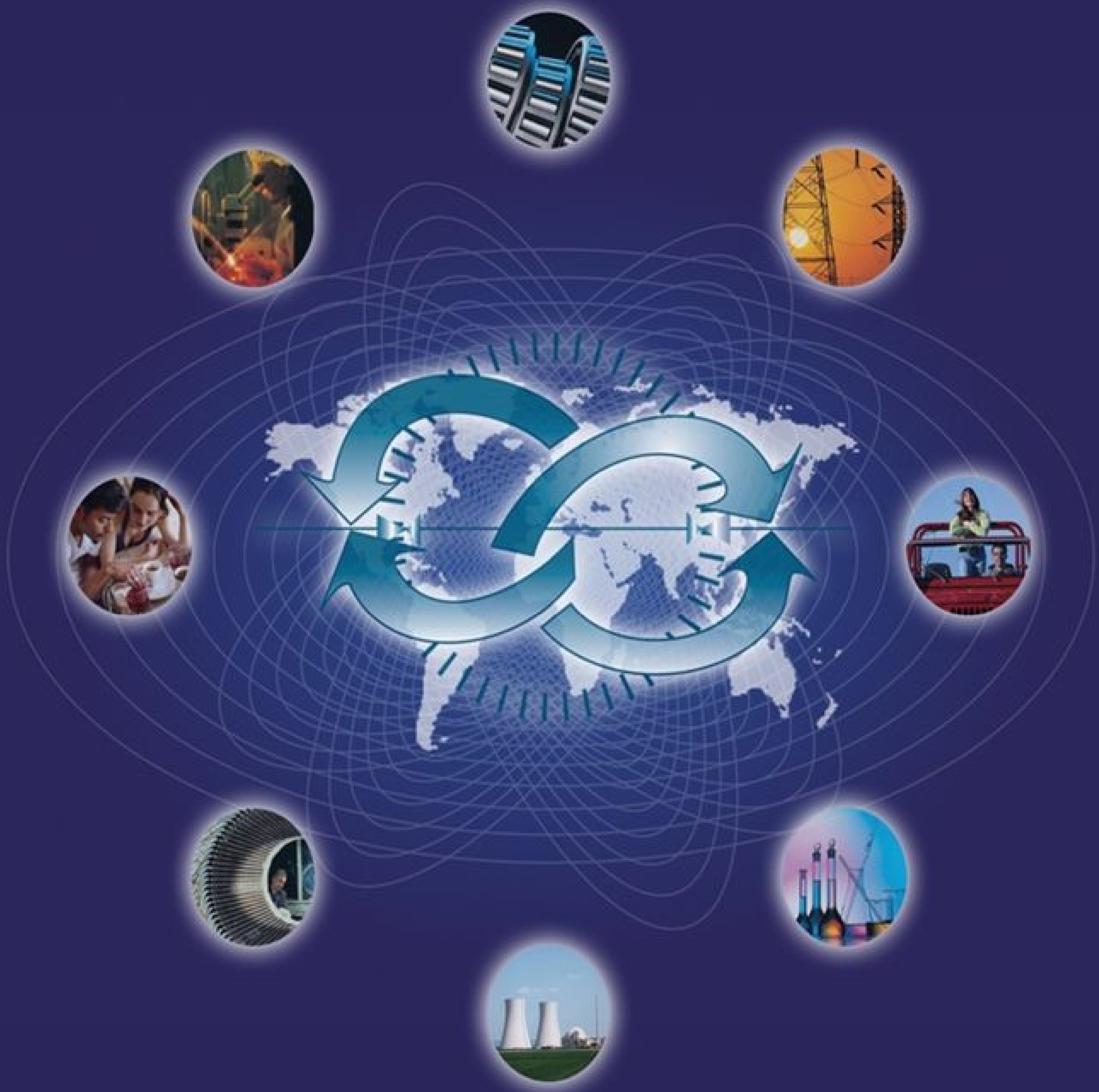


STE Preprint 11/2016

Schreiber, Andrea, Marx, Josefine, Zapp, Petra, Hake, Jürgen-Friedrich, Voßenkaul, Daniel, Friedrich, Bernd

Environmental impacts of rare earth mining and separation based on Eudialyte – a new European way

Institute of Energy and Climate Research
Systems Analysis and Technology Evaluation (IEK-STE)

JÜLICH
FORSCHUNGSZENTRUM

Environmental impacts of rare earth mining and separation based on Eudialyte – a new European way

Andrea Schreiber, Josefine Marx, Petra Zapp, Jürgen Friedrich Hake[1)]
Daniel Vossenkaul, Bernd Friedrich[2)]

1) Forschungszentrum Jülich, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), D-52425 Jülich, Germany
2) RWTH Aachen, Institute of Process Metallurgy and Metal Recycling (IME), Intzestraße 3, D-52056 Aachen, Germany

Executive Summary

Neodymium and dysprosium are two rare earth elements (REEs), out of a group of 17 elements with similar chemical properties. Due to their unique properties, REEs gained increasing importance in many new technologies like wind turbines, batteries, lighting, and medical technique. However, the production of REEs requires high material and energy consumption and is associated with considerably environmental burdens e.g. radioactive loaded dust and tailings. Due to the Chinese hegemony regarding REE production and the strong dependency of European industry on Chinese REE exports this paper presents a possible European production chain of REEs based on the mineral Eudialyte found in Norra Kärr (Sweden). Because almost 90% of the total mines production of 109,000 t REO equivalents in 2013 [USGS, 2013] occurred in China, the European production is compared to the Chinese route. Bayan Obo is the largest REE deposit in China located near Baotou in Inner Mongolia. Using the Life Cycle Assessment method (LCA), the environmental impacts of both production lines are assessed. Although LCA is a well-known methodology to determine environmental aspects from cradle-to-grave, there are only a few LCA studies available considering REE production, almost all based on process information gathered in the 1990s. This study presents newly estimated data of a possible European Eudialyte based production route collected in a corporate 4-year project together with Siemens AG, RWTH Aachen University and Forschungszentrum Jülich. The results for the new European process route show reduced environmental burdens although the total REE content in Eudialyte is much smaller than in the Chinese deposit. Especially, the results for dysprosium from Eudialyte outreach those for Bayan Obo, due to the higher content of heavy rare earth elements (HREEs).

Keywords

Rare earth metals, neodymium, dysprosium, life cycle assessment, Bayan Obo, Eudialyte

Contribution to Journal of Sustainable Metallurgy

I Introduction

Today the production of rare earth elements (REE) mainly takes place in China with approx. 90% of total world mine production [USGS, 2013]. Hence, European industries are totally depending on imports of REEs. A set up of an exclusively European supply chain is therefore economically and socially interesting. Although some European deposits are identified, hardly any mining activities take place so far. The mineral exploration company Tasman Metals Ltd has set out a prefeasibility study for a Swedish mine in Norra Kärr. The deposit contains resources of REE, yttrium (Y) and zirconium (Zr) with Eudialyte as the main REE ore mineral.

Eudialyte is a rare, nine member ring cyclosilicate mineral, which forms in alkaline igneous rocks. Although REEs are not main components of the crystallite structure, they occur in considerable amounts due to substitution. Depending on the mineral type REE concentrations from <1 up to 10% have been found so far. A huge advantage compared to conventional RE minerals is the high share of heavy rare earth elements, HREEs (up to 50% of total rare earth (TREO)). The very low concentration of radioactive elements, only a few g/t Eudialyte have been proven in experimental analysis, is a further major benefit. Moreover, Eudialyte comprises also other high-tech materials, e. g. niobium, tantalum or zirconium. Therefore, other associated economical important minerals like Nepheline, Microcline, Aegirine or Catapleiite can be mined together with Eudialyte. Today, 191 Eudialyte deposits are known worldwide. Beside Norra Kärr 8 further deposits (2 in Russia, 3 in Canada, 2 in Greenland, 1 in Malawi) show high potential for future mining of REEs [Gupta & Krishnamurthy, 2005] all outside Europe. Thus, mining of Swedish Eudialyte deposit in Norra Kärr, already close to an existing infrastructure of electricity, transport and supply industry, would decrease Chinese REE market power and increase security of supply for the European industry.

Conventional RE production from Bastnasite or Monazite is known to require high material and energy amounts. Environmental consequences and impacts on human health are again and again addressed, especially in connection with Chinese RE production. As the total REE content of Eudialyte is much smaller, this could even increase. On the other side, European environmental legislation inhibit uncontrolled release into the environment to prevent damages to human and nature. This paper, therefore, focuses on the comparison of environmental impacts of such a hypothetical European supply chain to those of the Chinese route. Using neodymium (Nd) and dysprosium (Dy) as two representatives of each light and heavy rare earth components, showing the differences is also addressed. Using the life cycle approach major environmental effects can be identified. Also, those processes can be distinguished which contribute most to these effects.

II Neodymium and Dysprosium Production

For this study a hypothetical production chain, located in Europe is assessed. It starts with mining, beneficiation, production of REOs, and finally the production of the RE metals, all located in Norra Kärr. Data for the different processes are derived from literature, deduced from existing production plants or based on laboratory experiments. The considered systems are shown in Fig. 2 and Fig. 3 and described briefly in the following. The environmental effects are compared to those of the conventional Chinese production routes, which are presented in Fig. 4 and Fig. 5.

