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2nd Seminar – Delft, the 6th December 2022

Materials and Recycling Research at TU Delft

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TU Delft

Co-funded by the European Union

TU Delft

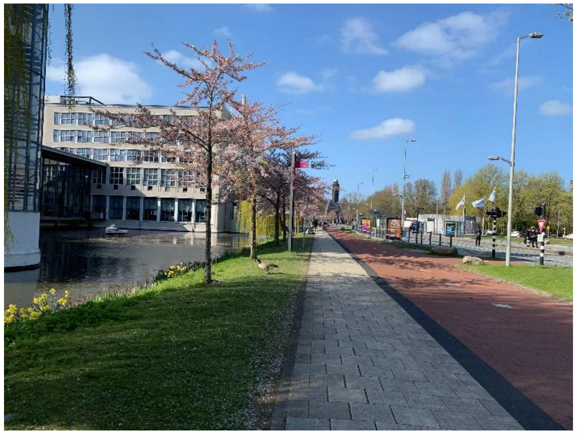
DELFT UNIVERSITY OF TECHNOLOGY – TU DELFT

- Largest, oldest (175+ years), most complete technical university in the Netherlands
- 26,000 students and over 6,000 employees
- 8 faculties
- 3 degrees
  - BSc: 3 years
  - MSc: 2 years
  - PhD: 4 years

Aerospace Engineering (AE)
Applied Sciences (AS)
Architecture (Arch)
Civil Engineering and Geosciences (CEG)
Industrial Design Engineering (IDE)
Mechanical, Maritime and Materials Engineering (3mE)
Electrical Engineering, Mathematics and Computer Science (EEMCS)
Technology, Policy and Management (TPM)

MATERIALS RESEARCH AT TU DELFT

- Materials research spreads over a number of faculties, embedded in various research groups
    - **Aerospace engineering:** materials for aviation industry, composite materials
    - **Civil Engineering and geoscience:** construction materials, materials recycling (physical separation technologies)
    - **Applied sciences:** polymers, energy materials
    - **Mechanical, Maritime and Materials Engineering** (3mE): dept. Materials Science and Engineering (MSE): metals, polymers and composites, centered on "circularity".
- Materials sustainability is addressed at all faculties, with a recent re-design of master curriculum 2.0.
    - Product design for sustainability (IDE)
    - Initiatives at faculty Architecture, TPM, etc.

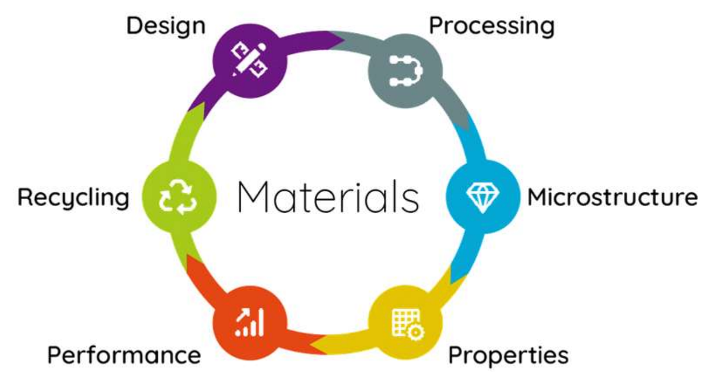


DEPARTMENT MATERIALS SCIENCE AND ENGINEERING (MSE)

Research programs

- Metals production and recycling
- Microstructure control of metals
- Joining and mechanical behavior
- Electrochemistry and corrosion
- Computational materials
- Materials in art and archaeology

The only department dedicated for materials research and education in Netherlands



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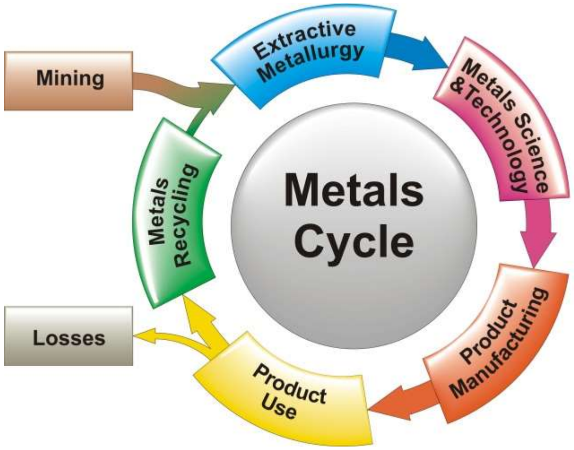
MPRR GROUP: METALS PRODUCTION, REFINING AND RECYCLING

The unique group of process metallurgy combined with metals recycling in the Netherlands.

