Photo by MIMplus Technologies

SUSMAGPRO
SUSTAINABLE RECOVERY, REPROCESSING AND REUSE OF RARE-EARTH MAGNETS IN THE CIRCULAR ECONOMY

REEsilience

Science on the Street
Ljubljana, 21. April 2023

Recycling of Magnetic Scrap: Challenges and Chances for a Circular Economy

Prof. Dr. Carlo Burkhardt

Pforzheim University – Institute for Precious and Technology Metals
University of Lubljana – International Postgraduate School

SUSMAGPRO und REEsilience werden von den Forschungs- und Innovationsprogrammen Horizont 2020 und Horizont Europa der Europäischen Union unter den Finanzhilfevereinbarungen Nr. 821114 und Nr. 101058598 gefördert.

Rare Earth as High Performance Materials

Magnets…

Loadstone
(iron oxide, artefact)

7-8 century
BC (China)

~ 1850
(Europe)

Photo by MIMplus Technologies

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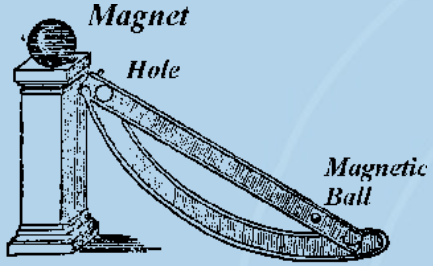
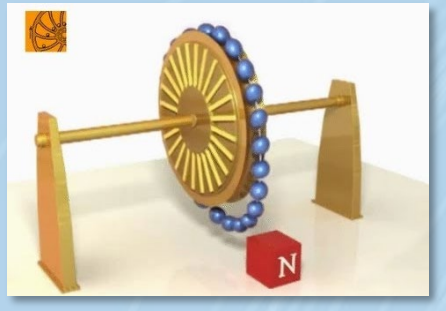
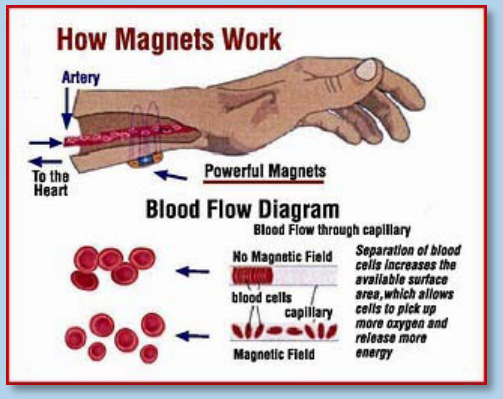
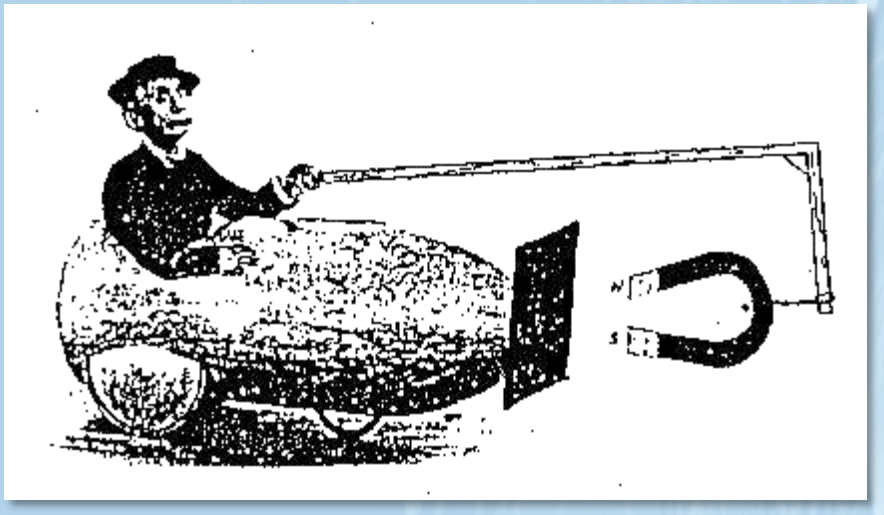
Rare Earth as High Performance Materials

Magnets…









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Rare Earth as High Performance Materials

Magnets…

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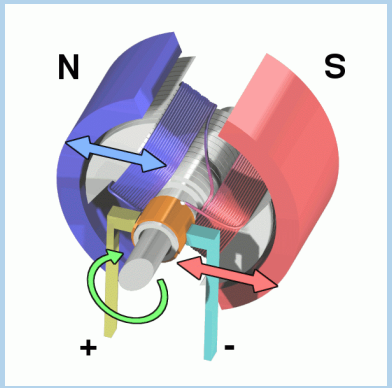
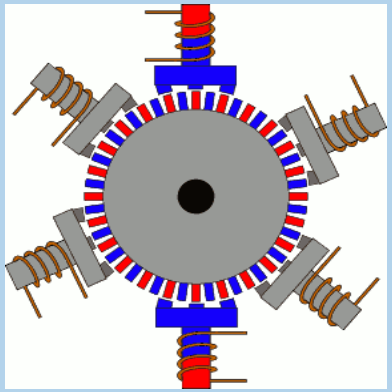
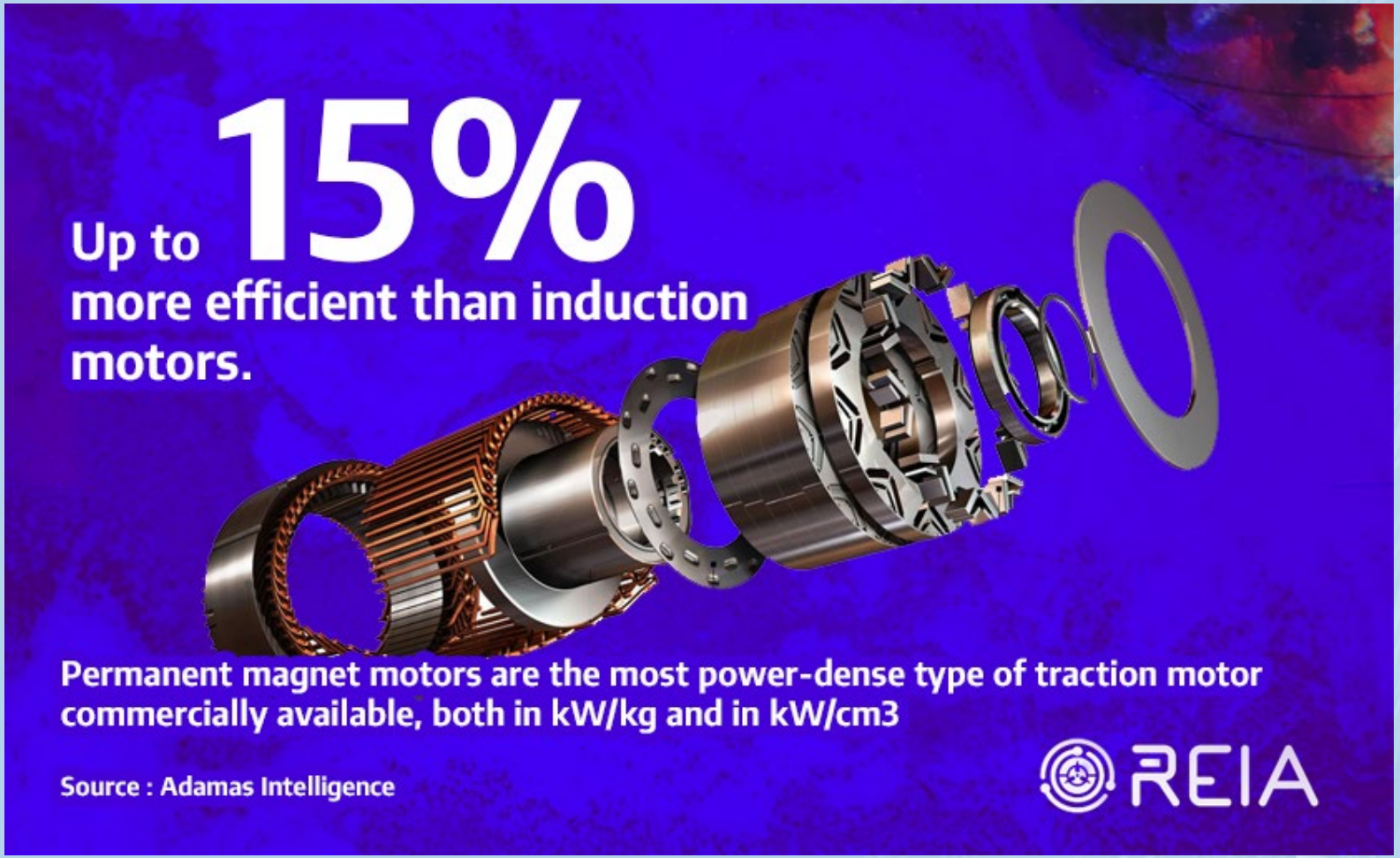
Photo by MIMplus Technologies

Rare Earth Magnets empower the devices of our future







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Rare Earth Magnets empower the devices of our future

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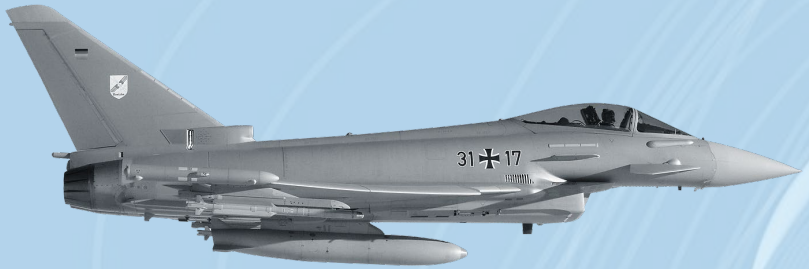

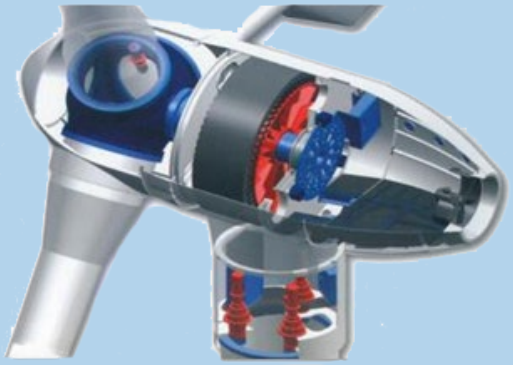

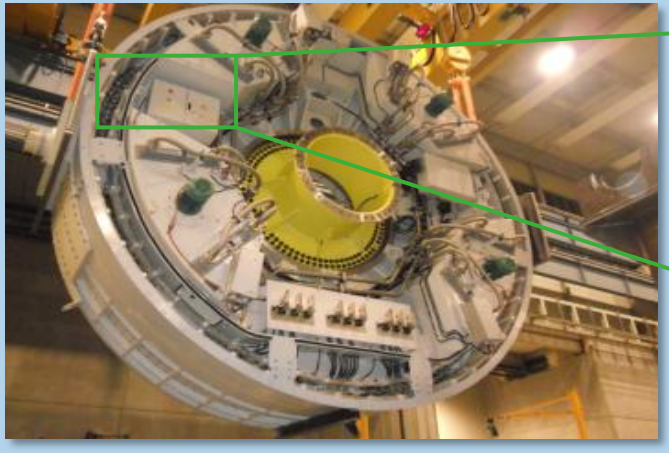

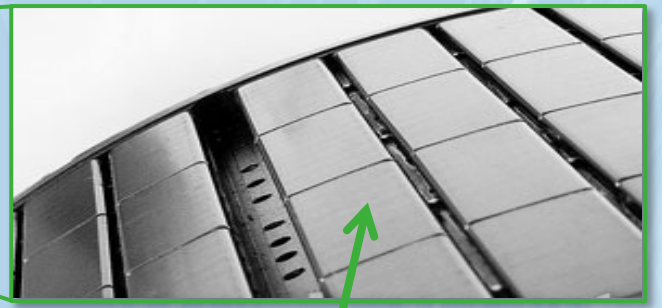

Permanent Magnets (NdFeB-type)

Photo by MIMplus Technologies

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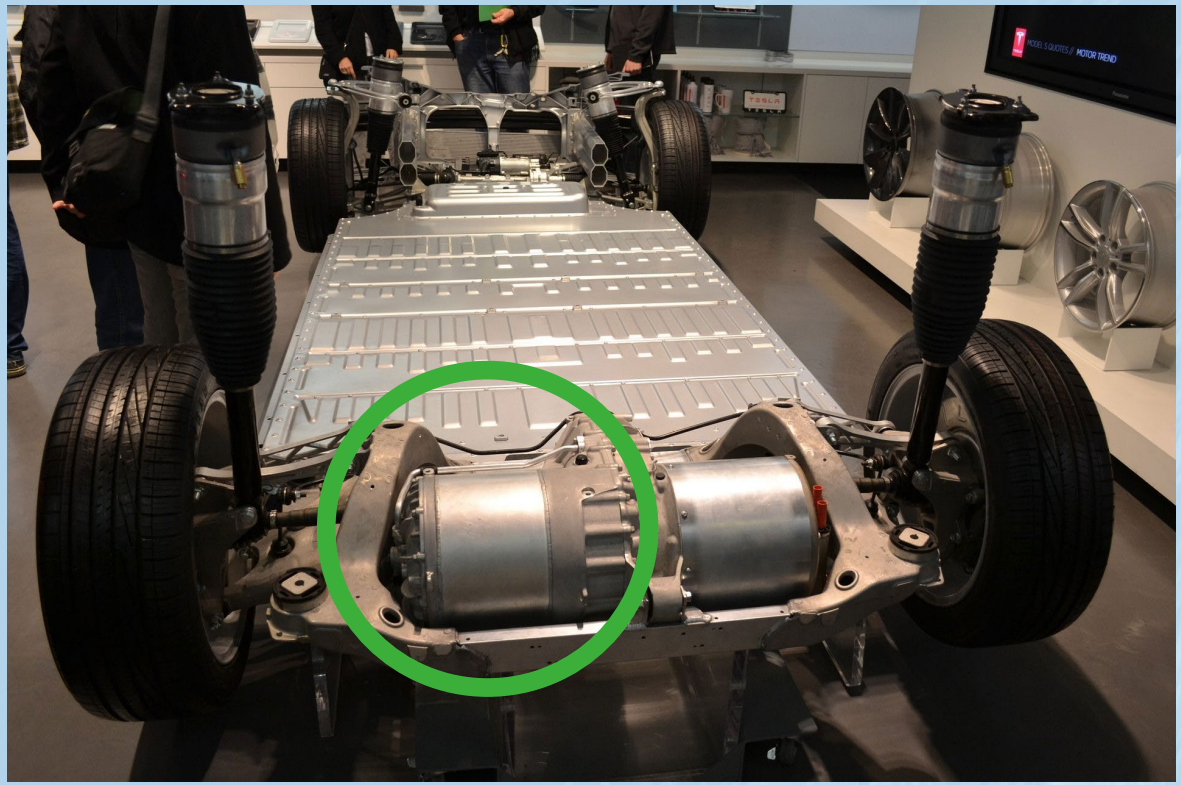
Rare Earth Magnets empower the devices of our future

