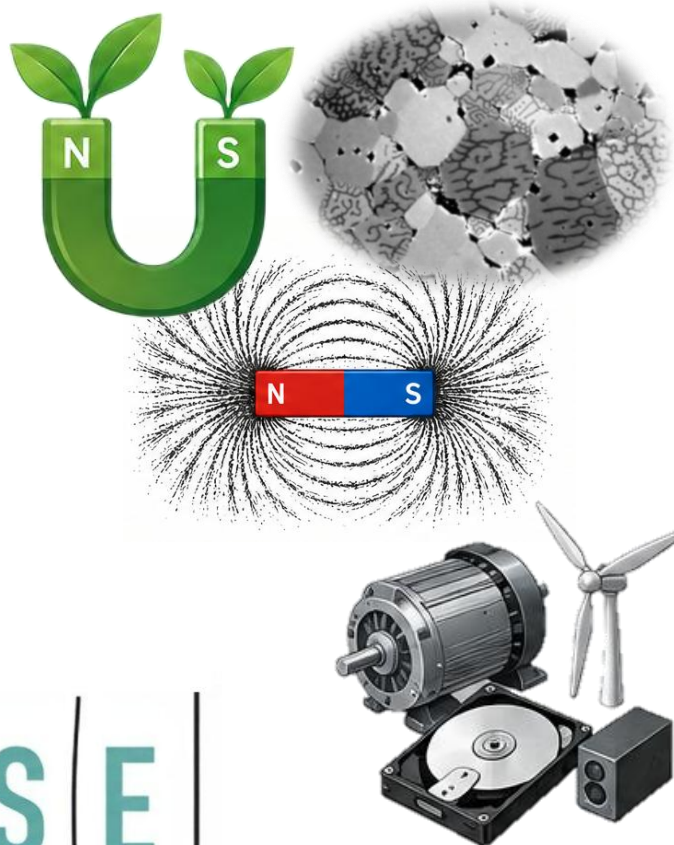




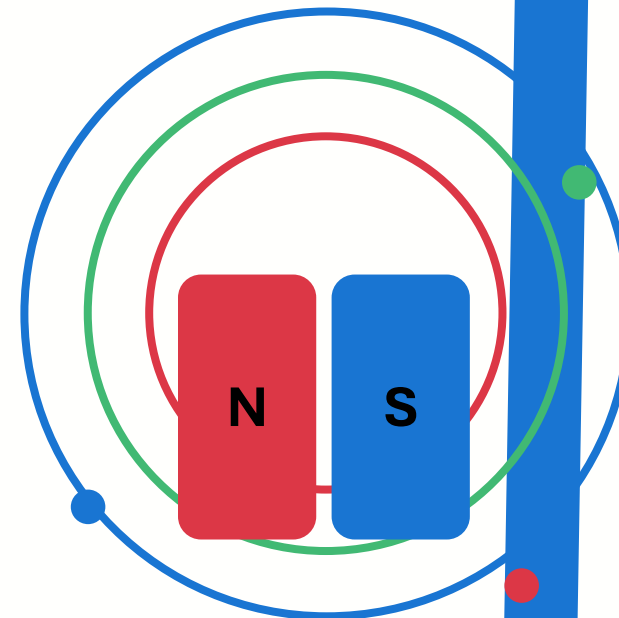
SUSTAINABILITY AND RECYCLING OF MAGNETS

Dr.-Ing. Matic Jovičević-Klug

| M | A | G | S | E | N | S | E |



16.09.2026, Jena

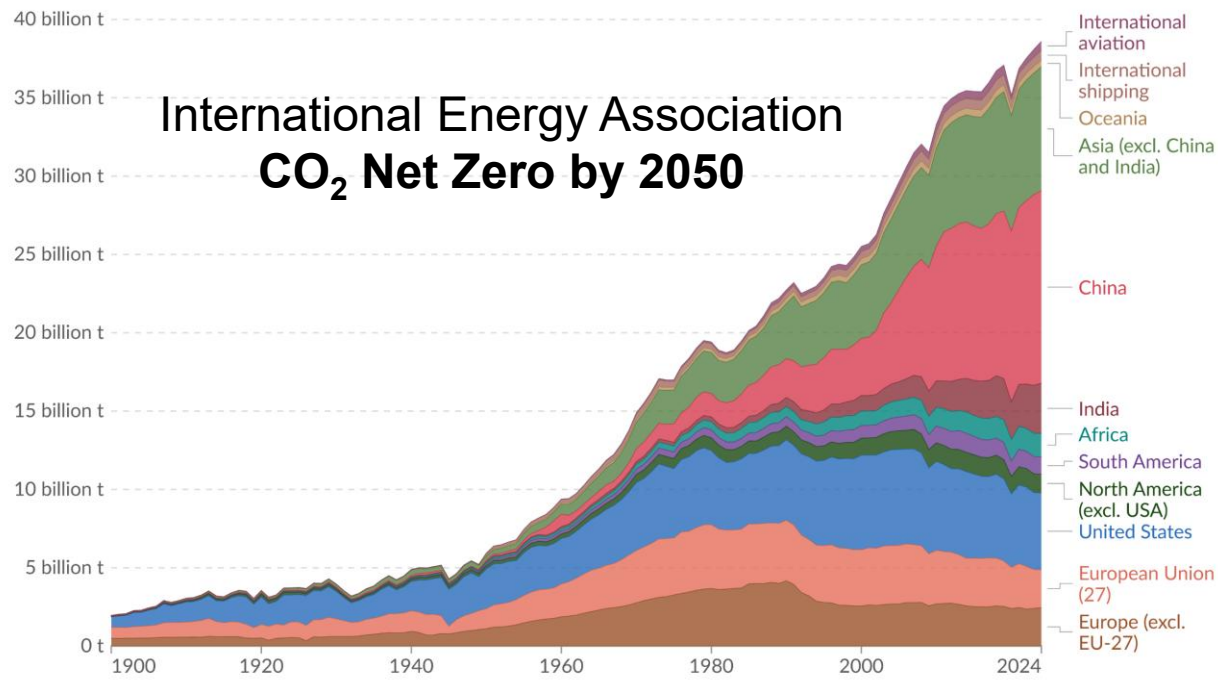




Motivation: GHGs and global warming

Annual CO₂ emissions by world region

Emissions from fossil fuels and industry¹ are included, but not land-use change emissions². International aviation and shipping are included as separate entities, as they are not included in any country's emissions.



Data source: Global Carbon Budget (2025)

OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

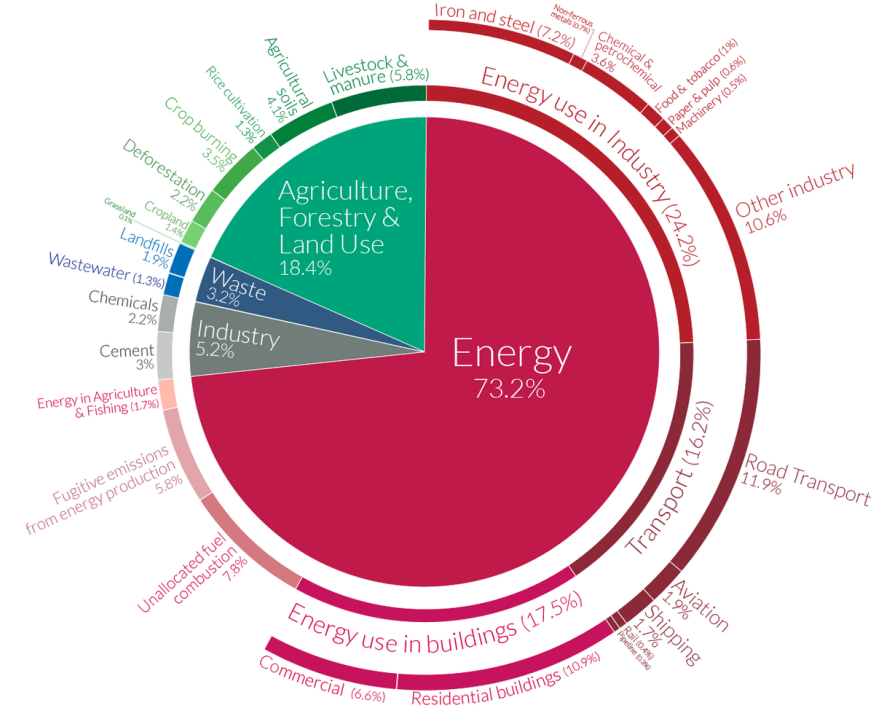
<https://ourworldindata.org/co2-emissions>

We need **BIG & FAST** changes

Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO₂eq.

Our World in Data

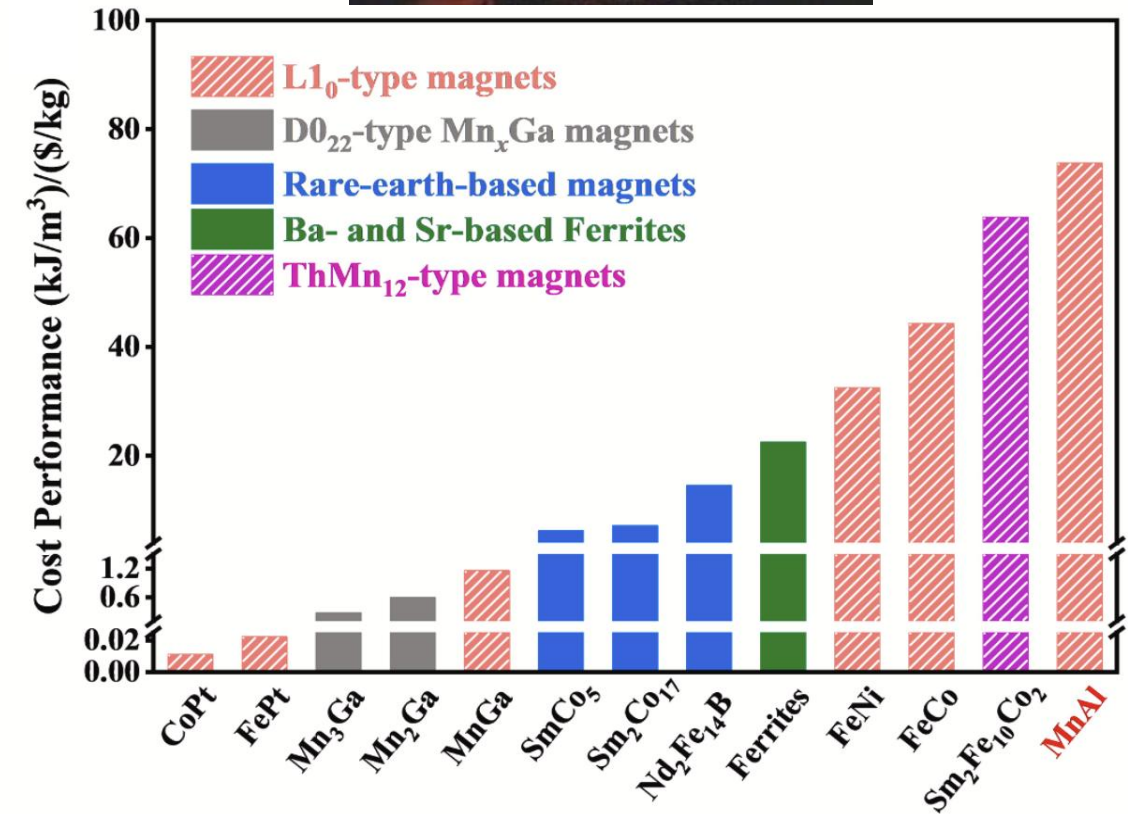
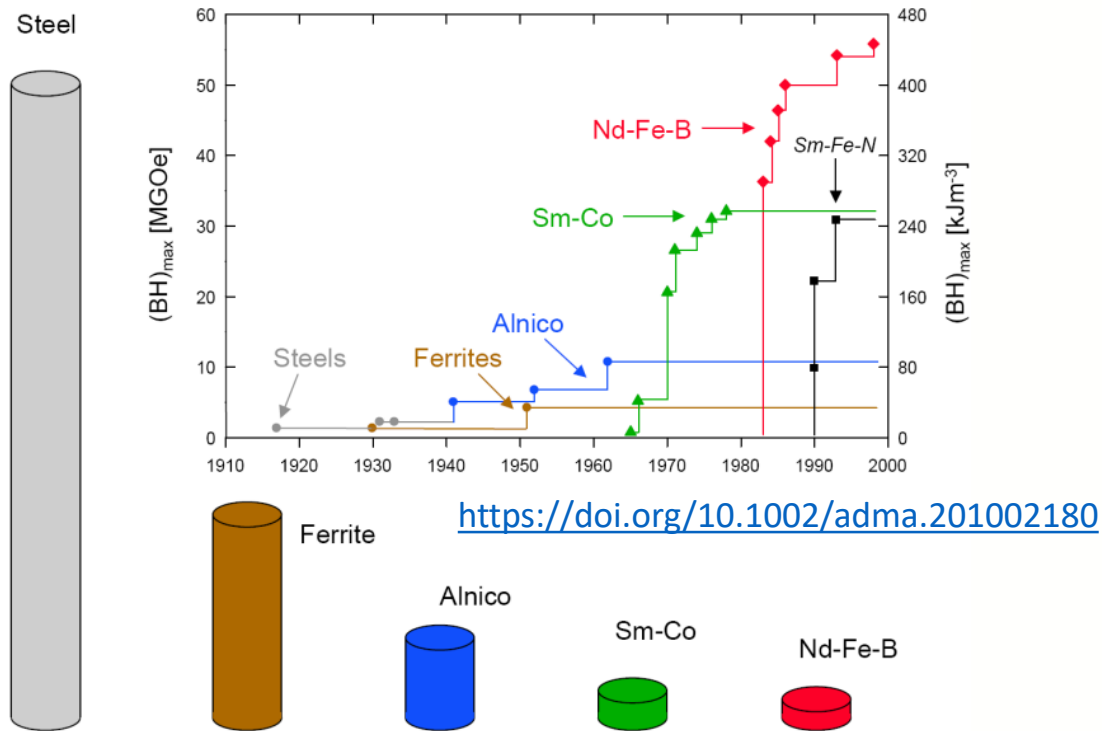


OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020).
Licensed under CC-BY by the author Hannah Ritchie (2020).

<https://www.visualcapitalist.com/a-global-breakdown-of-greenhouse-gas-emissions-by-sector/>

Urgent decarbonization: sustainable energy production systems and urban mobility

What can we use?

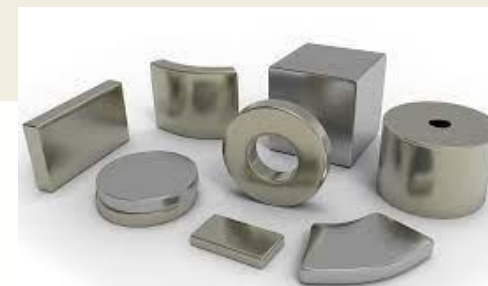
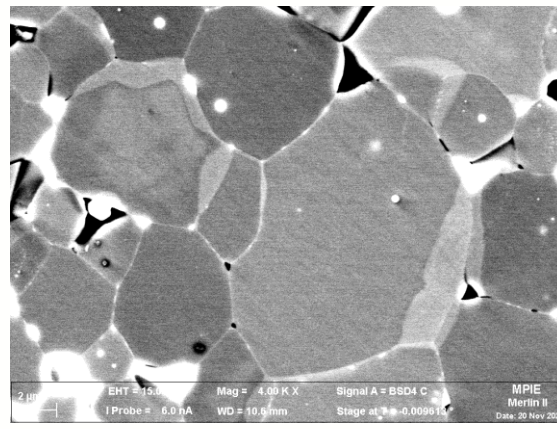
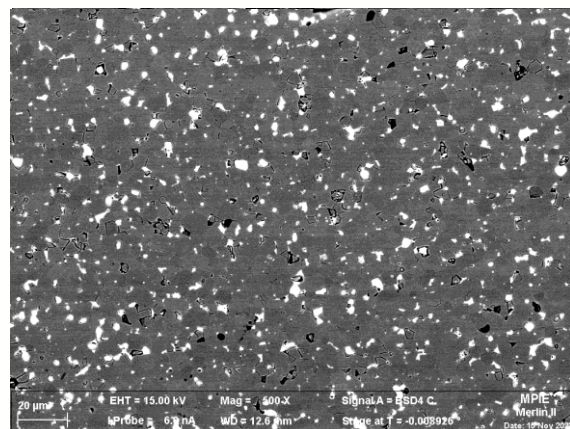
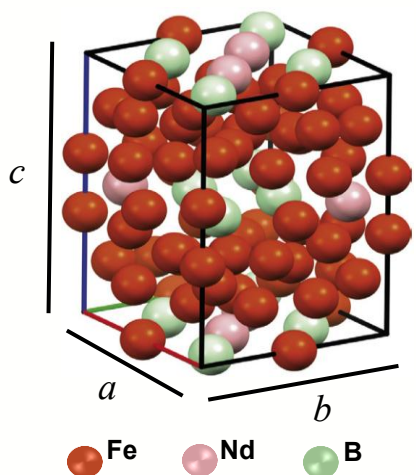


- Benchmark Nd-Fe-B type rare earth permanent magnet
- Unchallenged material on the market for high-performance magnets, since its invention
- However, for the metric “cost performance” several alloys surpass Nd-Fe-B

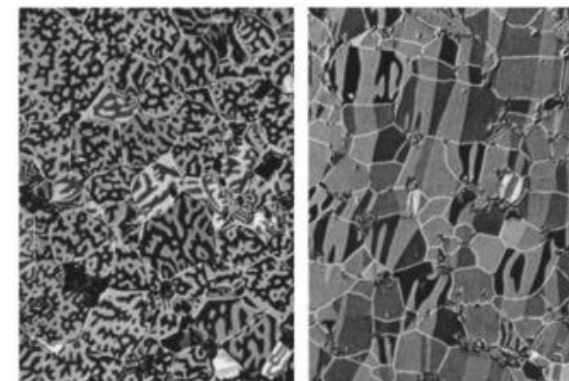
<https://doi.org/10.1016/j.actamat.2022.118654>

“The gold standard” $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets

- Non-symmetrical crystal structures
- Elevated intrinsic magnetic properties, essential for PMs – **large hysteresis, BH_{max}**

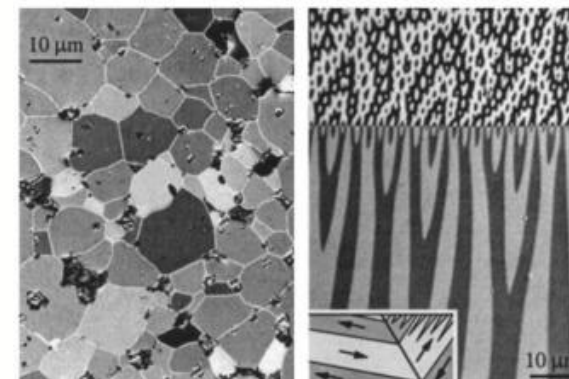


A very sensitive and intricate scientific and engineering construct



(a)

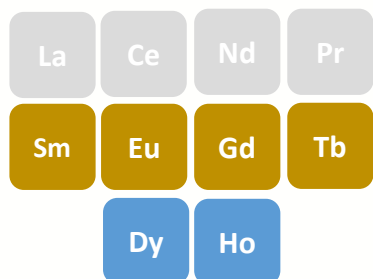
(b)



(c)

(d)

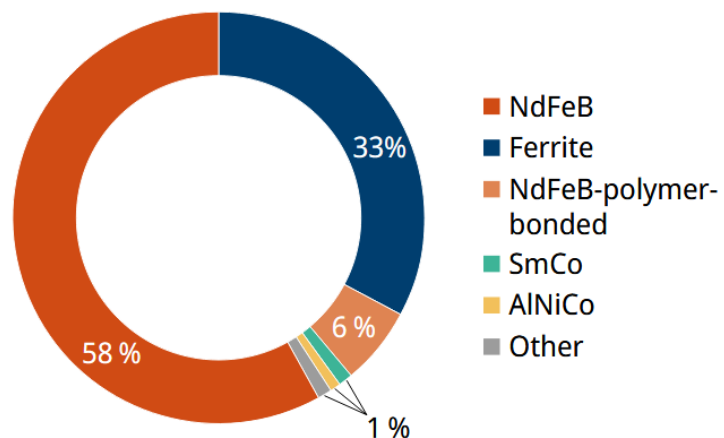
Element or phase	K_1 (MJ/m ³)	H_A (T)	κ
Fe	0.048	-	0.1
Co	0.41	-	0.4
$\text{BaFe}_{12}\text{O}_{19}$	0.33	1.7	1.3
$\text{Nd}_2\text{Fe}_{14}\text{B}$	4.9	7.7	1.5
SmCo_5	17.2	40	4.3



<https://doi.org/10.1016/B978-0-323-88658-1.00003-0>

<https://doi.org/10.1016/B0-08-043152-6/00893-7>

Permanent magnets – why do we need them?