Formed in 2006 (from old mining and metallurgy department dated back to 1910's)

Focus: closing materials cycle

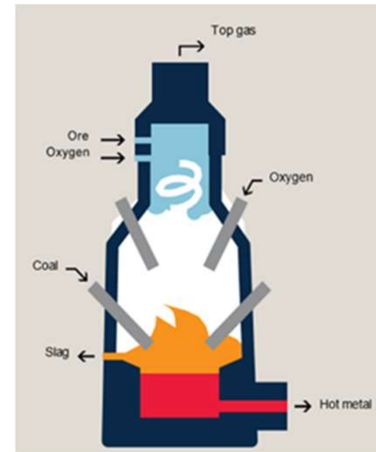
- Sustainable metals extraction
- Recycling of metals and materials
- Technology development for more efficient and cleaner production



GROUP OF METALS PRODUCTION, REFINING AND RECYCLING

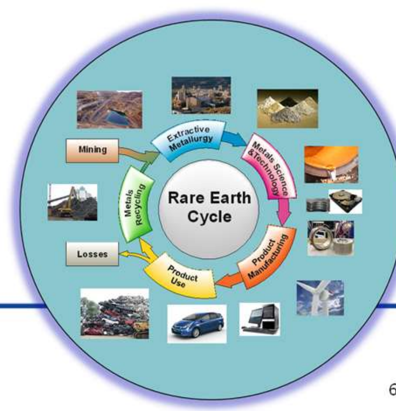
Main research fields

- Primary metals extraction and metals refining
  - Sustainable ironmaking and steelmaking
  - De-carbonization of metal production processes
- Metals recycling and resource recovery
  - Metals recovery from industrial wastes
  - Recycling of rare earth metals (REEs)
  - Recycling of EoL batteries



Research focus

- Metallurgical process fundamentals: thermodynamics and kinetics, transport phenomena
- Pyrometallurgy, hydrometallurgy, electrometallurgy (water based media and molten salt)



TU DELFT ACTIVITIES ON RECOVERY OF REES FROM END-OF-LIFE PERMANENT MAGNET

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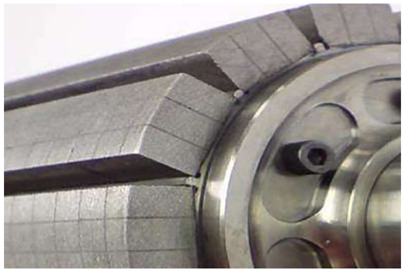
OVERVIEW

1. Introduction
2. Recycling strategy of EoL REE permanent magnet
3. Examples of recycling processes
4. Education activities
5. Concluding remarks



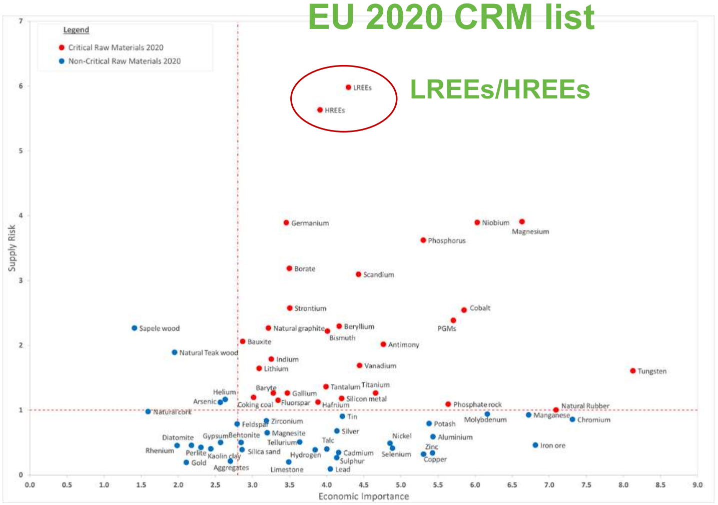
INTRODUCTION

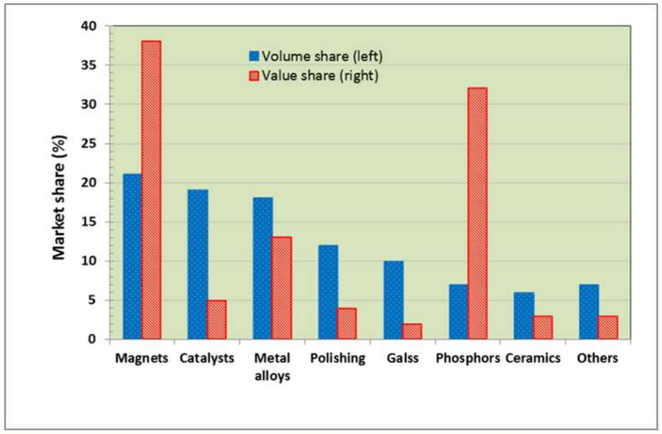
REEs are on the top of EU critical raw materials.

