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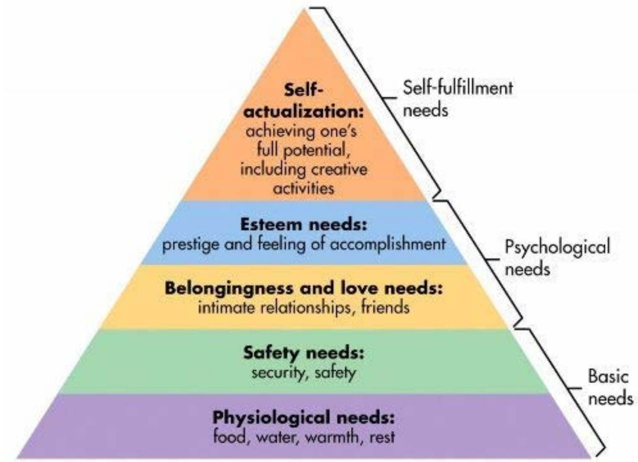
Extractive Industries III

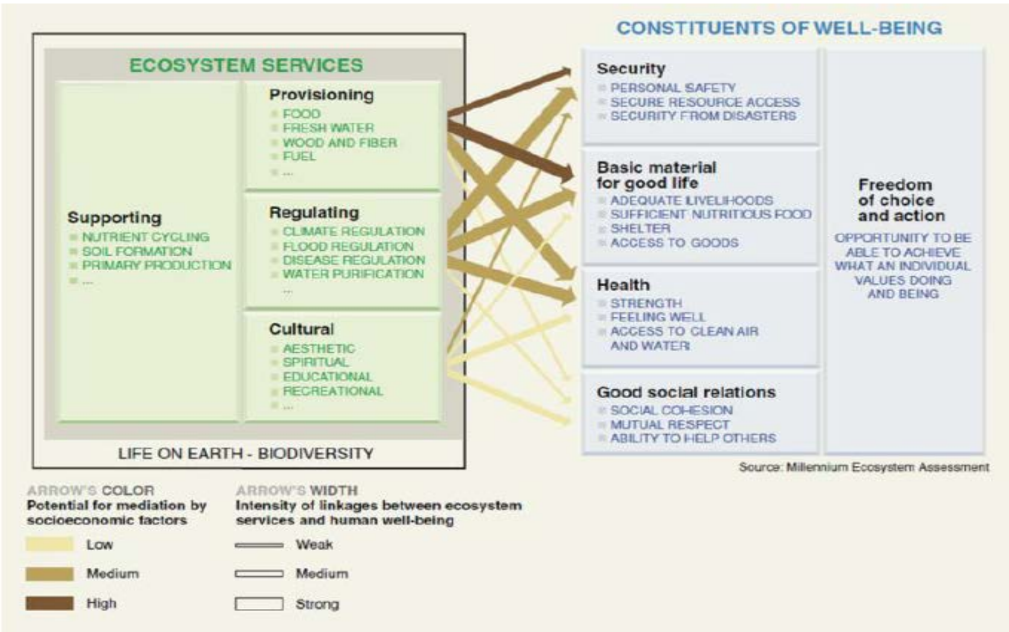
Survey of energy-related minerals and metals

Dr Mikael Höök, 2018-11-27

What is needed by society?

- Focus on basic needs
  - Maslow's pyramid is helpful
- Food and water supply
  - To ensure human survival
  - Agriculture
- Raw materials & goods
  - Needed for manufacturing, construction, etc.
- Energy
  - Required for all the above





Source: Millennium Ecosystem Assessment (2005)

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Natural resources?

- **Natural resources** are materials and capacities that exist in nature
  - They occur without any actions of humankind
  - Often also defined as useful/available for humans
  - "*Natural resources are natural assets (raw materials) occurring in nature that can be used for economic production or consumption*." – UN/OECD

Source: OECD (1997) Glossary of Environment Statistics, Studies in Methods, Series F, No. 67, United Nations, New York.

Raw materials

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- Raw materials are extracted, converted to engineered and commodity materials, and manufactured into products.
  - After use, they are disposed as waste or returned to the economy through reuse, remanufacturing, or recycling

- Sustainability in materials use has three components:
  1. the relationship between the rate of resource consumption and the overall stock of resources;
  2. the efficiency of resource use in providing essential services; and
  3. the proportion of resources leaking from the economy and impacting the environment.

- The first two topics reflect the sustainability of resource supply, while the third affects the sustainability of ecosystems

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Importance of geology

- Resources are defined as any substance vital or necessary for a society
  - **Mineral resources** refers to useful minerals
  - **Building resources** are materials like sand, gravel, cement, etc.,
  - **Energy resources** are fossil fuels, uranium, etc.
  - **Water resources** are supplies of drinking water, etc.
- Geologists are responsible for locating and extracting all of these substances
  - In fact, there is a saying that any resource that is not grown or raised, is ultimately geological in nature
  - But even growing plants rely on soil – which is geologic

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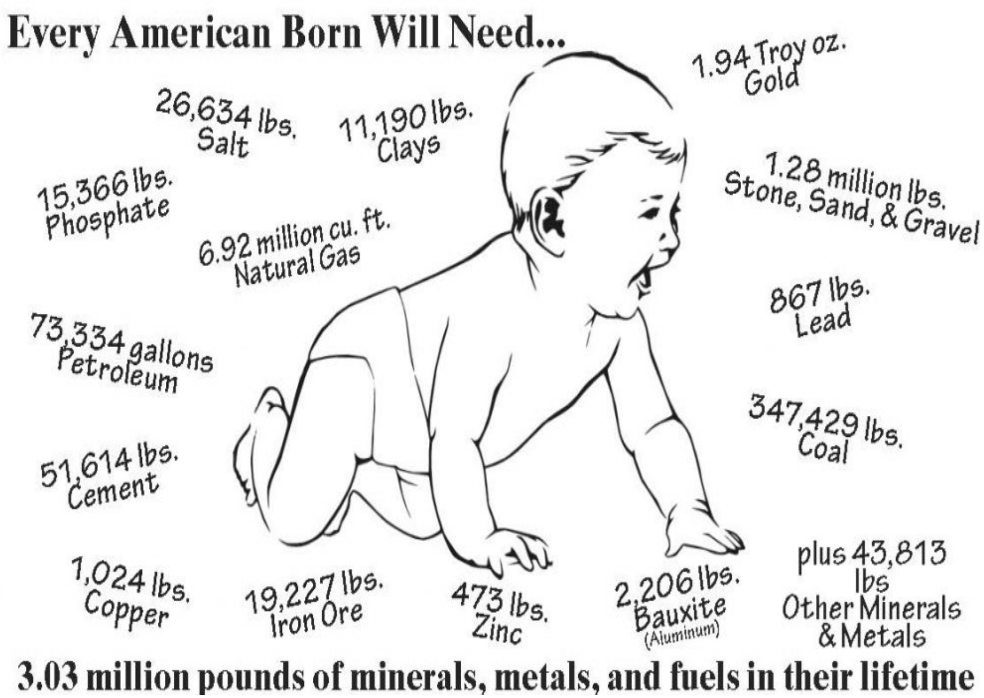
Mining is essential

- Mining (and extraction in a wider context) provides you with the basic elements of your life…

"A citizen in the western world uses about 1700 tons of minerals and metals per year. It is equivalent to 25 tons per year, for computers, cars, buildings, refrigerators and smart phones"



Source: Swedish Geological Survey (2008); Minerals Education Coalition (2018)

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Biking and minerals

Real economy

- **Real economy** is the part of the economy in a society that is concerned with actually producing goods and services in the physical reality
- Starkly opposed to the *financial economy* that is the part that is concerned with buying and selling on (imaginary) financial and stock markets
- <u>**Know the difference!**</u> But beware that it may be hard to differentiate them as developments in the real economy may be funded by the financial one

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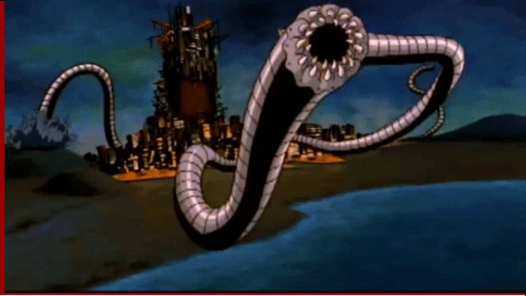
Industrial metabolism



- **Industrial ecology (IE)**
  - The study of material and energy flows through industrial systems using biological metabolism as analogy

- The real economy and global industrial supply chains are just complex network processes that extract raw materials and primary energy from the Earth and transform those into demanded commodities to meet human needs
  - Important concept underlying many integrated assessment models (IAMs) for planning and policymaking, such as the ones used by IMF or IPCC

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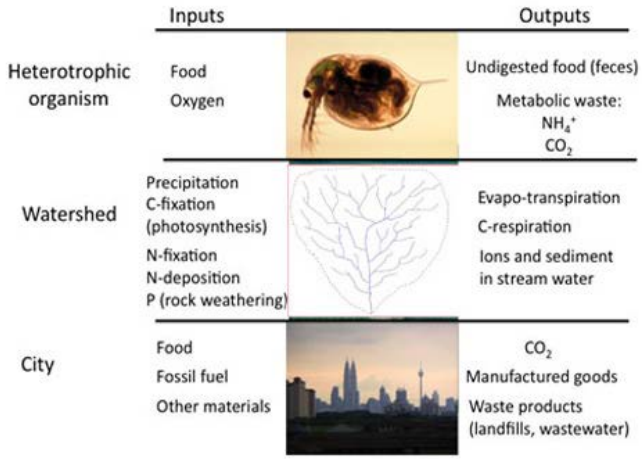
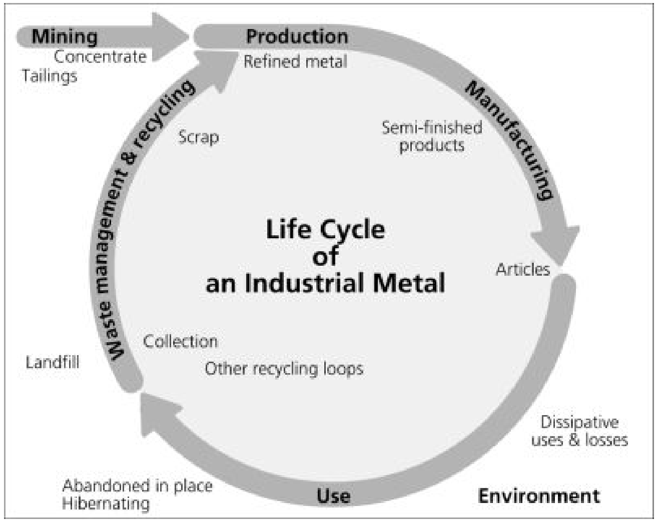
Some important natural laws

- What scientific ground can we find as a foundation for testing the sustainability of industrial systems?



- Some natural laws are very helpful for this
  - Thermodynamics I + II, conservation of mass, etc.



- Scientific approaches like system theory, etc.

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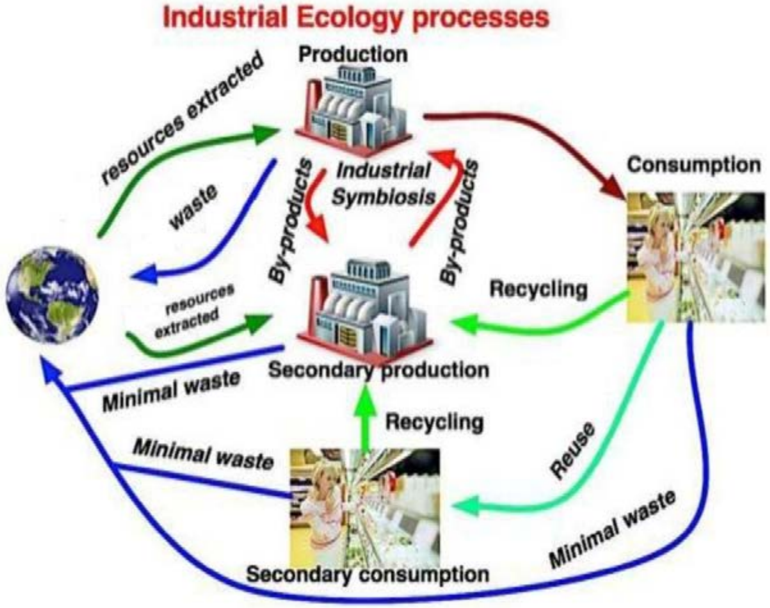
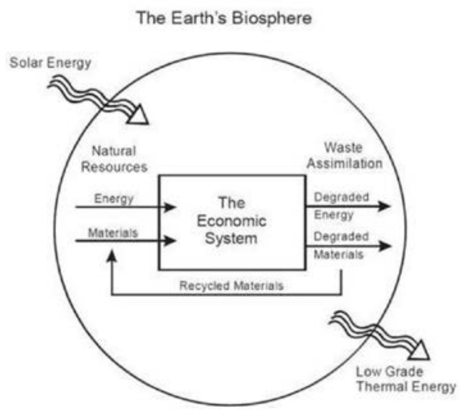
Material Flow Analysis





Meadows biophysical model from 1971 Limits to Growth

- The study of material flows within society and industrial systems
  - Relies on two fundamental and well-established scientific principles: **(1) systems approach** and **(2) mass balance**
- Underpinning recent nexus approaches and circular economy concepts