Mercedes AMG, 320 kW



Tesla Model 3, 320 kW

95% of electric cars use permanent magnet motors

Photo by MIMplus Technologies

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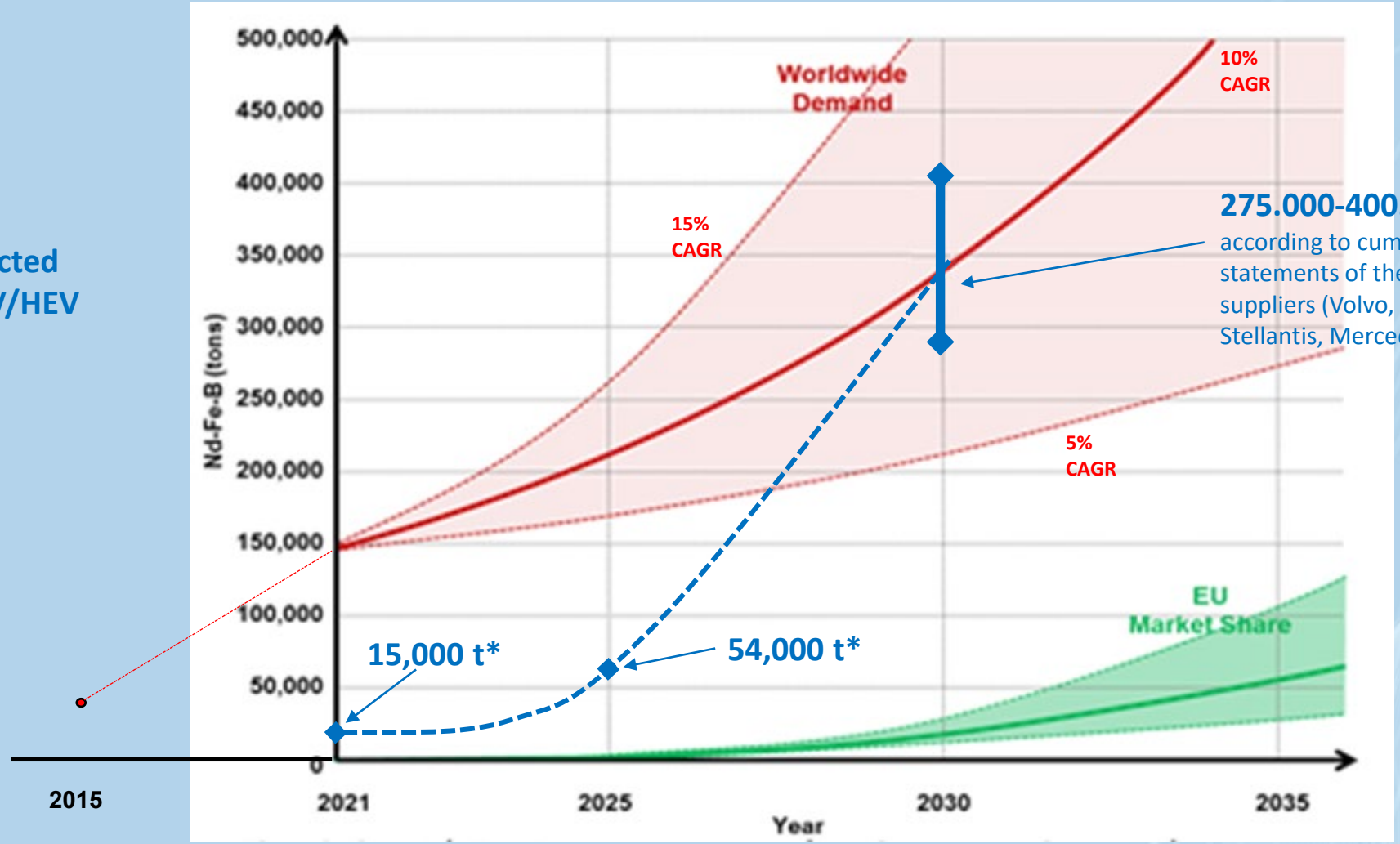
Green energy and transport increases material demand

Actual/predicted additional EV/HEV demand



*Source: *REIA (2022)*

**Source: *IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021*

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Rare Earth as High Performance Materials

Magnets…

Microstructure of sintered NdFeB magnets:

(Hard-)magnetic grains ($Nd_2Fe_{14}B$)

- magnetically coupled

Neodymium-rich intergranular Phase for insulation

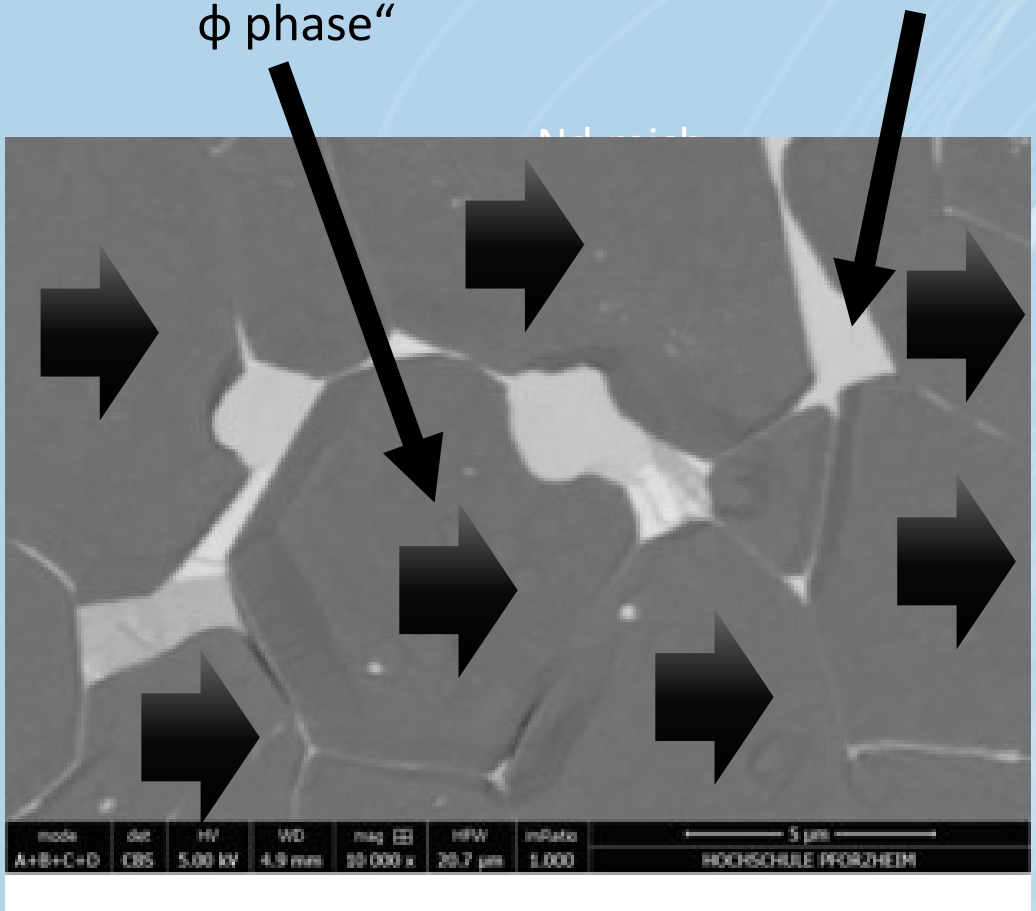
- magnetically decoupled

Dysprosium/Terbium needed for temperature stability

Neodymium, Dysprosium and Terbium are Rare Earth Metals

$Nd_2Fe_{14}B$
„hard magnetic ϕ phase“

Nd-rich phase
Non-magnetic, „insulating“



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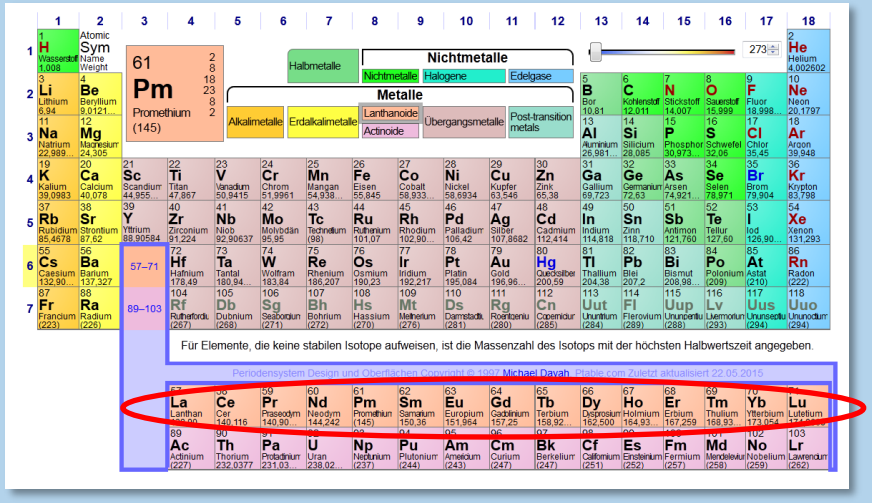
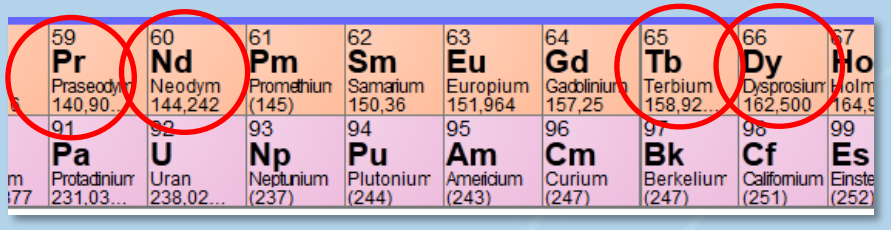
Rare Earth Metals





Abundant in the earth crust → not „rare“

Usually extracted in open pit mining

- very often as by-product

Difficult to separate

- low content in the ore
- all 17 elements together in varying contents
- often accompagnied by radioactive elements (Th, U)

https://hastingstechmetals.com/rar e-earths/neodymium/

Photo by MIMplus Technologies

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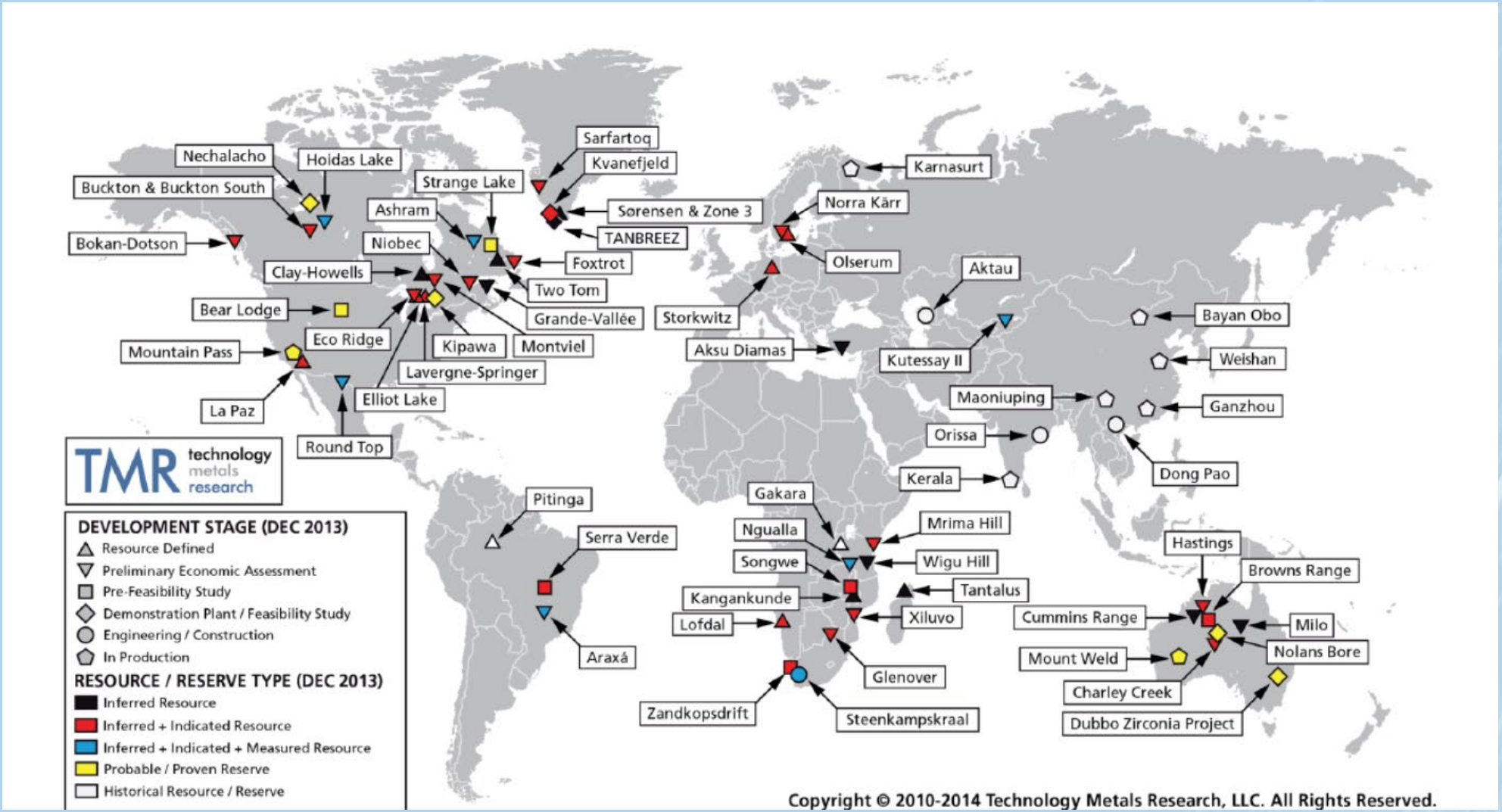
Rare Earth Mining



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Rare Earth Mining

Drilling

Blasting

Trucking

Loading

Hauling

Sources: Atlas Copco, African Mining Brief, Komatsu, Mining Technology.

Photo by MIMplus Technologies

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Rare Earth Refining

Value Chain (1)

Step 1	STEP 2	STEP 3	STEP 4	STEP 5
				
OPEN PIT MINING	**CRUSHING / MIXING**	**GRINDING / SLURRYING**	**SEPARATION / PRECIPATION**	**REMOVAL OF IMPURITIES**

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth Refining

Value Chain (2)

Step 6	Step 7	Step 8	Step 9	Step 10
				
SEPARATION OF LREE AND HREE CONCENTRATES	SEPARATION OF THE OXIDES	WATER TREATMENT (OPTIONAL)	REGENERATION OF ACIDS AND OTHER LEACHING CHEMICALS (OPTIONAL)	TAILINGS AND LANDFILL

Photo by MIMplus Technologies

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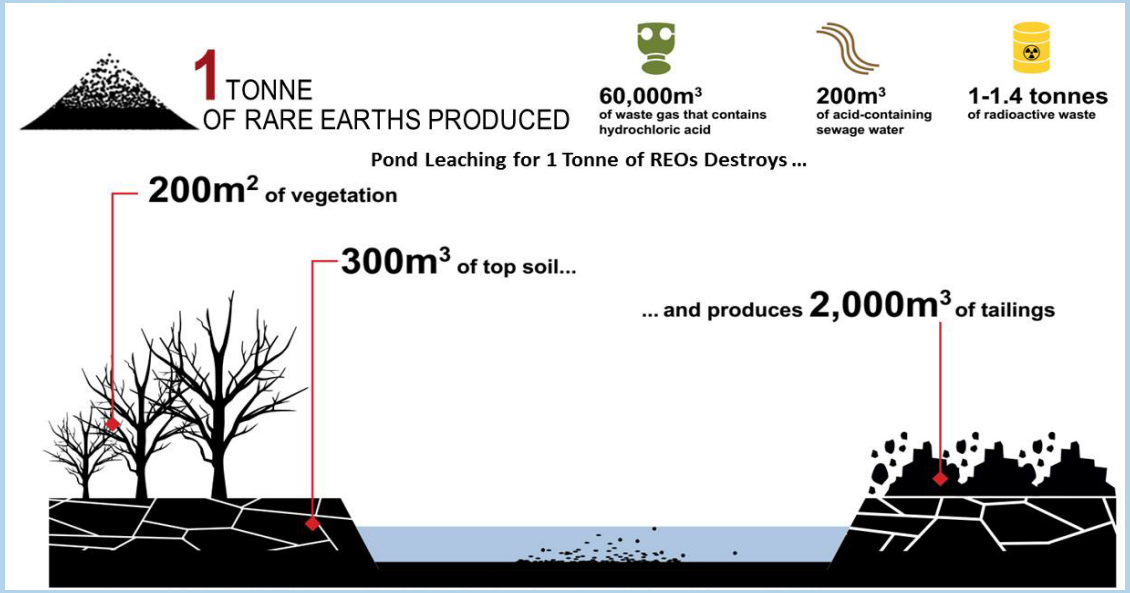
Rare Earth Refining