II.1 European Eudialyte System

Mining

The European process chain starts with open pit mining in Norra Kärr, considering ore composition, mining rate, stripping rate and REO content as proposed in a prefeasibility study from 2015 [GBM, 2015]. This process comprises drilling and blasting of ore and excavated materials, as well as transport and dumping of the materials. Data for the mining process is taken from literature [Classen et al., 2007, Althaus et al., 2007, Kippenberger] and adjusted to the local conditions. According to the prefeasibility study [GBM, 2015] the mining ratio is 1.15E06 t/a, stripping ratio 0.73:1 and a life time of 20 years is expected. Tab. 1 shows the ore composition of an average Norra Kärr Eudialyte. The share of the included REEs is measured and averaged based on 2 Eudialyte samples by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) (Tab. 2) and Data given in [Gates et al., 2012].

Tab. 1: Composition of ore in Norra Kärr

Component	Mean value %
SiO_2	55.1
Al_2O_3	17.17
Fe_2O_3	5.346
CaO	3.171
MgO	1.308
Na_2O	9.002
K_2O	3.989
Cr_2O_3	0.01
TiO_2	0.326
MnO_2	0.268
P_2O_5	0.0636
SrO	0.038
BaO	0.026
ZrO_2	1.1757
LOI*	2.7
SEO	0.59

Source: [Gates et al., 2012] IEK-STE 2016

Tab. 2: Composition of REEs in Norra Kärr ore in [%]

La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy
8.9	20.2	2.7	11.2	3.1	0.4	3.6	0.7	5.3
Ho	Er	Tm	Yb	Lu	Y			
1.2	3.7	0.5	3.4	0.5	34.6			

Source: based on own measurements and Data given in [Gates et al., 2012] IEK-STE 2016

Beneficiation

To separate the Eudialyte from the other ore components several process steps are necessary. It includes crushing, grinding, magnetic separation, flotation and finally filter pressing. The ore is crushed using a two-stage jaw crusher to a particle size of 20 - 40 mm first. The amount of dust emitted during crushing is estimated by experts from RWTH Aachen University. After that the ore is ground to < 250 µm in a conventional wet grinding process. The energy demand and steel abrasion is calculated using the Bond Work Index and abrasion index described in [Gates et al., 2012]. To remove the nonmagnetic part of the ore magnetic separation is used. The magnetic ore pulp containing Eudialyte is fed to the flotation cell. In the one stage flotation cell the ore is enriched from 0.59% TREO to 2.69% TREO in the concentrate with a yield of 62%. Type and amount of flotation chemicals are taken from experiments [Stark, 2016]. The energy demand for magnetic separation [MBE, 2015] and flotation [Outotec, 2015] are calculated by means of product information of the supplier.

Cracking and Separation

In an aging process the concentrate is mixed with hydrochloric acid. To prevent gelation every mineral particle muss be moisturized with acid. Gangue and minor elements are separated by washing and filtration. Adding lime milk to the filtrate to adjust a pH of 4 causes iron, zirconia and aluminum separation. After that several solvent extraction steps are necessary to separate each REE. The extraction process and the chemicals used are based on industrial extraction processes [DNV, 2010] and are adapted to the REE composition in Eudialyte. As extraction agents amines and phosphoric acid substituted by organic ligands are used. The subsequent precipitation is carried out using oxalic acid in case of a neodymium and soda in case of a dysprosium process chain. The resulting oxalates and carbonates are then calcined in a tunnel furnace at 900°C. The combustion is calculated by ASPEN PLUS®. For dysprosium production thermal decomposition, leaching of heavy rate earth oxide with hydrochloric acid and further solvent extractions to separate dysprosium from the other HREEs are assumed [Vossenkaul]. The landfilling of tailings from beneficiation and separation is managed in a tailing storage facility. Data for construction and operation are taken from the feasibility study [GBM, 2015] also. The amount of solids and chemicals leaking from the tailings causing pollution of ground water is estimated based on U.S. standards [Board, 2010].The composition of flotation tailings is assumed to be analog to the raw ore components and flotation chemicals. The composition of leaked particles from the tailings of cracking is based on an analysis of slurry from leaching. The solubility of particles is mostly assumed to 0.05%.

RE Metal Production

The usually used fused-salt electrolysis (RENO process) is assumed for neodymium reduction from oxide. Energy demand and the amounts of electrolyte, anodes and cathodes are estimated from literature [Cheng et al., 2011], [Pang, 2011], [Zhang, 2001], [Liu, 2001]. One component of the electrolyte is neodymium fluoride (NdF_3). For its production a process described in [Gupta & Krishnamurthy, 2005] is assumed, where neodymium oxide and ammonium fluoride react in a resistance furnace at 300°C. The energy demand is adopted from the analogous production of lithium fluoride [Ecoinvent, 2012a]. The demand of chemicals and emissions are calculated according to the reaction equation with 20% stoichiometric excess. Emissions of CO and CO_2 are based on [Keller, 1998] and CF_4 emissions on an aluminum melting process from the 1990s [Chase et al.]. Furthermore a wet scrubber with an efficiency of 96% to reduce fluoride emissions is assumed [Cheng et al., 2011]. The production of dysprosium is carried out by reduction of dysprosium fluoride (DyF_3) with calcium. DyF_3 is produced analogous to NdF_3. The amount of Ca and the composition of slurry is based on literature [Sharma, 1994] and [Velu & Reddy, 2005].

II.2 Conventional Chinese System

Mining

The raw ore is mined in an open pit mining process including drilling, blasting, loading, transportation and dumping. Because the mine in Bayan Obo is originally an iron ore mine data regarding energy demand and facility are used from an iron mine [Classen et al., 2007] and modified to site specific parameters (e. g. mining rate 10E06 t/a, stripping ratio 1:1) [Qifan et al., 2010]. Due to the inhomogeneity of the huge orebody [Castor & Hedrick, 2006], [Drew et al., 1990] a weighted average is assumed for the main orebody considering 4 ore types (Tab. 3).

Tab. 3: Composition of REEs in Bayan Obo (main orebody)

Component	**ore type**				**weighted share in [%]**
	Massive REE-Fe ore	Fluorite REE-Fe ore	Riebeckite REE-Fe ore	Magnetite-dolomite	
SiO_2	4.81	2.18	10.79	8.74	**4.713**
TiO_2	0.27	0.62	0.55	0.28	**0.465**
Al_2O_3	0.22	0.66	0.83	0.74	**0.569**
Fe_2O_3	74.73	39.29	44.59	11.69	**44.919**
MnO	0.79	0.12	5.95	1.18	**0.995**
MgO	0.99	0.31	3.52	13.23	**2.848**
CaO	8.78	26.26	16.15	27.09	**20.76**
SrO	0.36	3.90	1.15	0.25	**2.112**
BaO	n.a.	n.a.	n.a.	n.a.	-
Na_2O	0.25	0.25	0.62	0.12	**0.263**
K_2O	0.09	0.08	0.92	0.58	**0.238**
P_2O_5	0.94	2.71	1.16	1.47	**1.893**
F	5.89	16.83	8.31	1.83	**10.709**
CO_2	n.a.	n.a.	n.a.	n.a.	-
SO_3	n.a.	n.a.	n.a.	n.a.	-
RE_2O_3	2.73	9.49	3.24	3.98	**6.22**
Nb_2O_5	n.a.	n.a.	n.a.	n.a.	**0.13****
LOI*	2.89	5.15	5.60	25.23	**7.79**

*Loss on Ignition,** average concentration [Drew et al., 1990] n.a. = not available

Source: Own evaluation based on [Castor & Hedrick, 2006, Drew et al., 1990] IEK-STE 2016

The composition of REO (Tab. 4) is an average of orebodies at Bayan Obo [Friedrichs, 2016].

Tab. 4: Composition of REO in Bayan Obo ore in [%]

La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Y_2O_3	sum
23.8	50.1	5.8	17.8	0.9	0.2	0.69	0.08	0.07	0.1	99.51

Source: [Friedrichs, 2016] IEK-STE 2016

Beneficiation

Beneficiation of the ore takes place in Baotou. The following processes are included: crushing, grinding, magnetic separation and flotation [Zhang, 2013]. Products of this process chain are a primary iron concentrate as well as Monazite and Bastnasite concentrates.

The crushed ore is transported 150 km by train from the mine in Bayan Obo to the processing plant in Baotou. There it is ground to a size of <74 µm by conventional wet grinding with an integrated hydro cyclone classifier [Zhang, 2013]. Separation of the ferrous magnetite is carried out by low and high magnetic separation. The ore pulp of the magnetic separation passes through a multi-stage flotation resulting in a Bastnasite and Monazite concentrate with 55.6% and 34.1% REO, respectively [Stark, 2016]. The yield for Bastnasite and Monazite concentrate amount to 12.6% and 6%, respectively [Zhang, 2013].

The calculation of the energy demand for crushing and grinding is again based on the Bond Work Index and abrasion index. Producer information is used for calculation of the energy demand for magnetic separation and flotation [Outotec, 2015]. The dust emissions during crushing are estimated by experts from RWTH Aachen University. Due to the lack of information regarding flotation chemicals, the amounts used are deduced from older sources [Yu et al., 1992].

