Strategic Materials in the Energy Transition

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- The great challenge
- Energy supply and green house gas emission
- Material criticality and conflict metals
- Substitution and Recycling
- Raw material needs wind energy, E-mobility and cooling

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https://scholar.google.de/citations?user=IMtVJ68AAAAJ&hl=de

ResearcherID: C-7241-2011

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THE GRAND CHALLENGE

Transition to 100% renewables

There is growing awareness that human activities are having a major impact on the earth’s ecosphere—so much so that many are now defining a new geological era: the **Anthropocene**, a time when humans have become the driving force in the earth’s physical changes.

With the **global human population expected to reach over 9 billion by 2050**, urbanization, access to energy, infrastructure development, and poverty reduction will result in an **unprecedented strain on our planet’s natural resources and environment**.
(World Bank 2017)

ENERGY SUPPLY

SOLAR RESOURCE IS FUNDAMENTALLY INTERMITTENT → STEADY AND RELIABLE SOURCE OF ELECTRICITY

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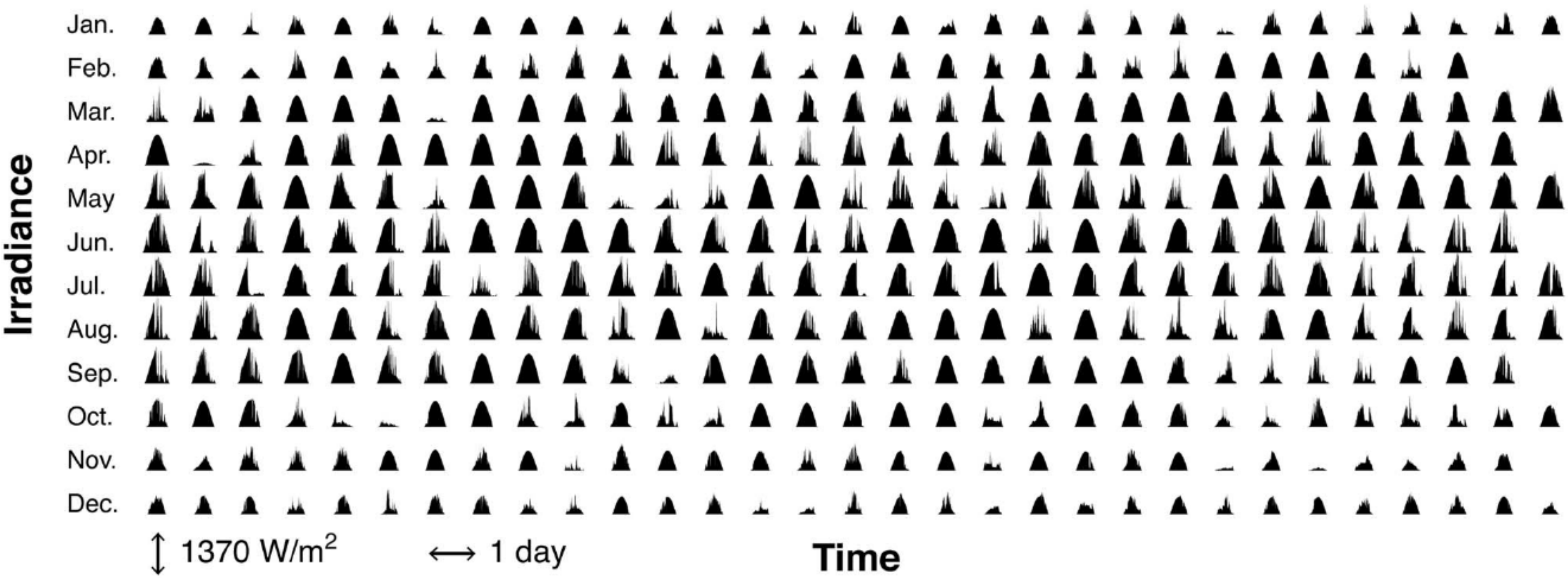


Fig. 1 Complete minute-by-minute solar irradiance profile in Golden, CO, for the year 2012. The time axis is to scale, with nights included.

Energy Environ. Sci. 2015, 8, 1200–1219

FUNKTIONALE MATERIALIEN

Average solar budget: 188 W / m² or 4.5 kWh per m²

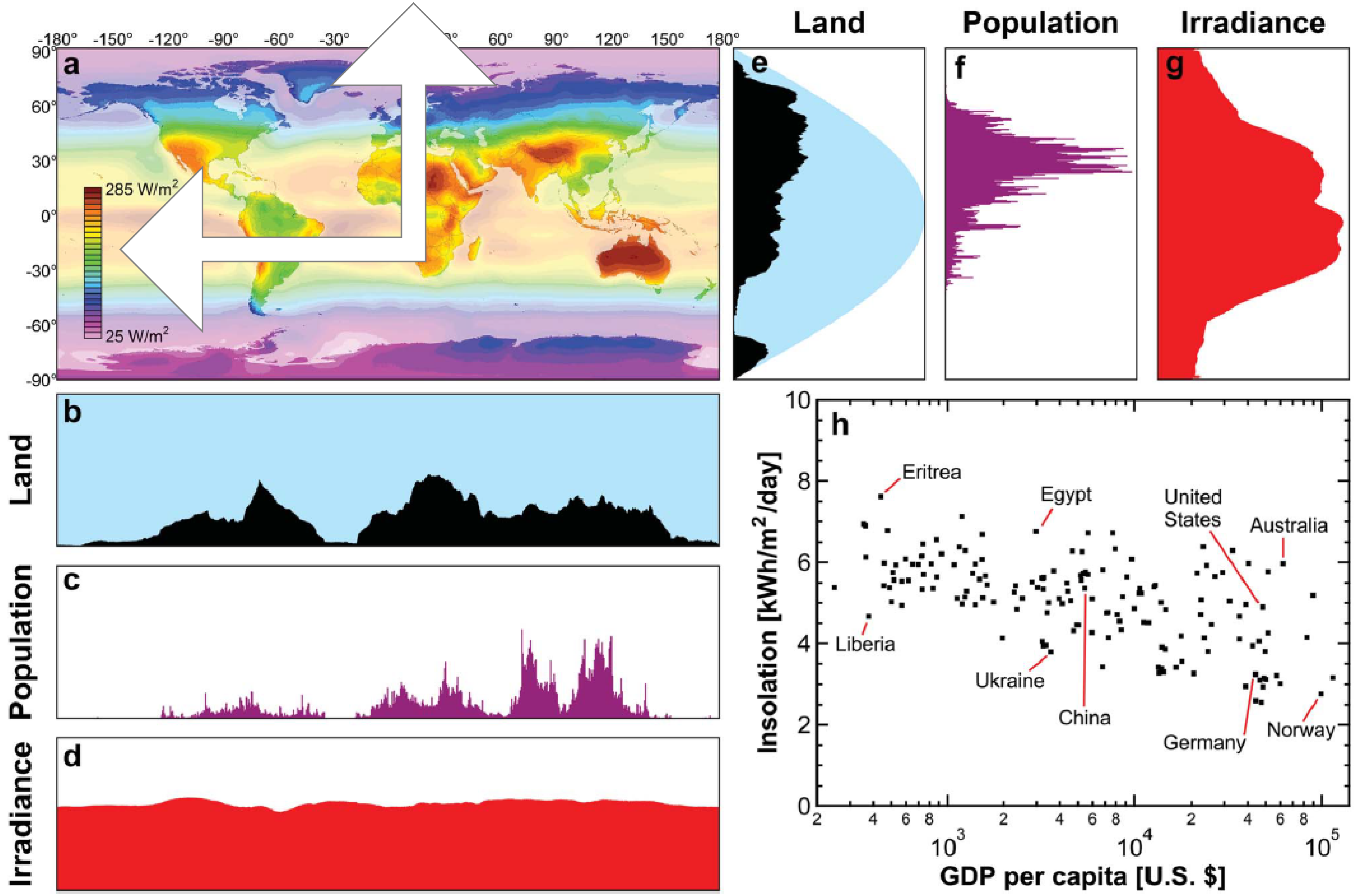
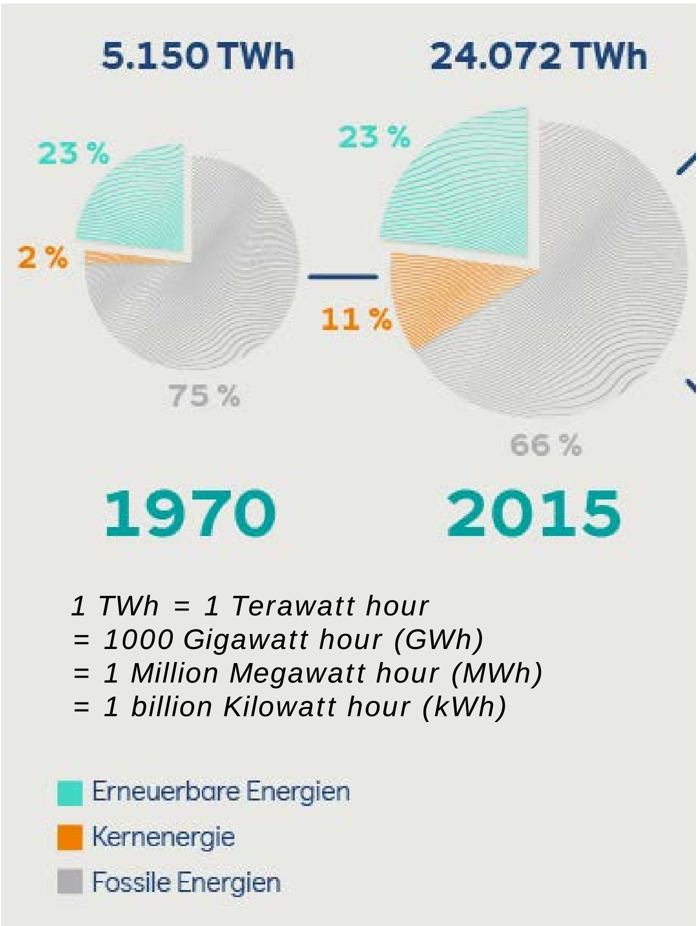
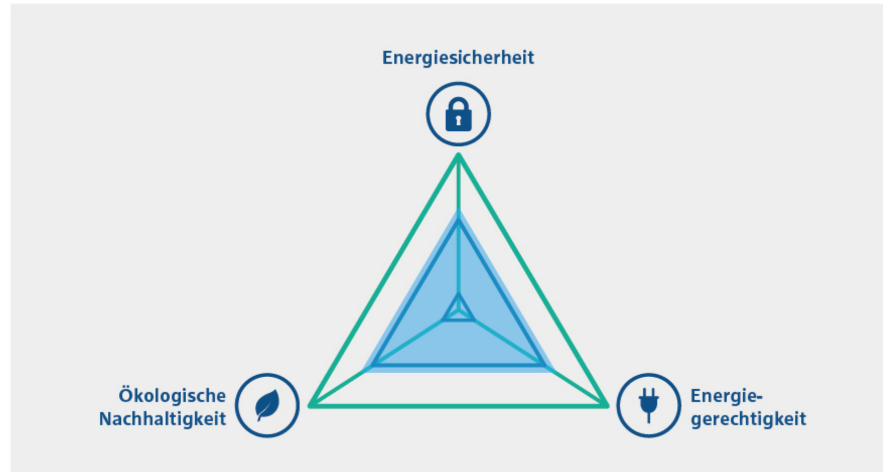


Fig. 2 Worldwide distribution of the solar resource. (a) Global map of solar irradiance [W m^{-2}] averaged from 1990 to 2004 (©Mines ParisTech/ Armines 2006).[20] Histograms of world land area [m^2 per °], population [persons per °] (reproduced with permission from ref. 21), and average irradiance at the Earth's surface [W m^{-2}] are shown as a function of longitude (b–d) and latitude (e–g). In (b) and (e), land area is shown in black, and water area is shown in blue. (h) Correlation of average insolation and GDP per capita by country for the year 2011.[18,19] Each dot represents one country.

ENERGY SYSTEMS – ENERGY SUPPLY



1 TWh = 1 Terawatt hour
= 1000 Gigawatt hour (GWh)
= 1 Million Megawatt hour (MWh)
= 1 billion Kilowatt hour (kWh)

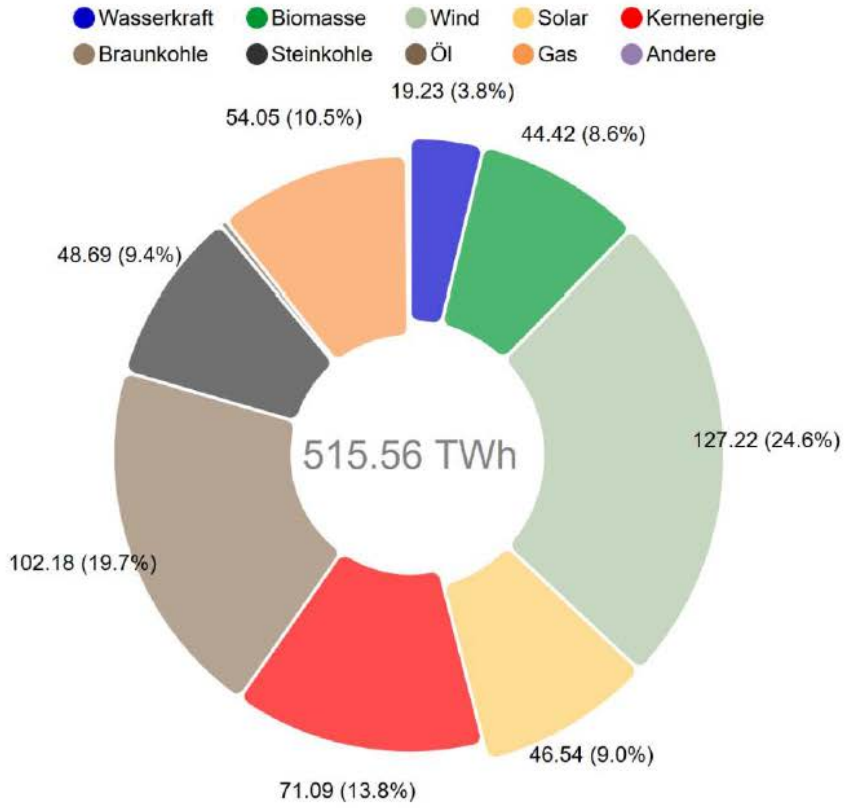


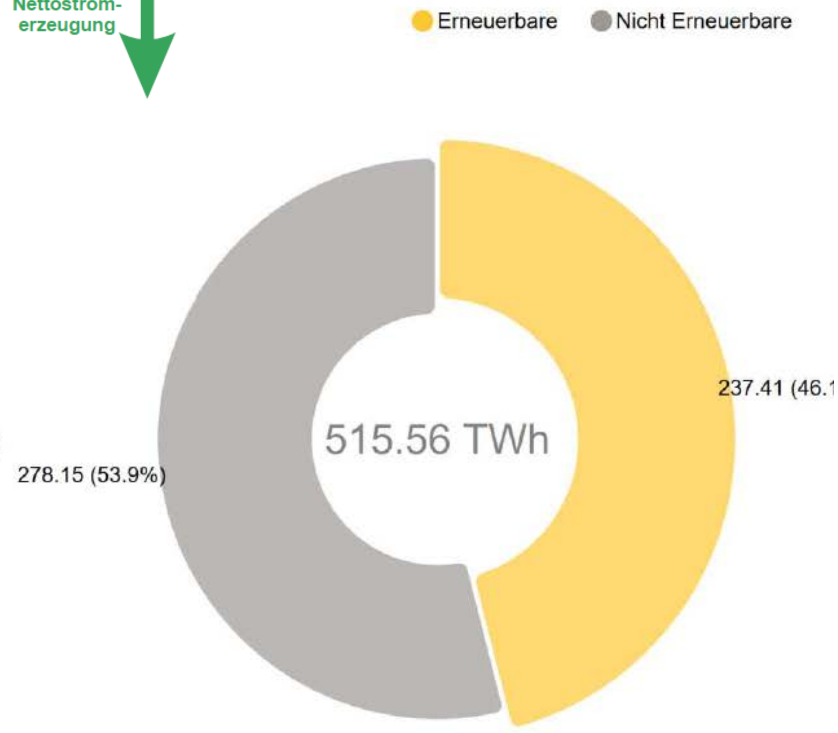
Threefold dilemma
(adapted from World Energy Council)

https://www.en-former.com/europaeische-energiesysteme-belegen-spitzenplaetze/

Global electricity generation (in TWh)
source: H.-W. Schiffer auf Basis von BP Statistical Review of World Energy und World Energy Council, Paul Scherrer Institute, Accenture Strategy: World Energy Scenarios/2019, September 2019.

Net electricity generation 2019 in Germany





https://www.ise.fraunhofer.de/content/dam/ise/de/documents/news/2019/Stromerzeugung_2019_2.pdf

NET ELECTRICITY GENERATION 2019 IN GERMANY

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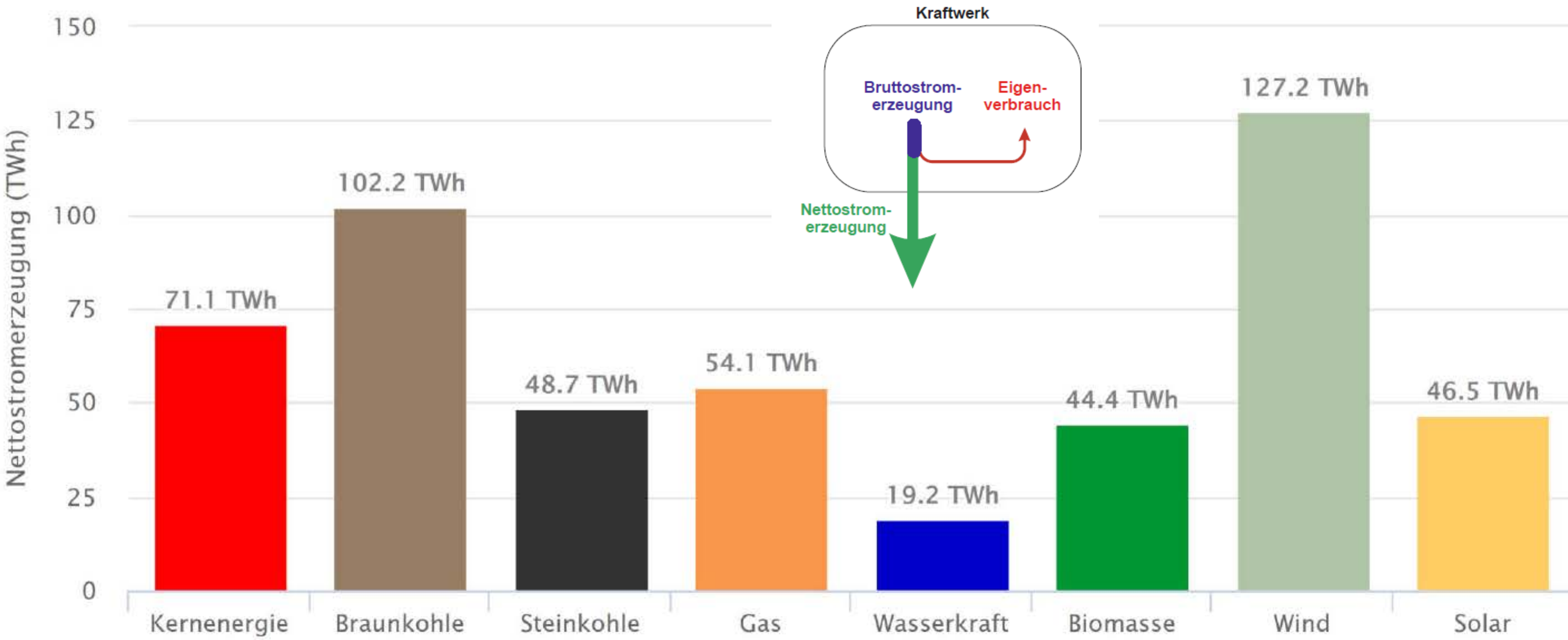

https://www.ise.fraunhofer.de/content/dam/ise/de/documents/news/2019/Stromerzeugung_2019_2.pdf

