ENVIRONMENTAL IMPACTS OF RARE EARTH PRODUCTION - STATUS, CHALLENGES, AND STRATEGIES FOR IMPROVEMENT

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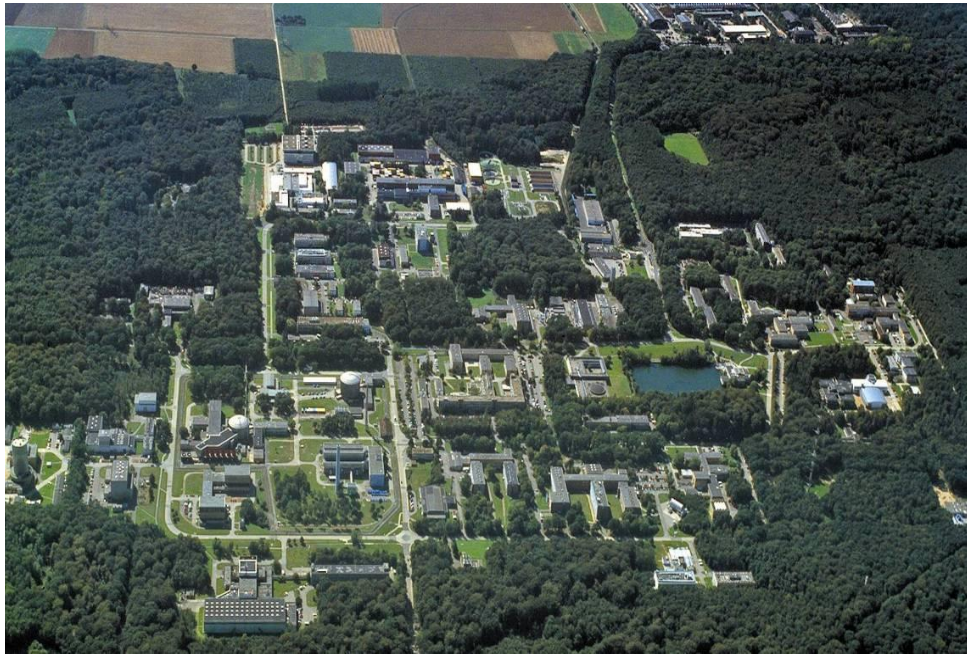
ENVIRONMENTAL IMPACTS OF RARE EARTH PRODUCTION
STATUS, CHALLENGES, AND STRATEGIES FOR IMPROVEMENT

- Who we are?
- Our experience with Rare Earths (Siemens-Projekt)
- What is Life Cycle Assessment (LCA)?
- Lessons learned from LCA of Rare Earths
- Brief insight into Life Cycle Sustainability Assessment (LCSA)?

AT FIRST GLANCE



Research campus: 11 institutes with 80 subinstitutes over 2,2 qkm

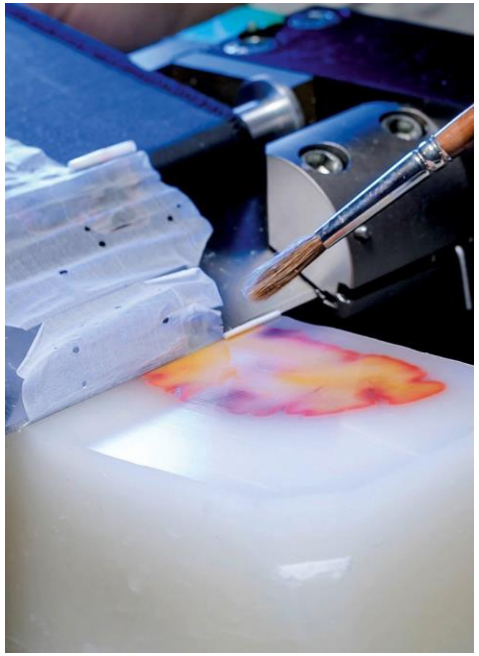
JÜLICH Forschungszentrum

AT FIRST GLANCE



Around 7120 employees

2800 scientists
1600 technical staff
1600 project management agency (PTJ)
300 trainees and interns
900 administration



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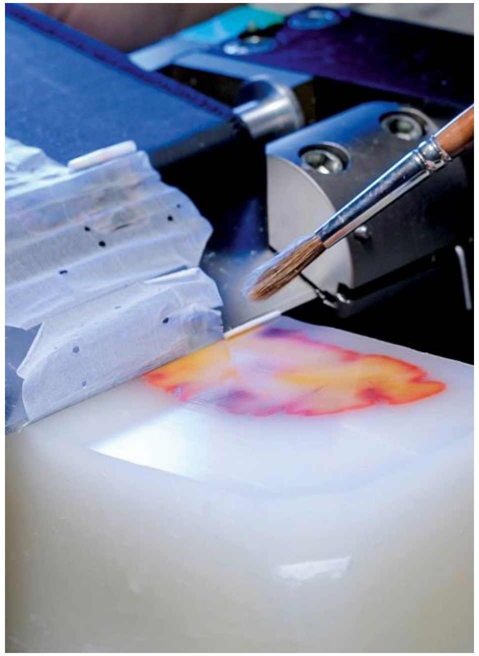
AT FIRST GLANCE

Budget:
€ 861 Millions in 2021



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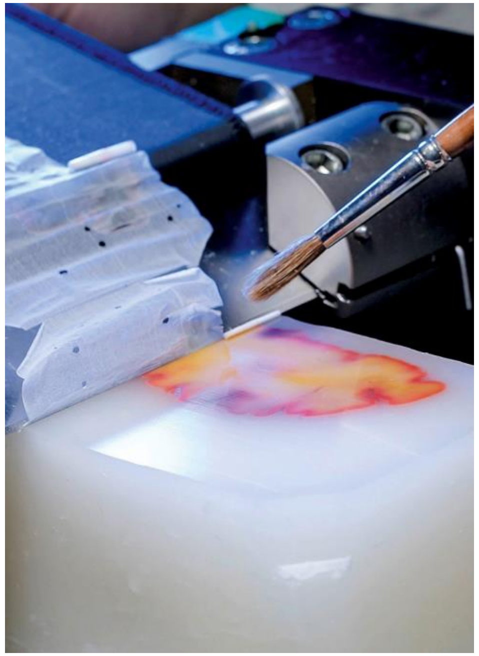
AT FIRST GLANCE



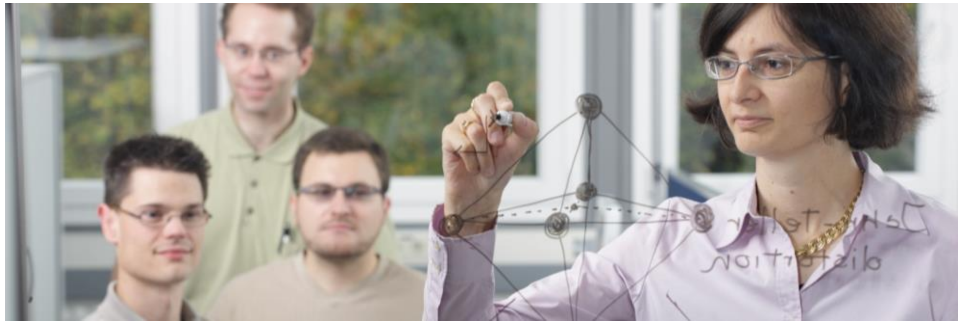





Shareholders: Federal Government (90%) and state of NRW (10%)

WE WORK HAND IN HAND

WE



Interdisciplinary:

physics,
computer science,
biology,
medicine,
chemistry,
engineering,
neuroscience,
mathematics,
geology,
social sciences
(…)