Cracking and Separation

After flotation both concentrates are roasted using sulfuric acid (98%) in a rotary kiln. The demand of natural gas is calculated by ASPEN PLUS®, the amount of sulfuric acid and the energy demand are estimated by references [Zhang, 2013], [Krüger.J, 2001]. Flue gas from the roasting process is cleaned by spray adsorption and the waste water is purified using quick lime [Xu et al., 2008]. The remaining pollutant concentration of the cleaned flue gas is based on Chinese emission standards for the rare earth industry [MEP, 2011]. CO_2 emissions are calculated stoichiometrically considering the reaction of Bastnasite with sulfuric acid as well as combustion of natural gas in the rotary kiln.

After roasting the RE sulfates are leached with water and sulfuric acid and then filtrated [Xu et al., 2008]. By addition of water and ammonium bicarbonate RE carbonates are precipitated [Xu et al., 2008]. By further addition of water and hydrochloric acid the precipitated RE carbonates are converted into RE chloride solution. The demand of ammonium bicarbonate and sulfuric acid is based on the content of ammonia and sulfate in the waste water [Xu et al., 2008]. The amount of hydrochloric acid considers a pH 4 adjustment and the assumption of an entire reaction of carbonate into CO_2.

The subsequent solvent extraction steps are the same as assumed for Norra Kärr. The energy demand, the chemicals used and the waste water produced are adapted to the REE composition. Also, the subsequent processes for the production of neodymium and dysprosium metals are the same as for Eudialyte. Only the electricity and natural gas mixes differ. However, the flue gas cleaning of the electrolysis and fluoride production have lower efficiencies as in Sweden.

The tailings from beneficiation and hydrometallurgical processes (without leaching) as well as the flue gas cleaning residues are stored in a tailing pond [Qifan et al., 2010]. The tailings from leaching are stored separately in the radioactive storage facility. The composition of tailings is derived from raw ore composition as well as from pollutant concentration in flue gas and waste water. For the calculation of environmental effects caused by storage processes a leakage of dissolved solids into soil is assumed (dissolubility 0.05% is assumed). The rate of leakage is estimated by references [GBM, 2015, Huang et al., 2014].

III Life Cycle Assessment

LCA is an adequate method for a holistic evaluation of environmental effects. It is well-established, internationally acknowledged, and defined in the ISO standards 14040 [(ISO), 2006a] and 14044 [(ISO), 2006b]. Within LCA all energy and material flows that occur during processing, production, operation, and end of life of products or systems are quantified and evaluated in terms of environmental impacts. LCA distinguish between four stages:

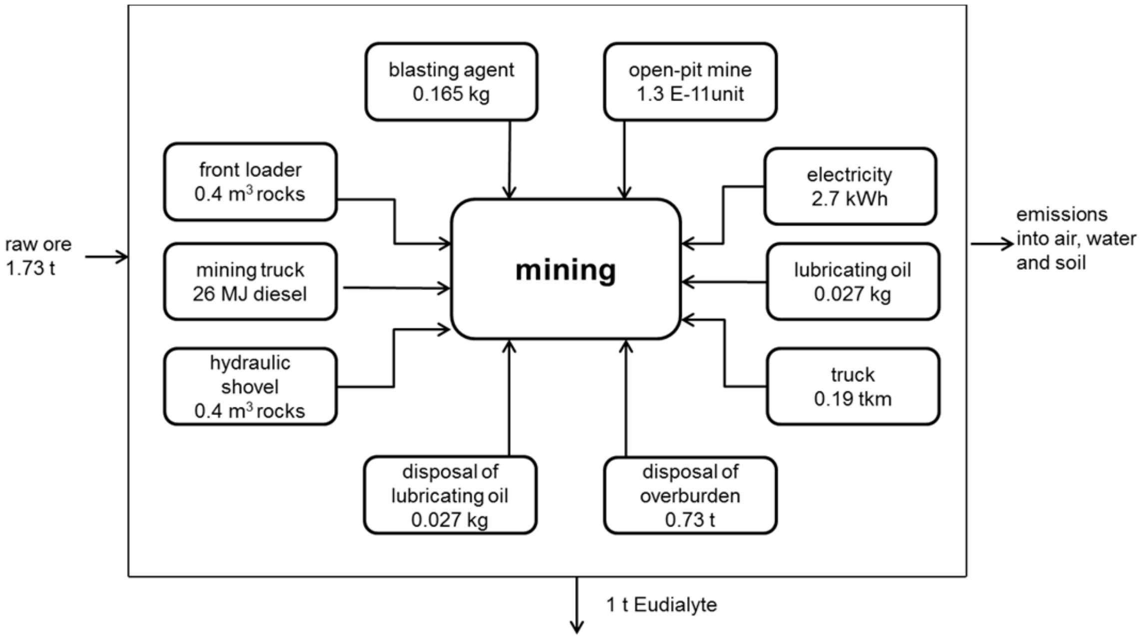
- The Goal and Scope Definition describes the main purpose of the analysis. The investigated system is described and the functional unit is defined, which is the basis for the comparison. The considered environmental effects are selected.
- In the Life Cycle Inventory (LCI) all relevant inputs and outputs (resources, material, energy, emissions, waste) of the investigated system are collected.
- During the Life Cycle Impact Assessment (LCIA) the gathered inputs and outputs of the system are translated into environmental effects, so called impact categories. In order to gain a better understanding of the relative importance of an environmental effect a normalization step should complete the LCIA. Each effect calculated for the life cycle is benchmarked against the known total effect of a reference system, such as the total impacts of a specific region (e. g. EU, world, specific country) or the contribution of a single person to this impact. So every impact category is translated into relative contributions. Thereby the different environmental impacts (e. g. global warming, acidification, eutrophication) are comparable.
- The Interpretation as the final step summarizes the results from the LCI and LCIA.

The software used for modelling and analyzing the whole production chain of neodymium and dysprosium is GaBi6 [GaBi, 2015]. Many of the data for the Eudialyte process chain are based on laboratory experiments. The data for Bayan Obo are collected from literature. Data of auxiliary processes (e. g. energy supply and chemical production used for the main production chain of REE) come from either the GaBi6 [GaBi, 2015] or Ecoinvent 2.2 [Ecoinvent, 2012b] database.

III.1 LCA – Goal and Scope Definition

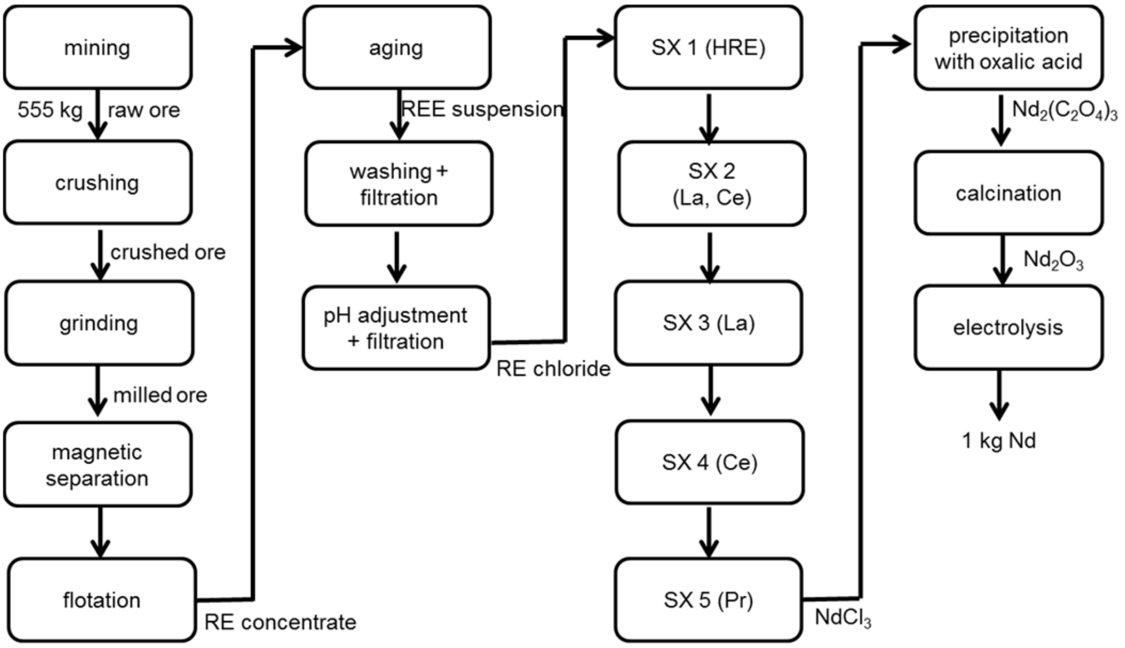
The goal of this investigation is to assess environmental impacts related to the production of neodymium and dysprosium from the Eudialyte deposit in Norra Kärr (Sweden; Fig. 2 and Fig. 3) and to compare them to those of conventional production routes from the iron mine in Bayan Obo (China; Fig. 4, Fig. 5). The functional unit of the investigation is therefore ’1 kg neodymium’ and ‘1 kg dysprosium’, respectively. In principle the workflow is very similar. The main process chains start always with mining, crushing, milling, magnetic separation, and flotation. Then in case of the new European process route an aging process with hydrochloride acid follows, whereas in Bayan Obo roasting is the next process. After several leaching and washing steps similar, intricate solvent extraction procedure follows. For calculation of the neodymium life cycle inventory 9 real solvent extraction steps (SX) are aggregated to 5 SX to reduce the complexity of modeling. The description in brackets in the figures refers to the elements separated in each SX step. Next to SX a precipitation with oxalic acid, a calcination to form an oxide and electrolysis to reduce the neodymium oxide to the metal follow. After the first SX step the production of dysprosium varies from that of neodymium. A precipitation with soda, calcination, a conversion to dysprosium fluoride and its reduction with calcium to dysprosium takes place. All transports per truck, trail and ship as well as energy and material supply for the main process chains (Fig. 2 – Fig. 5) are included also. According to all assumptions and data each single process/box in Fig. 2 – Fig. 5 is modelled analog to Fig. 1, serving as an example for all other single processes/boxes. In **Fehler! Verweisquelle konnte nicht gefunden werden.**all inputs necessary for the mining process are shown. As outputs all emissions into the environment are accounted. Inputs and outputs are related to the main output of this specific process (here 1 t Eudialyte mined). In this example for the mining of 1 t Eudialyte 0.156 kg blasting agent, 2.7 kWh electricity, 0.19 tkm by truck, 0.4 m^3 rock transported by front loader and hydraulic shovel etc. are needed (Fig. 1). Afterwards all single processes are combined to an entire process chain and all inputs and outputs are added accordingly using GaBi6 [GaBi, 2015]. For the entire process chain the functional unit is then either 1 kg Nd or 1 kg Dy (Fig.2 – Fig. 5).