Environmental issues



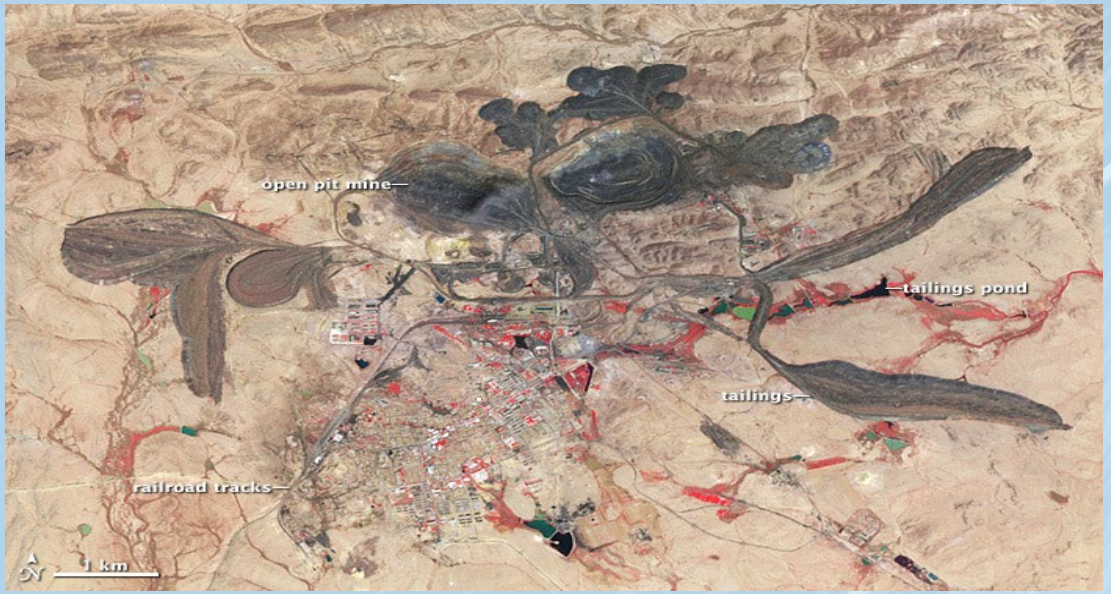


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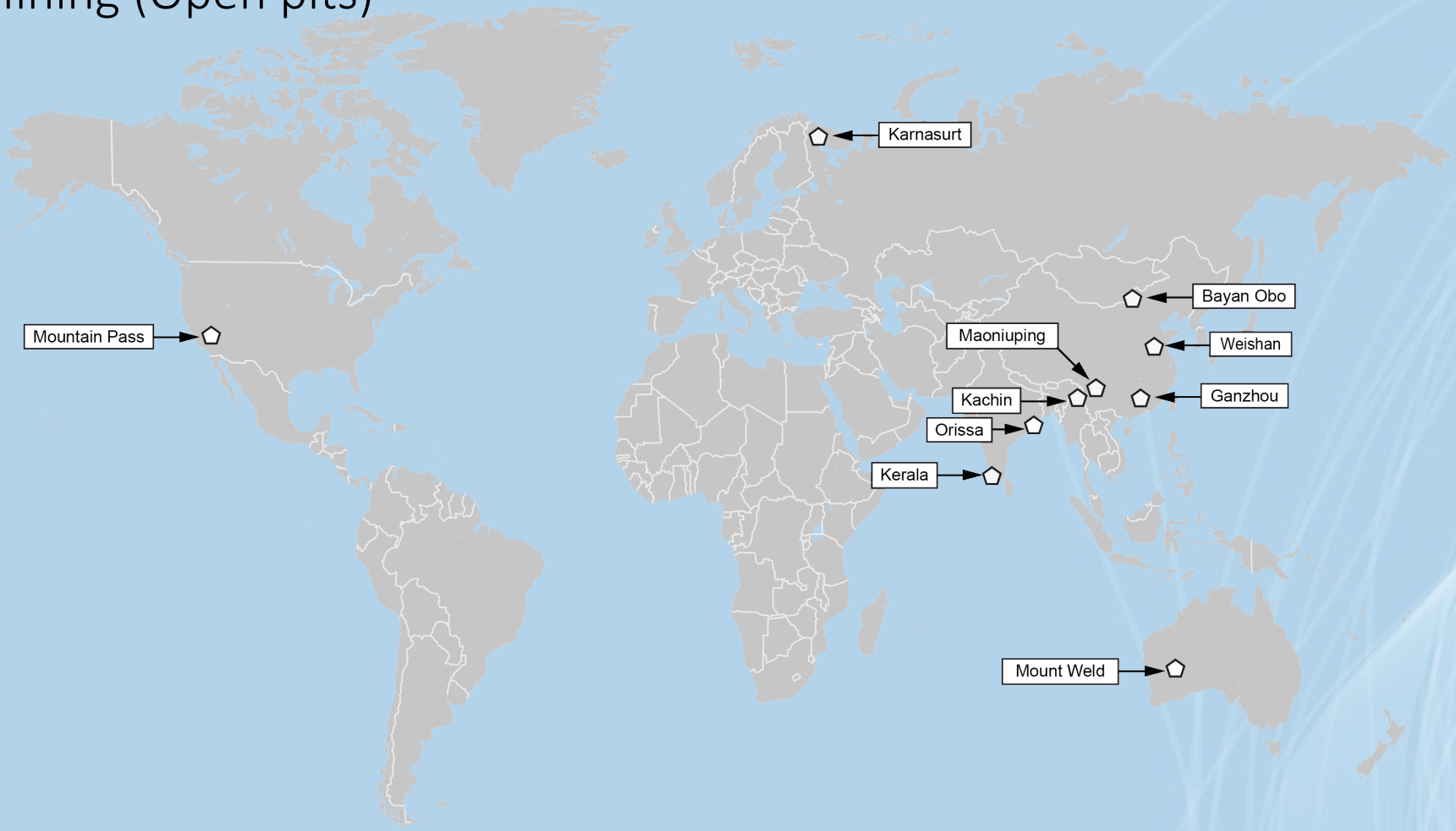
Photo by MIMplus Technologies

Rare Earth Mining

Primary Mining (Open pits)



Source: Strategic Materials Advisors

Photo by MIMplus Technologies

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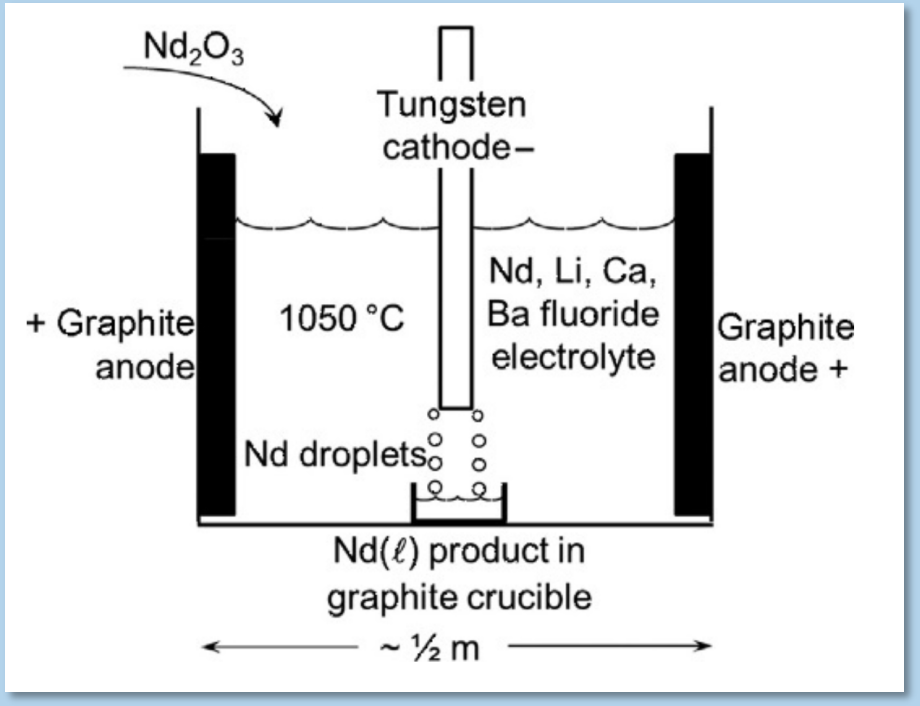
Rare Earth (cont.)

Metal making

Electrolytic Cell to produce molten Nd-metal



Highly pure Nd-metal.
Source: Less Common Metals.

Highly pure, Ca-reduced Tb-metal.
Source: Reade Advanced Materials.

Similar to aluminum electrolysis, **however currently at very low technological level**

→ Energy-intensive

→ Tremendous greenhouse gas potential due to harmful emissions of PFCs

Source: Lucas et al 2015.

Photo by MIMplus Technologies

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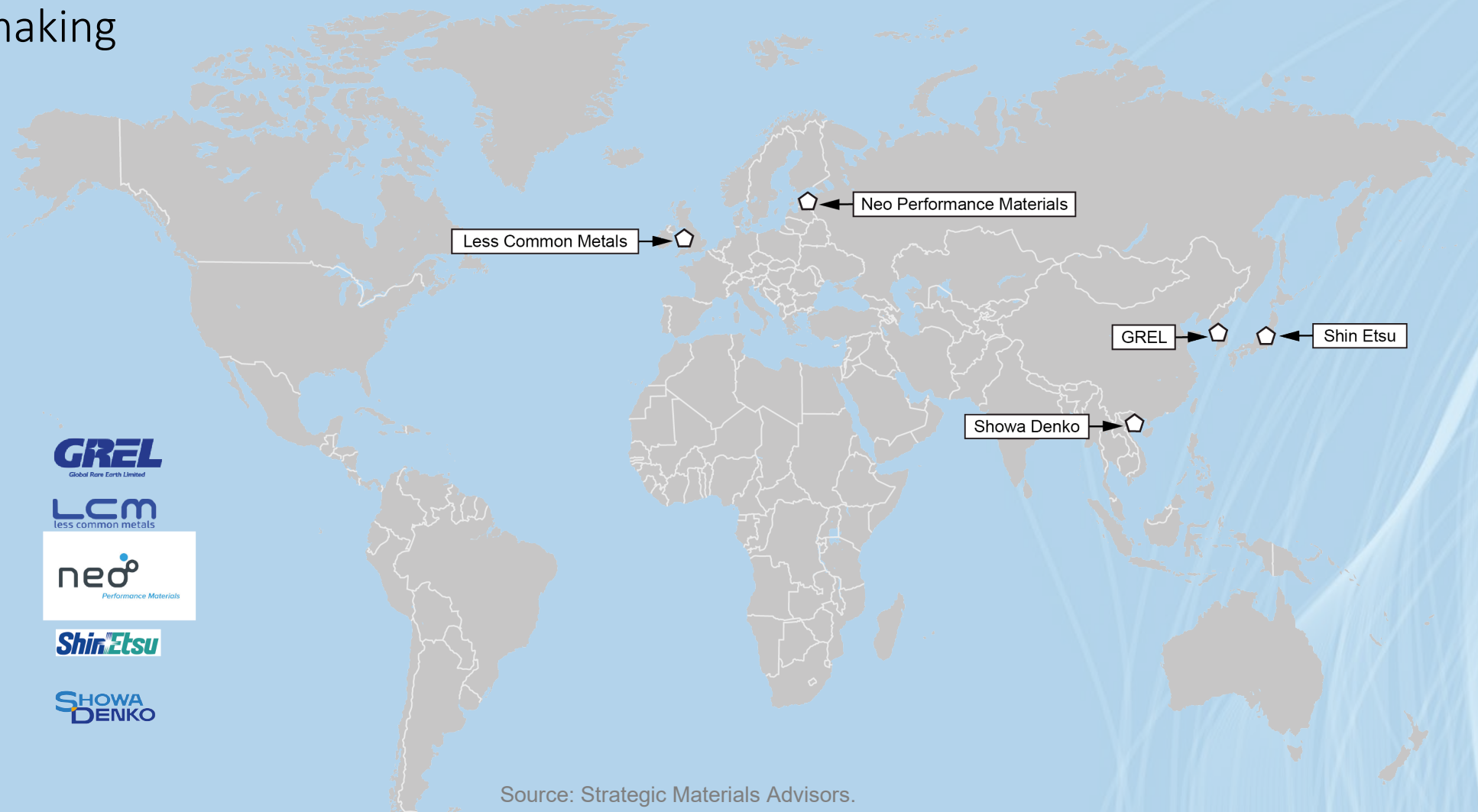
Rare Earth (cont.)

Metal making



Source: Strategic Materials Advisors.

Photo by MIMplus Technologies

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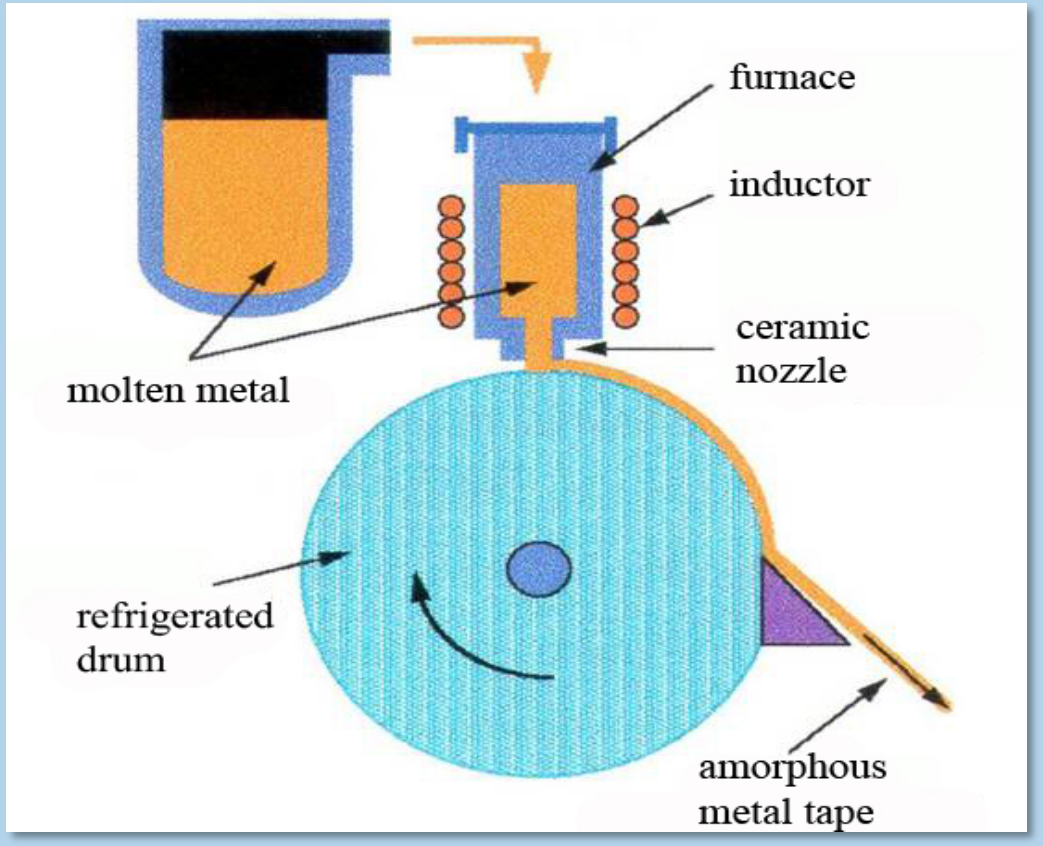
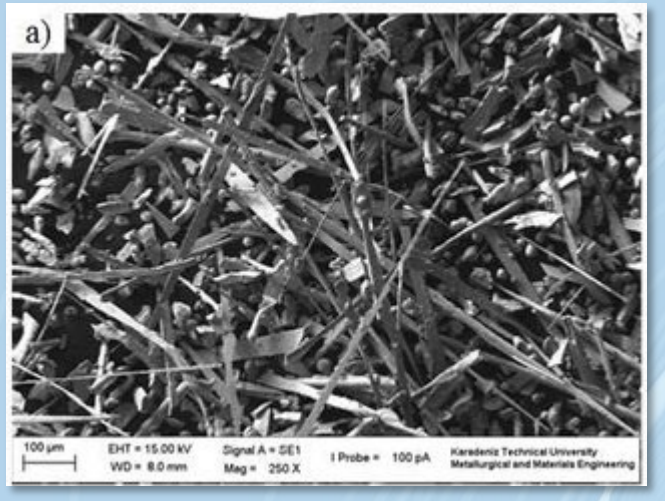
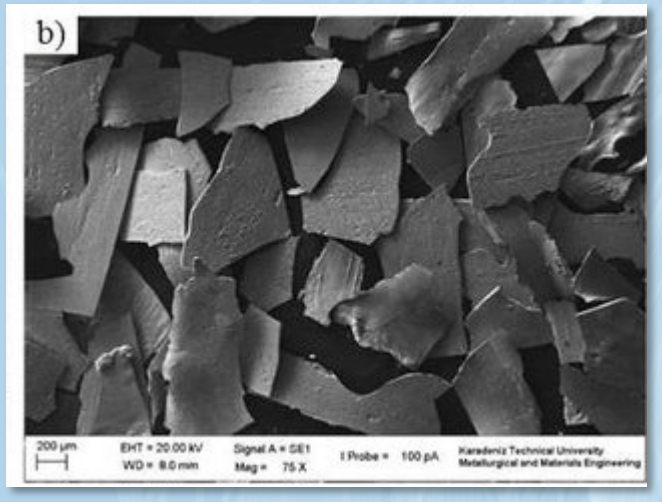
Rare Earth (cont.)