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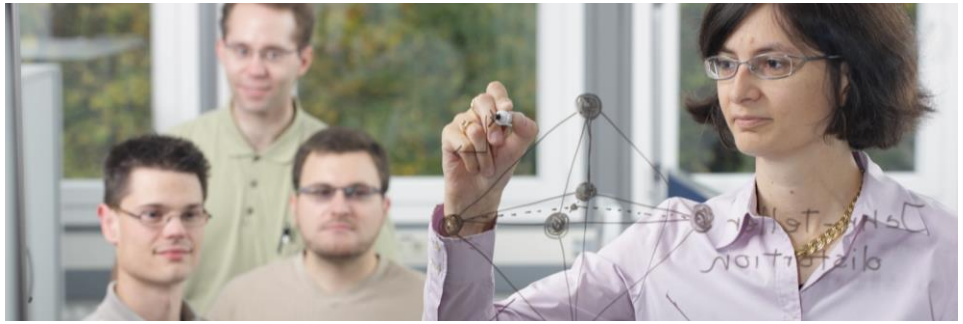
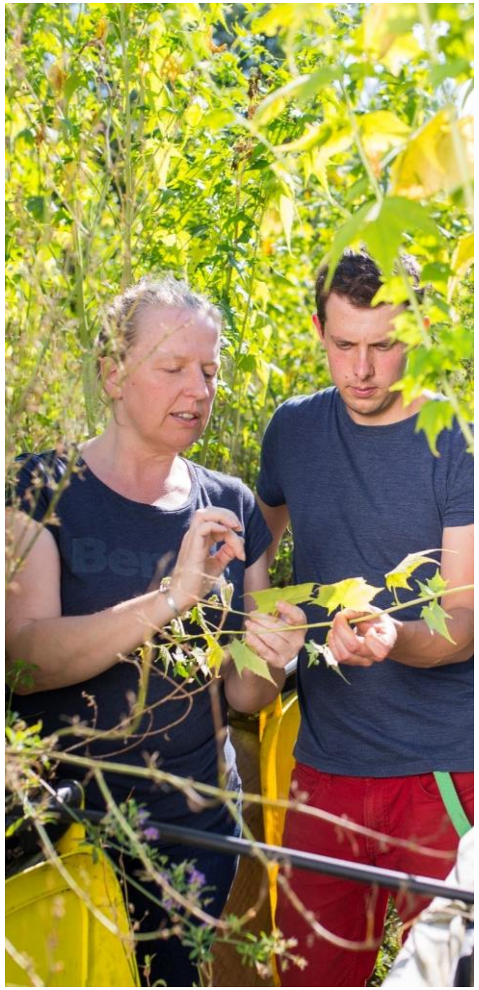
WE WORK HAND IN HAND

WE





International:

934 visiting scientists from 65 countries and

312 postdocs, 45 % of them from abroad

891 doctoral researchers, 44 % of them from abroad

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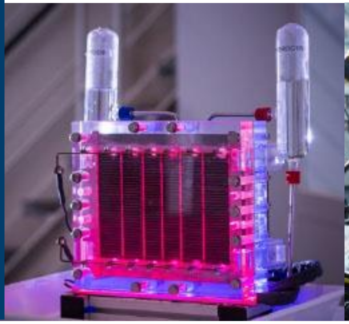
OUR FIELDS OF RESEARCH

WE CONDUCT RESEARCH for a changing society

OUR FIELDS OF RESEARCH

RESEARCH

Institute for Advanced Simulation	(IAS)
Institute of Bio- and Geosciences	(IBG)
Institute of Biological Information Processing	(IBI)
Institute of Energy and Climate Research	**(IEK)**
Institute of Neuroscience and Medicine	(INM)
Jülich Centre for Neutron Science	(JCNS)
Nuclear Physics Institute	(IKP)
Institute for Sustainable Hydrogen Economy	(INW)
Peter Grünberg Institute	(PGI)
Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons	(ER-C)
Central Institute for Engineering, Electronics and Analytics	(ZEA)



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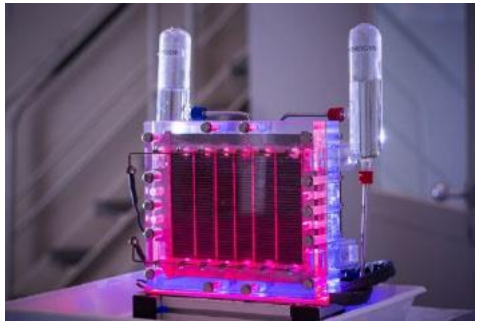
ENERGY

RESEARCH

Institute of energy and climate research



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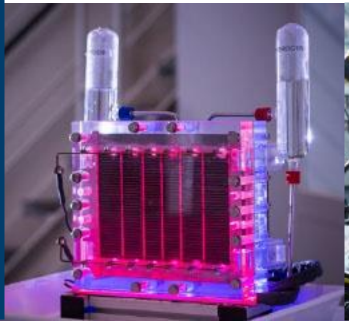
ENERGY

RESEARCH

Materials Synthesis and Processing (IEK-1)
Microstructure and Properties (IEK-2)
Techno-Economic Systems Analysis (IEK-3)
Plasma Physics (IEK-4)
Photovoltaics (IEK-5)
Nuclear Waste Management and Reactor Safety (IEK-6)
Stratosphere (IEK-7)
Troposphere (IEK-8)
Fundamental Electrochemistry (IEK-9)
Energy Systems Engineering (IEK-10)
Systems Analysis and Technology Evaluation (IEK-STE)
Helmholtz-Institutes Erlangen-Nürnberg for Renewable Energy (IEK-11)
Helmholtz Institute Münster: Ionics in Energy Storage (IEK-12)
Theory and Computation of Energy Materials (IEK-13)
Electrochemical Process Engineering (IEK-14)



RESEARCH

SYSTEMS ANALYSIS AND TECHNOLOGY EVALUATION (IEK-STE)

Research topics from the fields of
economics, environment, social sciences

- Life Cycle Sustainability Assessment
- Emerging Technologies, Resource Criticality
- Regions, Macro-Economics, and Structural Change
- Actors, Acceptance and Economic Behavior
- Resource Economics and the Water-Energy-Food-Nexus

OUR EXPERIENCE WITH RARE EARTHS

SIEMENS-FORSCHUNGSBEREICH (S-FB)

RARE EARTH – GREEN MINING & SEPARATION

- Participants: RWTH Aachen, FZJ (IEK-STE), Siemens
- Project period: 2012 – 2015
- Funding of 9 doctoral students and investments
- 6 sub-projects: Geology, Processing, Metallurgy, Electrolysis, Recycling, Sustainability
- Target: Environmentally compatible and efficient supply of rare earths for permanent magnets – using the methodology of Life Cycle Assessment

PROCESS CHAIN OF RARE EARTH PRODUCTION

RareEarth GREEN MINING AND SEPARATION

Ore → Exploration → Concentrating → Separation → REO reduction to RE Metals → Manufacturing of Magnets → Application