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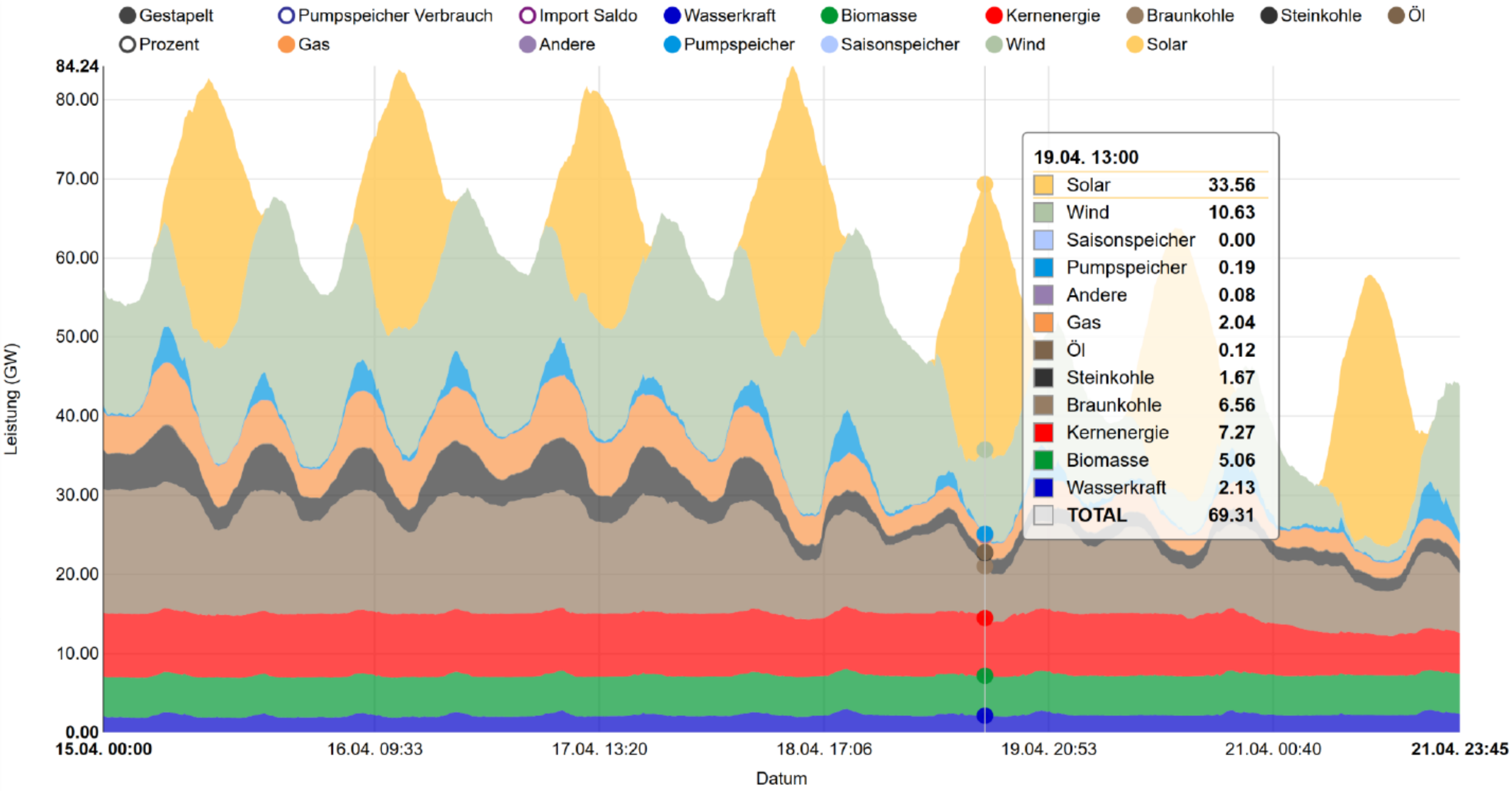
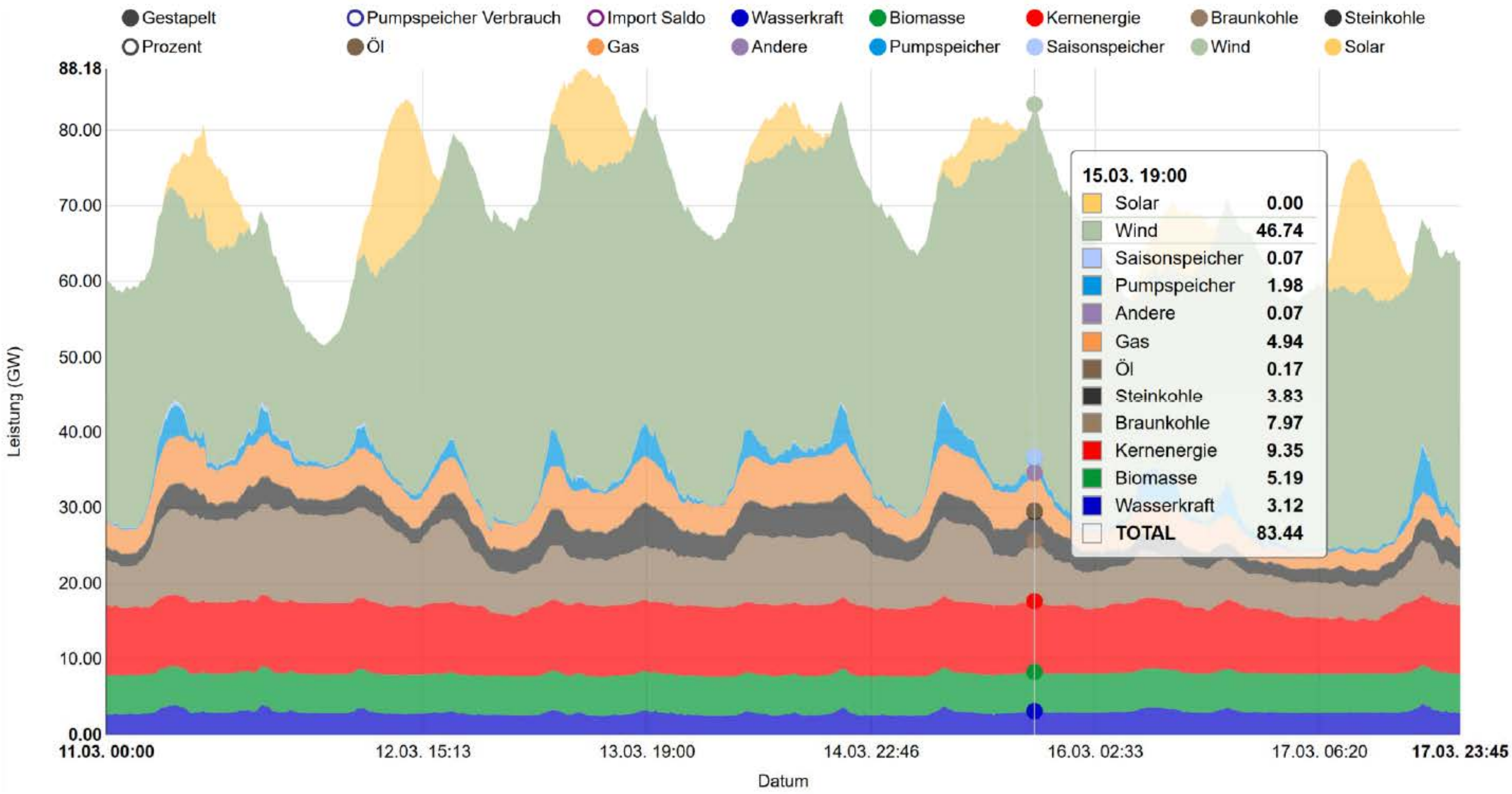
Highest electricity generation from Solar
week 16 2019 / Germany

Grafik: B. Burger, Fraunhofer ISE; Quelle: https://www.energy-charts.de/energy_de.htm?source=all-sources



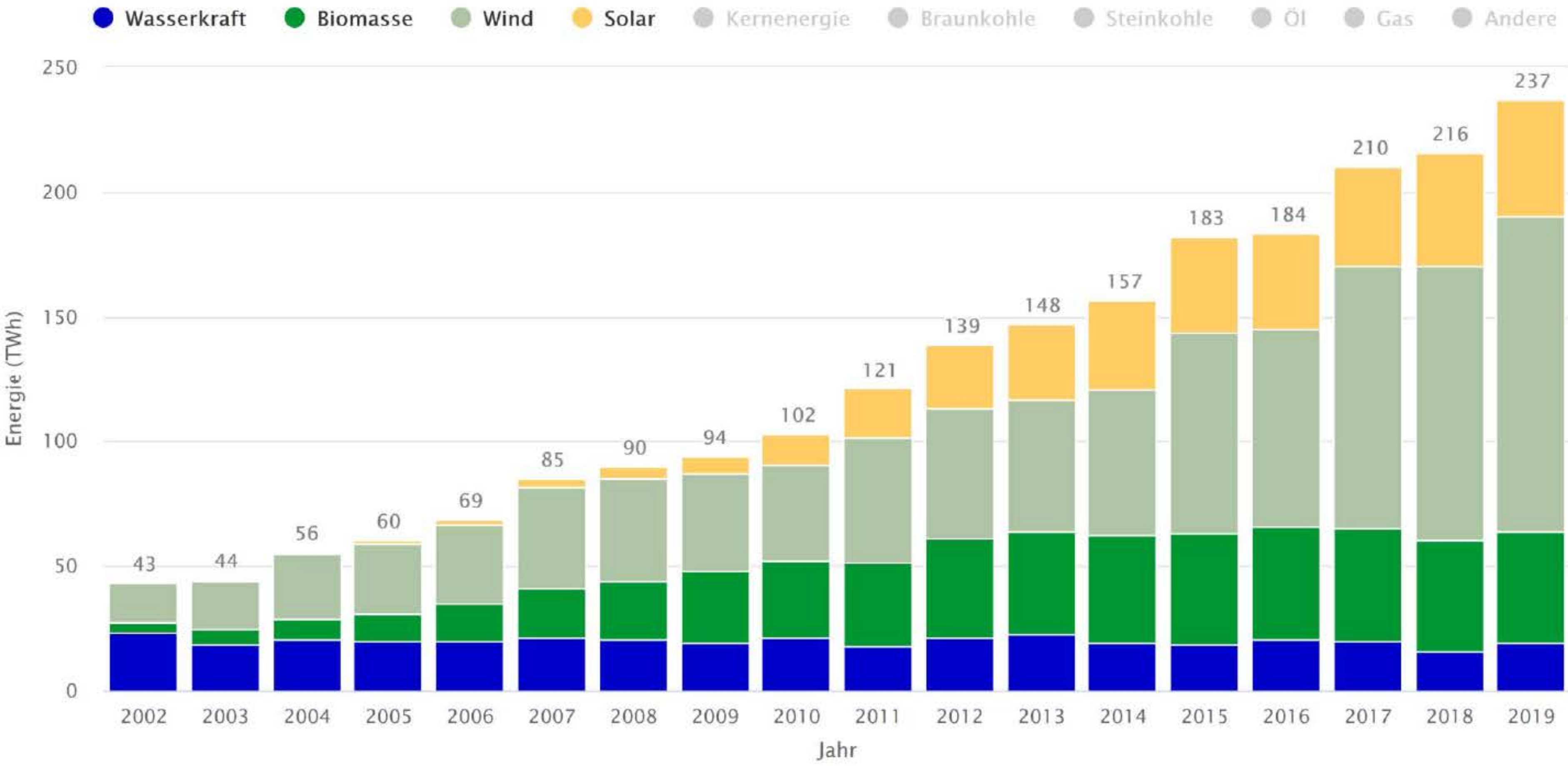
Highest electricity generation from Wind
week 10 2019 / Germany

Grafik: B. Burger, Fraunhofer ISE; Quelle: https://www.energy-charts.de/energy_de.htm?source=all-sources



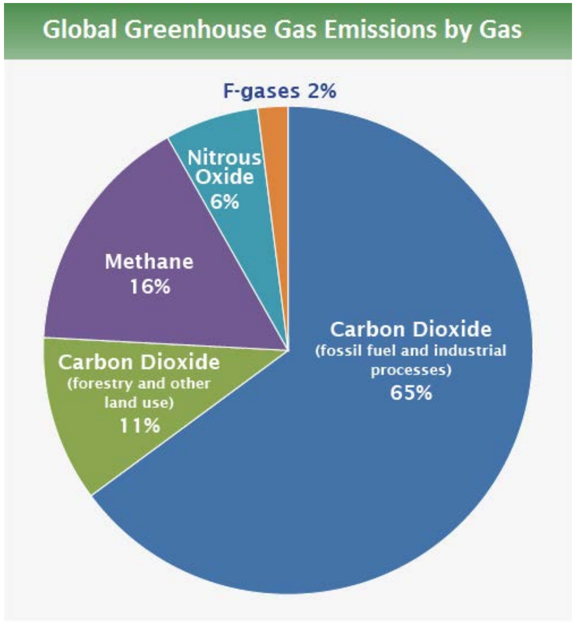
Net electricity generation from renewable energies 2002 - 2019

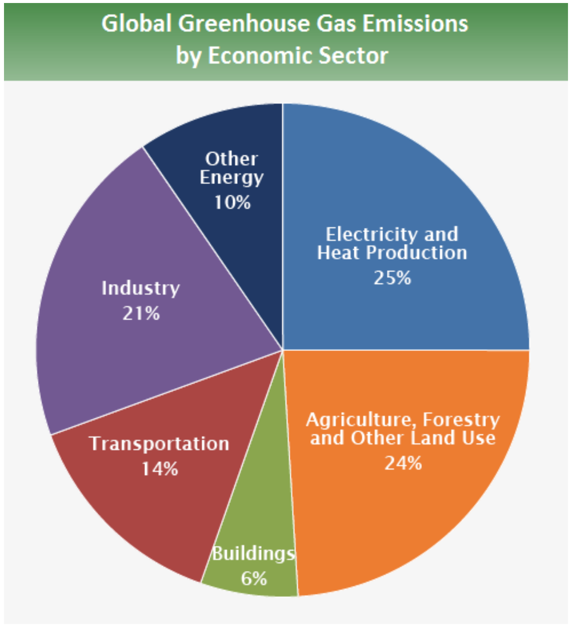
Grafik: B. Burger, Fraunhofer ISE; Quelle: https://www.energy-charts.de/energy_de.htm?source=all-sources

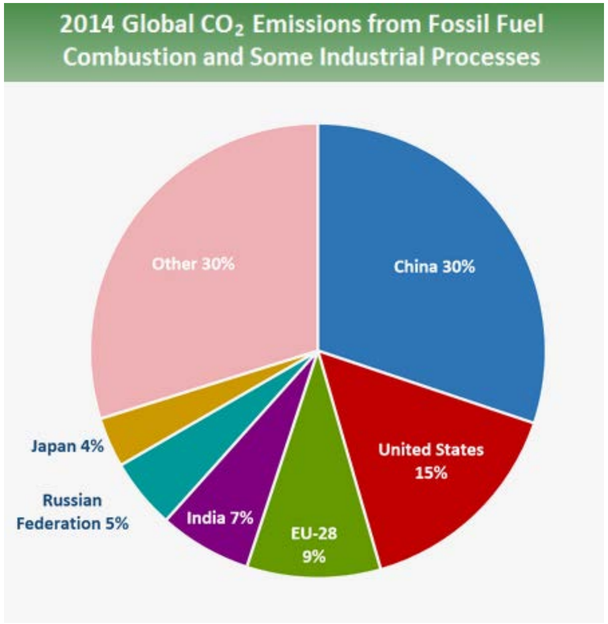


Green House Gas Emission

GLOBAL GREENHOUSE GAS EMISSIONS







Source: IPCC (2014) Exit based on global emissions from 2010. Details about the sources included in these estimates can be found in the Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

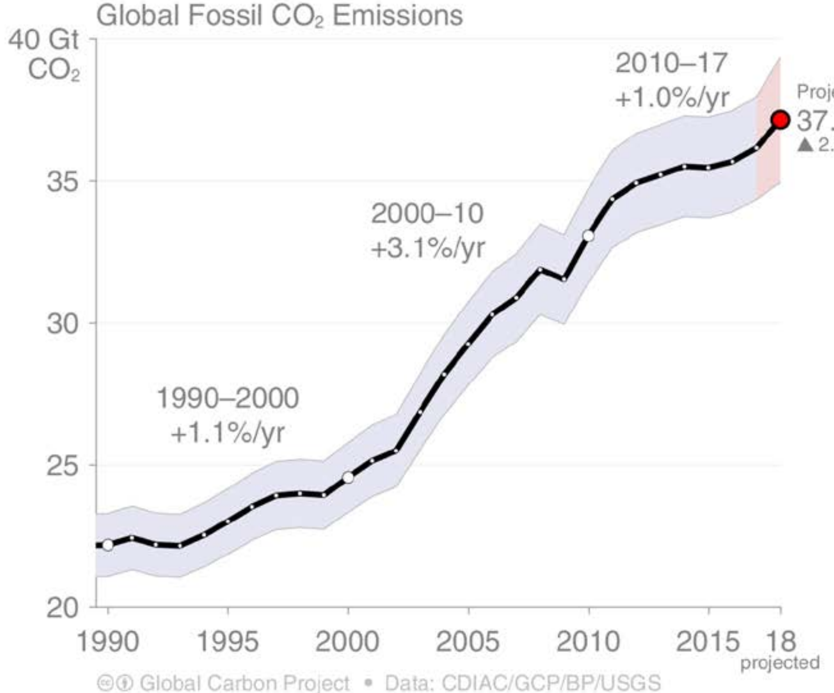
https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

GLOBAL GREENHOUSE GAS EMISSIONS

https://www.globalcarbonproject.org/

Global fossil CO_2 emissions: 36.2 ± 2 $GtCO_2$ in 2017, 63% over 1990

● Projection for 2018: 37.1 ± 2 $GtCO_2$, 2.7% higher than 2017 (range 1.8% to 3.7%)



Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

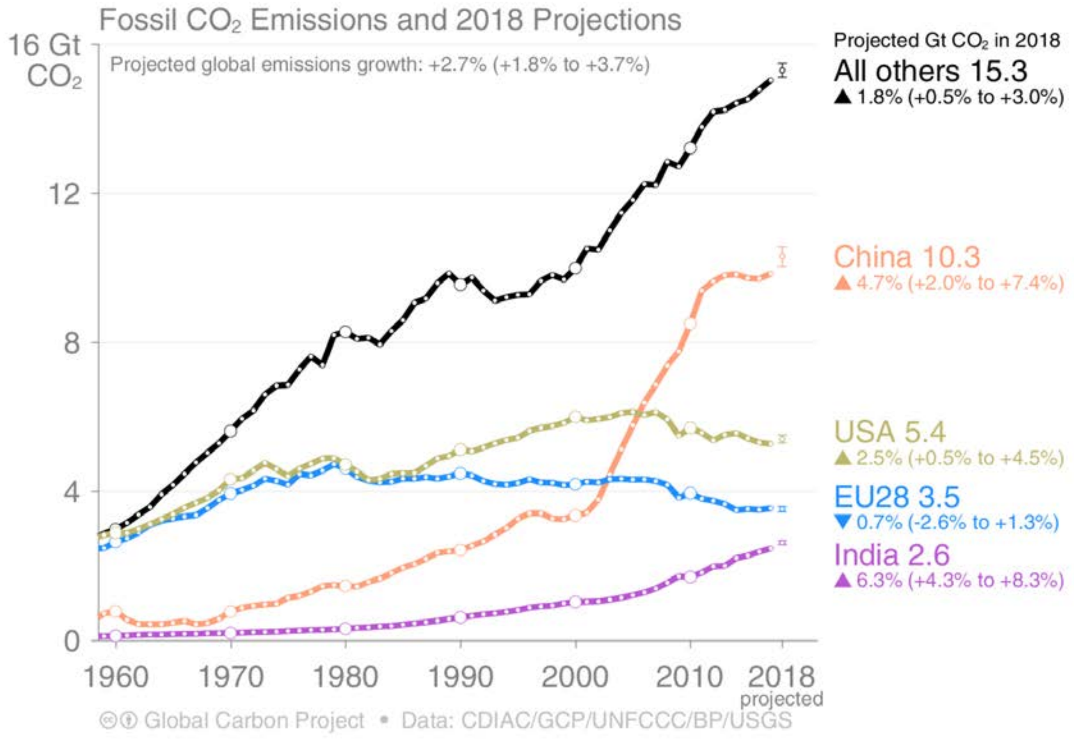
Estimates for 2015, 2016 and 2017 are preliminary; 2018 is a projection based on partial data.

Source: CDIAC; Le Quéré et al 2018; Global Carbon Budget 2018

GLOBAL GREENHOUSE GAS EMISSIONS

https://www.globalcarbonproject.org/

Global fossil CO_2 emissions are projected to rise by 2.7% in 2018 [range: +1.8% to +3.7%]
The global growth is driven by the underlying changes at the country level.

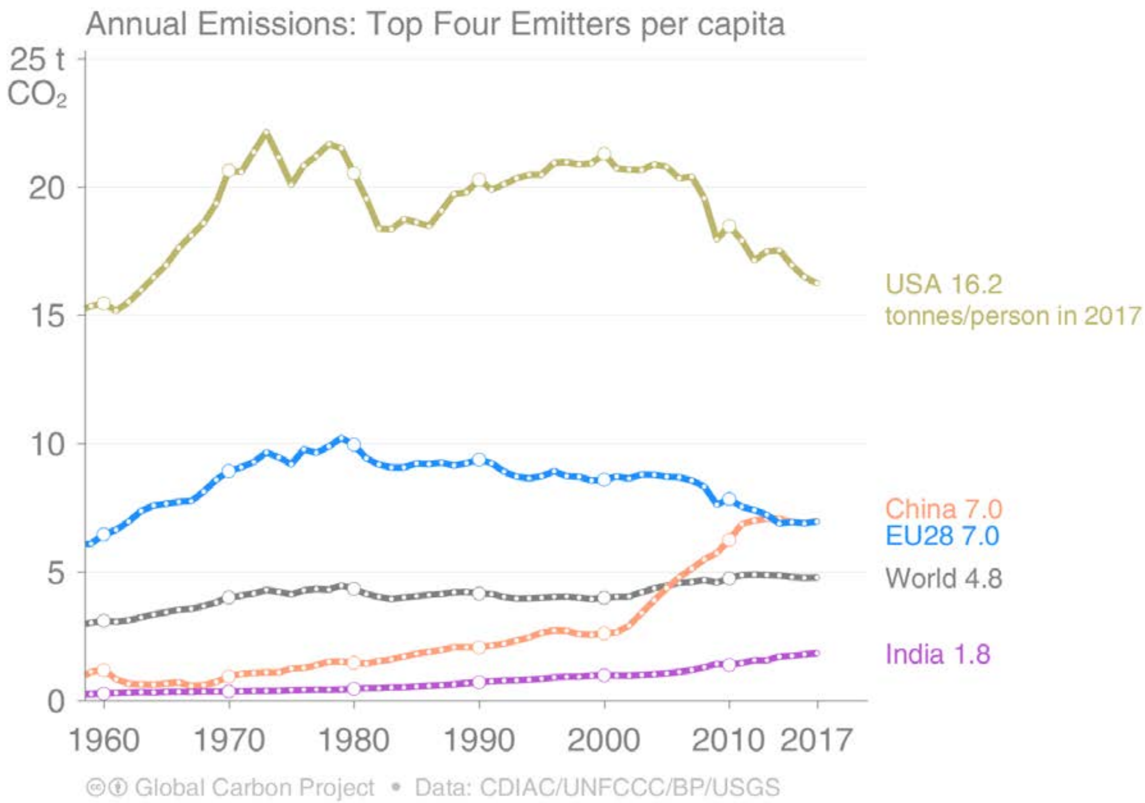


Source: CDIAC; Jackson et al 2018; Le Quéré et al 2018; Global Carbon Budget 2018

GLOBAL GREENHOUSE GAS EMISSIONS

https://www.globalcarbonproject.org/

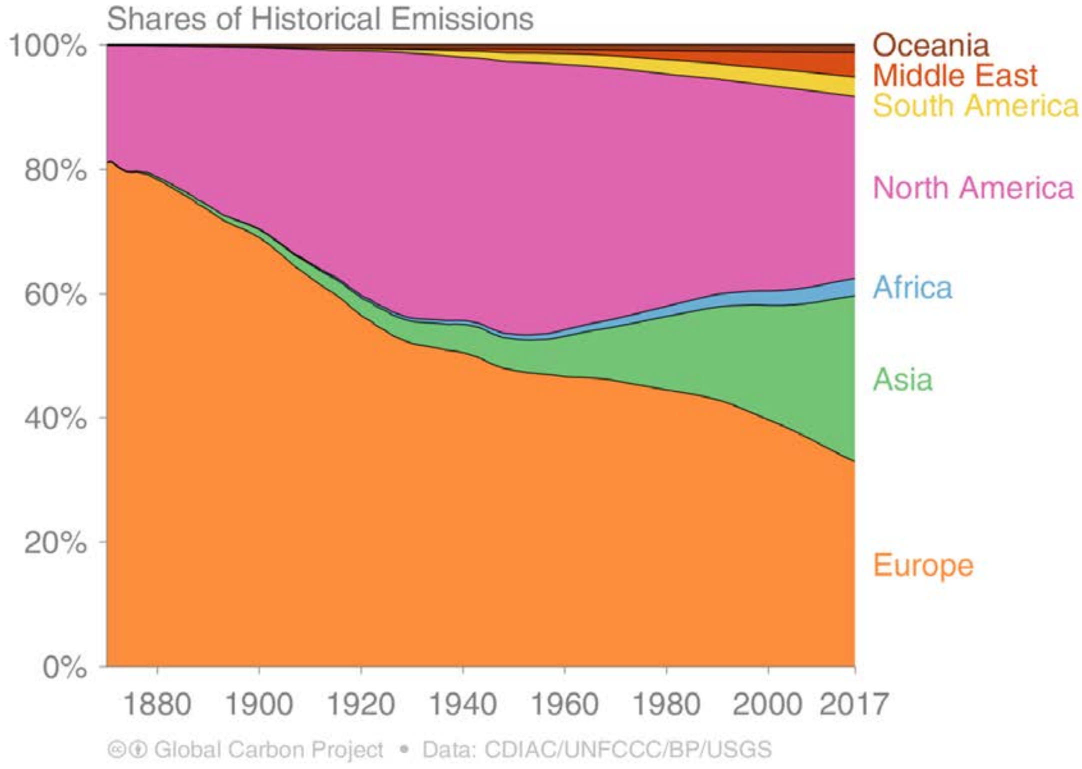
Countries have a broad range of per capita emissions reflecting their national circumstances