<https://www.deutsche-rohstoffagentur.de>:

DERA Rohstoffinformationen 60

Material	Market share – value in 2022 (EUR)	Market value in 2022 (EUR)	Predicted market value in 2030 (EUR)
Nd-Fe-B	14 B	23 B	40 B
Ferrites	7.6 B		
Sm-Co	230 M		
Alnico	230 M		
Others	230 M		

Wind turbines

500 – 600 kg of Nd-Fe-B magnets per MW



EV/HEV/PHEVs powertrains

~ 1.5-5 kg of Nd-Fe-B magnets per unit

MRI

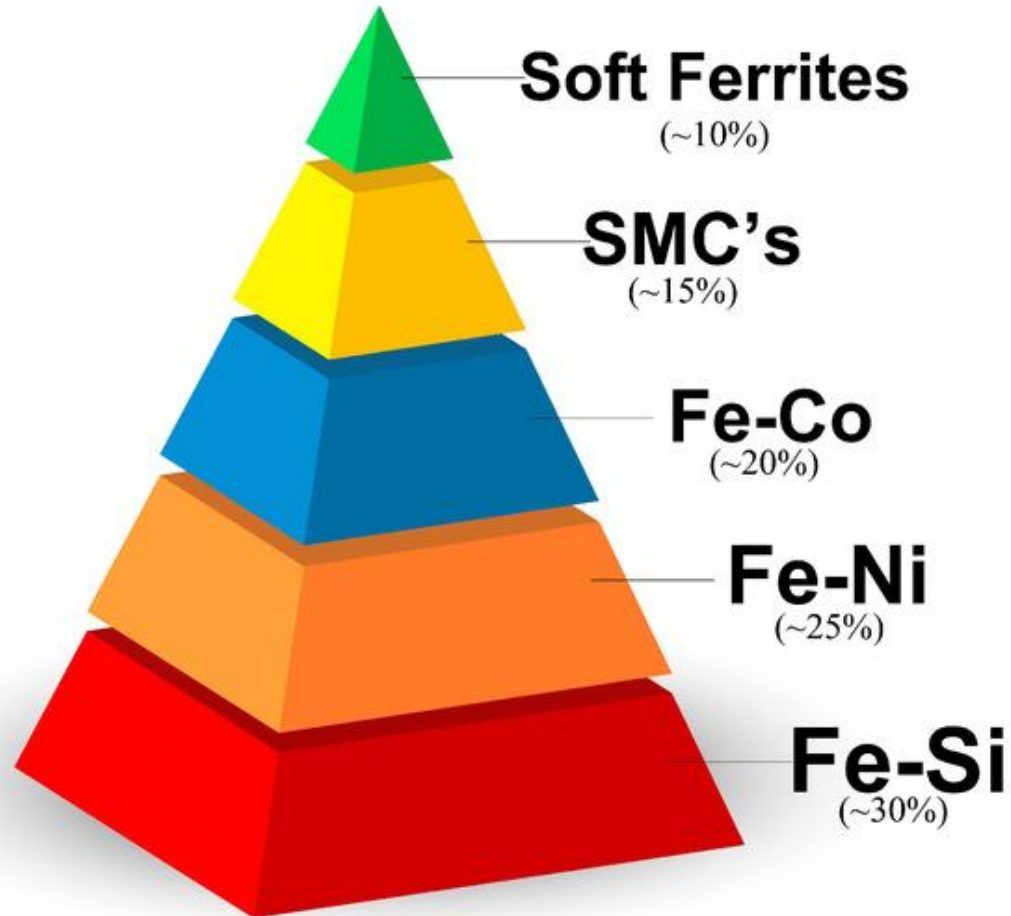
2500 kg of Nd-Fe-B magnets



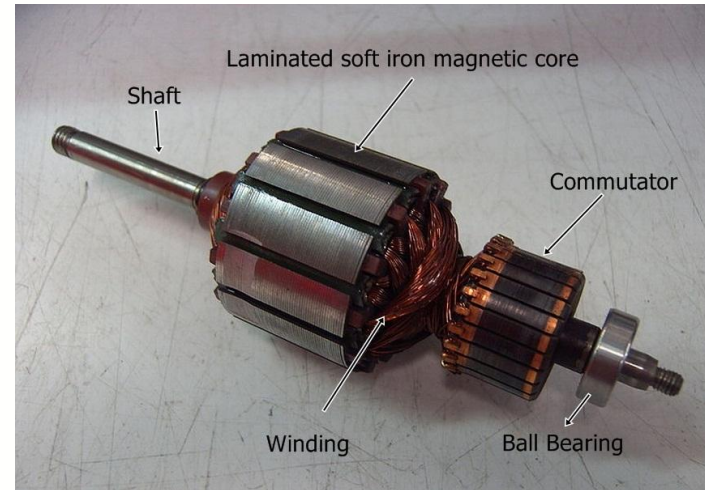
But we produce much more ferrites than NdFeB magnets!

<https://commons.wikimedia.org>

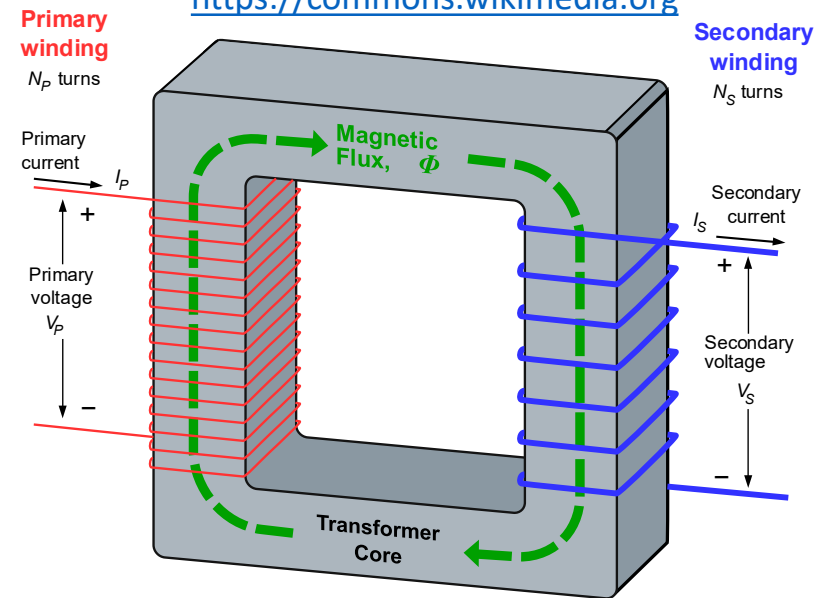
So, let's not forget soft magnets!



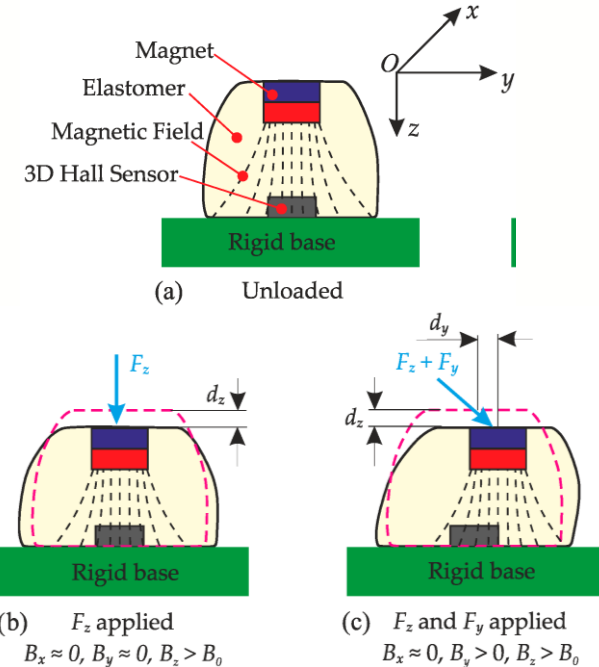
<https://doi.org/10.3390/ma16165610>



<https://commons.wikimedia.org>



<https://commons.wikimedia.org>



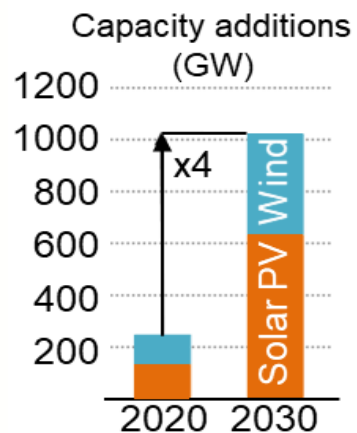
<https://www.mdpi.com/1424-8220/16/9/1356>

DC applications:
• **high permeability**

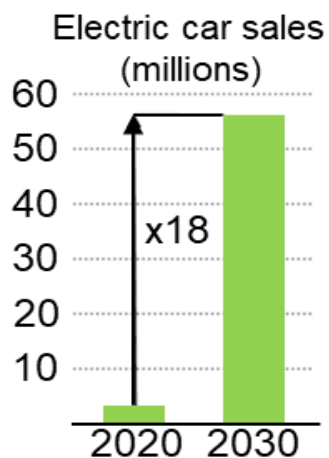
AC applications:
• **low energy loss**

LOW COERCIVITY!

The rising need of magnets

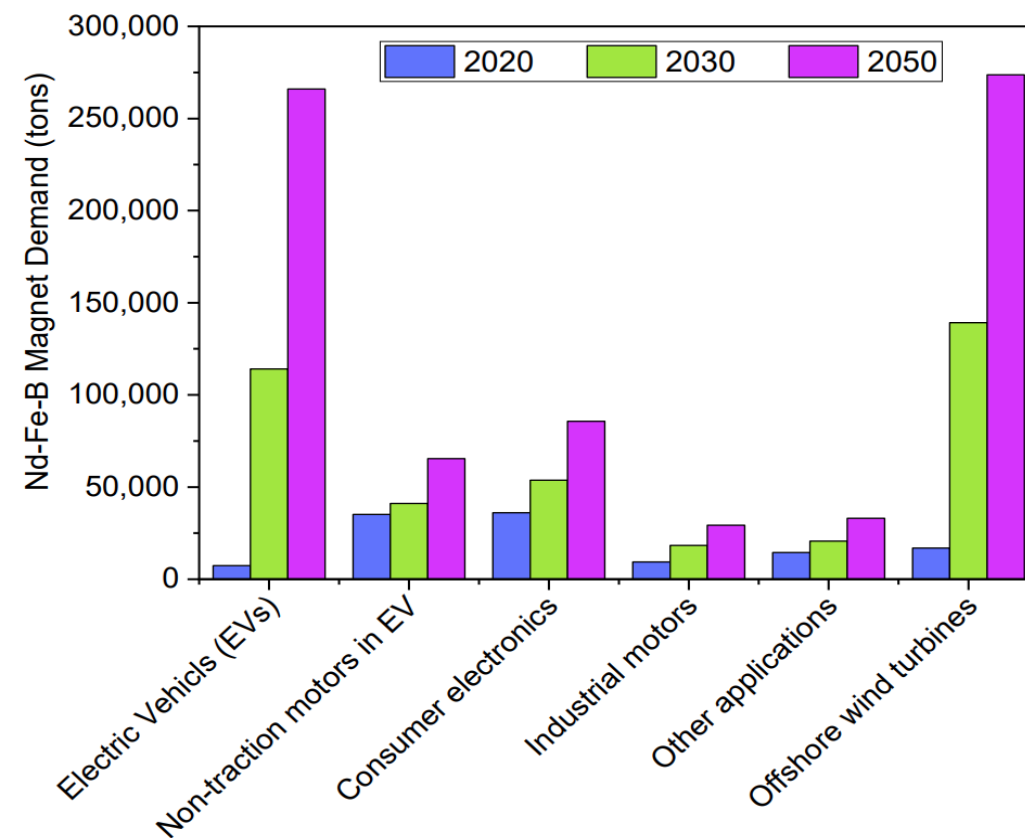


- **By 2030:**
 - **4-fold** increase of solar and wind energy systems
 - **18x more** electric/hybrid vehicles worldwide



More raw materials for functional materials production

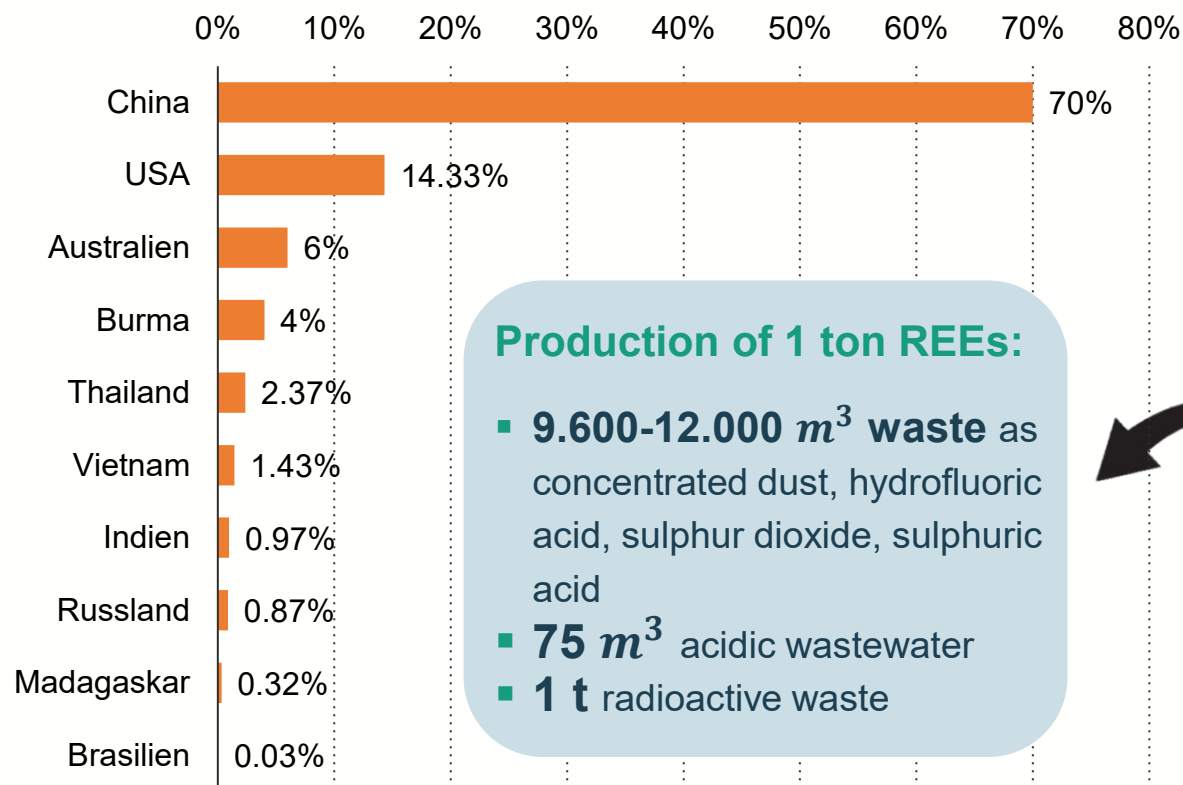
Development of new materials



<https://doi.org/10.11604/pamj.2018.30.240.14000>

Global production and CO₂

Global REE production¹

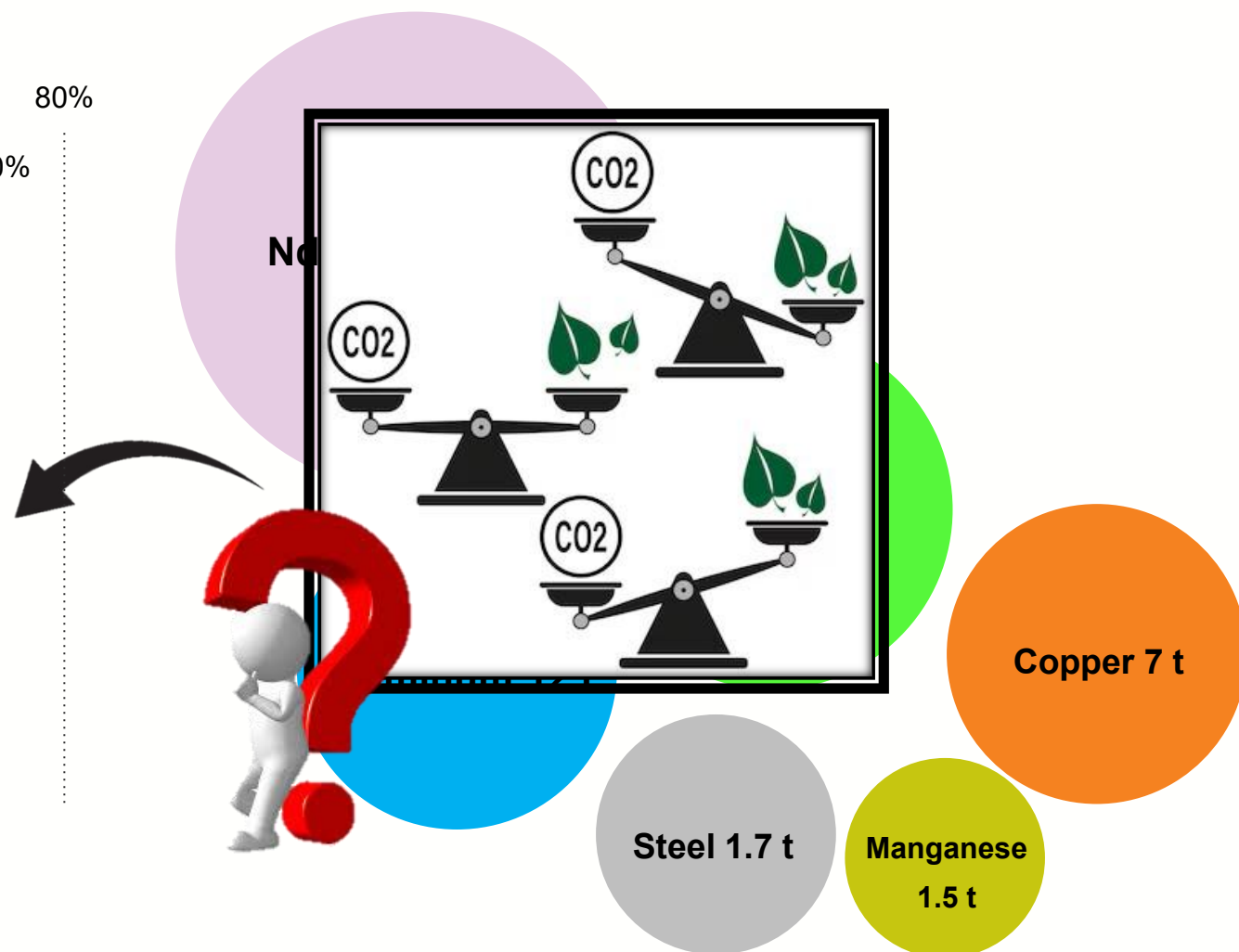


Production of 1 ton REEs:

- **9.600-12.000 m³ waste** as concentrated dust, hydrofluoric acid, sulphur dioxide, sulphuric acid
- **75 m³** acidic wastewater
- **1 t** radioactive waste