Monazit

Bastnäsit

Xenotime

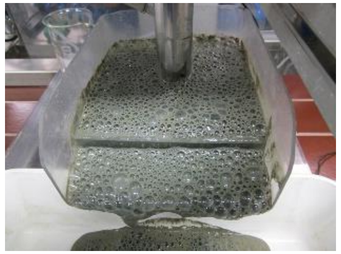
Eudialyte

China: Bayan Obo

USA: Mountain Pass

Australia: Mount Weld

China: Ion-adsorption Clays

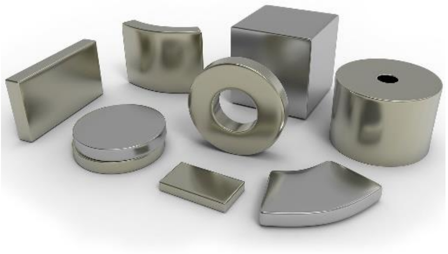


Flotation

Processing Plant

REO Powder

REO Electrolysis



RE Magnets

Wind Generator

Comparing different supply chains

- ore
- location
- technique

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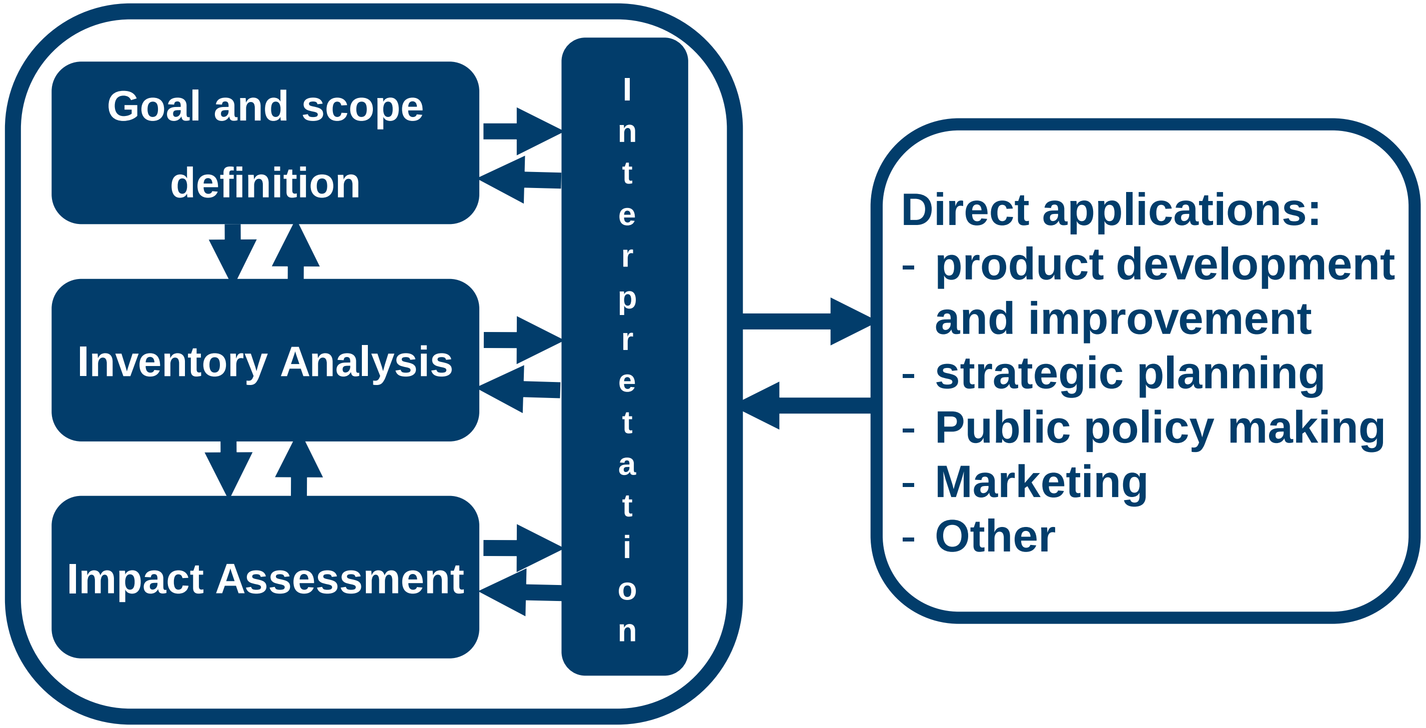
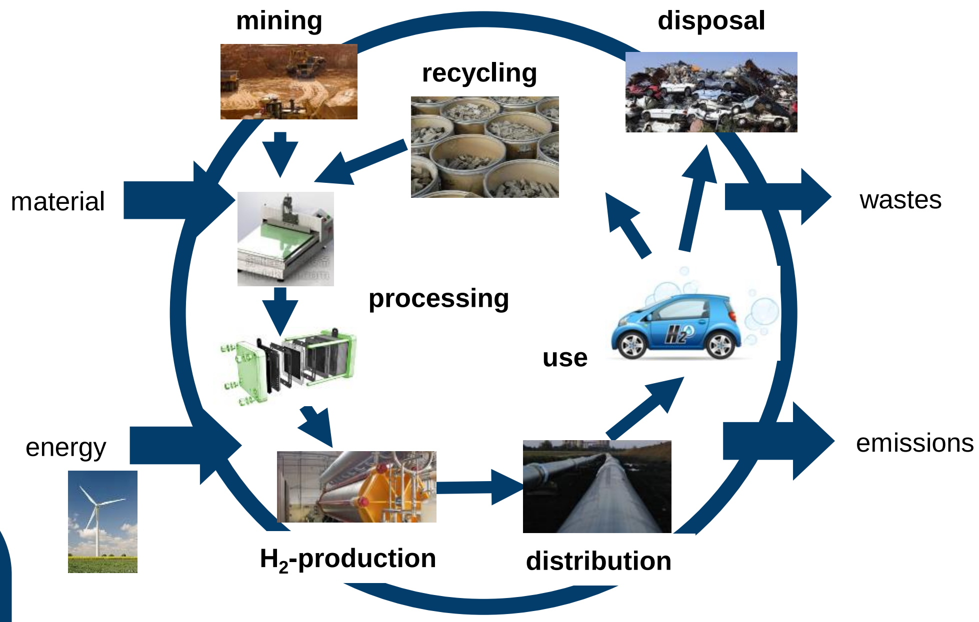
WHAT IS LCA?

“LCA is a tool for the analysis of the **environmental** burden of **products** at all stages in their **life cycle**”



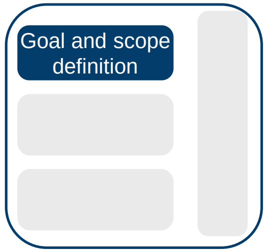
“life cycle thinking”



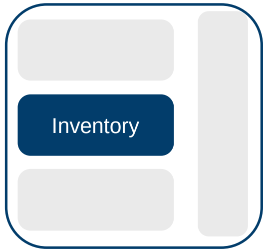
International Organization for Standardization

Source: ISO 14040, 14044

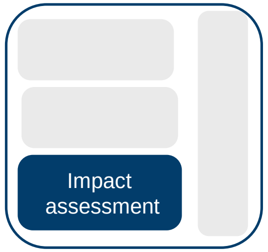
WHAT IS LCA?



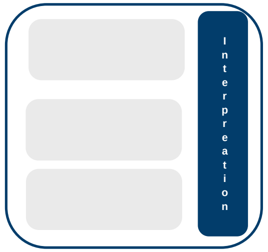
The **goal and scope** of the study shall be clearly defined and consistent with the intended application



Inventory analysis involves data collection and calculation procedures to quantify relevant **inputs and outputs** of a product system



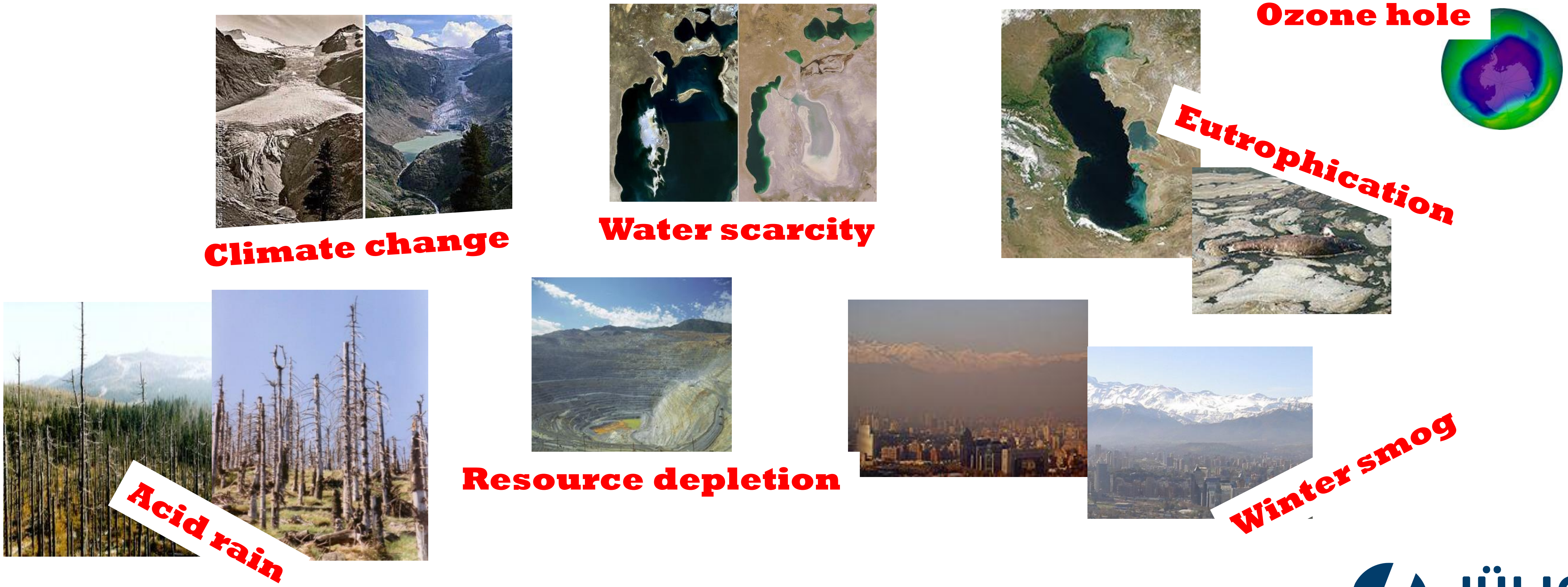
Impact assessment aims at evaluating the significance of **potential impacts** using the results of the inventory



