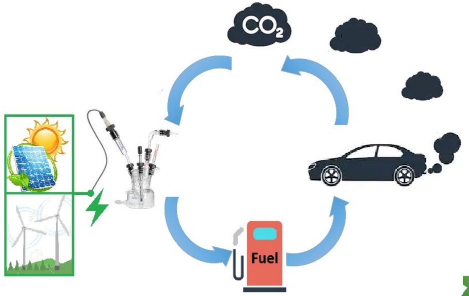
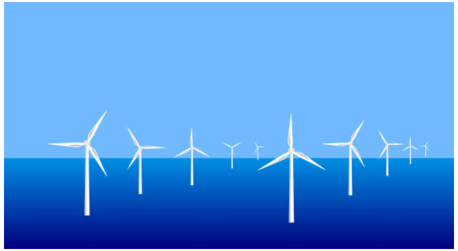
The Critical Role of Materials in the Energy Transition

Materials Technology Day, June 17, 2022



Shoshan Abrahami



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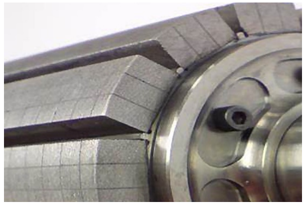
Materials Science and Engineering

Overview

- Introduction
- Case Study:
  - Permanent Magnets (PMs)
  - Li-ion Batteries
- Concluding Remarks



Introduction

Climate change is one of the biggest challenges of this century

Political and Economical drivers

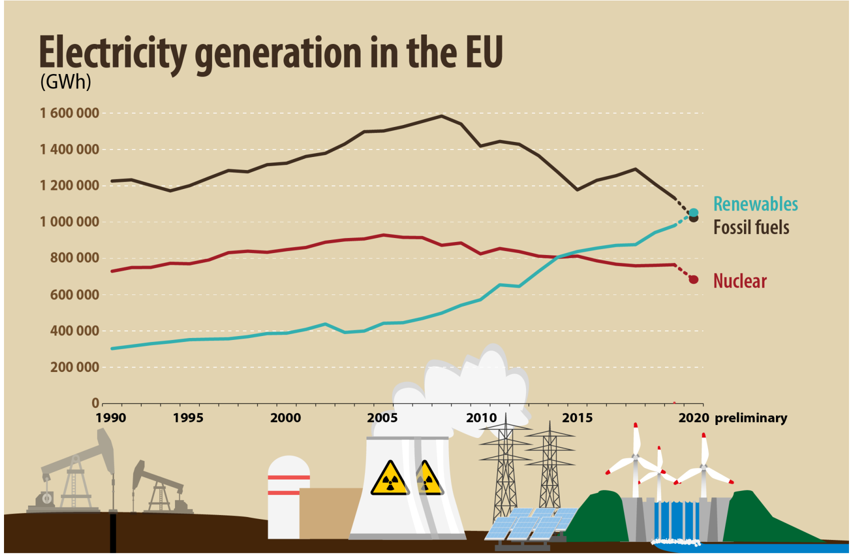
- Paris Climate Change Agreement
- UN Sustainable Development Goals
- EU Green Deal
  - 55% less CO_2 in 2030
  - Climate Neutral by 2050

Introduction

- *Renewables (38 %) overtook fossil fuels (37%) in EU electricity generation for the first time in 2020, State of the Energy Union Report, EU commission*

- In 2021, 39.1 GWh of electricity in EU came from renewable sources:
  - Solar (+30 %) to 11.4 GWh
  - Wind (+17 %) to 17.9 GWh
  - Biomass (+23 %) to 9.8 GWh

billion kWh



ec.europa.eu/eurostat

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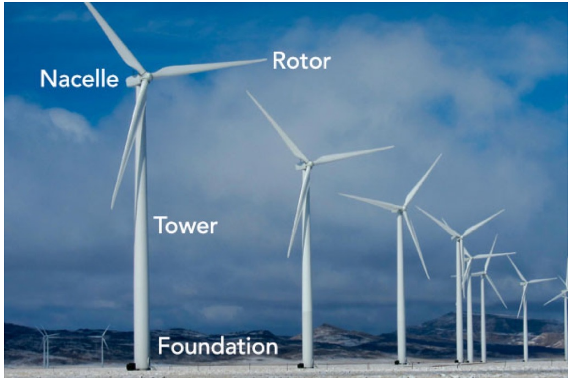
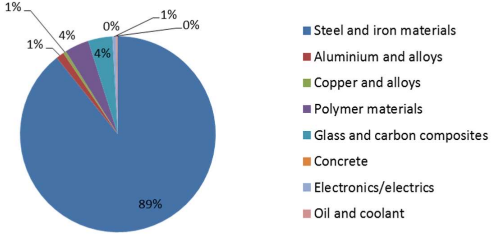
Introduction



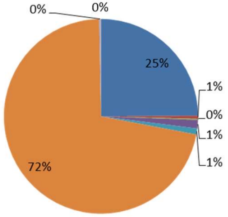
Material usage estimates in t/GW for different wind turbine types

Structural & Technology-specific raw materials

Material	Range	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG
Concrete	243 500-413 000	369 000	243 000	413 000	355 000
Steel	107 000-132 000	132 000	119 500	107 000	113 000
Polymers	4 600	4 600	4 600	4 600	4 600
Glass/carbon composites	7 700-8 400	8 100	8 100	8 400	7 700
Aluminium (Al)	500-1 600	700	500	1 600	1 400
Boron (B)	0-6	0	6	1	0
Chromium (Cr)	470-580	525	525	580	470
Copper (Cu)	950-5 000	5 000	3 000	950	1 400
Dysprosium (Dy)	2-17	6	17	6	2
Iron (cast) (Fe)	18 000-20 800	20 100	20 100	20 800	18 000
Manganese (Mn)	780-800	790	790	800	780
Molybdenum (Mo)	99-119	109	109	119	99
Neodymium (Nd)	12-180	28	180	51	12
Nickel (Ni)	240-440	340	240	440	430
Praseodymium (Pr)	0-35	9	35	4	0
Terbium (Tb)	0-7	1	7	1	0
Zinc (Zn)	5 500	5 500	5 500	5 500	5 500



V136-3.45MW (turbine only)
Mass = 601 tonnes



100MW power plant of 29 V136-3.45MW turbines
Mass = 75236 tonnes

Source: European Commission, JRC (2020)