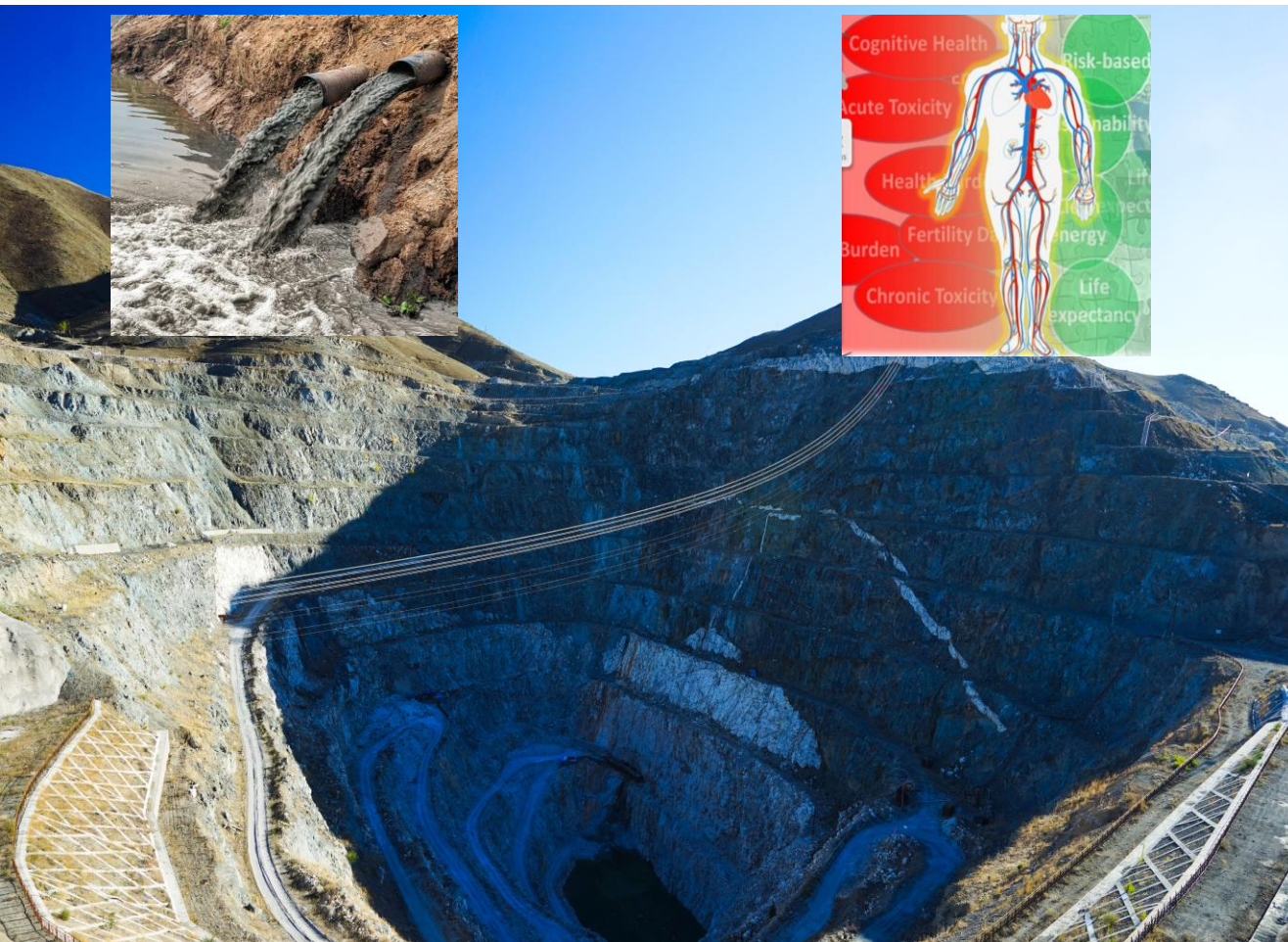
Source: US Geological Survey; [ID 281730](#)

CO₂ emissions per tonne

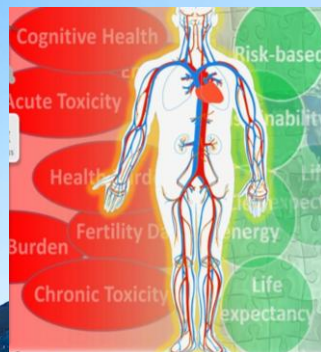


Environmental impact

Pollution



Health risks



Chemical processing alone:

40-70% of CO₂

40 – 75 t CO₂-eq

500-780 Mt of earth and ore excavation per year!



Acids such as HCl, H₂SO₄, and HNO₃

<https://doi.org/10.1021/acssuschemeng.7b04165>

Huge irreversible consequences

Sources depletion, lower ore quality will make it worse!

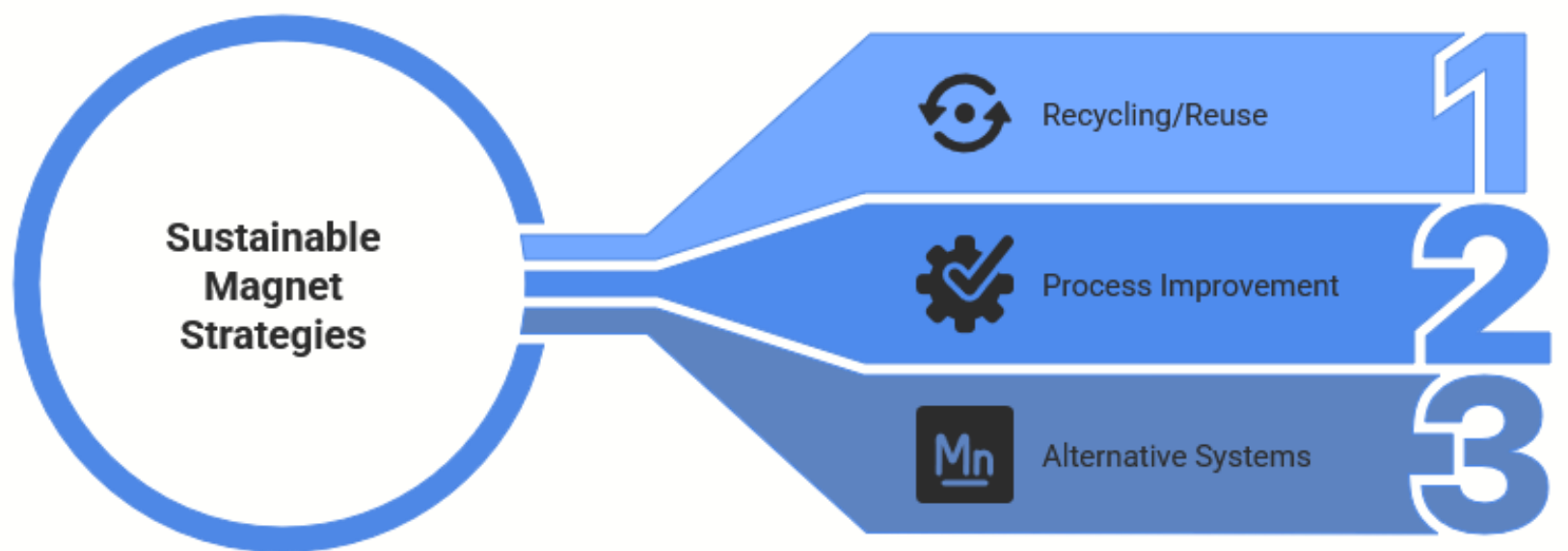
Energy demand for producing REE & recycling rates

																		MJ/kg												He			
H																		1x10 ¹ --1x10 ²	1x10 ² --1x10 ³	1x10 ³ --1x10 ⁴													-
Li	Be																	1x10 ⁴ --1x10 ⁵	1x10 ⁵ --1x10 ⁶	1x10 ⁶ --1x10 ⁷													Ne
69	5,724																																-
Na	Mg																																Ar
-	199																																-
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co ^{Cu}	Ni	Cu	Zn ^{Pb}	Ga ^{Al}	Ge	As	Se ^{Cu}	Br	Kr																
-	-	-	321	-	265	34	24	156	145	23	19	786	-	75	13,115	-	-																
Rb	Sr	Y ^{REE}	Zr	Nb	Mo ^{Cu}	Tc	Ru	Rh ^{PGM}	Pd ^{PGM}	Ag [*]	Cd ^{Zn}	In ^{Zn}	Sn	Sb	Te ^{Cu}	I	Xe																
-	27	378	410	75	88	-	-	1,558,329	122,789	11,246	14,171	27,716	64	34	217,825	-	-																
Cs	Ba	Lu ^{REE}	Hf	Ta	W	Re	Os	Ir	Pt ^{PGM}	Au	Hg	Tl	Pb ^{Zn}	Bi	Po	At	Rn																
-	24	14,184	-	1,195	161	-	-	-	76,135	243,437	125	-	10	-	-	-	-																
Fr	Ra	Lr	Rf	Db	Sq	Bh	Hs	Mt	Ds	Rq	Cn	Nh	Fl	Mc	Lv	Ts	Og																
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-																
La ^{REE}	Ce ^{REE}	Pr ^{REE}	Nd ^{REE}	Pm	Sm ^{REE}	Eu ^{REE}	Gd ^{REE}	Tb ^{REE}	Dy ^{REE}	Ho ^{REE}	Er ^{REE}	Tm ^{REE}	Yb ^{REE}																				
473	166	2,240	562	-	1,092	5,011	1,354	7,179	1,455	5,778	2,123	13,132	2,088																				
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No																				
-	-	-	-	-	-	-	-	-	-	-	-	-	-																				

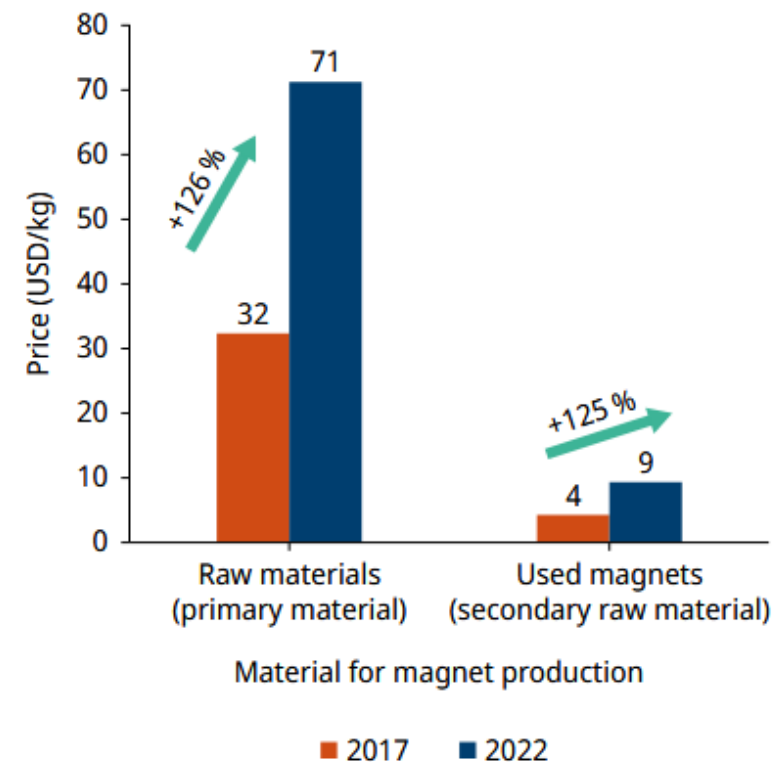
MJ/kg					
1x10 ¹ --1x10 ²	1x10 ² --1x10 ³	1x10 ³ --1x10 ⁴			
1x10 ⁴ --1x10 ⁵	1x10 ⁵ --1x10 ⁶	1x10 ⁶ --1x10 ⁷			

1																	2
H																	He
3	4											5	6	7	8	9	10
Li	Be											B	C	N	O	F	Ne
11	12											13	14	15	16	17	18
Na	Mg											Al	Si	P	S	Cl	Ar
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
55	56	*	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
87	88	**	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr	Ra		Rf	Db	Sg	Sg	Hs	Mt	Ds	Rg	Uub	Uut	Uug	Uup	Uuh	Uus	Uuo
* Lanthanides			57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
** Actinides			89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Exploring Sustainable Magnet Strategies



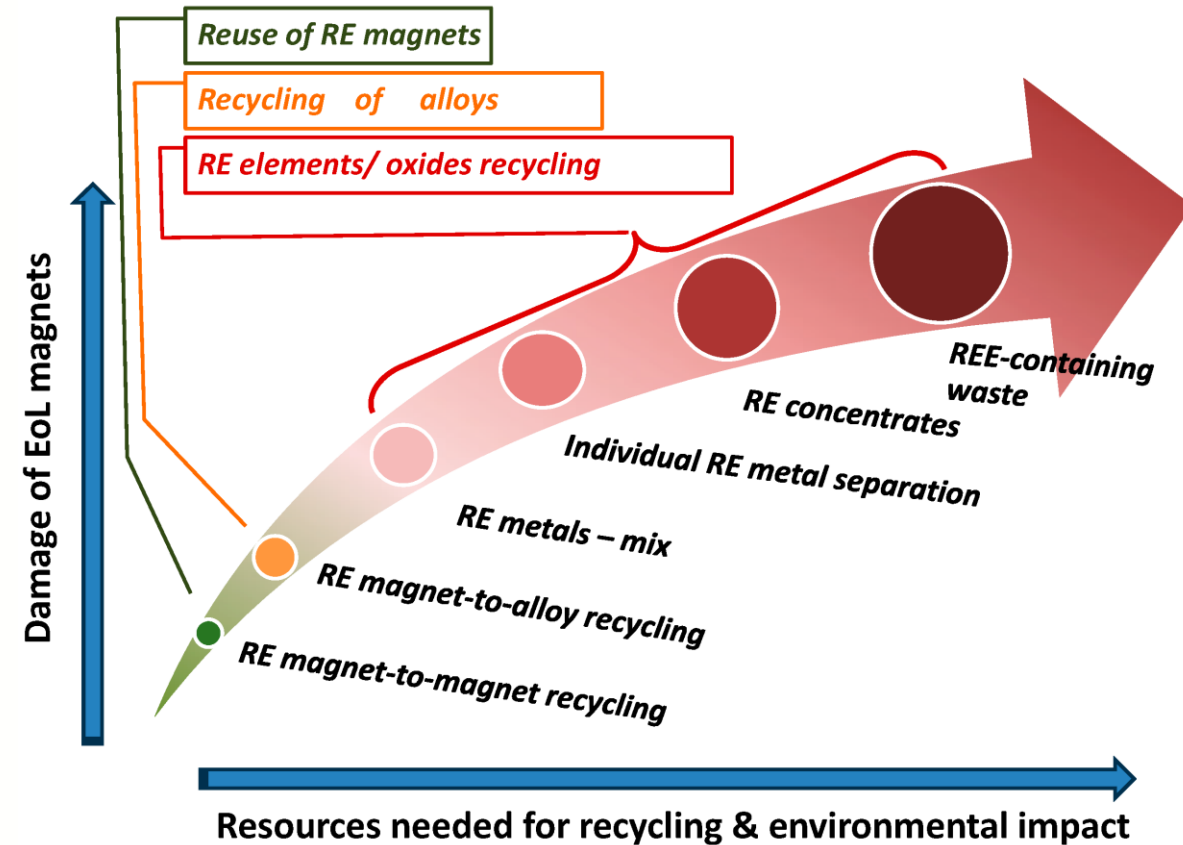
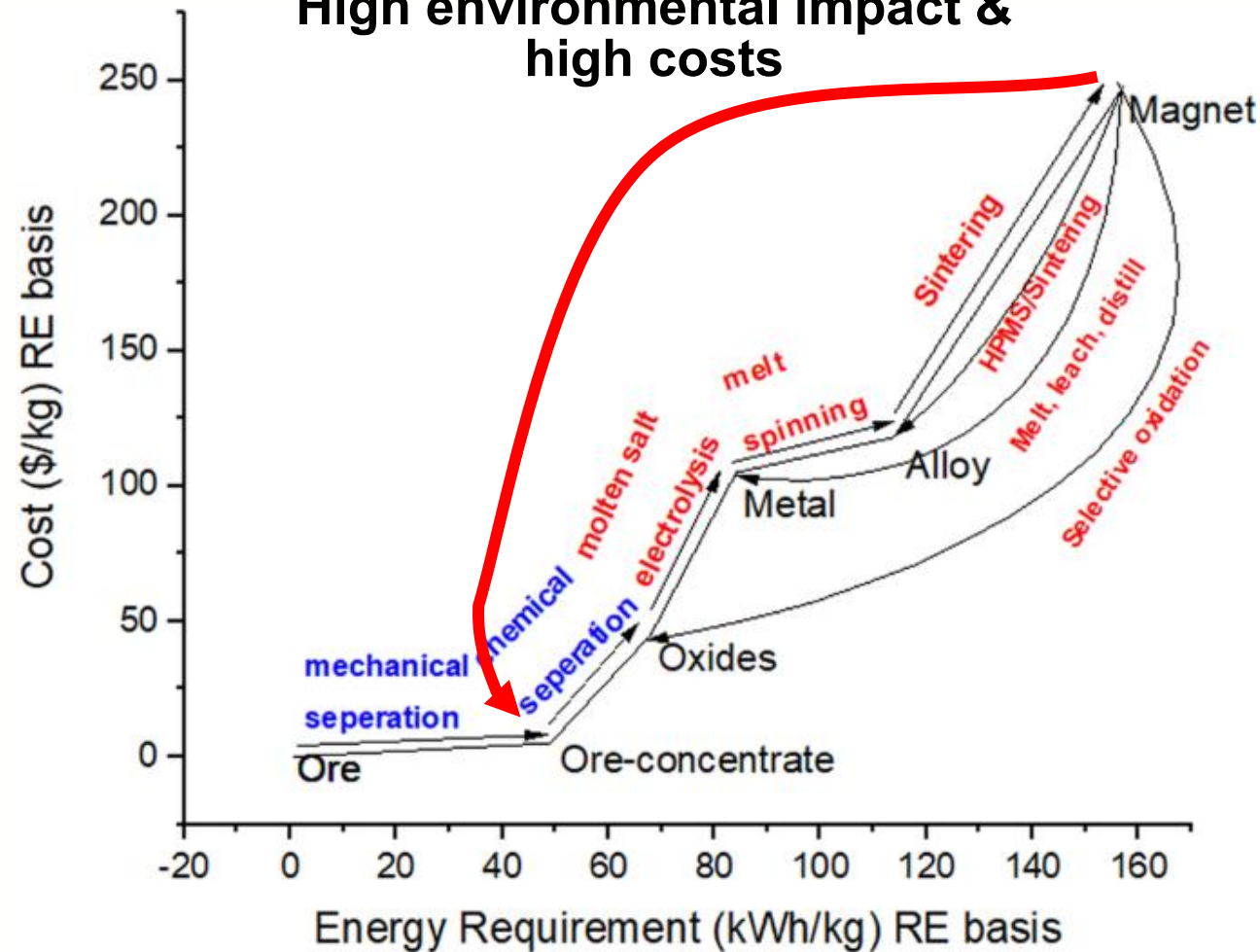
Made with Napkin