Magnet making (1a): melt spinning







amorphous NdFeB-ribbon;
a) after melt spinning
b) after millling

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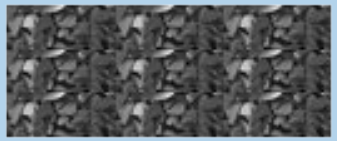
Rare Earth (cont.)

Magnet making (1b): polymer bonding

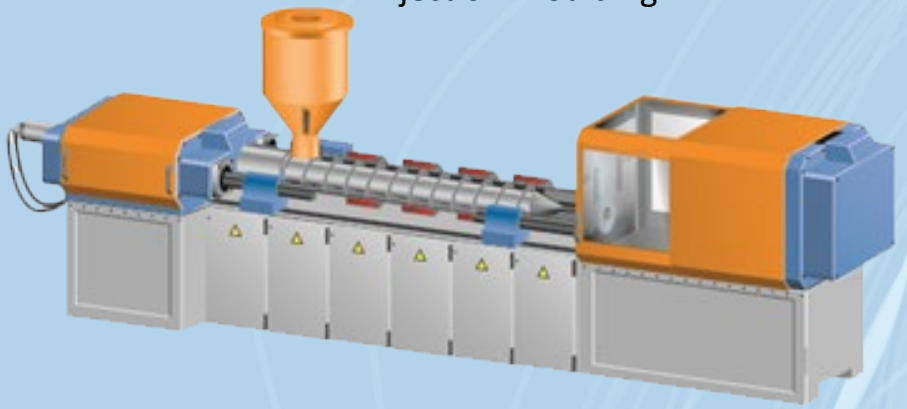
MQ-powder



Polymer-Binder

Mixing

Injection-moulding



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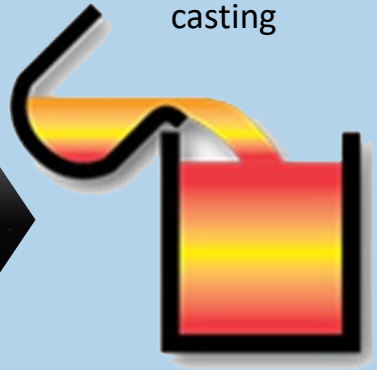
Rare Earth (cont.)

Magnet making (2a): powder production

Mixing of alloying elements

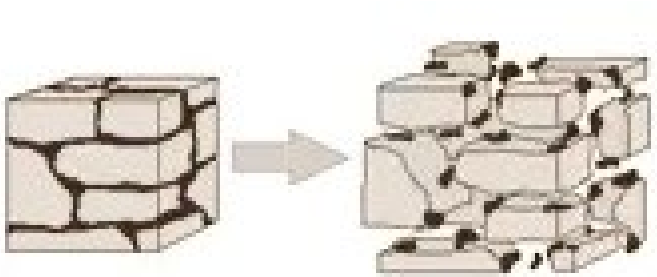
Nd, Fe, B (Pr, Dy, Co, Ga..)

(Strip) casting

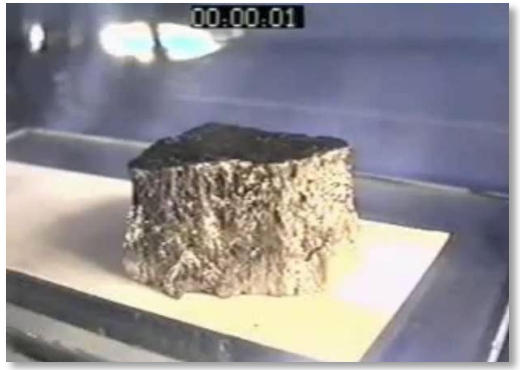


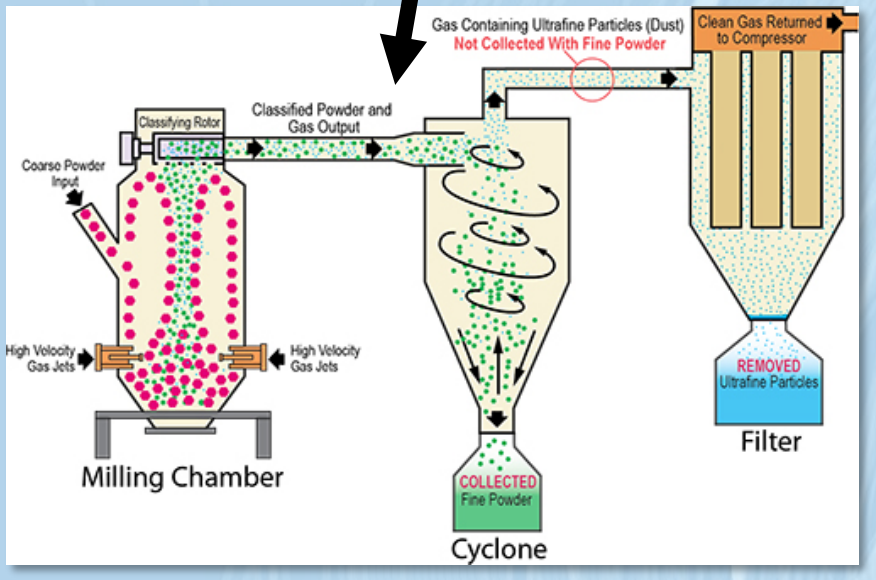
Coarse grinding

fine milling (jet milling)



+ Hydrogen





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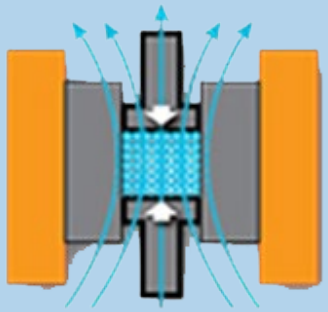
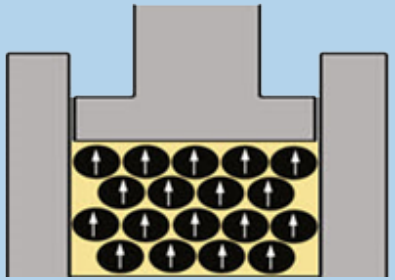
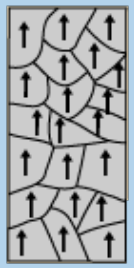
Rare Earth (cont.)

Magnet making (2b): pressing and sintering

Pressing in magnetic field



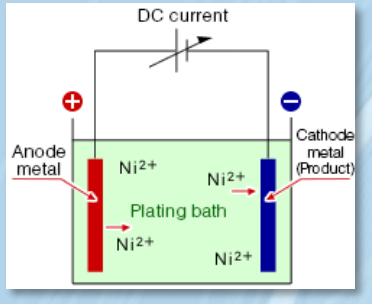


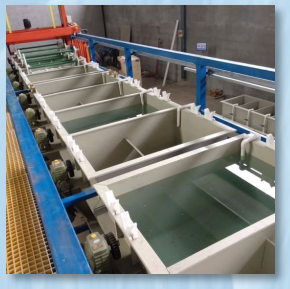


Sintering & heat treatment

Cutting & Eroding

Coating (corrosion)





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Rare Earth (cont.)

Magnet making (2b): pressing and sintering

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Rare Earth: politics

The Chinese strategy

"There is oil in the Middle East; the is rare earth in China"

Deng Xiaoping 1992

"Improve the development and applications of rare earth, and change the resource advantage into economic superiority"
Jiang Zemin 1999

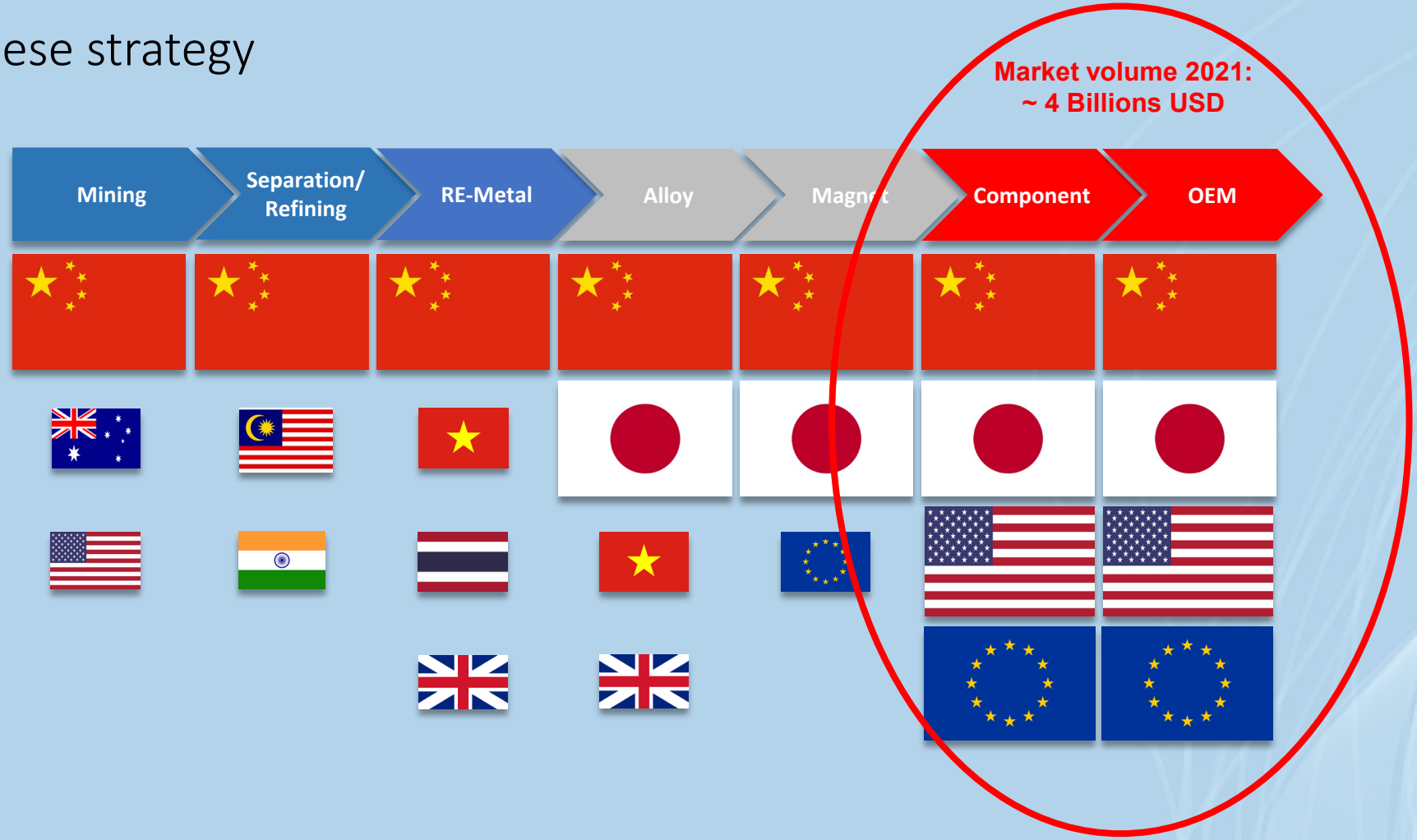
"China is making success in electric vehicles a national priority to take leadership in a key emerging technology"
Xi Jingpin 2017

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth: politics

The Chinese strategy

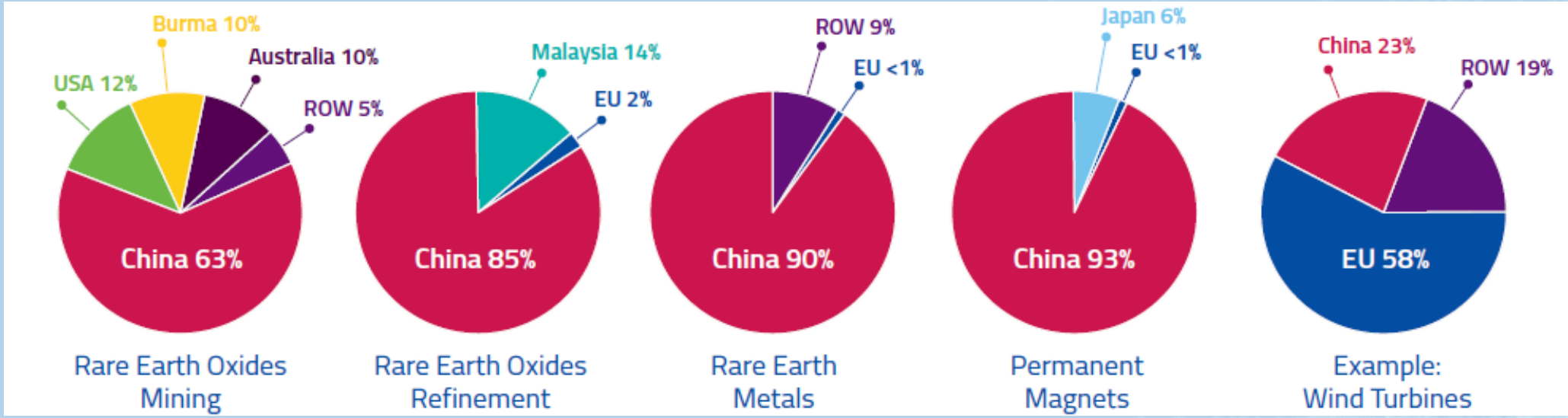


Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Photo by MIMplus Technologies

Rare Earth: politics

The Chinese dominated value chain



Rare Earth Magnets and Motors. A European call for Action; Report Cluster Rare Earth Magnets/Motors of European Raw Materials Alliance, 2021

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth: strategy (2)