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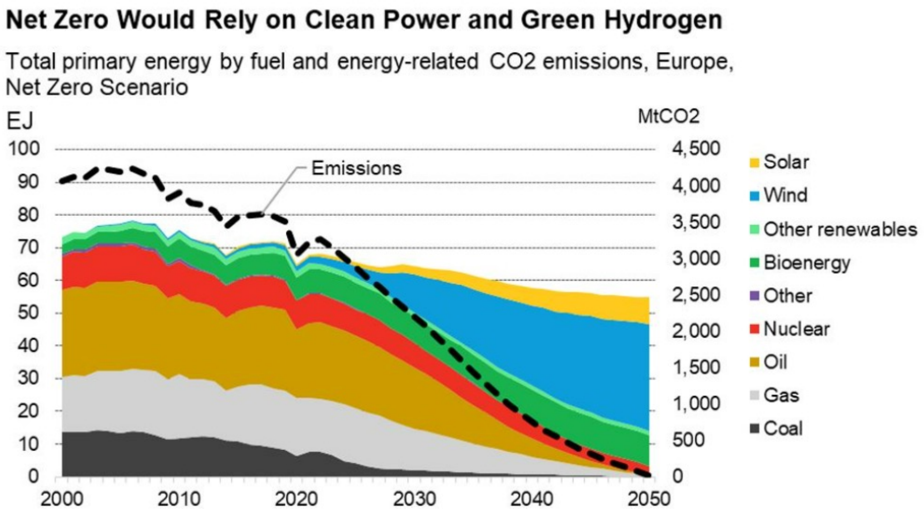
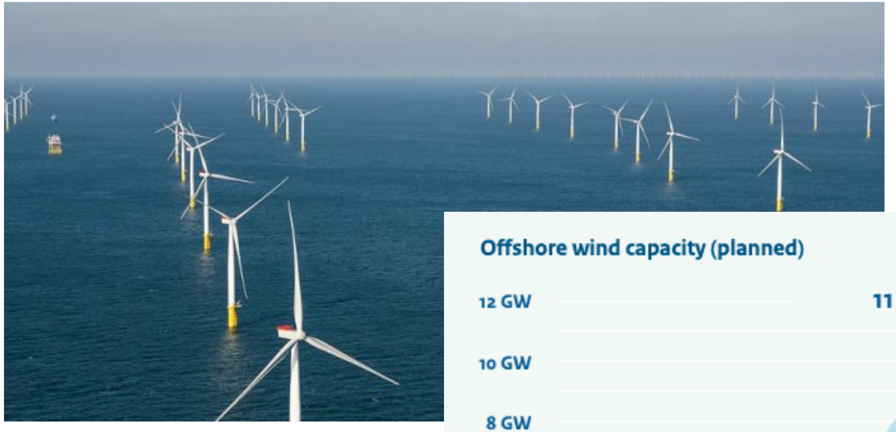
The challenge: Net-zero emissions

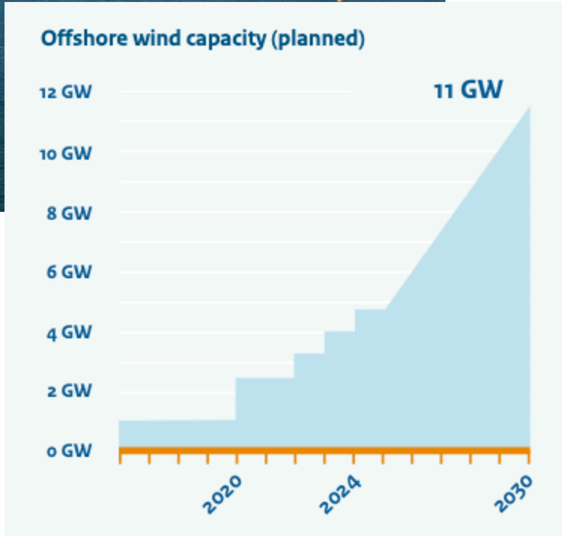
The increasing attention given to wind and solar energy throughout Europe will lead to a continuously growing demand for raw materials.

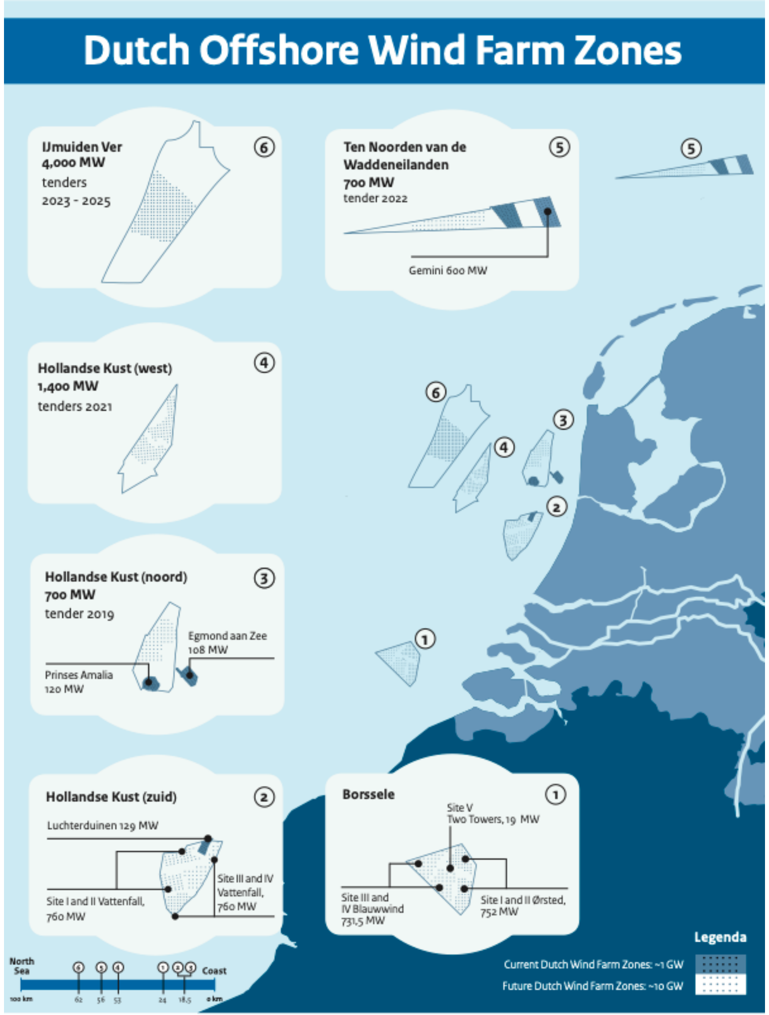


Source: BloombergNEF. Note: The Net Zero Scenario sees all energy-consuming sectors decarbonize by 2050, largely through electrification and switching to green hydrogen.