<https://www.deutsche-rohstoffagentur.de>

Recycling potential

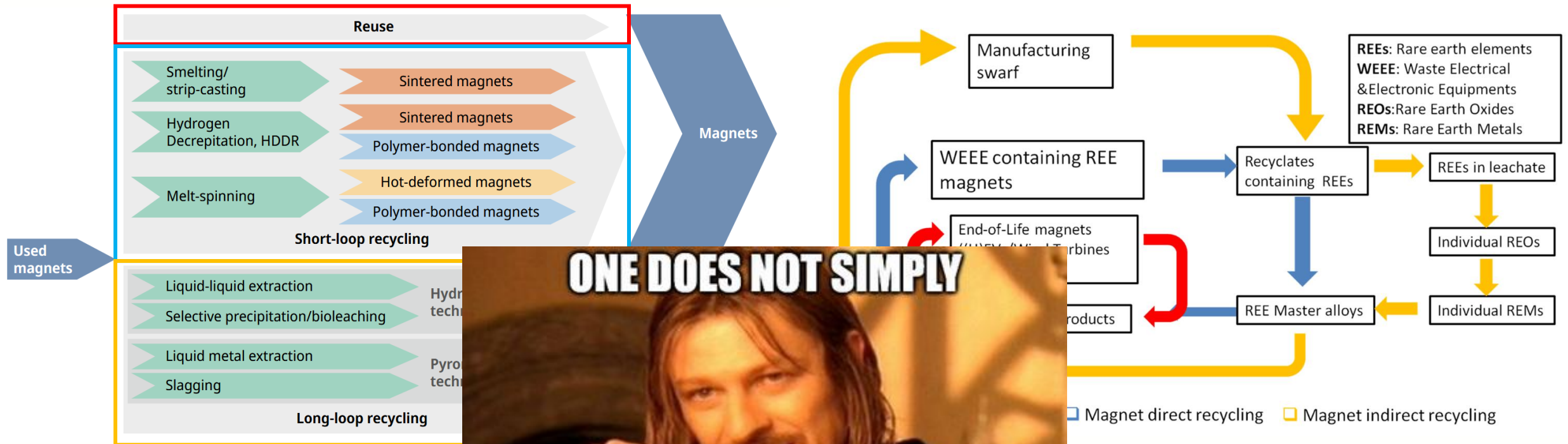
High environmental impact & high costs



<https://doi.org/10.3390/met14060658>

The loops of recycling

Recycling



<https://www.deutsche-rohstoffe.de>

<https://doi.org/10.1051/epjap/2019180289>



Short-loop recycling

- **HD**

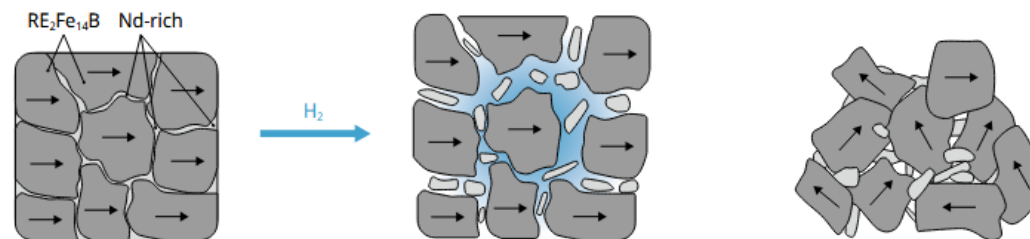
Hydrogen decrepitation

- **HDDR**

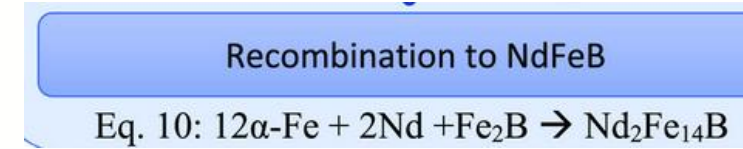
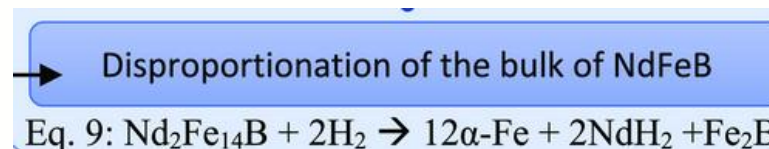
Hydrogenation disproportionation desorption and recombination

- **HPMS**

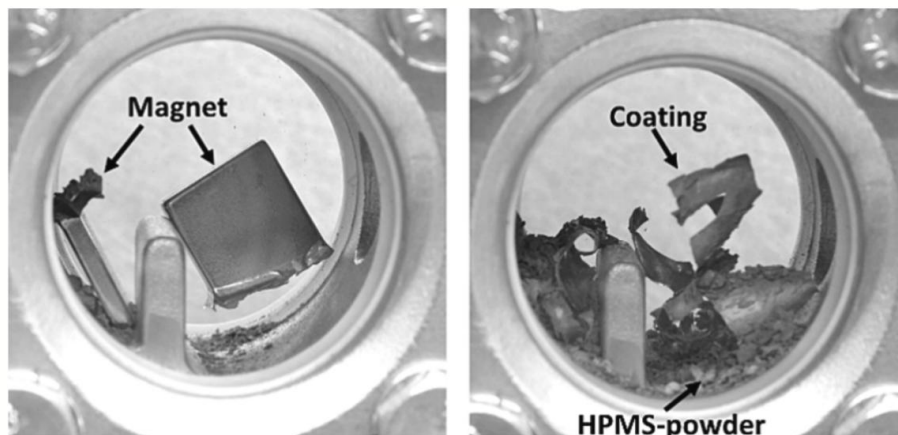
Hydrogen Processing of Magnetic Scrap



<https://www.deutsche-rohstoffagentur.de>, <https://www.youtube.com/watch?v=0OivtRfarVQ>



<https://doi.org/10.1021/acsomega.3c00299>

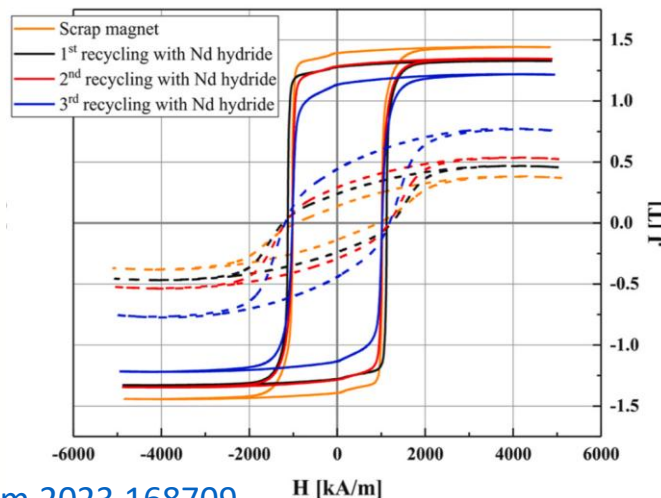
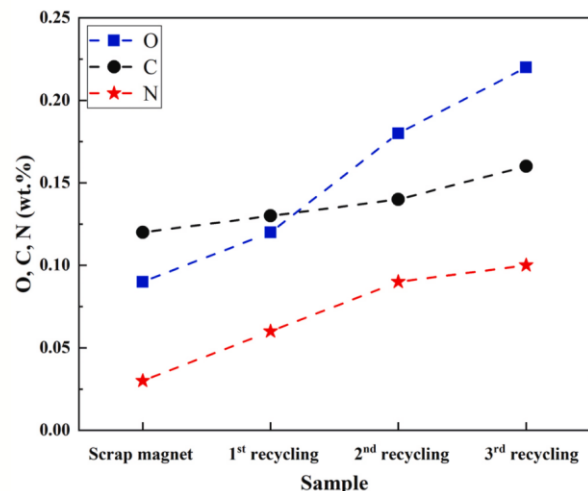


<https://doi.org/10.1016/j.jmmm.2023.171475>

Production of 1 kg of recycled sintered magnets vs primary production

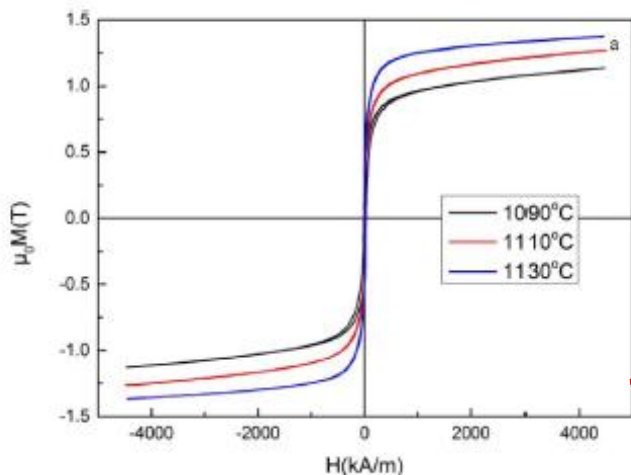
- 80% less CO₂ emissions
- 60% less energy consumption
- 70% less water needed

Shortfalls of (classical) hydrogen-based recycling

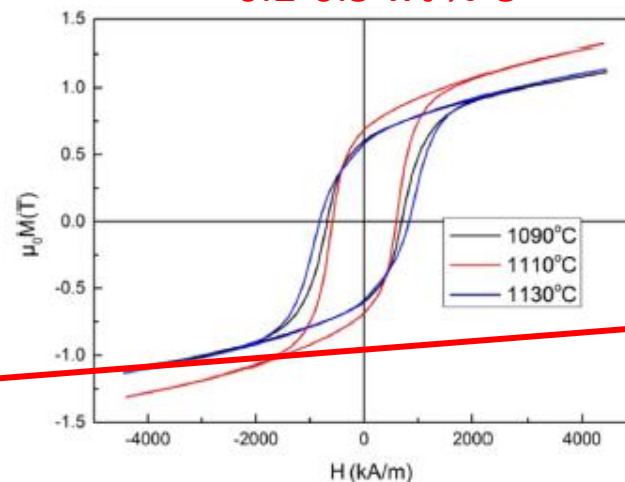


<https://doi.org/10.1016/j.jallcom.2023.168709>

> 4 wt % O



0.2-0.5 wt % O



Will this be possible after 3-4 recycling cycles?

Progressive oxygen/nitrogen contamination during recycling – limiting factor

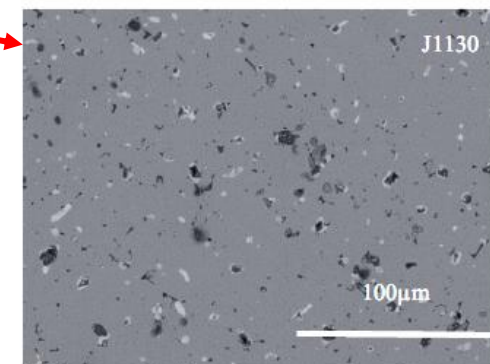
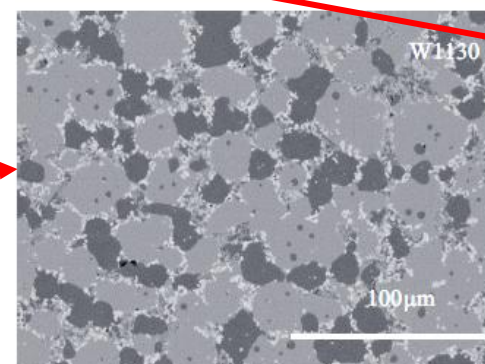
- 1 - Addition of RE-hydrides
- 2 - RE-rich phase replacement
- 3 – cannot remove contamination (C)

Use of recycled material is still **more sustainable - costs, energy and resources consumption**

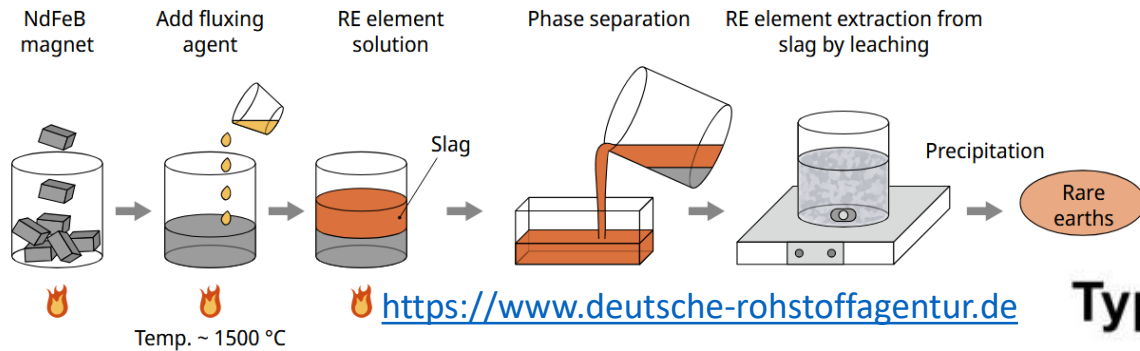
REEs from primary sources are still required!

< 600 ppm of O is ideal

< 800 ppm of C is ideal

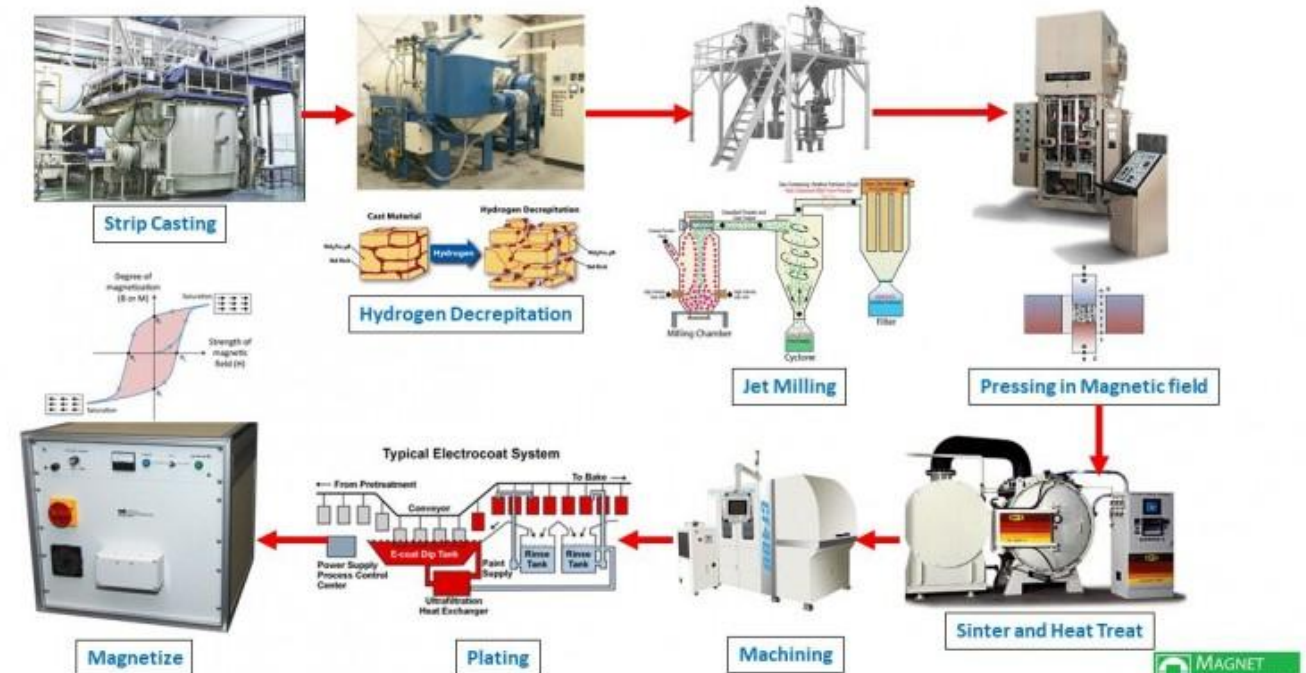


Short-loop recycling - smelting



Liquid metal extraction also possible, but expensive!

Typical Powder Metallurgical Processing of NdFeB



<https://doi.org/10.1007/s40831-016-0090-4>

Fast process, energy intensive
But potentially low CO₂ and large mass!

Universal, but not selective
– intrusions with metals is a problem

Losses can be high (20-30% of REE)

Reduce O content 5000 ppm to 300 ppm
Combine with long-loop recycling

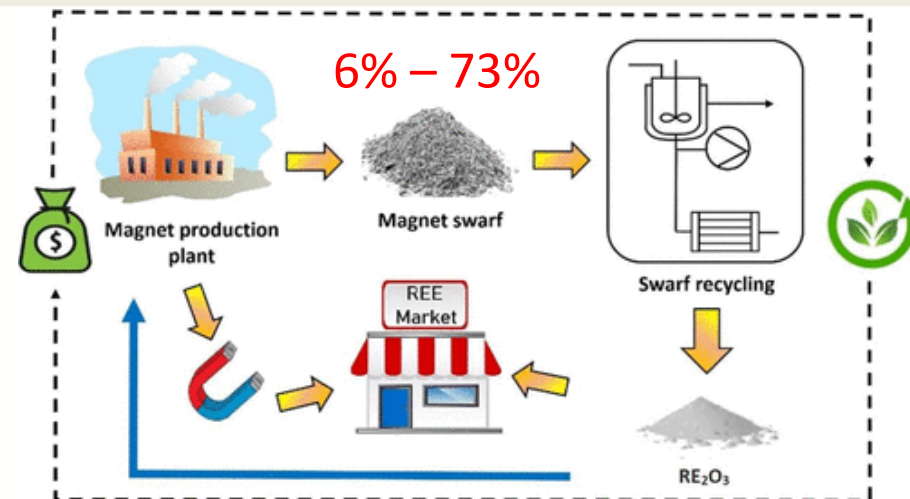
REEs from primary sources are still required!

Long-loop recycling: swarf and oxide waste

VALOMAG Project



<https://doi.org/10.3390/materproc2021005074>



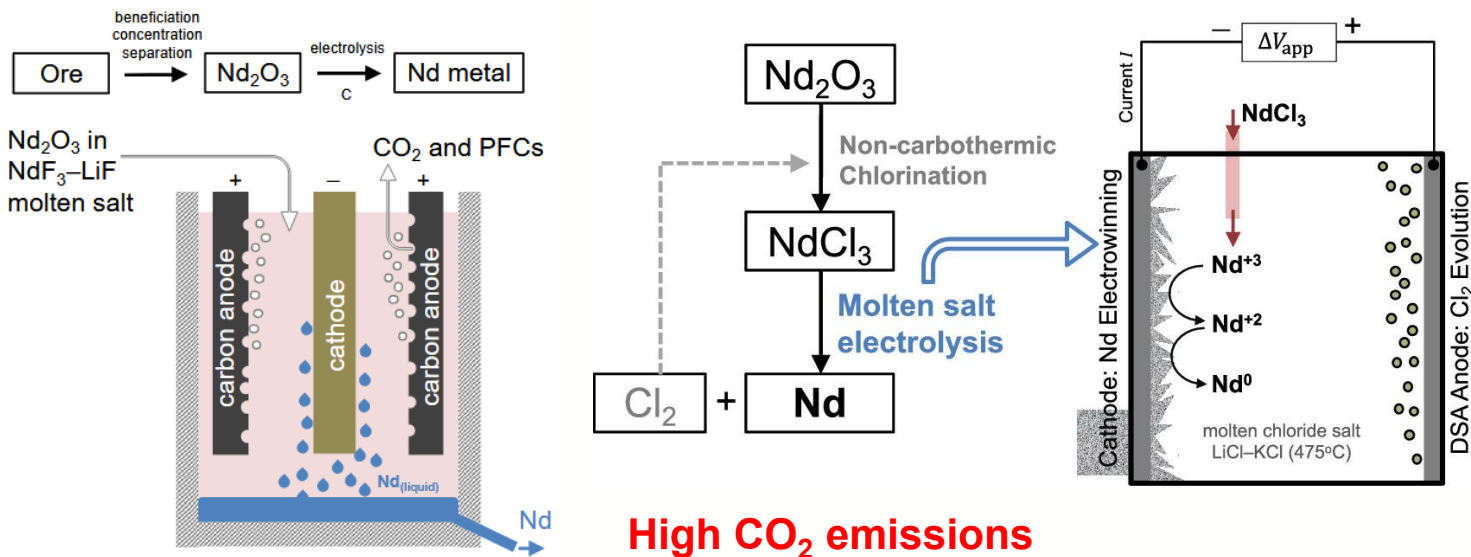
<https://doi.org/10.1021/acssuschemeng.1c05965>

The challenge of oxidized material and waste

- Swarf and sludge from polishing and grinding: **15 % in EU, 40 % in China**
- Material mostly oxidized (**5-6 wt.% of O**) → treatment as RE ores
- **HPMS and HDDR method cannot be used** (inability to purify material)
- Energy intensive and high amounts of CO₂ (**11 tons CO₂ per ton of NdFeB more**)
- **But more sustainable than primary sourcing with economic benefit!**
- **> 300,000 tons NdFeB stockpile**

<https://doi.org/10.1016/j.jenvman.2025.126513>

Long-loop recycling – molten salt electrolysis, metallothermic and solvent extraction

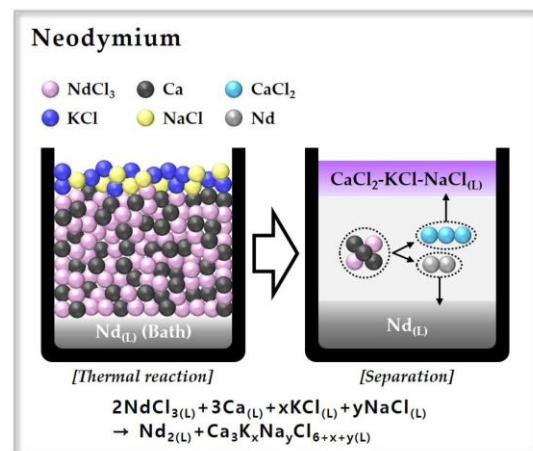


- Generally applicable to all types of magnets
- Applicable to nonoxidized and oxidized alloys
- Same processing as for primary ores
- Many process steps, can be complex
- A lot of chemicals, wastewater, high inherent CO₂

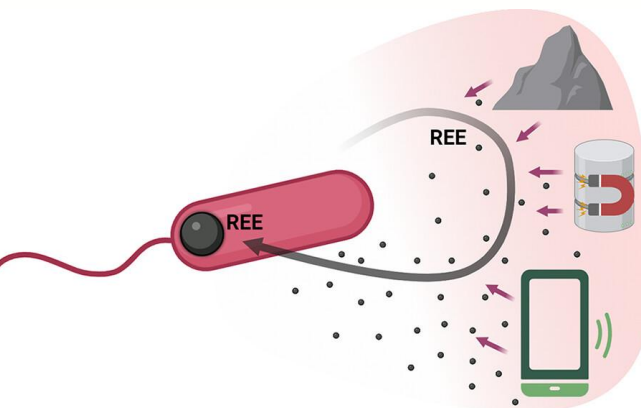
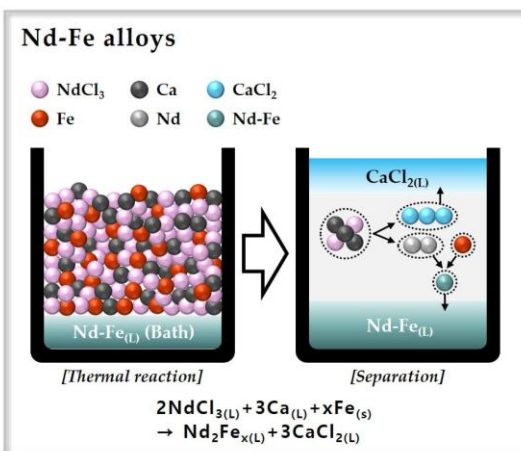
Room temperature electrolysis – very sustainable!
Green solvents, bio-based extraction alternatives!
Most recycling process focus on specific magnets!