GLOBAL GREENHOUSE GAS EMISSIONS

https://www.globalcarbonproject.org/

Cumulative fossil CO_2 emissions (1870–2017). North America and Europe have contributed the most cumulative emissions, but Asia is growing fast



The figure excludes bunker fuels and statistical differences
Source: CDIAC; Le Quéré et al 2018; Global Carbon Budget 2018

nature climate change

ARTICLES

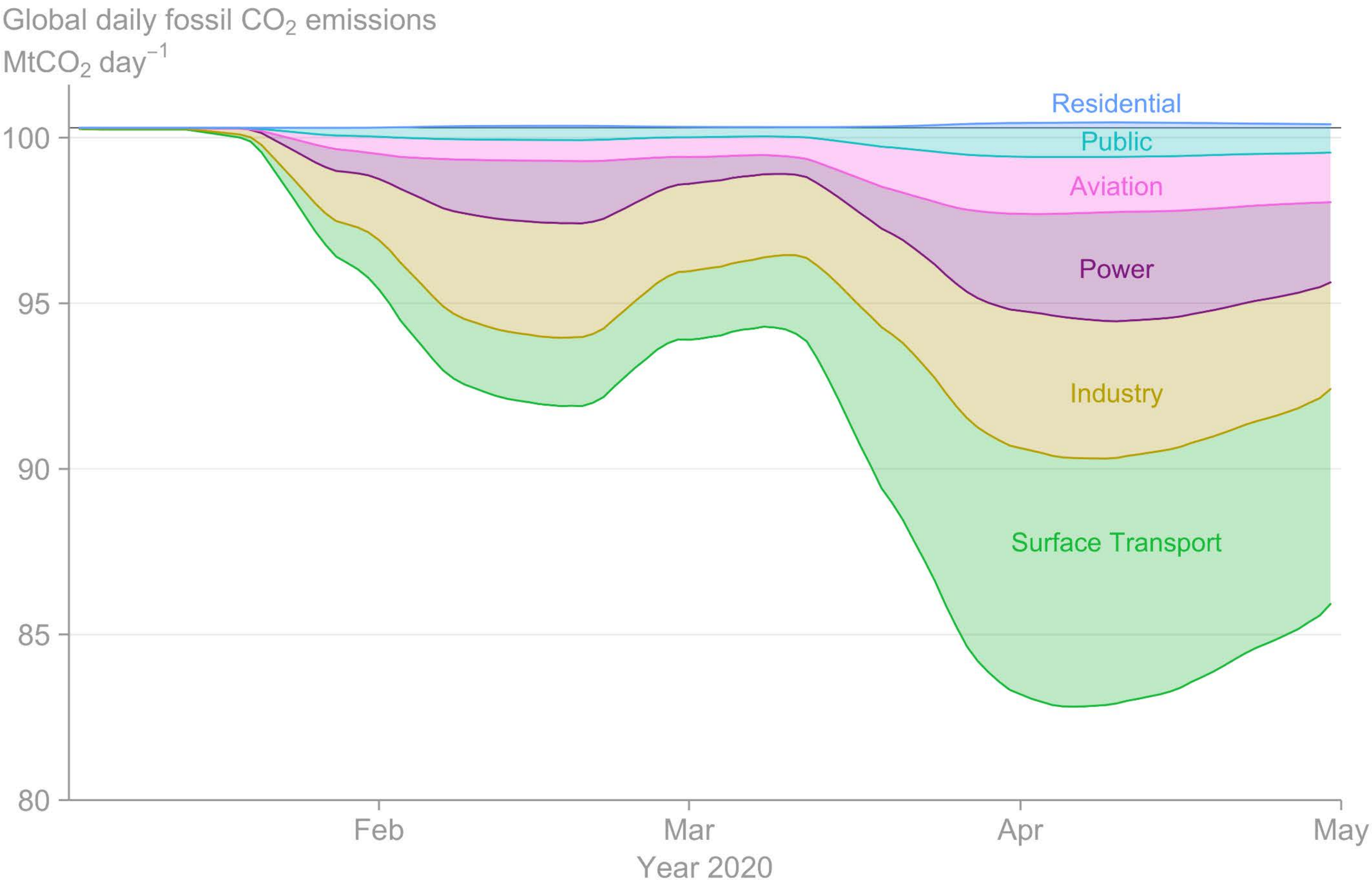
https://doi.org/10.1038/s41558-020-0797-x

Check for updates

Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement

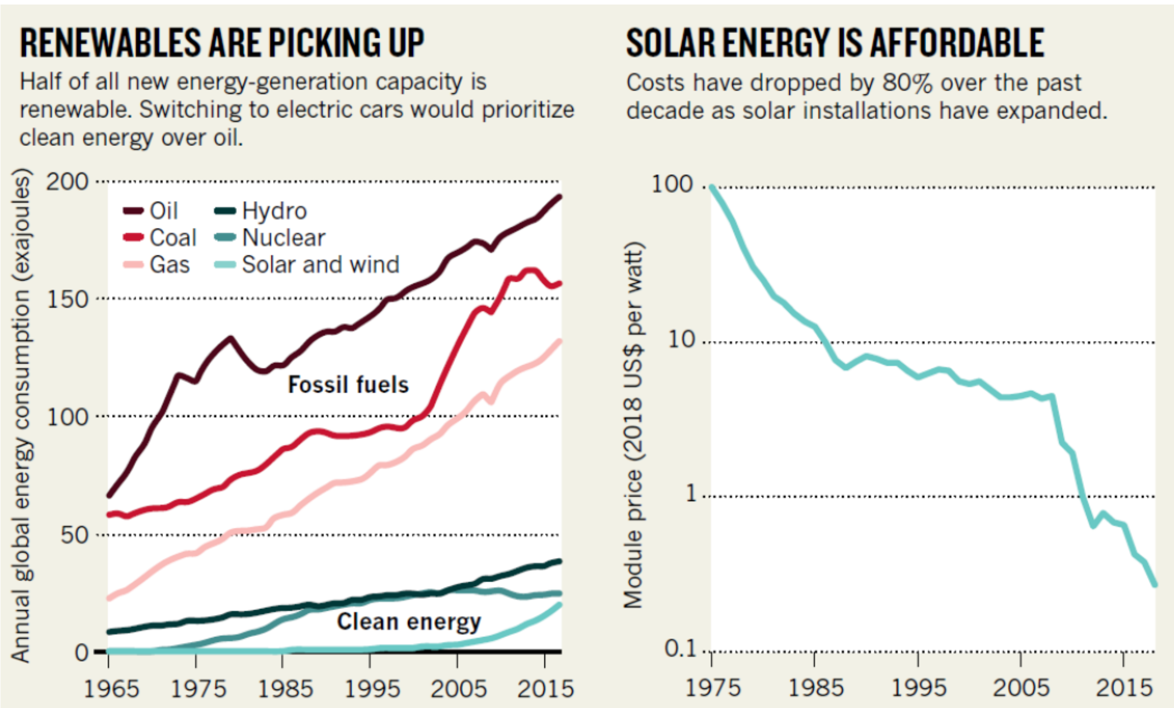
Corinne Le Quéré[1,2] ✉, Robert B. Jackson[3,4,5], Matthew W. Jones[1,2], Adam J. P. Smith[1,2], Sam Abernethy[3,6], Robbie M. Andrew[7], Anthony J. De-Gol[1,2], David R. Willis[1,2], Yuli Shan[8], Josep G. Canadell[9], Pierre Friedlingstein[10,11], Felix Creutzig[12,13] and Glen P. Peters[7]

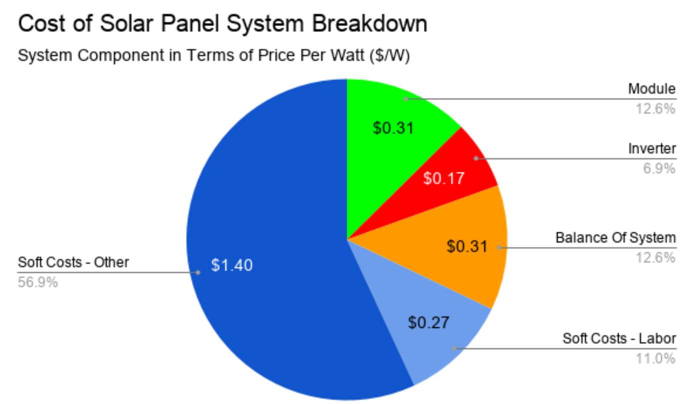
Government policies during the COVID-19 pandemic have drastically altered patterns of energy demand around the world. Many international borders were closed and populations were confined to their homes, which reduced transport and changed consumption patterns. Here we compile government policies and activity data to estimate the decrease in CO_2 emissions during forced confinements. Daily global CO_2 emissions decreased by −17% (−11 to −25% for $\pm 1\sigma$) by early April 2020 compared with the mean 2019 levels, just under half from changes in surface transport. At their peak, emissions in individual countries decreased by −26% on average. The impact on 2020 annual emissions depends on the duration of the confinement, with a low estimate of −4% (−2 to −7%) if prepandemic conditions return by mid-June, and a high estimate of −7% (−3 to −13%) if some restrictions remain worldwide until the end of 2020. Government actions and economic incentives postcrisis will likely influence the global CO_2 emissions path for decades.



Source: Le Quéré et al. Nature Climate Change (2020); Global Carbon Project

ENERGY GENERATION CAPACITY





Source: U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017, NREL

Source: Figueres et al 2018; Global Carbon Budget 2018

https://www.globalcarbonproject.org/

Element and Mineral Intensity

Strategic Elements

THE ENERGY TRANSITION IS A MATERIAL TRANSITION

- Wind, water, sun are intermittent and have strong geographic, seasonal, daily variations: a material, technology and infrastructure challenge to facilitate efficient conversion, storage and transport
- The mineral intensity in the great transformation to a carbon neutral society is growing quickly
- Assessment of criticality of a metal
- How “green” is a (strategic) metal for green technologies?
- What is the environmental footprint of a renewable technology?
- What mitigation strategies to improve the resource basis for the great transformation can we employ?

RAPID DEPLOYMENT OF STRATEGIC METALS IN ENERGY AND RELATED TECHNOLOGIES

- electronic and solar energy applications (gallium, germanium, selenium, indium, and tellurium)
- several rare earth elements (praseodymium, neodymium, terbium, dysprosium, and lutetium) important in offshore wind, e-mobility, lighting, and medical imaging
- platinum group metals for catalysts in fuel cells / chemical energy conversion
- thermoelectric conversion of waste heat (cadmium, tellurium)
- magnetic cooling (gadolinium, germanium, indium, cobalt)
- batteries (lithium, cobalt)
- yttrium for high TC superconductors
- alloying elements in high-temperature turbines (cobalt, hafnium, and rhenium)



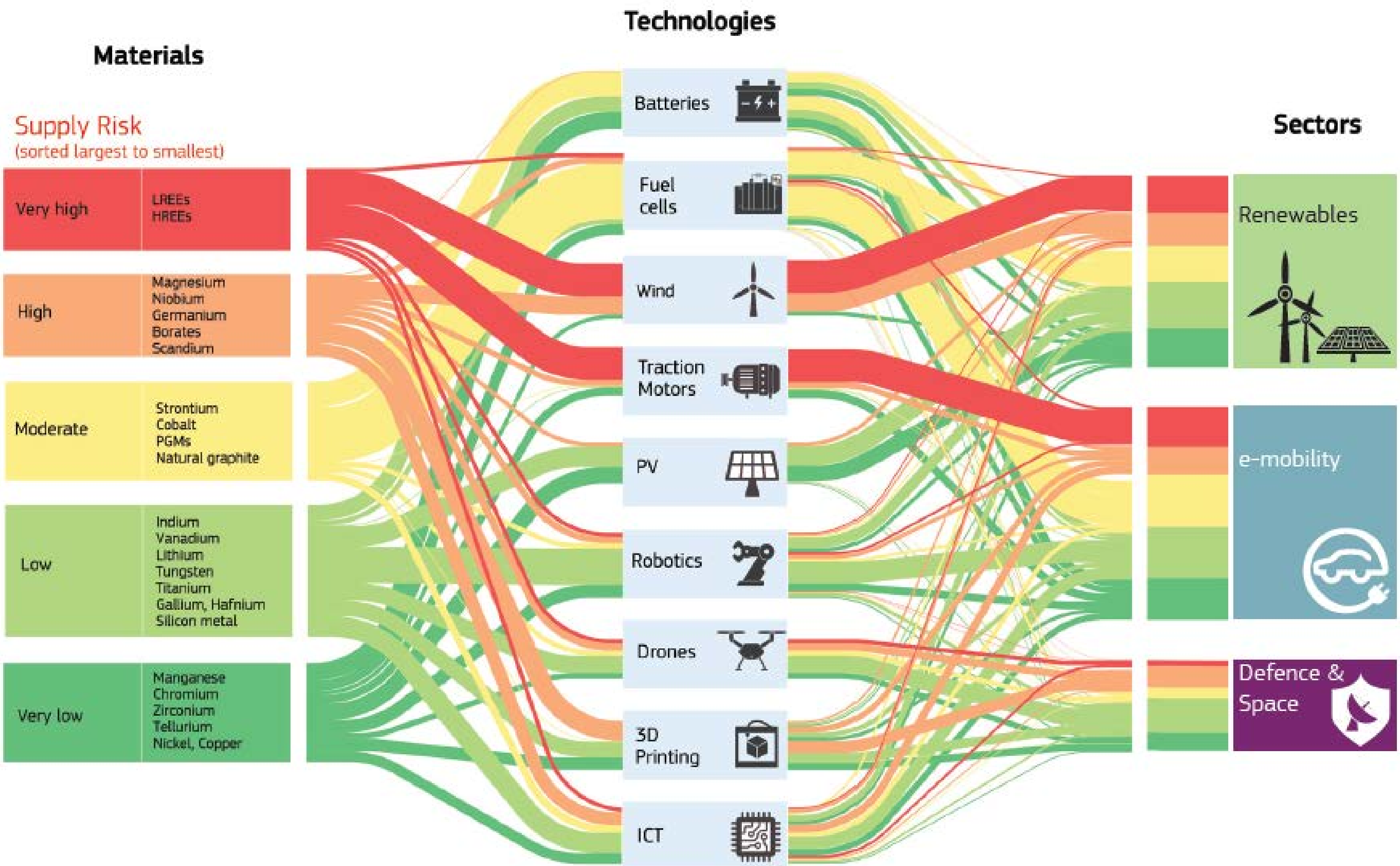




https://en.wikipedia.org/wiki/cobalt/gallium/rhenium/Lutetium/terbium/lithium/platinum

SEMI-QUANTITATIVE REPRESENTATION OF FLOWS OF RAW MATERIALS AND THEIR CURRENT SUPPLY RISKS TO THE NINE SELECTED TECHNOLOGIES AND THREE SECTORS (BASED ON 25 SELECTED RAW MATERIALS

European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)



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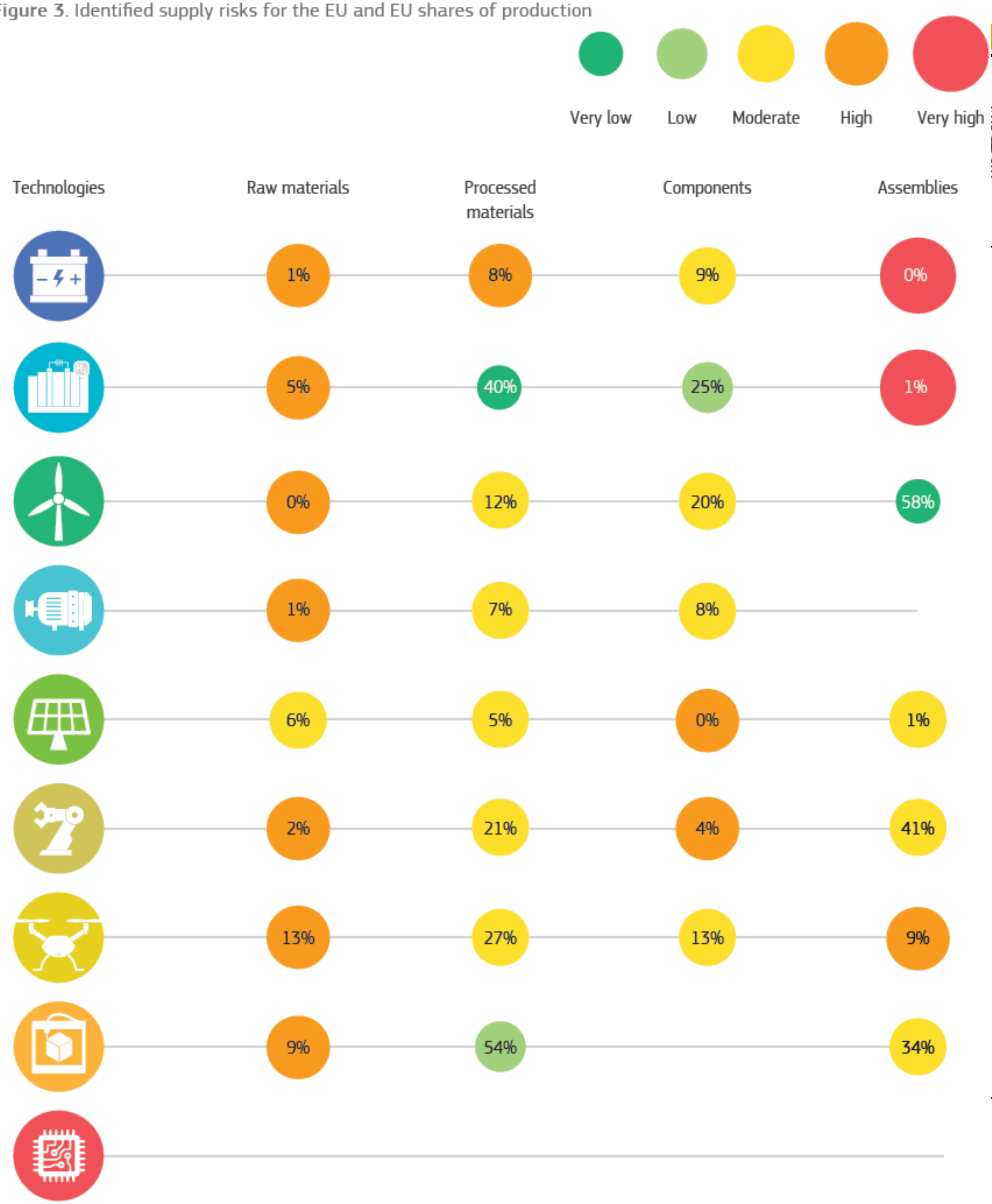
“Pressure on resources will increase - due to increasing global population, industrialisation, digitalisation, increasing demand from developing countries and the transition to climate neutrality with metals, minerals and biotic materials used in low-emission technologies and products. OECD forecasts that global materials demand will more than double from 79 billion tonnes today to 167 billion tonnes in 2060. Global competition for resources will become fierce in the coming decade. Dependence of critical raw materials may soon replace today's dependence on oil. “

European Commission, Study on the EU’s list of Critical Raw Materials – Final Report (2020)

European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Figure 3. Identified supply risks for the EU and EU shares of production



European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

CRITICALITY

Factors for criticality of metals

Geological Availability

(Range, Reliance on by-product production)

Technical Development

(Need for Raw Materials, Primary Production, competing technologies)

Geopolitics

(Interests of defence industry, US ORE act , Frank Dodd act, ..)

Ecological and Social Consequences

(Extraction, Application Disposal)

Economical Development

(Pricing, Offering, Demand, Trade War, Customs and Border Protection)

Substitution and Recycling

(possibly reduced cost and performance vs sustainability)

Criticality is dynamic !