Introduction







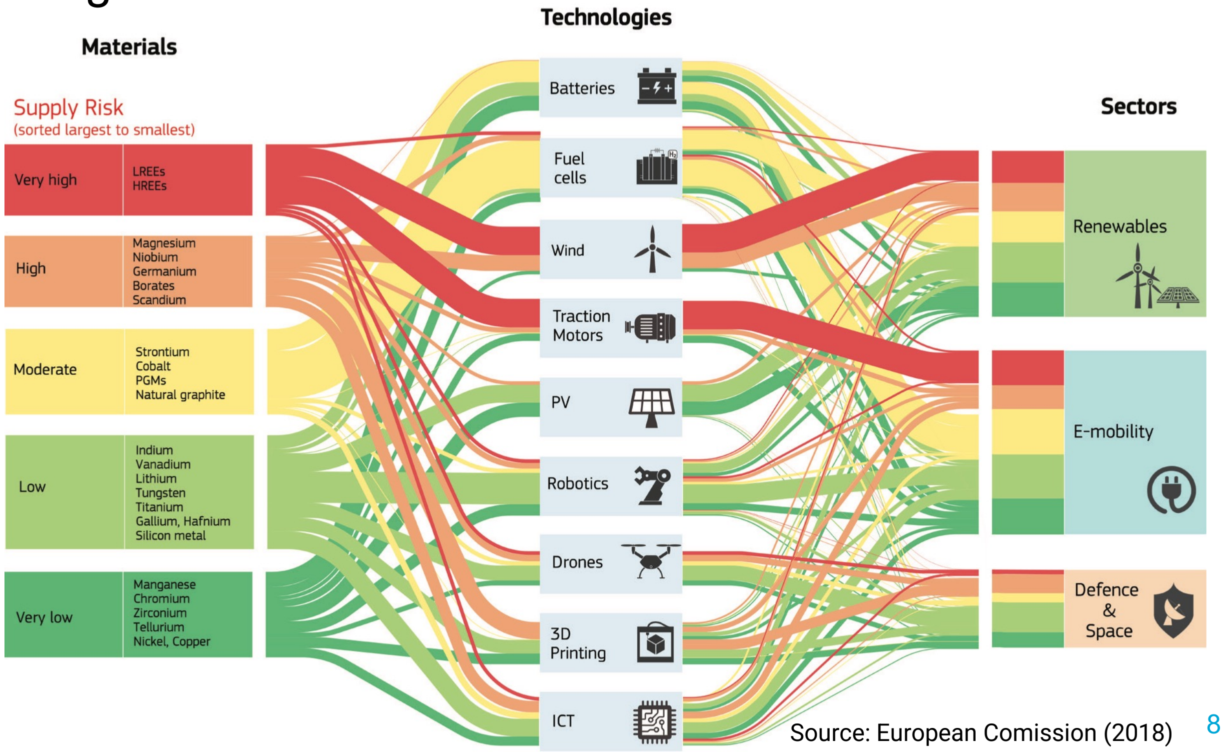
Source: www.offshorewind.rvo.nl

The challenge: Net-zero emissions

Many critical metals are needed for the production of sustainable generation, transport and storage technologies

- Future raw materials demand may exceed availability!
  - (current) mining capacity
  - Supply risk (geopolitical)
  - value chains disruptions

- High purity requirements



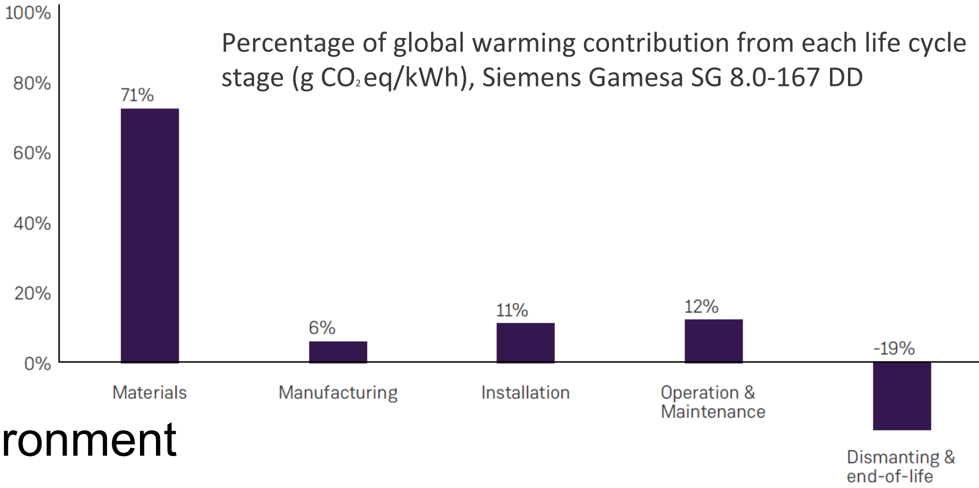
Source: European Comission (2018)

What can **WE** do?

1. **Reuse, Remanufacturing, Recycling**: Make high-quality use of raw materials in existing products

2. **Materials substitution:** Replace fossil, critical and unsustainably produced raw materials with sustainably produced, renewable and generally available raw materials

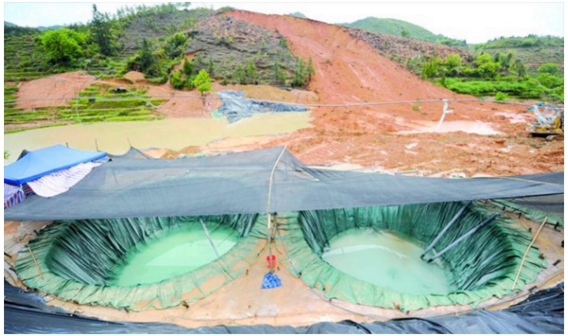
Why Recycle?