Fig. 1: Mining of Eudialyte



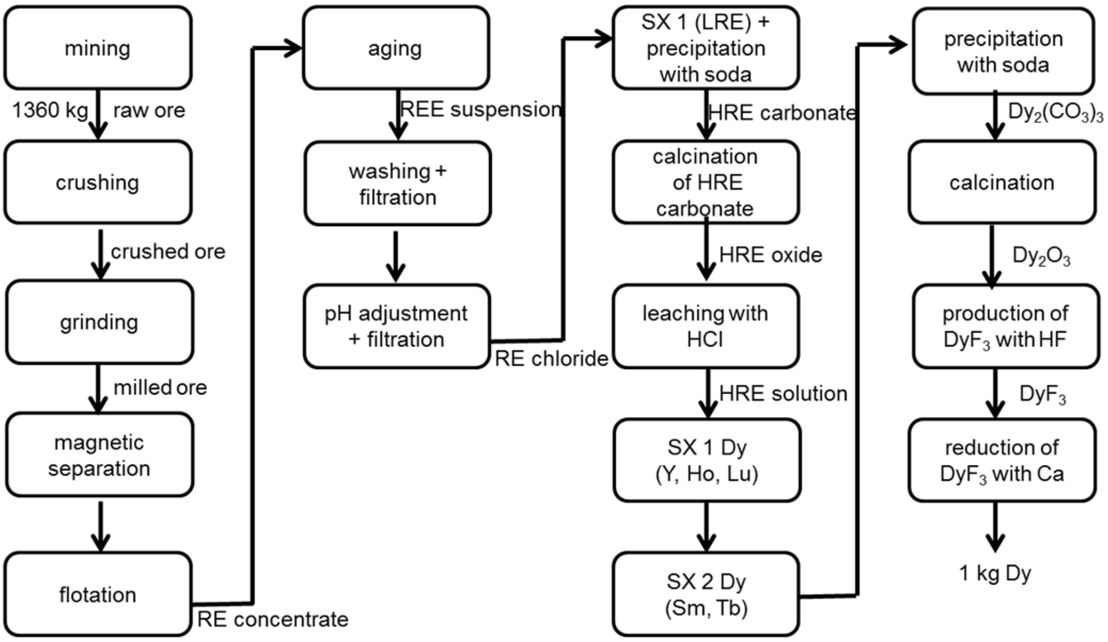
Source: Own diagram IEK-STE 2016

Fig. 2: Process chain of the production of 1 kg neodymium (allocated) based on Eudialyte



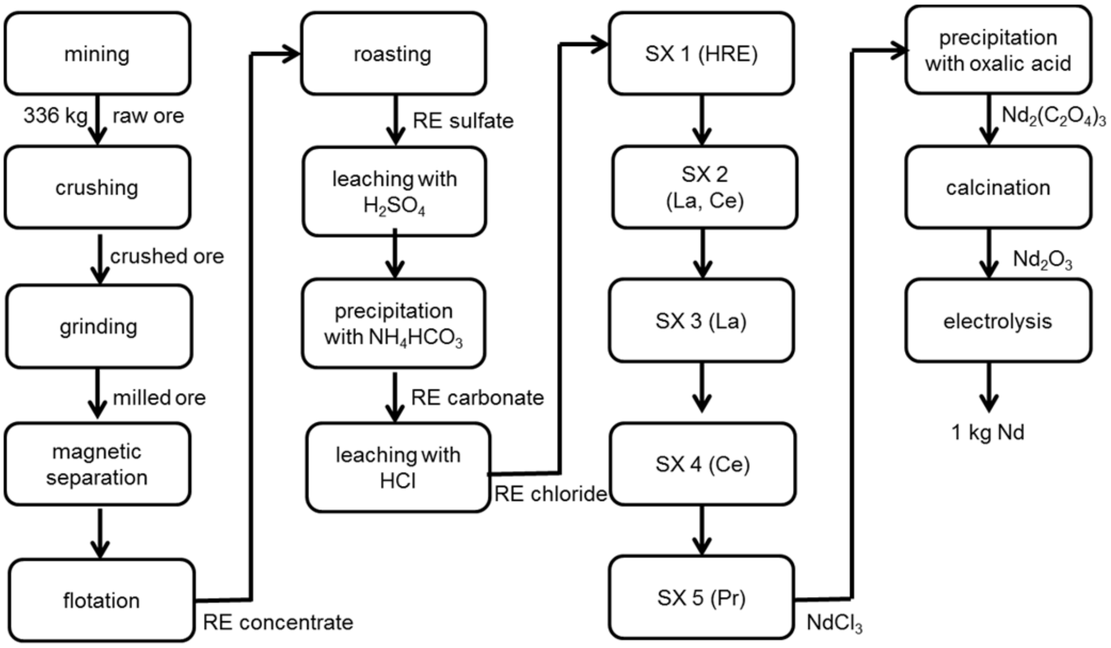
Source: Own diagram IEK-STE 2016

Fig. 3: Process chain of the production of 1 kg dysprosium (allocated) based on Eudialyte



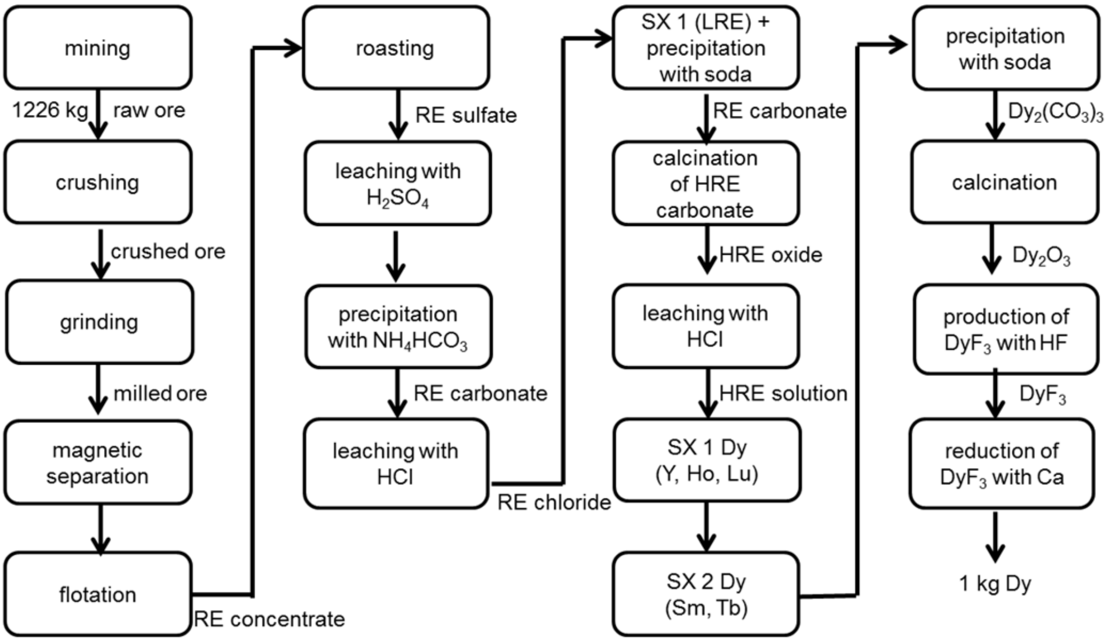
Source: Own diagram IEK-STE 2016

Fig. 4: Process chain of the production of 1 kg neodymium (allocated) in Bayan Obo



Source: Own diagram IEK-STE 2016

Fig. 5: Process chain of the production of 1 kg dysprosium (allocated) in Bayan Obo



Source: Own diagram IEK-STE 2016

Since the production of REE is a multi-product system due to the strong paragenesis of the REEs the environmental burdens have to be allocated appropriately. This means that for example the energy demand or the particulate matters emitted during mining are divided between the products, considering the causer principle. Different allocations methods exist, addressing this causer principle. In this study an allocation method based on the mass of the produced REEs combined with their market prices [Asianmetals, 2015] from an international metals market analysis and pricing index company in June 2015) were considered, typically used for multi-component ores. As the ores have different compositions and components, the allocation factor has to be assessed individually for each site. Tab. 5 shows the prices assumed (third column), and the resulting allocation factors calculated for each SX step. Allocation factors for lanthanum, cerium, neodymium and praseodymium are very similar for the Chinese and Eudialyte based production routes. However the amount of HREEs in Eudialyte is much higher and therefore the resulting allocation factors vary widely.