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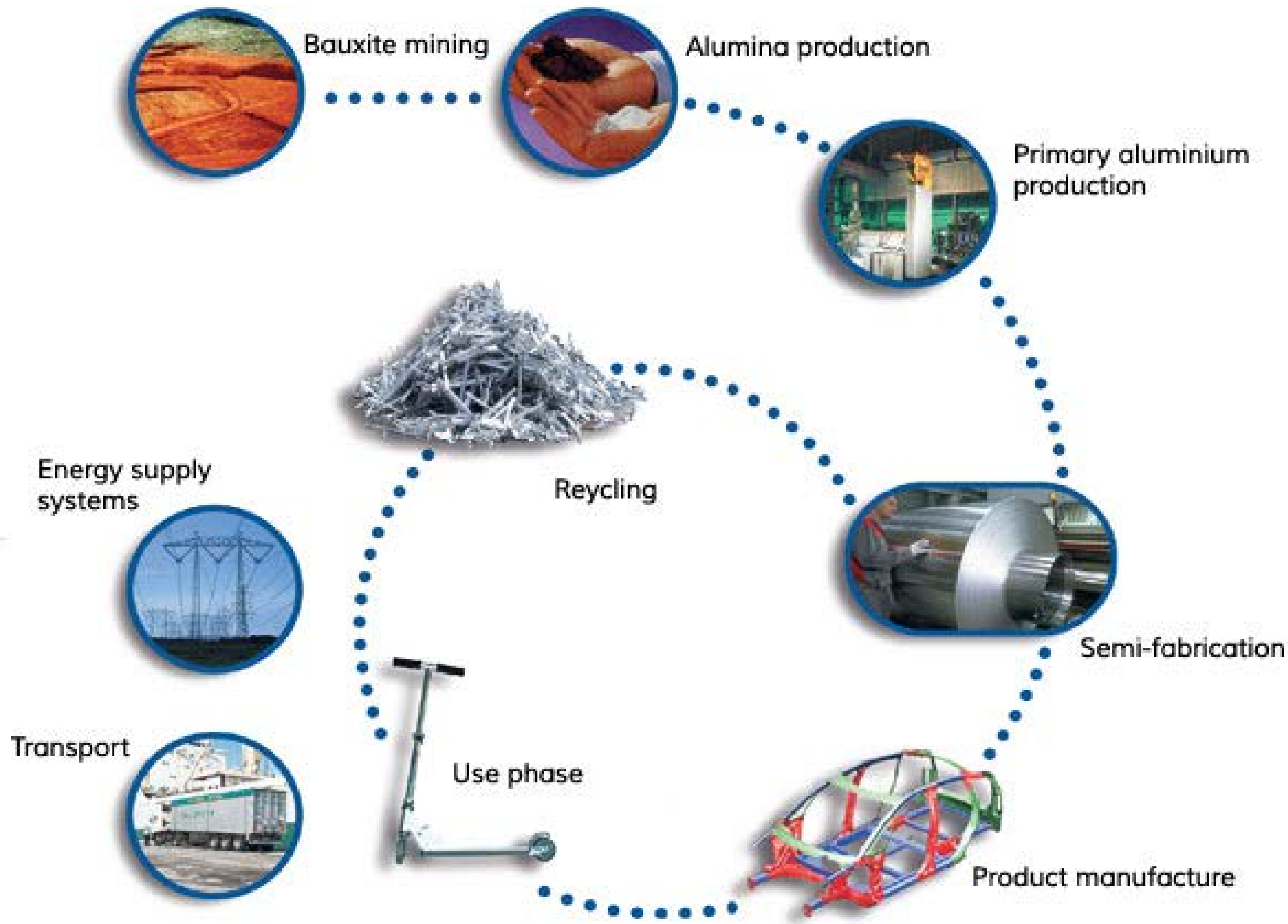
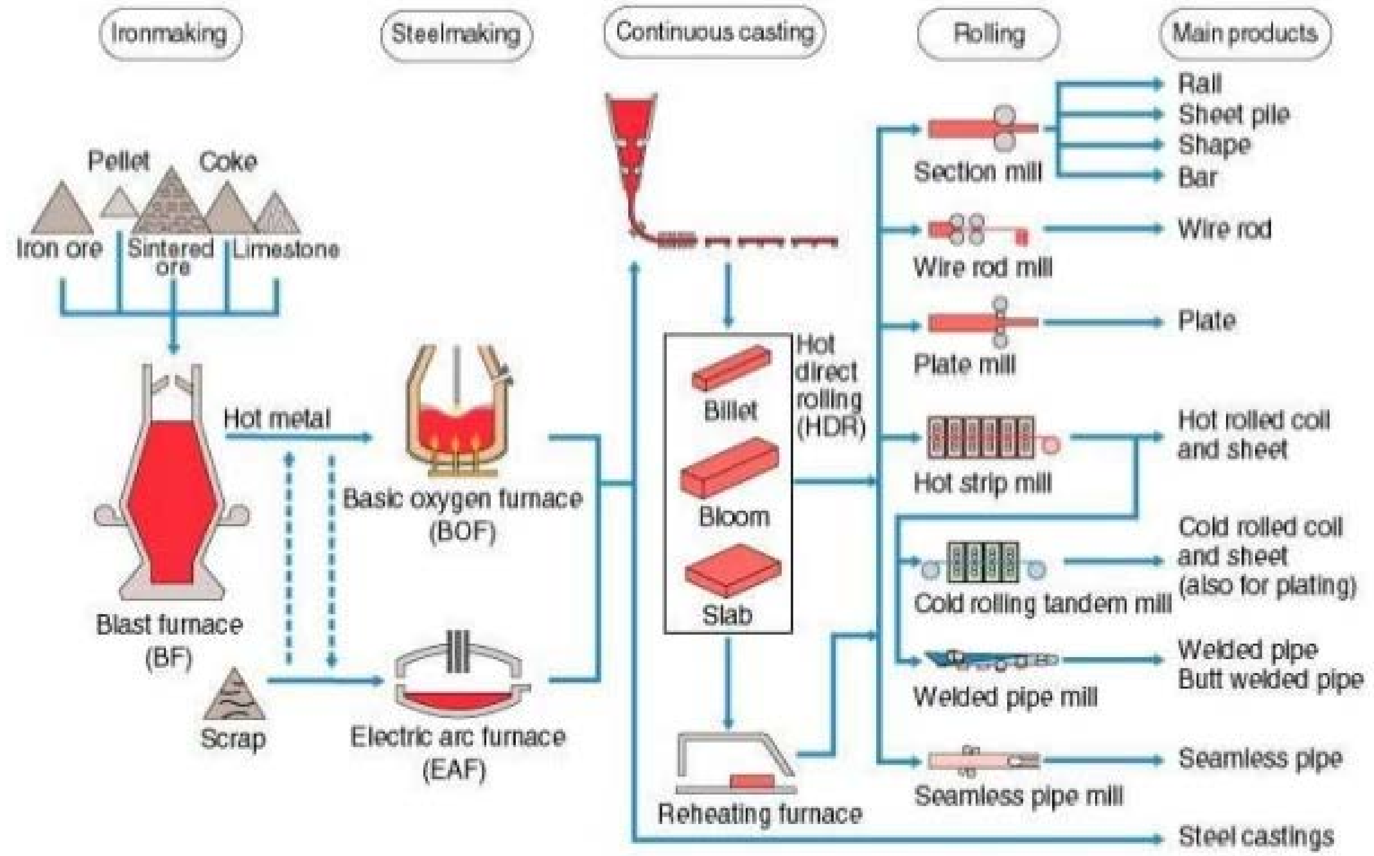
Example of aluminium flows



Example: Iron and steel

Manufacturing process for iron and steel



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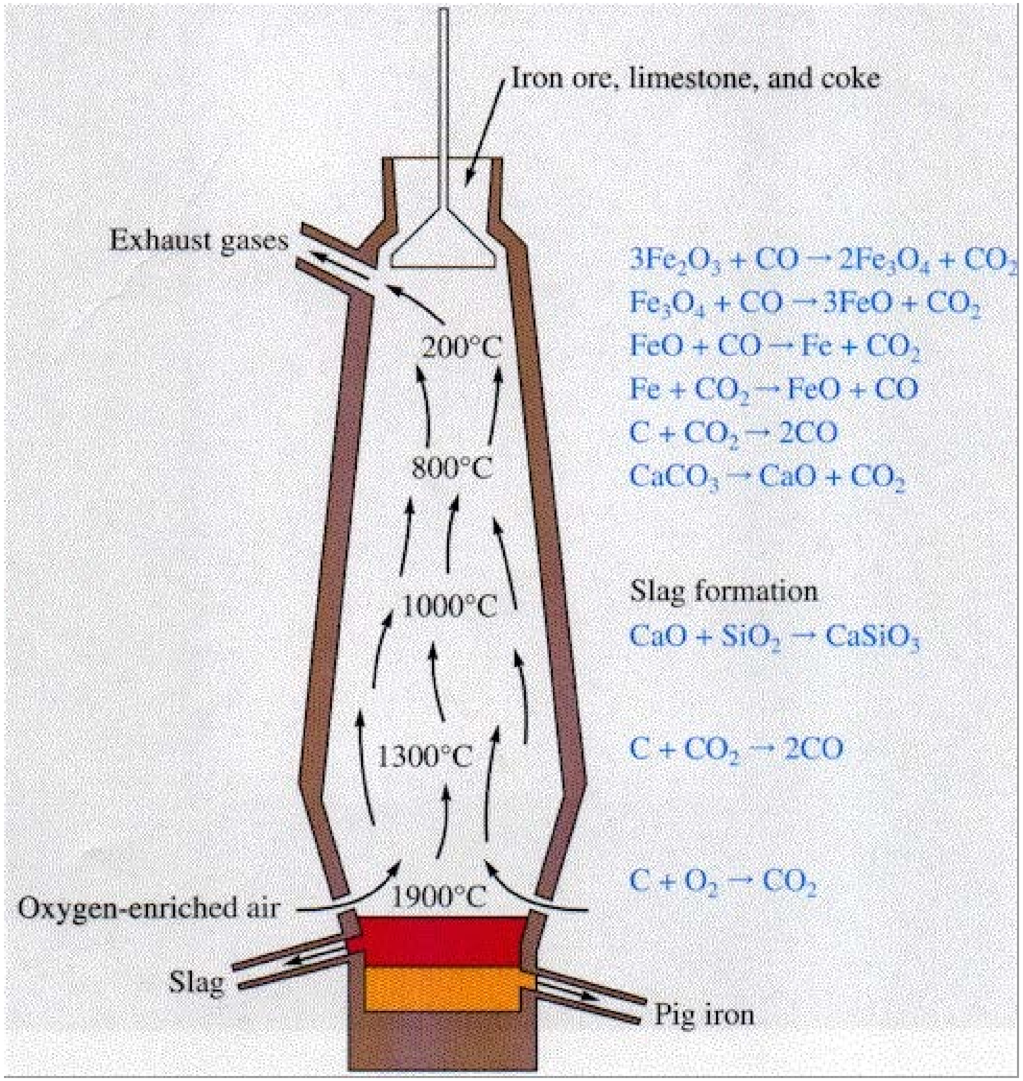
Iron and coal hand in hand



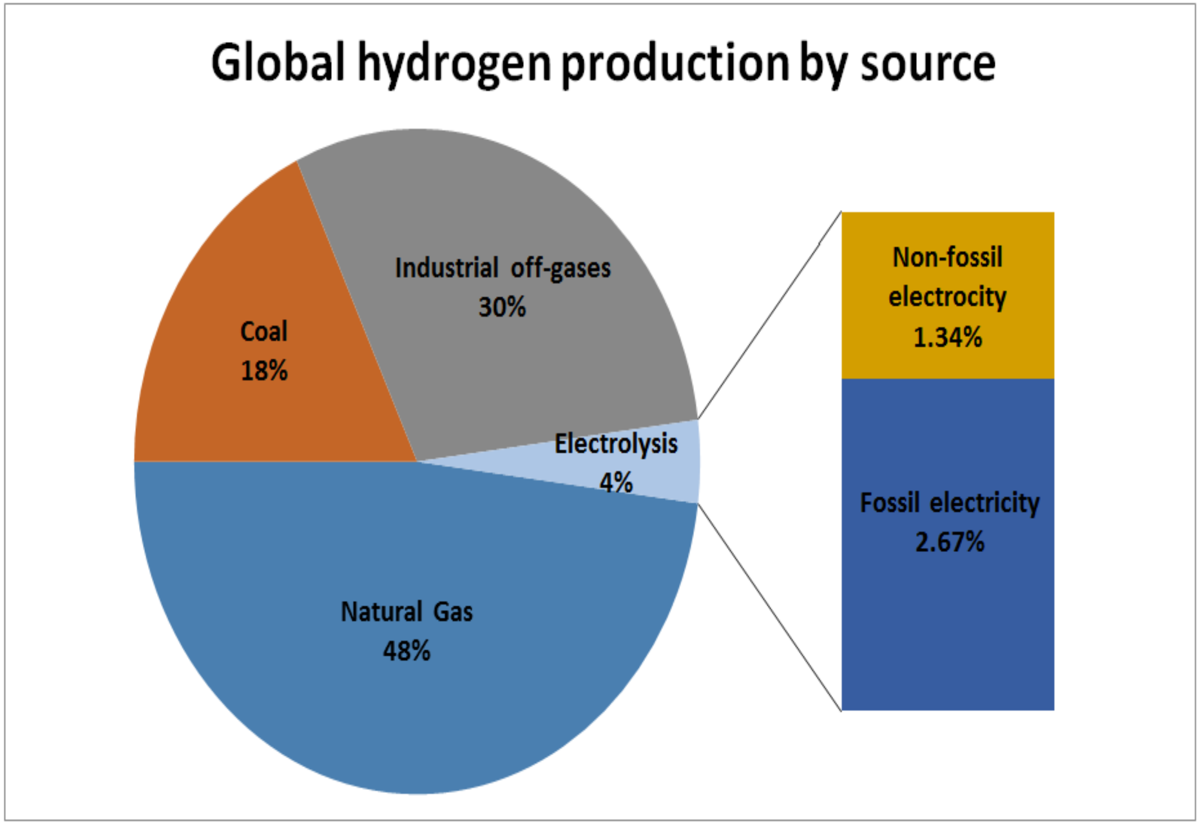
Iron ore and many other ores are chiefly oxides, such as Fe_2O_3

Oxygen reacts with carbon atoms from coal and gives pure metal and CO_2

$Fe_2O_3 + C \rightarrow Fe + CO_2$

Pure carbon compounds are superior as reduction agents and irreplaceable in most metal processing

Hydrogen from a Mineral-Energy nexus perspective



- Replacing coking coal with hydrogen do not reduce fossil dependency
- Neither does hydrogen fuel cells
- Complete redoing of industrial hydrogen production is needed and won't be easy or quick to achieve

Figure 2. *Global hydrogen production by source. Output from thermal splitting of water, plasma reforming, and other peripheral production processes are minor. Data taken from IEA (2007) and electricity is divided into fossil and non-fossil parts using IEA (2017)*

Source: Tokimatsu, K., Höök, M., et al, 2018. Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 ° C target with 100 percent renewable energy. *Applied Energy*, 225(9):1158–1175.

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Sulphur and fossil fuels

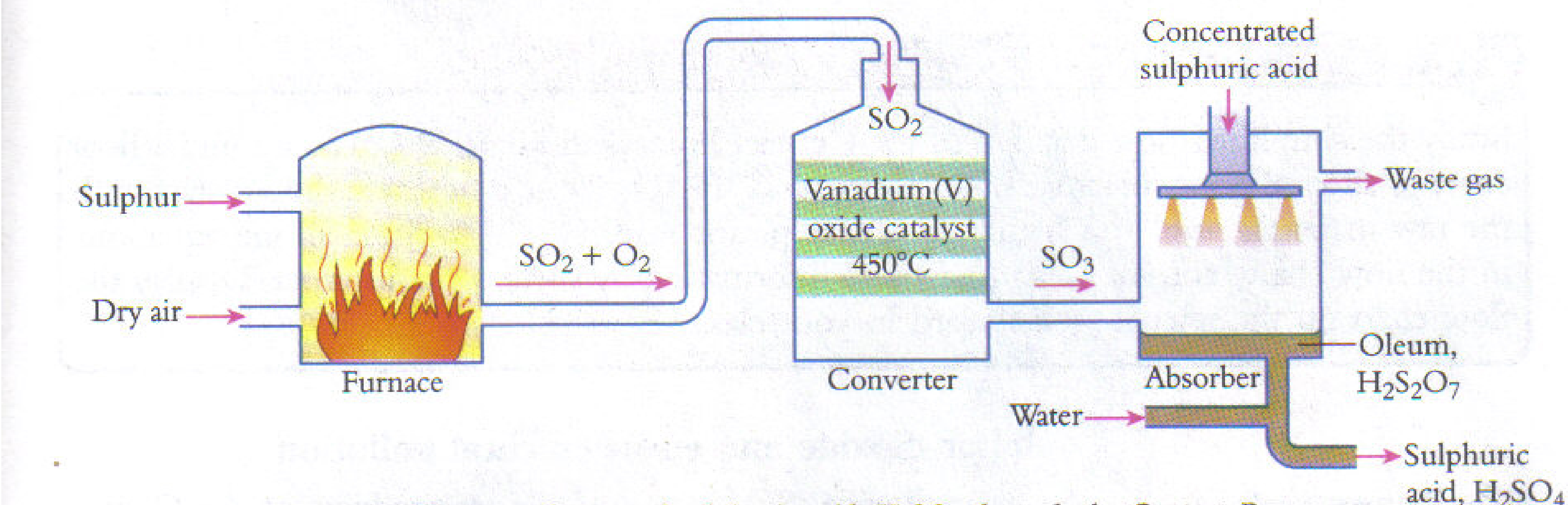
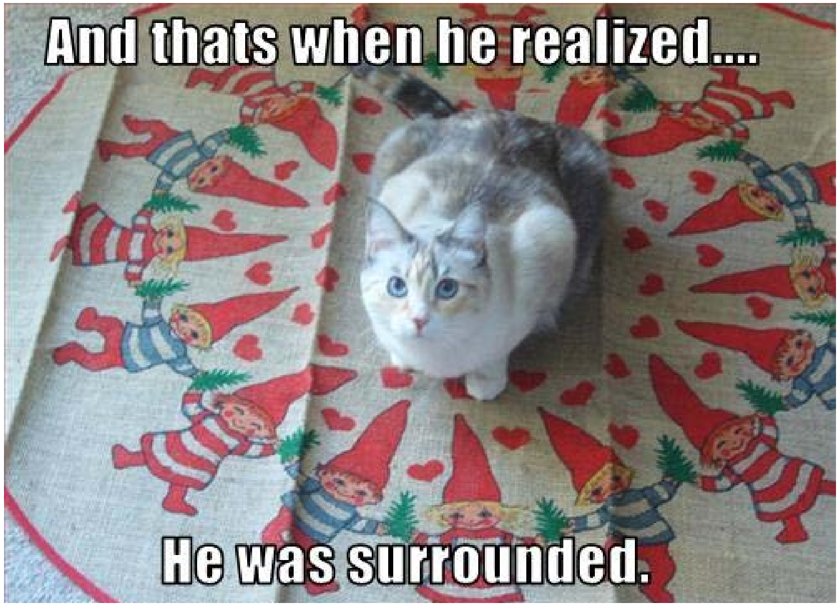


Figure 9.1 The manufacture of sulphuric acid, H_2SO_4 through the Contact Process

- Global sulfur is chiefly recovered from desulfurization waste from fossil fuel refineries followed by sulfide ore processing and used for irreplaceable and vital chemical sulfuric acid (H_2SO_4)
  - About 60% of all is consumed for fertilizers,
  - About 20% is used for production of detergents, synthetic resins, dyestuffs, pharmaceuticals, petroleum catalysts, insecticides, antifreeze, aluminium reduction, paper sizing, water treatment, etc.
  - About 6% of uses are related to pigments, paints, enamel, printing inks, coated paper and fabrics
  - Remaining 14% is dispersed into a multitude of applications such as production of explosives, cellophane, acetate and viscose textiles, lubricants, non-ferrous metals and batteries