Raw material use

- Depletion
- Destroying and polluting the environment
- Current low capacity & quality
- Comes with high CO_2 emissions
- Economically & energetically expensive
- Supply security & geopolitical dependency
- ~~Expected future waste piles~~

Secondary resources

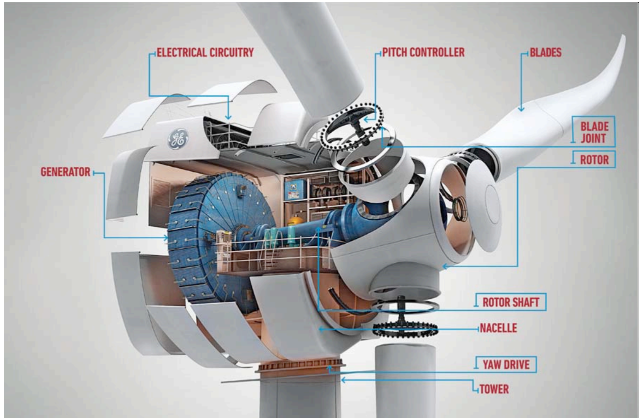


Illegal mining of REEs in China, (Packey, 2019)

Case Study:
Permanent Magnets (PMs)

Applications of NdFeB PMs

Generator in wind turbines
(400 kg magnet/MW)
(1.2 ton for 3.0 MW capacity)



E-bikes
(300-350 g)

Electric vehicles (EV/HEVs)
(1.2 kg/car)

Computer HDDs
(10-20 g)

Ear buds
(1.5 - 3 g)

mobile devices

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Applications of NdFeB PMs

Critical for both renewable energy & electrification of transport

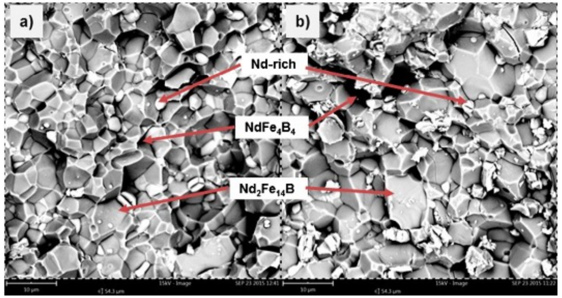
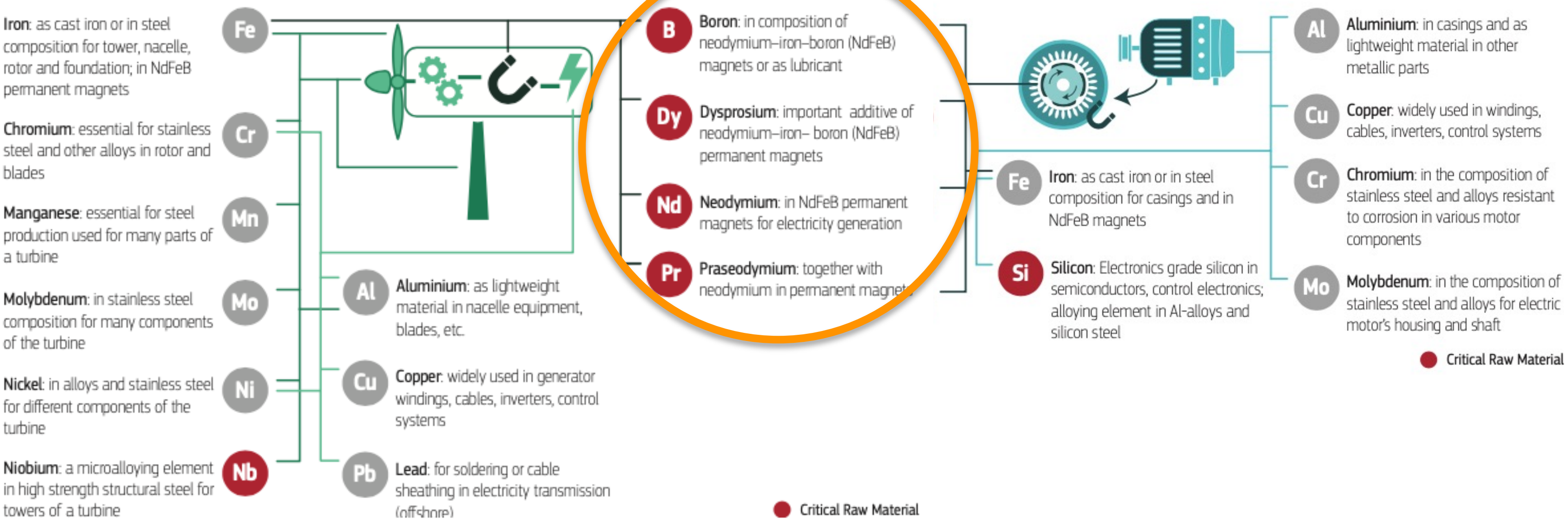


Fig. 5. Laptop (a) and desktop (b) microstructures and phases.

Wind Turbines

Traction motors



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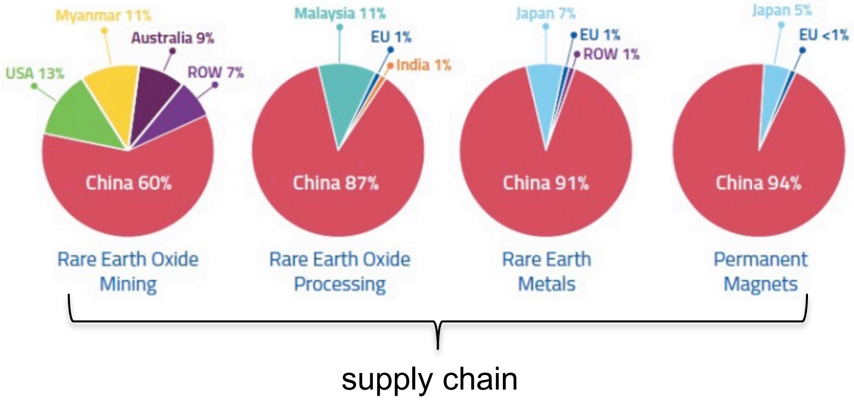
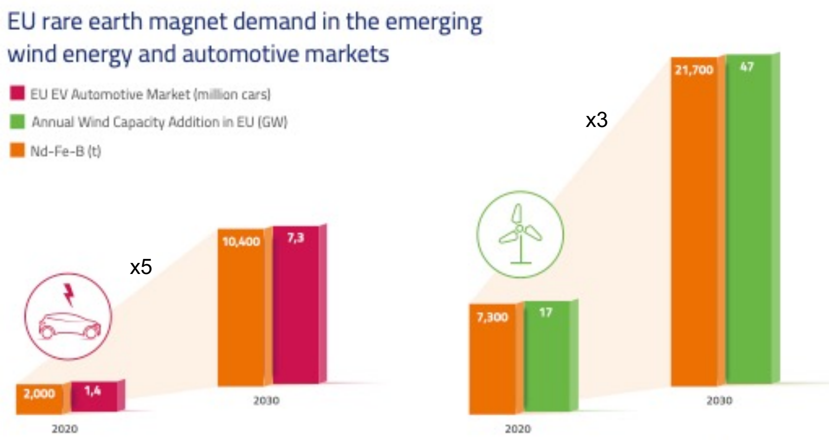
The challenge: Future Materials Supply



High economic importance + Supply risk

→REEs are on the **top** of EU list of critical raw materials!