Nd together with Pr and Dy are among the most demanded REEs now and in the future.

Permanent magnets are the main use of Nd (Pr, Dy), but in many different and diversified forms and sizes.

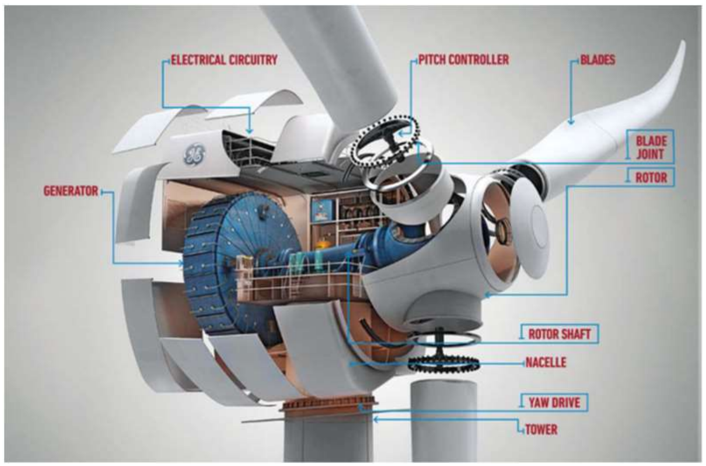
Recycling of the REEs from permanent magnets are crucial to meet future magnet demand.





APPLICATIONS OF NDFEB MAGNETS

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



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

E-bikes
(300-350 g)

Computer
HDDs
(10-20 g)

Ear buds
(1.5 g)

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DESTINATIONS OF EOL PERMANENT MAGNETS

Wind turbines: 100% collection, affordable manual dismantling

Conventional vehicles: 100% collection, but go to shredder and diluted in ferrous scrap and ASRs (<300 ppm)

EV/HEVs: 100% collection, manual dismantling or to shredder

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

Small consumer electronics: very low collection rate (~30%), no dismantling, shredding together with the whole unit

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TECHNOLOGY OPTIONS FOR REE PERMANENT MAGNET RECYCLING

1) "Re-use" whenever it is possible
   - Suitable for large magnets (e.g. wind turbines or EVs)
   - No damage or corrosion
2) "Direct alloy recycling" when "re-use" is not possible
   - Re-sintering of scrap magnet
   - Hydrogen decrepitation
   - Suitable for dismantled and relative pure magnet scrap
3) Metallurgical "indirect recycling"
   - Contaminated scrap
   - Low REE concentration
   - Physical upgrading necessary
   - Combined metallurgical processes

Magnet-to-magnet route (no processing)

Magnet-to-alloy route (physical processing)

Magnet-to-metal route (chemical processing)

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EXAMPLES OF REE RECOVERY FROM EOL NDFEB PERMANENT MAGNETS

EU REEcover project (Low REE concentration)

- (1) Hydrometallurgical route
- (2) Combined pyro- and hydrometallurgical route

REE recovery from HDD shredder residue

(Mid-level REE concentration)

- Hydrometallurgy and Pyro-hydro combined route

EU EREAN project (Relatively pure magnet waste)

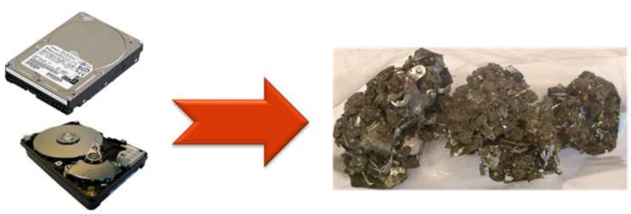
- REE recovery from magnet waste using electrochemical oxidation