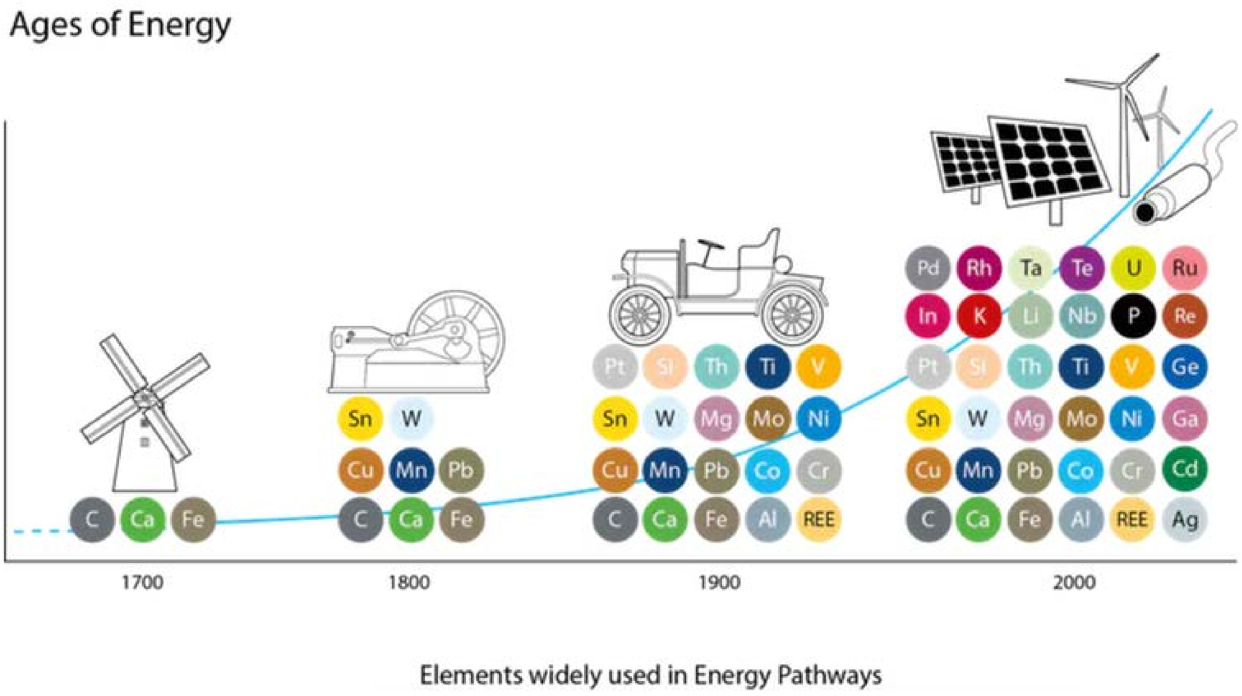
Fossil entanglement

- Fossil fuels are deeply entangled into most non-energy material sectors
- Rapid decarbonization is complicated and also requires major restructuring of global industrial supply chains
  - Green/clean energy tech is also caught in this net



Energy and materials

- New energy developments increase demand for many elements and minerals
- Understanding material supply is essential!



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Sustainable energy and materials

- For sustainability and environmental reasons, reducing fossil fuel reliance is essential as you all know…
  - Renewable energy is often presented as more or less automatically sustainable by many, but there is more to the story…
  - Renewable energy technologies are more metal intensive than current energy sources and would increase demand for raw materials (Kleijn et al, 2011; Fizaine & Court, 2015)
  - Material flows from mining, manufacturing, and recycling industry gets increasingly tied together with the energy sector as the share of renewable energy increases (Elshkaki & Graedel, 2013; Davidsson et al, 2014; Kim et al, 2015; Davidsson & Höök, 2017)

Source: Kleijn et al, 2011. Metal requirements of low-carbon power generation. *Energy* 36:5640–5648
Fizaine & Court, 2015. Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI. *Ecological Economics* 110:106–118
Elshkaki & Graedel, 2013. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *Journal of Cleaner Production* 59:260–273
Davidsson et al, 2014. Growth curves and sustained commissioning modelling of renewable energy: Investigating resource constraints for wind energy. *Energy Policy*, 73:767–776
Kim et al, 2015. Critical and precious materials consumption and requirement in wind energy system in the EU 27. *Applied Energy* 139:327–334
Davidsson & Höök, 2017. Material requirements and availability for multi-terawatt deployment of photovoltaics. *Energy Policy*, 108(9), 574–582

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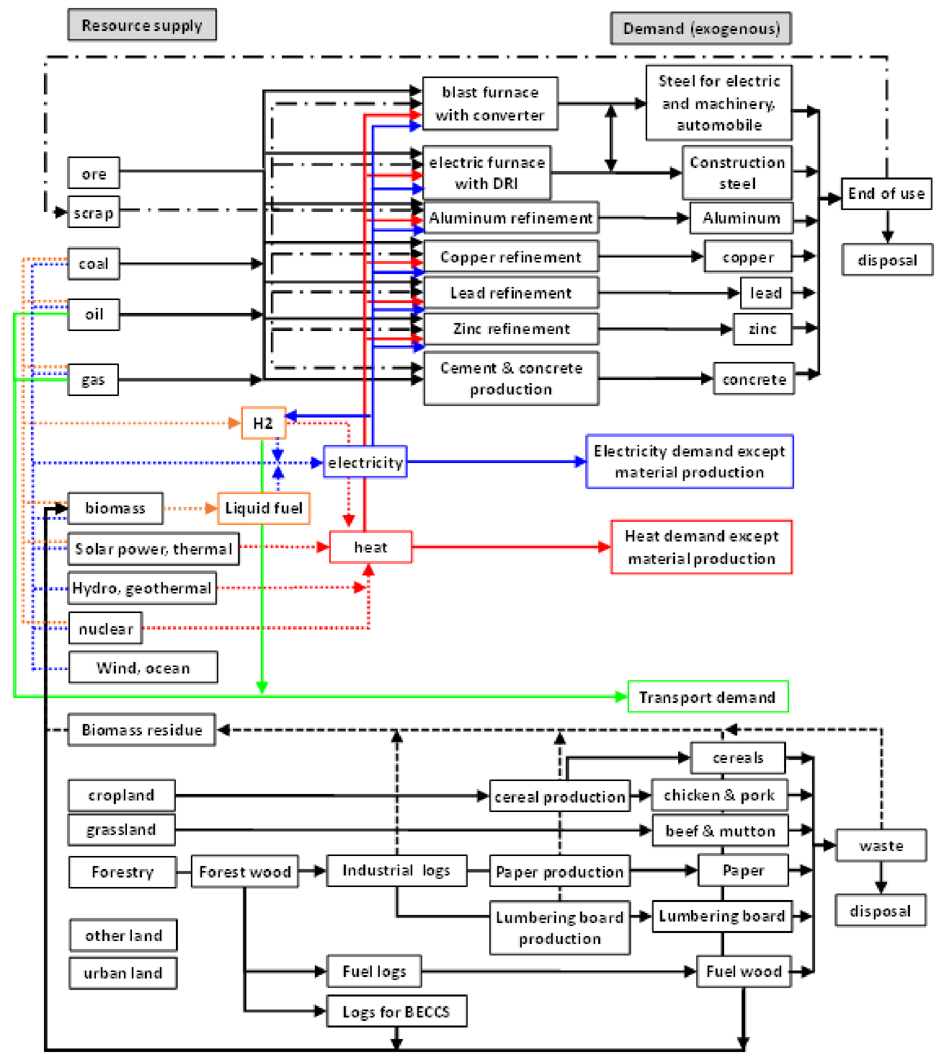
Nexus approaches

- Global sustainable development issues such as manmade climate change, financial and macroeconomic instability, welfare development, growing urbanization and income inequality, are deeply connected with energy, mineral food and water resources
- The nexus perspective incorporates the interdependencies sectors and how they are connected to the challenge of achieving sustainable development
- As a concept, the nexus is supported by a rapidly growing evidence base and a community of practitioners and policy makers, providing a powerful but largely disconnected knowledge base to understand the relationships and trade-offs between the different sectors and disciplines characterising the nexus

Mineral-Energy Nexus

- Further development capable of capturing interconnections between energy and mineral sectors
- Bridging energy and raw material sectors for more holistic analysis of systems

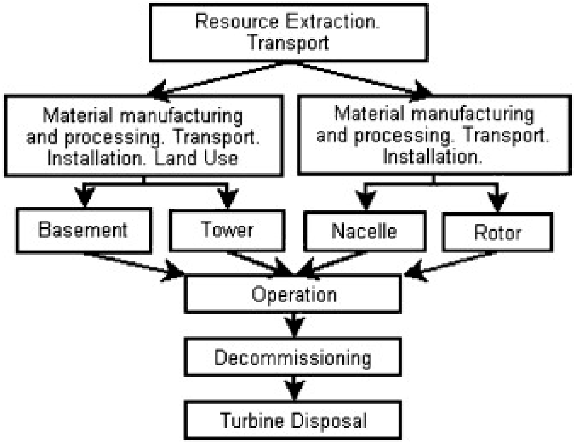


Source: Tokimatsu & Höök, et al. (2018). Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 ° C target with 100 percent renewable energy. *Applied Energy*, 225(9):1158–1175.

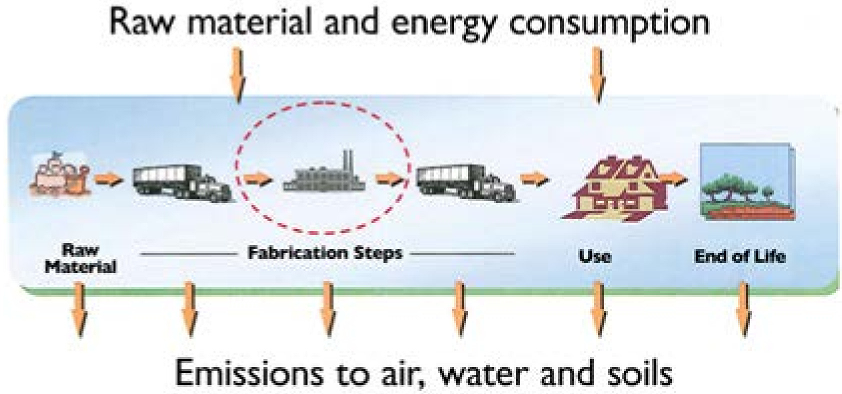
Systematic analysis

Life cycle stages

1. Raw material extraction
2. Fabrication
3. Operation
4. Decommissioning
5. Waste management



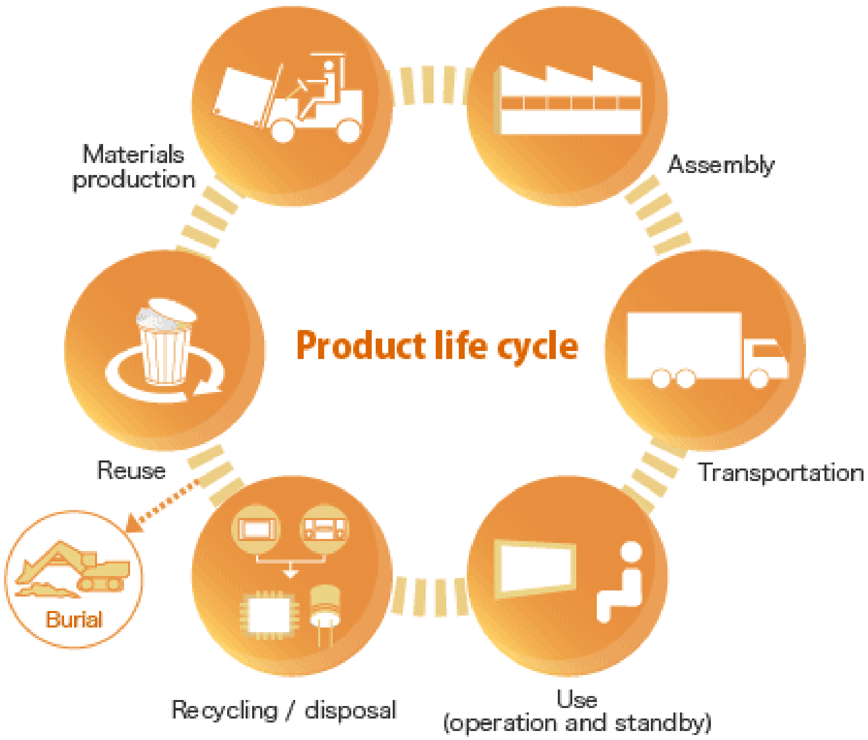
Source: Martinez et al (2009) Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy* 34(3): 667–673.



Local or global issues?

- Environmental impact can be local and/or global depending on the specific energy system

- A *Life Cycle Perspective* is important to fully grasp the complexity of the entire process chain



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One example

Mine-mouth coal power

Potential local impacts

- *Landscape modification, noise and dust from mining operations, acid mine drainage, water pollution*

Potential global impacts

- CO_2 emissions, acid rain, particulate emissions

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Another example

Direct-drive wind turbine

<u>Potential local impacts</u>

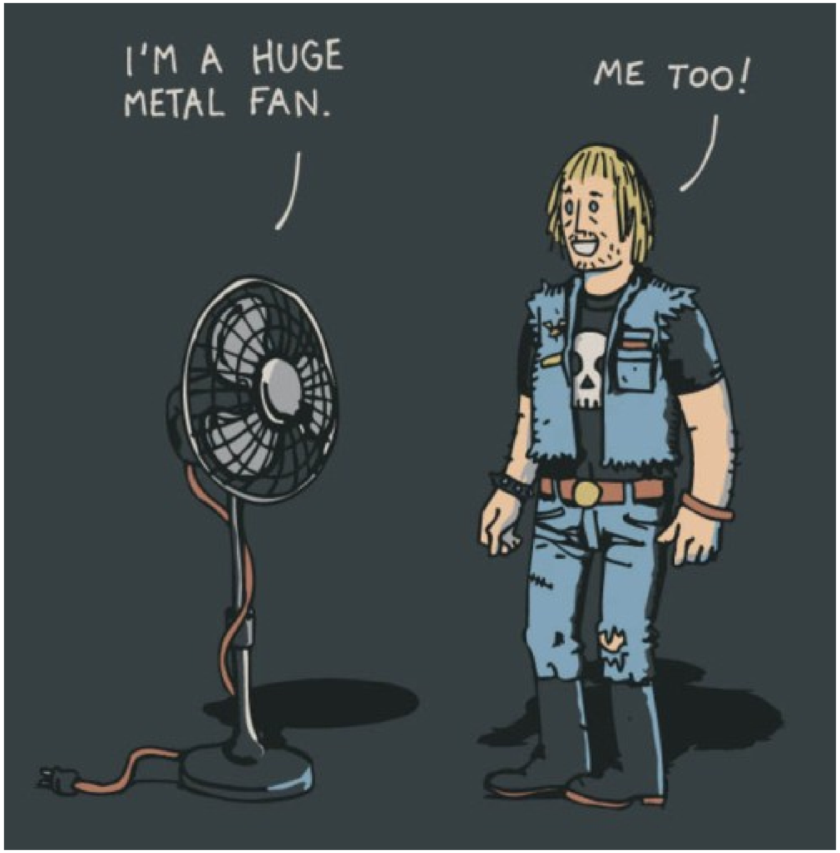
- *Landscape modification, noise and dust from mining operations, acid mine drainage, water pollution, release of radioactive heavy metals*

<u>Potential global impacts</u>

- *Negligible*

Metals are important

- Metal and raw material mining is the source of environmental impacts for green and clean tech
- Metal supply also has potential bottlenecks that can limit expansion
- Metal rocks and matter



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Global metal resources

- Every metal is formed in fusion processes or explosive nucleosynthesis in dying stars
- All metals on the Earth came here when the planet was formed
- Ore formation is limited by a number of geological parameters, similar to the case of fossil fuels
- Occurs as ores and mineralizations that contain certain desirable metals for technological uses

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Important metals

- Iron, aluminium, copper, lead etc (base metals)
  - Used in nearly everything in society
- Other metals (tungsten, lithium, niobium, etc.)
  - Often irreplaceable in energy technologies such as batteries, photovoltaic cells, etc.
  - Occurs as by-products to base metals
- Nuclear metals (uranium and thorium)
  - Fundamental as fuel in nuclear reactors
- Short overview follows