Source: Gauß et al. 2021. Rare Earth Magnets and Motors: A European Call for Action.

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Technology options for REE PMs recycling

1) **"Re-use" whenever it is possible**
   - Suitable for large magnets (e.g. wind turbines or EVs)
   - No damage or corrosion
   - Similar design!

Magnet-to-magnet route
(no processing)

2) **"Direct alloy recycling" when "re-use" is not possible**
   – Re-sintering of scrap magnet
   – Hydrogen decrepitation (HDDR)
   – Suitable for dismantled and relative pure magnet scrap

Magnet-to-alloy route
(physical processing)

3) **Metallurgical "indirect recycling"**
   – Contaminated scrap
   – Low REE concentration
   – Physical upgrading necessary
   – Combined metallurgical processes

Magnet-to-metal route
(chemical processing)

Selection criteria for a recycling route:
Size of the magnet
Complexity in the product
REE concentration in magnet waste

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EoL PMs recycling: Current

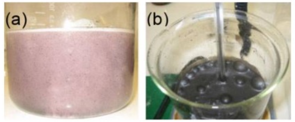
Computer HDDs:

Collection: mostly collected but go to the shredder with the PCs, or sometimes dismantled for separate shredding

Mechanical separation

- Manual dismantling: labor-intensive
- Shredding: NdFeB magnets stick to steel scrap and lost in the ferrous stream

Metallurgical refining: Chemical extraction routes needed for complex & diluted scrap



Key tech. issues

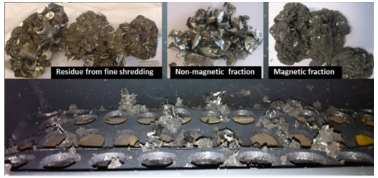
Magnet separation from ferrous
Complex impurities
Fe – REE separation
Minimized waste generation

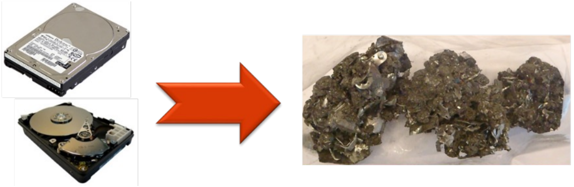
REE recovery from HDD shredder residue

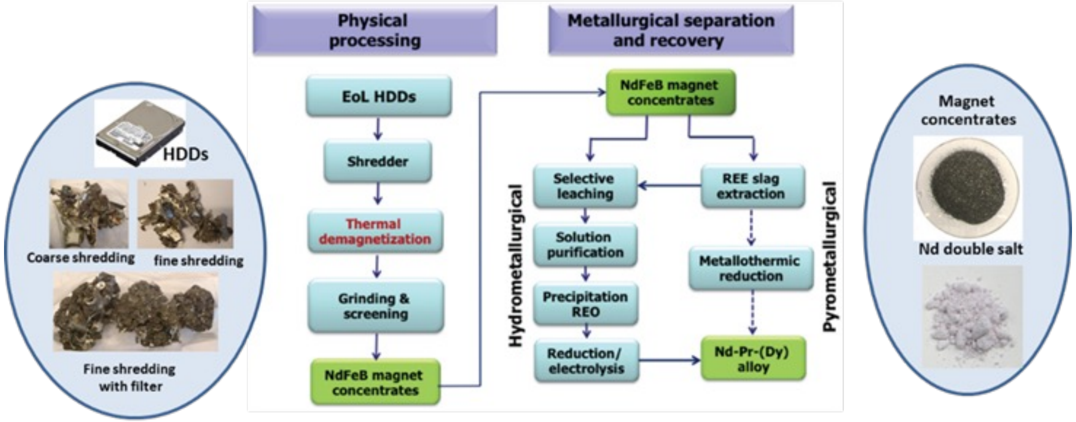
Hydrometallurgical and pyro-hydro combined routes

Residue collection rate (70%)
Relatively high REE concentration in the collected residue
Physical upgrading of REE to ~20% (grinding – screening)
Recovery rate: 95% of the total collected residue

Hydrometall. H_2SO_4 leaching: 97%
Pyrometall. smelting: 100% REE – Fe separation
Slag (25%REE) leaching: 60-70% recovery







Abrahami, et al., Mineral Processing and Extractive Metallurgy (Trans. Inst. Min. Metall. C), 2015, 124 (2), 106–115.