<https://doi.org/10.1149/1945-7111/ac6075>

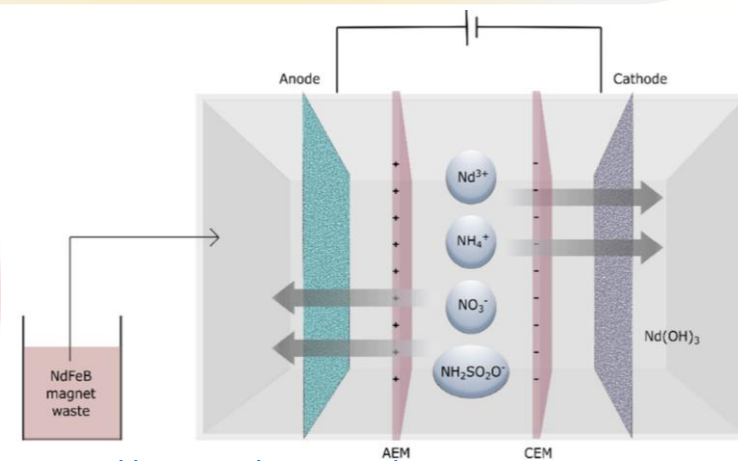
<https://doi.org/10.1021/acssuschemeng.3c07720>



<https://doi.org/10.3390/ma18050971>



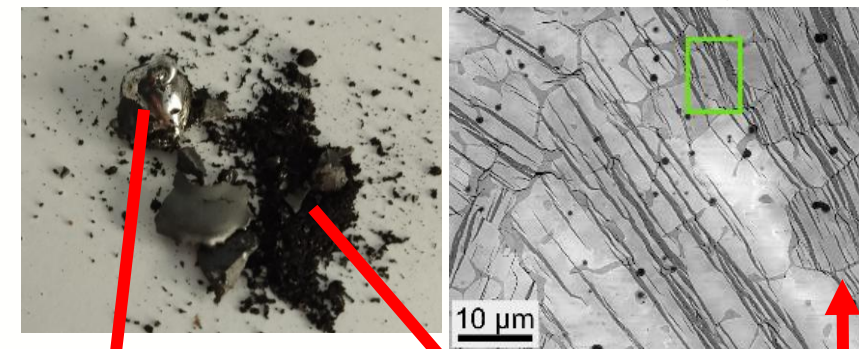
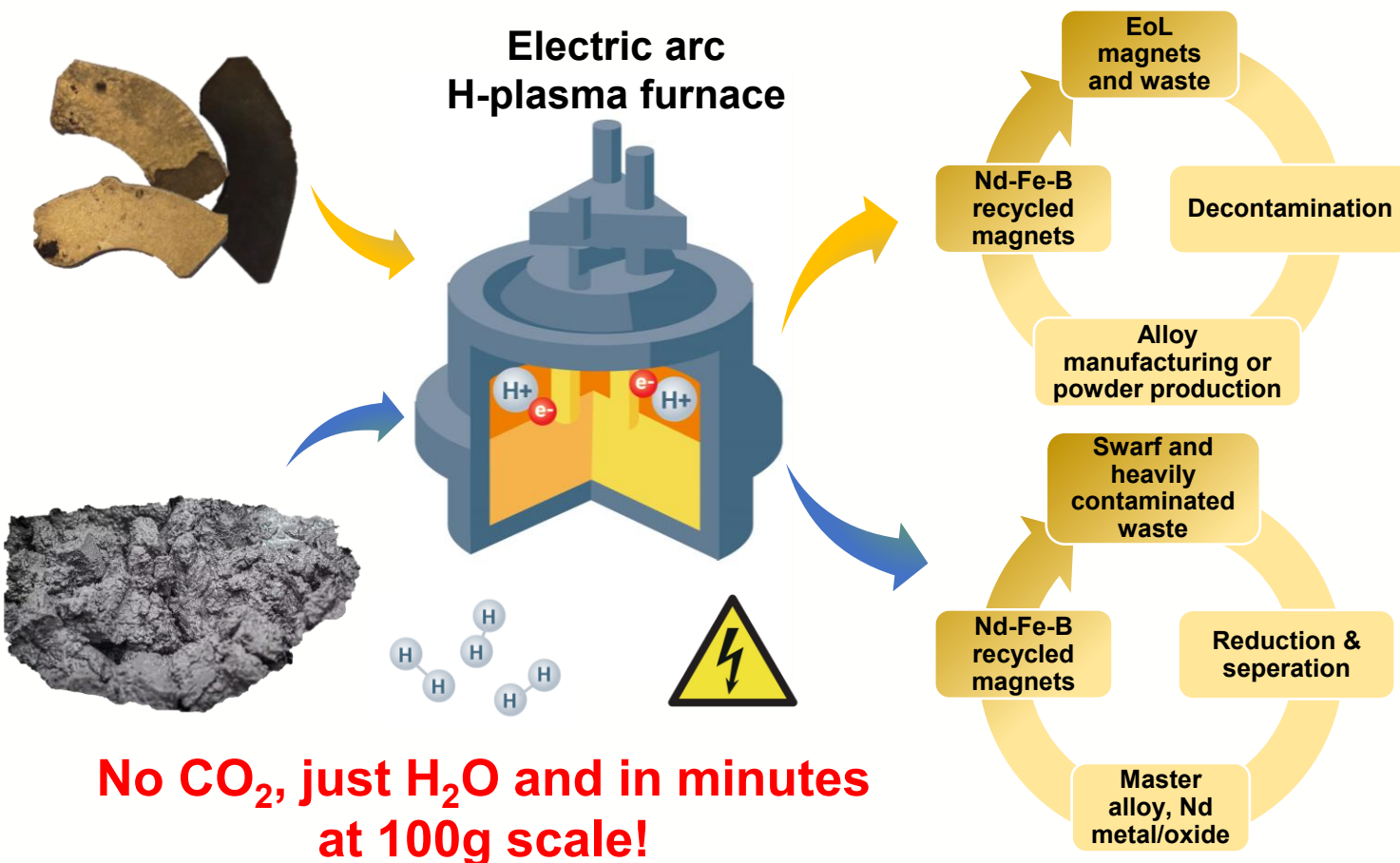
<https://doi.org/10.1021/acs.est.3c06775>



<https://doi.org/10.1021/acssusresmgt.5c00003>

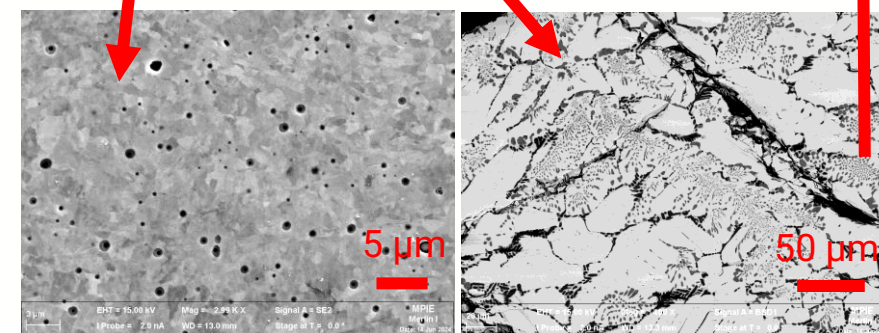
Intermediate loop: Hydrogen plasma recycling of Nd-Fe-B

Nd metal/hydride

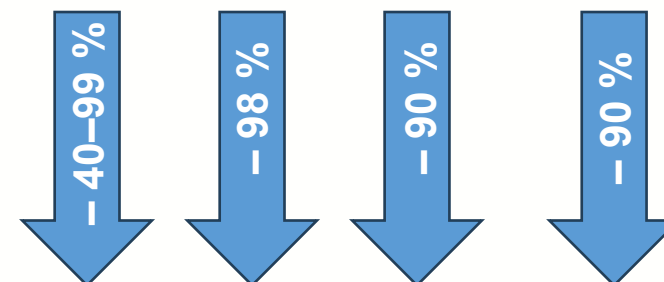


99% Fe

Nd oxide

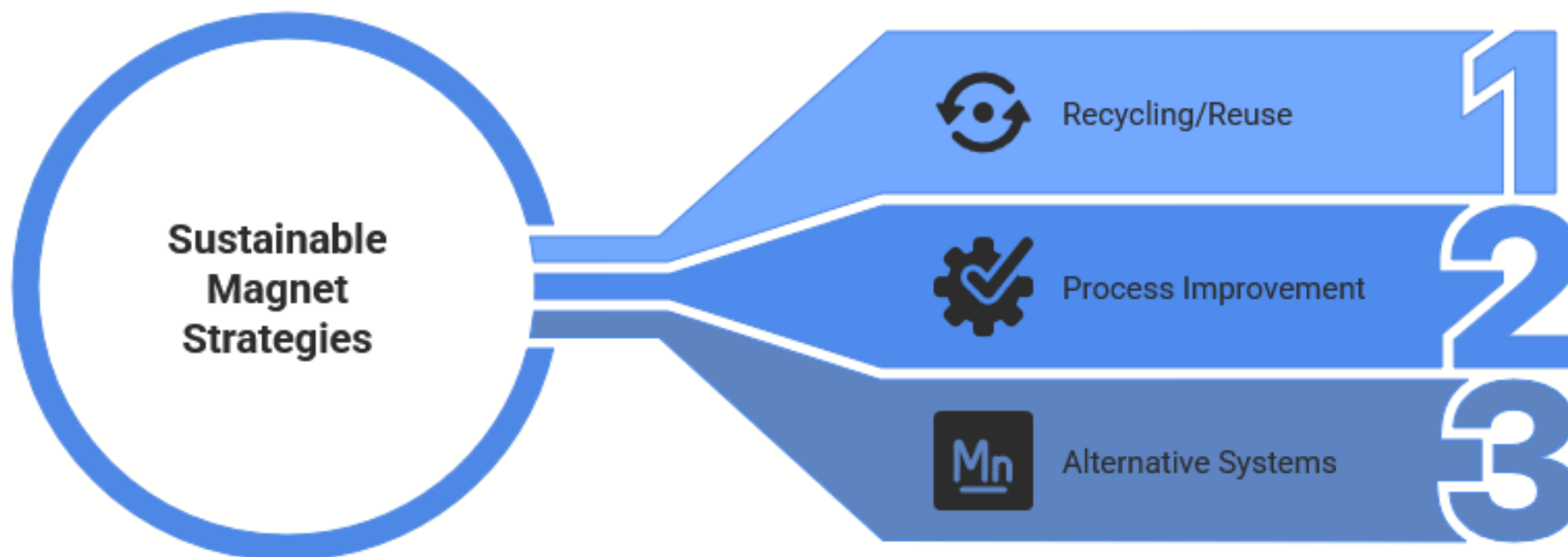


Oxygen Carbon Nitrogen Hydrogen

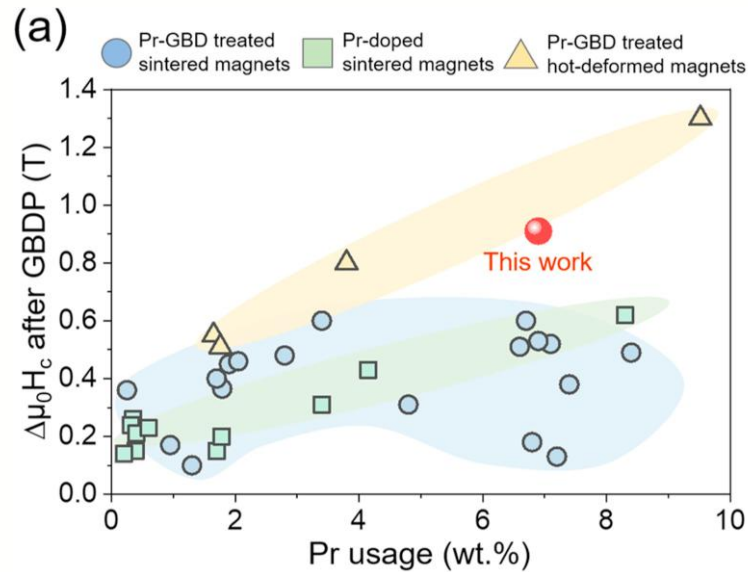
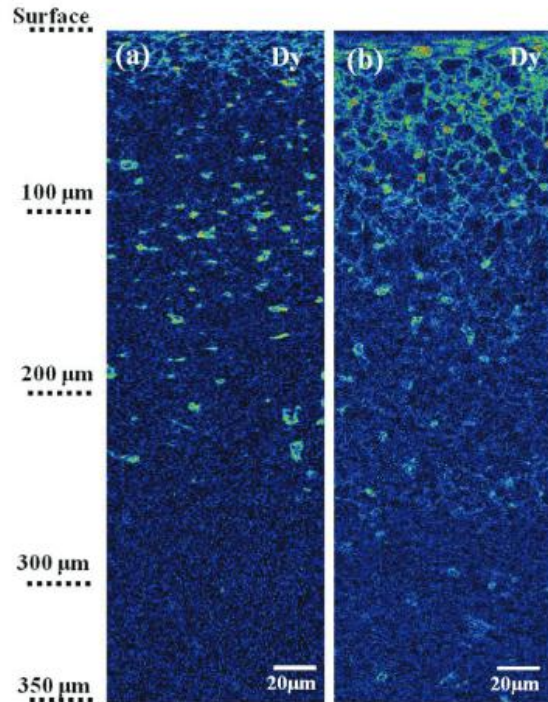


Versatile 1-pot processing scheme to overcome multiple recycling challenges

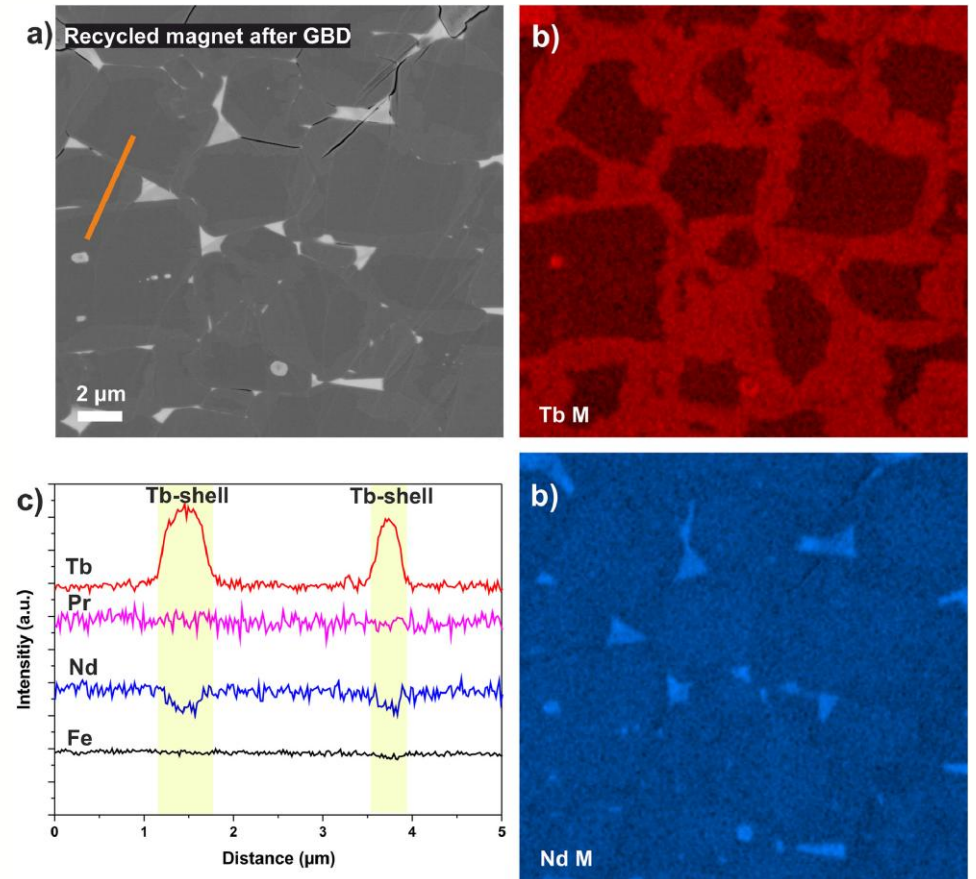
Exploring Sustainable Magnet Strategies



Grain boundary diffusion & infiltration process



<https://doi.org/10.1016/j.actamat.2024.120660>



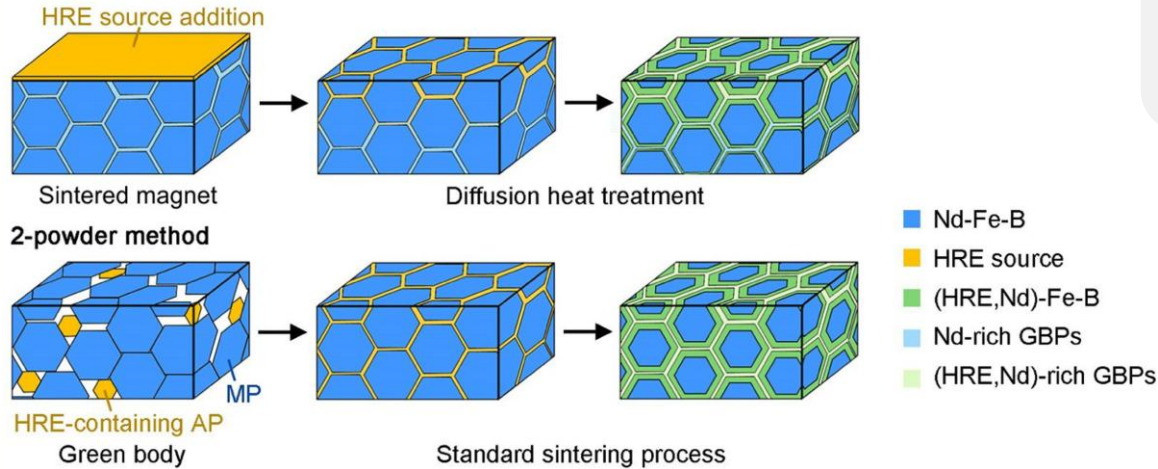
<https://doi.org/10.1016/j.actamat.2024.120532>

- Higher performance, lower magnet mass requirement
- Lower CO₂ footprint
- Limits with scale and efficiency
- Challenging recycling/proper recovery of Dy/Tb
- Alternatives with less-critical REE, but limited effect

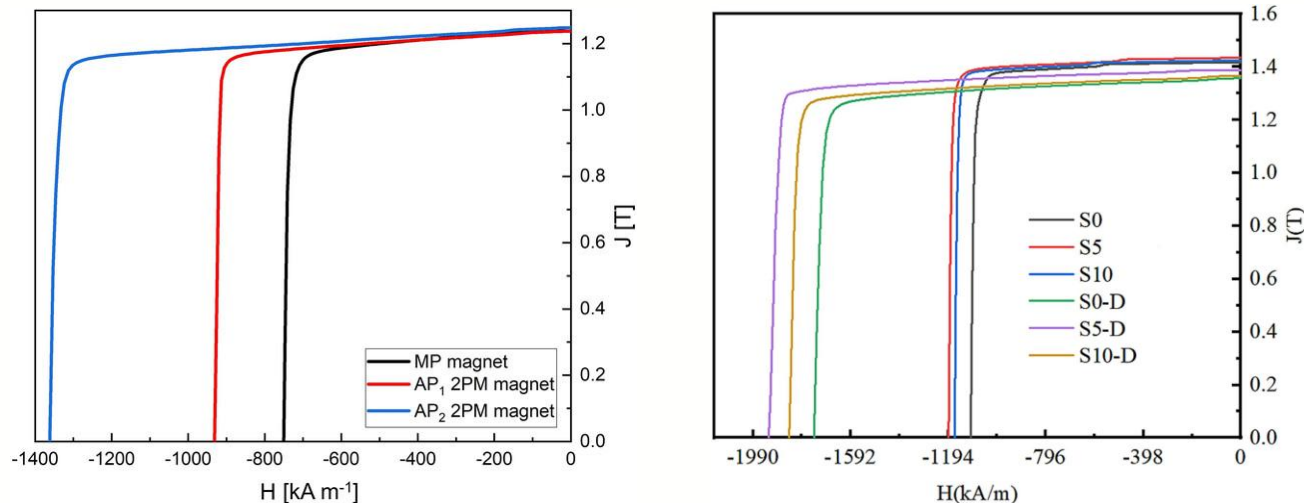
Requires HREEs!