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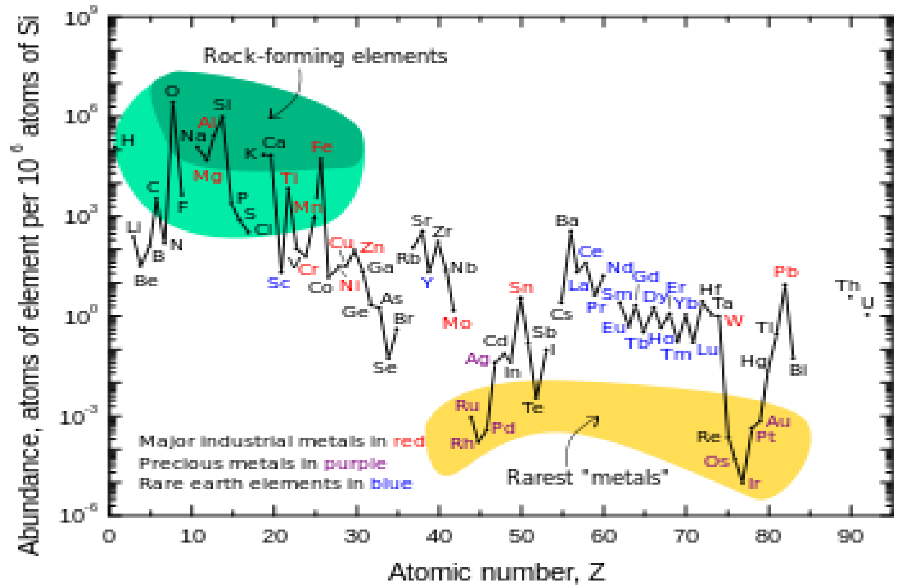
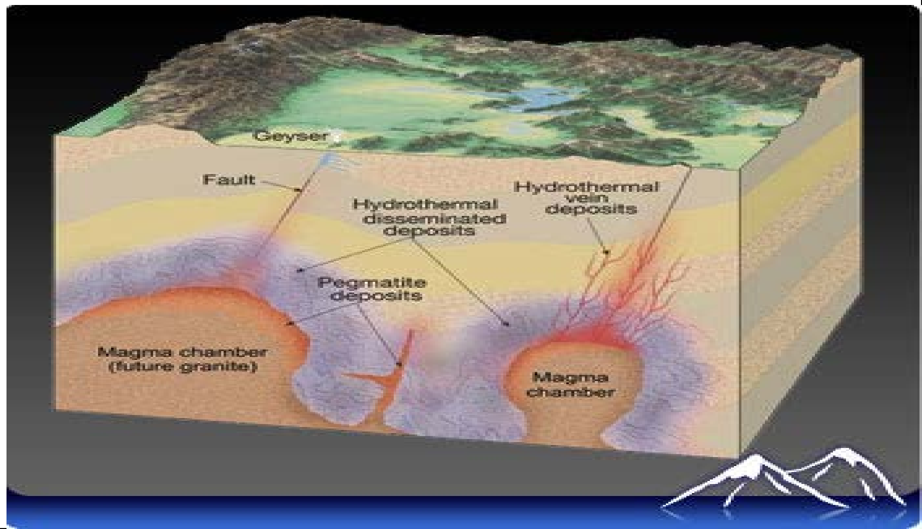
Abundance of ore and minerals

- Geochemistry explain both abundance and distribution of minerals
  - Metal ores are by definition non-renewable
  - Rarely concentrated to sufficiently high grades to merit commercial mining
  - Metal ore is by definition a economic concept and dependent on price





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Pure vs real ores

Almost pure copper from a high class deposit

Chalcopyrite, $CuFeS_2$
34.5% copper in pure form
Real ores have ~1%

Energy consumption is about 22-211 MJ/kg for base metals
Zinc requires 42 MJ/kg

Source: Bardi (2008) The future of mining: an energy analysis, presented at ASPO VII, 20-21 October, Barcelona, Spain

Some important ores

- Argentite: Ag_2S
- Barite: $BaSO_4$
- Bauxite Al_2O_3
- Beryl: $Be_3Al_2(SiO_3)_6$
- Bornite: Cu_5FeS_4
- Cassiterite: SnO_2
- Chalcocite: Cu_2S
- Chalcopyrite: $CuFeS_2$
- Chromite: $(Fe, Mg)Cr_2O_4$
- Cinnabar: HgS
- Cobaltite: (Co, Fe)AsS
- Coltan: $(Fe, Mn)(Nb, Ta)_2O_6$
- Galena: PbS
- Gold: Au,
- Hematite: Fe_2O_3
- Ilmenite: $FeTiO_3$
- Magnetite: Fe_3O_4
- Molybdenite: MoS_2
- Pentlandite:$(Fe, Ni)_9S_8$
- Pyrolusite:MnO_2
- Scheelite: $CaWO_4$
- Sphalerite: ZnS
- Uraninite (pitchblende): UO_2
- Wolframite: $(Fe, Mn)WO_4$

Interdependent extraction

- Extraction of metals is interdependent processes involving several types of polymetallic ores
  - found in various ores, consisting of several elements combined commonly as oxides, sulphides or silicates
  - Trace amounts of other elements occur

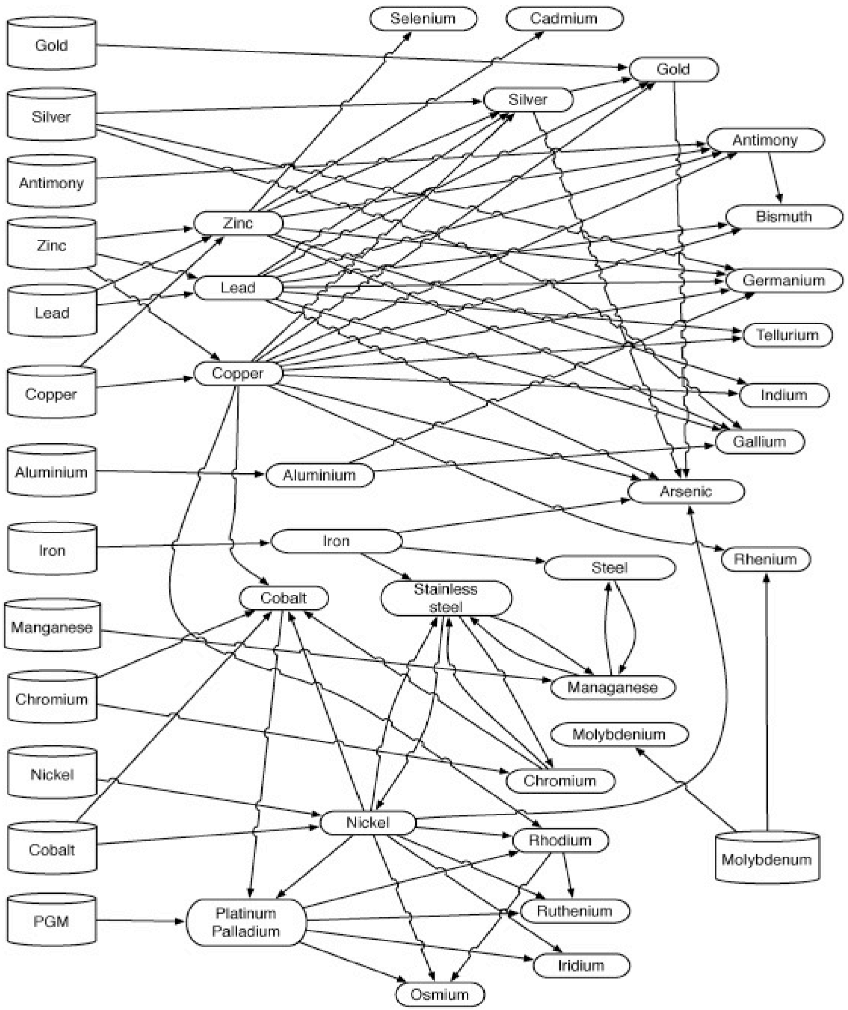
- Iron, aluminium, copper, lead, etc. (primary ores)
  - Used in nearly everything and mined directly

- Other metals (tungsten, lithium, indium, REEs, etc.)
  - Often irreplaceable components in energy technologies such as batteries, photovoltaic cells, etc.
  - Generally occurs as by-products to primary ores

Complex material flows

- Production dominance is also in *patents* and *technical know-how* in addition to mining the available reserves
  - Many countries are sending raw materials to China for refining and purification
  - Export quotas and other political impacts are also important to consider

- Potential bottlenecks above ground due to system layout and the transnational nature of many material flows



Source: Svedrup et al (2015) An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity. *Journal of Cleaner Production*, 140: 359-372.

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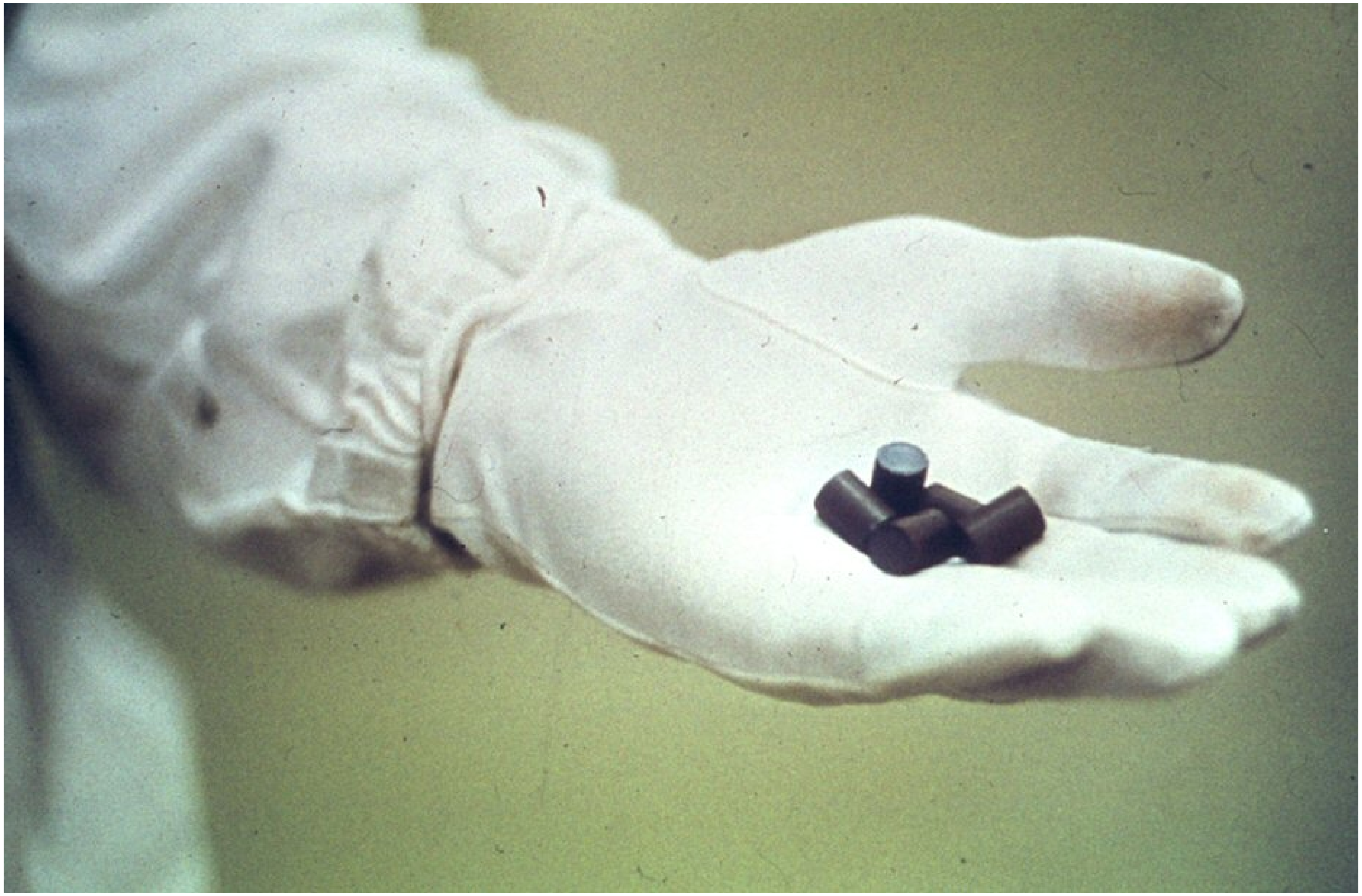
Sphalerite

- Indium is vital for thin-film solar cells (CIGS), light emitting diodes (LED) and flat screens
- Sphalerite (ZnS) is the chief source for indium
  - Contains 3-11% zinc, **0.0001-0.2% cadmium**, and less than 0.0001-0.01% indium, copper, silver, iron, gold, germanium and thallium
  - Indium is not always recovered due to costs
  - Cadmium is an environmental hazard and always appears as a unwanted by-product to zinc processing
  - Indium availability is largely governed by global zinc demand and production chains

Nuclear fuels



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Uranium

- Heavy metal formed in space via explosive nucleosynthesis in dying stars and
- Uranium is used in nuclear power stations and deliver about 5% of global primary energy and 16% of global electricity
- Also used in nuclear weapons, which make it an strategic energy resource under strict control

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Geological properties

- Complex chemistry, especially in U-O-systems
- Water soluble, which implies large amounts of uranium in sea water in low concentration
- The most common oxides in nature are U_3O_8 and UO_2
- Several other oxidation states exist under specific conditions, but generally lack economic importance due to lack of major occurrences

Uranium minerals

- There are 13 different types of uranium deposits according to NEA and IAEA geological classification

- The most important ores are uraninite/pitchblende and tobernite

- Some secondary ores also exist




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Global uranium reserves

1 Australia	36.0%
2 Canada	14.7%
3 Kazakhstan	14.3%
4 Niger	8.9%
5 Brazil	7.2%
6 South Africa	4.5%
7 Namibia	3.2%
8 Uzbekistan	3.1%
9 Russia	3.0%

95% of the world uranium is located in just 9 countries

Yellowcake – uranium based half-fabricate used to make nuclear fuel

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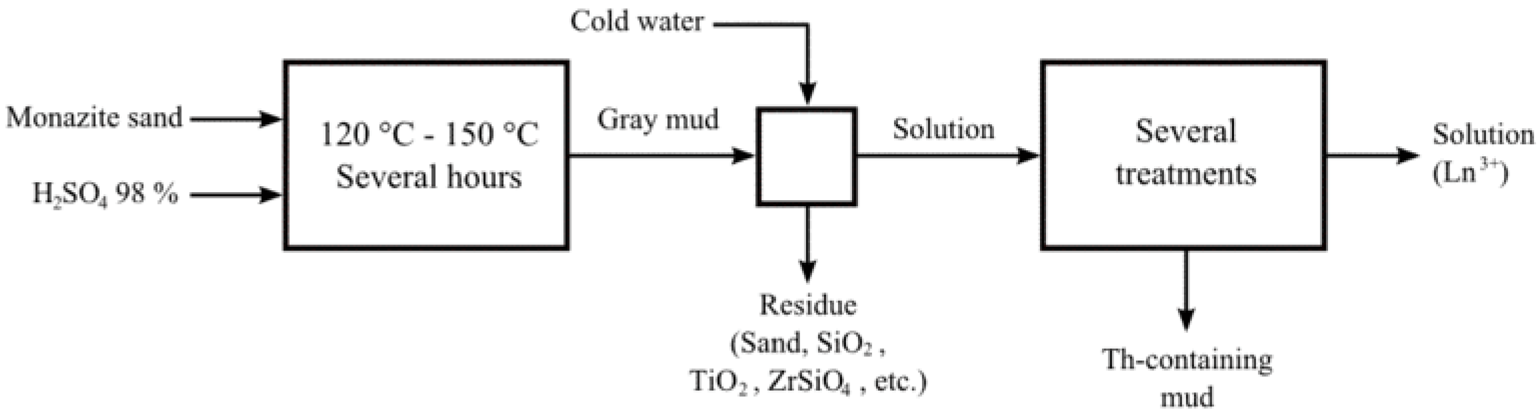
Social acceptance

- Uranium deposits will always contain higher content of radon and often toxic heavy metals
- This is problematic from an environmental point of view and often critizied by opponents to uranium mining and nuclear technology

Thorium

- Thorium is 3 times more abundant than uranium, but not water soluble leading to fewer enriched accumulations beining formed
- Primarily found in heavy metal enriched sandbased sediments near beaches (monazite sand) where wave motions have enriched thorium
- A few important vein deposits have also been discovered

Monazite sand processing



Global thorium reserves

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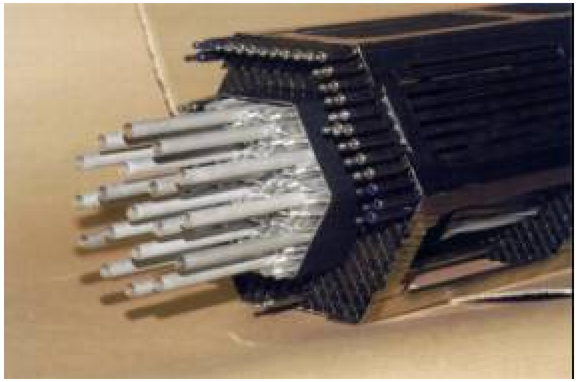
(Reasonably assured and inferred resources recoverable at up to $80/kg Th)

Country	Ton	% of total
Australia	489,000	19
USA	400,000	15
Turkey	344,000	13
India	319,000	12
Venezuela	300,000	12
Brazil	302,000	12
Norway	132,000	5
Egypt	100,000	4
Russia	75,000	3
Greenland	54,000	2
Canada	44,000	2
South Africa	18,000	1
Other countries	33,000	1
World	**2,610,000**	

85 % of all thorium is located in just 6 nations



Thorium fuel rods

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Summary: nuclear fuels

- Rather evenly occurring worldwide, but a few countries have the largest reserves
- Most of them are stable Western countries
- A lot of technology is necessary to process the ores into usable fuel for reactors (enrichment, reprocessing, etc.)
- Strategic international control makes this resources rather limited for political reasons and far from available to every country

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Criticality of materials

- Studies on critical materials represent a new and rapidly increasing domain of MFA
  - Criticality captures both supply risks and the vulnerability of a system to a potential supply disruption (Erdmann & Graedel, 2011).