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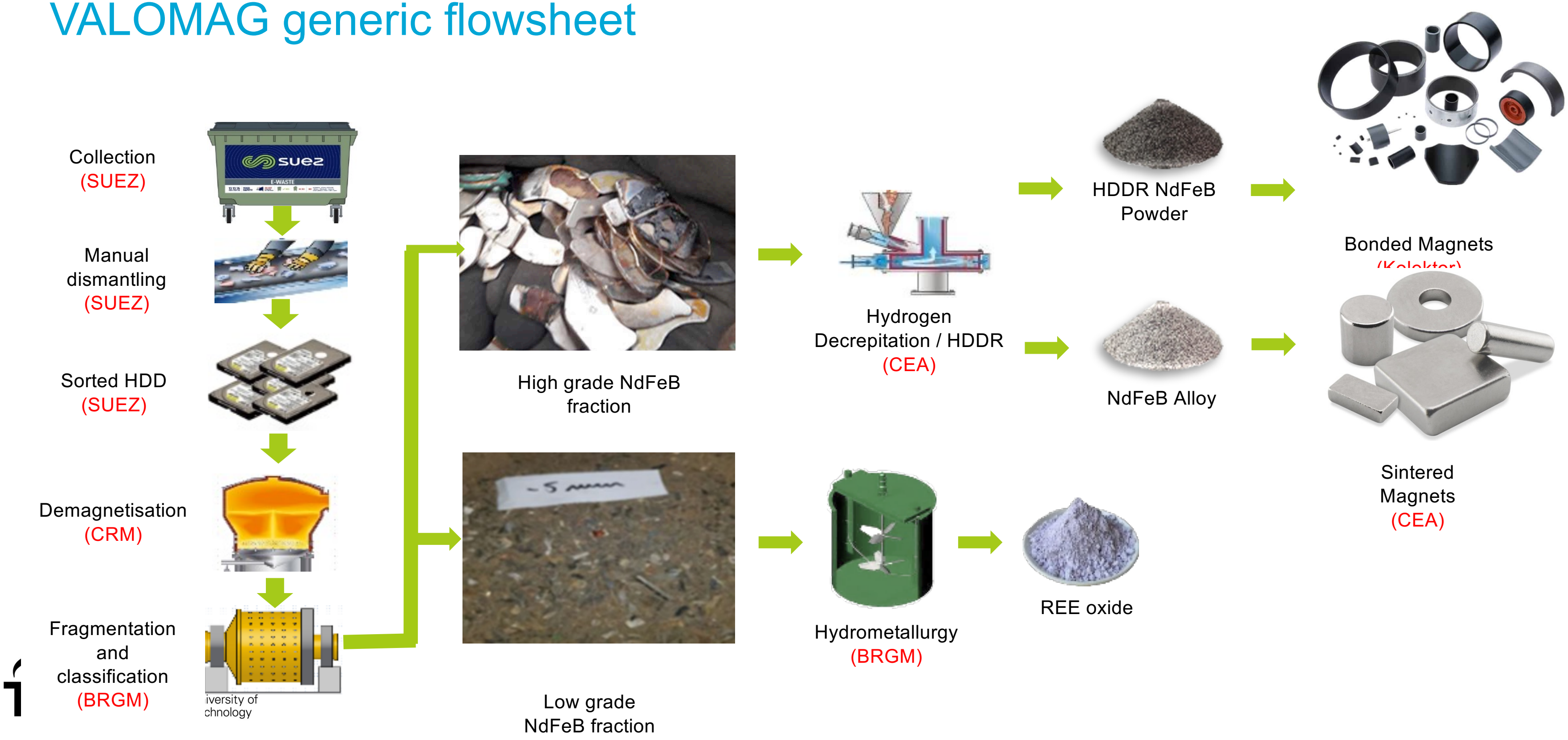
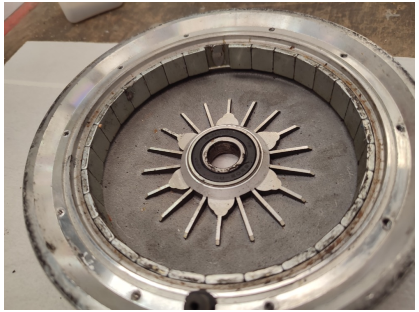
VALOMAG: EIT RM upscaling project

VALOMAG generic flowsheet



EoL PMs recycling: Future



Wind turbines & EV/HEVs

Collection: 100% due to regulations (extended producer responsibility)

Mechanical separation

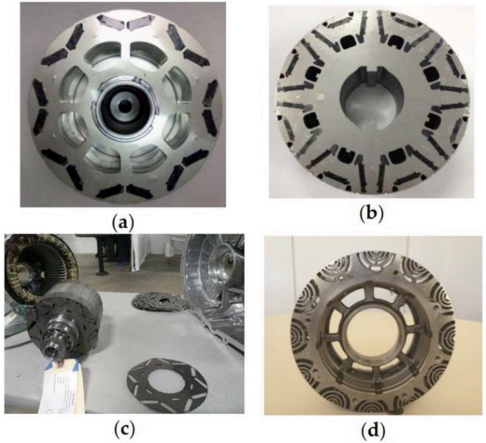
WT: affordable manual dismantling, but challenging → robots?
demagnetization?
EVs: manual dismantling, but difficult liberation or to a shredder

Metallurgical processes:

1) Direct recycling
2) indirect recycling

Key tech. issues

Magnet liberation from components
Different coating impurities
Comprehensive value recovery



a) 2010 Prius V-shaped rotor; b) 2017 Prius double U rotor; c) 2017 Tesla Model 3 IPM V rotor; d) 2016 Chevy Bolt IPM rotor

Source: Alan Walton, Birmingham University

Case Study:
Li-ion Batteries

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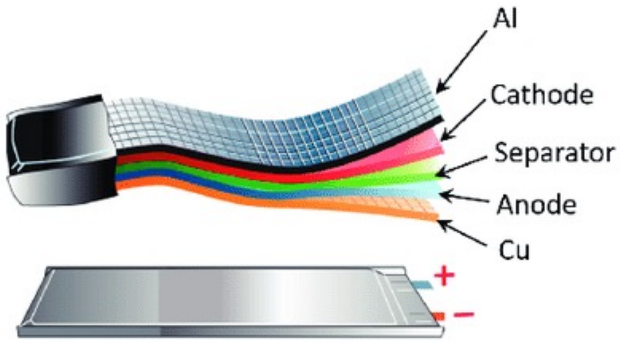
Composition of spent LiBs

