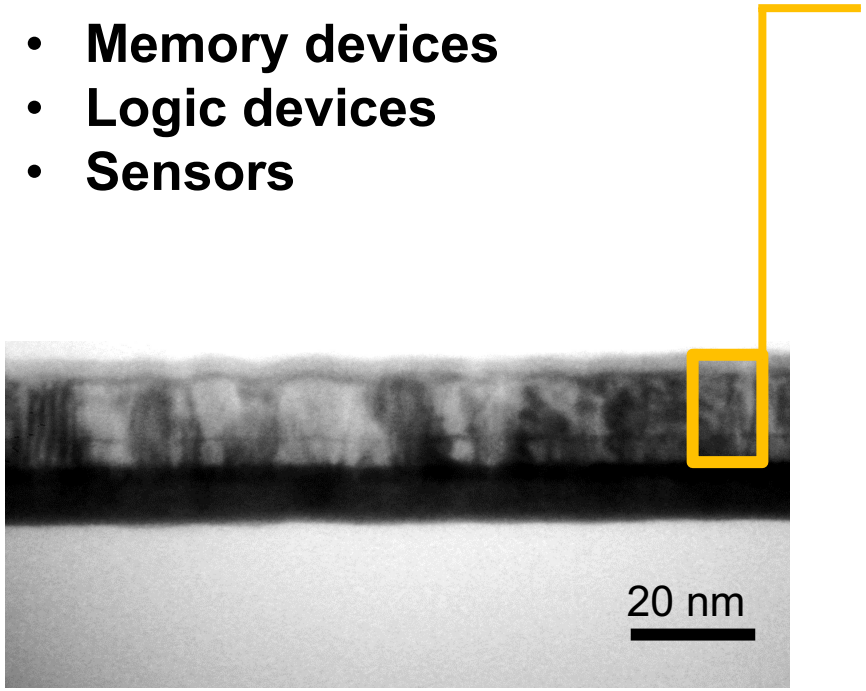


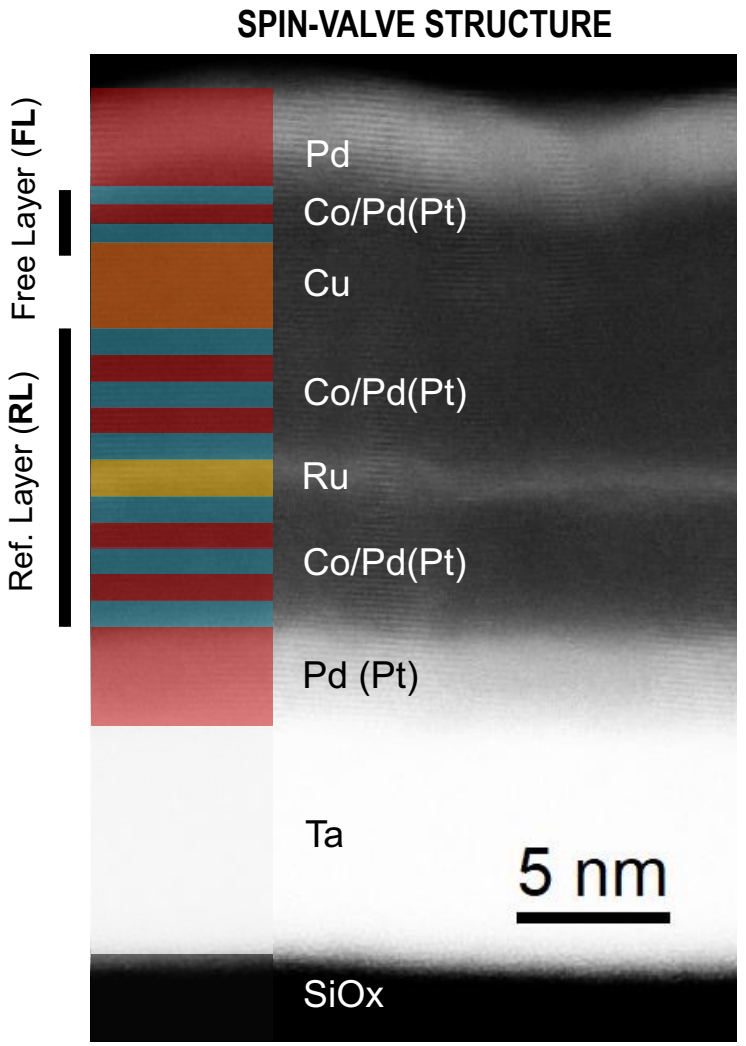


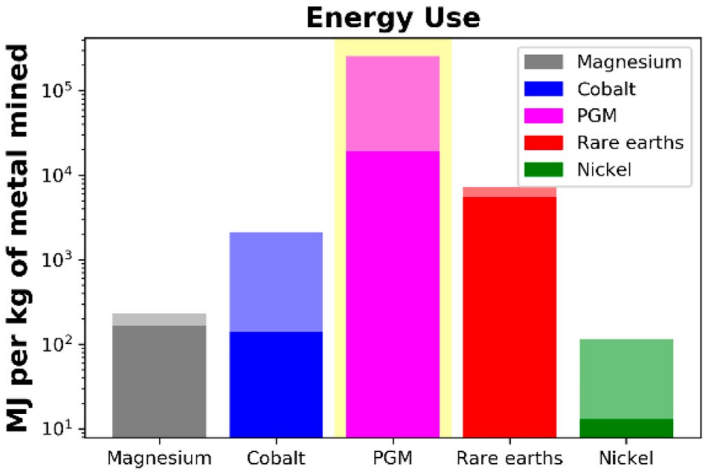


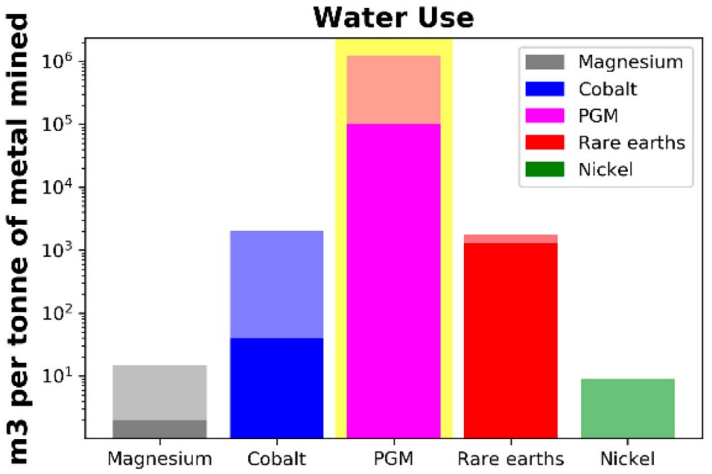
MATERIALS FOR SPINTRONIC DEVICES

- **Memory devices**