Interpretation delivers results that are consistent with the goal and scope, and which reach **conclusions**, explain **limitations** and provide **recommendations**

WHAT IS LCA?
Motivation

Different technologies cause different environmental impacts:



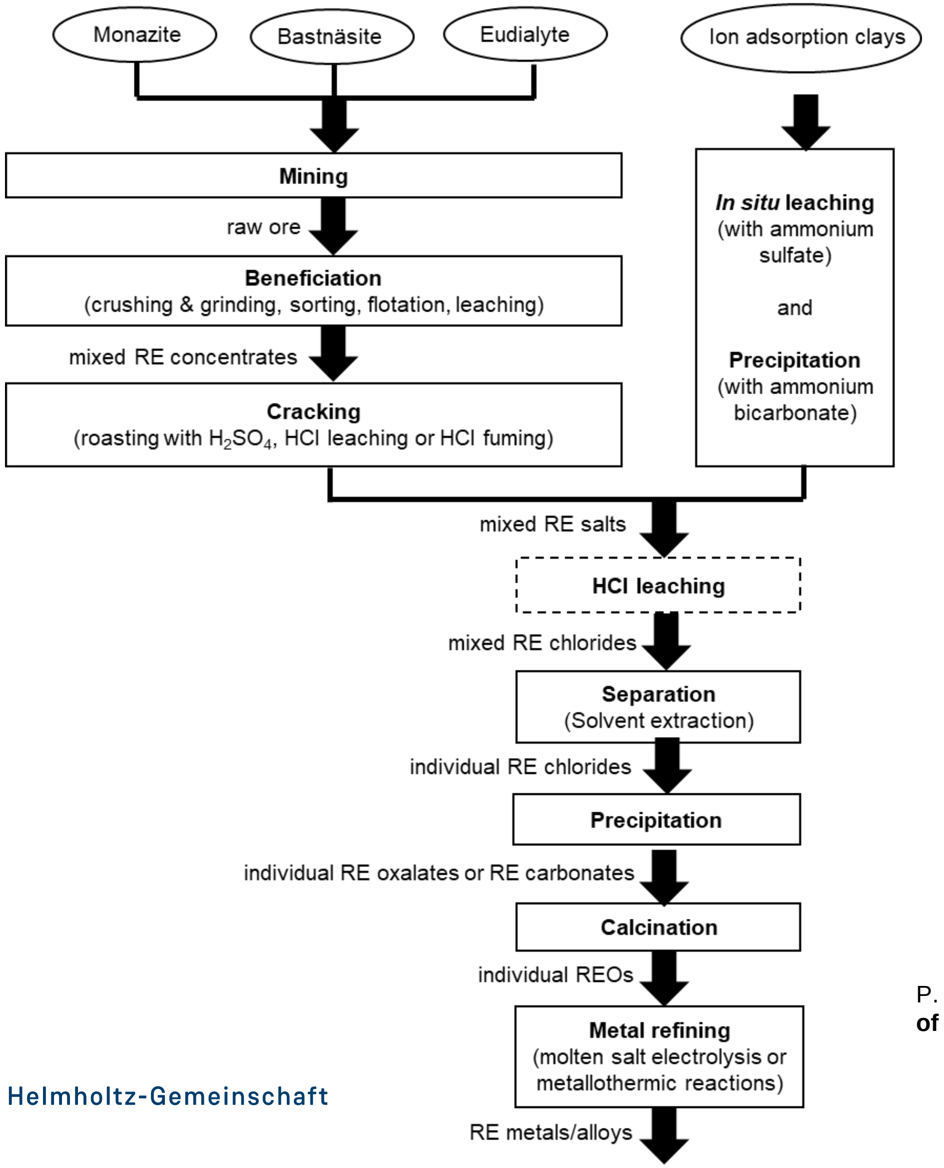
WHAT IS LCA?

Potential impacts

▪ Climate Change Potential (Global Warming)	GWP	kg CO_2 eq.
▪ Eutrophication Potential (Over-fertilization)	EP	kg P eq./kg N eq.
▪ Photochemical Ozone Depletion Potential (Summersmog)	POCP	kg Ethene eq.
▪ Ozone Depletion Potential (Ozone hole)	ODP	kg CFC-11 eq.
▪ Acidification Potential (Acid rain)	AP	kg SO_2 eq.
▪ Human toxicity	HTP	kg 1,4-DCB eq.
▪ Ecotoxicity	FAETP / MAETP / TETP	kg 1,4-DCB eq.
▪ Abiotic Resource Depletion (Resource scarcity)	ADP	kg Cu eq.
▪ Water scarcity		m^3 world eq.
▪ Land use		m^2a
▪ ……	…….	

LESSONS LEARNED

Simplified process chain of RE production from different mineral types



(dashed line for optional process)

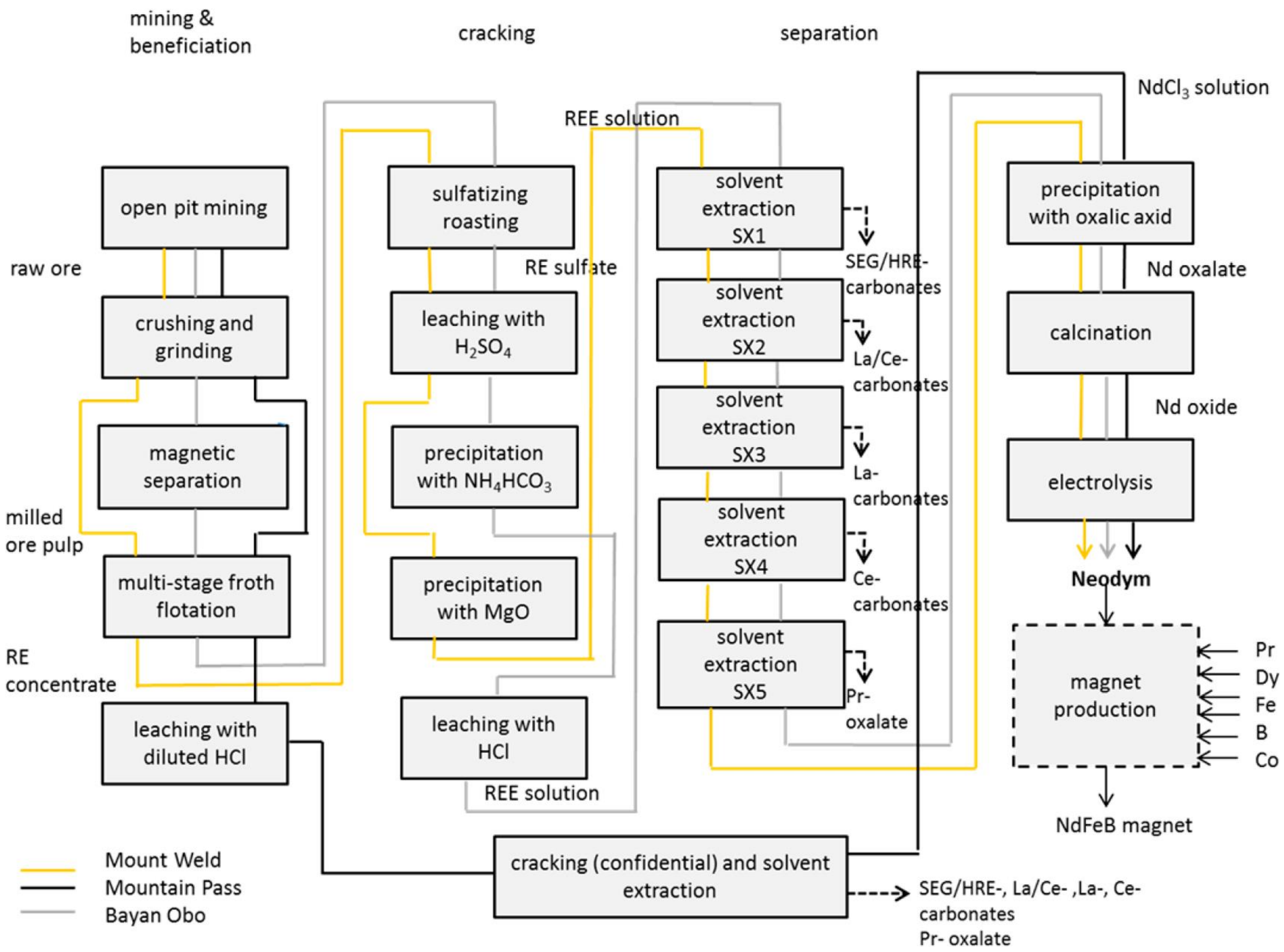
P. Zapp, A. Schreiber, J. Marx and W. Kuckshinrichs: **Environmental impacts of rare earth production**; MRS Bulletin ***2022*** Vol. 47 Issue 3 Pages 267-275

LESSONS LEARNED

Three detailed supply chains to produce Neodymium

Each process chain is different!