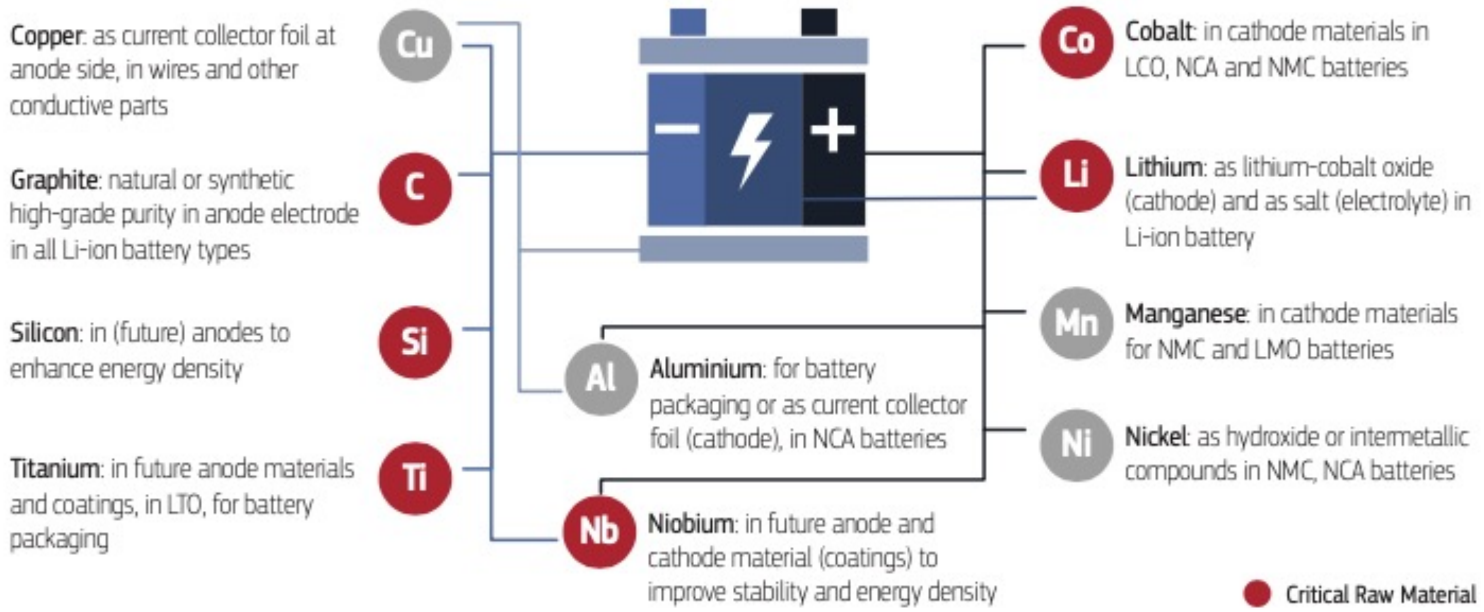
Main applications

- e-mobility (EVs, scooters, e-bikes, heavy construction equipment etc.)
- Portable tools & electronics
- Grid energy storage (solar, wind)

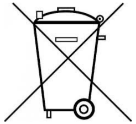


Component	Mass fraction (wt%)	Commonly used materials
Case	25%	Steel, plastics
Cathode	27%	$LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$, $LiNi_xMn_yCo_zO_2$, $LiFePO_4$
Anode	17%	Graphite (C_6), $Li_4Ti_5O_{12}$
Foils and current collectors	13%	Copper metal (Cu), Aluminium metal (Al)
Electrolyte	10%	$LiPF_6$, $LiBF_4$, $LiClO_4$ or $LiSO_2$, dissolved in polar org. solvents. (DMSO, propylene carbonate, ethylene carbonate)
Separator	4%	Polypropylene (PP)
Binder	4%	Polyvinylidene fluoride (PVDF)

Materials: Li-ion Batteries



EoL LiBs: Current state



Collection: High collection rate (by legislation, EPR)

Separation: manual (safety)

– Challenging due to the large variety of battery designs, capacities, shape, size, and chemistries

Metallurgical refining:

– Large-scale operations are mostly pyrometallurgical →

- recycling specific components
  – steel casing, Al, Cu
  – economical elements: Co, Ni
  – Secondary “recoveries” (downcycling)
  – Challenges: complexity, diverse components, and available chemistries, financial viability is linked to specific elements (Co, Ni, Cu).

- No closed-loop recycling; Losses of electrolyte, Li, plastics/polymers, graphite
- Benefits
  – Robust processes, mixed scrap
  – Recovery of some important materials

EoL LiBs: Future

- Extensive recovery of materials (incl. Li, graphite, electrolyte)
- **Drivers**: New battery directive - targets for collection, recovery and recycling content.
- Hydrochemical processes

Key tech. issues

- High recovery from mixed chemistries
- No economic value = no recycling ($LiFePO_4$)
- Complex impurities
- Minimized waste generation

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Concluding remarks

- The energy transition is material-intensive!
- Different strategies are needed to reach the environmental targets while assuring future materials supply

- Recycling critical materials is crucial to reaching environmental targets
- New products = new challenges, but also opportunities!

- Development of low-cost & efficient liberation and separation technologies
- Many available technology options, but no EoL wastes streams (yet) → market and economics of operation will decide!

Thank you for your attention!

Questions?

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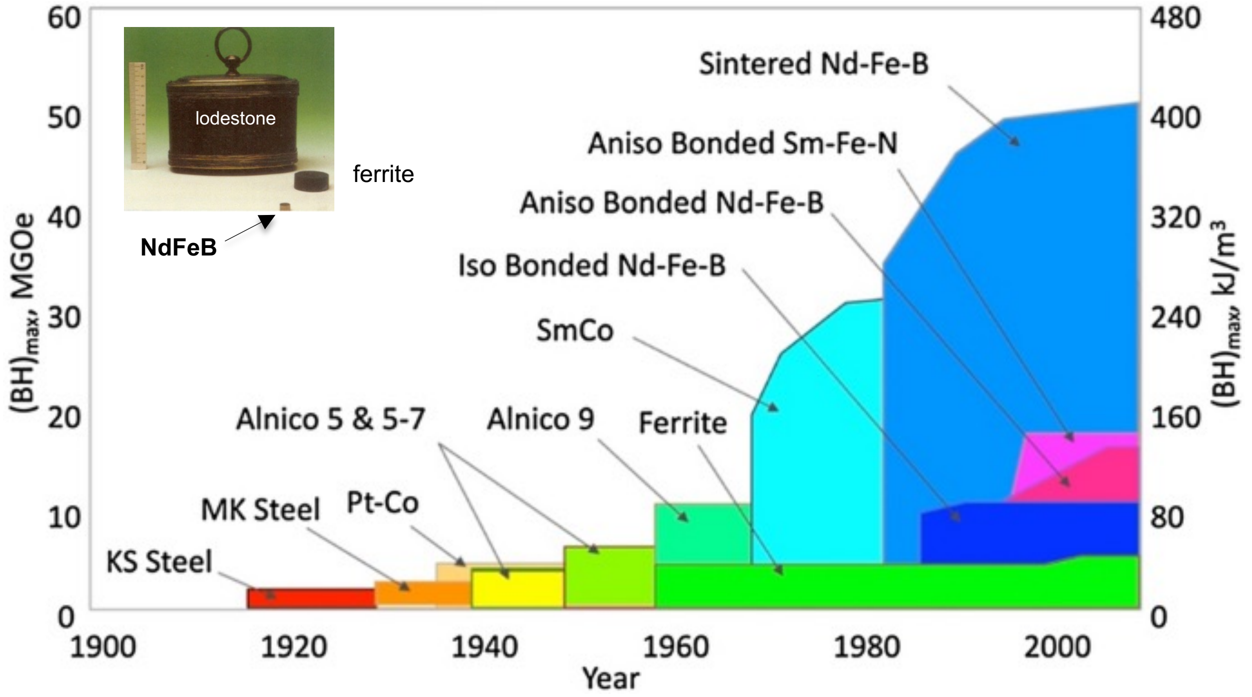
Materials Science and Engineering