- The term '*criticality*' could also be seen as an assessment of risks connected to a wide array of factors such as geological occurrences, geographical concentration of deposits or production facilities, market and regulatory structures, social issues, geopolitics, environmental aspects, recycling potential, and sustainability over the full life cycle of a certain material (Achzet & Helbig, 2013; Graedel & Nuss, 2014).

Source: Erdmann & Graedel, 2011. Criticality of non-fuel minerals: a review of major approaches and analyses. *Environmental Science and Technology*, 45:7620–7630
Achzet & Helbig, 2013. How to evaluate raw material supply risks—an overview. *Resources Policy*, 38(4):435–447
Graedel & Nuss, 2014. Employing considerations of criticality in product design. *JOM*, 66(11):2360–2366

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Uses of a few elements

Metal	Area of use
Antimon	Batteries
Beryllium	Nuclear tech
Gallium	LEDs, electronics, solar cells
Germanium	Solar cells
Indium	Nuclear tech, solar cells
Cobolt	Batteries, magnets, catalysts
Lithium	Batteries, refrigeration tech
Platina Group Metals (PGMs)	Fuel cells technologies
Rare Earth Elements (REE)	Generators, electric motors, batteries, etc.
Rhenium	Catalysts
Selenium	Solar cells
Tantal / Niobium	Special alloys, filaments
Tellurium	Solar cells

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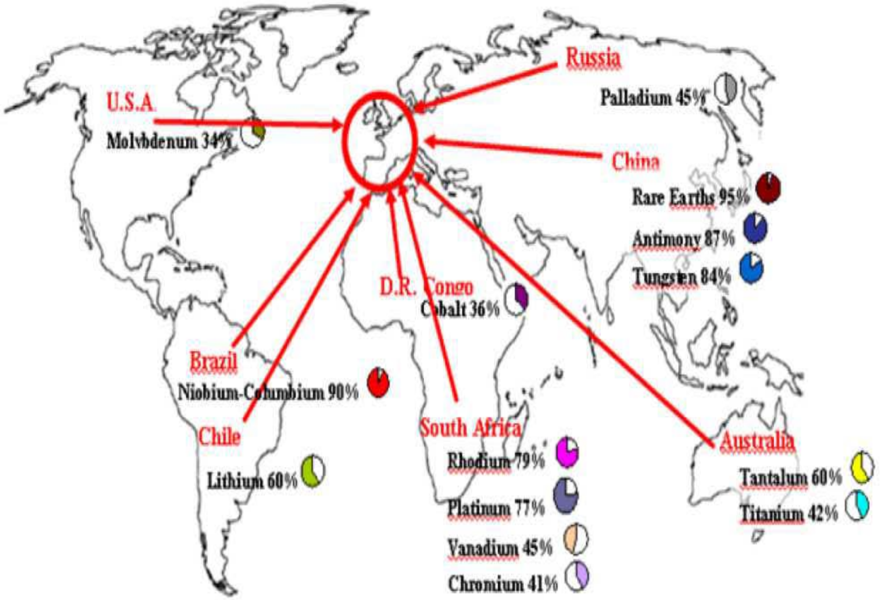
Critical materials

- EU:s expert group identified a number of critical metals with vital functions for high tech and green/cleantech industries

- Almost nothing is produced in EU and nearly everything imported



Data source : World Mining Data (2008) **=USGS (2008)
The figures and pie graphs indicate the proportion of world production

EU-perspectives

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De viktigaste procucenterna utanför EU:

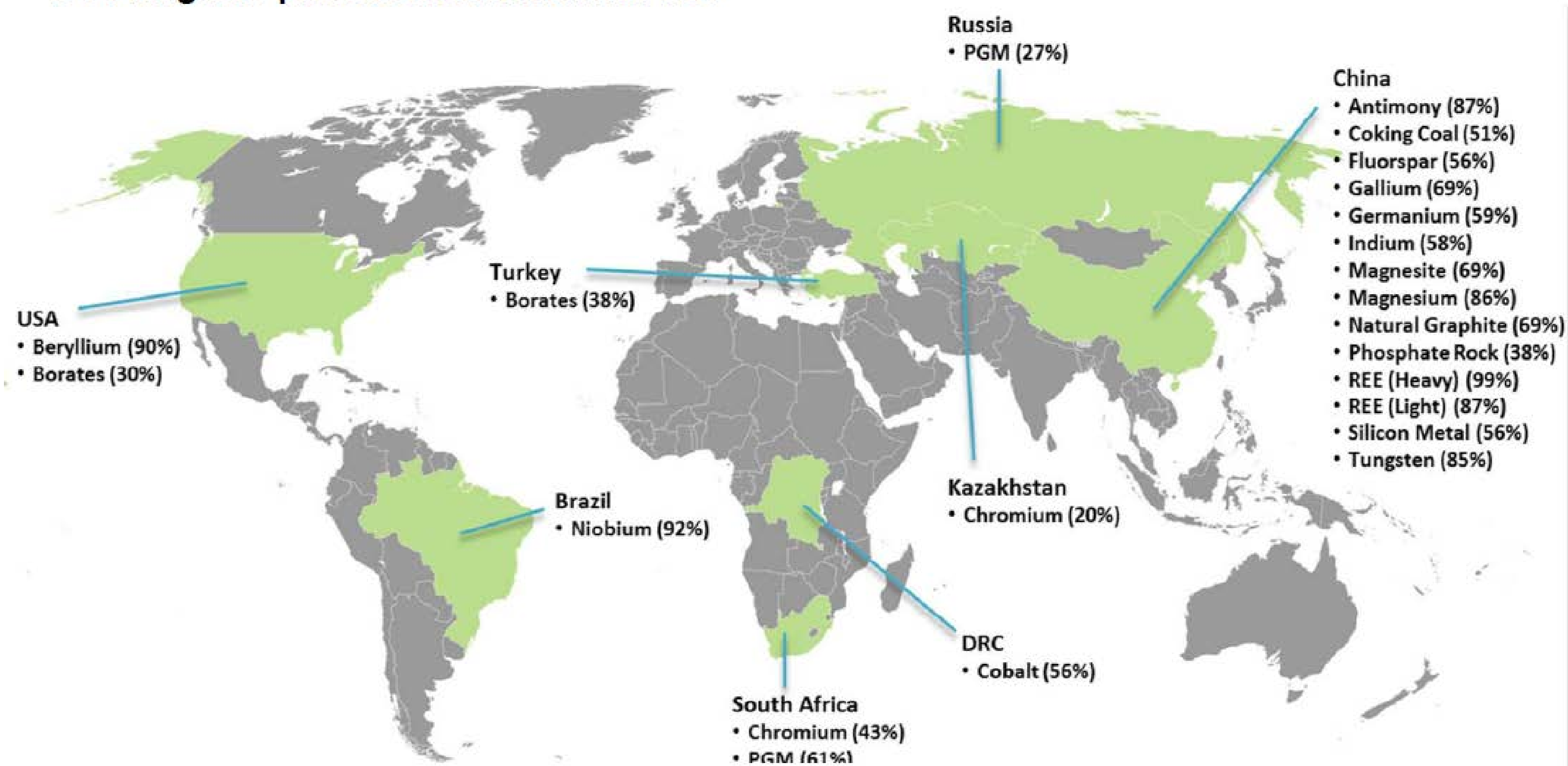

Table 1: Countries supplying raw materials to the global market

Country	Materials Produced*	Total % of supply	Country	Materials Produced*	Total % of supply
China	48	30%	South Africa	26	3.9%
USA	36	10%	Chile	18	3.4%
Russia	42	4.9%	Canada	30	3.2%
Brazil	36	4.6%	India	30	2.5%
Australia	34	4.0%	Turkey	25	2.1%

European Commission

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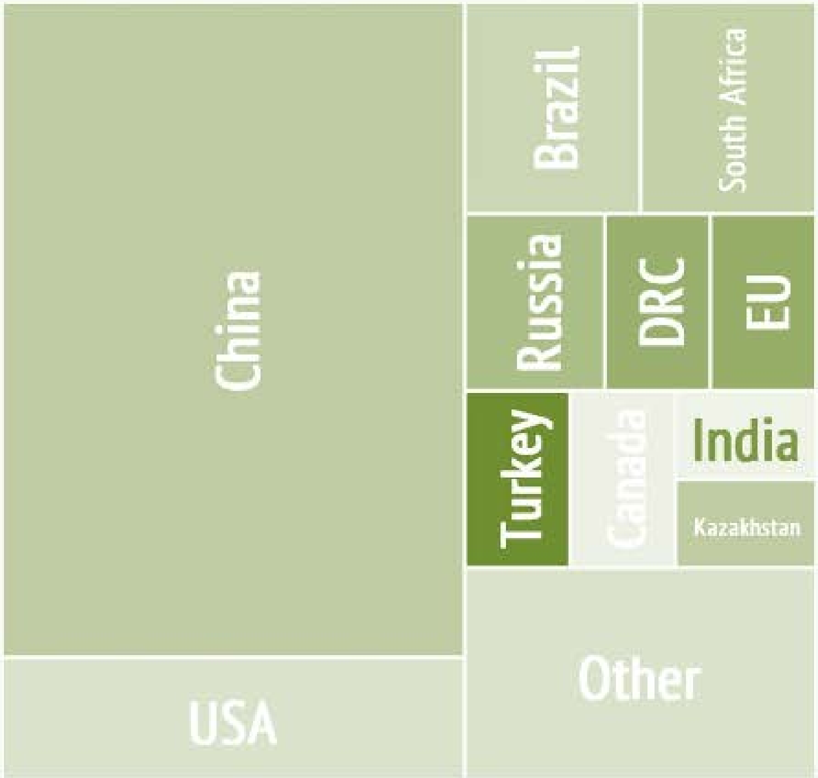
Chinese dominance

World primary supply of the 54 candidate raw materials



World primary supply of the 20 critical raw materials

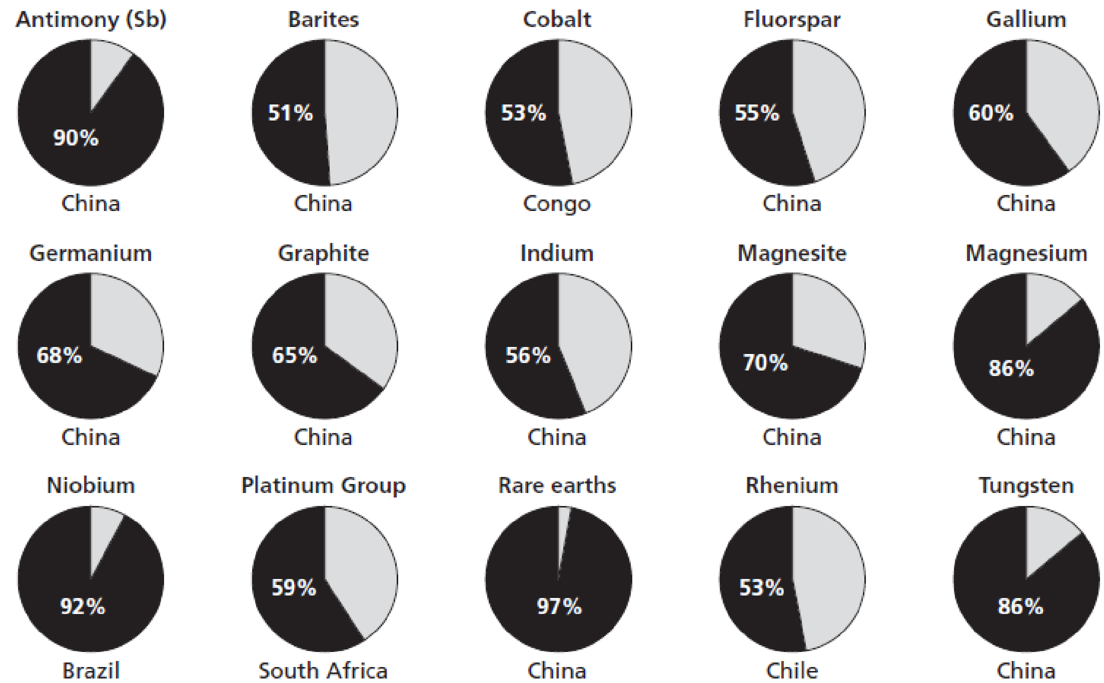
Source: The European Critical Raw Materials review (2014)

Market dominance

- Many elements are very dominated by one single producer affecting world market dynamics

- China's produce raw materials at lower cost than other producers because of its relatively lax environmental and occupational health and safety standards and regulations

Figure S.1
Percentage of Global Production (Mining) of Key Materials Within a Single Country



Source: RAND (2013) *Critical Materials: Present Danger to U.S. Manufacturing*. Technical Report

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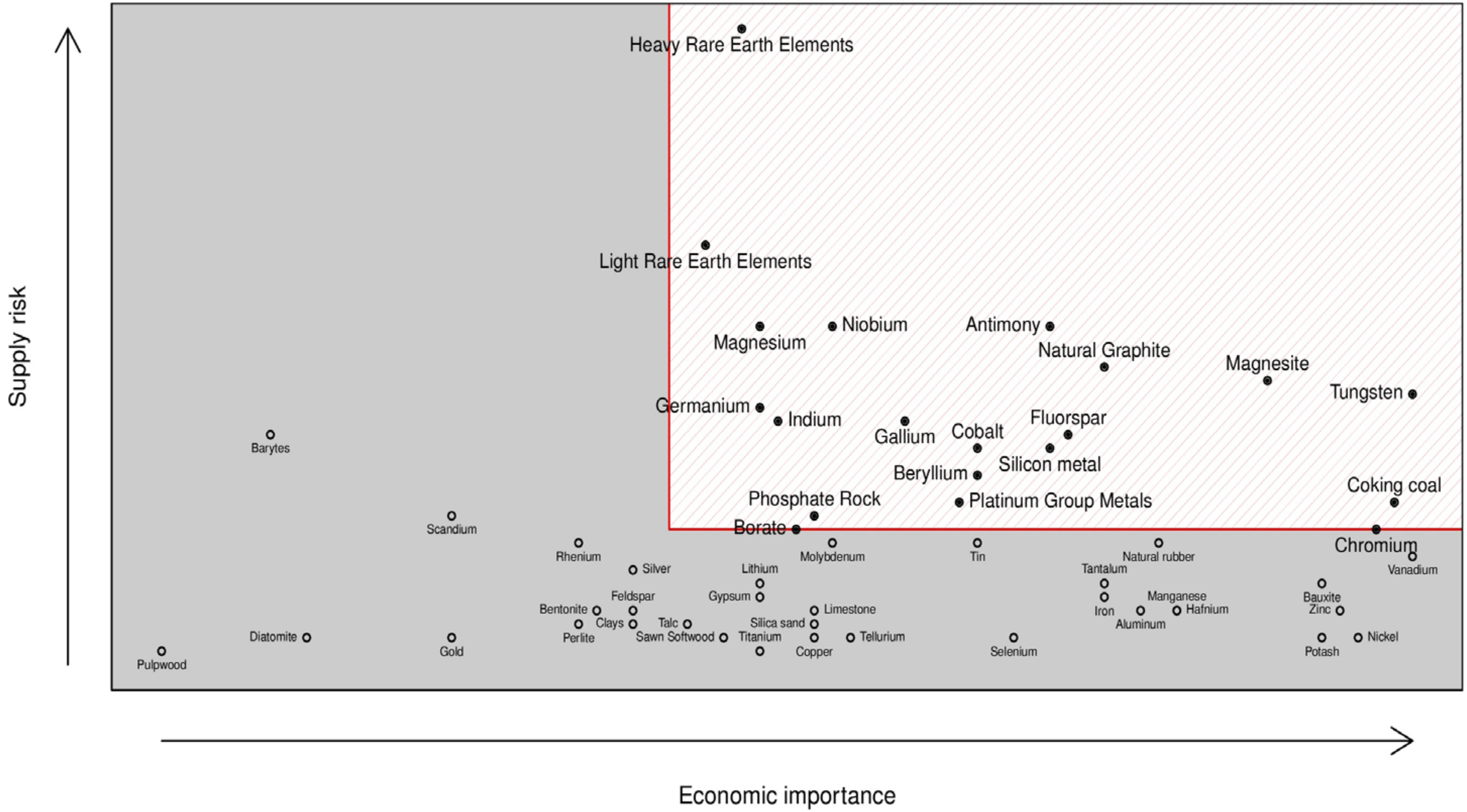
EU and Critical Materials



Source: The European Critical Raw Materials review (2014)

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Material issues

- Available critical material could potentially be a significant constraint for different solar and wind technologies in the future
  - Certain solar energy concepts are unrealistic in terms of achieving TW scales

- Renewable energy is driving EU into China’s monopolistic supply chain control unless new mines could be found elsewhere
  - China's reliability is compromised, necessitating non-Chinese mining and processing (Stegen, 2015)

Sources: Dutta et al (2016) Global demand for rare earth resources and strategies for green mining. Environmental Research, 150:182-190
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Stegen (2015) Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. *Energy Policy*, 79, 1-8.