- Ore composition and concentration
- Impurities
- Yield and efficiencies of processes
- Energy supply
- Waste and wastewater treatment
- Stripping rate, mining rate
- Losses
- Flue gas cleaning (HF removal efficiency)
- Radioactivity
- Electrolysis technique
- …



J. Marx, A. Schreiber, P. Zapp and F. Walachowicz: **Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits;** ACS Sustainable Chemistry and Engineering ***2018*** Vol. 6 Issue 5 Pages 5858-5867

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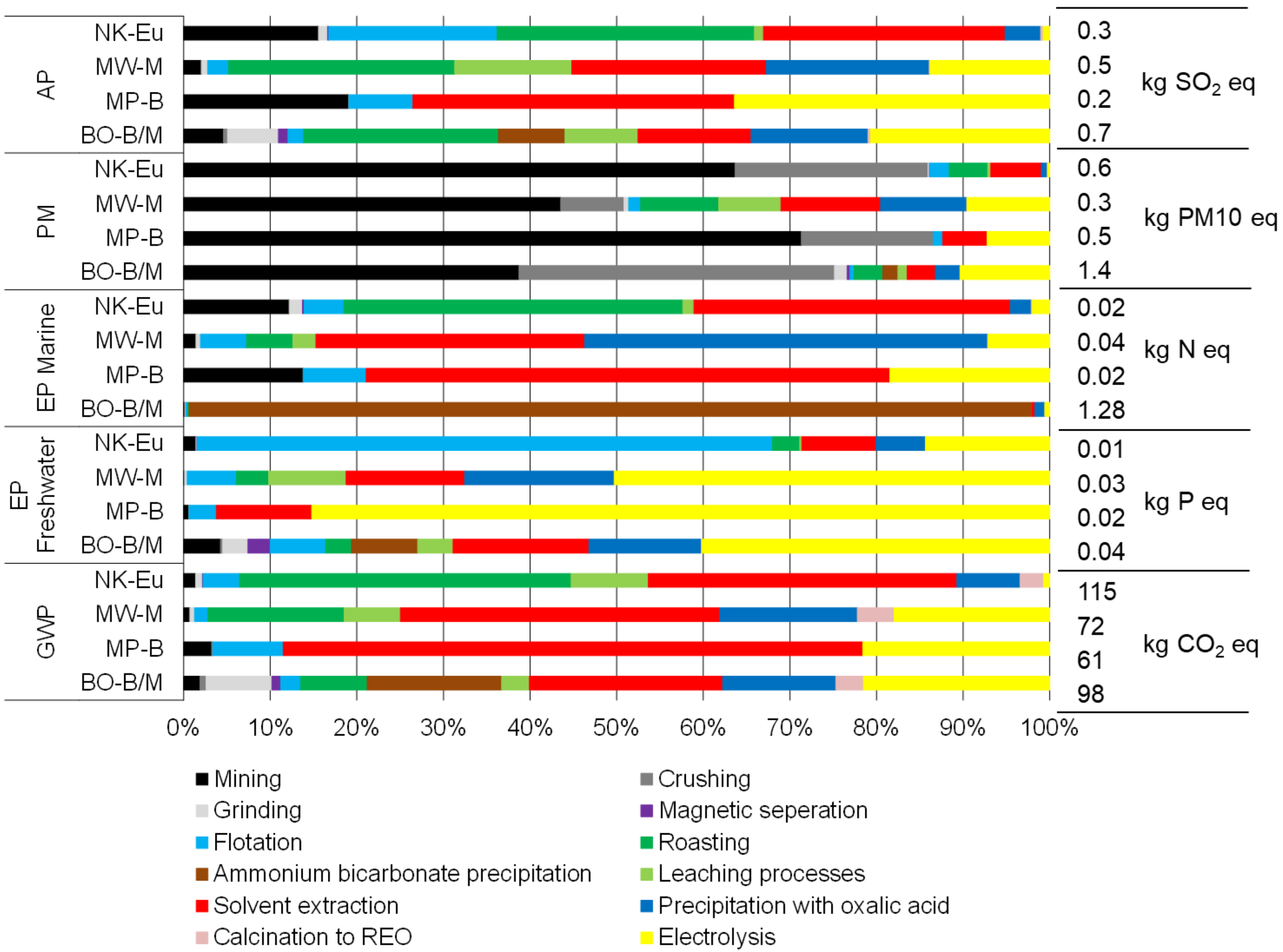
LESSONS LEARNED

Impacts of single processes

- Mining and crushing dominate PM
- Flotation and magnetic sorting have lower impacts than hydrometallurgical processes
- Roasting, solvent extraction, oxalate precipitation and calcination contribute most to GWP and AP, mainly caused by electricity demand required for chemical supply
- Roasting causes AP, due to HF and SO_2
- Electrolysis contributes to GWP (CO_2, CF_4, C_2F_6), AP (HF) and $EP_{Freshwater}$ (PO_4^{3-} during cathode production)
- Supply of ammonium bicarbonate for precipitation to RE carbonates dominates EP_{Marine} in Bayan Obo (NH_4^+ emissions)



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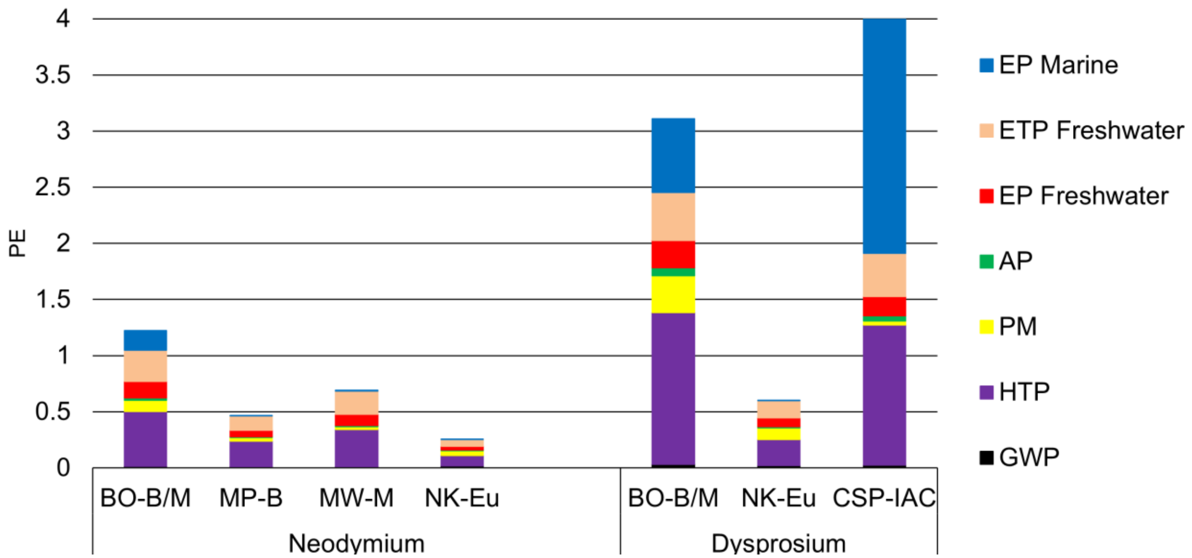
LESSONS LEARNED