Alternative diffusion processes

Grain boundary diffusion process



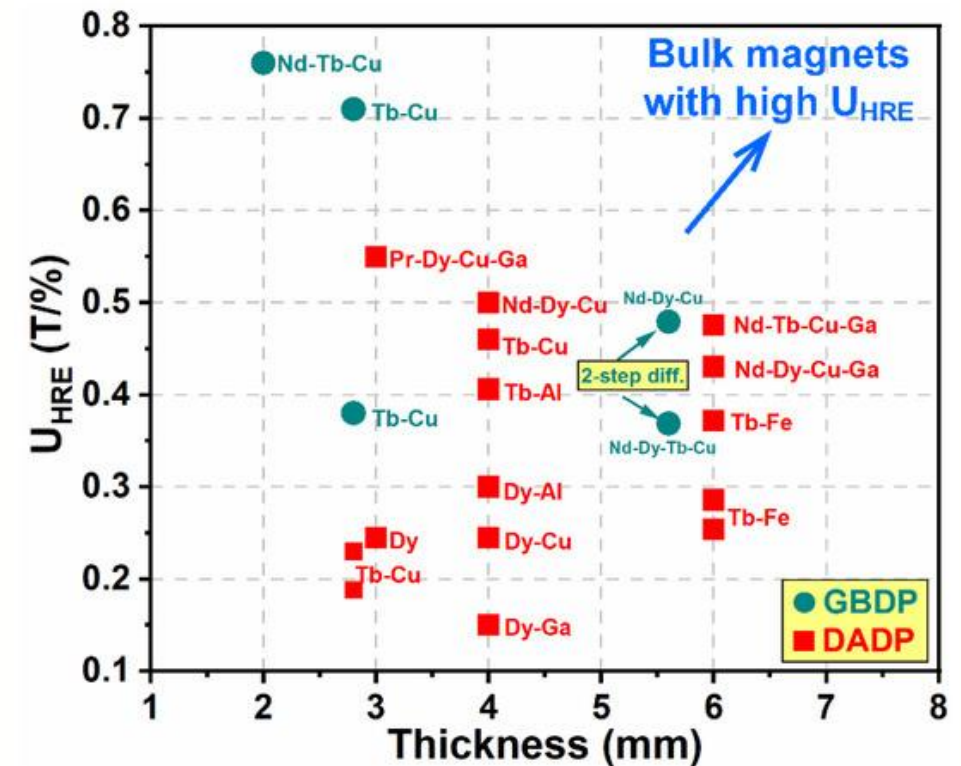
<https://doi.org/10.1016/j.actamat.2024.119871>



<https://doi.org/10.1002/adem.202500054>

- Sustain good properties with lower HREE content
- Good scaling potential
- Heterogenous material – difficult control and recycling
- Complex processing/longer processing

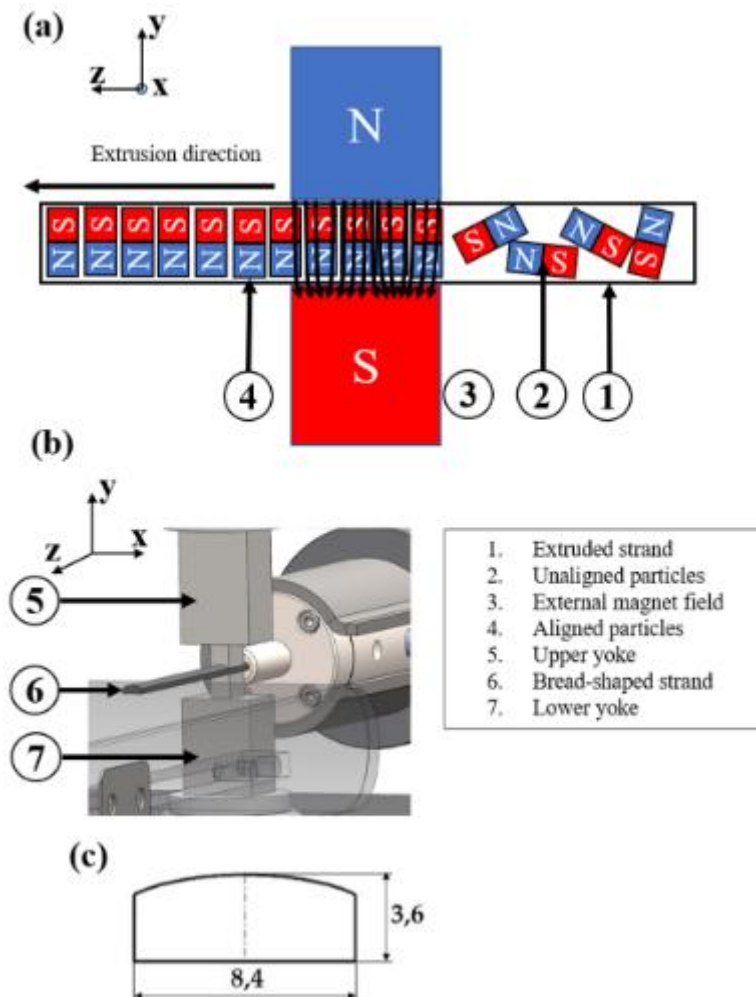
Dual alloy diffusion process (DADP)



<https://doi.org/10.3390/ma16134789>

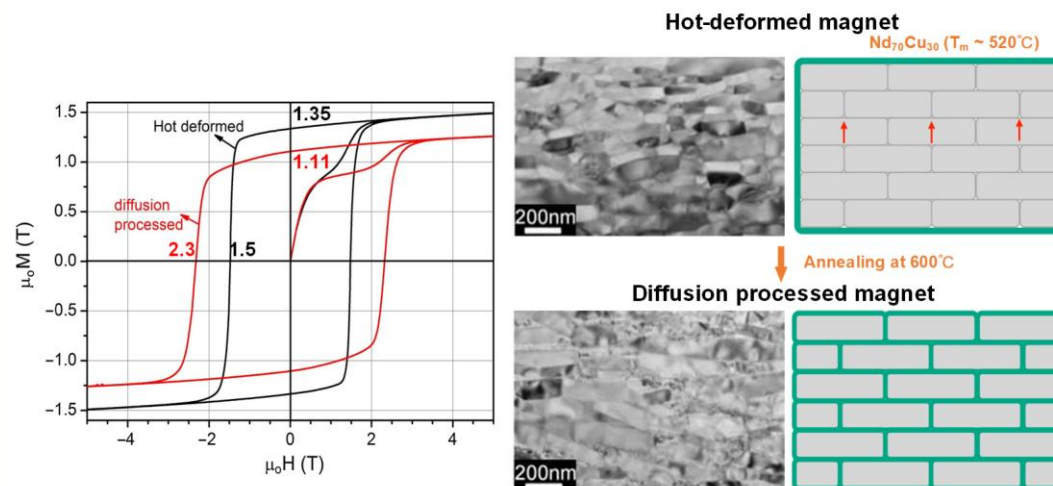
Deformation-based processing

Powder extrusion



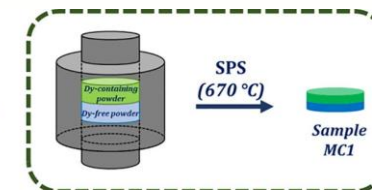
- Emerging alternatives and versatility
- Fine grain size and flexible chemistry
- Complex processing and controllability
- Can have size limitations!
- H_c limitation – combination with GBDP

Hot deformation process

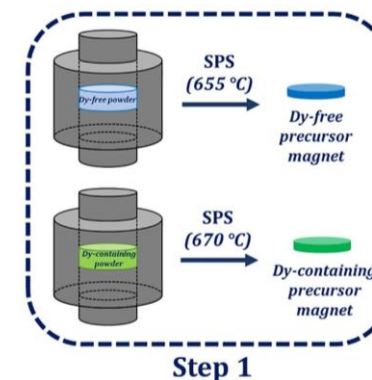


Spark Plasma Sintering

One-step SPS approach:

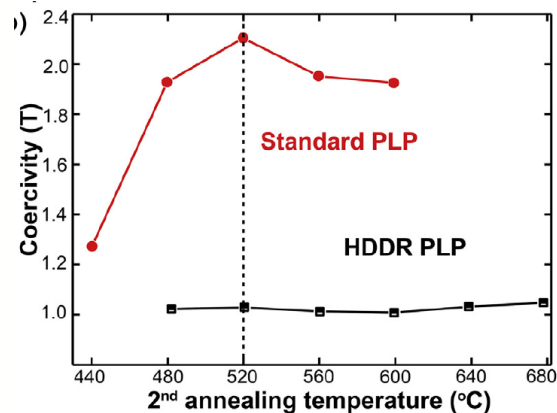
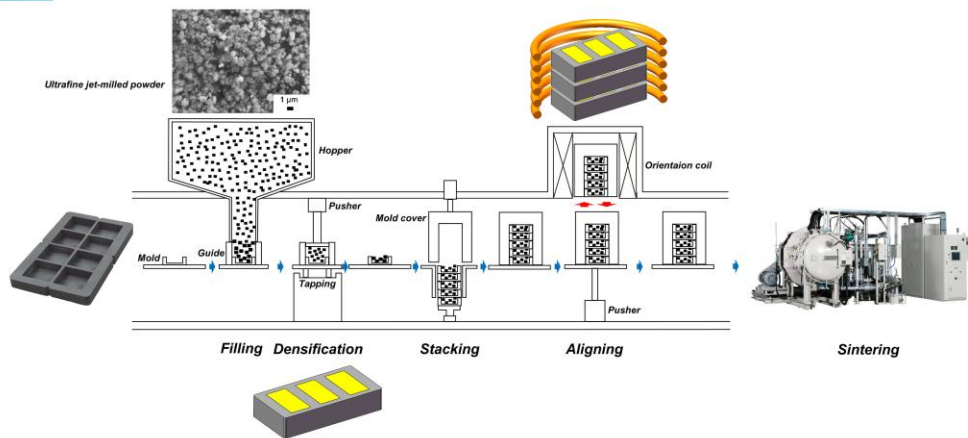


Two-step SPS approach:

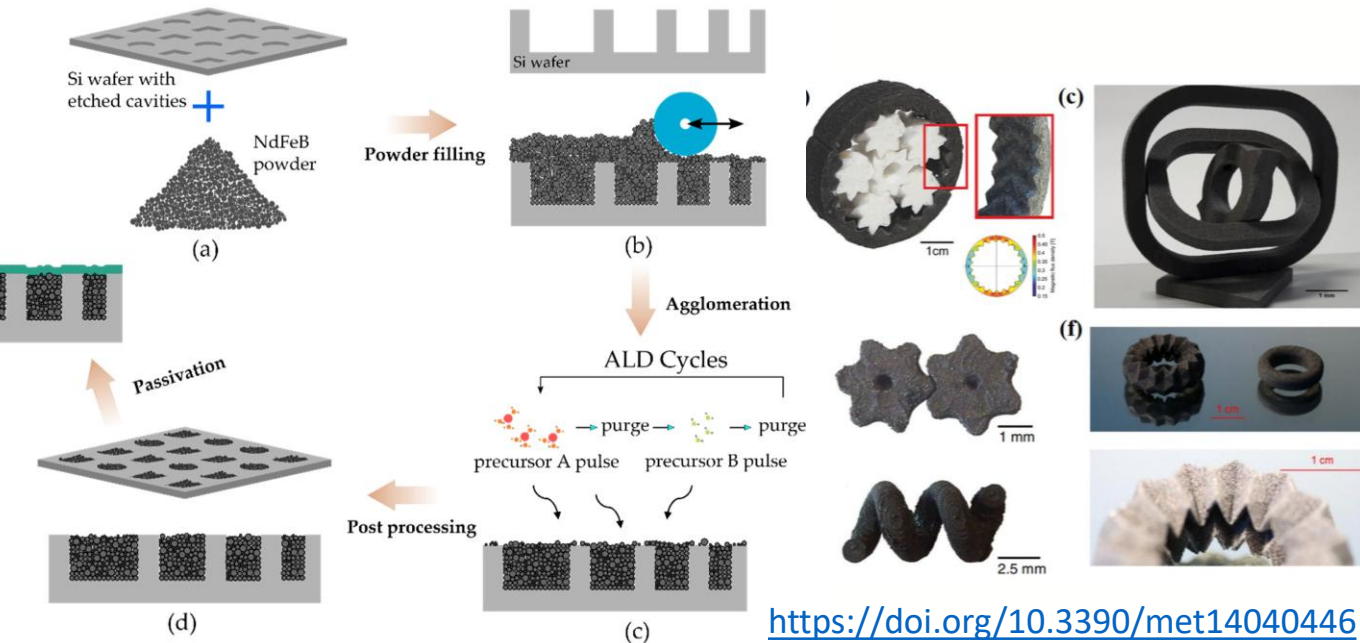
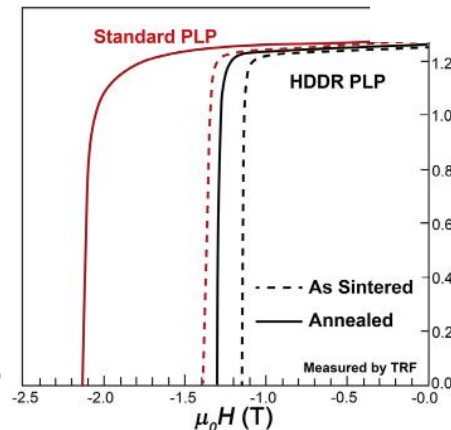


Pressless processing, powder MEMS and additive manufacturing

SDM MAGNETICS



<https://doi.org/10.1016/j.actamat.2018.03.062>

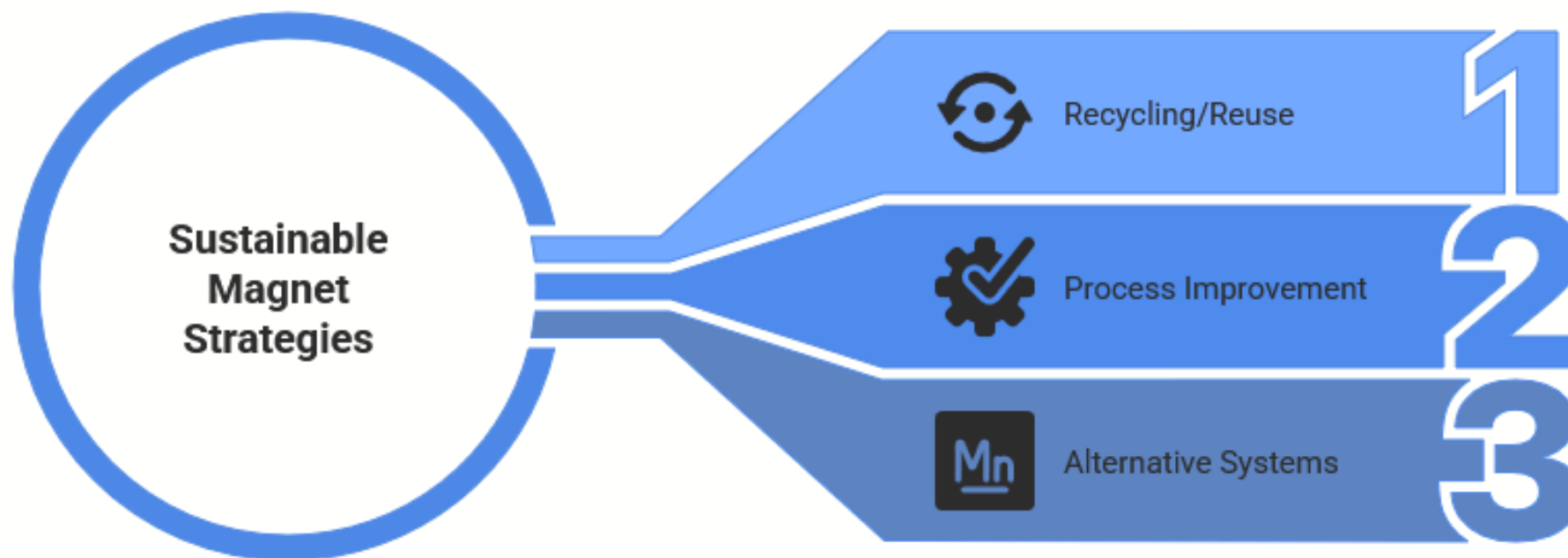


<https://doi.org/10.3390/met14040446>

<https://www.mdpi.com/2072-666X/13/5/742>

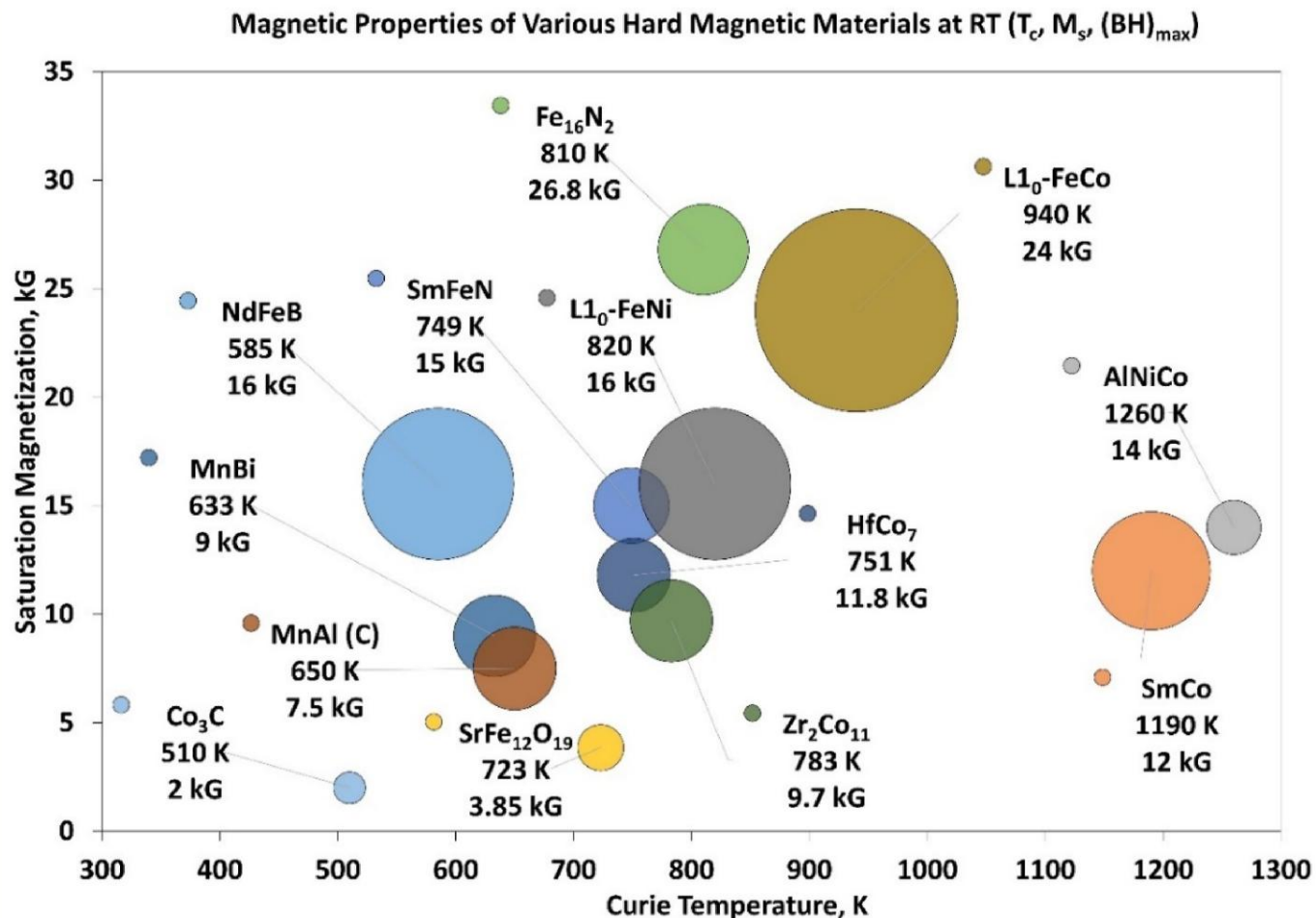
- Alternative processing
- Flexible in shape and design, complex forms possible
- Dynamic tailoring of properties
- Use of fine powder advantageous for high H_c
- But challenge of “chains”, lowered density and M_s