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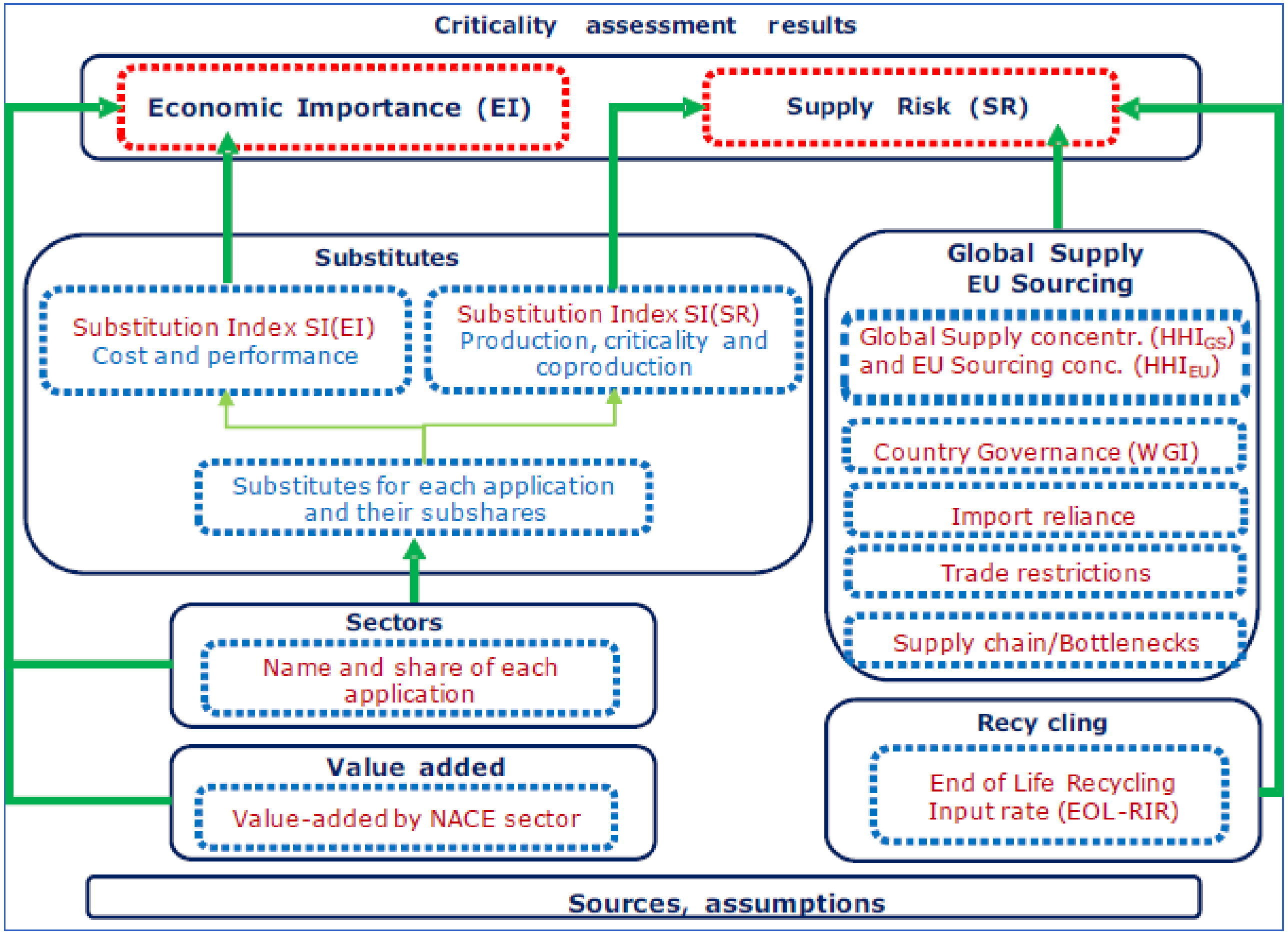
2020 Critical Raw Materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

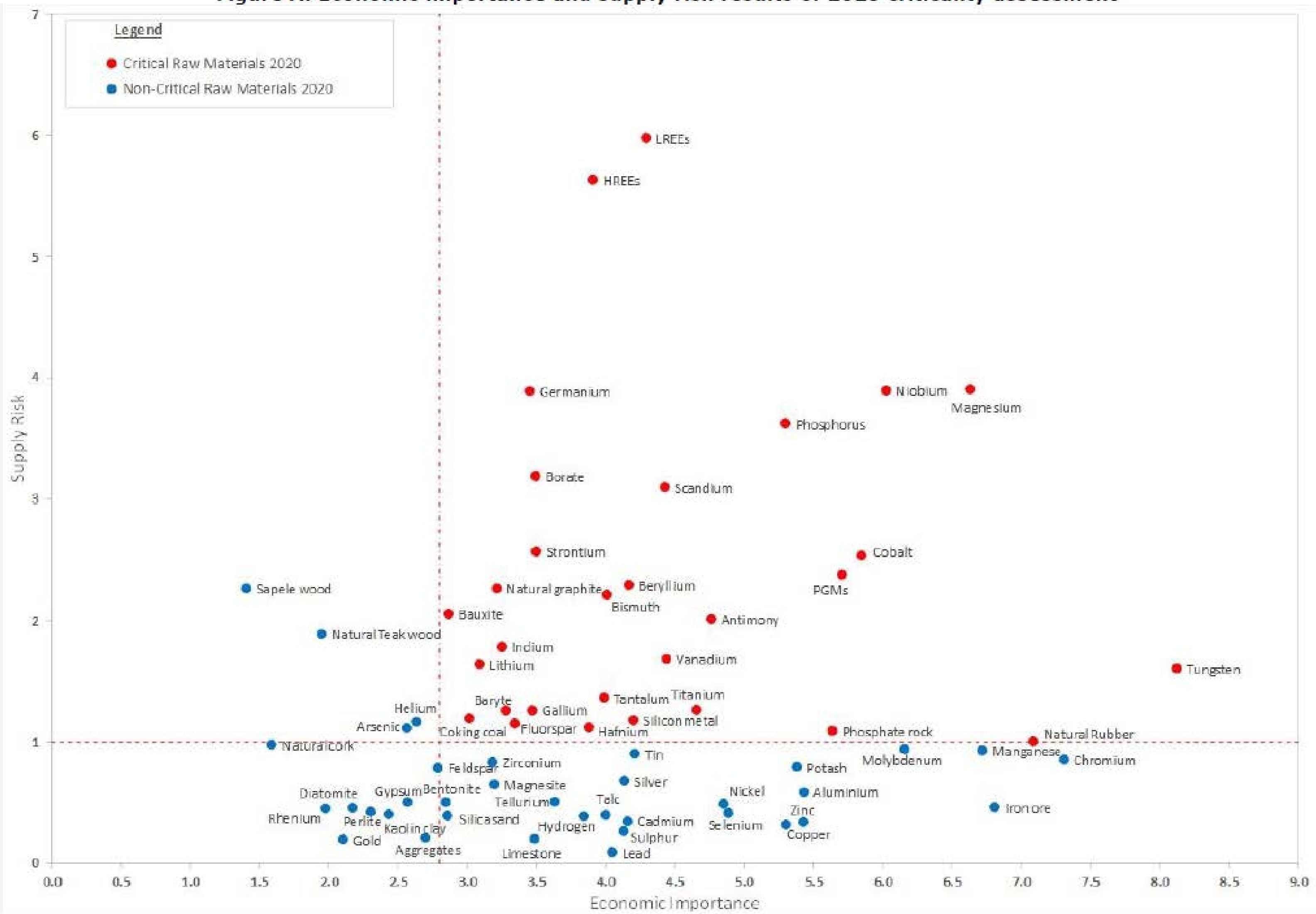
European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Figure 2: Overall structure of the criticality methodology[32]



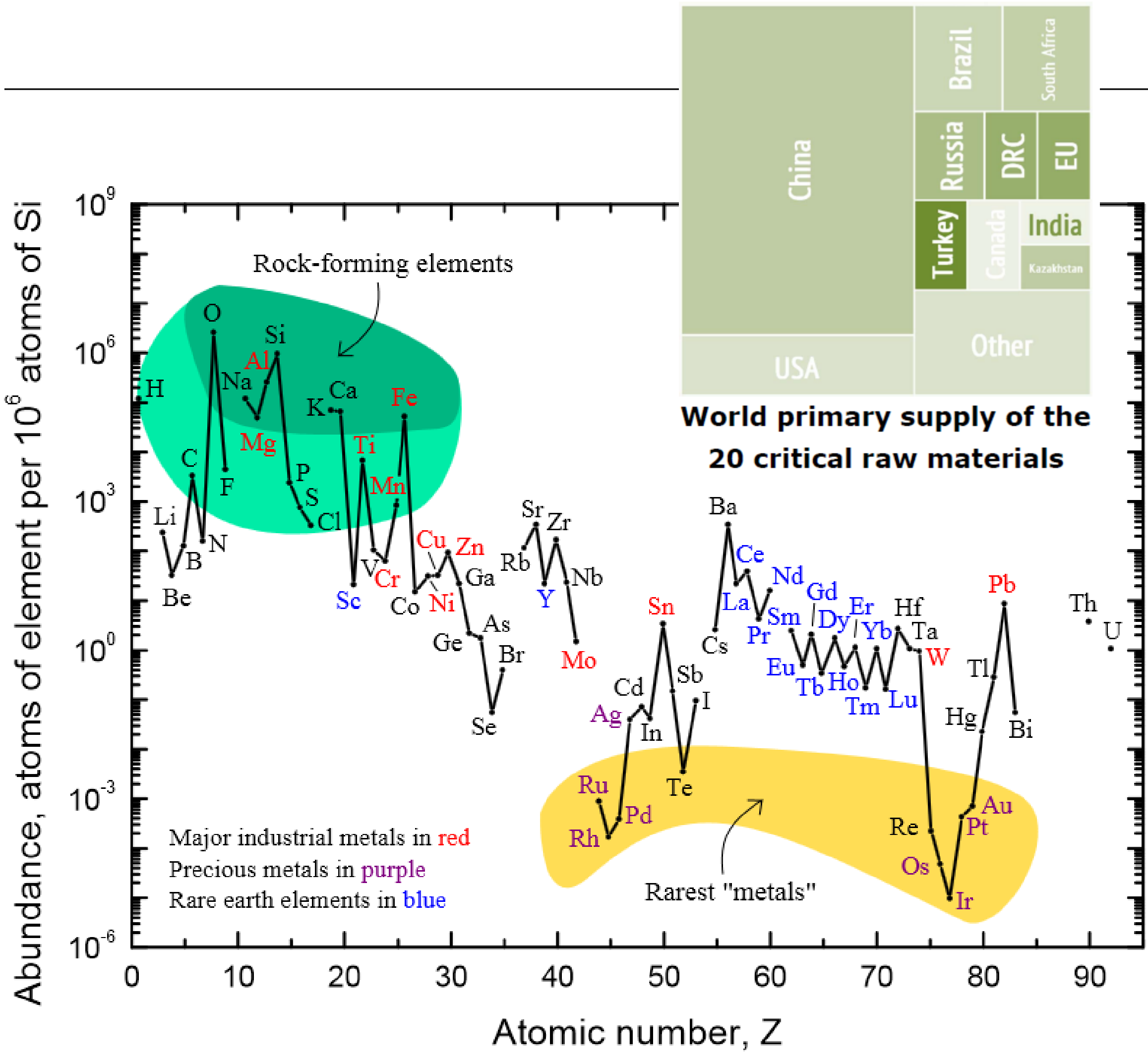
European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Figure A: Economic importance and supply risk results of 2020 criticality assessment



European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

ABUNDANCE OF THE CHEMICAL ELEMENTS



World primary supply of the 20 critical raw materials

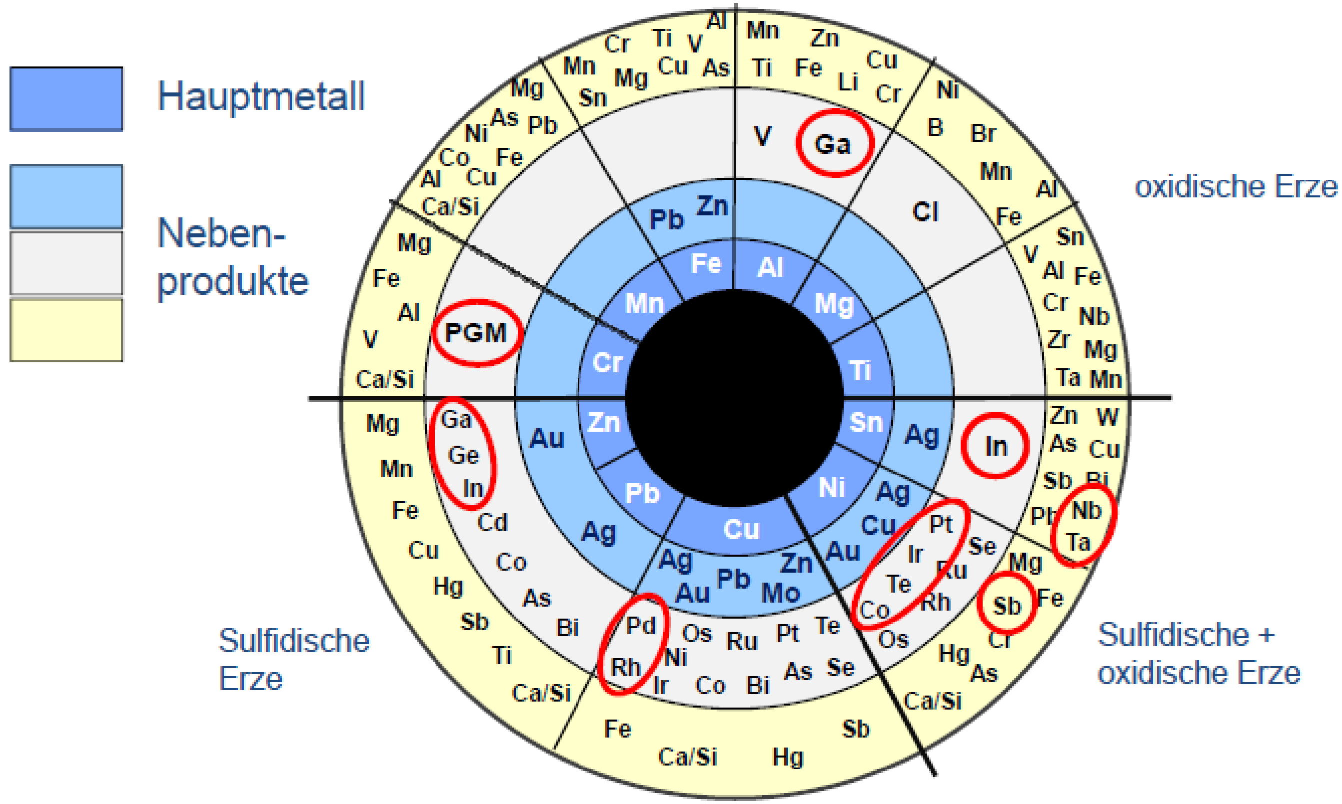
Abundance of the chemical elements in Earth's upper continental crust

(1) Rock-forming elements (major elements in green field and minor elements in light green field);
(2) Rare earth elements (lanthanides, La–Lu, and Y; labelled in blue);
(3) Major industrial metals (global production >~3×10^7 kg/year; labelled in red);
(4) Precious metals (purple);
(5) The nine rarest "metals"—the six platinum group elements plus Au, Re, and Te (a metalloid).

US Geological Survey

The metrics of metal ecology

Metal wheel after *Reuter et al. and Verhoef et al.* - the coupling of elements



The periodic table of companionality

Nassar, Graedel, Harper Sci. Adv. 2015;1:e1400180 3 April 2015

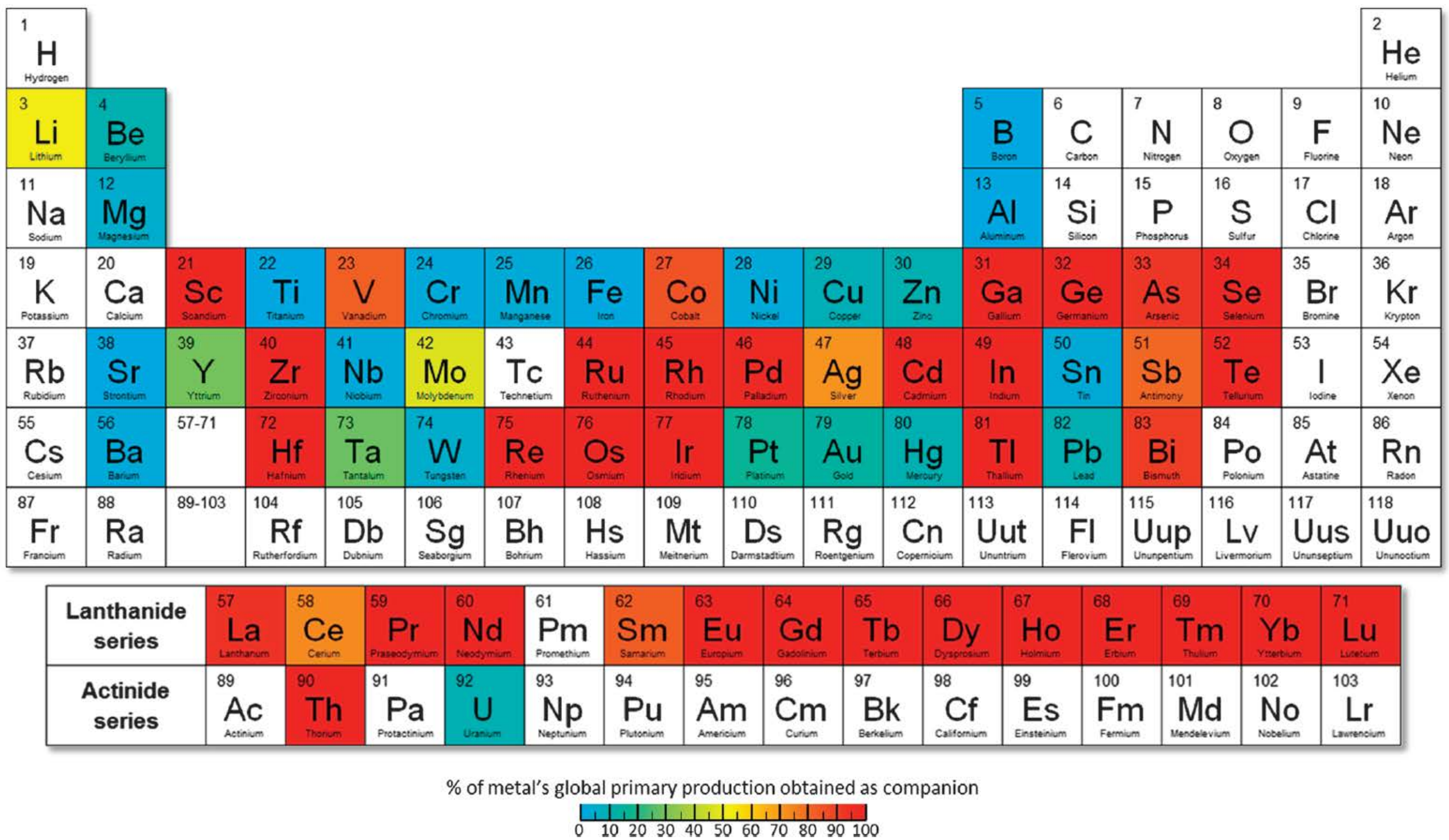


Fig. 1. The periodic table of companionality on a global basis for 2008. Metals that are mainly produced as hosts appear in blue, and those that are mainly produced as companions are in red. Details regarding data sources and assumptions are presented in the Supplementary Materials.

Classification of resources (McKelvey-diagram)
after McKelvey 1965

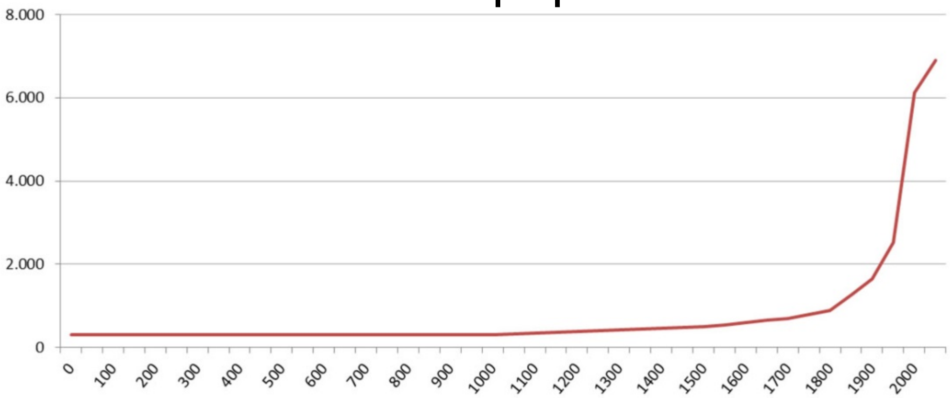
Cumulative Production	IDENTIFIED RESOURCES			UNDISCOVERED RESOURCES	
	Demonstrated		Inferred	Probability Range (or)	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserves		Inferred Reserves		
MARGINALLY ECONOMIC	Marginal Reserves		Inferred Marginal Reserves		
SUB-ECONOMIC	Demonstrated Subeconomic Resources		Inferred Subeconomic Resources		

Other Occurrences	Includes nonconventional and low-grade materials

FINITENESS OF RAW MATERIAL RESERVES

Constantly increasing demand

- Extraction of raw materials grows permanently, range is subsequently being reduced
  - New technologies
  - Growth of population

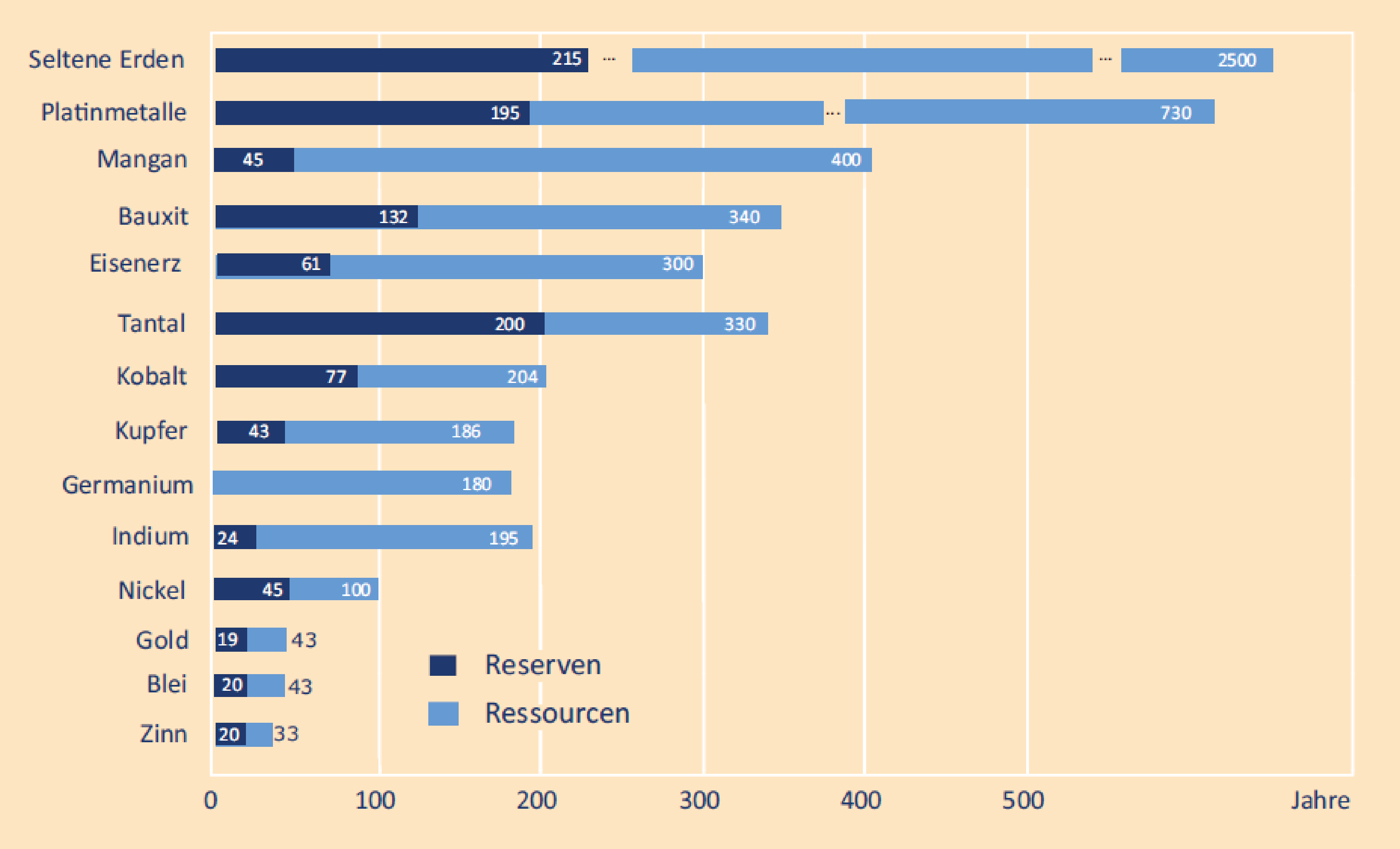


Source: Armin Reller, Universität Augsburg
Tom Graedel, Yale University

Critical elements with a low range:

Antimony	15 – 20 years
Hafnium	≈ 10 years
Indium	5 –10 years
Platinum	≈ 15 years
Silver	15 – 20 years
Tantalum	20 – 30 years
(Uranium	30 – 40 J years)
Zinc	20 – 30 years

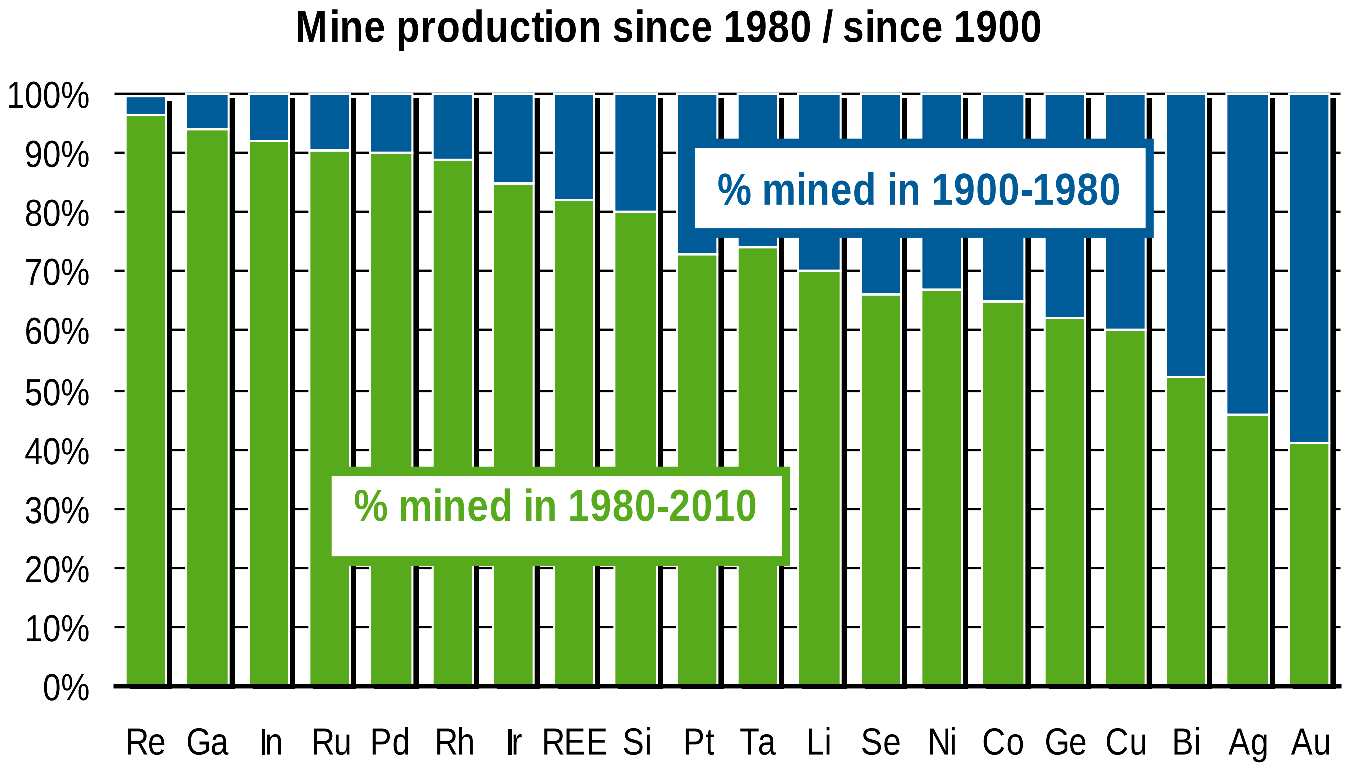
ABB. 8 REICHWEITE DER METALLROHSTOFFE



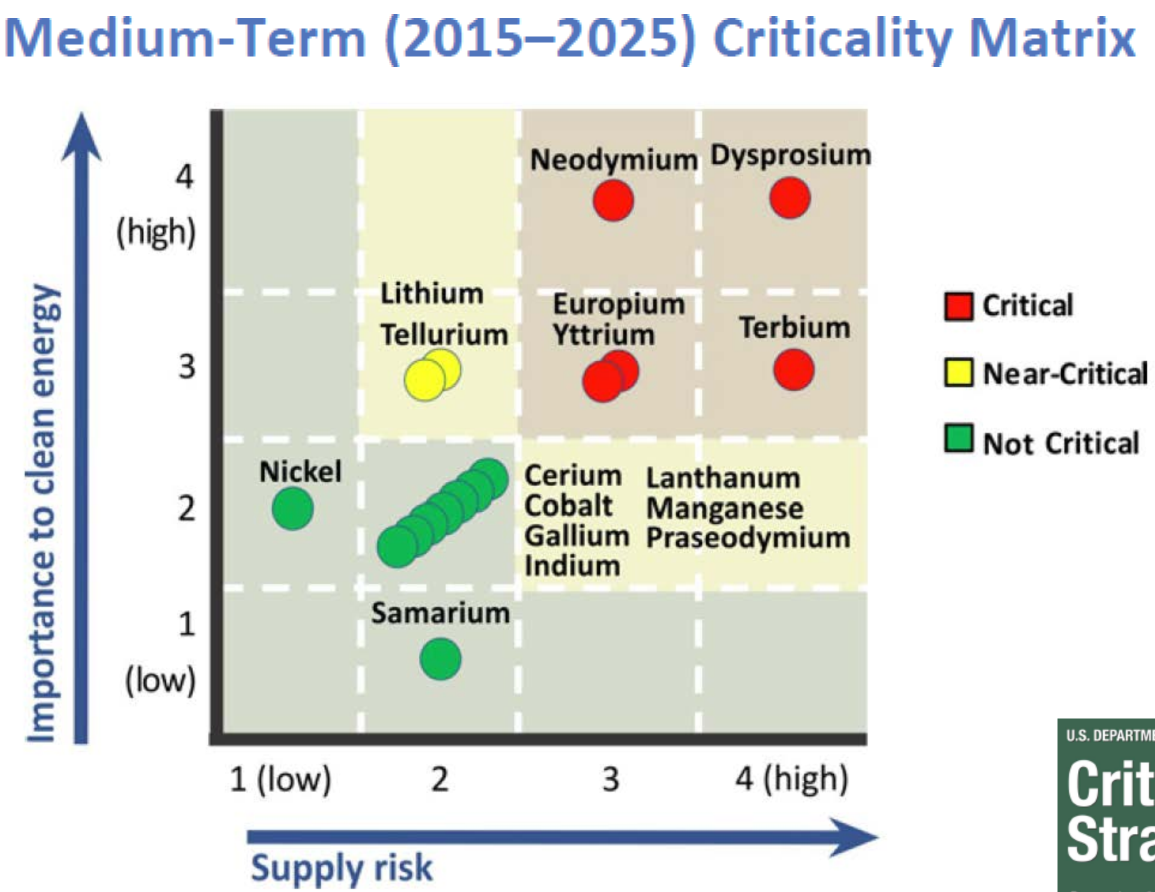
Die statische Reichweite für einige Metallrohstoffe bezogen auf die Reserven (dunkelblau) und Ressourcen (heller blau). Die Werte beziehen sich auf die vom USGS für 2011 publizierten Produktions- und Reservenangaben; für SE, Ta, Ge und In wurden andere Schätzungen verwendet [27].

Extraction of strategic metals

> 80% of the extraction of rare earths, PGM, Gallium, Indium, Rhenium … took place in the last 30 years



Criticality matrix
here for PV, wind power and E-mobility



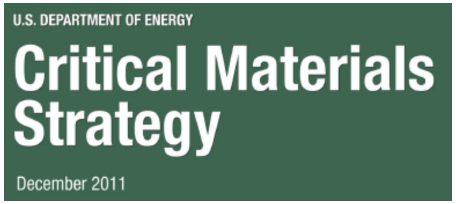
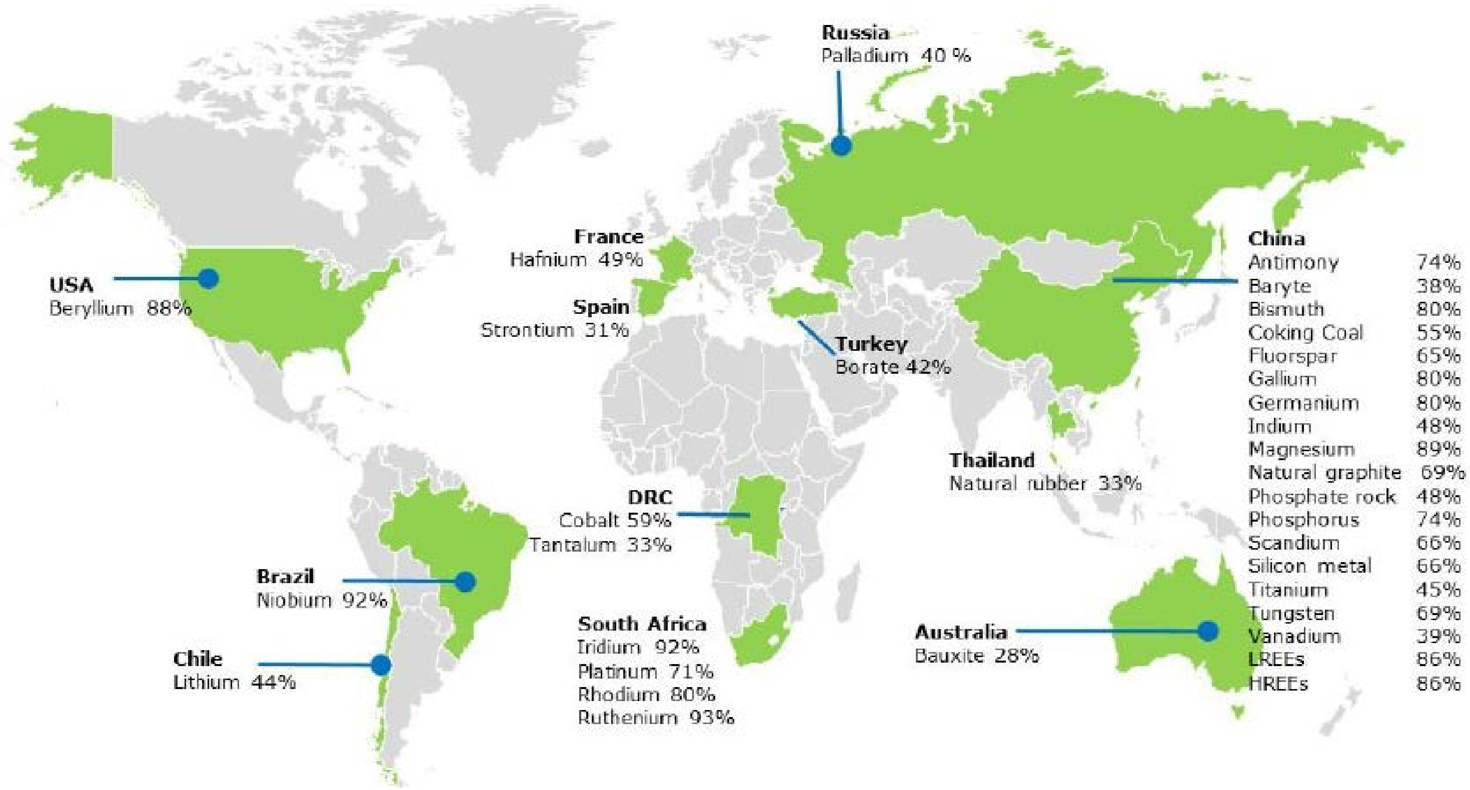
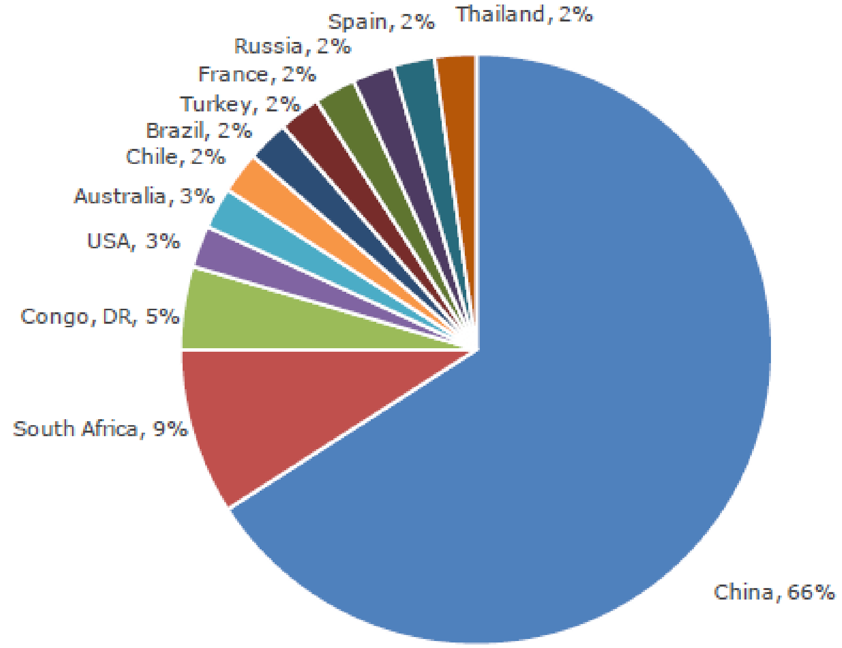


Figure B: Countries accounting for largest share of global supply of CRMs



European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Figure C: Main Global supply countries of CRMs[8] (based on number of CRMs supplied, average 2012-2016)



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Global estimates of end-of-life **recycling** rates for 60 metals and metalloids (2008)

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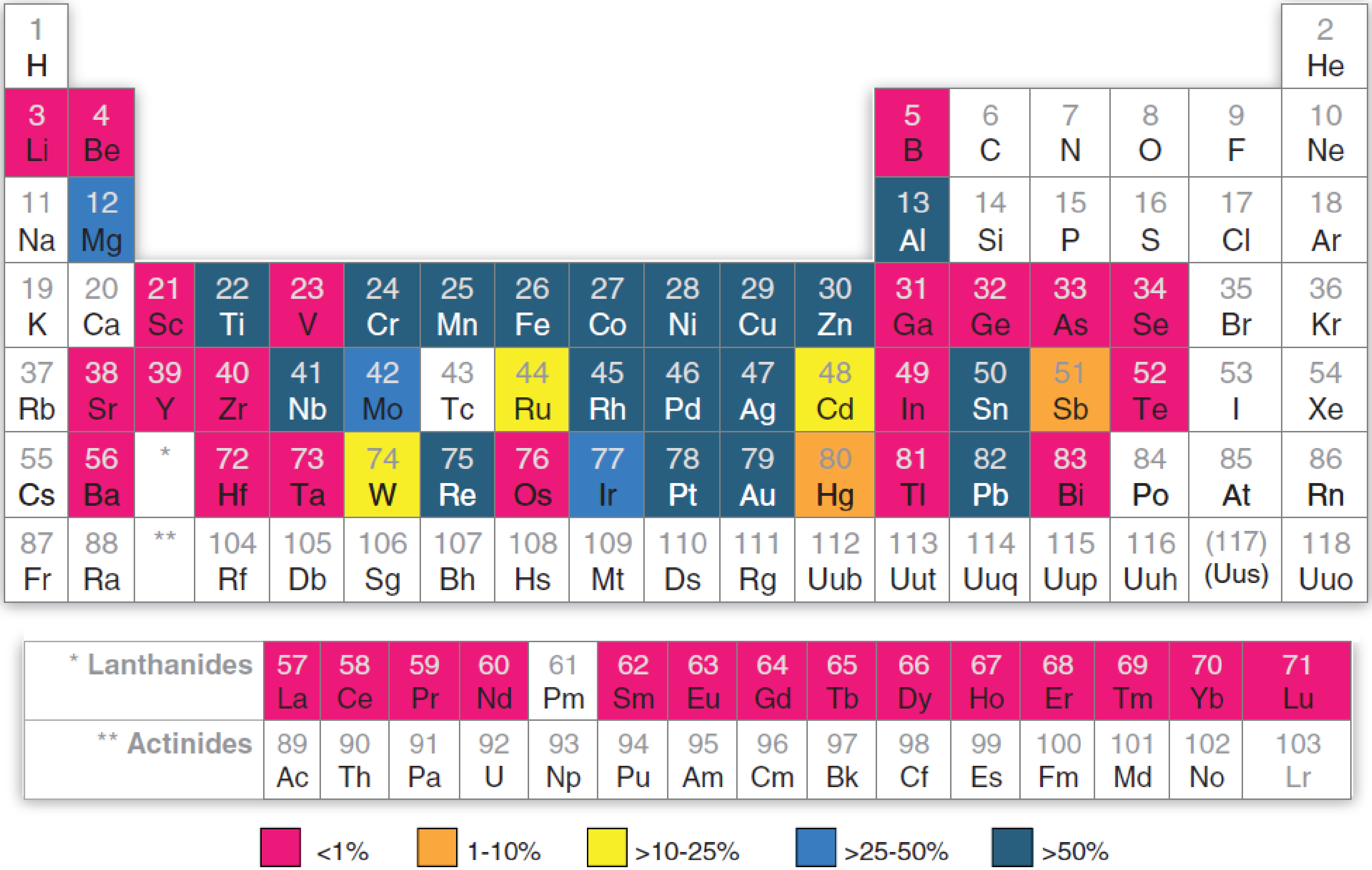

T. E. Graedel et al., J. Ind. Ecol. 15, 355 (2011).

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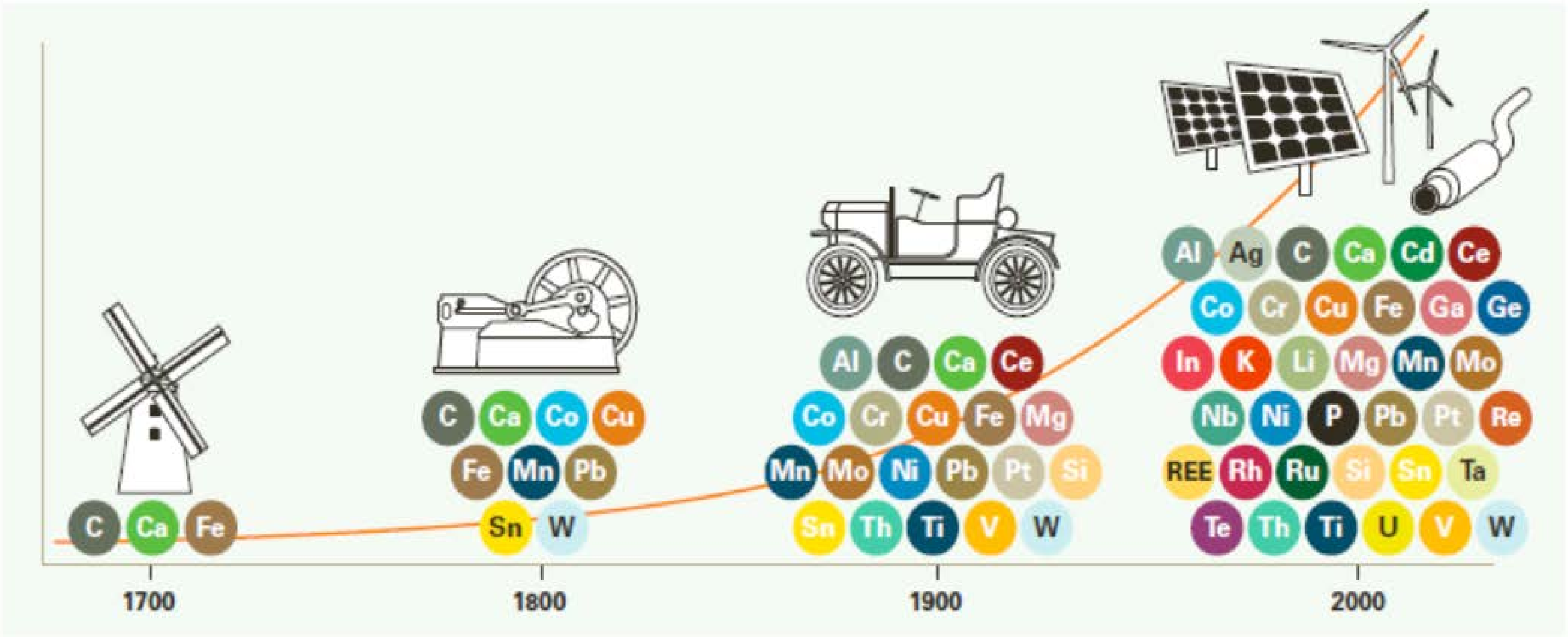
Ever more elements per product