- **Logic devices**
- **Sensors**





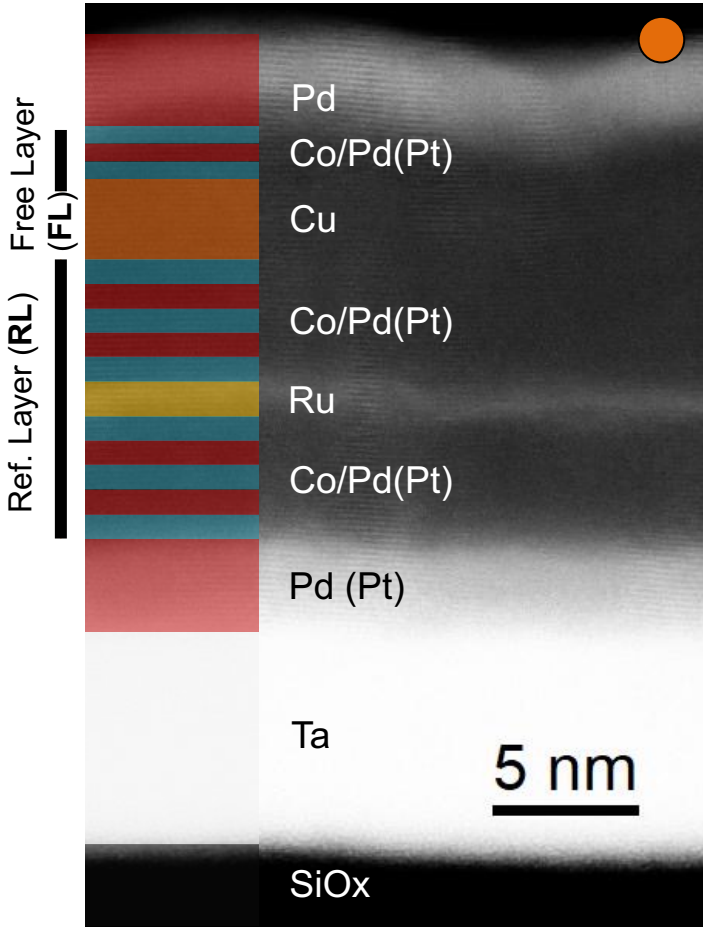


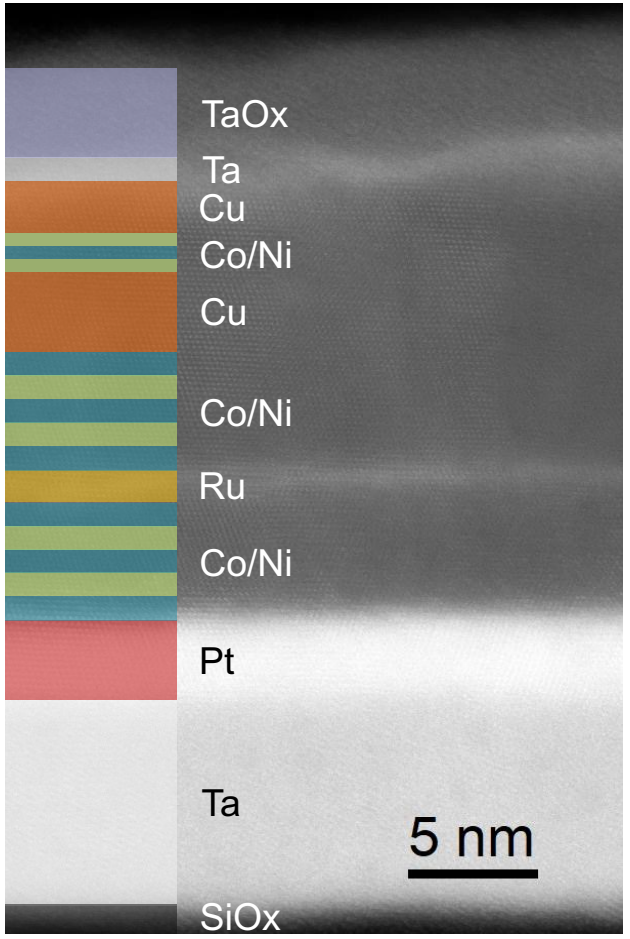


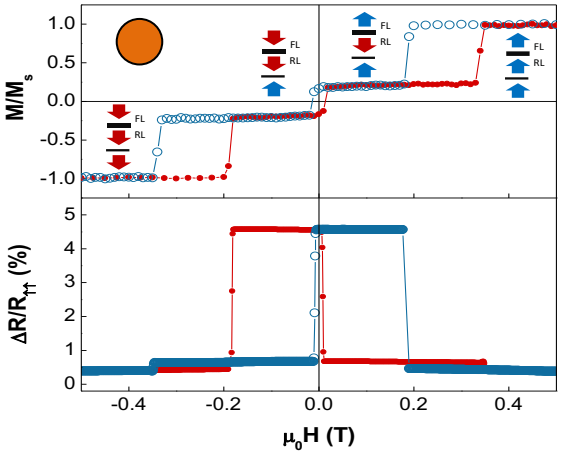
A. Palomino et al., Sust. Mat. and Tech. 28 (2021) e00270