Advantage China…

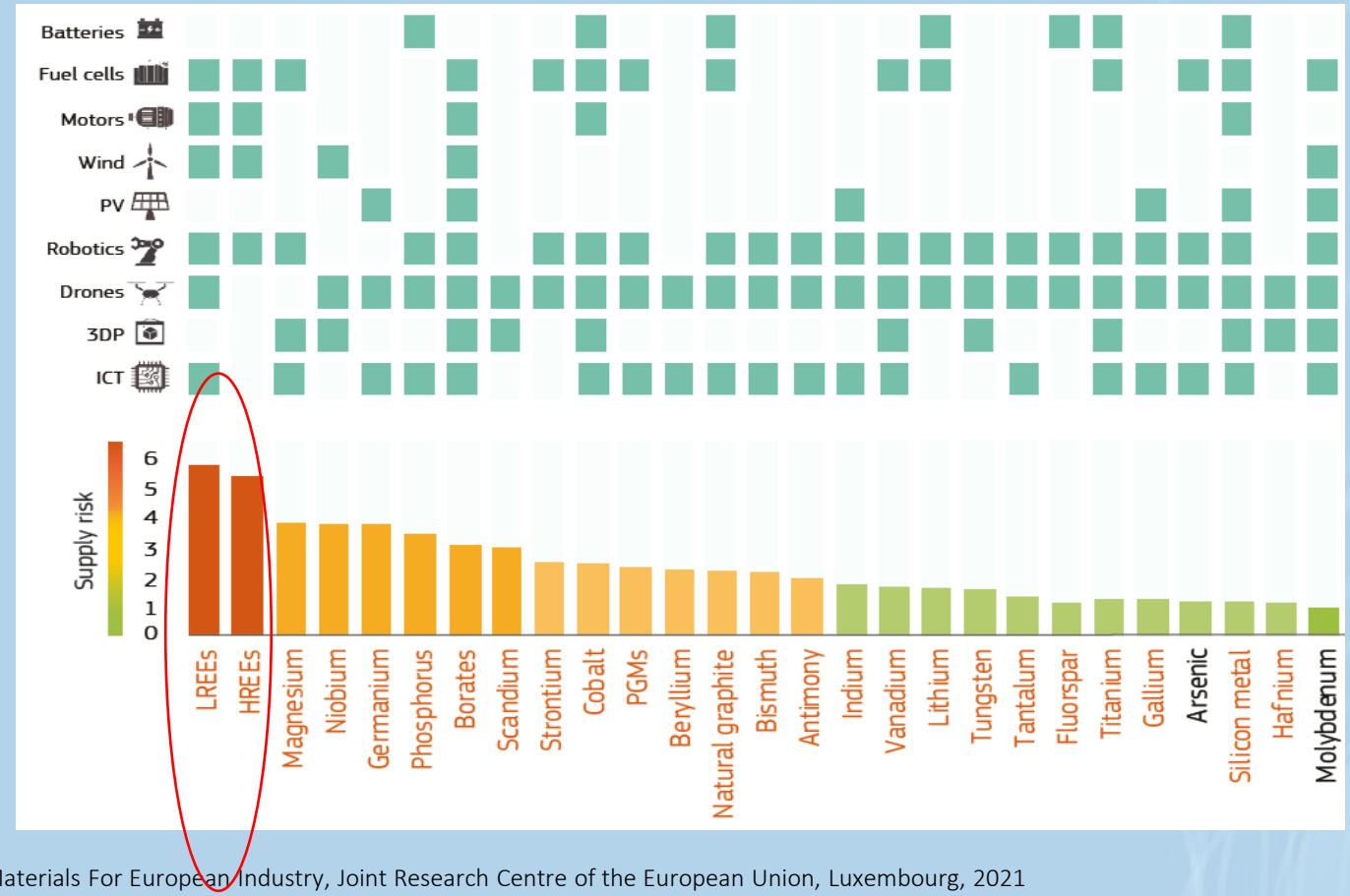
- 36% of the known resources are in China
- 92% of all NdFeB magnets are currently produced in China
- Large, strategic investments in the RE value chain for more than 50 years
- (Still) lax environmental regulations
- State controlled pricing
- 30% tax advantage compared to Europe
- Strategic increase of the market share of **RE- containing products** by 25% p.a. since 2020

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth: strategy

Europe in the need…



Source: Foresight On Critical Raw Materials For European Industry, Joint Research Centre of the European Union, Luxembourg, 2021

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth: strategy

European answers

- Supporting mining project in Europe and in „reliable partner countries“

  → Canada, Australia, Indonesia, Malawi, Namibia and others

- Supporting strategic investments over the whole value chain

  → mining, refinery, metal making, magnets making, recycling

- Critical raw materials act (16.03.2023)
  - → 40% of consumption to be produced in Europe
  - → 15% of consumption from recycling

Photo by MIMplus Technologies

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Rare Earth: strategy

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  → mining, refinery, metal making, magnets making, recycling

- Critical raw materials act (16.03.2023)

  → 40% of consumption to be produced in Europe

  → 15% of consumption from recycling

Stopping a huge mine: how an Inuit party won Greenland's elections

Mount Kuannersuit, the site for the unpopular mining project © Iaea Imagebank/Flickr

14 April 2021, by Valentina Neri

The immense rare earth and uranium mine on Mount Kuannersuit won't go ahead. This is the promise that helped the Inuit community win Greenland's elections.

https://www.lifegate.com/greenland-election-inuit-mining

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth: strategy

European answers

- Supporting mining project in Europe and in „reliable partner countries“

  → Canada, Australia, Indonesia, Malawi, Namibia and others

- Supporting strategic investments over the whole value chain

  → mining, refinery, metal making, magnets making, recycling

- Critical raw materials act (16.03.2023)
  - → 40% of consumption to be produced in Europe
  - → 15% of consumption from recycling

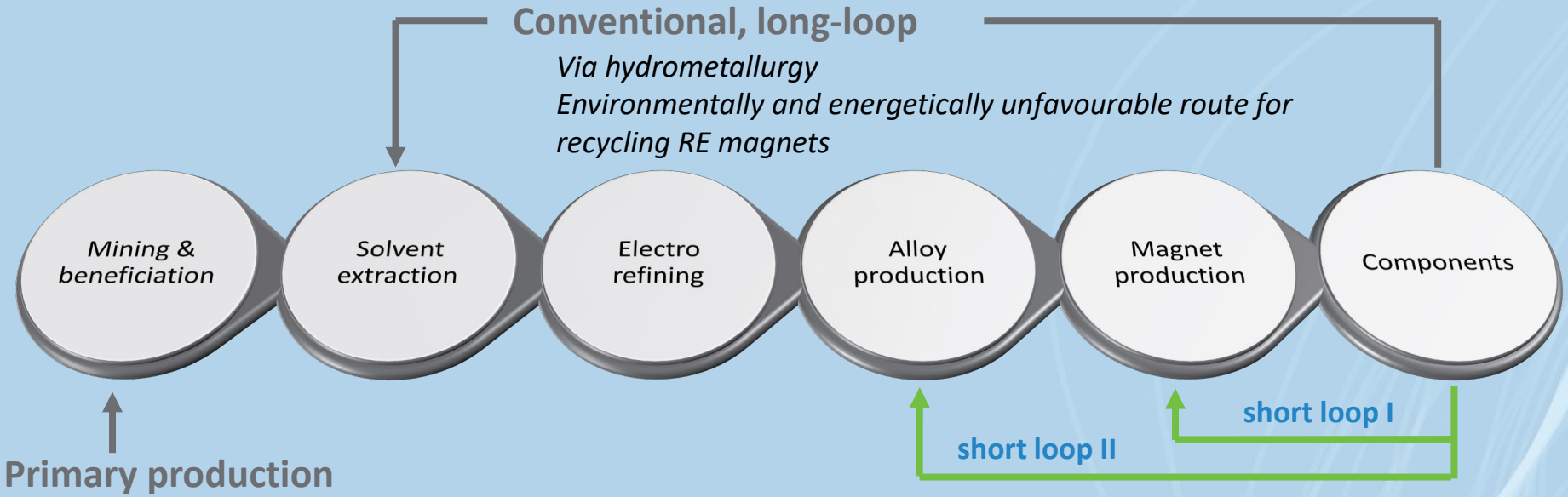
Recycling

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Rare Earth Recycling

Long loop vs. short loop



Materials	Primary			Recycled		
	Embodied Energy (MJ/kg)	CO2 Footprint (kg/kg)	Water Usage (L/kg)	Embodied Energy (MJ/kg)	CO2 Footprint (kg/kg)	Water Usage (L/kg)
Steel	29 - 80	2.2 - 5.0	23 – 112	8.0 – 22	0.6 – 1.4	-
Aluminium	200	11	125	18	1.1	-
Copper	68	4.9	150	17	1.2	-
NdFeB Magnets *	370	20	150	20	2.0	-

* HPMS process

Source: Speight, J.; Climate Change from a Materials Perspective, The University of Birmingham, 02.08.2019

Photo by MIMplus Technologies

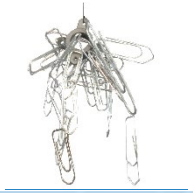
Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

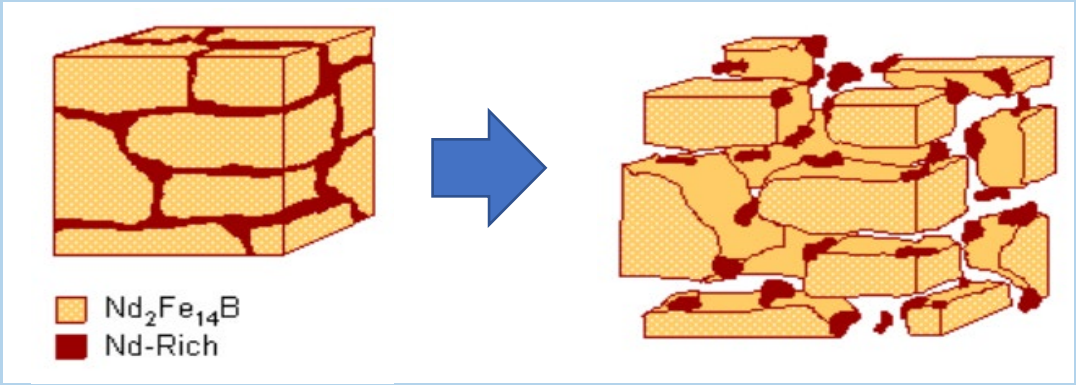
Rare Earth Recycling

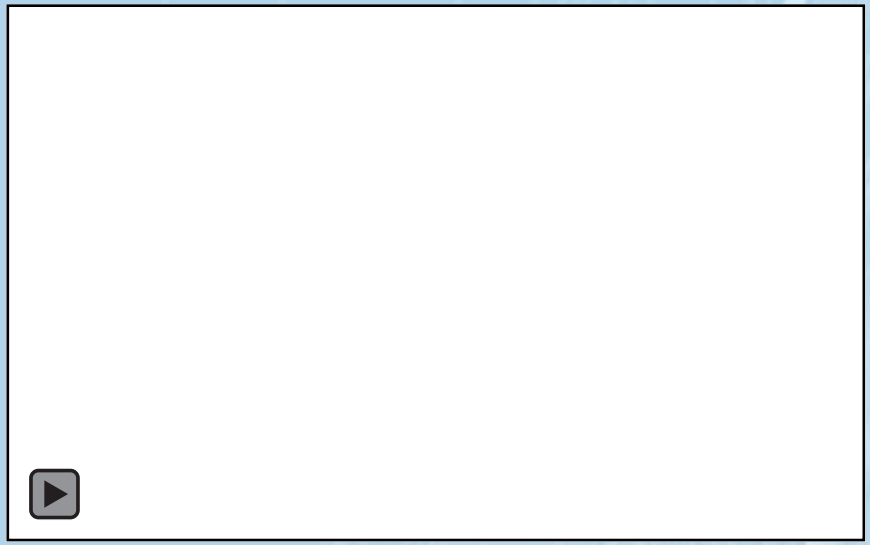
Short loop

Recycling is technically feasible

- High yield
- High quality
- Low carbon footprint

Route A: Sintering	Route B: HDDR/poly-mer bonding	Route C: Metal Injection Moulding	Route D: Recasting
			





Source: Speight, J.; Climate Change from a Materials Perspective, The University of Birmingham, 02.08.2019

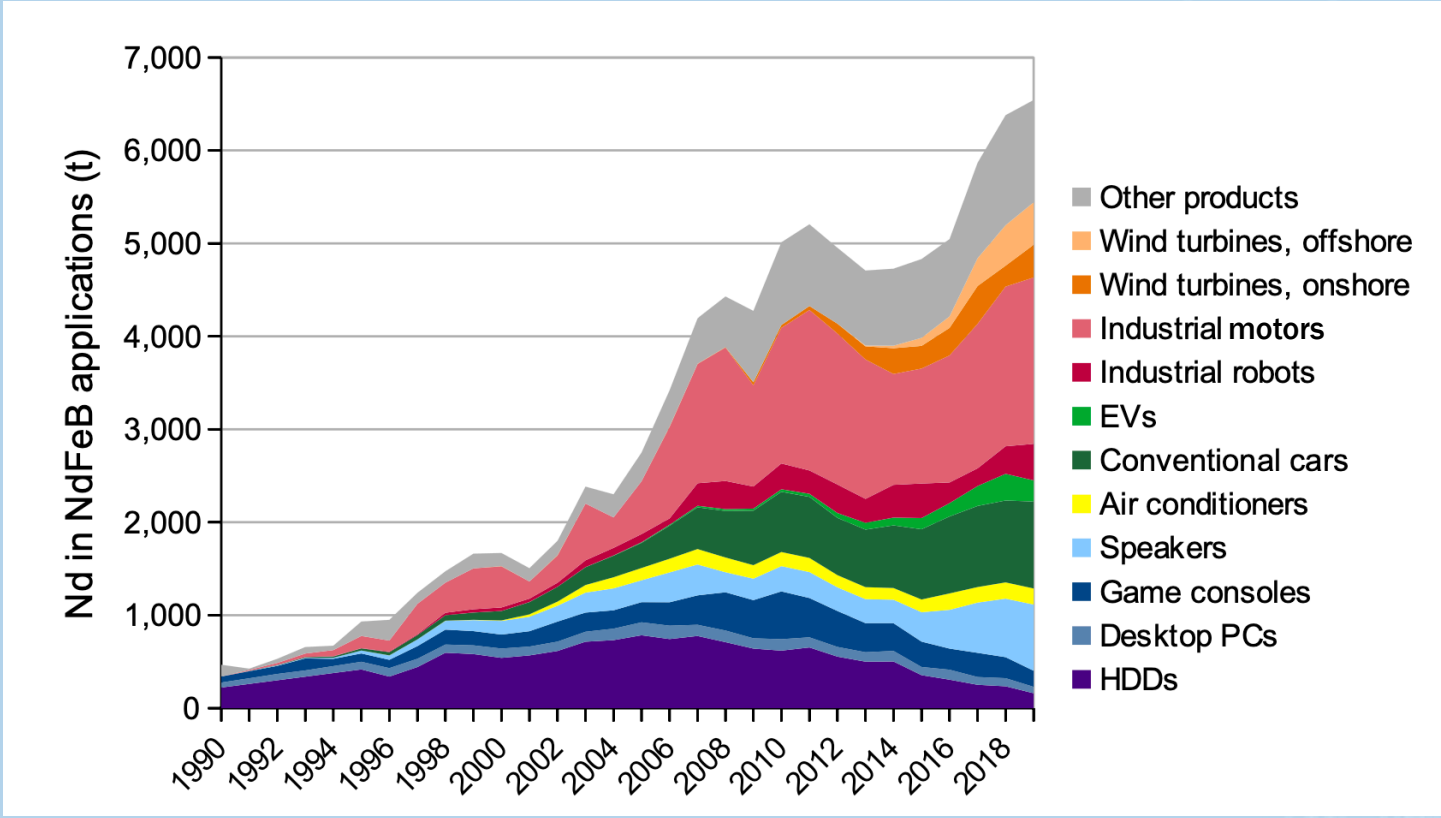
Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Photo by MIMplus Technologies

Rare Earth Recycling

Material availability

Nd material flow trends for application types in EU-28



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RE Magnets Recycling

Technical issues

Other technology metals (Ag, Pt, Pd) have recycling rates of ~30%

- Recycling rate of Nd is **<1%**

→ Large diversity of End-of-Life Magnets:

- SmCo, Ferrite, NdFeB....
- no design for recycling

→ Underdeveloped recycling schemes

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

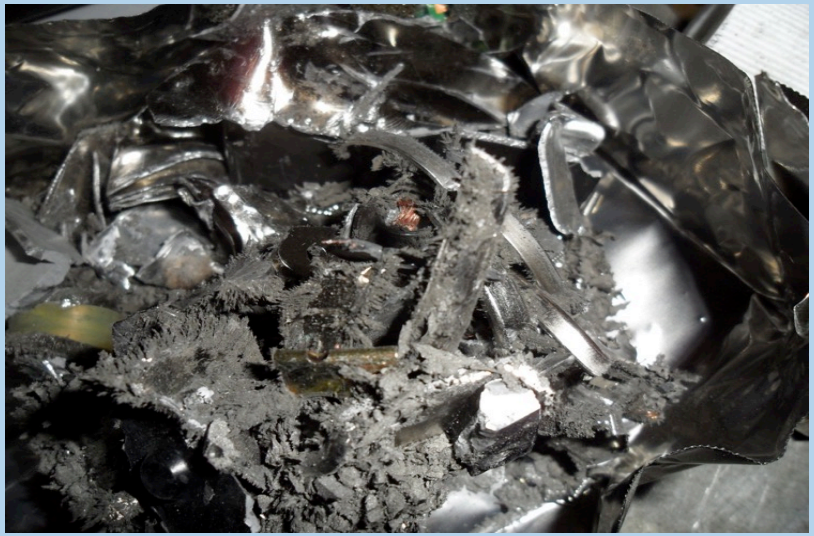
RE Magnets Recycling

Technical issues

Other technology metals (Ag, Pt, Pd) have recycling rates of ~30%

- Recycling rate of Nd is **<1%**

→ Components are often shredded, as dismantling requires expertise and is costly



Source: Shredded HDD; courtesy of René Klein, Universiteit Leiden, shredded traction motor: courtesy of Axion

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

RE Magnets Recycling

Technical issues

→ Magnet content in products is often low

CHEMISTRY: ELEMENTS // ENGINEERING: ELECTRICAL

CELL PHONE CHEMISTRY

A look at the elements that make up your smartphone

A typical cell phone contains some of the most valuable elements on Earth. With everything from gold to silver, it's like having a little treasure chest in your pocket.