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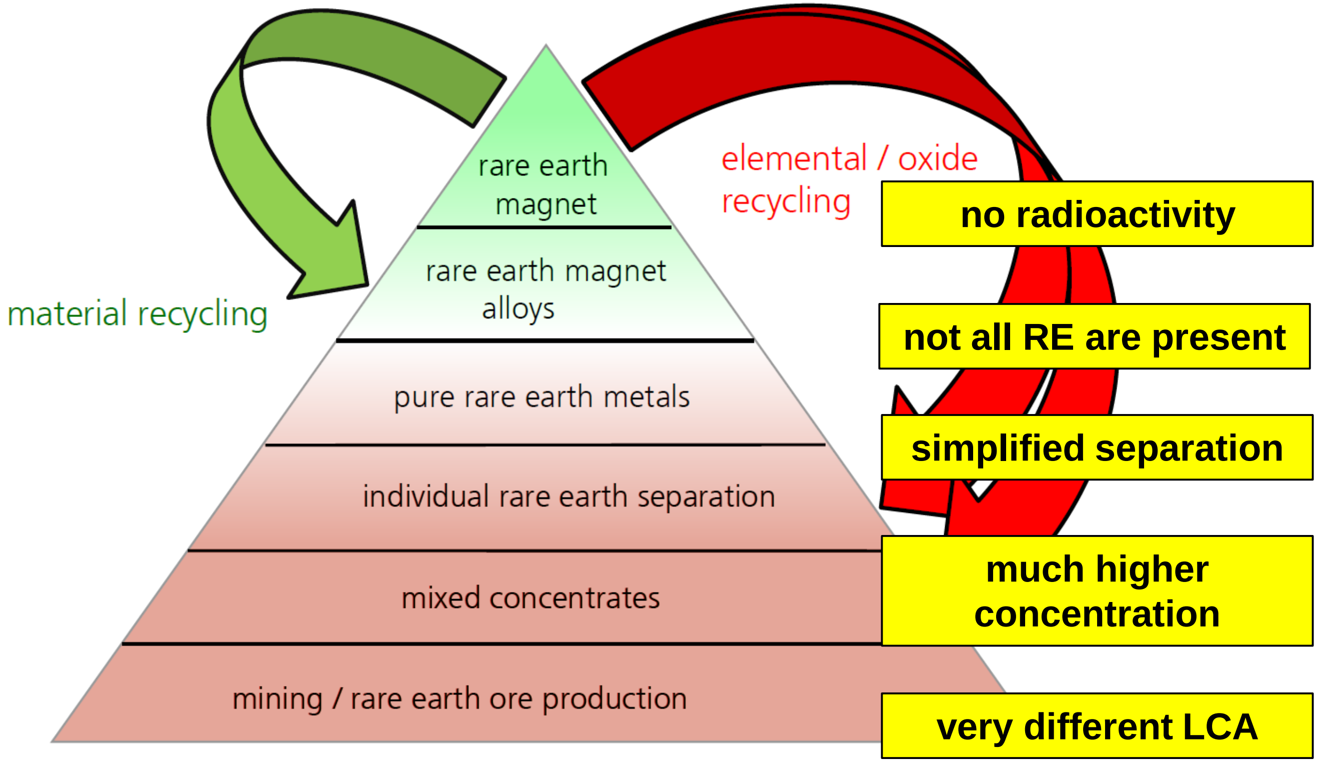
Rare earth value chain for magnets

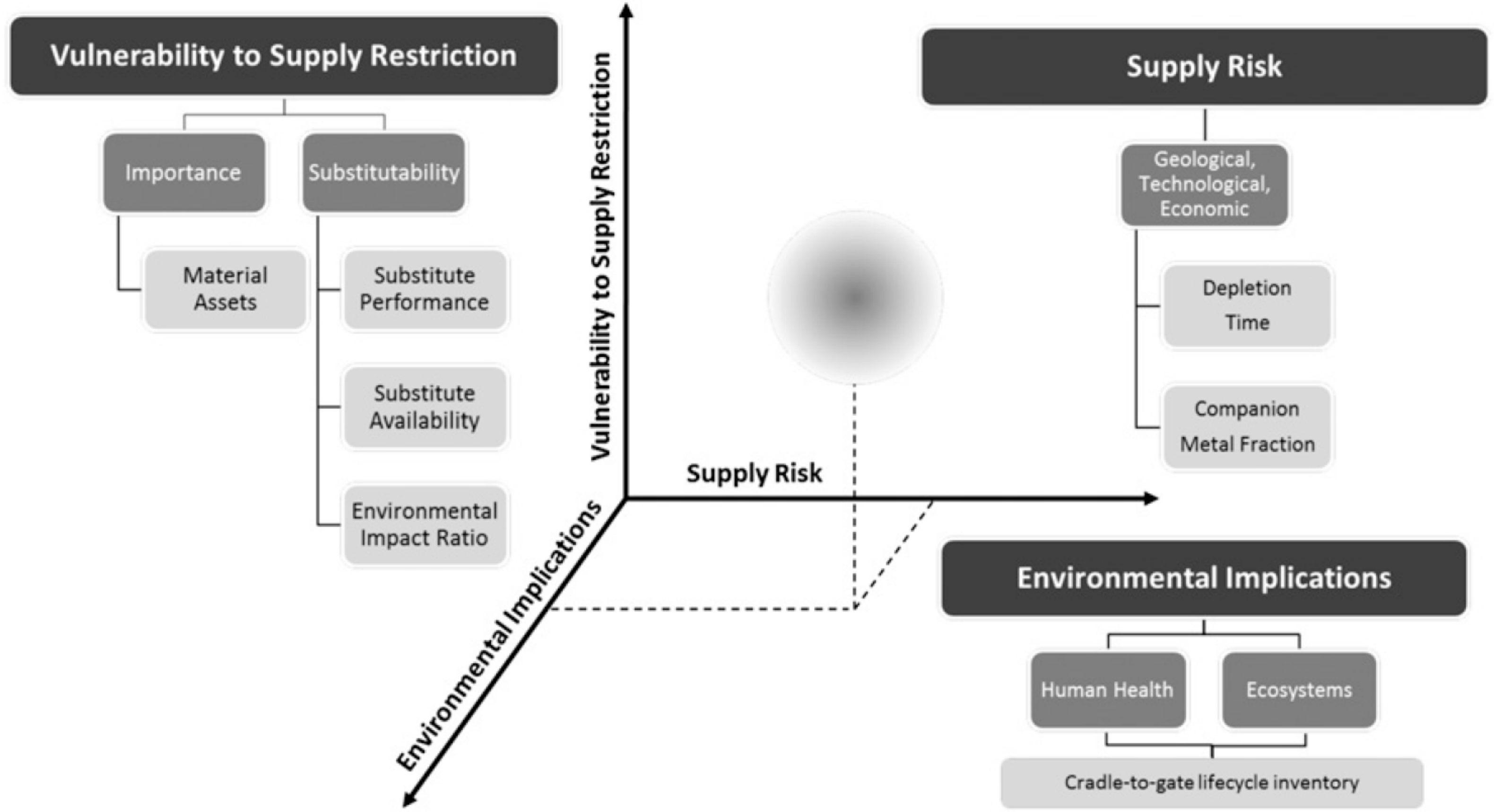
Advanced Functional Recycling of EoL products



R. Gauß und O. Gutfleisch,
„Magnetische Materialien – Schlüsselkomponenten für neue Energietechnologien"
Springer Spektrum Verlag, 2016

The Yale analytical framework for determining metal criticality at the global level

metrics described in Graedel TE, et al. (2012) Methodology of metal criticality determination. Environ Sci Technol 46(2):1063–1070



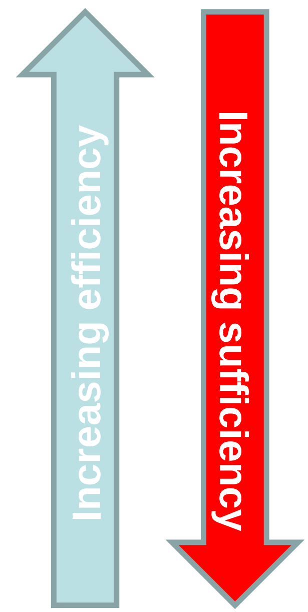
http://www.pnas.org/content/112/20/6295.full.pdf
PNAS | May 19, 2015

SUBSTITUTION

Options for Substitution

Replacing Critical Materials and Products

Material substitution	One material substitutes another material: several metals or compounds as part of the material or a material as a whole.
Technological substitution	Material consumption reduced by technological progress and improvements manufacturing with same functionality.
Functional substitution	A (new) product can substitute another product, provided it fulfils the same function.
Quality substitution	Products with lower quality and performance are produced by material savings instead of high-quality products.
Non-material substitution	An increase in the use of non-material factors such as work and energy can reduce the material consumption.



Source: Ziemann/Schebek 2011, nach Tilton 1983

Substitutability of elements

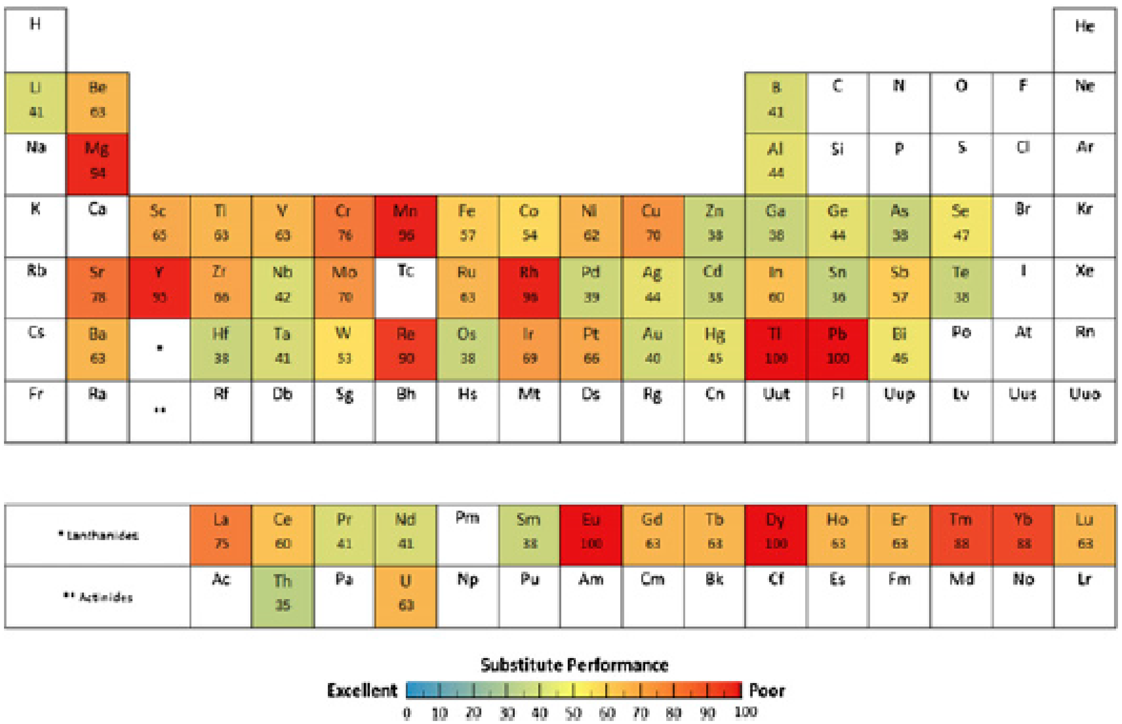


Fig. 5. The periodic table of substitute performance. The results are scaled from 0 to 100, with 0 indicating that exemplary substitutes exist for all major uses and 100 indicating that no substitute with even adequate performance exists for any of the major uses.

http://www.pnas.org/content/112/20/6295.full.pdf
PNAS | May 19, 2015

VIABILITY OF A SUBSTITUTIONALL STRATEGY

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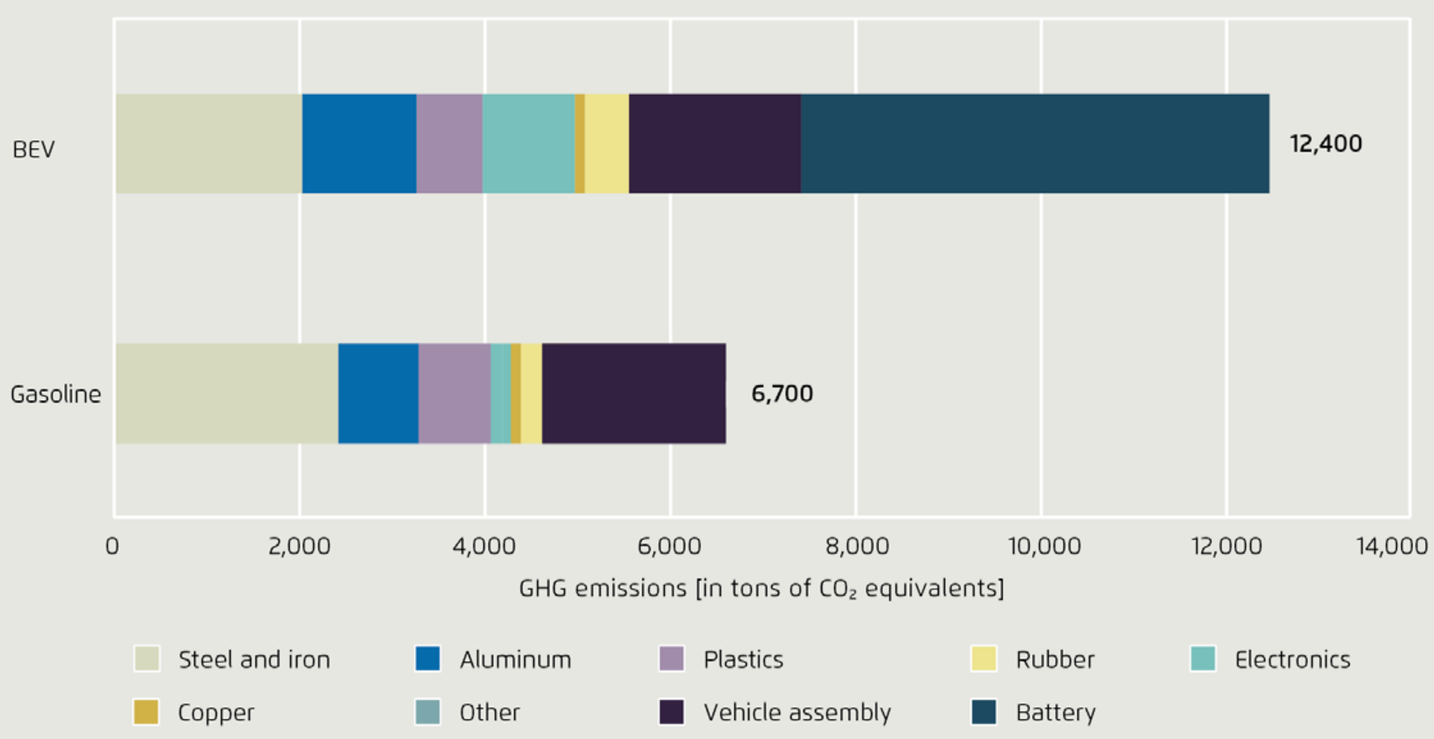
GHG Emissions of Manufacturing (without Disposal):
Electric versus Gasoline Vehicles

Figure 14



IFEU calculations

Source: Agora Verkehrswende (2019): *Klimabilanz von Elektroautos. Einflussfaktoren und Verbesserungspotenzial.*

FUNKTIONALE MATERIALIEN

VIABILITY OF A SUBSTITUTIONALL STRATEGY

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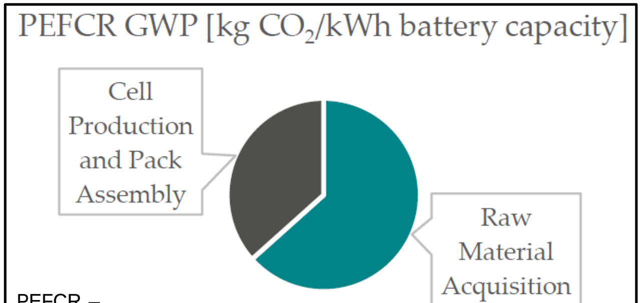
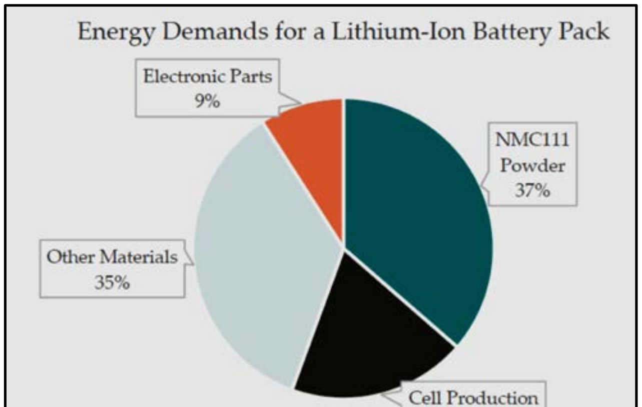


PEFCR –
Product Environmental Footprint Category Rules



$LiNi_{0,333}Mn_{0,333}Co_{0,333}O_2$ - NMC111

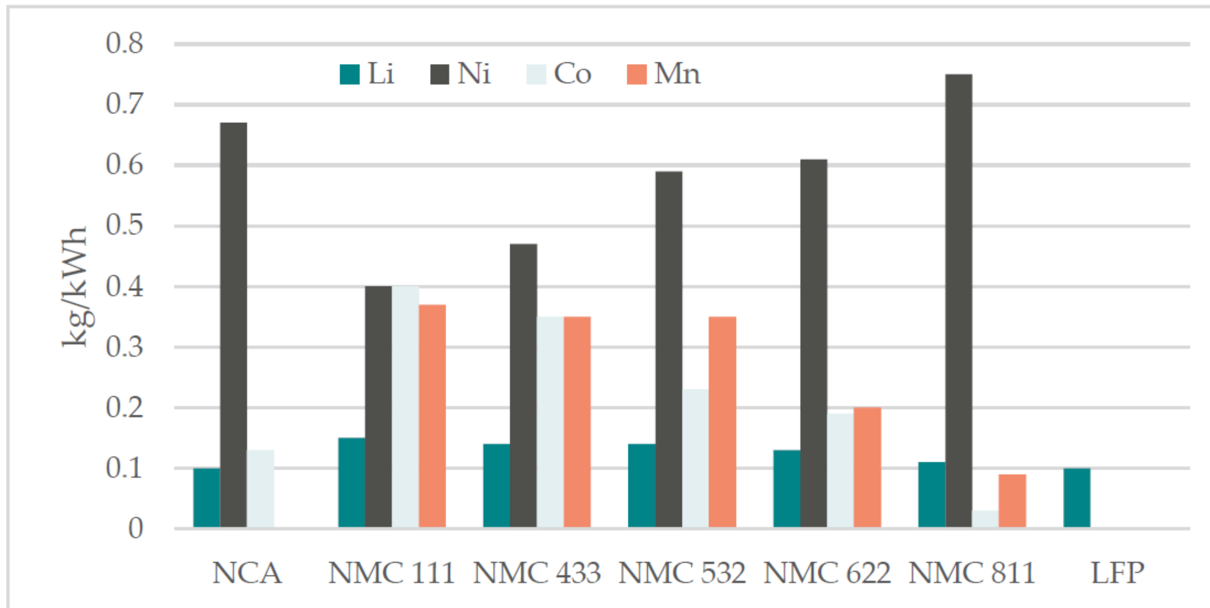


Figure 8. Material energy intensities for lithium-ion batteries with varying cathode chemistries. Moving from the left to the right on the NMC battery chemistries the amounts of cobalt and manganese required decrease while the amount of nickel increase. The source is (IEA, 2018) while the data came originally from ANL's BatPac.

Source: Erik Emilsson, Lisbeth Dahllöf, Lithium-Ion Vehicle Battery Production, 2019 IVL Swedish Environmental Research Institute.

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VIABILITY OF A SUBSTITUTIONALL STRATEGY

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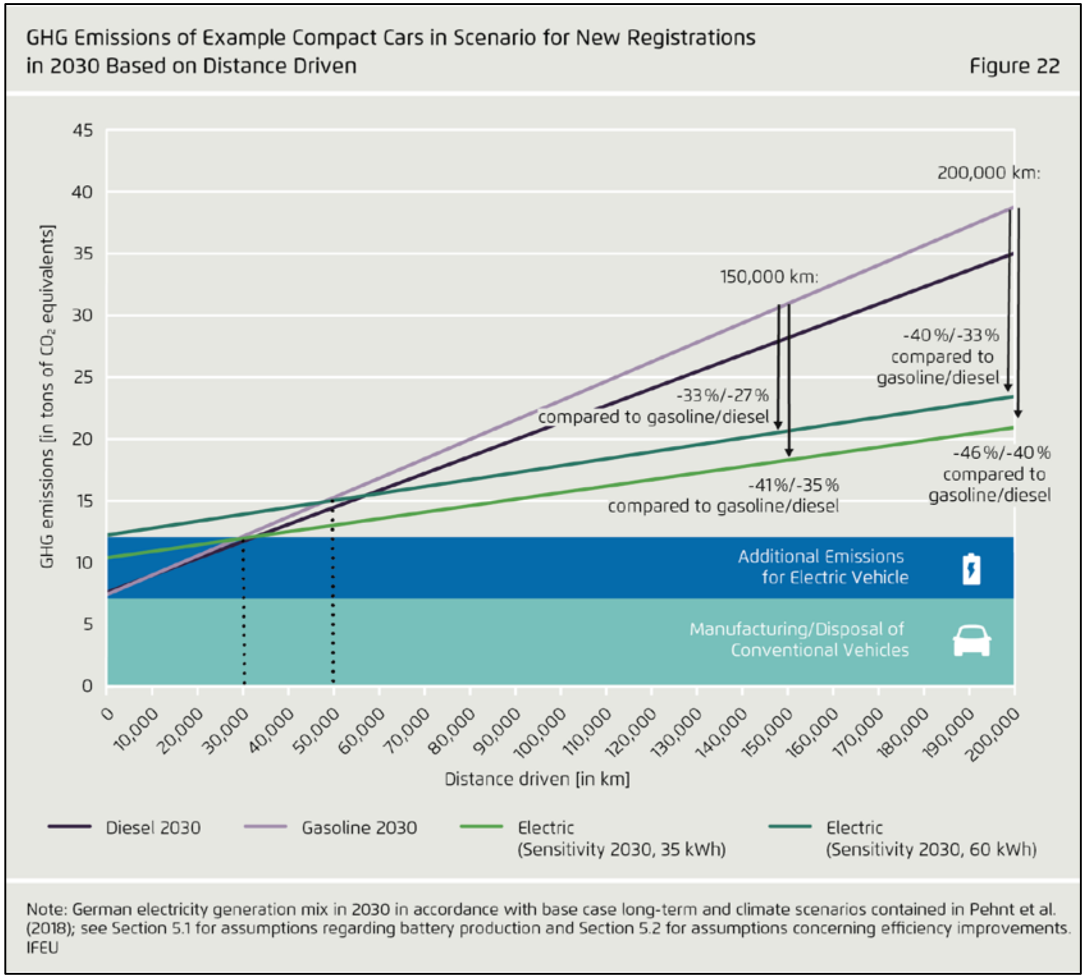

Source: Agora Verkehrswende (2019): *Klimabilanz von Elektroautos. Einflussfaktoren und Verbesserungspotenzial.*