Circular economy

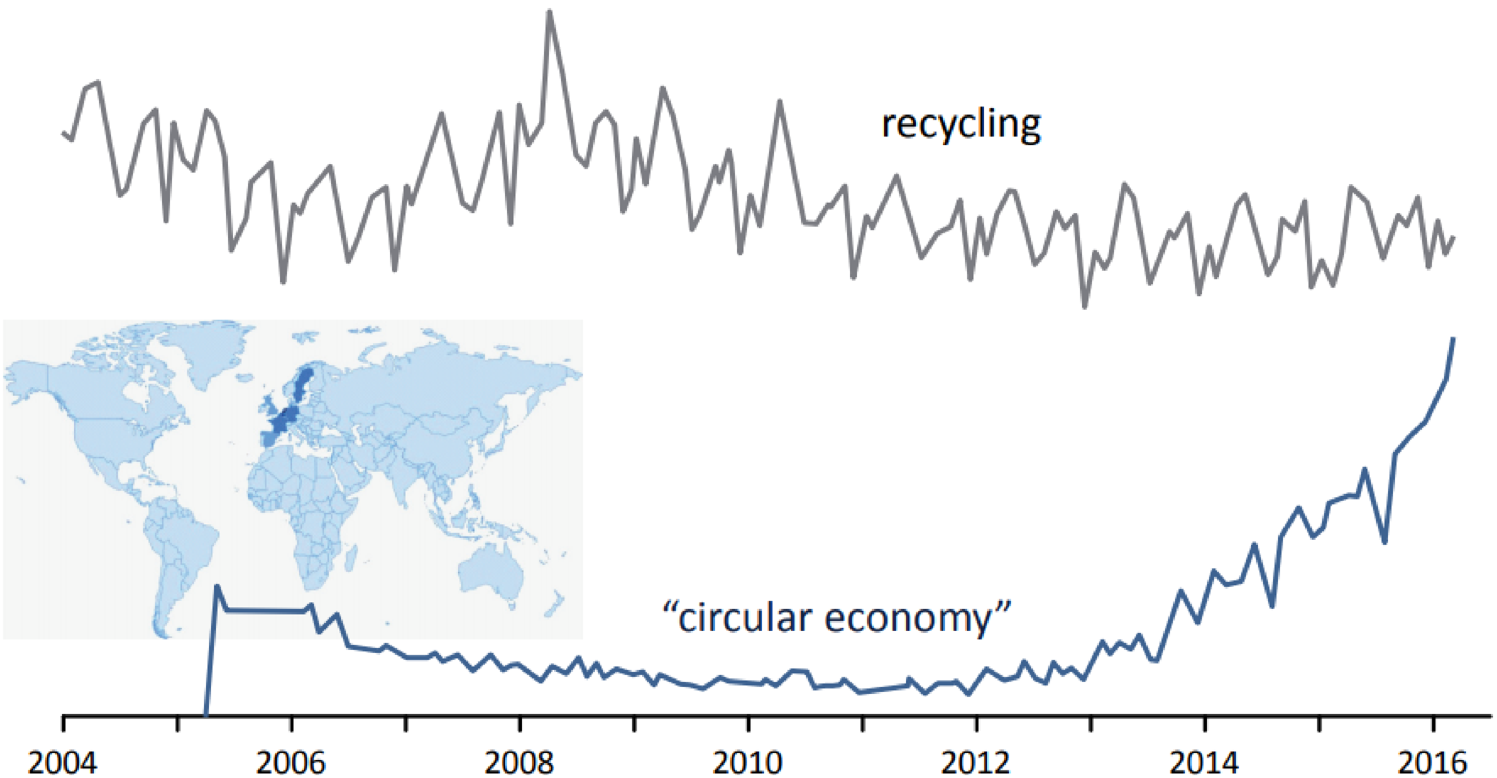

Figure 1. A Google Trends analysis of the interest in the topics 'circular economy' and 'recycling'. In absolute terms, circular economy was ca. 100-fold less popular than recycling. For 'circular economy' the regional distribution of interest in the term is shown, showing it to be a very European interest.

Source: Sprecher, B. (2016) When materials become critical : lessons from the 2010 rare earth crisis. PhD Thesis, Leiden University.

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Circular economy (CE)

- CE means many different things to different people
  - Ambiguousness blurs their conceptual contours and constrain efficiency of use (Gleissdoerfer et al, 2017)
  - based on key literature, *CE can be defined as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling*.

- Weak links to sustainable development (particularly social equity) among 114 examined CE definitions
  - Kirchherr et al found that most authors see CE as an avenue for economic prosperity
  - CE understandings mostly neglect social considerations

References: Kirchherr et al. (2017) Conceptualizing the circular economy: an analysis of 114 definitions. *Resources, Conservation, and Recycling*, 127:221-232.
Gleissdoerfer et al. (2017) The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143:757-768.

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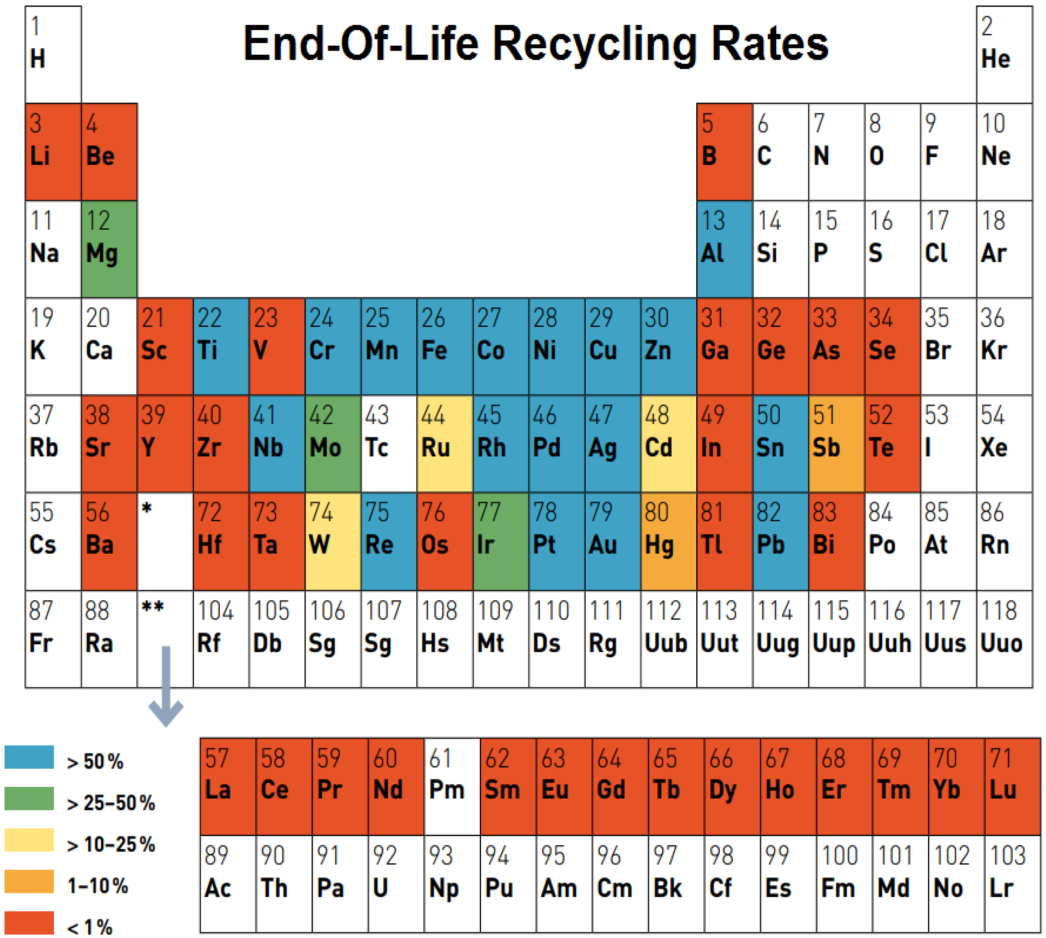
Recycling?



- Ongoing research and development for recycling, but it is challenging
  - REE, Li and other materials are often used in low concentration, making recycling challenging or even impractical
  - All REEs have similar chemical properties, making separation chemically challenging
  - Usually expensive compared to virgin material – economics matter!!!
- Significant lack of large scale recycling systems and regulations
  - It will take decades to build up a significant recycling industry with any major impact
- **Recycling should not be confused with circular economy or sustainability!**
  - It is relevant for CE and S, but not a guarantee
  - some authors misleadingly equate CE with just recycling (Kirchherr et al, 2017)

Source: *United Nations Environment Programme – Recycling Rates of Metals: a status report*
Kirchherr et al. (2017) Conceptualizing the circular economy: an analysis of 114 definitions. *Resources, Conservation, and Recycling*, 127:221-232.

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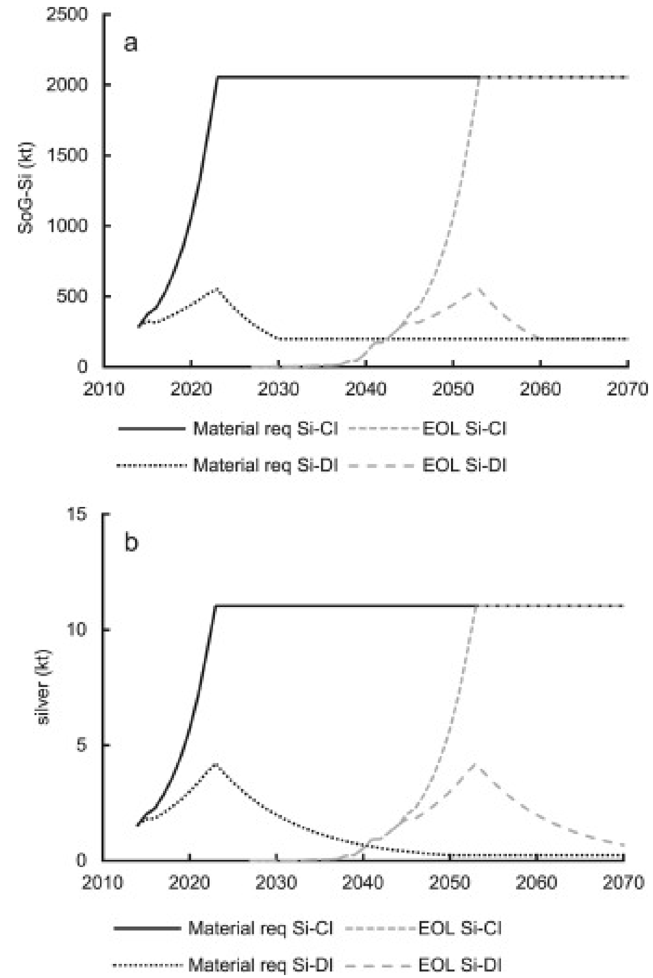
Material lock-in effects

- Even if all material from renewable tech was recycled, such contributions would not help a rapid growth

- Material lock-in effects
  - Most energy techs have >20 years of commercial life before scrapping and recycling



Source: Davidsson & Höök (2017) Material requirements and availability for multi-terawatt deployment of photovoltaics. *Energy Policy*, 108(9):574-582

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Future costs and recycling

- Over 14,000 abandoned wind turbines can be found in the USA, slowly rusting away
- Value of scrap steel is too low to make it viable for dismantling and proper recycling
- Economics and metal markets affect recycling and can change over operational life cycle

The rusting wind turbines of Hawaii

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Electrified transportation

- In 2013, 865 million passenger cars globally
  - Of this, 665 000 or 0.08% were EV/plug-in-hybrids
- In 2030, about 1.6 billion cars are on the roads if historical growth patterns remain
  - The IEA expects 100 million electric cars
  - Competition for Li from other sectors
- Unreasnable to assume that Li will be enough to electrify all cars within forseeable future

Sources: IEA

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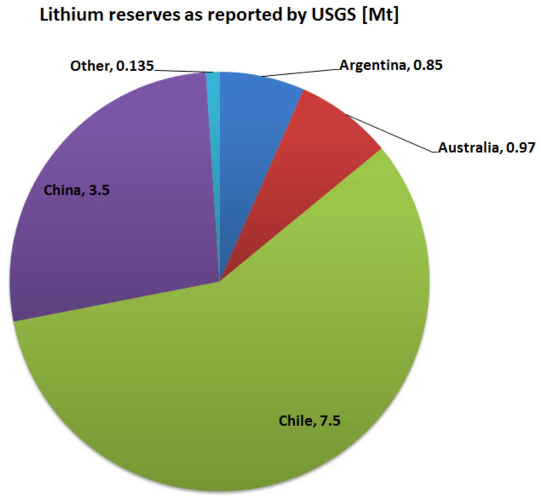
Lithium and security of supply

- Electrification is another hot topic for future carbon-free transportation

- However, will it improve energy security?
  - Lithium reserves are unevenly distributed



Is it sustainable to replace our Middle-eastern oil dependency with a Chilean lithium dependency?

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Lithium

- Large geological occurrences, but only in low concentrations (0.25-70 parts per million)
- Enrichment to high concentration only occurs in a few cases
- Strategic resource for high tech batteries and electric cars

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Lithium deposits

Pegmatites

- Hard rocks that must be pulverized
- The production chains requires just 3-5 days, but is expensive
- Australia & Russia are important producers

Salt lakes (brines)

- Can be found on high altitutes in dry regions
- Long production chain that requires >1-2 year
- Chile and Latin America is dominating

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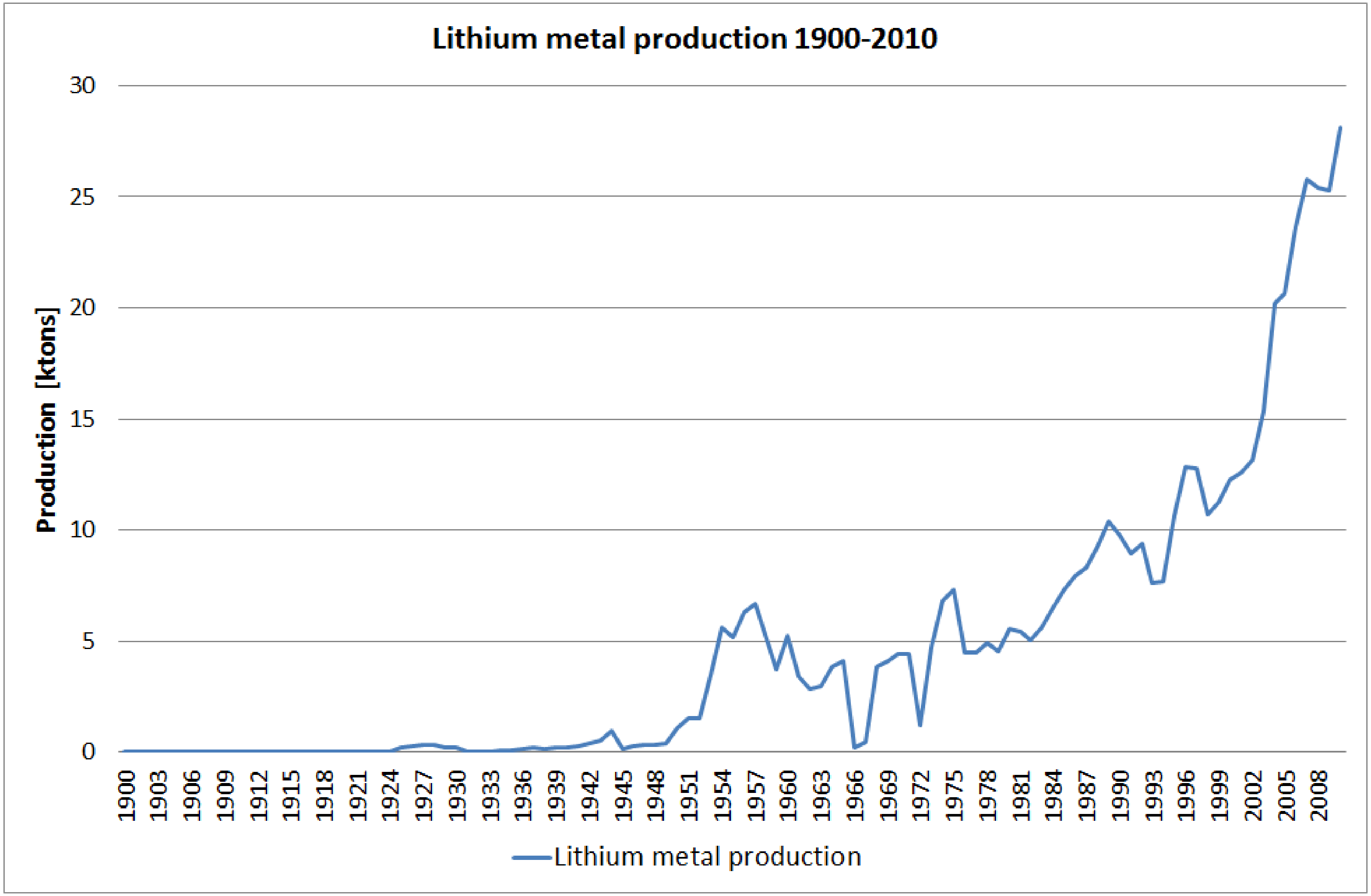
Lithium reserves