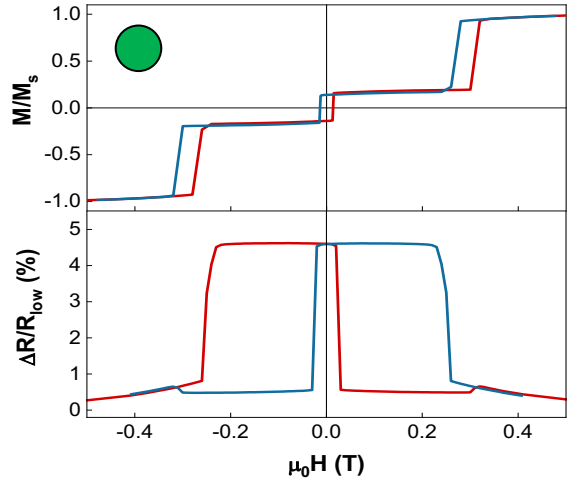
MATERIALS FOR SPINTRONIC DEVICES

Mitigation Actions | **Development of systems with reduced CRMs content**







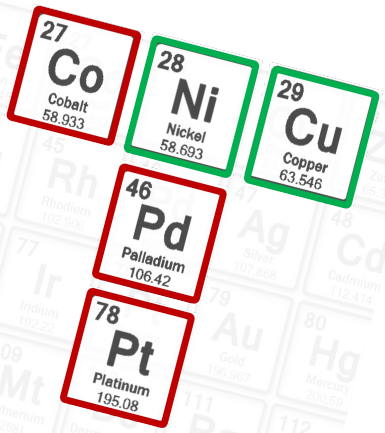


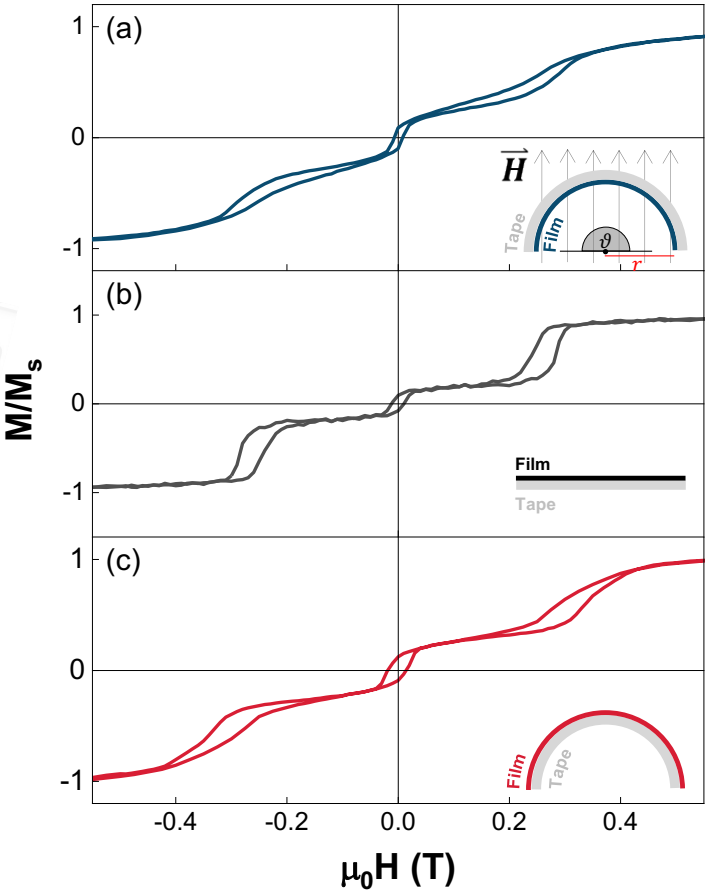
M. Hassan, GV et al., ACS Appl. Mater. Interfaces 14 (2022) 514969

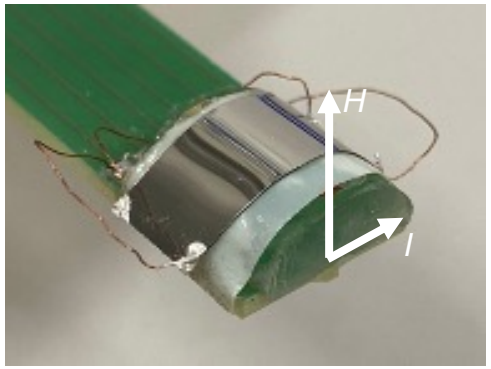
MATERIALS FOR SPINTRONIC DEVICES

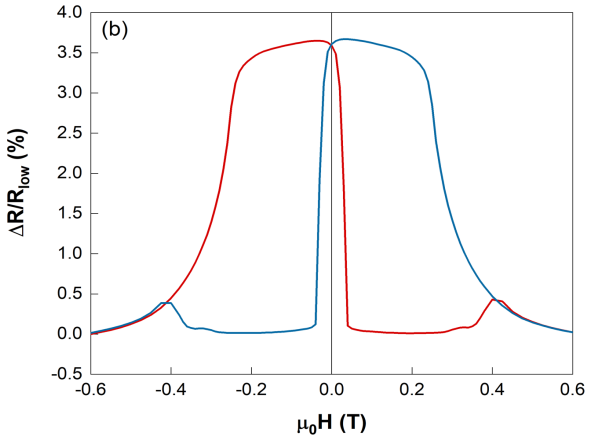
Mitigation Actions | **Development of systems with reduced CRMs content**