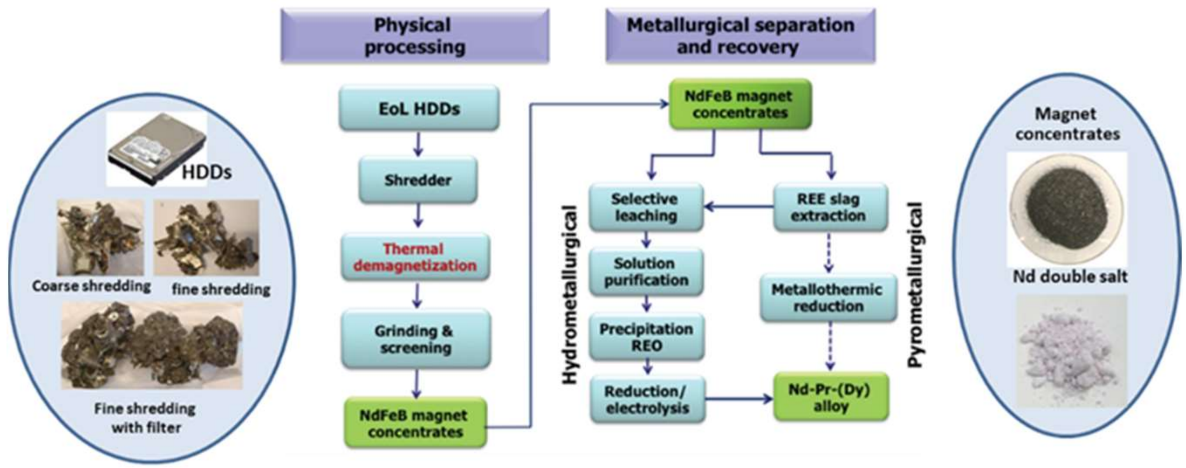
REE RECOVERY FROM HDD SHREDDER RESIDUE

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

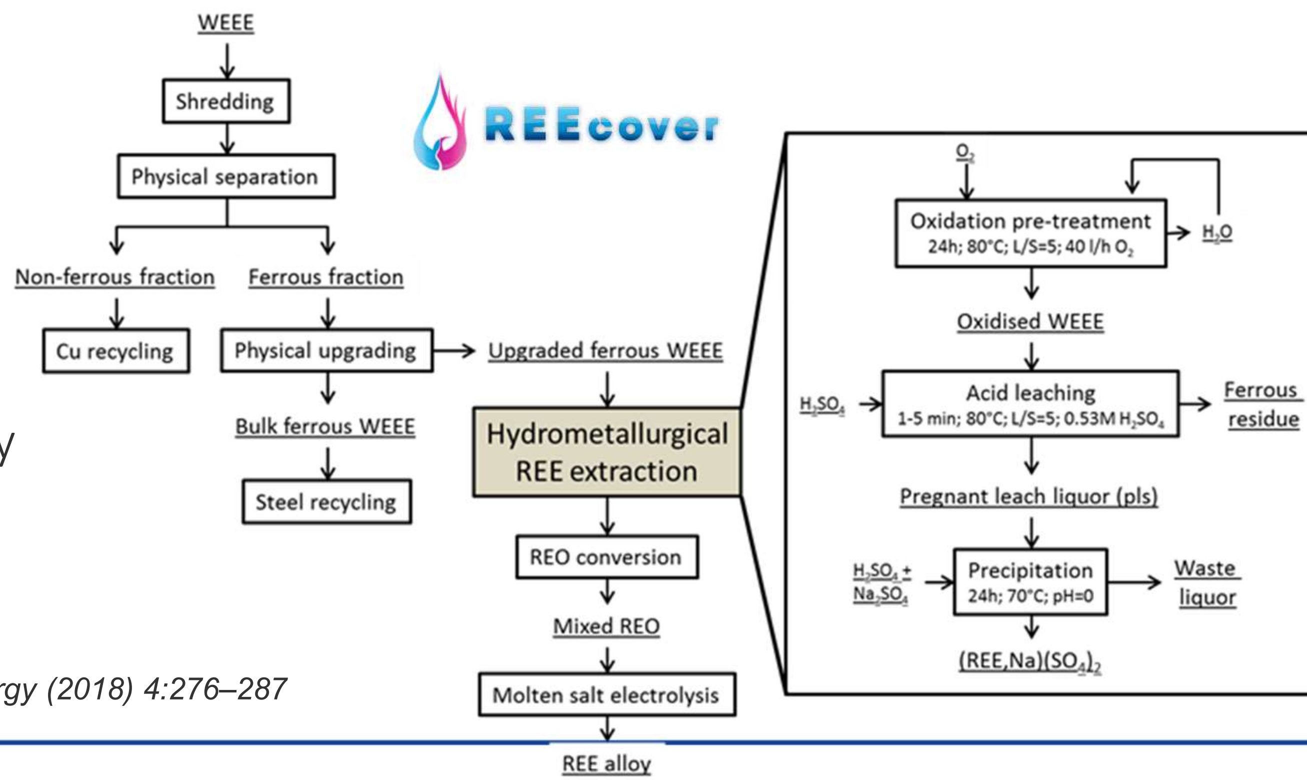




Abrahami, et al., Mineral Processing and Extractive Metallurgy (Trans. Inst. Min. Metall. C), 2015, 124 (2), 106–115.