A smartphone is packed with at least 40 elements, says Andy Brunning, a chemistry teacher in Bournemouth, U.K. His website, Compound Interest, illustrates the chemistry of everyday items, like phones. "As far as everyday chemistry goes, the cell phone that most of us carry around is up there," he says.

Check out the diagram to find out about some of the elements and compounds that put the smarts in your phone.

—Andrew Klein

KEY
Alkali metals · Other metals · Transition metals · Nonmetals · Inner transition metals · *Denotes a gas

WATCH A VIDEO
4 BONUS SKILLS SHEETS

TOUCH SCREEN
O Oxygen · In Indium 114.8 · Sn Tin 118.7

A thin layer of indium tin oxide—a mixture of indium oxide (In_2O_3) and tin oxide (SnO_2)—conducts electricity. When you touch the screen, a change in the electrical field occurs and communicates your finger's location to the phone's chip.

GLASS
O Oxygen · Al Aluminum 26.98 · Si Silicon · K Potassium 39.10

Smartphone screens contain aluminosilicate glass, made from the compounds alumina (Al_2O_3) and silica (SiO_2). If you've ever dropped your phone and its screen has stayed intact, you can thank potassium *ions* (atoms that have gained or lost electrons). They help strengthen the glass.

DISPLAY
Y Yttrium 88.91 · La Lanthanum 138.9 · Eu Europium 152.0 · Gd Gadolinium 157.3 · Tb Terbium 158.9 · Dy Dysprosium 162.5

A cell phone's display contains several *rare earth elements*. These elements are spread out widely in Earth's crust, making them hard to mine. Small quantities of yttrium, europium, and dysprosium help produce the colors on the phone's liquid crystal display (LCD) screen. Gadolinium, lanthanum, and terbium give the screen its glow.

CIRCUITRY
Cu Copper 63.55 · Ag Silver 107.9 · Sn Tin 118.7 · Au Gold 197.0

The circuit board has gold, copper, and silver—good electrical *conductors*. The *connectors* (pins that join circuits to the circuit board) are coated in gold because it's highly resistant to corrosion. The wiring is copper. Solder—an *alloy* of tin, silver, and copper—binds parts of the circuit board.

MICROPHONE AND SPEAKERS
B Boron · Fe Iron 55.85 · Ni · Nd Neodymium 144.2

The microphone's super-thin *diaphragm*, which vibrates when sound waves strike it, is made of nickel. The vibrations are converted into an electrical current that becomes the audio signal. Magnets vibrate in the speaker to create audible sound. Magnets of neodymium ($Nd_2Fe_{14}B$) are used because they're the strongest magnets, so even though they're small, they're powerful.

COMPUTER CHIP
Si Silicon · P Phosphorus 30.97 · Ga Gallium 69.72 · As Arsenic 74.92 · Sb Antimony 121.8

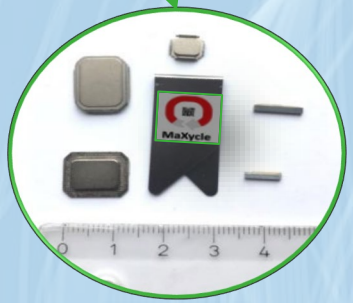
The chip is the phone's brain. It has many *transistors* made of antimony, phosphorus, and gallium arsenide (GaAs). Transistors act as paths and switches that tell the phone to follow or stop following commands. The chip is embedded with silicon—which has low conductivity—to channel electricity only through the conductive transistors.

BATTERY
Li Lithium · Al Aluminum 26.98

When you turn on your phone, positively charged lithium ions move through a lithium-salt solution that conducts electricity. Electrons flow out of the battery, producing the electric current that powers your phone. The rechargeable battery's casing is made of aluminum.

CORE QUESTION
What are three elements used in a cell phone? What are their applications?

18 JANUARY 12, 2015 · WWW.SCHOLASTIC.COM/SCIENCEWORLD 19



Source: https://Thinklink.com

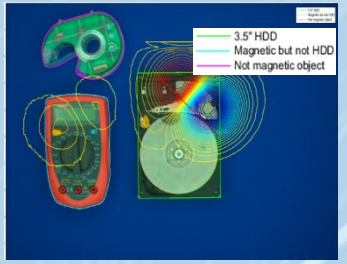
Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

RE Magnets Recycling

Project SUSMAGPRO

- Applications containing Nd-Fe-B magnets are identified, the components containing Nd-Fe-B magnets are separated from the waste stream
- After separation, the magnets are removed from the housings, glues, mechanical fixtures and coatings
- The magnets are recycled using the IP-protected HPMS short cycle processing route (extracting and re-processing the Nd-Fe-B as an alloy), leading to significant energy and cost savings compared to chemical or pyrometallurgical recycling
- The recycled material is re-processed into new magnets by four different manufacturing routes



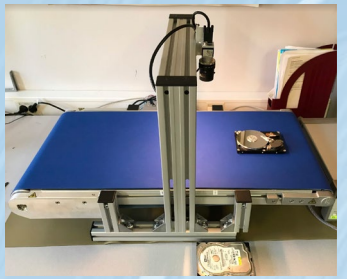


Photo by MIMplus Technologies

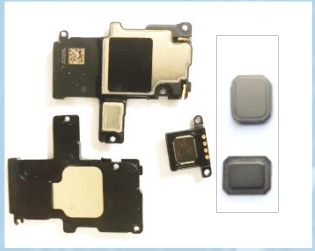
Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

RE Magnets Recycling

Project SUSMAGPRO: Info gathering

- So far, over 160 applications have been dismantled and analysed for re-cyclability
- Parameters I: Accessibility, fixation, contaminations […]
- Parameters II: Magnetic properties, microstructure,coatings, chemical composition
- Setup of a comprehensive database
- Input for automatic disassembly and labelling
- Input for design-for-recycling





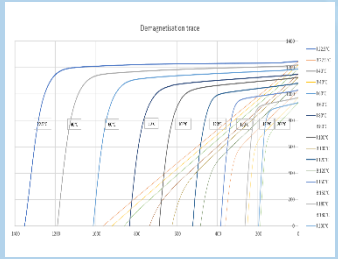
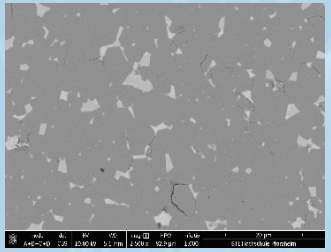
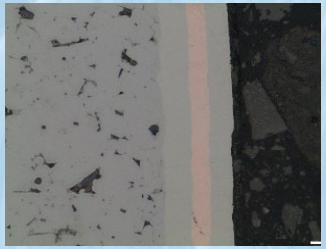





Photo by MIMplus Technologies

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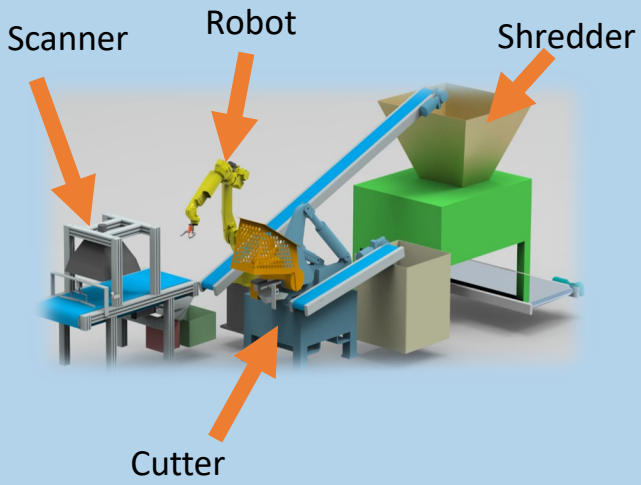
RE Magnets Recycling

Project SUSMAGPRO: automated disassembly



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RE Magnets Recycling

Project SUSMAGPRO: automated disassembly

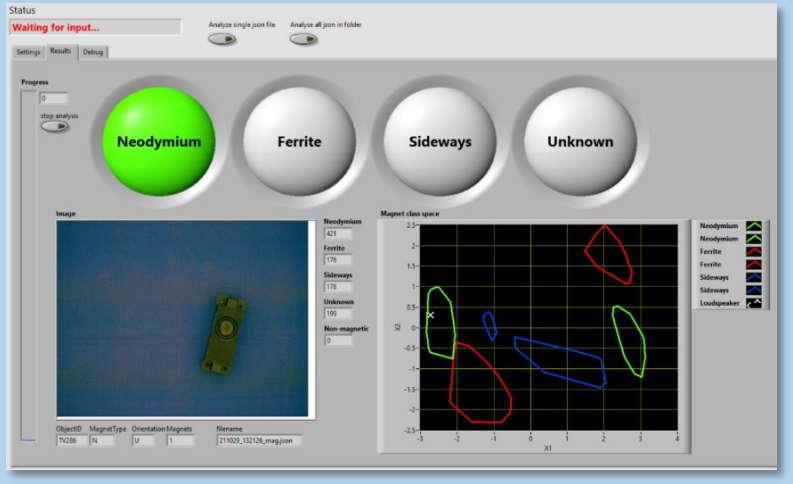

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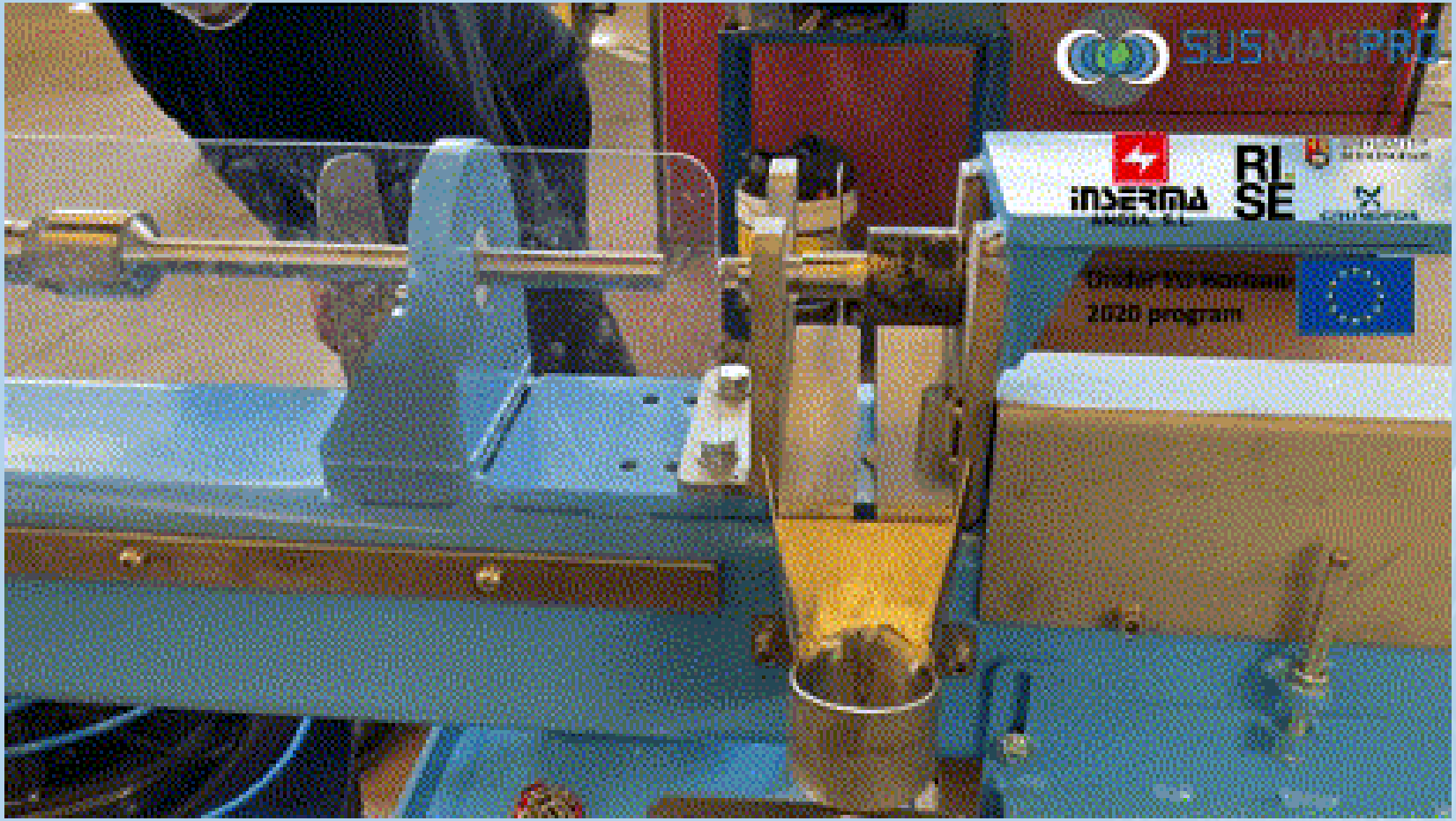
Photo by MIMplus Technologies

RE Magnets Recycling

Project SUSMAGPRO: automated disassembly



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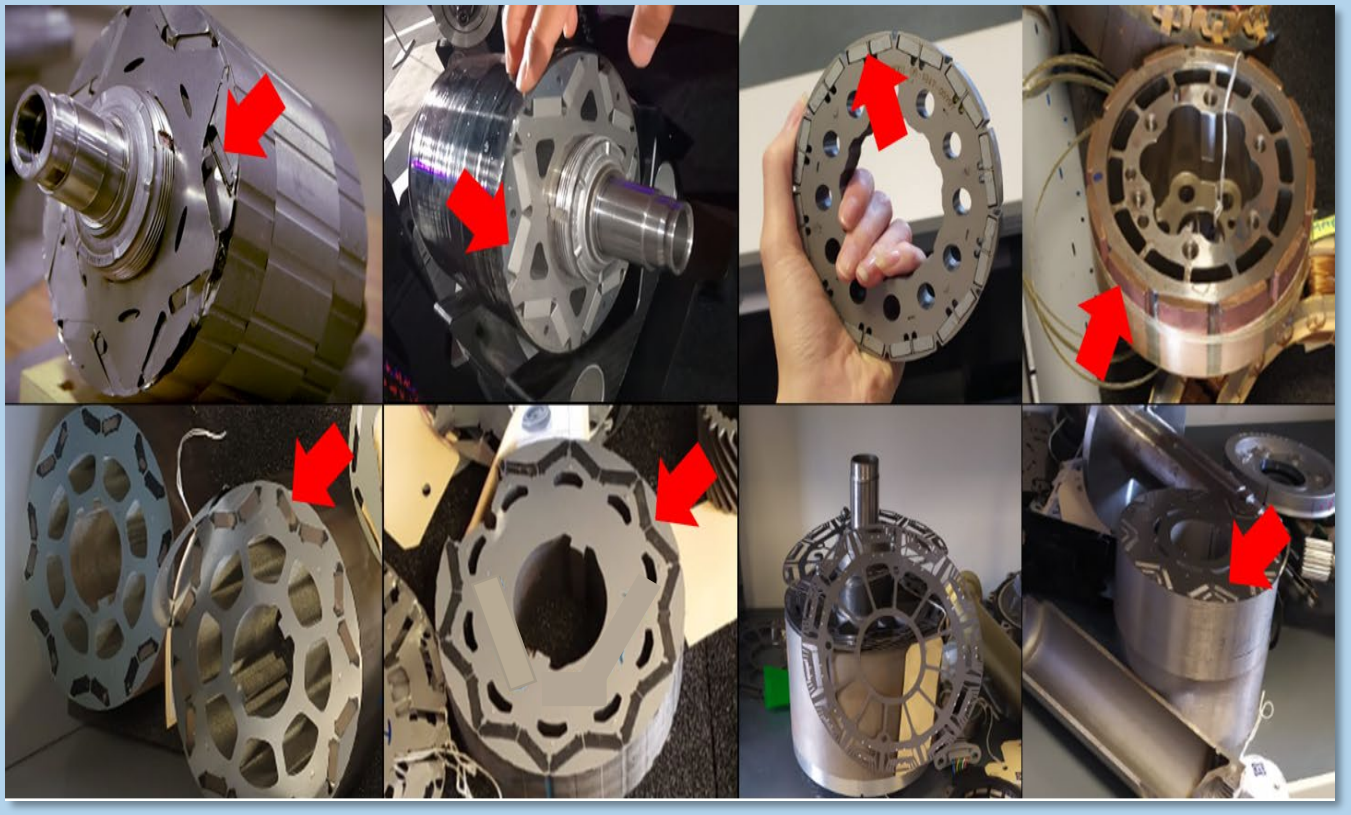
RE Magnets Recycling