The selection of impact categories is widely based on the ILCD recommendations [European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2011] as implemented into GaBi6 [GaBi, 2015] and is listed in Tab. 6**Fehler! Verweisquelle konnte nicht gefunden werden.**. For all impact categories the ReCiPe 1.08 midpoint (H) method [Goedkoop, 2009] were used to carry out a normalization step based on a consistent reference unit (‘ReCiPe person equivalent, world’ means the average annual share of a person contributing to an environmental impact). No environmental effect is prioritized in its importance, so that no weighing between the impact categories is necessary.

Tab. 5: Allocation factors of neodymium and dysprosium for Norra Kärr (NK) and Bayan Obo (BO)

SX[1]	Product	Price $/kg	NK-Nd	NK-Dy	BO-Nd	BO-Dy
SX 1	HREEs	40.87[2]	67.3	70.5	4.0	4.6
SX 2	La/Ce	1.12[3]	1.4	-	2.1	-
SX 3	Ce	3.39	2.8	-	4.1	-
SX 4	La	3.95	1.8	-	2.7	-
SX 5	Nd/Pr	94.21 Pr 56.55 Nd	66.6 / 33.4	-	66.6 / 33.4	-
SX1 Dy	Y/Ho/Lu[4]	40.87	-	61.1	-	5.6
SX2 Dy	Sm/Tb[5]	30.41	-	21.1	-	82.4

[1] SX = solvent extraction; [2] price of YEu oxide mixture; [3] La/Ce-chloride; [4] the price of YEu oxide mixture is also assumed for yttrium/holmium/lutetium carbonate; [5] for samarium/terbium carbonate the price of a samarium/europium/gadolinium oxide mixture is assumed [Asianmetals, 2015]

Source: own evaluation based on [Asianmetals, 2015] IEK-STE 2016

Tab. 6: Overwiew of investigated ReCiPe impact categories

Impact category	Abbreviation	Unit
Resources demand, fossil	RD	kg oil-eqv.
Global Warming Potential	GWP	kg CO_2-eqv.
Acidification Potential	AP	kg SO_2-eqv.
Eutrophication, freshwater	EP	kg P-eqv.
Ozone Depletion Potential	ODP	kg CFC-11-eqv.[1]
Photochemical Ozone Formation	POCP	kg NMVOC-eqv.[2]
Human Toxicity	HTP	kg 1,4-DB-eqv.[3]
Ecotoxicity - terrestrial	ETP_{terr}	kg 1,4-DB-eqv.
Ecotoxicity - aquatic, freshwater	ETP_{aq}	kg 1,4-DB-eqv.
Ionizing Radiation	IR	kg U235-eqv.
Particulate Matter	PM	kg PM10-eqv.

[1] CFC-11: Trichlorofluoromethane; [2] NMVOC: non-methane volatile organic compound; [3] 1,4-Dichlorobenzole

Source: [European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2011] IEK-STE 2016

III.2 Life Cycle Inventory, LCI

In the LCI the main energy and material inputs and outputs are summed up (Tab. 7) after every single process of Fig. 2 - Fig. 5 has been assembled with corresponding data. The values for the two RE materials as well as for both production sites are very different regarding the amounts and types of material and energy. For example, the dysprosium production based on Eudialyte uses the highest amount of energy resources, process water, caustic soda, hydrochloric acid and transport service due to the highest amount of raw ore mined. On the other hand most of the emissions released have their highest values at Bayan Obo (e. g. HF, NMVOC, heavy metals into air, radioactive emissions into air) due to poor process control as well as hardly existing waste and sludge treatment. Due to the roasting process the facilities in Bayan Obo use great amounts of sulfuric acid but lower amounts of hydrochloric acid than in Norra Kärr. However hydrochloric acid is the main input in Norra Kärr due to the aging process instead of roasting. The amount of lithium fluoride (LiF) is almost 1000 times higher for neodymium production in China than in Norra Kärr due to the assumed better process control and re-use of LiF and NdF_3 by dust recycling during electrolysis in Norra Kärr. Ammonia, calcium chloride and calcium are mainly used for the production of dysprosium fluoride and the reduction to dysprosium. Therefore the amounts of these three chemicals are higher for dysprosium production than for neodymium. Altogether almost all inputs and outputs for Dy production are higher than for Nd due to the allocation described above.

Tab. 7: Main inputs and outputs of the process chains per kg neodymium and dysprosium

	unit	NK-Nd	NK-Dy	BO-Nd	BO-Dy
Inputs					
Primary energy resources	MJ	1907	4075	1404	3707
Transport service, lorry	tkm	21.4	45.1	6.3	14.6
Transport service, rail	tkm	-	-	60.6	204
Process water	kg	325	784	118	136
Lubricating oil	kg	0.015	0.036	0.011	0.038
Polypropylene	kg	0.003	0.007	-	-
Caustic soda solution (50%)	kg	12.4	20.0	6.72	16.11
Hydrochloric acid (32%)	kg	136.7	310.0	30.8	81.5
Sulfuric acid (96%)	kg	1.25	3.06	19.8	69.91
Soda	kg	2.95	4.32	3.21	2.41
Oxalic acid	kg	2.06	2.13	1.85	0.299
Lithium fluoride	g	0.008	-	10	-
Ammonium hydrogen carbonate	g	0.154	-	7.93	27.94
Ammonia	kg	$2.2*10^{-5}$	0.42	1.8	6.76
Calcium chloride	kg	-	0.85	0.009	0.88
Calcium	kg	-	0.4	-	0.4
Hydrogen fluoride	kg	$5.14*10^{-5}$	0.982	0.078	0.982

Continuation Tab.7

	unit	NK-Nd	NK-Dy	BO-Nd	BO-Dy
Inputs					
Graphite	kg	0.135	-	0.285	-
Lime	kg	-	37.88	20.4	37.7
Steel	kg	0.9	2.3	0.4	1.4
Magnesium oxide	kg	3.84	9.40	0.25	0.88
Sodium phosphate	kg	0.875	2.144	-	-
Sodium silicate	kg	-	-	0.224	0.79
Sodium sulfate	kg	0.011	-	0.017	-
Phosphoric acid	kg	0.195	0.442	0.049	0.175
Calcium chloride	kg	-	0.853	0.009	0.877
Kerosene	kg	0.5	0.8	0.02	0.6
Diesel	kg	-	-	0.32	1.07
Other inorganic chemicals	kg	0.087	-	11.3	39.4
Other organic chemicals	kg	0.20	0.44	0.14	0.505
Outputs					
HF	g	5.4	54	162	1320
CO_2	kg	247	522	96.3	289
CO	kg	0.695	0.585	0.338	0.785
SO_2	kg	0.268	0.686	0.751	2.33
NO_x	kg	0.437	1.069	0.302	0.878
NMVOC	kg	0.090	0.186	0.201	0.511
Methane	kg	0.389	0.855	0.371	1.158
Particles into air	kg	1.46	3.63	1.95	4.42
Radioactive emissions into air	Bq	$1.3*10^{-6}$	$2.8*10^{-6}$	$8.9*10^{-6}$	$2.7*10\text{-}^{5}$
Heavy metal into air	g	0. 479	1.5	1.22	3.48
Heavy metal into water	kg	0.118	0.257	0.110	0.256
Inorganic emissions into water	kg	15.9	30.34	15.41	48.83
Organic emissions into water	kg	0.075	0.157	0.020	0.057
Inorganic and organic emissions into salt water	kg	431.5	450.63	3.13	9.49