HYDROMETALLURGICAL REE RECOVERY FROM WEEE SHREDDER SCRAP

- Extremely low REE concentration (~1%)
- Ferrous-based (60%) complex scrap
- Physical upgrading essential (REE)
- Comprehensive value recovery essential
- Total REE recovery: >90%



Peelman et al.,Journal of Sustainable Metallurgy (2018) 4:276–287

REEcover

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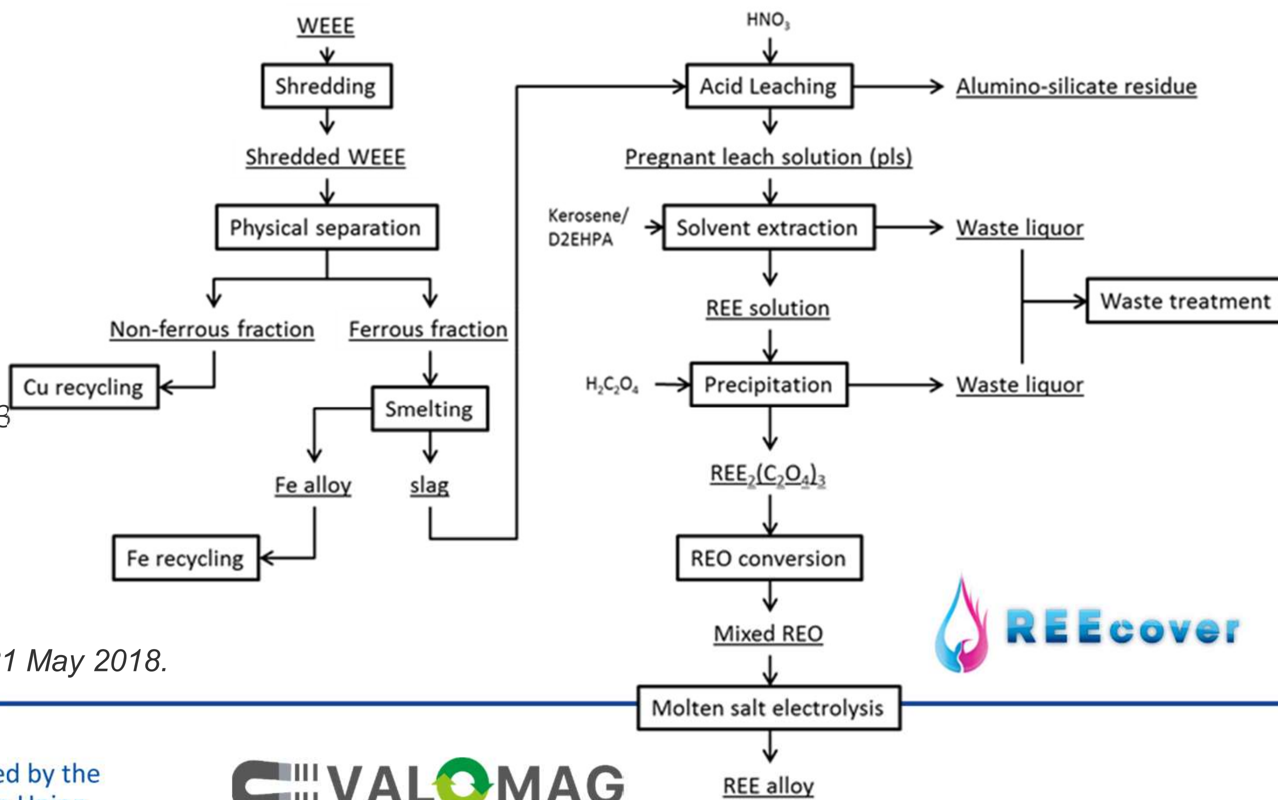
COMBINED PYRO- AND HYDROMETALLURGICAL REE RECOVERY FROM WEEE SHREDDER SCRAP

- Extremely low REE concentration
- No physical upgrading
- Smelting at 1650°C to generate REE-bearing slag and Fe-based alloy
- REE-slag (~1.5%REE) for acid HNO_3 leaching
- Overall REE recovery >90%



Peelman et al.,Journal of Sustainable Metallurgy, online 21 May 2018.