Project SUSMAGPRO: challenges inautomated disassembly



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SUSMAGPRO
SUSTAINABLE RECOVERY, REPROCESSING AND REUSE OF RARE-EARTH MAGNETS IN THE CIRCULAR ECONOMY

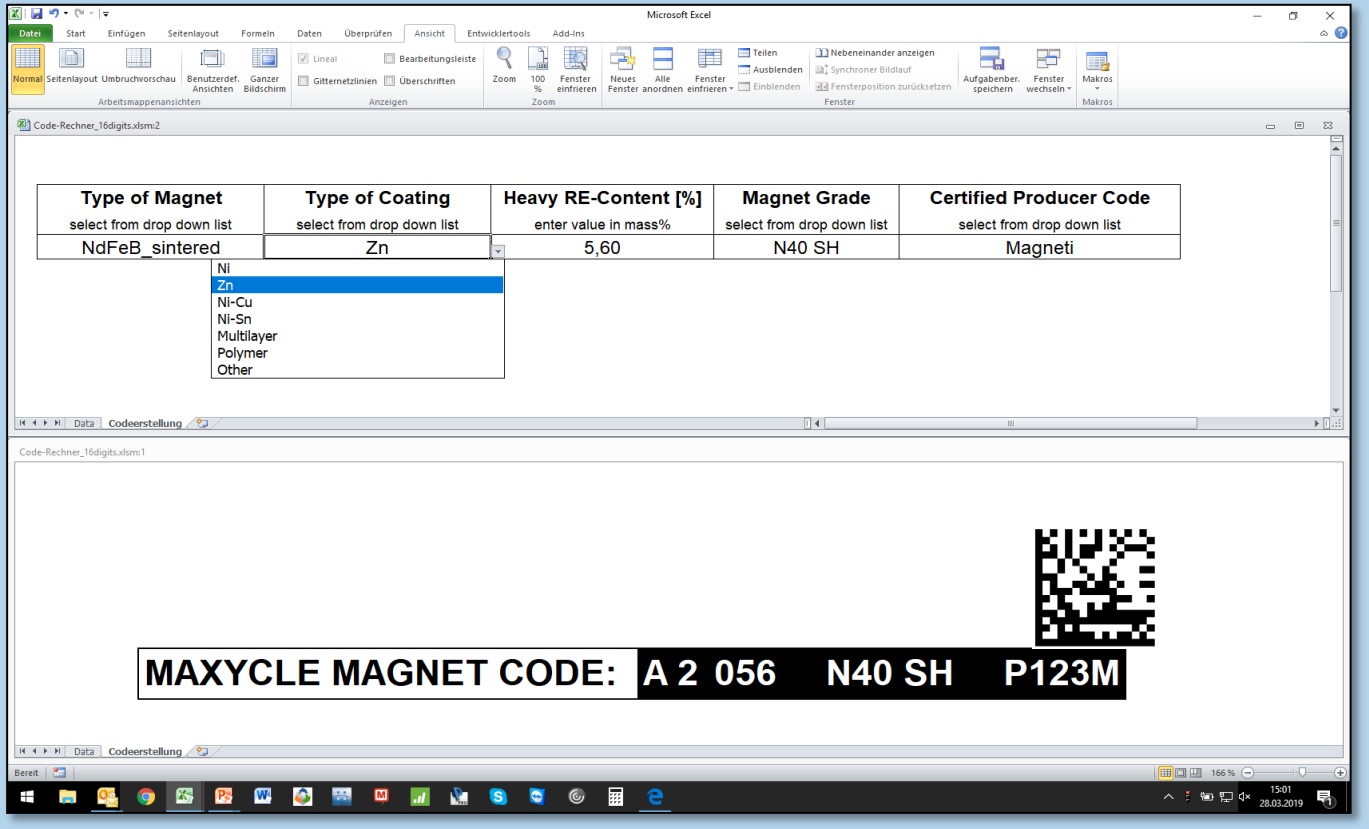
REEsilience

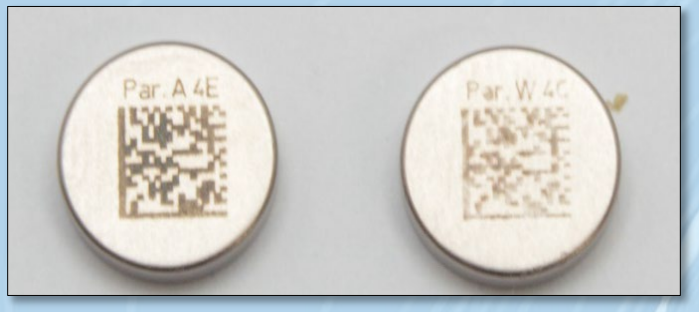
Science on the Street
Ljubljana, 21. April 2023

RE Magnets Recycling

Project MaXycle: Labelling

ERA-MIN 2
RESEARCH & INNOVATION PROGRAMME ON RAW MATERIALS TO FOSTER CIRCULAR ECONOMY
MaXycle





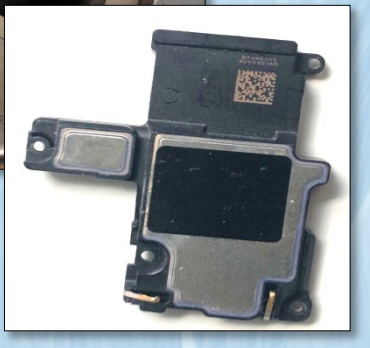


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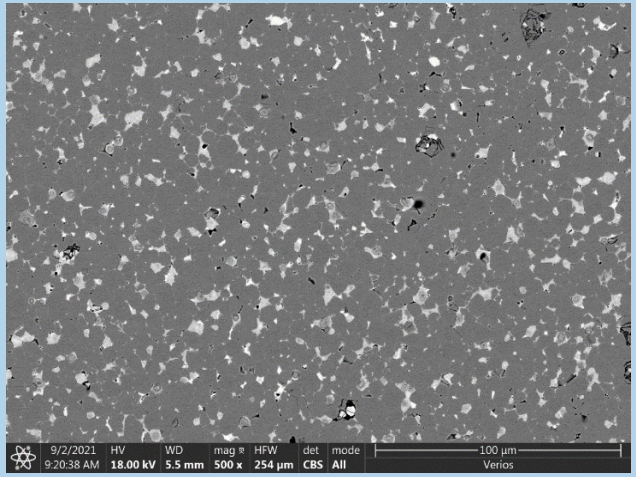
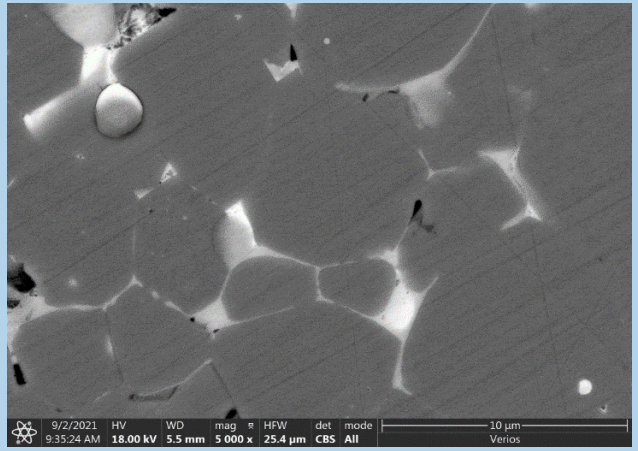
Photo by MIMplus Technologies

RE Magnets Recycling

Project SUSMAGPRO: sintered magnets





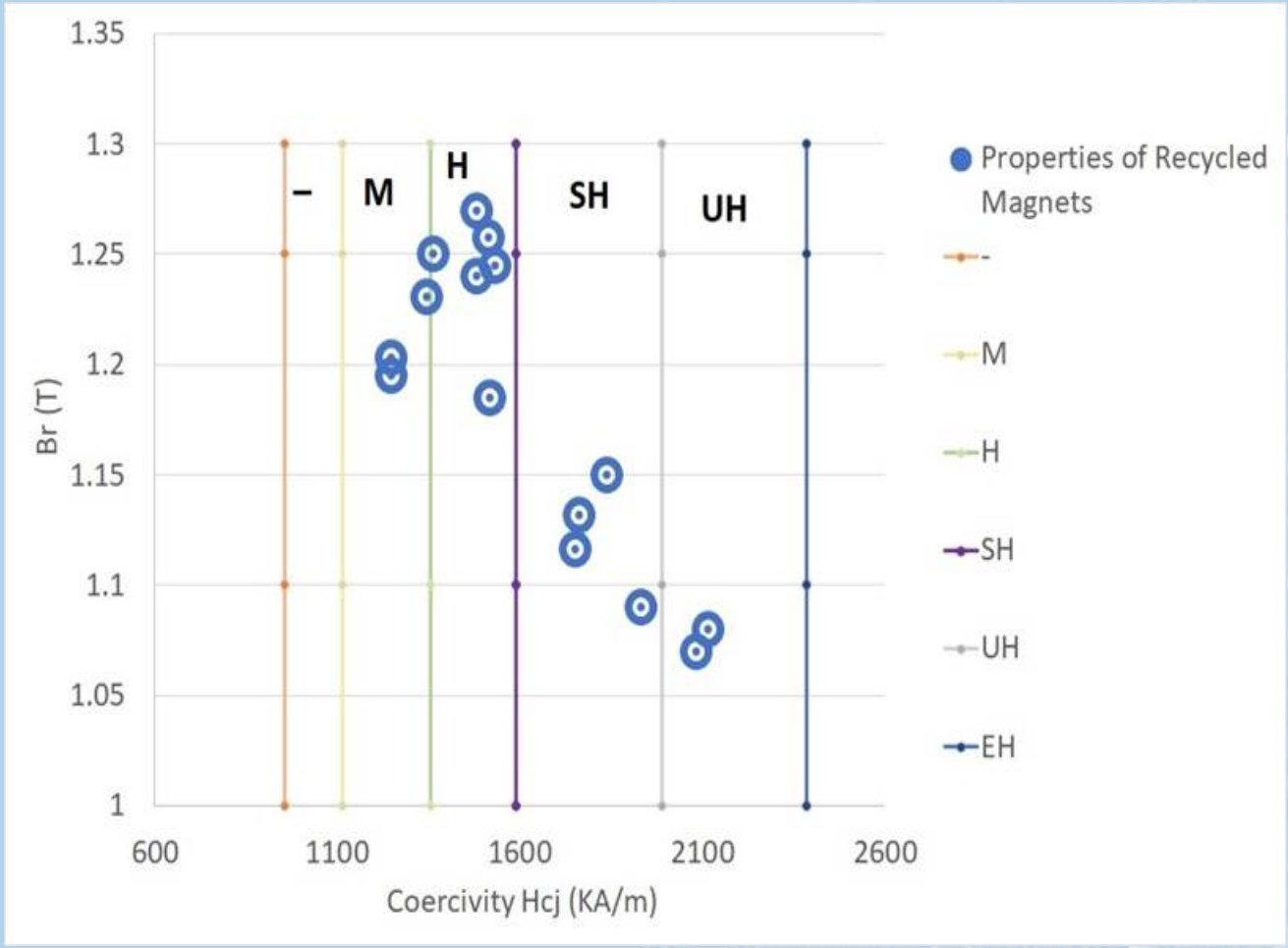


Photo by MIMplus Technologies

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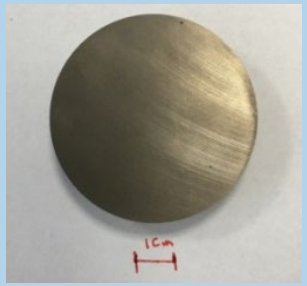
RE Magnets Recycling