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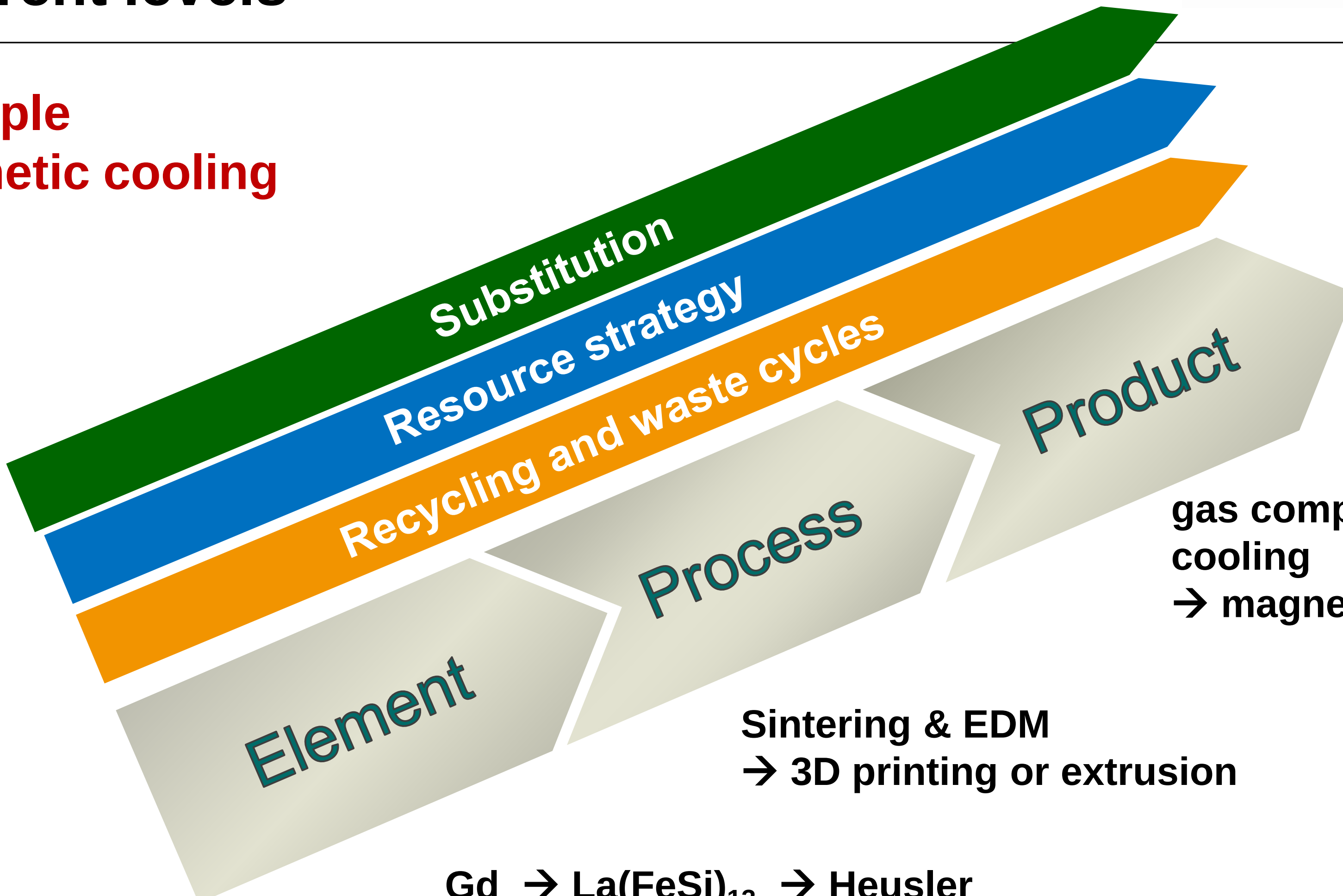
Efficient use and substitution on different levels

example
magnetic cooling



gas compression cooling
→ magnetic cooling

Sintering & EDM
→ 3D printing or extrusion

Gd → La(FeSi)$_{13}$ → Heusler

Substitution

- Substitution is one of several mitigation strategies to deal with the criticality of strategic metals.
- Substitution can be addressed on several levels of technology and material science advancement.
- Viability of a substitutional strategy needs to be proven by LCA and LCC.
- All steps of the value chain leading to e.g. a high performance magnet or a battery, the two essential ingredients for electro mobility, are subject to constant improvements.
- Regulations, legislation or disruptive innovation can change the need for substitution quickly.

MULTI LEVEL ASSESSMENT

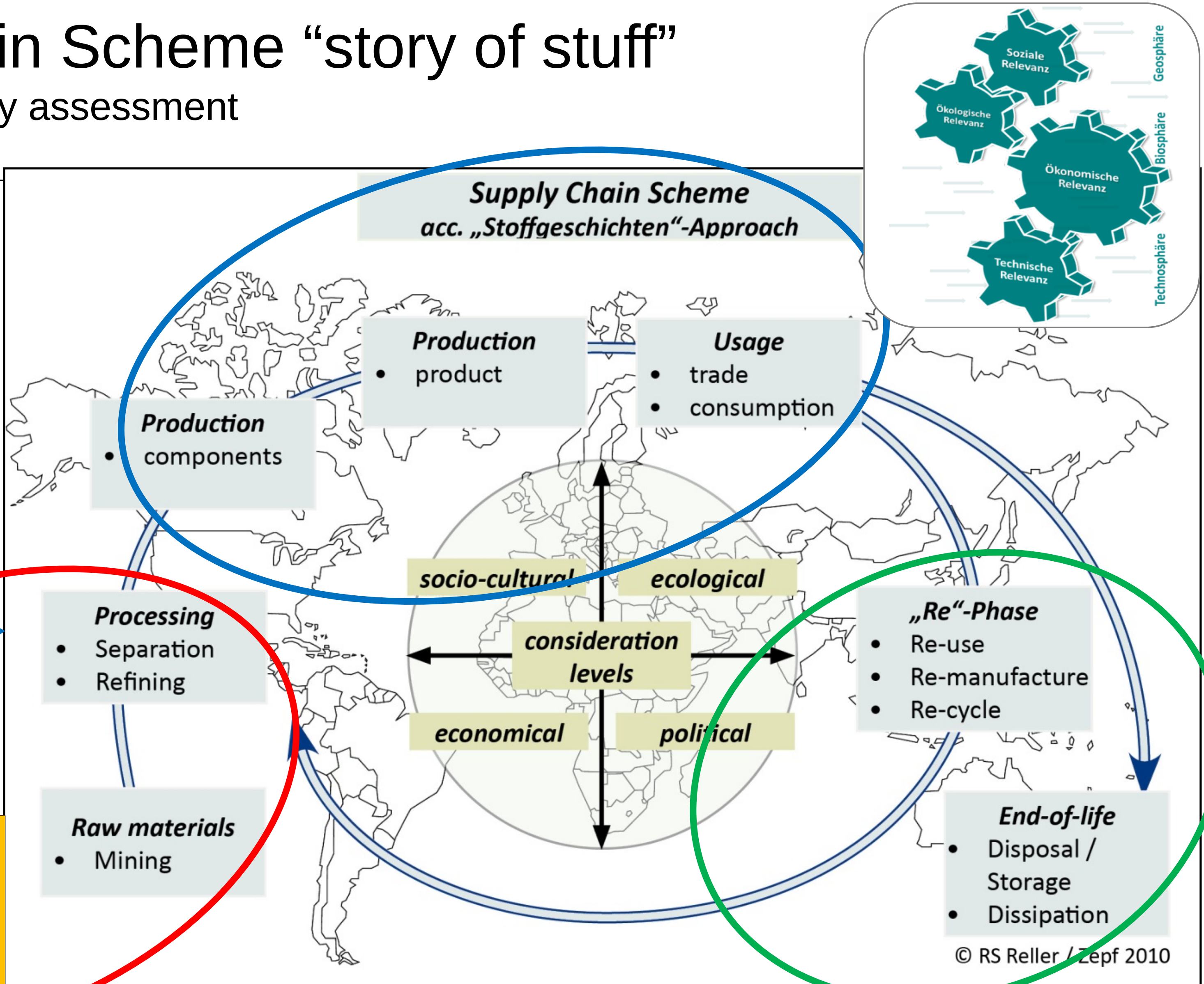
Story of stuff

LCA

Supply Chain Scheme “story of stuff”

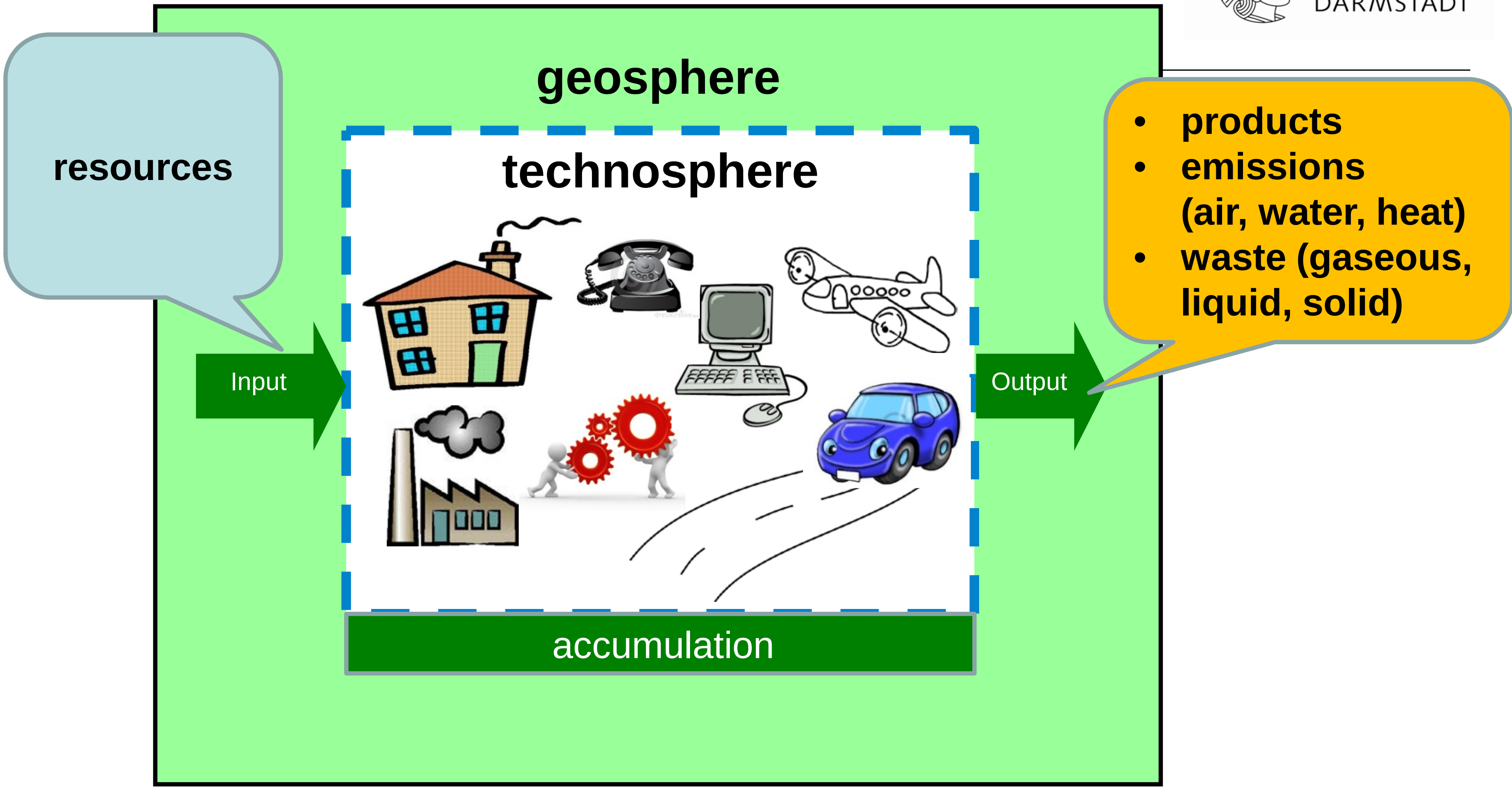
Multi-level criticality assessment

Geography of a metal in time and space



Energy conversion
- ***Mining, drilling***
- ***Separation***
- ***Refining***
- ***De-sulphurization***

FUNKTIONALE MATERIALIEN



from Prof. L. Schebek, IWAR, TU Darmstadt

LIFE-CYCLE ASSESSMENT - LCA

https://www.innovationservices.philips.com/news/life-cycle-assessment-finding-best-approach-company/

A **Life Cycle Assessment (LCA or Life Cycle Analysis)** is a method to calculate the environmental impact of a product over its entire life-cycle. In this context, the term 'product' also includes services.
Taking the entire product life-cycle into consideration – from resource extraction to production, use, and disposal – guarantees an integrated evaluation of all inputs and outputs, thus making sure negative environmental impacts aren't shifted to other life cycle phases of the product.
The methodology is defined in the ISO 14040/14044 standard.

https://www.ifu.com/en/life-cycle-assessment/

CONCLICT METALS

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IISD
International Institute for Sustainable Development

Clare Church
Alec Crawford

August 2018

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THE GRAND CHALLENGE

Transition to 100% renewables

Conflict Minerals:
The fuels of conflict in the transition to a low-carbon economy

1. What minerals and metals are required for the low-carbon energy transition?

2. Where are these minerals and metals found?

3. What are the conditions of fragility, conflict, and violence in these regions?

(IISD 2018)

GREEN CONFLICT MINERALS - THE FUELS OF CONFLICT IN THE TRANSITION TO A LOW-CARBON ECONOMY (IISD)

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- At least **23 key minerals** will be critical to the development and deployment of **solar panels, wind turbines, electric vehicles and energy storage technologies**.
- Many of these minerals are projected to **surge in demand in the coming decades**, in part due to the global transition to the low-carbon economy.
- Significant reserves of all of these identified minerals are found in states perceived to be both fragile and corrupt, as defined by **Transparency International's Corruption Perceptions Index** and the **Fund for Peace's Fragile States Index**.

The Fragile States Index defines fragility using indicators relating to internal cohesion, the economy, politics, crosscutting factors including demographic pressures, refugees and internally displaced persons, and external intervention (Fund for Peace, 2018).
Transparency International calculates perceptions of corruption in the public sector (Transparency International, 2017).

IISD: Green Conflict Minerals: The fuels of conflict in the transition to a low-carbon economy, August 2018

Fragility indicators can then be overlaid with established mineral reserves

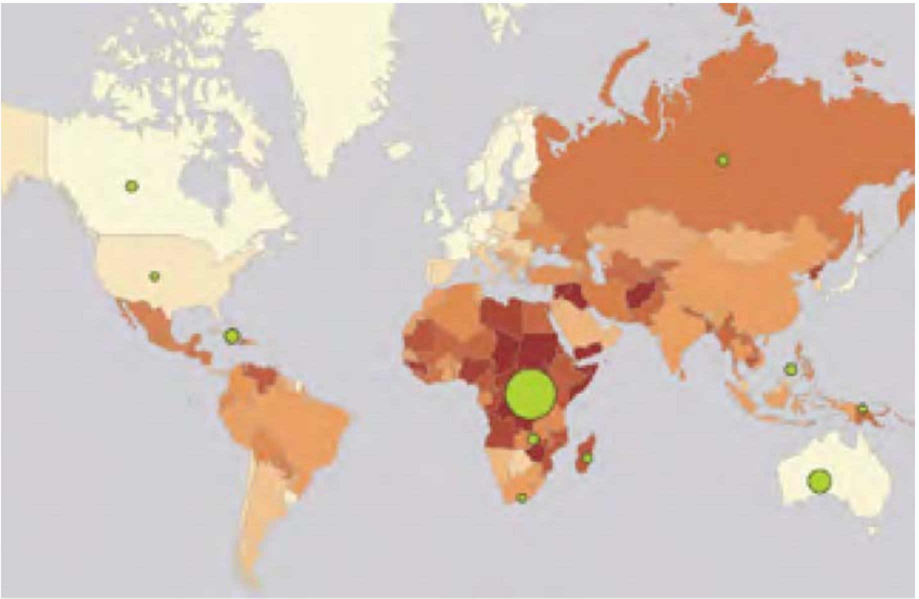


Figure 5. **Cobalt reserves 2018**

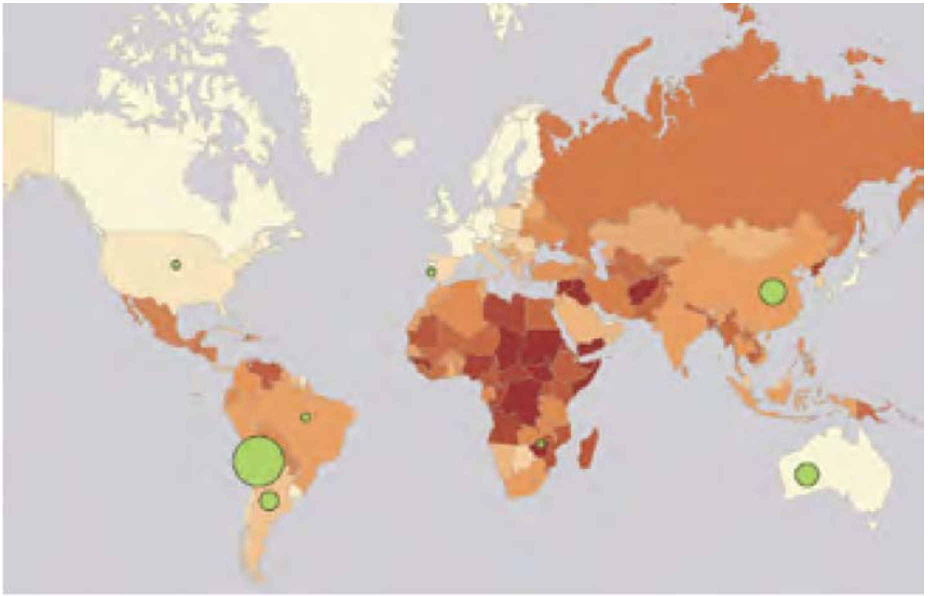


Figure 10. **Lithium reserves 2018**

the size of the circle corresponds to the relative global quantity of the country's reserves in metric tonnes

MINERAL PROFILE OF COBALT

Cobalt is used in the batteries of most modern electronics, like smartphones, digital music players and laptops.
Critical to the low-carbon economy, cobalt is also instrumental to the development and facilitation of EVs and energy storage
technologies.
For EVs in particular, cobalt is found in three out of the four major lithium-ion batteries on the market:
lithium cobalt oxide, nickel manganese cobalt and nickel cobalt aluminum
(Levin Sources, 2017a).

Lithium-ion batteries are also used to store energy derived from solar, wind and other green technologies, thereby making the batteries—and the minerals required to power them—an integral part the transition to a low-carbon economy.

CONFLICT MINERALS

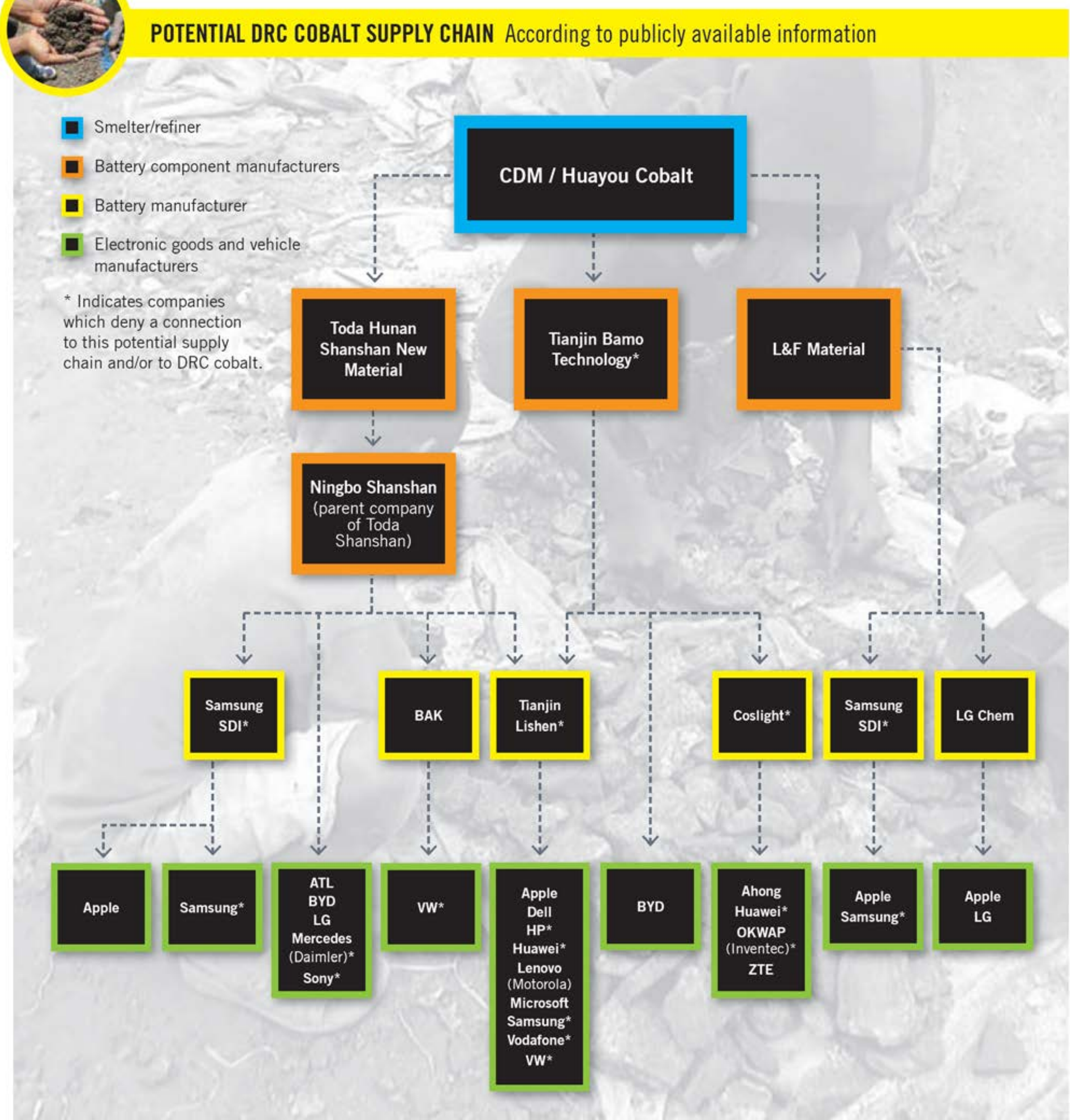
- **Conflict minerals** are defined as those minerals that “finance armed groups, fuel forced labour and other human rights abuses, and support corruption and money laundering” (European Commission, 2017).
- The **Dodd Frank Act Section 1502**, part of the U.S. government’s Dodd-Frank Wall Street Reform and Consumer Protection Act, signed into law in July 2010, requires publicly traded companies to ensure that the raw materials they use to make their products are not tied to the conflict in Congo, by tracing and auditing their mineral supply chains.