ELECTROCHEMICAL REE RECOVERY FROM MAGNET WASTE

EREAN
EU FP7 Marie-Curie Initial Training Network

(1) Electrochemical Fe(II) oxidation

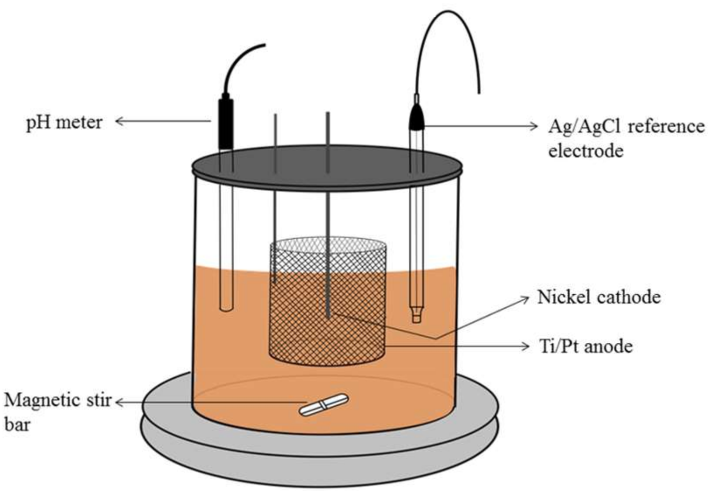
HCl chemical leaching

$$2RE + 6\,HCl \leftrightarrow 2RECl_3 + 3H_2 \uparrow$$

$$Fe + 2\,HCl \leftrightarrow FeCl_2 + H_2 \uparrow$$

Inert anode: $Fe^{2+} - e \rightarrow Fe^{3+}$

Cathode: $2H^+ + 2e \rightarrow H_2$

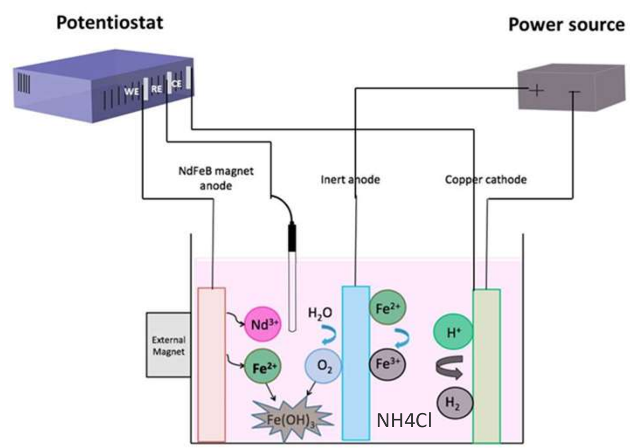


Complete Fe removal (by-product)
>98% REE oxalate recovery
>99% purity of REO
1.5 kWh/kg magnet power

(2) Dual-anode reactor

NbFeB reactive anode
Anodic dissolution of magnet
$Fe - 2e \rightarrow Fe^{2+}$
$Nd(REEs) - 3e \rightarrow Nd^{3+}$

Inert anode (Ti/Pt)
Oxidation of iron
$Fe^{2+} - e \rightarrow Fe^{3+}$



Complete Fe removal
>97% REE leaching recovery
>99% purity REO product
3 kWh/kg magnet power

(3) anion-exchange membrane

Anodic chamber
$Fe^{2+} - e \rightarrow Fe^{3+}$
$Fe^{3+} + 3H2O \rightarrow Fe(OH)3 + 3H^+$
$Fe^{3+} + (3OH^-)cat \rightarrow Fe(OH)3$
Iron removal and acid generated for final magnet leaching

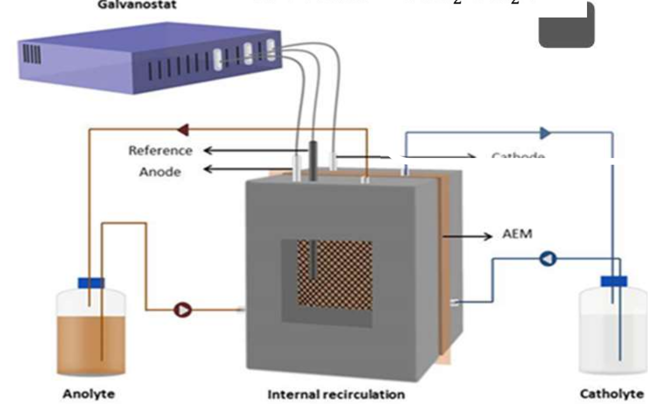
Cathodic chamber
$H2O + 2e \rightarrow H2 + OH^-$
OH^- migrates to anodic chamber via anion exchange membrane.