Project SUSMAGPRO: demonstrators



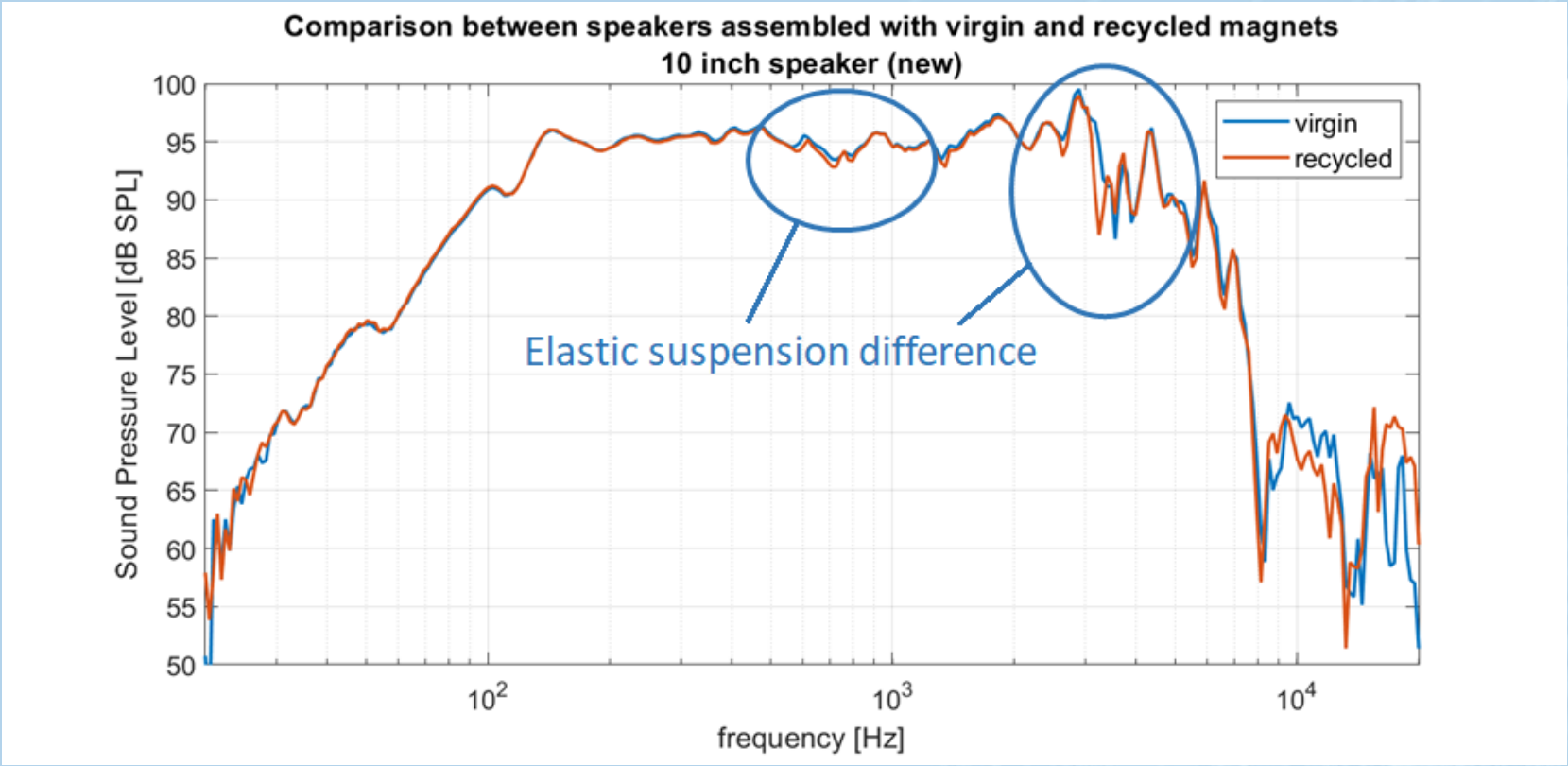


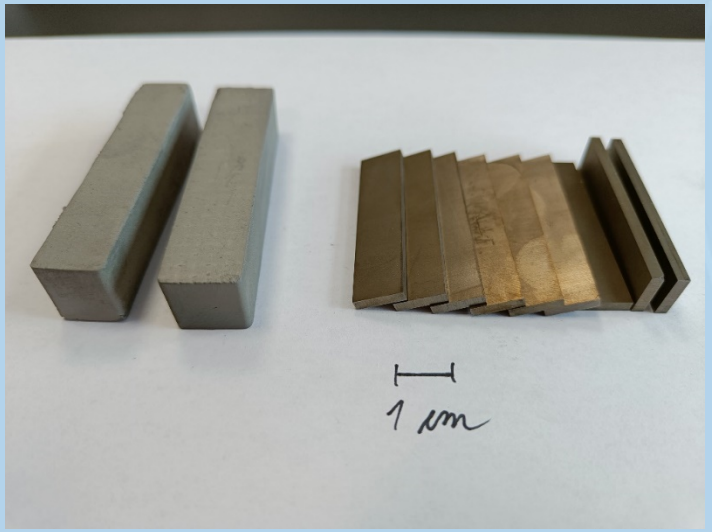
Photo by MIMplus Technologies

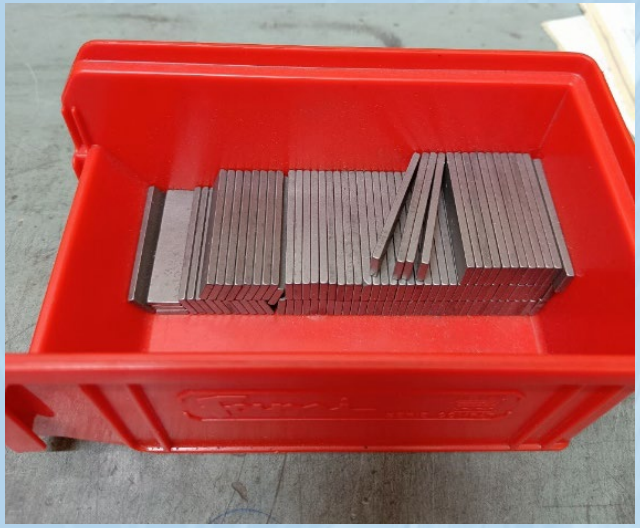
Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

RE Magnets Recycling

Project SUSMAGPRO: demonstrators

Magnets for heat pumps have been pressed, sintered, heat treated, cutted and grinded to the final dimensions and passivated, currently in assembly





B_r (T)	$BH_{(max)}$ (kJ/m^3)	H_{cj} (kA/m)	ρ (g/cm^3)	O (wt%)	C (wt%)
1,185	270	1374	7.58	0.43	0.03

Funded by the European Commission under the Horizon Europe research and innovation program, grant agreement no. 821114

Photo by MIMplus Technologies

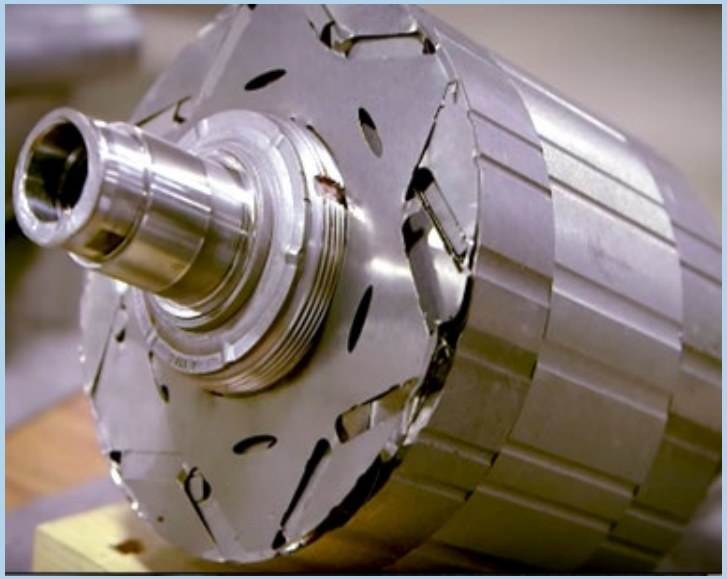
Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

RE Magnets Recycling

Project SUSMAGPRO: demonstrators

Magnets for traction motors have been sintered, cut and coated for assembly

Currently, motor is setup on the testbench for perfomance measurements



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SUSTAINABLE RECOVERY, REPROCESSING AND REUSE OF RARE-EARTH MAGNETS IN THE CIRCULAR ECONOMY

REEsilience

Science on the Street
Ljubljana, 21. April 2023

RE Magnets Recycling

Supported by eit RawMaterials Connecting matters

Funded by the European Union

INSPIRES

Project INSPIRES

INSPIRES is a regional innovation scheme (RIS) to demonstrate a RE magnets circular economy at the example of domestic appliances

- **CSIC** (Madrid, Spain)
- **CEPS** (Bruxelles, Belgium)
- **CNR** (Italy, Firenze e Parma)
- **DOMEL** (Zelezniki, Slovenia)
- **GORENJE** (Velenje, Slovenia)
- **JSI** (Ljubljana, Slovenia)
- **KOLEKTOR** (Idrija, Slovenia)
- **PFORZHEIM UNIV.** (Pforzheim, Germany)
- **SUROVINA** (Maribor, Slovenia)
- **DTU** (Lyngby, Denmark)
- **ZEOS** (Ljubljana, Slovenia)

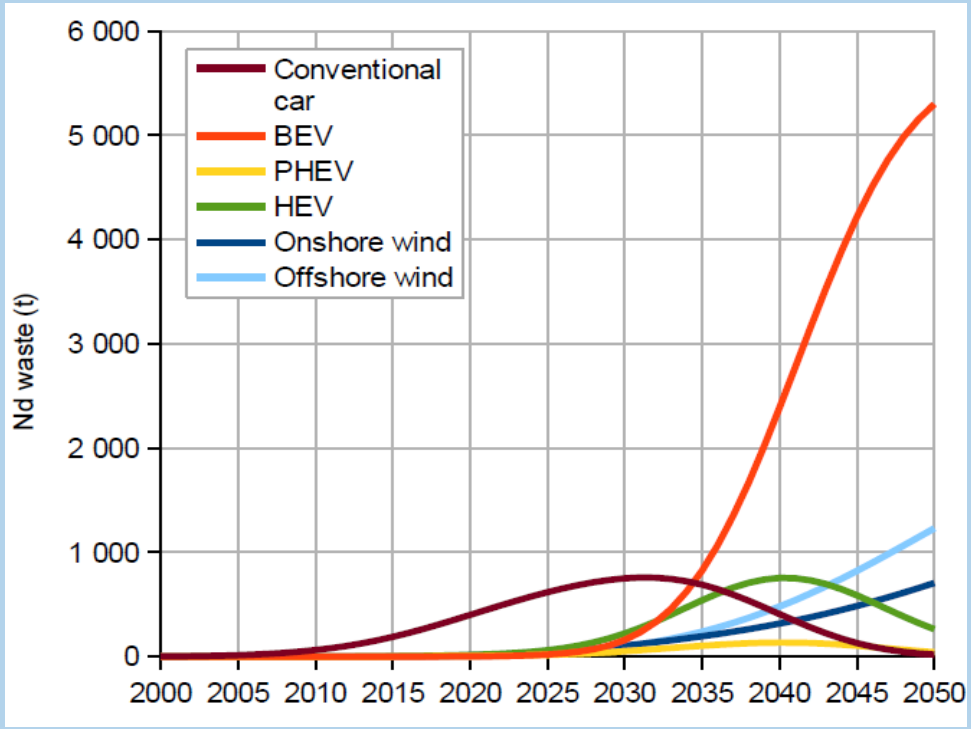
Duration	1.4.2021-30.03.2024
Total budget	1,519,598 EUR

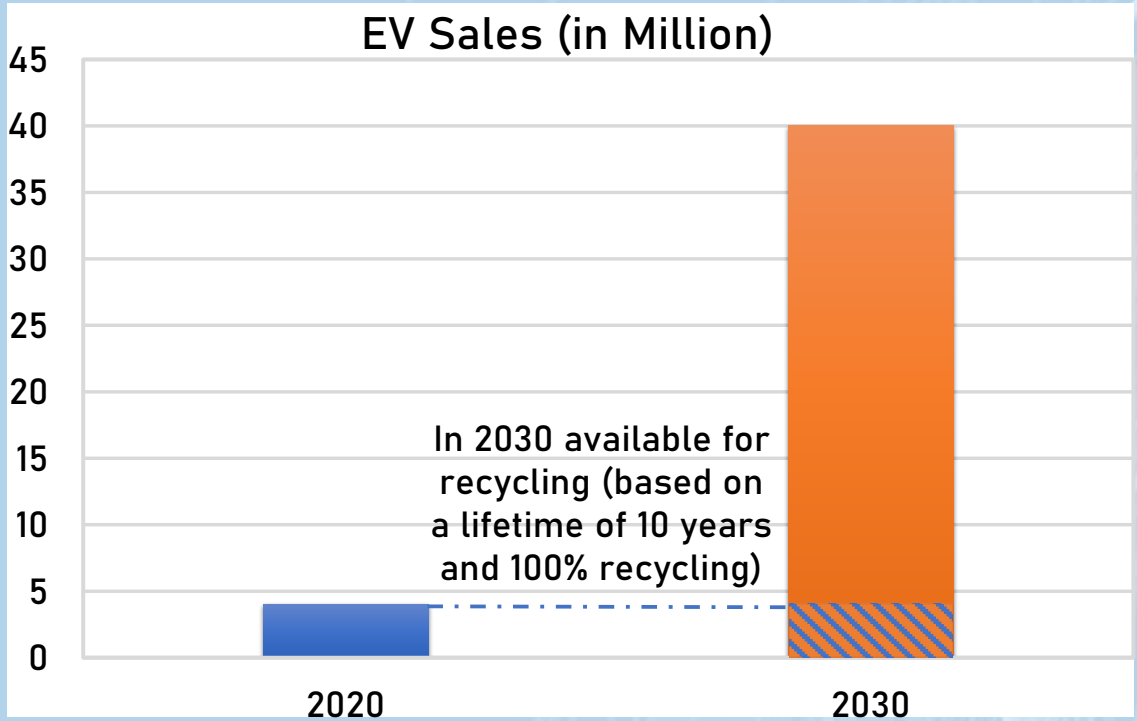
Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

RE Magnets Recycling

Issue: Availability of EOL material





Recycling in an exponentially growing EV market

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598

Photo by MIMplus Technologies

RE Magnets Recycling

Project REEsilience: Concept and Approach

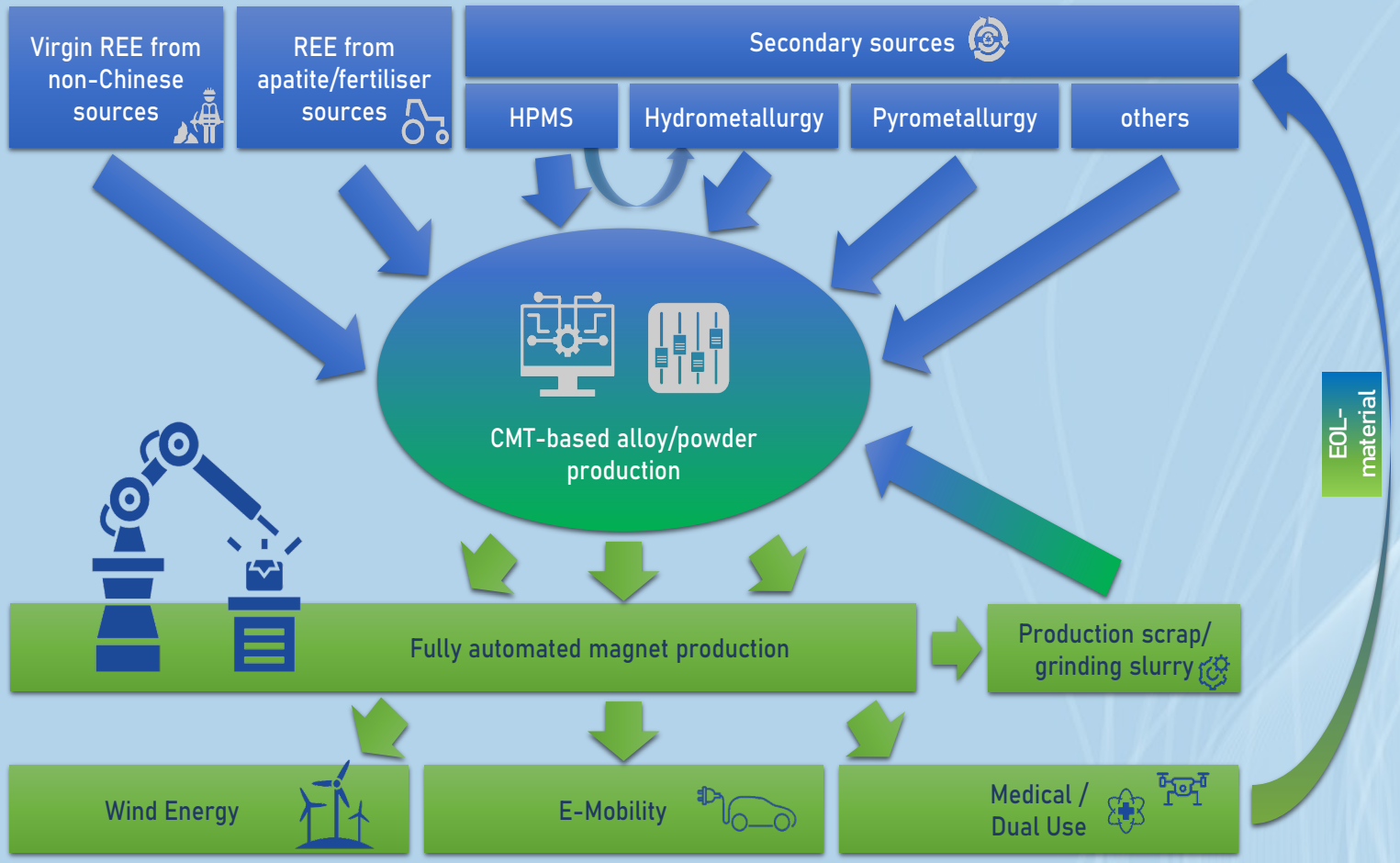


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Photo by MIMplus Technologies

RE Magnets: Sustainable Production

Solutions

- Meeting rising demand
  - Securing a resilient and sustainable REE supply
  - Establishing a circular economy for REE magnets through consistent increase of recycling rates
  - Bringing transparency into the material flow (traceability, labelling, standardisation)
  - Increasing EU production figures (incl. refinery and metal making) by creation of an “equal level playing field”)
- Design for Recycling
- Developing magnets with enhanced functionalities (technical leadership)
- Developing a concept to educate magnets experts

Photo by MIMplus Technologies

Funded by the European Commission under the Horizon 2020 and Horizon Europe research and innovation program, grant agreements no. 821114 and 101058598


Photo by MIMplus Technologies

SUSMAGPRO
SUSTAINABLE RECOVERY, REPROCESSING AND REUSE OF RARE-EARTH MAGNETS IN THE CIRCULAR ECONOMY

REEsilience

EFFEKTE
17. Januar 2022
19:00 – 22:00 Uhr

Najlepša hvala!

Ostanite v stiku z nami:

www.susmagpro.eu www.reesilience.eu

SUSMAGPRO Project REEsilience

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