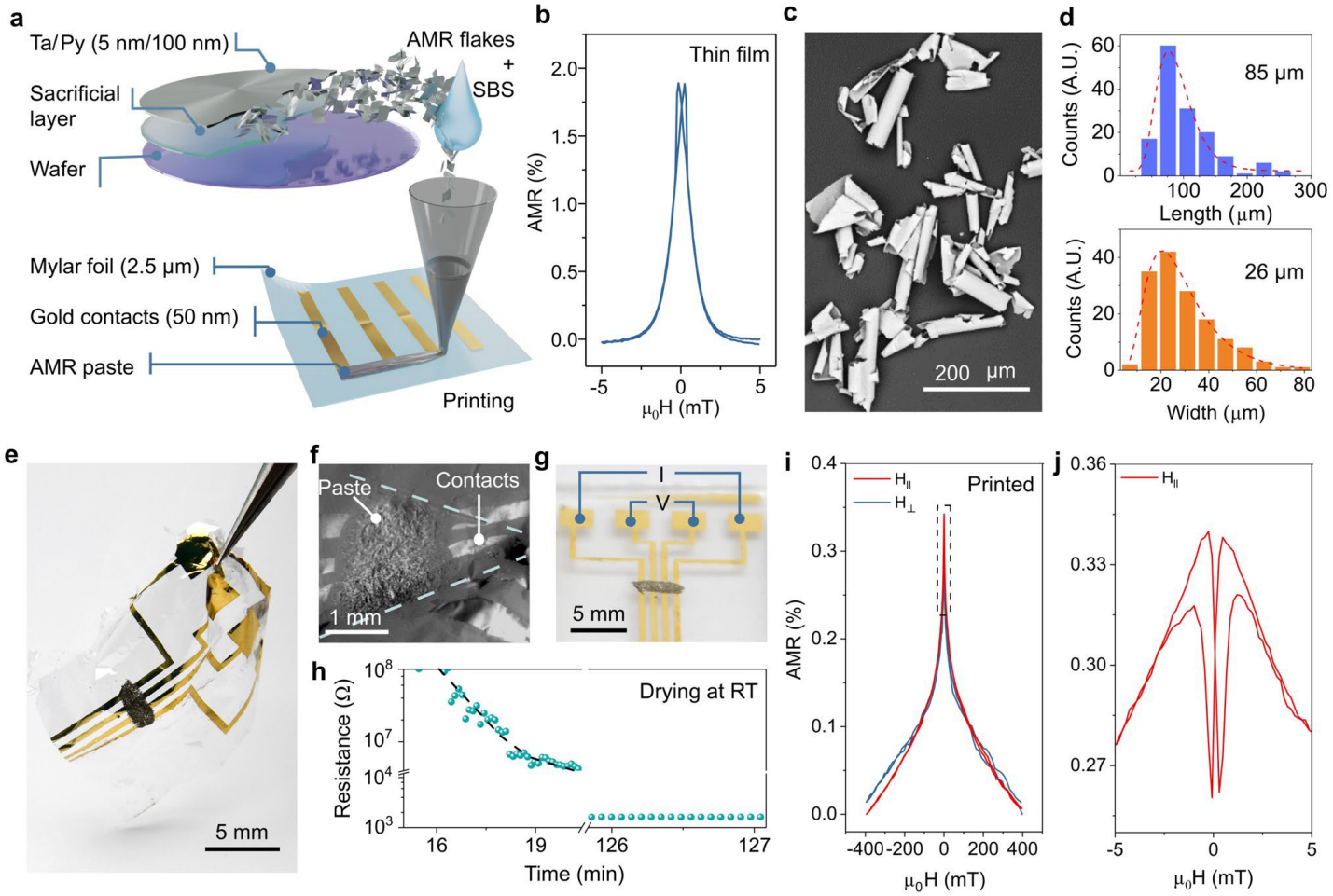




M. Hassan, GV et al., ACS Appl. Mater. Interfaces 14 (2022) 514969

MATERIALS FOR SPINTRONIC DEVICES

Mitigation Actions | **Sustainable synthesis approaches**

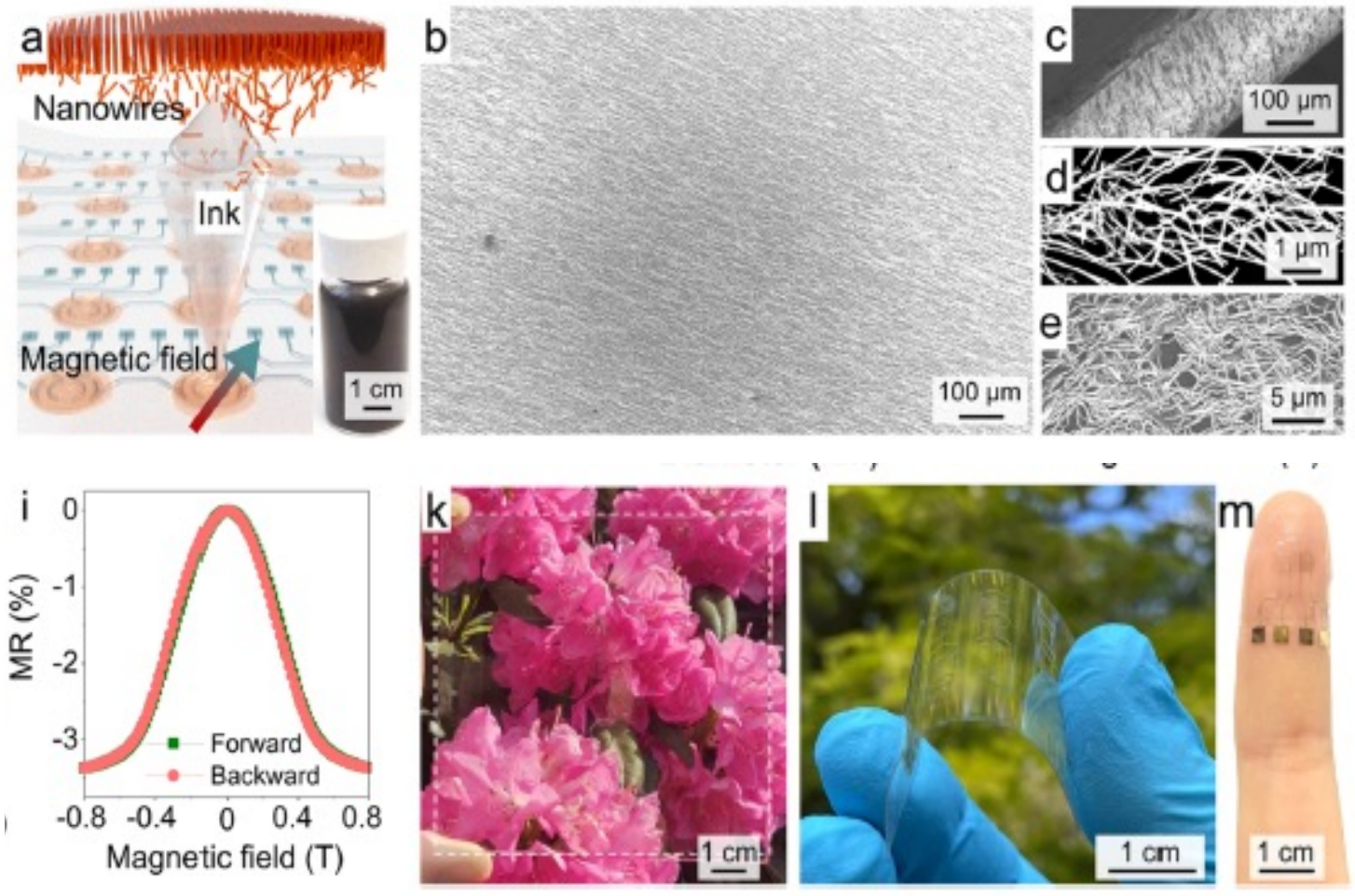


S. Gomez-Gijon et al., Adv. SustainableSyst. 9 (2025) 2400486

E. S. Oliveros Mata et al., Applied Physics A 127 (2021) 280

MATERIALS FOR SPINTRONIC DEVICES

Mitigation Actions | **Sustainable synthesis approaches**



R. Xu et al., ACS Nano 2025, 19, 21891−21903

LECTURE OVERVIEW

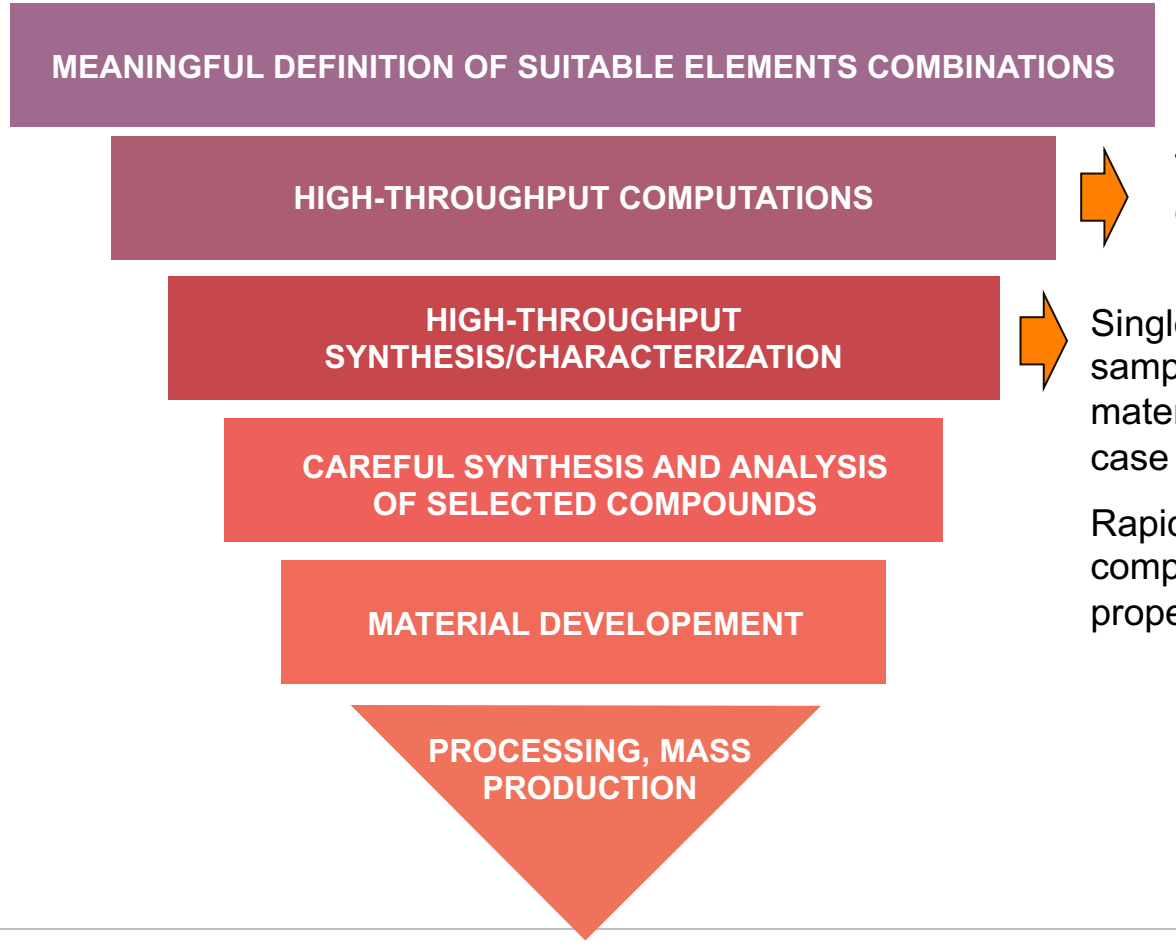
- Introduction to Sustainability
  Four dimensions: ecological, social, economic, and cultural
- Sustainability in Materials Science
  Focus on Critical Raw Materials (CRMs); Challenges in high-performance magnetic materials
- Case Studies in Magnetism