Exploring Sustainable Magnet Strategies



Made with  Napkin

Alternative/sustainable magnet systems



<https://doi.org/10.1016/j.mtphys.2022.100675>

#1: Stability

Phases with high intrinsic magnetic properties must be found and stabilized

#2: Anisotropy

High magnetocrystalline anisotropy must be induced for reaching high coercivity

#3: Remanence

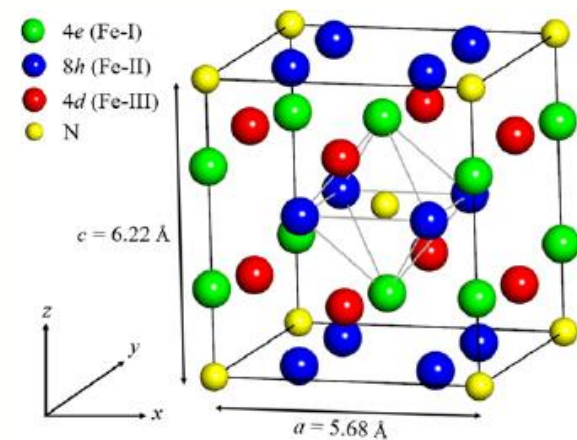
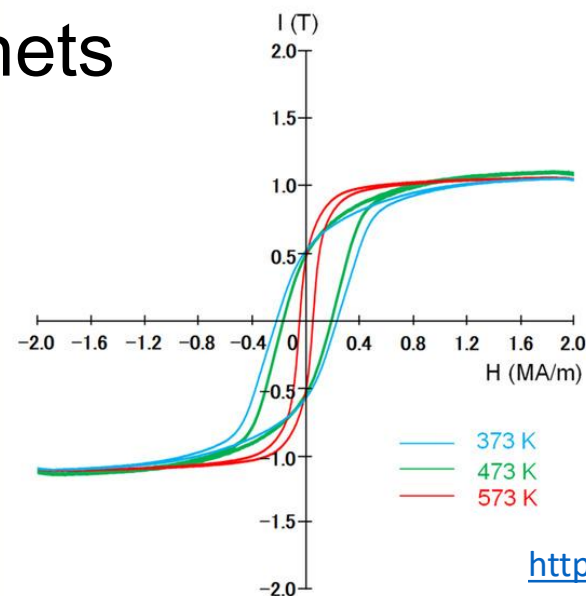
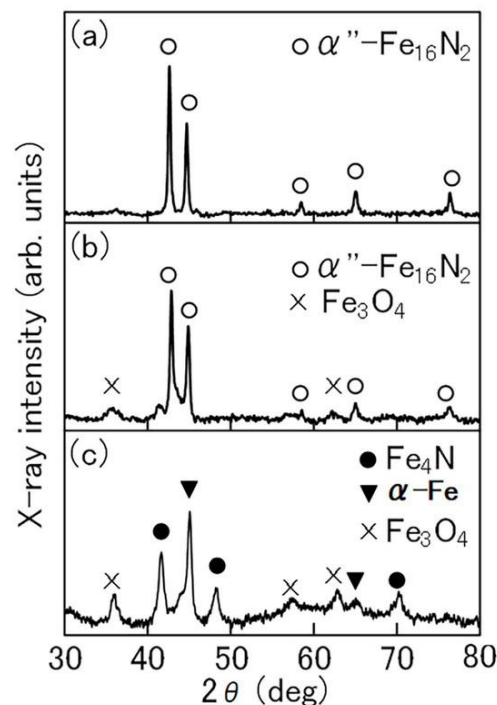
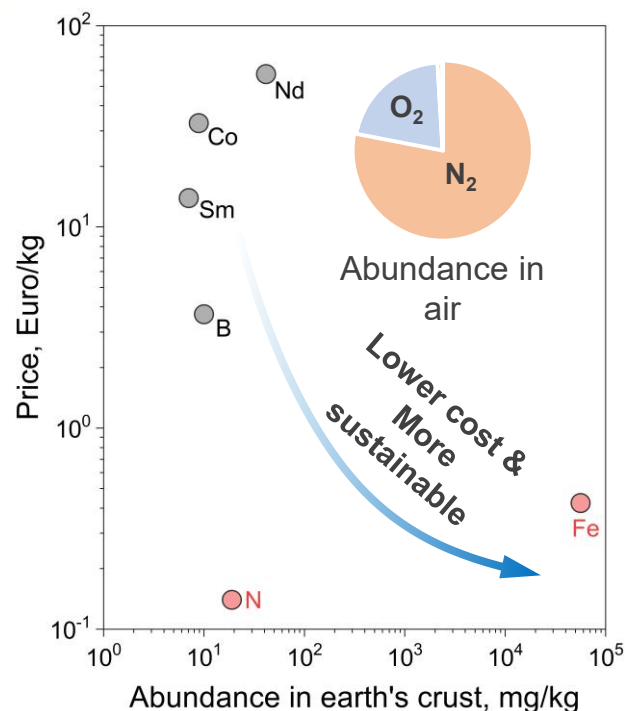
High density and alignment for high remanence

#4: Bulk magnets

All properties need to be conserved in bulk magnets

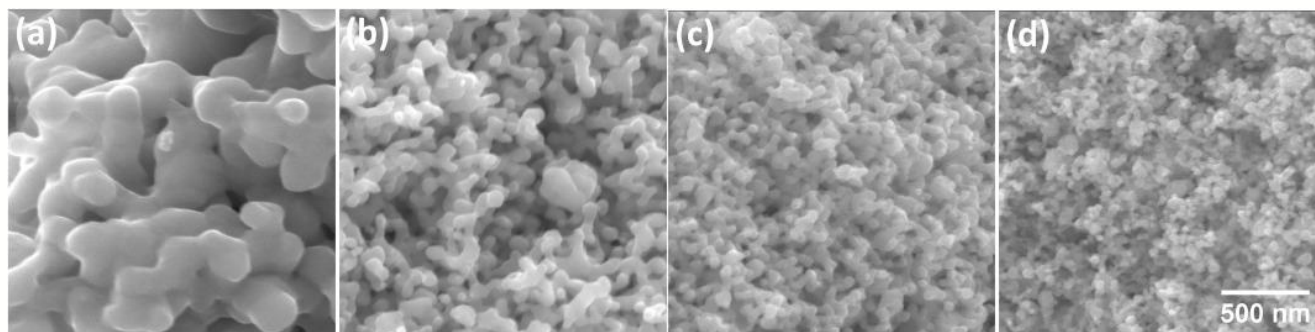
Economic and ecologic fabrication technology for **industrial** production needed

Fe-N system: α'' -Fe₁₆N₂ hard magnets



<https://doi.org/10.1088/1361-648X/ab422c>

<https://doi.org/10.3390/met14060734>

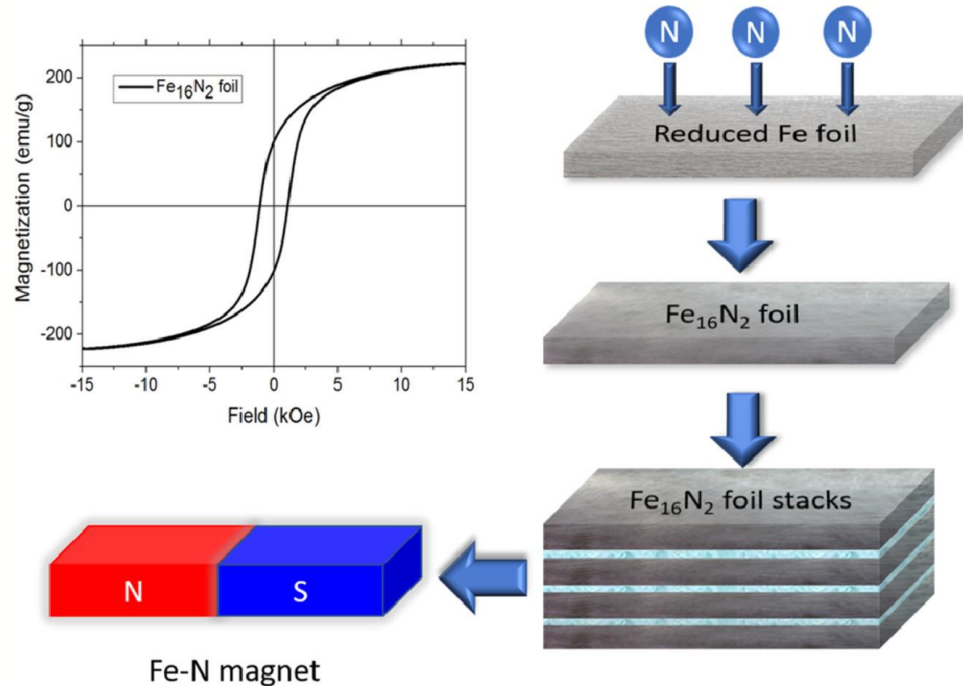


<https://doi.org/10.1016/j.actamat.2016.10.061>

- **Highly sustainable**
- High theoretical M_s (2.4 T) and BH_{max}
- Processing is "simple" & sustainable
- Low thermal stability (limited application)
- Limited bulk production
- Mostly thin film and nanopowder pathways

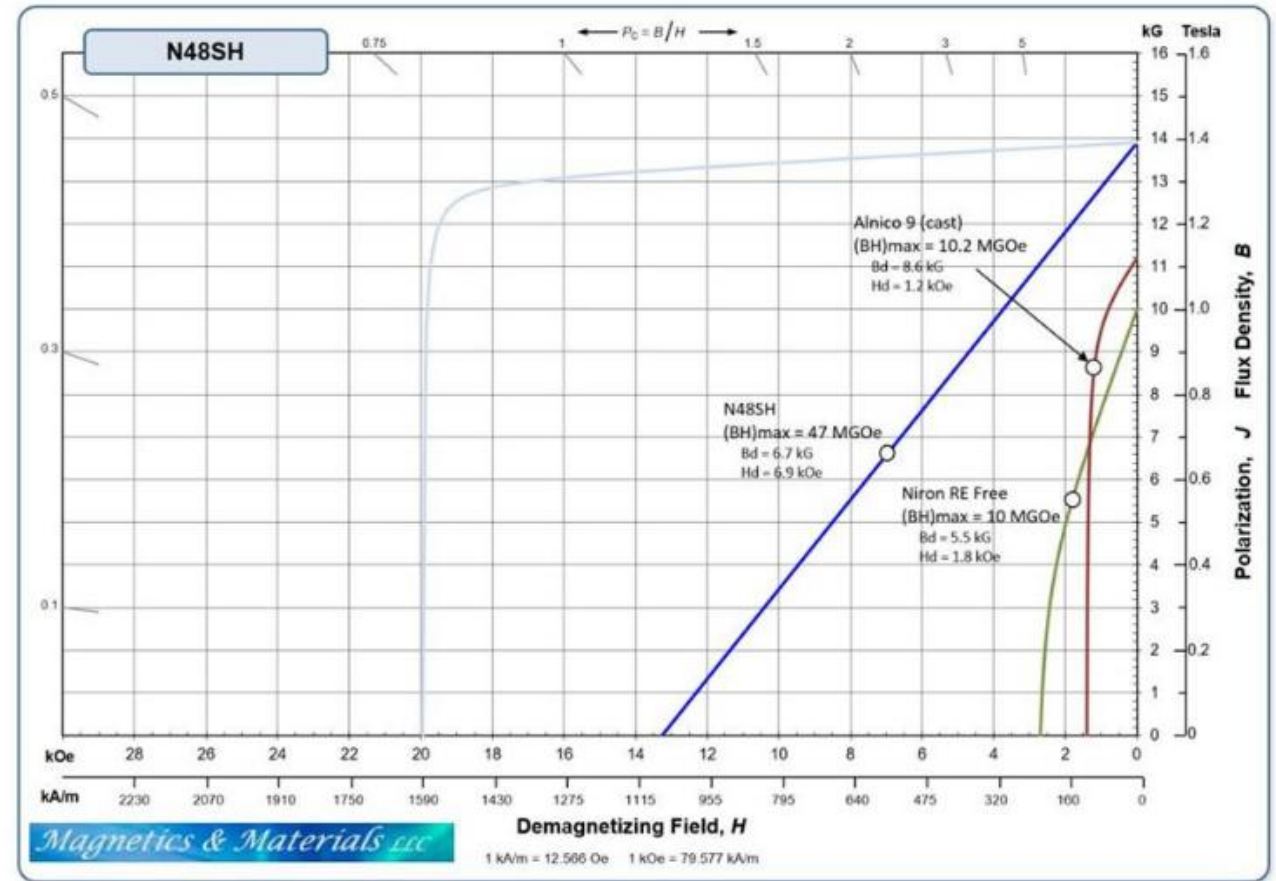
Great potential but limited synthesis!

Fe-N system: potential for industrial production?



<https://doi.org/10.1016/j.actamat.2019.11.052>

BHmax = 160 kJ/m³, but no bulk scale thus far!

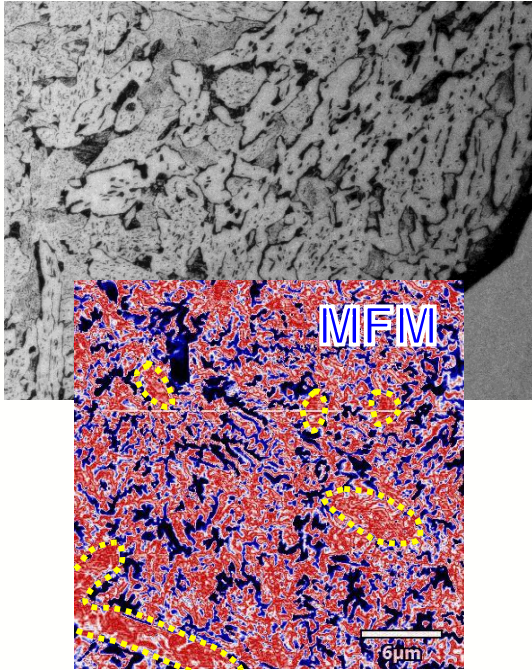


https://ukmagsoc.org/wp-content/uploads/2025/07/MS_2025_FeN_Hype_or_Heavy_Hitter.pdf

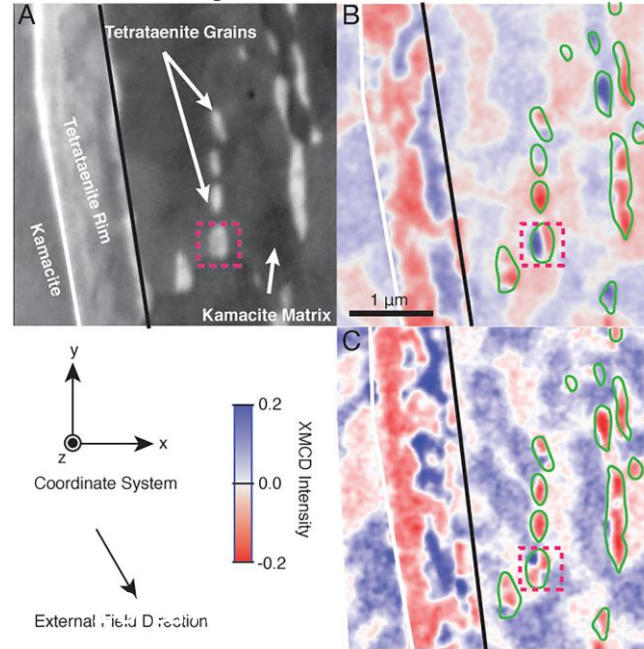
**Commercial production with 80 kJ/m³ and T_{operation} = 150°C
not overtaking the REEs magnet market so far!**

Fe-Ni/Fe-Co system: $L1_0$ phase

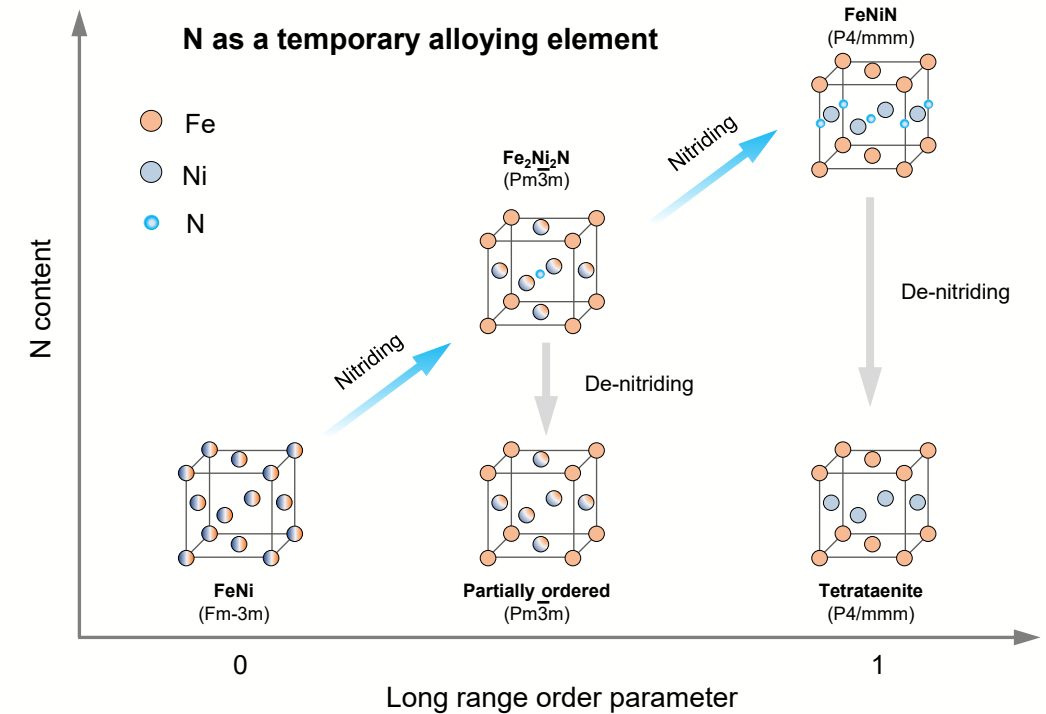
Meteorite NWA 6259



[10.26434/chemrxiv-2025-rp08n](https://doi.org/10.26434/chemrxiv-2025-rp08n)