Normalized impacts of 1 kg of Neodymium (Nd) and Dysprosium (Dy) production

- Dy has higher environmental impact than Nd because more ore has to be processed (lower Dy concentration in ore)
- Dy based on IACs has the highest environmental impacts (NH_4^+ emissions during *in situ* leaching with ammonium sulfate)
- Nd from Swedish eudialyte has the lowest impacts, followed by bastnäsite from Mountain Pass, monazite from Mt Weld and bastnäsite/monazite from Bayan Obo
- Mountain Pass shows the effectiveness of measures such as recycling of saline wastewater to save chemicals, cleaner power generation using a natural gas-fired cogeneration plant, and an alternative cracking process without roasting
- Reasons for worse Chinese RE production are e.g., illegal mining and processing with unsatisfactory environmental protection, poor recovery rates, leaking tailing ponds and an unfavorable electricity mix (coal)



BO-B/M: Bayan Obo bastnäsite/monazite (China)
MP-B: Mountain Pass bastnäsite (U.S.)
MW-M: Mt. Weld monazite (Australia/Malaysia)
NK-Eu: Norra Kärr eudialyte (Sweden)
CSP-IAC: Chinese southern provinces ion-adsorption clays

P. Zapp, A. Schreiber, J. Marx and W. Kuckshinrichs: **Environmental impacts of rare earth production**; MRS Bulletin ***2022*** Vol. 47 Issue 3 Pages 267-275

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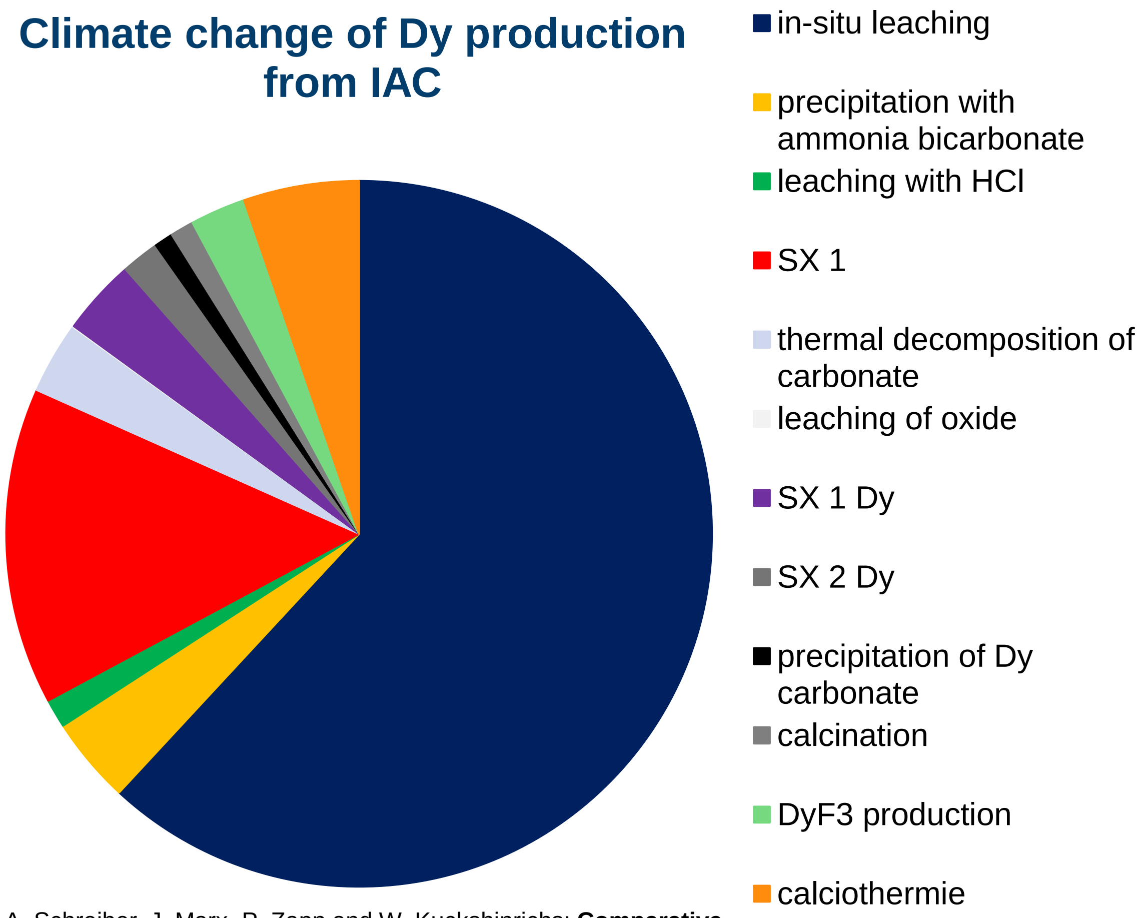
LESSONS LEARNED

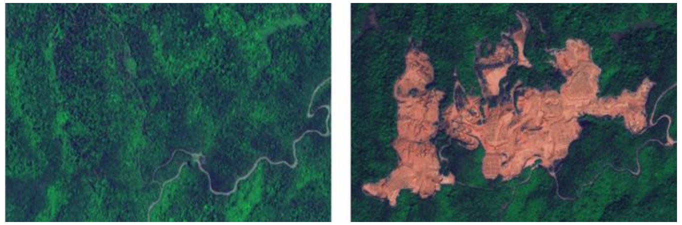
Challenges of REE production from ion-adsorption clays (IAC)



A. Schreiber, J. Marx, P. Zapp and W. Kuckshinrichs: **Comparative Life Cycle Assessment of Neodymium Oxide Electrolysis in Molten Salt;** Advanced Engineering Materials ***2020*** Vol. 22 Issue 6

- In-situ leaching with ammonium sulphate contributes most to almost all impact categories
- 78% − 96% of the total in-situ leaching impacts are generated during ammonium sulphate supply (**upstream**)
- 100% of eutrophication (EP_{Marine}) is caused by **direct** NH_4^+ emissions of in-situ leaching at the mineral deposit

IAC mining site in Ganzhou 2005 (left) and 2009 (right)



Yang et al.: **China's ion-adsorption rare earth resources, mining consequences and preservation**, Environmental Development 8 (2013) 131–136

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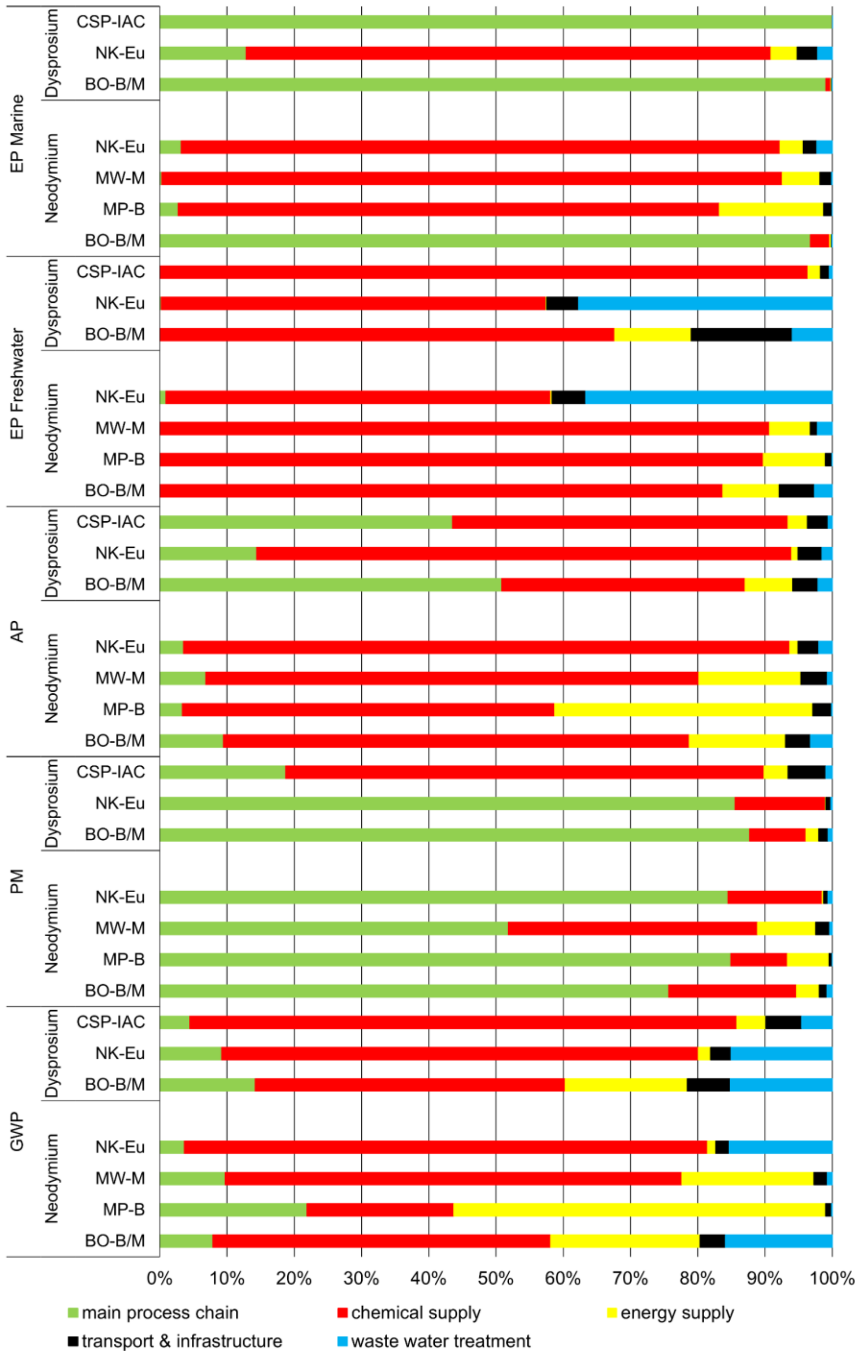
LESSONS LEARNED