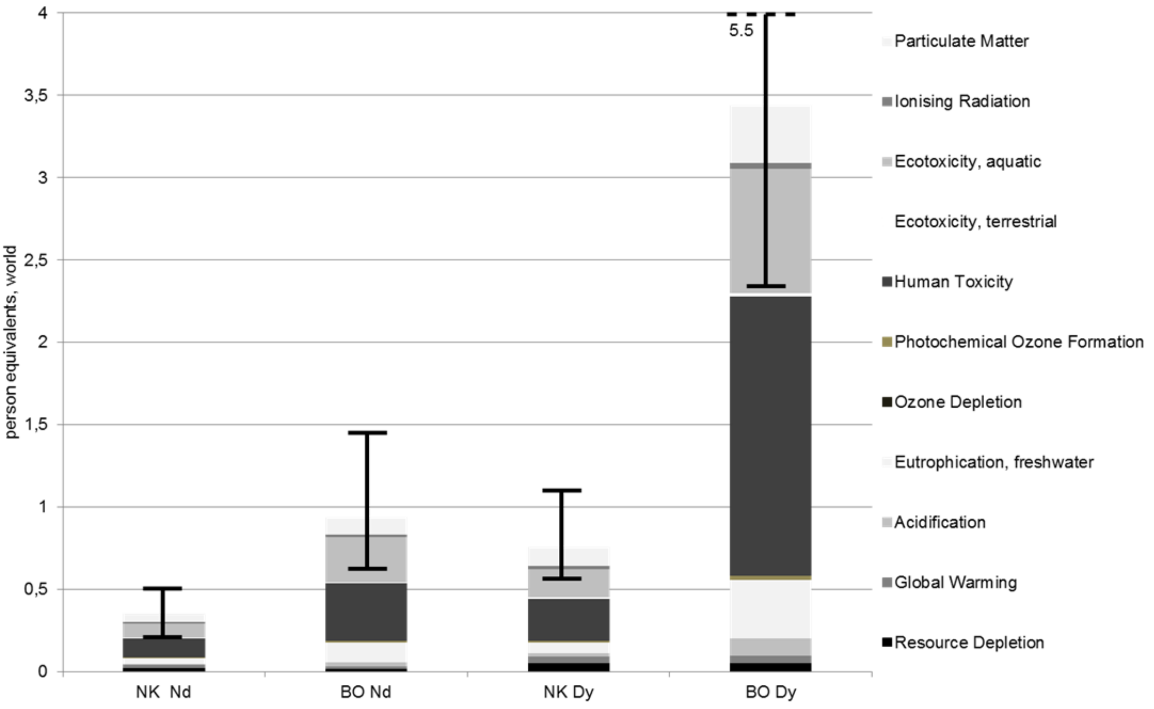
Source: own evaluations IEK-STE 2016

III.3 Life Cycle Impact Assessment

The gathered inputs and outputs are allocated to specific environmental effects. To classify the importance of the various effects, each is related to the average annual share a person contributes to this environmental impact worldwide, in the normalization step. Hence, Fig. 6

shows the summarized results for each production chain in terms of normalized impacts (inclusive error bars, see chapter 3.4, Tab. 8) in person equivalents related to the functional unit. The production of neodymium and dysprosium based on Eudialyte in Sweden is much less polluting than in Bayan Obo, although the amounts of raw ore needed per kg neodymium and dysprosium are higher for Eudialyte (Fig. 2 – Fig. 5). The impacts for the new European neodymium production only amount to approx. 40% of the impacts occurring in Bayan Obo. Especially for dysprosium, the results of the Eudialyte based production show a considerable advantage against the production in Bayan Obo due to the higher content of HREEs in the Eudialyte mineral. The impacts for the new European dysprosium production only amount to approx. 20% of the impacts of Bayan Obo.

Fig. 6: Normalized impacts for the production of 1 kg neodymium and dysprosium in Norra Kärr and Bayan Obo

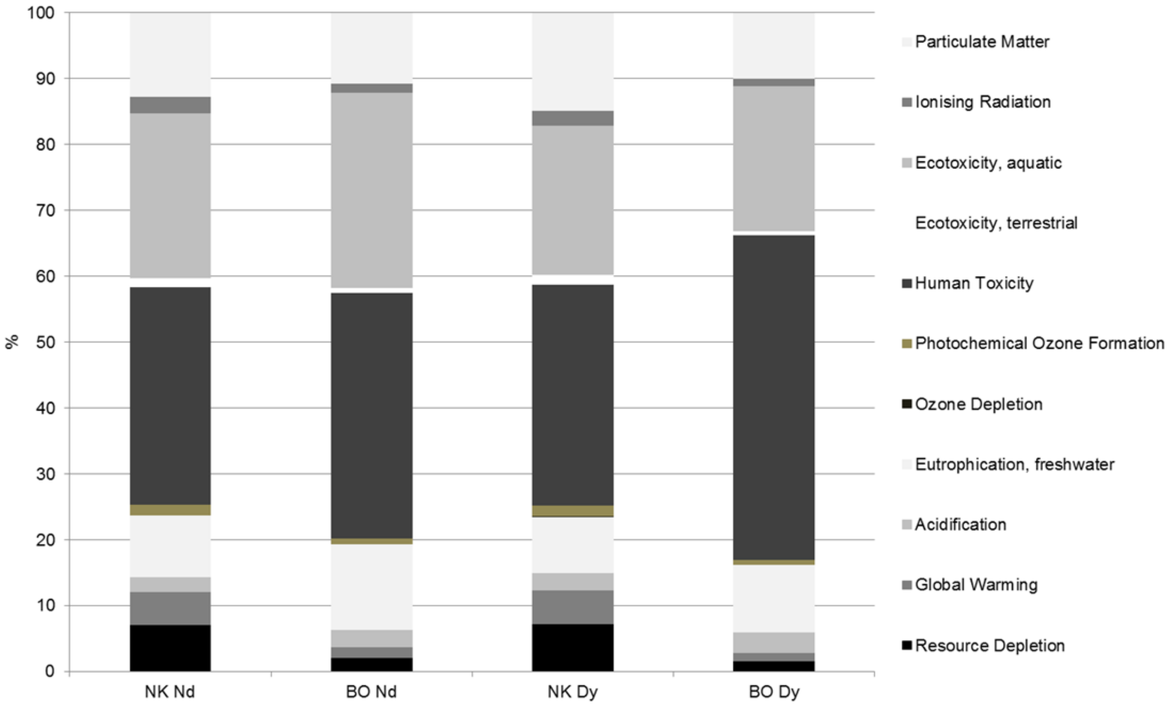


Source: Own evaluation IEK-STE 2016

If the values are plotted in relative numbers (%) (Fig. 7**Fehler! Verweisquelle konnte nicht gefunden werden.**), the various importance of the different environmental impacts becomes even more visible. The main impact categories are human toxicity, ecotoxicity (aquatic), particulate matter, and eutrophication followed by resource depletion and global warming at both production sites (Fig. 7**Fehler! Verweisquelle konnte nicht gefunden werden.**). The share of human toxicity amounts to 33 – 49% of the total impacts. Human toxicity is predominately caused by emissions during production of chemicals (e. g. hydrochloric acid, hydrofluoric acid, extracting agents) used for aging, precipitation, and solvent extraction. Also heavy metal emissions into water during waste water treatment and hydrofluoric acid emissions during production of DyF_3 contribute to this effect. The latter are much lower for dysprosium production in Sweden due to an assumed enhanced flue gas cleaning during DyF_3 production.

Aquatic ecotoxicity follows with a share of 22 – 30% on the total impacts and is largely caused by heavy metal emissions during waste water and sludge treatment. The share of particulate matter lies between 10 – 15% and is higher for the Eudialyte based production although the absolute values are much smaller. The reason for the smaller relative share of particulate matter in Bayan Obo is the particularly high importance of human toxicity. Although Bayan Obo has a lower stripping rate and therefore less raw ore has to be broken per kg neodymium and dysprosium, the dust emissions per kg broken ore are much higher due to the higher hardness grade of the Bayan Obo ore (iron ore mine). Furthermore the Chinese electrolysis has much higher dust emissions than the electrolysis in Norra Kärr due to the assumed optimized process control there (Fig. 8)**Fehler! Verweisquelle konnte nicht gefunden werden.**. The share of eutrophication accounts for 9 – 13% and is mostly induced by phosphoric emissions (e. g. P_2O_5, phosphor, phosphate) during waste water and sludge treatment. The share of all waste water and sludge treatment processes along the whole process chain on the total human toxicity, ecotoxicity (aquatic) and eutrophication impacts adds up to approx. 30 – 50%.

Fig. 7: Comparison of relative impacts for the production of 1 kg neodymium and dysprosium in Norra Kärr and Bayan Obo

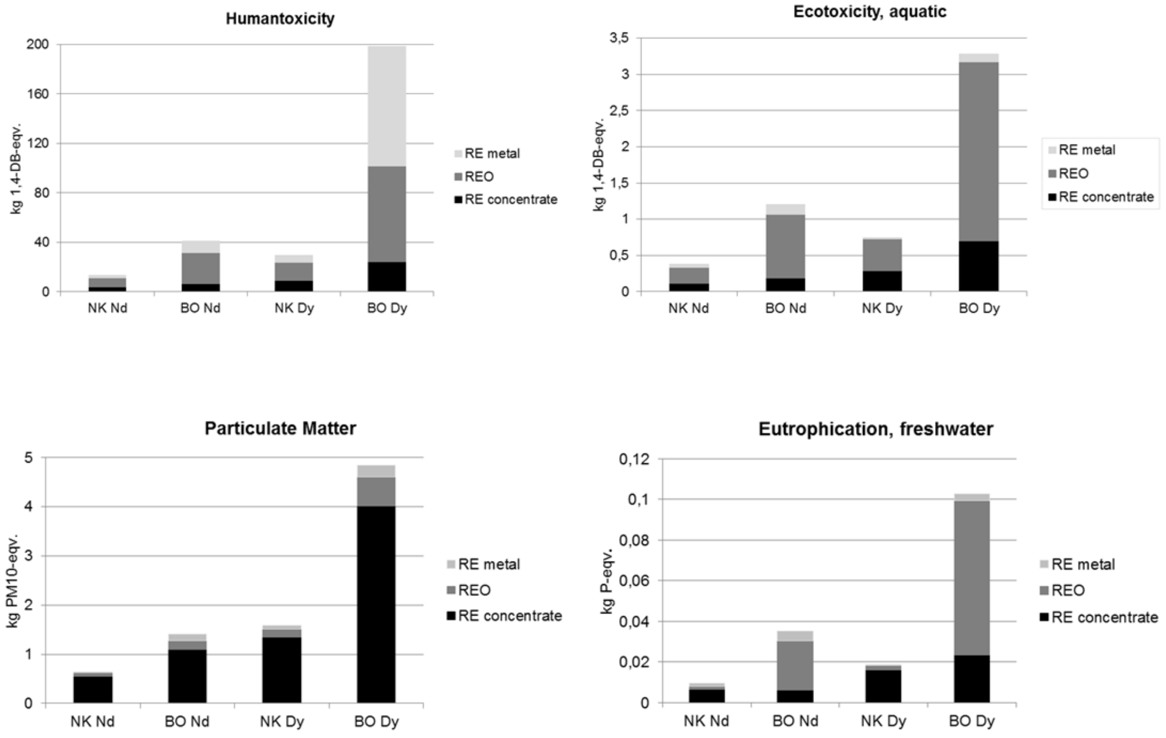


Source: Own evaluation IEK-STE 2016

The share of the other impacts on the total environmental burdens is always smaller than 3%. Although mining of REE is always associated with Thorium, ionizing radiation is hardly visible. The reason for that is the assumed safe storage of tailings in the ponds. Only if a damaging event (e. g. earthquake, dam failure) occurs, the radioactive emissions would be released.