<https://doi.org/10.1029/2022GC010631>

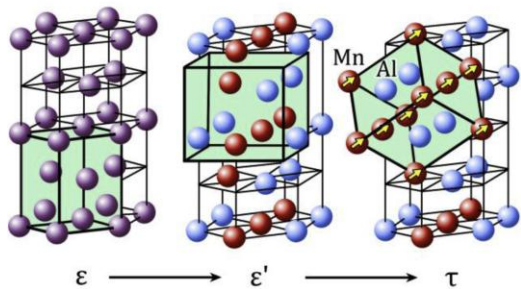
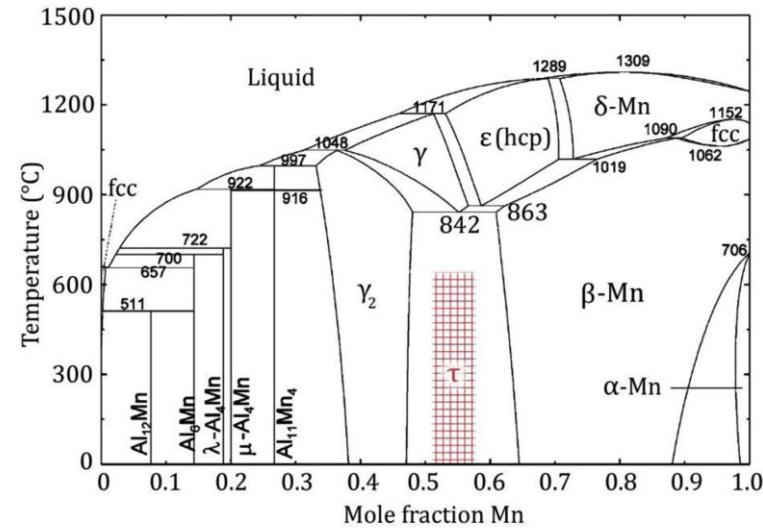


<https://doi.org/10.1038/s41598-017-13562-2>

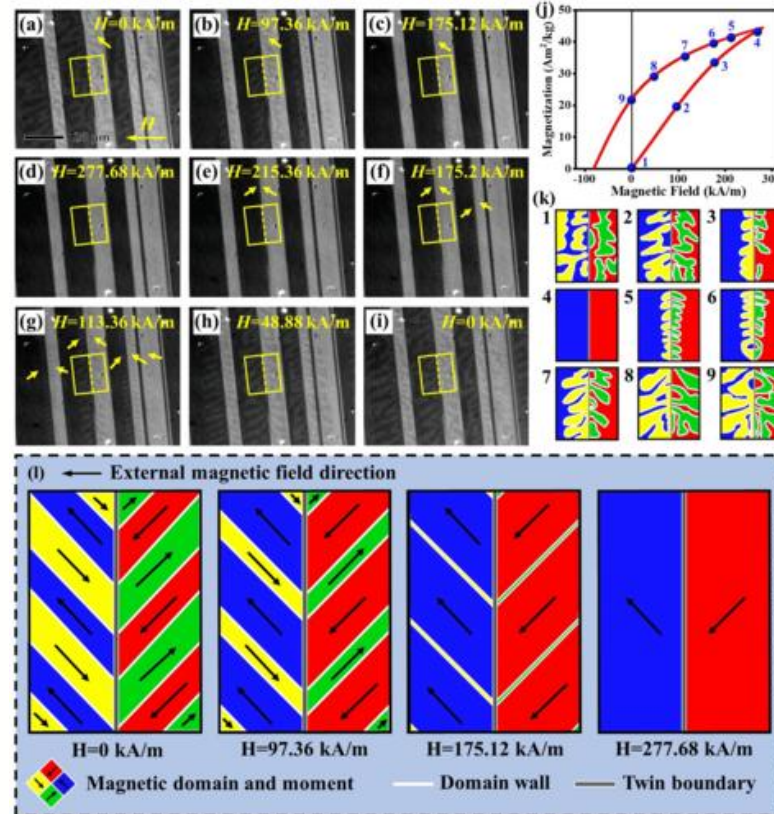
- High potential and natural material exists – meteorites, $BH_{\max} = 335 \text{ kJ/m}^3$
- Difficult processing – slow kinetics and overlapping instability of the phase
- Limited bulk production
- Sustainability (Ni) and industrial production (kinetics) is questionable

Current synthesis massively relying on pure compounds!

Mn-Al system: another L1₀ phase



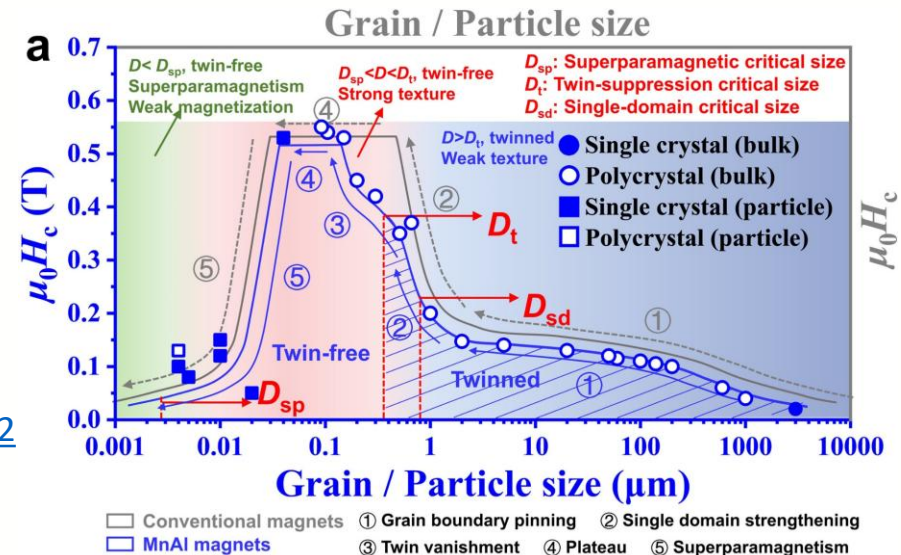
<https://doi.org/10.1016/j.actamat.2018.07.049>



<https://doi.org/10.1103/PhysRevMaterials.4.094402>

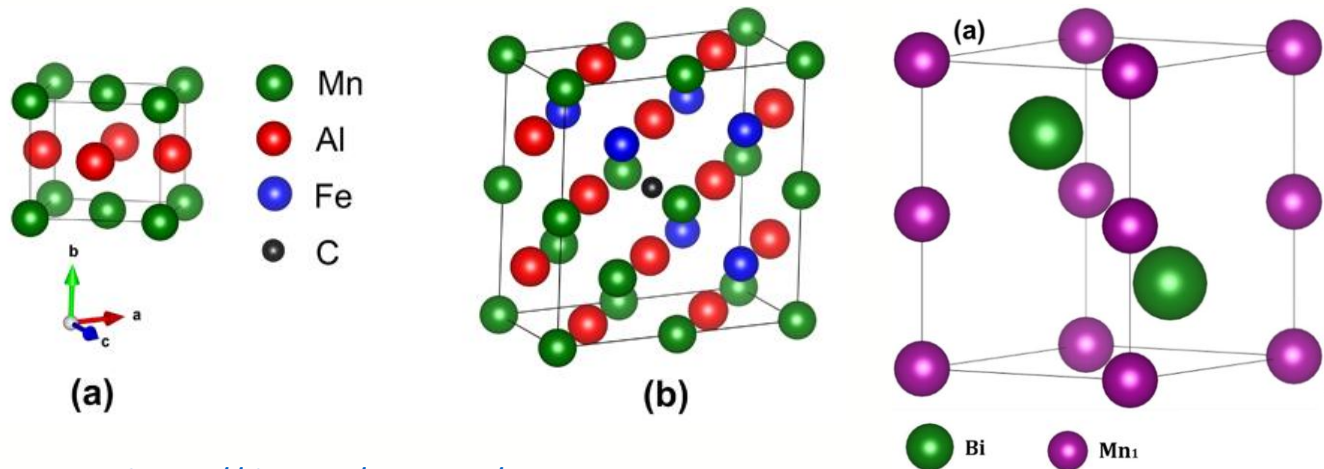
- Attractive energy density per unit mass (density of 5.2 g/cm³)
- Twinning difficulty
- Sustainability is good, low price
- Processing not too complex
- Operating temperature limit – aging!

Currently best candidate as alternative gap magnet!

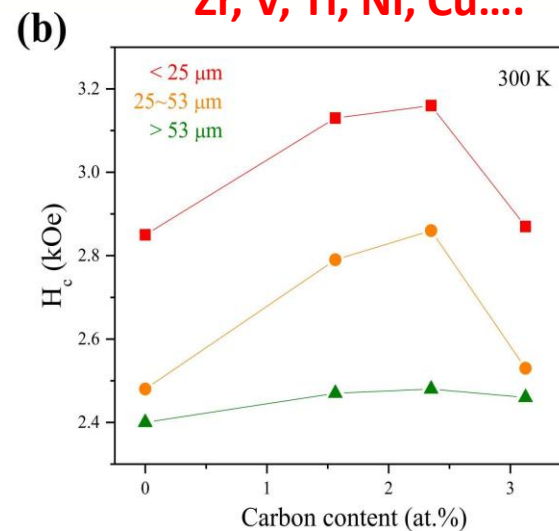
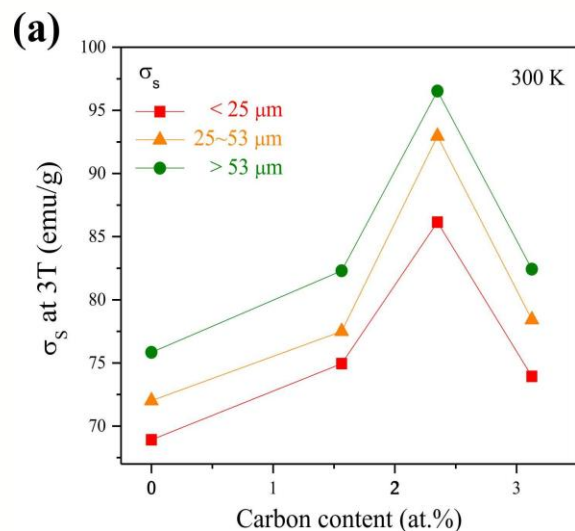


<https://doi.org/10.1016/j.actamat.2022.118654>

Mn-based systems



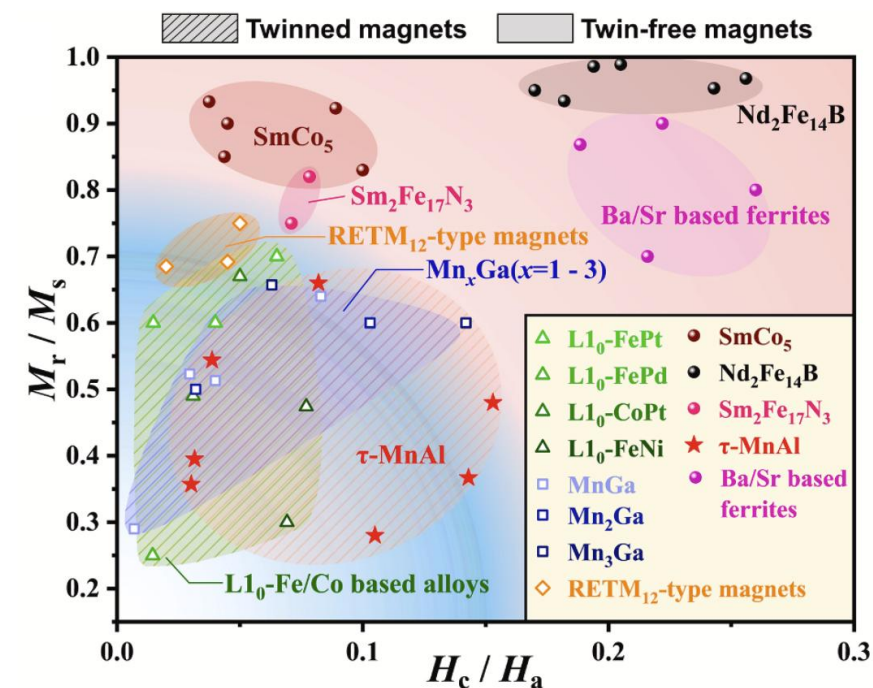
<https://doi.org/10.1063/5.0172356>



Zr, V, Ti, Ni, Cu....

Many of the systems in development

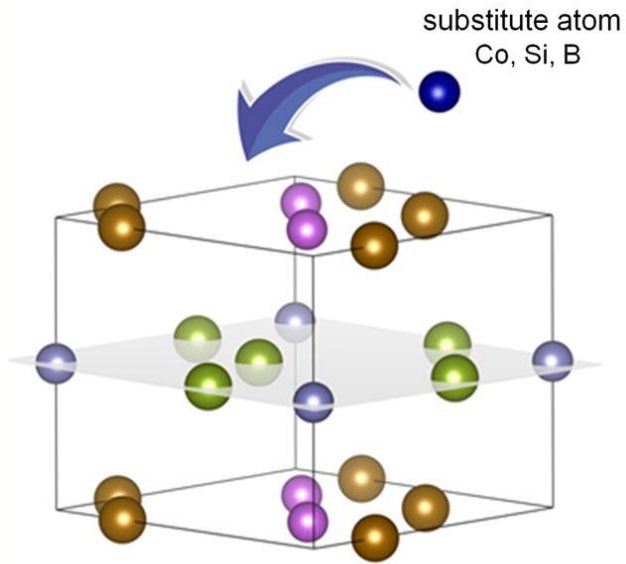
- High potential
- Certain elements limited sustainability
- Complex processing
- Stabilization of τ phase, but reduced magnetic properties



<https://doi.org/10.1016/j.actamat.2022.118654>

<https://doi.org/10.1016/j.jallcom.2022.165773>

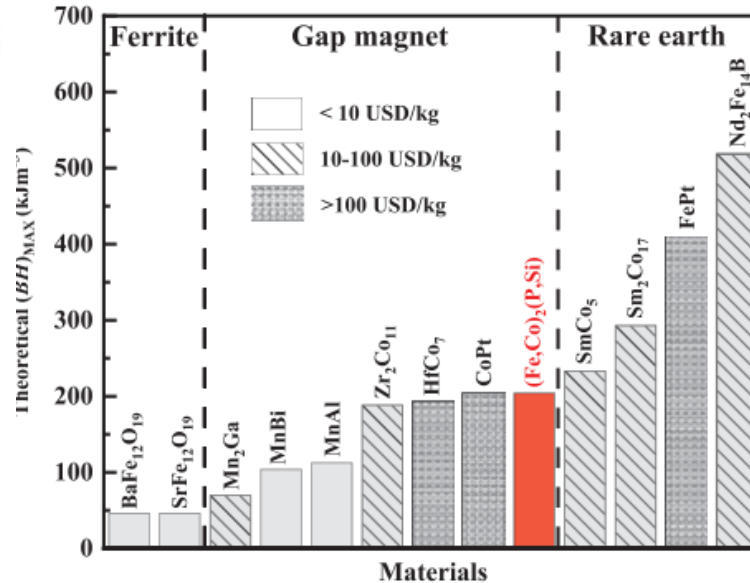
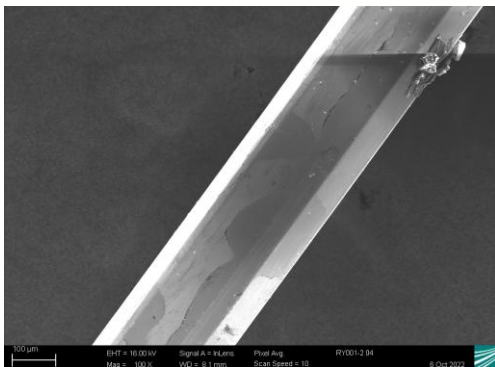
Fe-P system: The “new” kid on the block



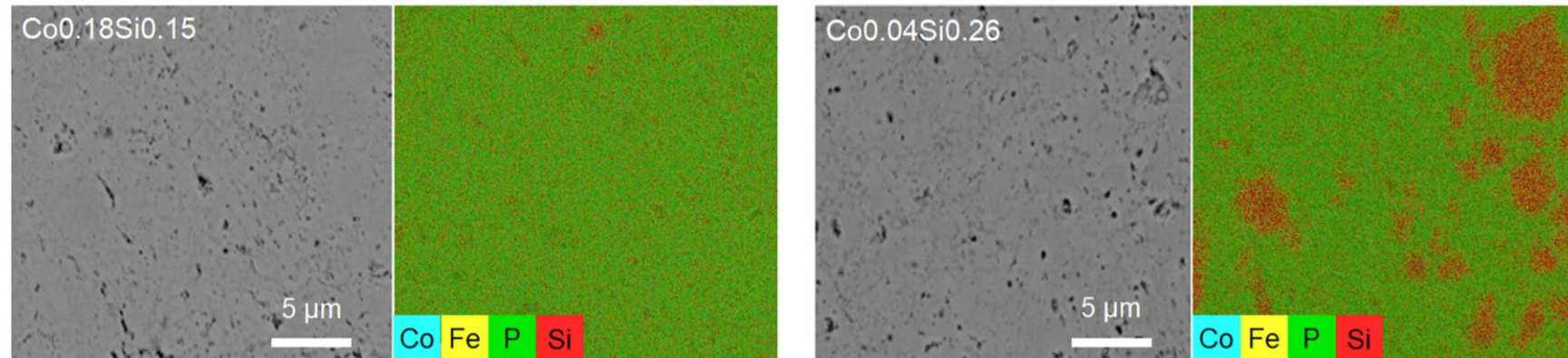
Hexagonal Fe_2P

<https://doi.org/10.1016/j.actamat.2025.120848>

Fe-Co-P-Si



<https://doi.org/10.1002/adfm.202107513>



<https://doi.org/10.1016/j.actamat.2025.120848>

- Potentially high properties
- Limited bulk production
- Affordable and use of “abundant” materials
- Bulk trials show limited H_c and uncontrolled chemistry
- Alloying increases T_c , lowers K_u & BH_{max} !
- Reliance on P is a sustainability issue

Alternative magnet that has potential!

Conclusions

- ☞ Magnets are needed for **green transition, lowering CO₂ and electrification**
- ☞ However, magnets can have high prior **environmental impact** (mining and purification!)
- ☞ **Sustainable production routes and alternatives are needed**
- ☞ **Recycling shows potential**, but certain aspects are limited – collection and initiative
- ☞ Short- and long-loop recycling routes are well developing, but **missing intermediate pathways**
- ☞ Sustainability can be **improved through different processing**, i.e. GBDP, SPS, DCT, AM, PLP
- ☞ Processing with chemical additions/changes **have great potential and versatility**
- ☞ Alternative system that **avoid REEs are good options**, but have challenges to overcome
- ☞ **Mn-Al and Fe-N** closest to commercialization, others need more development



- **Laboratory for Demonstration of H_2 and CO_2 Technologies**
- **Materials development:** Synthesis, testing, preparation etc.
- **Clean energy & carbon:** Catalysis and electrochemical processes for hydrogen production, CO_2 capture, and H_2/CO_2 conversion
- **Sustainable engineering:** Decarbonization, resource efficiency, renewable resources, waste utilization, and energy-intensive industries





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Demonstration and Training for
Carbon-Free Technologies*

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H₂ and CO₂ Technologies*