Extra slides

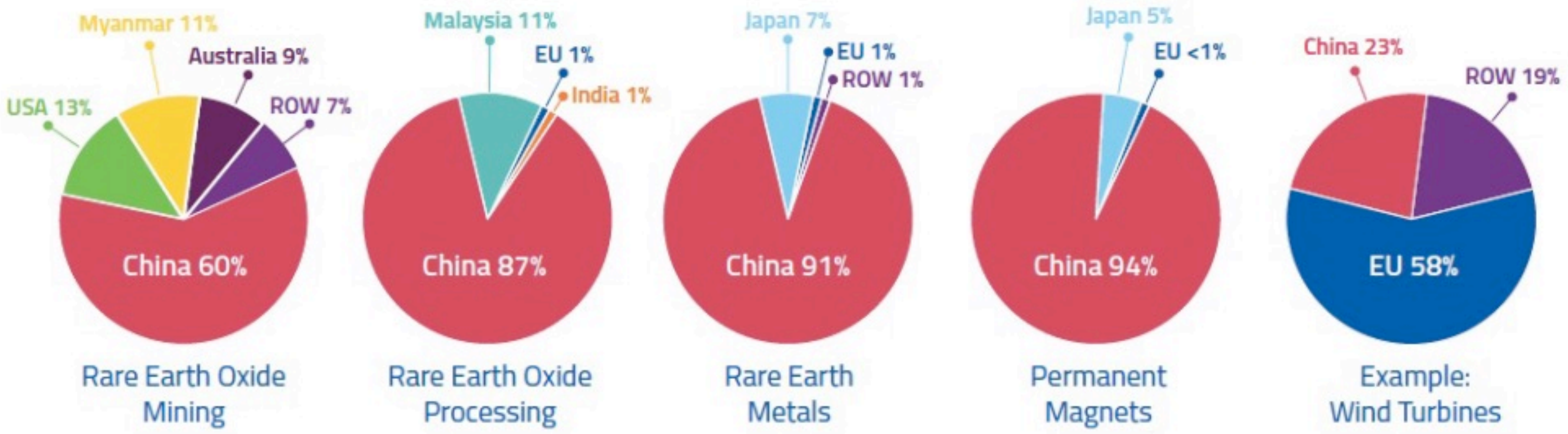
Permanent Magnets (PMs)

Trends in the maximum energy product (BH_{max}) for commercially produced PMs

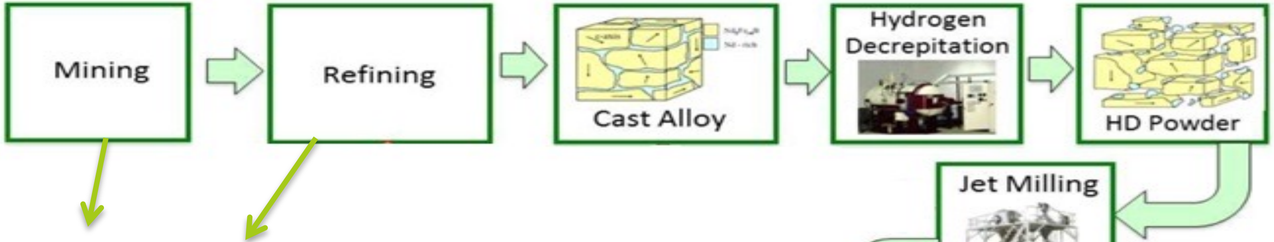


Adapted from M. J. Kramer

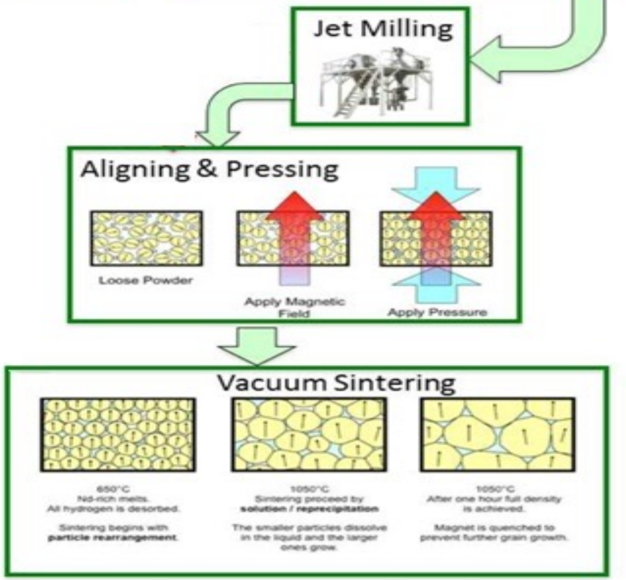
Rare-earth value chain



Nd-Fe-B manufacturing



-Energy intensive
-Toxic by-products (acid leaching process)
-Radioative elements (thorium)



Optical and electron microscopy

Scanning electron microscopy (SEM)

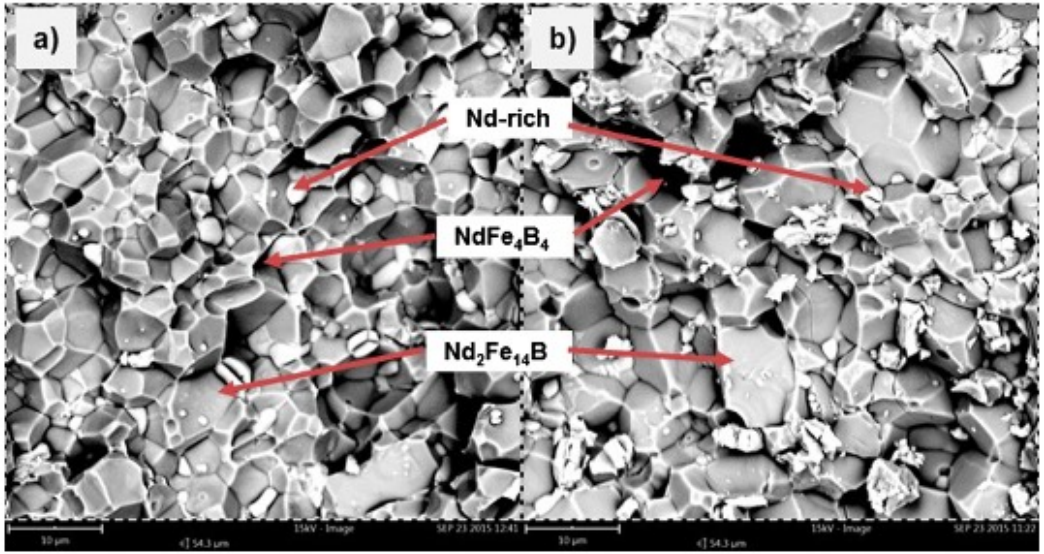


Fig. 5. Laptop (a) and desktop (b) microstructures and phases.

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Magnet recycling from HDD

Short route – hydrogen decripitation