Fig. 8 shows the share of three process chain segments (1. mining - flotation (REO concentrate); 2. roasting/aging - calcination (REO); 3. Nd/Dy reduction (RE metal)) for the four highest impact categories. In the case of human toxicity, ecotoxicity and eutrophication the share of REO production (all processes between aging/roasting and calcination) is the biggest due to the high amount of chemicals used, the emissions into water as well as the waste and sludge treatment processes. For particulate matter the first process chain segment (all processes between mining and flotation) is the most important one due to the dust emission mostly during crushing. In case of human toxicity also the particularly high HF emissions during DyF_3 for the reduction process are main causer in the third process chain segment for Dy production in Bayan Obo.

Fig. 8: Environmental impacts of Nd and Dy production in Norra Kärr and Bayan Obo



Humantoxicity

Ecotoxicity, aquatic

Particulate Matter

Eutrophication, freshwater

Source: Own evaluation IEK-STE 2016

III.4 Data Quality

To determine the quality of the results each single process in the process chain is assigned with a data quality indicator (DQ) between DQ1 – DQ5, whereat DQ1 is the best quality (measured data) and DQ5 has the worst quality (rough estimations). DQ1 was not given to any process, because no measures were conducted at the production sites in Norra Kärr and Bayan Obo. Tab. 8 presents the average data qualities for each impact category of the 4 process chains. The most occurring DQs are marked by the darkest shade. The impacts of the

Eudialyte based process chains are mostly derived from processes with DQ2 and DQ3 whereas the impacts of the Bayan Obo process chains largely originated from processes with DQ3 and DQ4. For example, 78% of the data used for the assessment of resource depletion are characterized by DQ2 in case of Norra Kärr for Nd and Dy respectively, but only 2% of the data in case of Bayan Obo Dy (zero for Nd). The different impact categories present no consistent pattern regarding data quality. Generally, the toxicity categories rely on processes with low data qualities. However, as discussed before, those are the categories which contribute most to the overall effects.

Tab. 4: Share of data qualities for the different impact categories for the 4 process chains in [%]

	NK Nd				NK Dy				BO Nd				BO Dy			
Impact	**DQ 2**	**DQ 3**	**DQ 4**	**DQ 5**	**DQ 2**	**DQ 3**	**DQ 4**	**DQ 5**	**DQ 2**	**DQ 3**	**DQ 4**	**DQ 5**	**DQ 2**	**DQ 3**	**DQ 4**	**DQ 5**
RD	78	6	2	14	78	10	2	10	0	27	41	33	2	22	40	36
GWP	72	8	1	19	73	11	1	16	0	91	4	5	2	27	28	43
AP	72	4	14	10	59	14	13	15	0	31	52	16	3	49	31	16
EP	23	7	1	70	28	10	1	61	5	19	42	35	6	19	34	40
ODP	13	29	1	57	18	35	2	46	0	5	51	44	0	6	45	48
POCP	67	9	14	9	62	7	15	15	0	43	38	20	13	33	28	27
HTP	42	20	1	38	44	36	1	19	2	14	53	31	2	55	21	22
ETP_{terr}	11	73	0	16	12	76	1	12	0	8	46	46	1	10	34	55
ETP_{aq}	27	40	1	32	32	50	1	17	1	13	42	45	1	14	37	47
IR	84	5	1	11	85	7	1	8	1	9	54	37	1	12	43	44
PM	94	3	2	2	90	4	2	4	35	48	14	3	41	48	6	5

Source: own evaluation IEK-STE 2016

Hence the following averaged variations are calculated: NK/Nd -25 to +43, NK/Dy -24 to +40, BO/Nd -32 to +58, BO/Dy -33 to +60. The corresponding error bars are shown in Fig. 6. The differences between neodymium and dysprosium produced along a production chain are small in contrast to the process chains at different sites. The results for the European production are associated with a lower variation than the results of Bayan Obo. Overall the data quality of this study is moderate due to the lack of knowledge for Chinese production sites and due to the fictitious process chain based on Eudialyte.

IV Interpretation and Conclusion

From a technical point of view the creation of a solely European supply route is possible. Several specific studies have proven this approach. Beside the desired weakening of economic dependence from a Chinese supply also environmental advantages can be achieved by replacing the production route. Especially due to a better emission control and waste and sludge treatment caused by a stricter environmental legislation in Sweden the normalized total value of effects per kg LREEs can be reduced by approx. 60%. This effect becomes even more prominent for the HREEs. Here a reduction of approx. 80% can be reached in comparison to a Chinese production. With the high share of HREEs the Eudialyte ore has an additional advantage over the Bastnasite and Monazite based Bayan Obo ore. However, it has to be kept in mind, that most of the Chinese Dy originates from other sources (mostly Ion Adsorption Clays) than Bayan Obo. However the production from Ion Adsorption Clays is not considered in this study.

Even with this very different composition of the two ores and the different production routes necessary, the environmental effects which are stressed are the same. Although the absolute figures vary significantly between the production sites and also between the RE-metals processed, human toxicity is always the dominant environmental impact, followed by aquatic ecotoxicity, particulate matter and eutrophication. While particulate matter is mostly related to emissions during mining and beneficiation, human toxicity and ecotoxicity as well as eutrophication is caused during beneficiation and separation of REOs. Here waste water as well as waste and sludge treatment processes are the biggest causer. Also during the production of chemicals emissions with human toxicity impacts occur. For Dy reduction DyF_3 is necessary, which production in China is causing high amounts of toxic emissions for humans. A flue gas treatment as assumed for the Swedish DyF_3 production can reduce this effect drastically. Stricter environmental legislation on waste treatment, but also on emission control in Sweden reduces the absolute environmental effects caused directly during processing. But also the supply of operating materials, as in case of the chemicals or energy supply, is more environmentally friendly and therefore contributes to the high overall difference between the two production sites.

This enormous difference is striking when the different level of maturity is considered also. Although Bayan Obo is originally an iron ore mine the RE production has been optimized for several years now. The production route of Eudialyte has only been tested in laboratory scale with no overall optimization of the processes or any reuse option of chemicals. So the environmental performance could be further improved by process optimization and adjustment. On the other hand data sources and quality for China are assumed to be much worse than up-scaled data for laboratory scale for Eudialyte. Whether promised improvement and stricter control of environmental performance, as announced by the Chinese government has already been put into action is not known. The figures used in this study are all based on the few studies available.

So far, the assessment of the European process chain is focused on the production of REEs only. As in case of the (additional) iron production in Bayan Obo, other minerals occur in the Norra Kärr ore. An additional production of further products the expenses from mining and beneficiation can be allocated to more products and therefore decrease the specific amount per kg product. The other process chain segments stay the same.

However, it is most likely, that a European production route with its high standards will yield in considerable higher costs. Also, the much higher demand for chemicals due to lower ore quality will determine production costs. As the price for Chinese Nd and Dy has decreased drastically in the last years, it is doubtful that production in Norra Kärr will start shortly. Eudialyte stays an option for decrease of dependence supply with high environmental benefits, but market conditions will regulate its use.

V Acknoledgement

We kindly thank the SIEMENS AG for their significant financial support in the years 2012-2015 allowing us to conduct the collaborative research center ´rare earths – green mining and separation´ combining five institutes of the RWTH Aachen University and the Forschungszentrum Jülich.

VI References

(ISO), I. O. F. S. (2006a) ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework.

(ISO), I. O. F. S. (2006b) ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

ALTHAUS, H. J., CHUDACOFF, M., HISCHIER, R., JUNGBLUTH, N., OSSES, M. & PRIMAS, A. (2007) *Lifecycle Inventories of Chemicals. Phosphate Rock. Final Report Ecoinvent data v 2.0 No.8*. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

ASIANMETALS (2015). www.asianmetals.com.

BOARD, C. R. W. Q. C. (2010) Board Order NO. R6V-2010-0047 Revised Monitoring and Reporting Program. Lahontan Region.

CASTOR, S. B. & HEDRICK, J. B. (2006) Rare Earth Elements. *Industrial minerals and Rocks,* 7**,** 769-792.