  Permanent magnets, Spintronic devices
- Strategies to Reduce Impact
  Novel materials with reduced or zero CRMs; Recycling; Sustainable synthesis approaches (printing)
- **Emerging Tools and Approaches**
  Combinatorial materials science; Artificial intelligence
- Life Cycle Assessment
  Evaluating circularity and sustainability

EMERGING TOOLS AND APPROACHES

Combinatorial Materials Science

Combinatorial (High-throughput) search for new materials

…for accelerated materials discovery



To screen hundreds of possible compositions

Single-run synthesis of material "library" samples that contain variation of the materials' parameter of interest (in our case the composition).

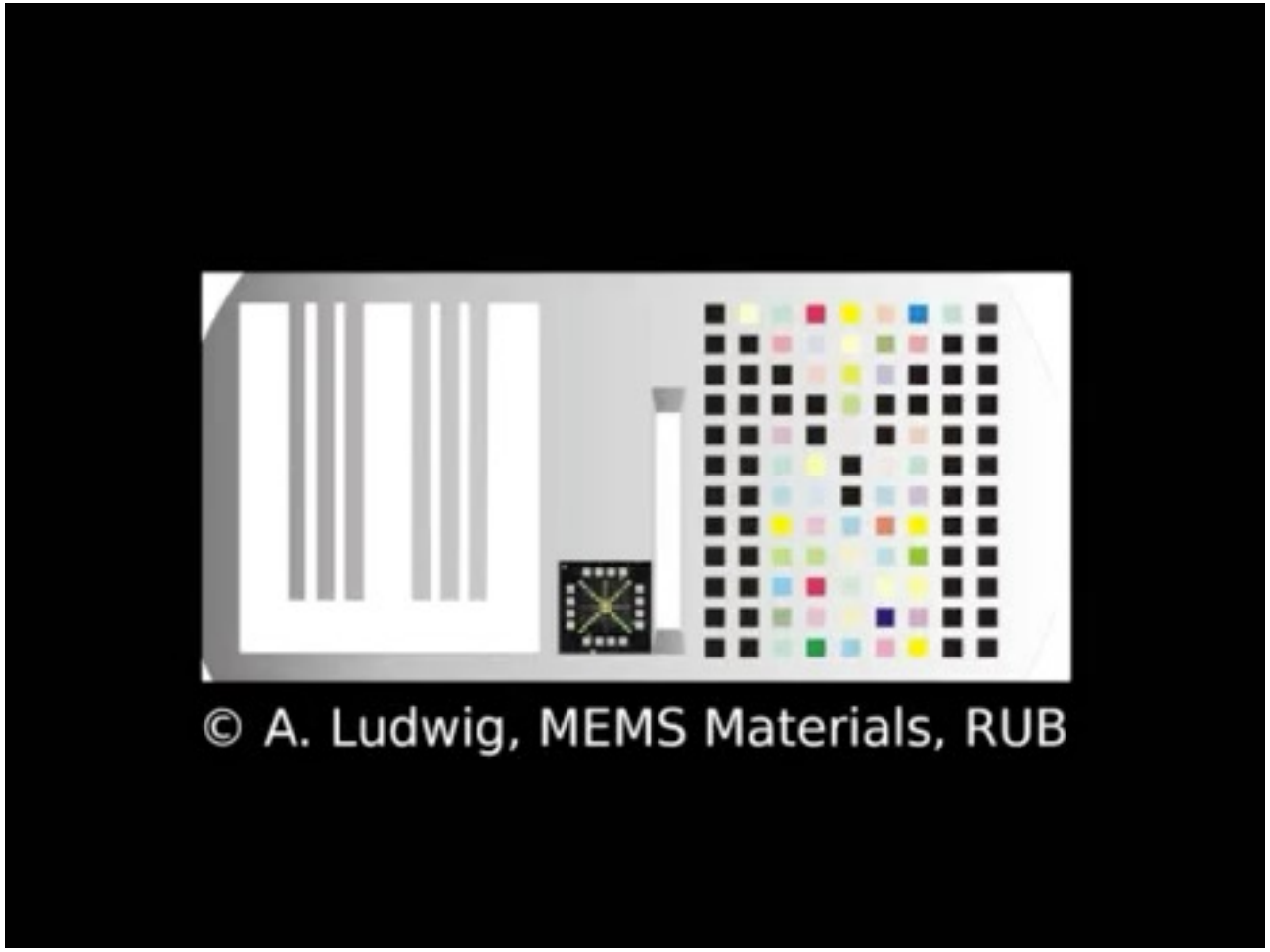
Rapid mapping (screening) of compositional, structural and physical properties