Land	Production [ton]	Reserves [ton]
Argentina	2,200	800,000
Australia	4,400	580,000
Brazil	110	190,000
Canada	480	180,000
Chile	7,400	7,500,000
China	2,300	540,000
Portugal	490	Not available
USA	classified	38,000
Zimbabwe	350	23,000
World	**18,000**	**9,900,000**

Source: USGS (2010)

Lithium production



Source: Vikström et al. (2013) Lithium availability and future production outlooks. *Applied Energy,*

Lithium consumption

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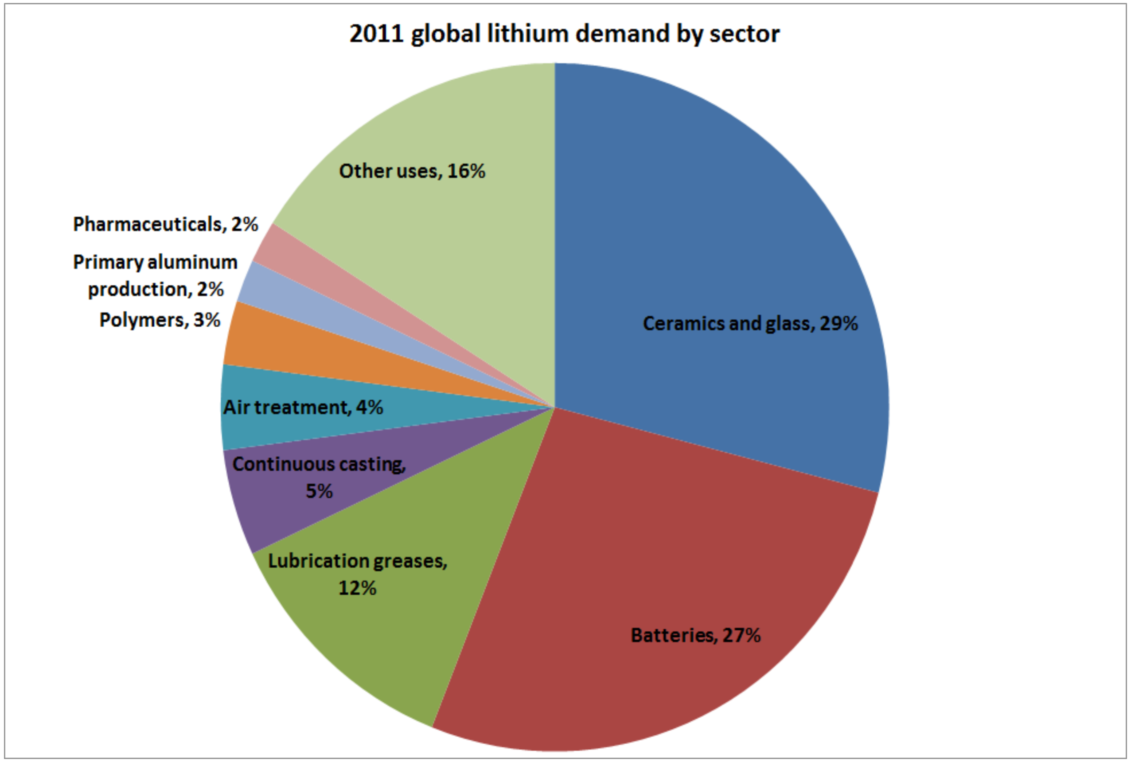

Estimated lithium consumption for Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicle (PHEV)

Reference	EV [kg]	PHEV [kg]
Falås and Troeng (2010)	2.7–4.3	1.2–2.0
Gruber et al. (2012)	5.1–7.7	1.5–2.3
JOGMEC (2009)	2.8–5.7	1.4–3.1
Kushnir and Sandén (2012)	5.8	1.4
Mean value	4.9	1.9

Källa: Vikström et al. (2013) Lithium availability and future production outlooks. Undergoing revision

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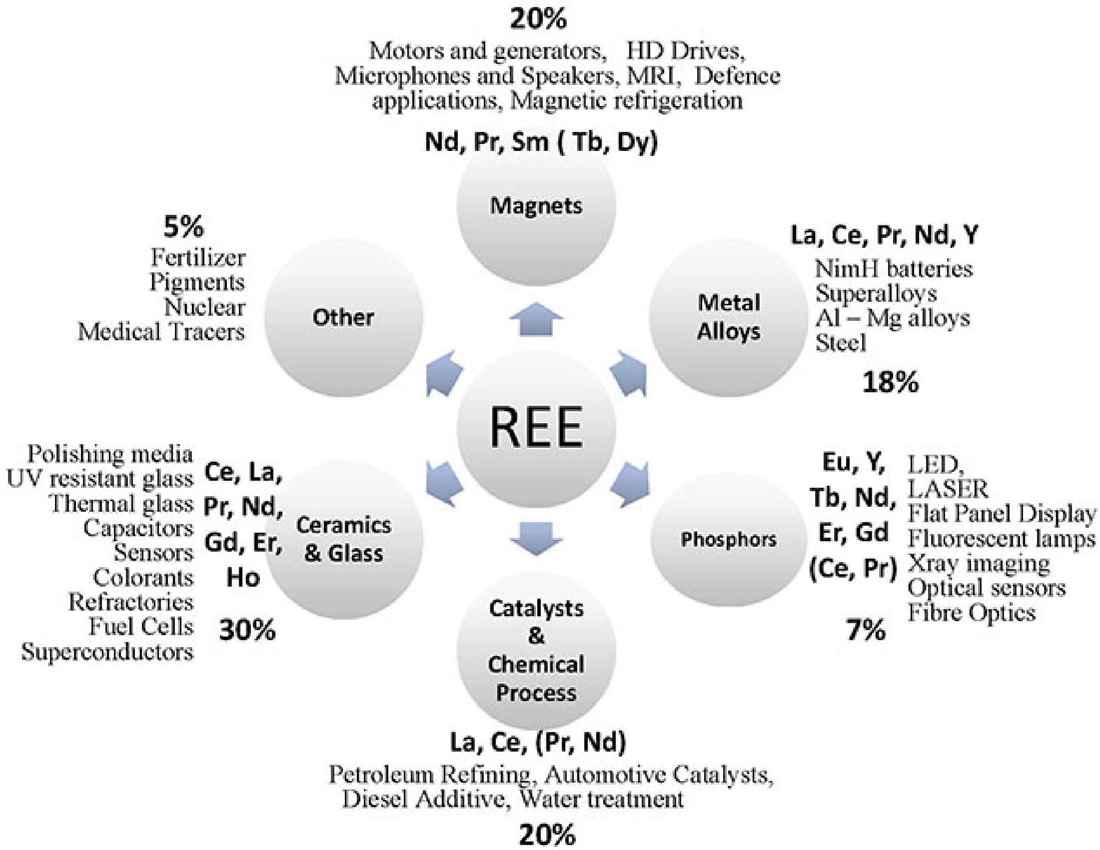
Types of lithium batteries

Battery type	Energy density	Uses
Lithium-Cobolt-Oxide ($LiCoO_2$)	150-240 Wh/kg	Mobile phones, laptops, cameras, etc.
Lithium-Manganese-Oxide ($LiMn_2O_4$)	100-150 Wh/kg	Tools, medical applications, EVs, etc.
Lithium-NMC ($LiNiMnCoO_2$)	90-120 Wh/kg	Electric bikes, EVs, industry, etc.
Lithium-Iron-Phosphate ($LiFePO_4$)	90-120 Wh/kg	Portable and stationary uses with high current
Lithium-NCA ($LiNiCoAlO_2$)	200-260 Wh/kg; expected up to 300 Wh/kg	EVs (Tesla), medical applications, etc.
Lithium-Titan-Oxide (LTO) ($LiTi_5O_{12}$)	70-80 Wh/kg	UPS, EVs (Mitsubishi i-MiEV, Honda Fit EV), etc.

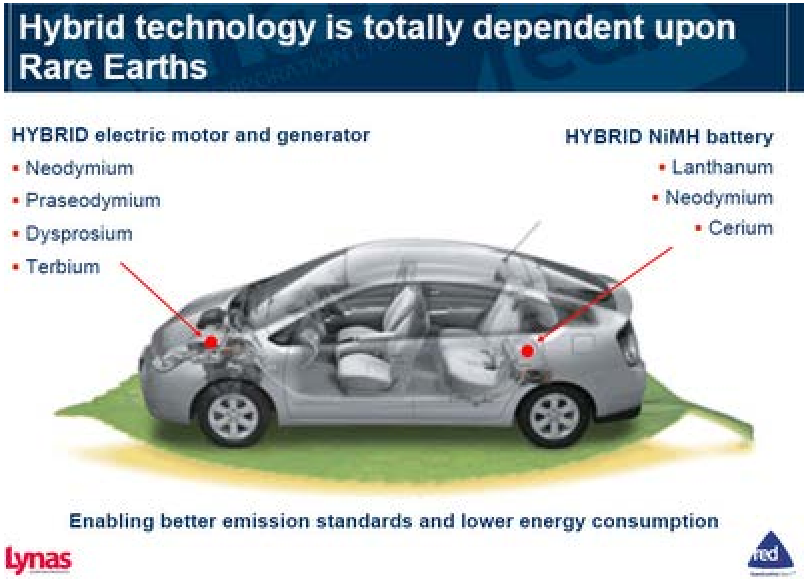
Source: Buschmann (2016) Types of Litium-Ion batteries

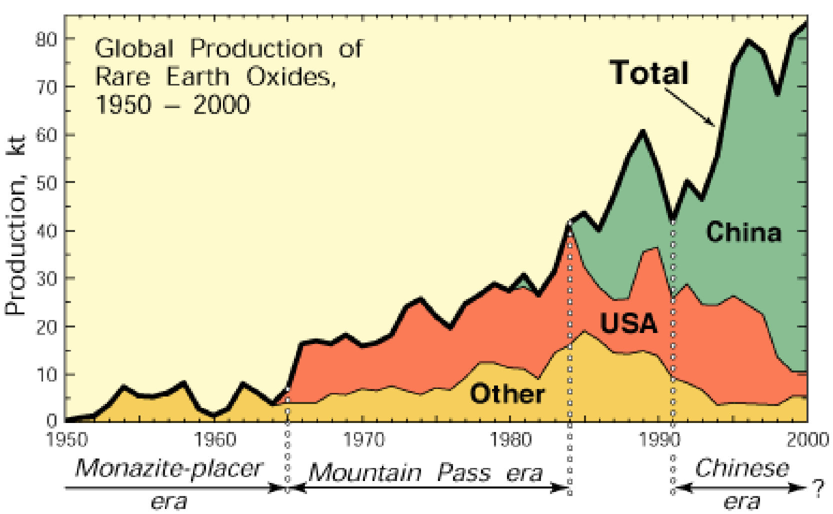
Rare earth elements

- REE is found in nearly all modern high tech
  - Motor and generator parts for electric systems
  - In fuel cells and various batteries
  - As addidatives in LED lights
  - As catalysts in chemical industry



Rare Earth Elements





- Fundamental for present high tech
- Reserves are concentrated to a few countries
- Import dependence applicable to many nations
- Energy security concerns for many green energy technologies

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Photovoltaics and rare elements

- Several solar energy technologies are dependent on rare materials and metals, such as:

- Gallium (CIGS-cells)
- Indium (thinfilm cells)
- Cadmium (thinfilm cells)
- Tellurium (thinfilm cells)
- Ruthenium (Grätzelcells & artificial photosynthesis)

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Global zinc resources

- 1.9 billion ton zinc in identified resources
- Only 180 million tons are economic to recover
- About 50% is located in China and Australia
- Governs the supply of by-products
- Future zinc mining is vital for future production of rare metals

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Indium

- The crust contains about 50 parts per billion of Indium, but this is uneconomic and impractical for recovery
- Can be extracted as a by-product from certain zinc ores where it can reach concentrations of 10-100 parts per million
- Also exists in bismuth, lead and tungsten ores, but hard to recover due to generally low concentration

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Indium production

- Only about 500 ton were mined in 2008, while 1200 ton came from recycling
- R/P = 18 years, hence recycling is important
- Indium is a likely constraint for future and wont suffice for massive expansion of In-dependent technologies
- Must be replaced with other and more abundant materials

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Ruthenium

- Extracted from platinum group ores
- Even more rare than gold (0.1 parts per billion on average crustal abundance)
- Mainly used in electronics and for coatings, but also as catalyst in oil refineries
- World reserves are just 5000 ton
- 75% of the world production of 12 tons comes from South Africa

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Significant limitations

Supply of raw materials could become a significant barrier for various solar energy technologies

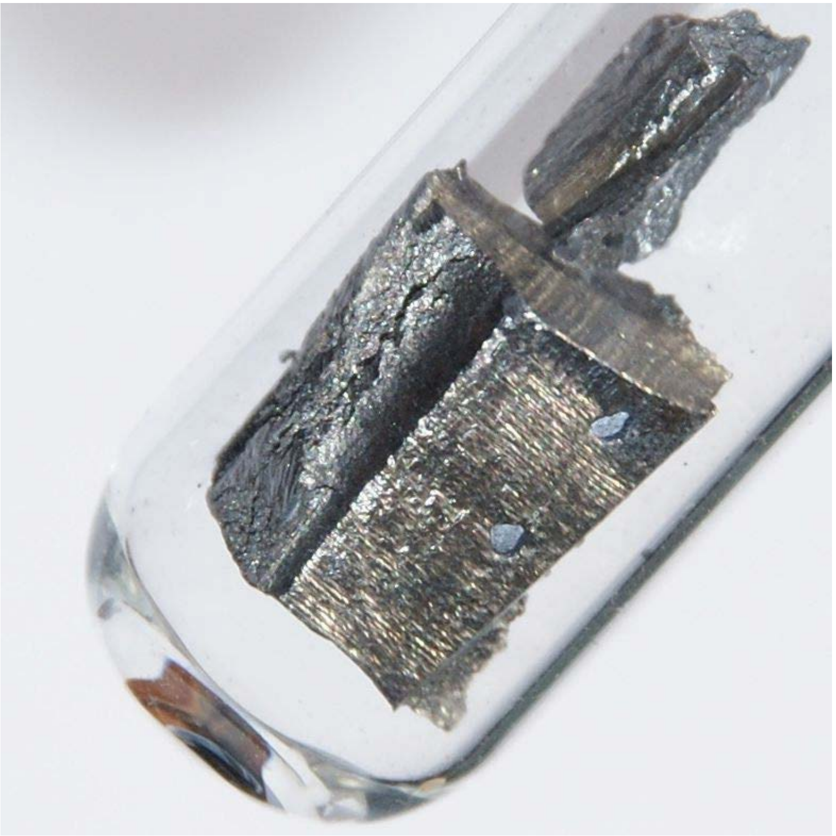
Table 2. Potential contribution to future world energy supply constrained by available reserves and resources. Three cases with 10%, 50% and 100% diversions to solar energy applications were considered. For comparison, world primary energy consumption in 2014 was slightly more than 13,000 Mtoe, final energy consumption 4700 Mtoe and electricity consumption 1600 Mtoe [6].