Breakdown of impacts caused by upstream and downstream processes

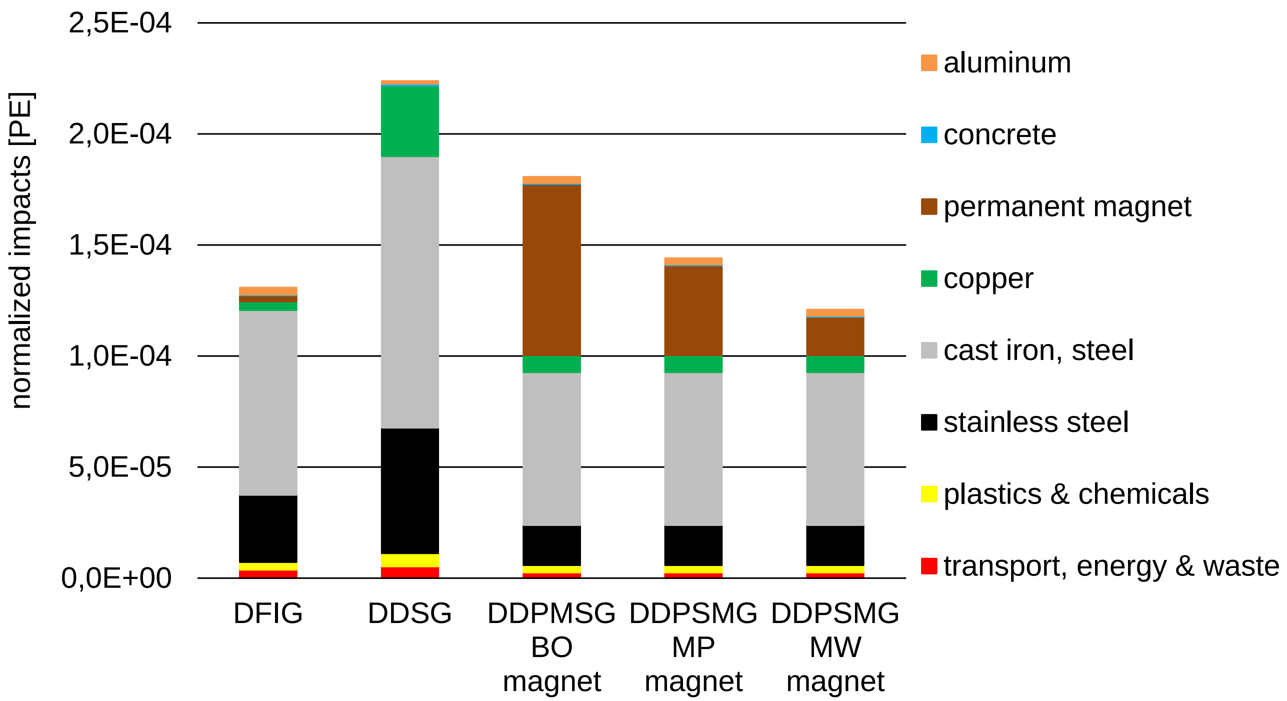
- Dominant share of chemicals in almost all impact categories
- PM is dominated by dust emissions during mining
- NH_4^+ emissions during *in situ* leaching of IACs and REE carbonate precipitation with ammonium bicarbonate (China) dominate EP_{Marine}
- Energy consumption is mostly reflected in GWP and AP
- Share of transport and infrastructure facilities on the total environmental impacts is negligible

P. Zapp, A. Schreiber, J. Marx and W. Kuckshinrichs: **Environmental impacts of rare earth production**; MRS Bulletin ***2022*** Vol. 47 Issue 3 Pages 267-275



LESSONS LEARNED

Influence of RE origin (ore type, mining location, specific site conditions) on environmental impacts per 1 kWh electricity generated by 3 MW wind power plant



DFIG: doubly-fed induction generator
DDSG: direct driven synchronous generator
DDPMSG: electrically excited and direct drive permanent magnet synchronous generator

- Electricity generation by DDPMSG with permanent magnet produced from Chinese RE (Bayan Obo) has higher normalized environmental impacts compared to
  - U.S. Mountain Pass (→ 20%)
  - Mt. Weld (Aus) (→ 33%)
- Electricity generation by Australian DDPMSG is 8% better than by DFIG

A. Schreiber, J. Marx and P. Zapp: **Comparative life cycle assessment of electricity generation by different wind turbine types;** Journal of Cleaner Production ***2019*** Vol. 233 Pages 561-572

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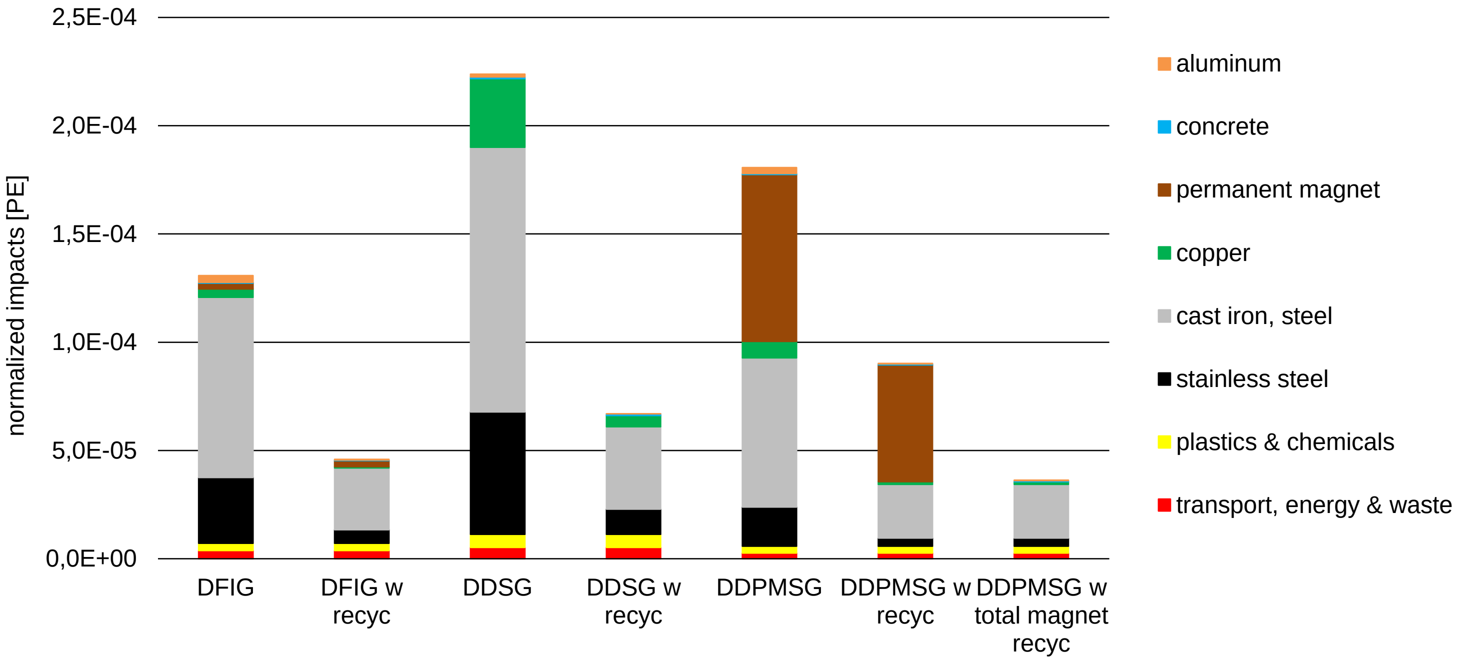
LESSONS LEARNED