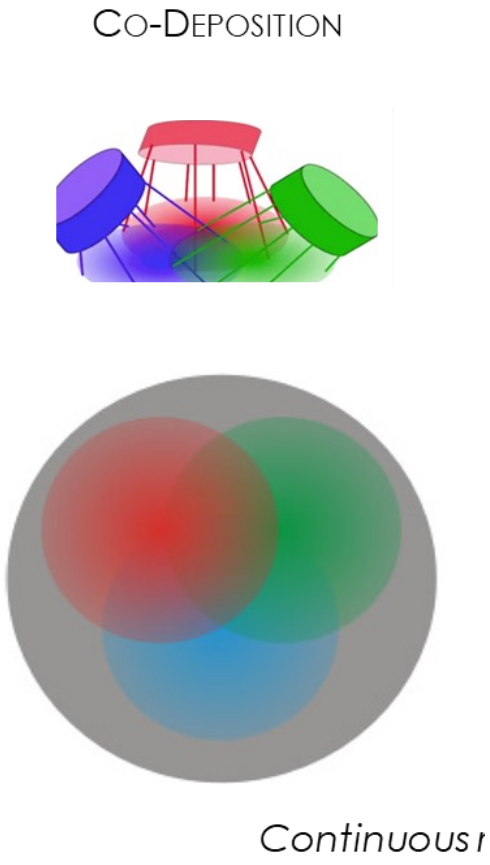
C. Tan et al., Adv. Mater. Technol. 9 (2024) 2302038

M.L. Green et al., JAP 113 (2013) 231101

EMERGING TOOLS AND APPROACHES

Combinatorial Materials Science | **High-throughput Deposition Techniques**

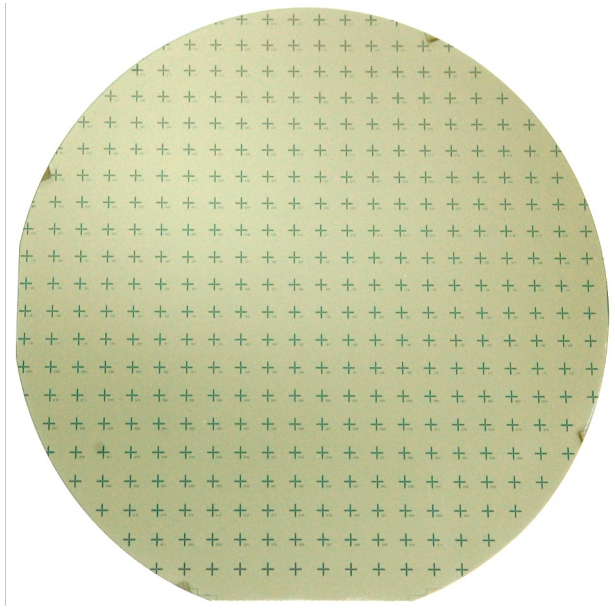


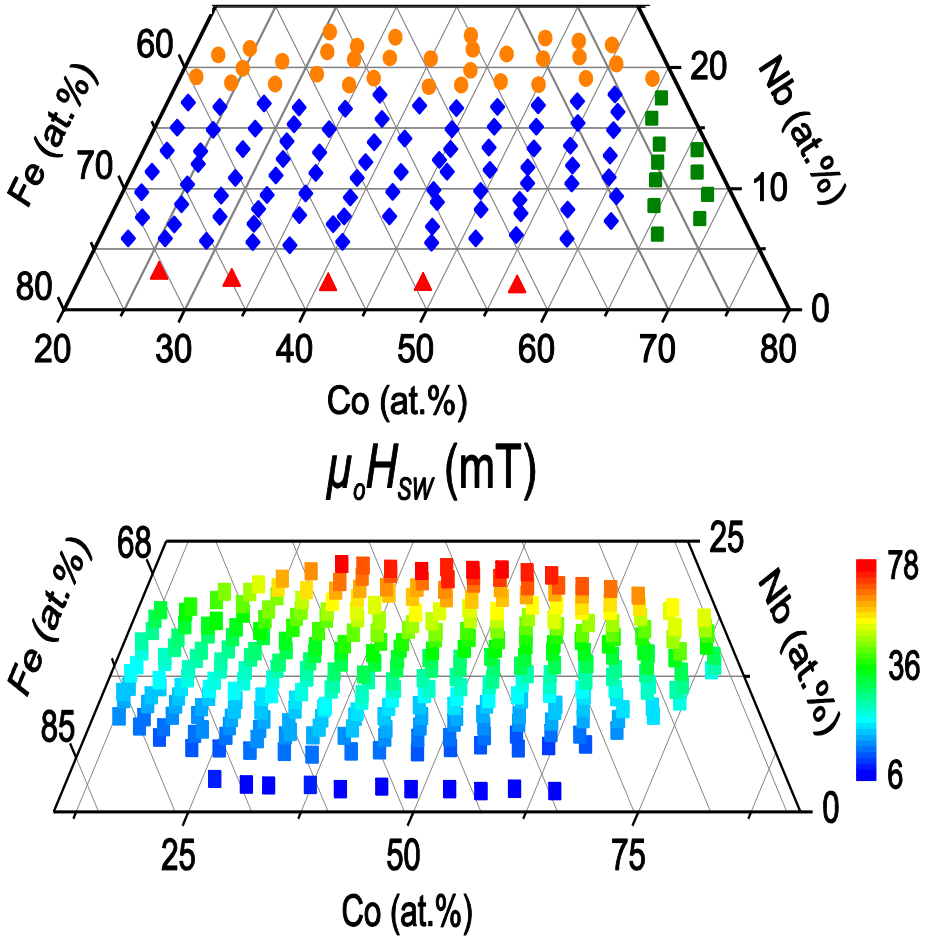


Source: Bochum University (A. Ludwig's Group)