Partial HCl leaching

$$2RE + 6\,HCl \leftrightarrow 2RECl_3 + 3H_2 \uparrow$$

$$Fe + 2\,HCl \leftrightarrow FeCl_2 + H_2 \uparrow$$

Galvanostat



Complete Fe removal
>95% REE+Co recovery
1kWh/kg magnet
~3 €/kg REO

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Venkatesan et al., Separation and Purification Technology 191 (2018) 384–391

VALOMAG: EIT RM UPSCALING PROJECT



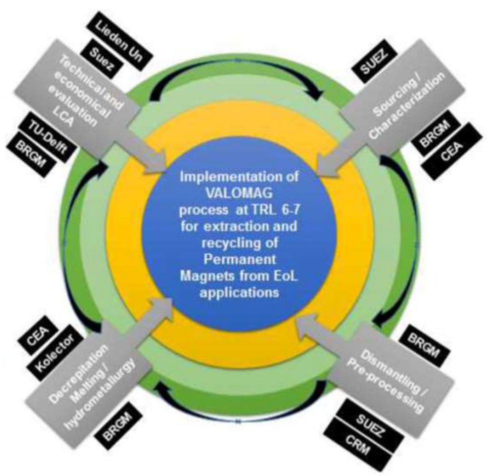


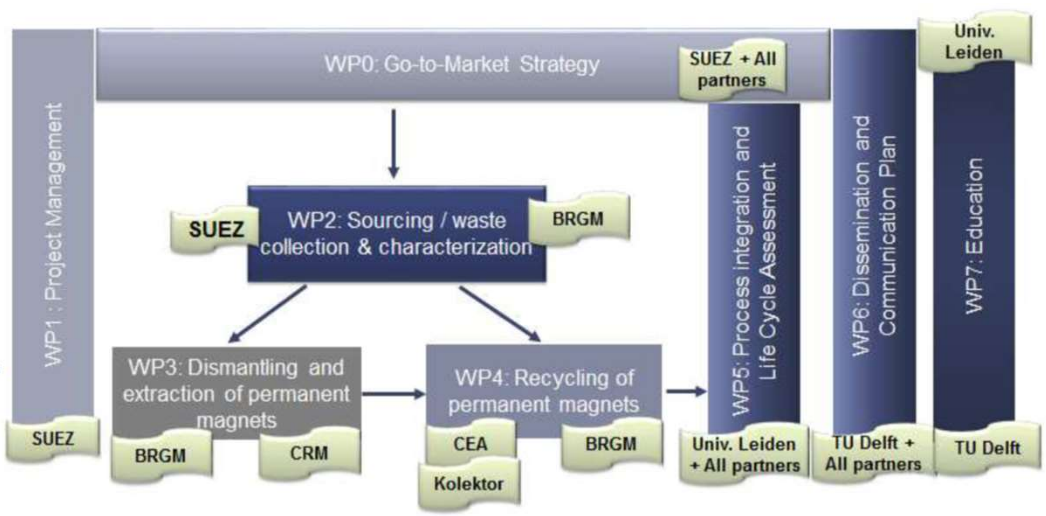
Upscale of Permanent Magnet Extraction from EoL Applications Dismantling and Recycling of NdFeB Magnets

Project period: 1.2020 – 12.2022 (3 years)

EIT RM funding: M€ 2.0

TU Delft: WP5 – process integration; WP6 & WP7 Dissemination and education





MATERIALS ENG. PROJECTS (BSC COURSE)

Project title: "Materials Scarcity & Environmental Impact – Neodymium Permanent Magnet from End-of-Life hard-disc-drives (HDDs) Case Study"

Tabel 2.1: Specificaties van de vijf verschillende HDD's.

	1.	2.	3.	4.	5.
Model	Hitachi	WD Blue	Hitachi	Seagate	WD Black
Opslag	500 GB	250 GB	250 GB	40 GB	500 GB
Productiejaar	2012	2012	2007	2006	2013
Productieland	China	Thailand	Thailand	China	Malaysia
Gewicht HDD (gram)	391.73	445.64	586.48	533.28	436.46
Demontagetijd (minuten)	16	18	25	26	10

Tabel 2.2: Gewicht en gewichtspercentage van magneten in HDD.

		1.	2.	3.	4.	5.
Total magnet weight (g)	Totaal gewicht magneten (gram)	2.810	3.110	13.582	8.811	4.884
Wt.% of HDD (g)	Gw % magneten van HDD	0.72%	0.70%	2.32%	1.65%	1.12%