Technology	Material	Global Production	Reserves	Constrained Contribution			Resources	Constrained Contribution		
				10%	50%	100%		10%	50%	100%
		tons	tons	Mtoe	Mtoe	Mtoe	tons	Mtoe	Mtoe	Mtoe
CdTe	Cd	22,000	500,000 (2014)	190	930	1860	1,200,000 (2009)	450	2230	4470
	Te	~500	24,000 (2015)	8	40	80				
CIGS	In	820	11,000	9	40	90	65,000	50	260	510
	Ga	440	6500	30	140	280	N/A			
	Se	~2000	120,000	60	290	570	Se in coal deposits			
aSiGe or aSi/nc/Si	Ge	165	N/A				27,000	100	520	1040
	In	820	11,000	50	250	490	65,000	290	1450	2900
Grätzel	Ru	12	5000	60	320	640	N/A			

Source: Grandell & Höök (2015) Assessing rare metals availability challenges for solar energy technologies. *Sustainability*, *7*(9):11818-11837

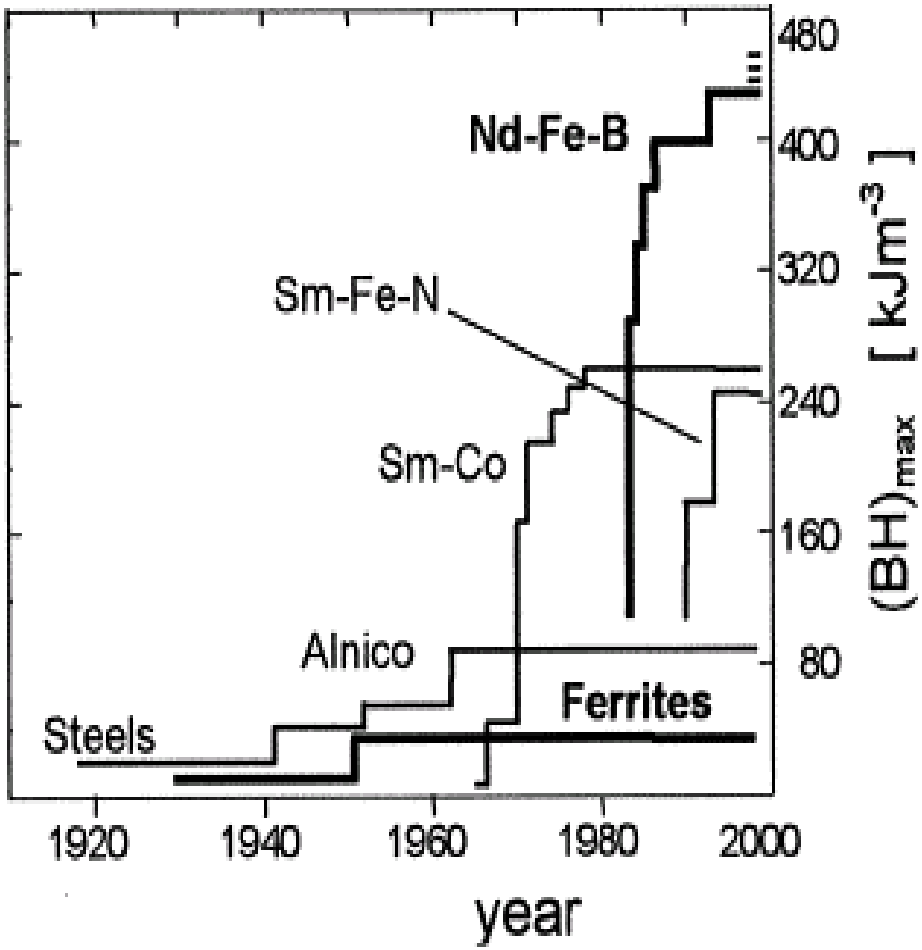
Neodymium (Nd)

- Rare Earth Element
- Rarely occurs in economic concentrations due to its ion radius
- Only a few important minerals provide it, mostly bastnäsite or monazite



Nd magnets

- The strongest permanent magnets that are available
- Used in generators in wind turbes to reduce weight
- Special designs can contain several hundreds of kg of Nd



Source: Muller (2001) *New Permanent magnets*. Journal of Magnetism and Magnetic Materials

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Vestas V112 - 3 MW

- Contains 105 kg Neodymium, which saves about 10 ton of steel
- This is still a conventional design with gear-box but Nd allows for both size and weight reductions
- Direct driven turbines without gearboxes can contain even more Nd per turbine (estimated to be between 100 to 600 kg/MW capacity)

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Nd mining

- Neodymium has only been mined as primary ore in one single mine, Mountain Pass in the USA
- In over 90% of all cases, Nd has just been a by-product to other ores such as iron, thorium, uranium, etc.
- Mining of monazite sand is forbidden in Europe, Australia and China due to associated radioactivity, but is still mined in small scales in some countries

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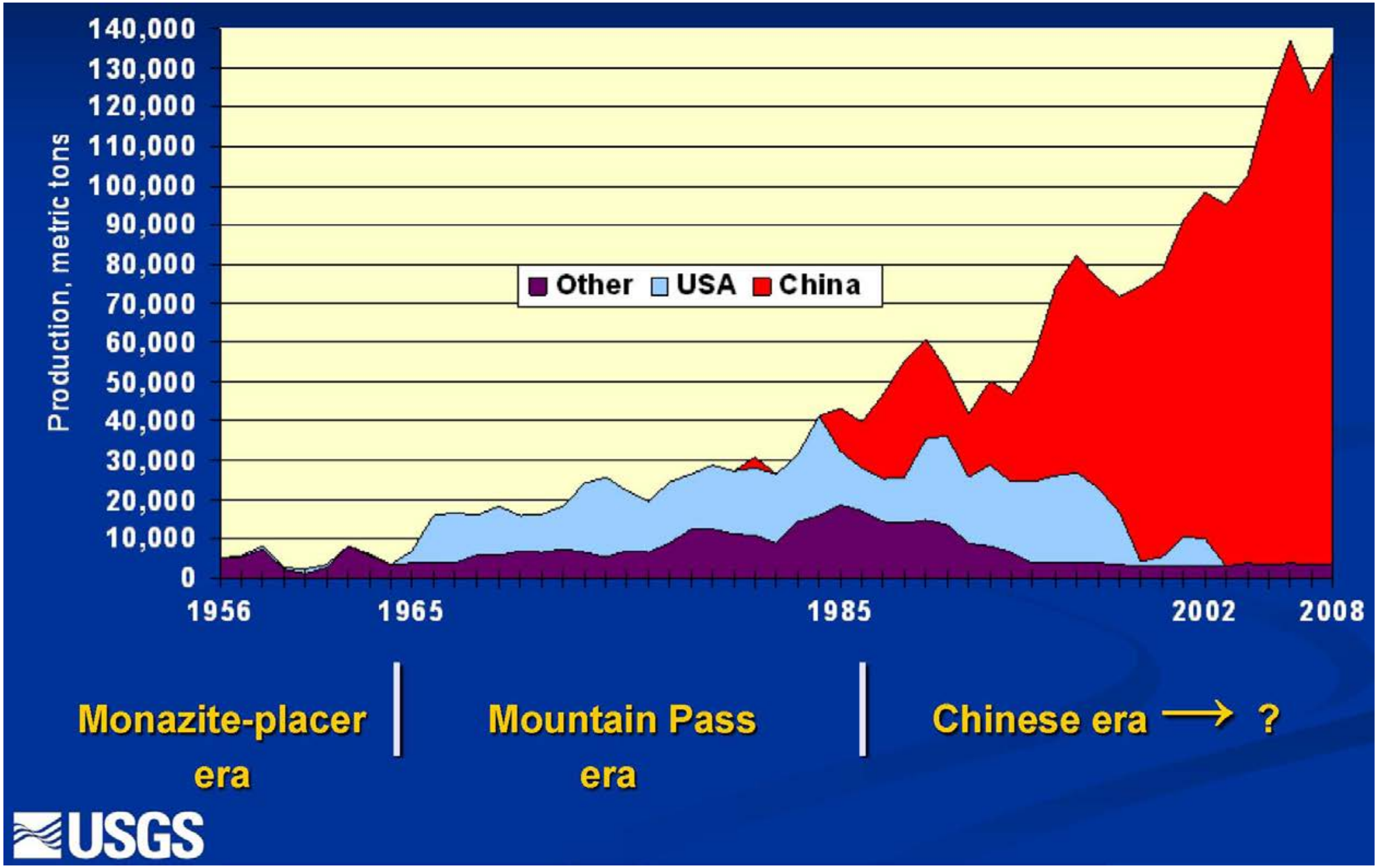
Environmental impact of Nd

- Co-existence with radioactive heavy metals makes Nd-production comparable with uranium mining
- The Mountain Pass mine had to close in 2002 due to severe environmental hazards and radioactive contamination (although its being reopened)
- Certain investors have decided to remove Nd-based wind power from the list of environmentally friendly energy technologies

China accounts for 95% of world production



Source: Tse (2011) China's rare-earth industry: U.S. Geological Survey Open-File Report 2011–1042, 11 p.

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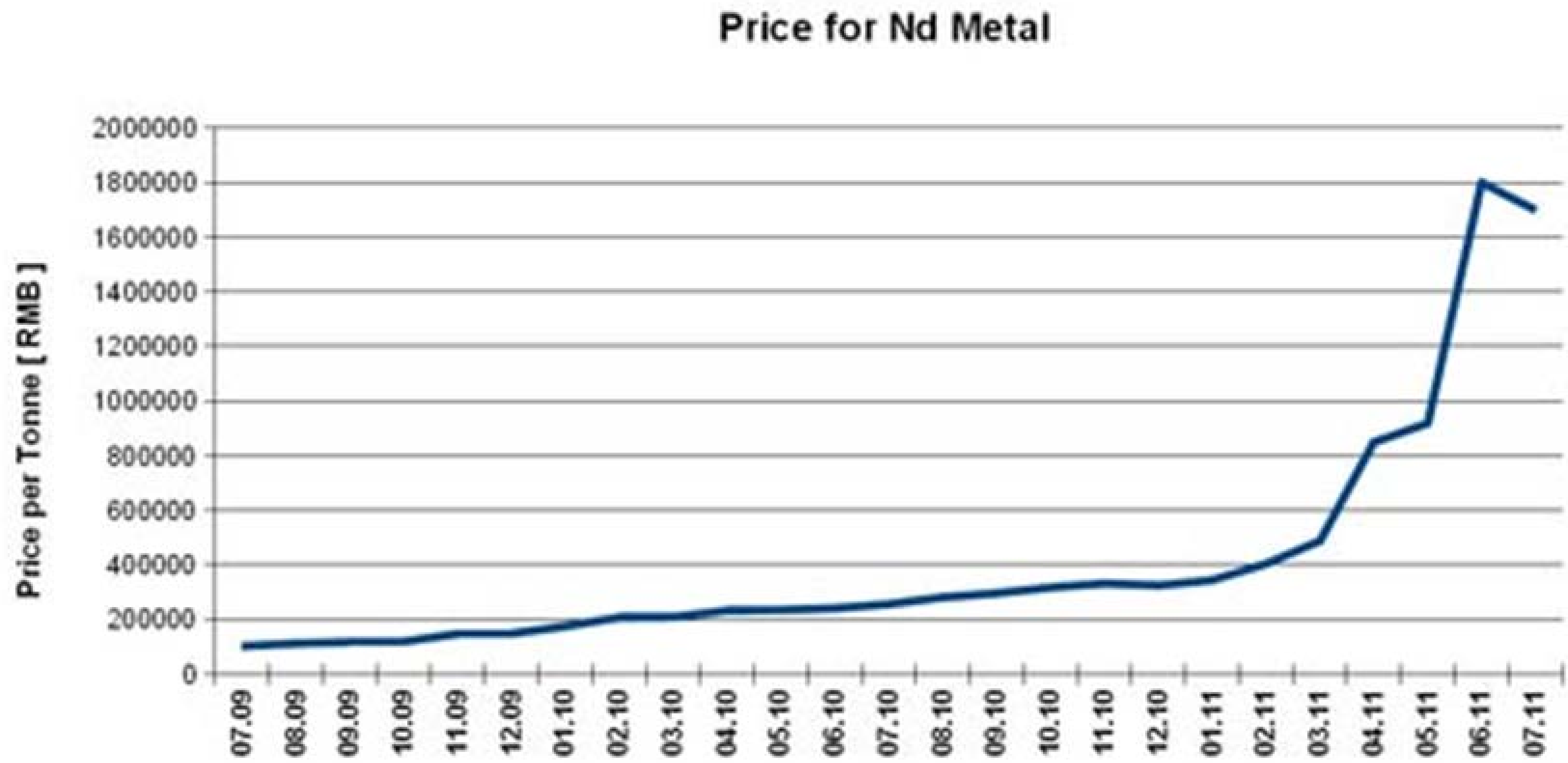
Rising prices and export quotas



In 2011, China increased the export fee for Nd from 300 000 yuan per ton to 600 000 RMB per ton and reduced the allowed export volume

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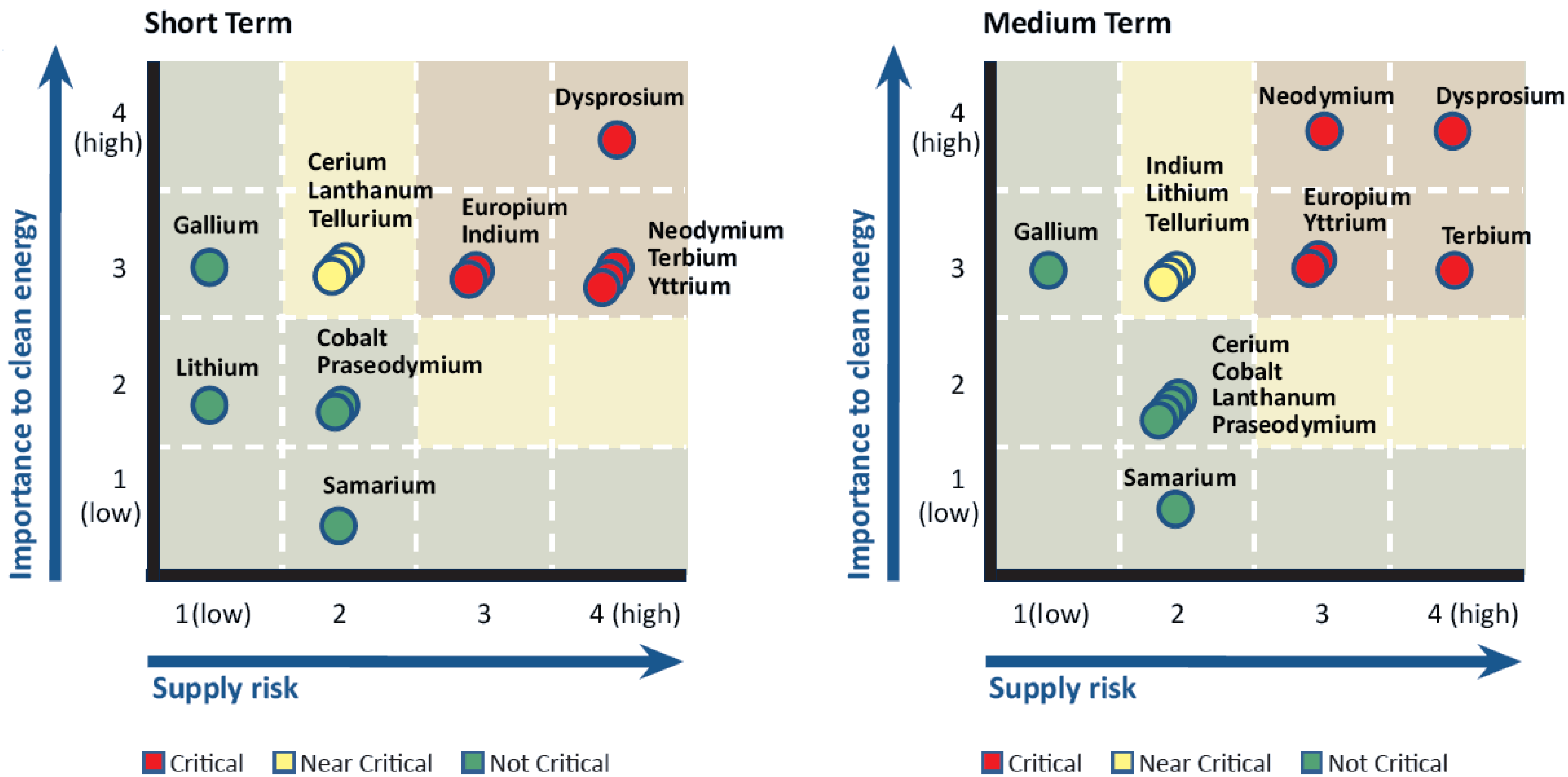
Determining risks



Source: Davidsson et al (2012) A review of life cycle assessments on wind energy systems. *International Journal of Life Cycle Assessment*, 17(6):729-742

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Even low-carbon minerals have ethical burdens

Amnesty warns on use of child labour in cobalt mining

Companies 'not doing enough' to ensure ethical supply of metal used in batteries

A woman and child break rocks extracted from a cobalt mine in Lubumbashi in the Democratic Republic of Congo © AFP

Henry Sanderson and **Chloe Cornish** NOVEMBER 15, 2017 1

Workshop – Blood Batteries: The dark side of renewable energy

A STAKEHOLDER CONFERENCE ARRANGED BY LUND UNIVERSITY AND RAOUL WALLENBERG INSTITUTE

Sources: Amnesty International (2016) *"This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt*. Amnesty Report Index number: AFR 62/3183/2016

U.S. Fish and Wildlife Service (2014) Avian mortality at solar energy facilities in Southern California: a preliminary analysis

Reilly (2016) *The Human Cost of the Lithium Battery Revolution*. MIT Technology Review, 3 October 2016

Kesselring (2017) The electricity crisis in Zambia: Blackouts and social stratification in new mining towns. *Energy Research & Social Science*, 30:94-102 .

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Stegen (2015) Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. *Energy Policy*, 79, 1-8.

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Summary

- Renewable energy sources are not always more secure or ”*sustainable*” since they still rely on natural resources and external supply
  - A renewable energy transition is no different as it relies on many imported material flows and is exposed to external and geopolitical risks
- Minding the full transnational flow picture of material risks, environmental and social impacts are essential for holistic views on sustainability in line with SDG12
  - Securing material for green/clean energy requires full life cycle views on risks

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Thanks for your attention!

Read more here:

Global Energy Systems: http://www.geo.uu.se/