CHASE, R., GIBSON, R. & MARKS, J. *PFC emissions performance for the global primary aluminum industry*. Light Metals 2005, 134th TMS Annual Meeting, San Francisco, Feb 13-17, 2005

CHENG, Y., LIANG, Y. & TAO, D. (2011) Clean Production Technology in Electrolysis Process in a Rare Earth Plant. *Chinase Rare Earth,* 32:5**,** 92 - 96.

CLASSEN, M., ALTHAUS, H. J., BLASER, S., SCHARNHORST, W., TUCHSCHMID, M., JUNGBLUTH, N. & EMMENEGGER, M. F. (2007) *Life cycle Inventories of Metals.Part II Iron and Steel. Final report ecoinvent data v2.0 No 10* EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

DNV (2010) *Technical Report No EP029020, Quantitative Risk Assessment Study of Proposed Advanced Material Plant within the Gebeng Industrial Estate, Kuantan, Pahang*. Kuala Lumpur, Malaysia.

DREW, L. J., QINGRUN, M. & WEIJUN, S. (1990) The Bayan Obo iron-rare-earth-niobium deposits, Inner Mongoia, China. *Lithos,* 26**,** 43-65.

ECOINVENT (2012a) Datenbank des Swiss Centre for LCI.

ECOINVENT (2012b) Datenbank für Ökobilanzdaten. *Swiss Center for Life Cycle Inventory, St. Gallen, Schweiz,* Version 2.2.

EUROPEAN COMMISSION - JOINT RESEARCH CENTRE - INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY (2011) International Reference Life Cycle Data System (ILCD) Handbook - Recommendations for Life Cycle

Impact Assessment in the European context. Luxemburg, Publications Office of the European Union.

FRIEDRICHS, P. (2016) *Development of a Rare Earth Element Resource Database Management System*. RWTH Aachen, planned dissertation.

GABI (2015) GaBi 6.0 (Ganzheitliche Bilanzierung) Software https://www.thinkstep.com/software/gabi-lca.

GATES, P. A., HARLACHER, C. & REED, G. (2012) *Perliminary Economic Assessment NI 43-101 Technical Report for the Norra Kärr (REE-Y-Zr) Deposit Gränna Sweden* Pincock Allen & Holt, Lakewood, Colorado.

GBM (2015) *Preafisibility Study -NI43-101-Technical report for the Norra Kärr Rare Earth Element Deposit*.

GOEDKOOP, M., HEIJUNGS, R., HUIJBREGTS, M.A.J., DE SCHRYVER, A., STRUIJS, J., VAN ZELM, R. (2009) *ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors, first edition*.

GUPTA, C. K. & KRISHNAMURTHY, N. (2005) *Extractive metallurgy of rare earth*. CRC Press.

HUANG, X., CAO, G., LIU, J., PROMMER, H. & ZHENG, C. (2014) Reactive transport modeling of thorium in a cloud computing environment. *Journal of Geochemical Exploration*.

KELLER, R. (1998) Electrolytic Production of Neodymium With and without Emission of Greenhouse Gases. *Electrochemical Society Proceedings,* 97-28**,** 143 -145.

KIPPENBERGER, C.-M. *Stoffmengenflüsse und Energiebedarf bei der Gewinnung ausgewählter mineralischer Rohstoffe- Auswertende Zusammenfassung*.

KRÜGER.J (2001) *Sachbilanz Zink*. Institut für Metallhüttenkunde und Elektrometallurgie der RWTH Aachen, Aachen.

LIU, K. (2001) Analysis of anodic gases in neodymium electrolysis. *Chinese Journal of Nonferrous Metals,* 11:6**,** 1118-1121.

MBE (2015). http://www.mbecoalandmineral.in/magnetic_separator.php.

MEP (2011) Emission Standards of Pullutants from Rare Earth Industry. Ministry of Environmental Protection Beijing.

OUTOTEC (2015). http://www.outotec.com/ImageVaultFiles/id_794/d_1/cf_2/OTE_Outotec_OK-R_and_OK-U_flotation_cells_eng_web.PDF

PANG, S. (2011) Development on Molten Salt Electrolytic Methods and Technology for Preparing Rare Earth Metals and Alloys in China. *Chinese Journal of Rare Metals,* 35:3**,** 440-450.

QIFAN, W., HUA, L., CHENGHUI, M., SHUNPING, Z., XINHUA, Z., SHENGQING, X. & HONGYAN, W. (2010) The Use and Management of NORM Residues in Processing Bayab Obo Ores in China. *Naturally Occuring Radioactive Material.* Marrakesh, IAEA.

SHARMA (1994) Metallothermic reduction of Rare Earth fluorides. General Motors 5314526.

STARK, T. (2016) *Aufbereitung von Eudialyt und anderen Seltenerdmineralen mit Fokus auf Korngrößen unter 20 µm*. RWTH Aachen, planned dissertation.

USGS (2013) *USGS Mineral Yearbook 2013*. http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/index.html.

VELU, P. T. & REDDY, R. G. (2005) Calciothermic reduction of neodymium fluoride. *Light metals* 2005**,** 1155-1159.

VOSSENKAUL, D. *Entwicklung eines Aufschlussverfahrens zur Gewinnung seltener Erdelemente aus Eudialyt*. RWTH Aachen, planned dissertation.

XU, Y., GUO, W., MA, Y., XU, H., HU, W. & QIAO, J. (2008) Treatment and Utilization of Wastewater of Baotou Rare Earth Concentraet Hydrometallurgy Process. *Chinese Rare Earth,* Vol.29:No. 2.

YU, Y., LUO, J. & LI, Y. (1992) Tests and Studies on Separation of Iron and Rare-Earths from Bayan Obo Low and Medium Grade Oxide Ores. *Mining and Metallurgical Engineering*.

ZHANG, J. E., C. (2013) Review of rare earth minaral processing technology. *Canadian Institut of Mining,* 4**,** 38-52.

ZHANG, Z. (2001) Present Situation and Latest Progress of Process for Producing Metallic Neodymium by Electrolysis of Neodymium Oxide with Fluoride Salts. *Non-ferrous Smelting* 30:2**,** 23-25.

Preprints 2016

01/2016 Stenzel, Peter, Linssen, Jochen, Fleer, Johannes, Busch, Florian: Impact of temporal resolution of supply and demand profiles on the design of photovoltaic battery systems for increased self-consumption

02/2016 Kunz, Paul, Vögele, Stefan, Rübbelke, Dirk: Innovationsökonomische Analyse der Entwicklung von Solarstromspeichern in Deutschland.

03/2016 Vögele, Stefan, Matthies, Ellen, Kastner, Ingo, Buchgeister, Jens, Kleemann, Max, Ohlhors, Dörte, Nast, Michael: Reduktion des gebäuderelevanten Energiebedarfs als Herausforderung für die Energiewende – sechs Thesen zu unterschätzten Barrieren und Potenzialen

04/2016 Fleer, Johannes, Zurmühlen, Sebastian, Badeda, Julia, Stenzel, Peter, Hake, Jürgen-Friedrich, Sauer, Dirk Uwe: Model-based economic assessment of stationary battery systems providing primary control reserve.

05/2016 Stenzel, Peter, Hennings, Wilfried, Linssen, Jochen, Wulf, Christina: Energiespeicher.

06/2016 Schlör, Holger, Hake, Jürgen-Friedrich, Venghaus, Sandra: A culture of reflected numbers for the water, energy and land (WEL) nexus.

07/2016 Schlör, Holger, Hake, Jürgen-Friedrich, Koj, Jan, Zapp, Petra, Schreiber, Andrea: The Social hotspot index – a social life cycle assessment (S-LCA) of three hydrogen production sites.

08/2016 Fleer, Johannes, Stenzel, Peter: Impact analysis of different operation strategies for battery energy storage systems providing primary control reserve.

09/2016 Markewitz, Peter: Energietransport und –verteilung.

10/2016 Hake, Jürgen-Friedrich, Koj, Jan, Kuckshinrichs, Wilhelm, Schlör, Holger, Zapp, Petra, Ketelaer, Thomas, Schreiber, Andrea, Wulf, Christina: LCSA Hydrogen Production

Research Reports 2016

Systems Analysis and Technology Evaluation at the Research Centre Jülich

Many of the issues at the centre of public attention can only be dealt with by an interdisciplinary energy systems analysis. Technical, economic and ecological subsystems which interact with each other often have to be investigated simultaneously. The group Systems Analysis and Technology Evaluation (STE) takes up this challenge focusing on the long-term supply- and demand-side characteristics of energy systems. It follows, in particular, the idea of a holistic, interdisciplinary approach taking an inter-linkage of technical systems with economics, environment and society into account and thus looking at the security of supply, economic efficiency and environmental protection. This triple strategy is oriented here to societal/political guiding principles such as sustainable development. In these fields, STE analyses the consequences of technical developments and provides scientific aids to decision making for politics and industry. This work is based on the further methodological development of systems analysis tools and their application as well as cooperation between scientists from different institutions.

Leitung/Head: Prof. Jürgen-Friedrich Hake

Forschungszentrum Jülich

Institute of Energy and Climate Research

IEK-STE: Systems Analysis and Technology Evaluation

52428 Jülich

Germany

Tel.: +49-2461-61-6363

Fax: +49-2461-61-2540,

Email: preprint-ste@fz-juelich.de

Web: www.fz-juelich.de/ste