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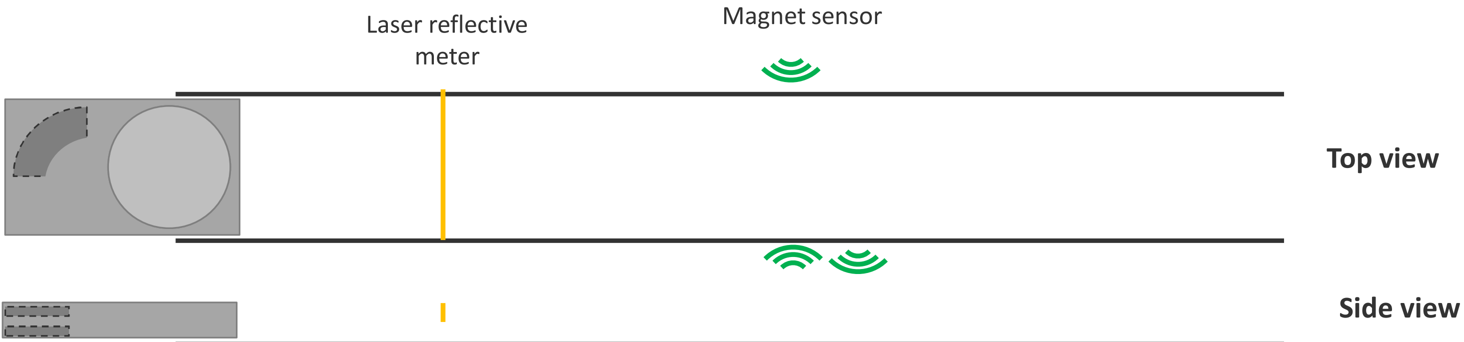
MATERIALS ENG. PROJECTS (BSC COURSE)

Grinding – Half and Angle HDD

- Very slow process
- Accurate

Cut - Angle HDD

- Fast process
- Less accurate



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CONCLUDING REMARKS

Diversified magnet sources

Many available recycling & recovery routes

Proper selection of the recycling route and technology: important

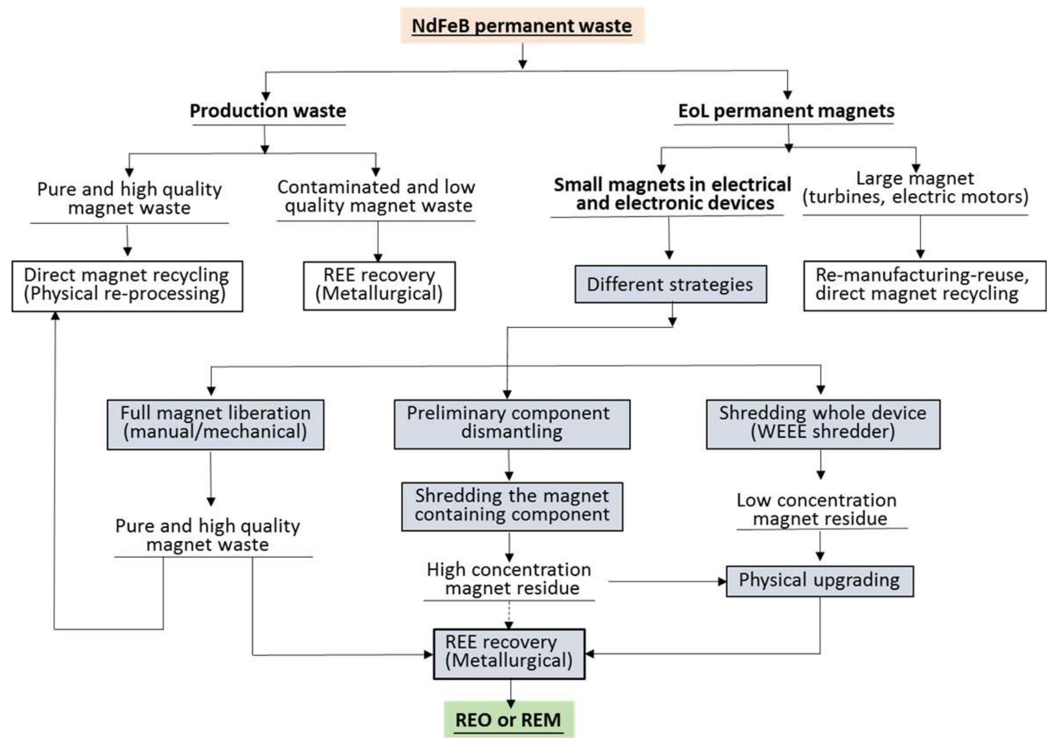
Selection criteria

- Size of the magnet
- Complexity in the product
- Magnet concentration in the waste: high – middle - low

Key tech. issues

- Fe – REE separation
- Comprehensive value recovery
- Minimized waste generation
- Development of low cost of magnet dismantling technologies: crucial for the metallurgical REE recovery.

Finally, market and economics of operation will decide!



ACKNOWLEDGMENTS

Financial supports

- EU FP7 MC-ITN "EREAN": European Rare Earth Magnet Recycling Network (grant no. 607411).
- EU FP7 "REEcover": Recovery of Rare Earth Elements from magnetic waste in the WEEE recycling industry and tailings from the iron ore industry (grant no. 603564).
- Van Gansewinkel Group (now Renewi) for the development of the REE recovery process to treat the shredded computer HDDs.

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THANK YOU FOR YOUR ATTENTION!

…QUESTIONS?

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