EMERGING TOOLS AND APPROACHES

Combinatorial Materials Science | **High-throughput Characterization Techniques**

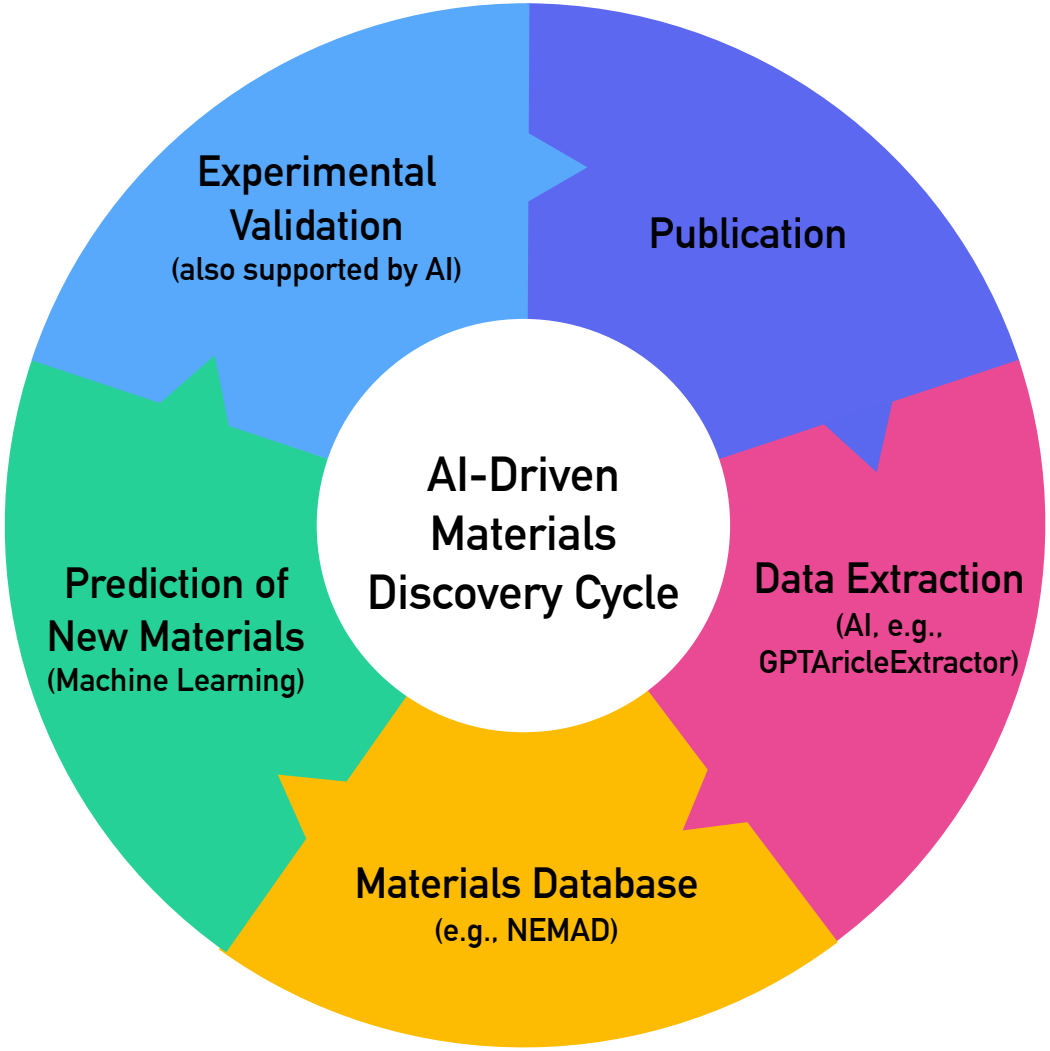




V. Alexandrakis, GV et al., ACS Combinatorial Science 17 (2015) 698

EMERGING TOOLS AND APPROACHES

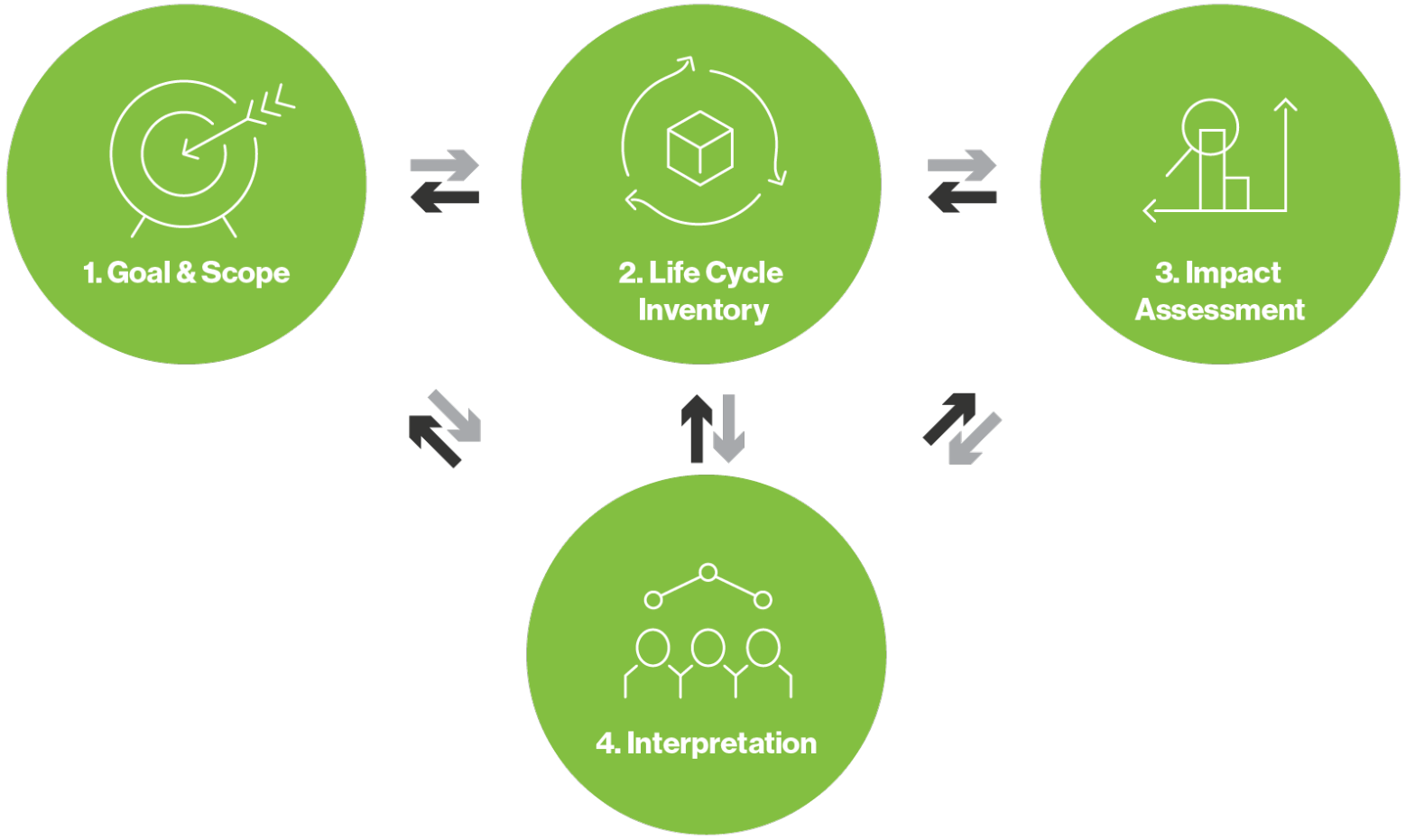
Artificial Intelligence



I. Papadimitriou et al., Computational Materials Science, 235 (2024) 112793

LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a standardized method (governed by the ISO 14040 series) employing mathematical models, large databases, and specialized software to measure a product's environmental effects from its raw materials through disposal



1. Goal and Scope Definition
- Define why the assessment is being done and what it will cover.
- Specify system boundaries, functional unit, and assumptions.

2. Life Cycle Inventory (LCI)
Collect data on energy, materials, water, emissions, and waste for each stage.

3. Life Cycle Impact Assessment (LCIA)
Analyze the potential environmental impacts (e.g., global warming, toxicity, resource depletion).

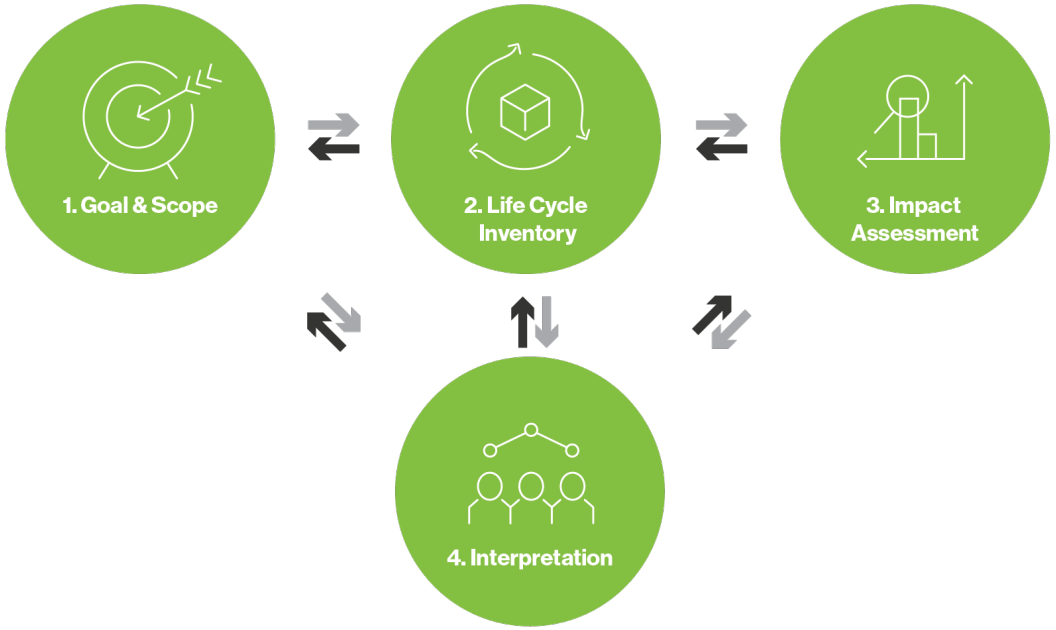
4. Interpretation
- Evaluate results, identify hotspots, and suggest improvements.
- Ensure conclusions are consistent with the goal.

Thamires Martinho Prados et al., Clean Technologies and Environmental Policy 27 (2025) 471

LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a standardized method (governed by the ISO 14040 series) employing mathematical models, large databases, and specialized software to measure a product's environmental effects from its raw materials through disposal

CASE STUDY: PERMANENT MAGNET



1. Goal and Scope Definition

- Goal: Reduce environmental impact of neodymium magnets used in electric motors.
- Functional unit: 1 kg of permanent magnet.
- System boundary: From raw material mining to end-of-life recycling.

2. Life Cycle Inventory

Collect the input data (energy, materials, water, emissions, and waste) for each processing step)

- Raw Material Extraction: Mining of neodymium, iron, boron.
- Processing: Alloy production, magnet shaping, sintering.
- Use Phase: Installed in motors (low maintenance).
- End-of-Life: Recycling or disposal of magnets.

3. Life Cycle Impact Assessment

Analyze the potential environmental impacts (e.g., global warming, toxicity, resource depletion)

- Energy use: High during extraction and sintering.
- Emissions: Mining and refining can release CO_2 and heavy metals.
- Resource depletion: Rare earth elements are limited.

Step 4: Interpretation

- Hotspots: Neodymium mining and processing.
- Improvement: Recycling rare earth elements and optimizing energy use in production.

Thamires Martinho Prados et al., Clean Technologies and Environmental Policy 27 (2025) 471



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A. Monteduro (Un. Salento)
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