First rough estimation on recycling



A. Schreiber, J. Marx and P. Zapp: **Comparative life cycle assessment of electricity generation by different wind turbine types;** Journal of Cleaner Production ***2019*** Vol. 233 Pages 561-572, DOI: 10.1016/j.jclepro.2019.06.058

Assumptions:

- Decreasing impacts if recycling of metals (steel, Al, Cu) is considered by giving credits for avoiding virgin metal production (minus 50% for DDPMSG)
- Complete reuse of rare earth permanent magnet in DDPMSG turbines decreases impacts by 80% (unlikely scenario)
- Efforts for recycling processes have not been considered here so far!

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SUMMARY OF LIFE CYCLE ASSESSMENT (LCA)

Challenges

- High energy demand
- High water consumption → Sinking of the groundwater level
- High chemical consumption (organic solvents, acids, flocculants, ammonia and nitrate compounds)
- High amount of emissions, effluents, and solid waste
- Discharge of radioactive elements (^{232}Th, ^{238}U) and their decay products into the environment
- Salinization and toxic and radioactive contamination of groundwater in mining/processing regions
- Land occupation for mining, processing plant(s), additional infrastructural facilities, waste disposals, tailings, dams, permanent storage of radioactive waste materials
- Transportation distances and routes (for separately located processing facilities)
- Accidents: uncontrolled leakage of contaminated wastewater (pipeline leaks, dam bursts) – not considered in LCA

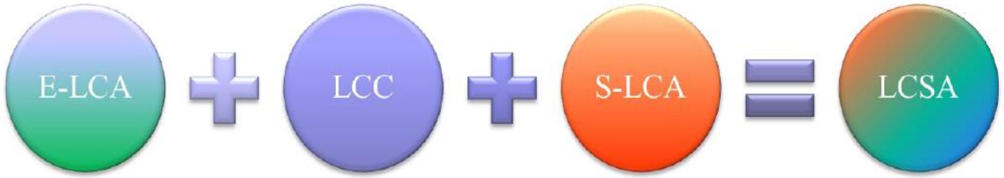
SUMMARY OF LIFE CYCLE ASSESSMENT (LCA)

Innovation and strategies for improvement

- Potential for improvement through emission treatment technologies and recycling of chemicals
- Closing illegal mines and raising environmental standards
- Identifying of new primary resources with high REE content, little radioactive associated elements and located outside sensitive ecosystems (alternatives to China) ⟶ Per Geijer (Kiruna)
- New or improved processing technologies
- Reprocessing of industrial waste streams
- Identifying of secondary REE resources
- Increased end-of-life recycling of products

LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)

Keeping the Life Cycle approach by combining **environmental assessment** (**E-LCA**), **Life Cycle Costing** (**LCC**) and **social assessment** (**S-LCA**)



Ecological Evaluation

Economic Evaluation

Technical Assessment

Social Evaluation

LCC is "…an assessment of all costs associated with the life cycle of a product that are directly covered by anyone or more of the actors in the product life cycle…."

S-LCA is an impact assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle.

LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)

Typical LCC Indicators:

- Investment costs
- Variable operation and maintenance costs
- Fixed operation and maintenance costs (wages, taxes, heating, lighting)
- Levelized costs of electricity (Σ Invest, fix & variable O&M)
- Internalized external effects (CO_2 taxes)

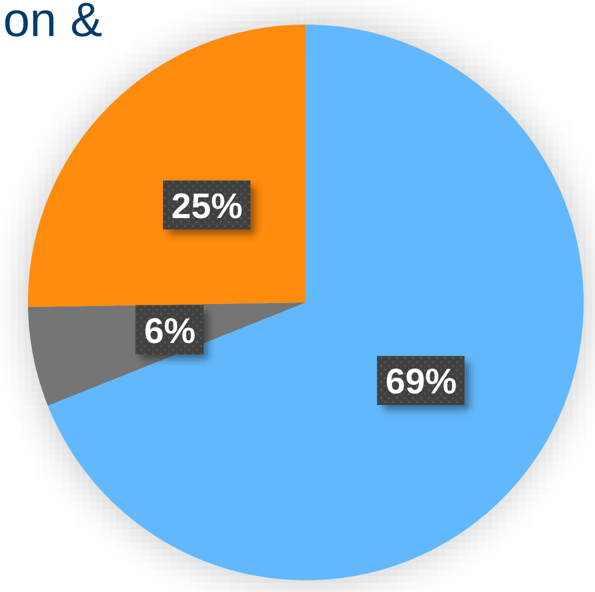
Stakeholder Groups and typical S-LCA Indicators:

- **Workers**
  - Child labor
  - Fatal accidents
  - Fair salary
- **Local communities**
  - Unemployment rate
  - Drinking water coverage
  - Indigenous rights
- **Society**
  - Illiteracy
  - Contribution to economic development
- **Consumers**
  - Deceptive or unfair business practices
  - End of life responsibility
- **Value chain actors**
  - Fair competition
  - Corruption

LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)

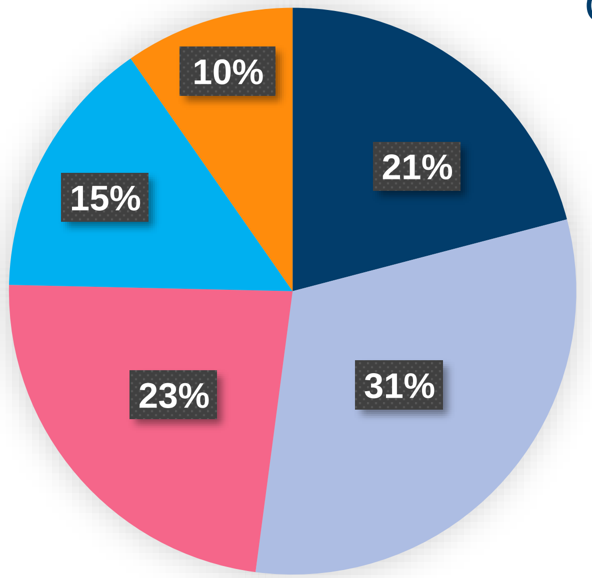
Example: Impact category - Public sector corruption

CN: Beneficiation & Separation



- Chemical products for daily use - CN
- Chemicals for special usages - CN
- Others

CN: Magnet production



- Dysprosium prodcution
- Nd/Pr production
- Non-metal minerals and other mining - CN
- Electricity and steam production and supply - CN
- Others

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- A. Schreiber, J. Marx and P. Zapp: **Comparative life cycle assessment of electricity generation by different wind turbine types;** Journal of Cleaner Production ***2019*** Vol. 233 Pages 561-572, DOI: 10.1016/j.jclepro.2019.06.058
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ENVIRONMENTAL IMPACTS OF RARE EARTH PRODUCTION - STATUS, CHALLENGES, AND STRATEGIES FOR IMPROVEMENT

INSTITUT FÜR ENERGIE- UND KLIMAFORSCHUNG – SYSTEMFORSCHUNG UND TECHNOLOGISCHE ENTWICKLUNG (IEK-STE)

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