The cobalt pipeline

Tracing the path from deadly hand-dug mines in Congo to consumers' phones and laptops

https://www.washingtonpost.com/graphics/business/batteries/congo-cobalt-mining-for-lithium-ion-battery/

AMNESTY INTERNATIONAL JANUARY 2016, INDEX: AFR 62/3183/2016



“THIS IS WHAT WE DIE FOR”

HUMAN RIGHTS ABUSES IN THE DEMOCRATIC REPUBLIC OF THE CONGO POWER THE GLOBAL TRADE IN COBALT

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Raw Materials Consumption in

Batteries

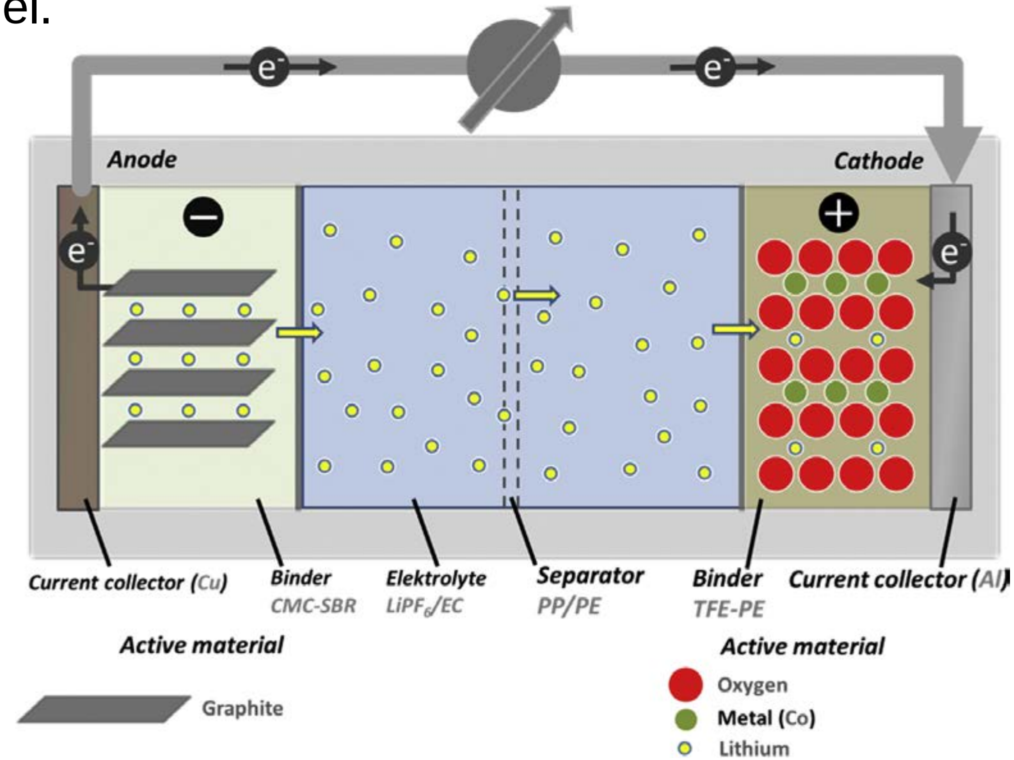
Wind turbines

Traction motors

FUNKTIONALE MATERIALIEN

Supply risks associated with lithium-ion battery materials

Schematic illustration of a rechargeable **Li-ion battery cell** - here the original $LiCoO_2$/graphite (LCO-C) cell. A battery may consist of several such cells connected in series or in parallel.



C. Helbig et al, Journal of Cleaner Production 172 (2018) 274-286

Performance parameters and supply risks associated with lithium-ion battery materials

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battery parameters: energy density, power density, specific energy, capacity, charging time, cyclic performance, aging characteristics and lifetime, safety, (socio-economic-ecological) costs

Functional materials involved:
graphite lithium intercalation compound as **anode** with copper as current collector; **cathode**: LCO - lithium cobalt oxide ($LiCoO_2$) have a high energy density, the high price of cobalt and political problems associated with its supply led to the development of alternative cathode materials - $LiMn_2O_4$.

Table 1
Common commercial battery types and the electrochemical properties for representative, but specific cells based on corresponding references (Nitta et al., 2015; Sterner and Stadler, 2014).

Type	Cathode active material	Anode active material	Potential cathode Li/Li^+ (V) (Nitta et al., 2015)	Usable Li share (Sterner and Stadler, 2014)	Specific capacity (Ah/kg cathode) (Nitta et al., 2015)	Specific energy (Wh/kg cathode) (calculated)
LCO-C	$LiCoO_2$	graphite	3.8	55%	150	570
LMO-C	$LiMn_2O_4$	graphite	4.1	80%	120	492
NCA-C	$Li(Ni_{1-x-y}Co_xAl_y)O_2$	graphite	3.7	70%	200	740
NMC-C	$Li(Ni_xMn_yCo_{1-x-y})O_2$	graphite	3.7	66%	170	629
LFP-C	$LiFePO_4$	graphite	3.4	95%	165	561
LFP-LTO	$LiFePO_4$	$Li_4Ti_5O_{12}$	3.4	95%	165	305

C. Helbig et al, Journal of Cleaner Production 172 (2018) 274-286

Raw materials used in batteries

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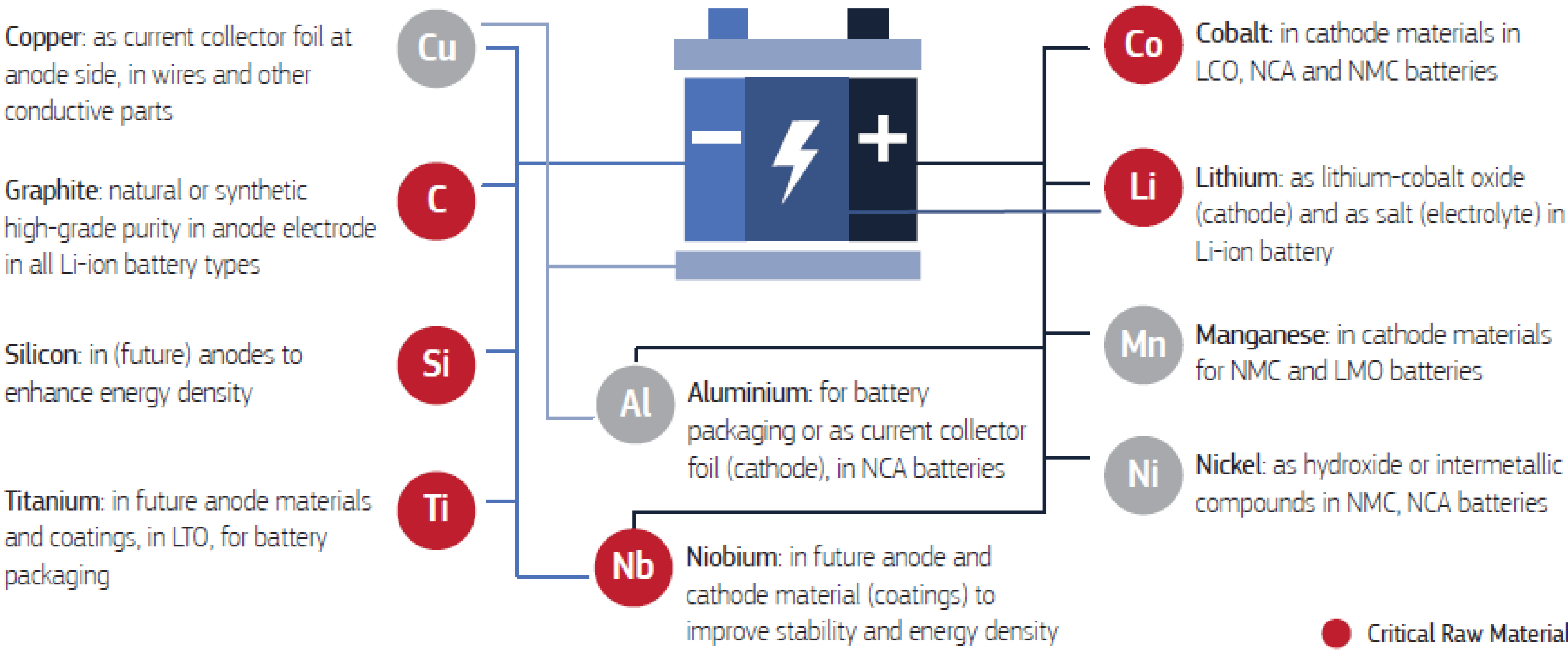
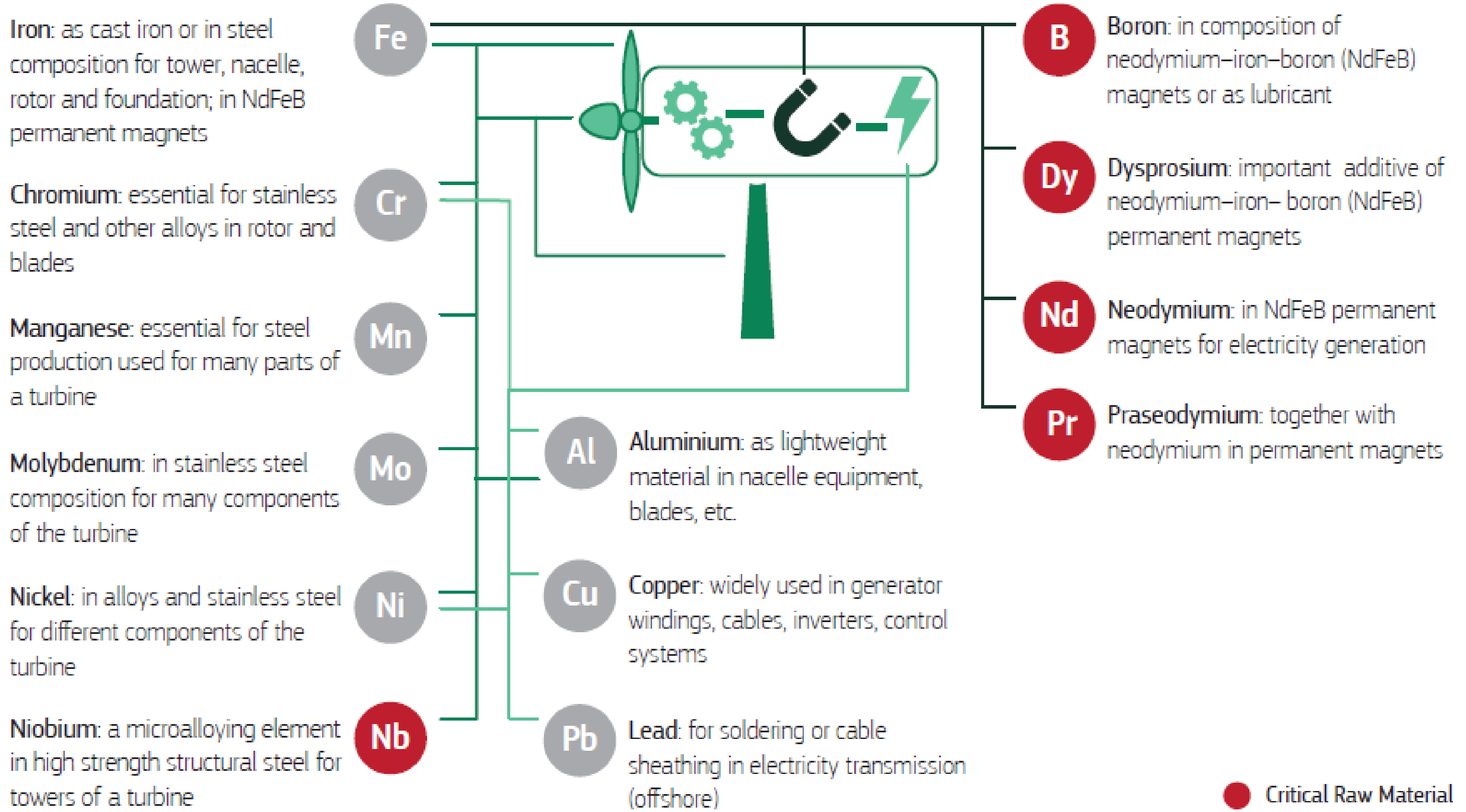


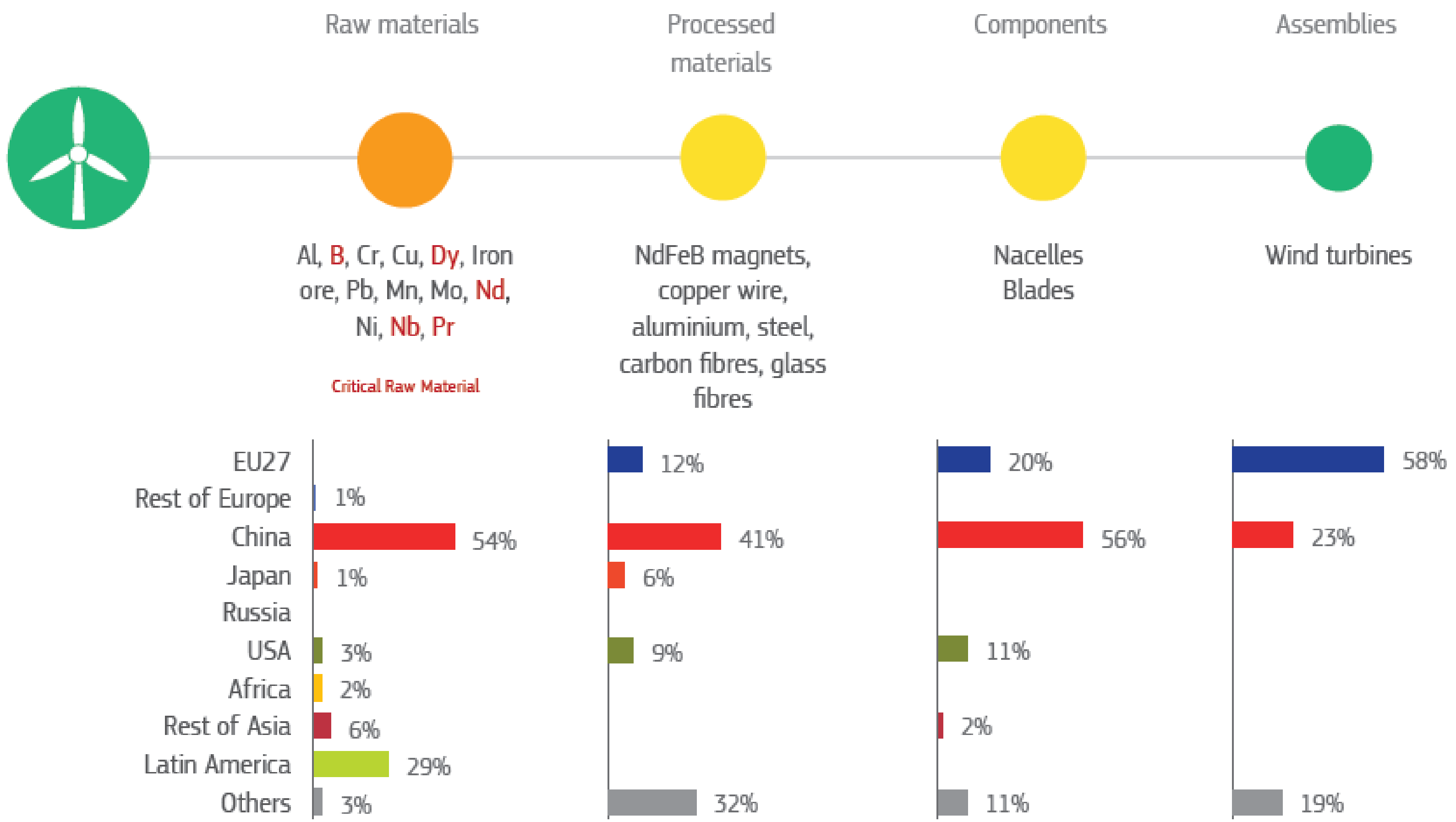
European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Raw materials used in wind turbines



European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Overview of supply risks, bottlenecks and key players along the supply chain of wind turbines

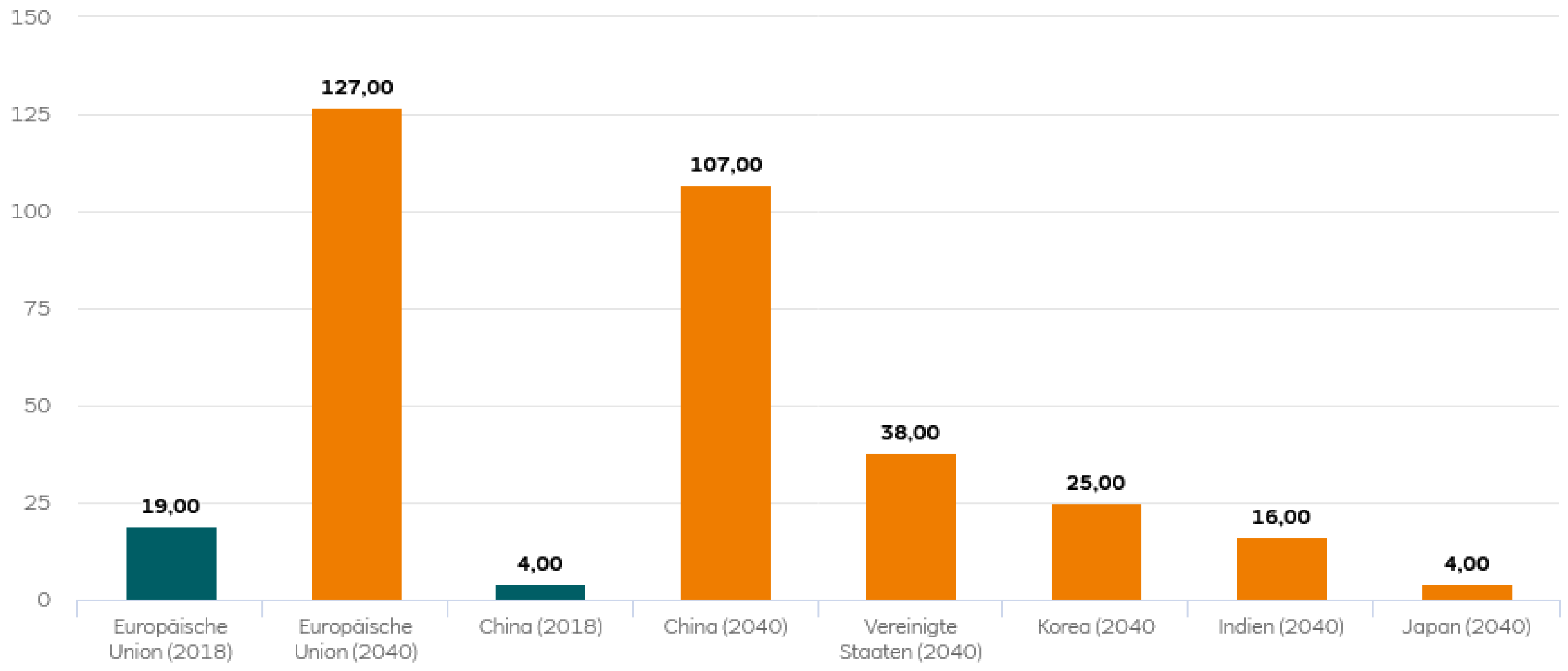


European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Wind turbines global offshore

Gesamte Leistungskapazität durch Offshore-Windanlagen 2018 sowie die Prognose für 2040 in Gigawatt

Diese Prognosen basieren auf dem Szenario der Stated Policies. Für die EU und China werden diese mit den aktuellen Zahlen verglichen (Quelle: Internationale Energieagentur IEA).



Overview of supply risks, bottlenecks and key players along the supply chain of traction motors

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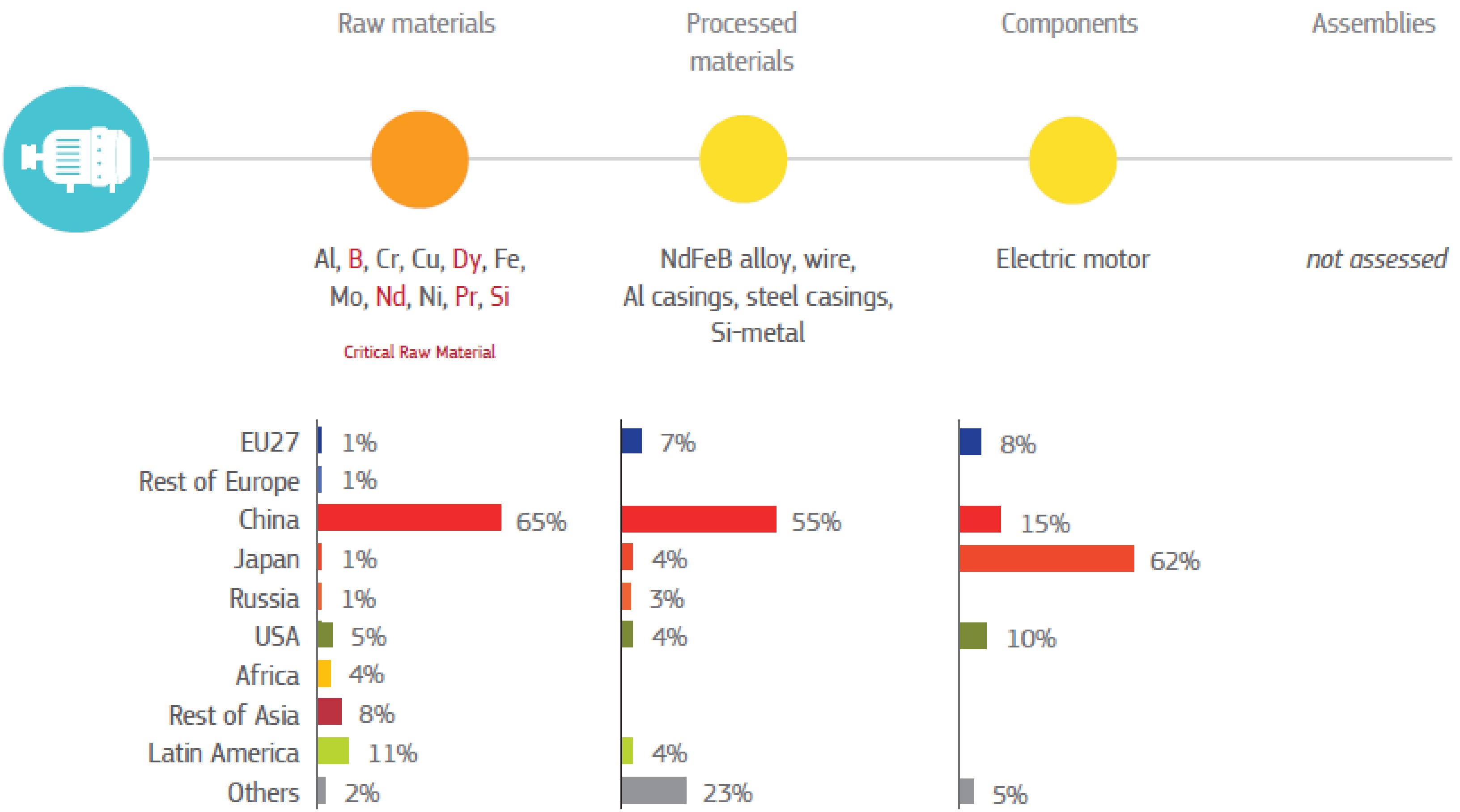

European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

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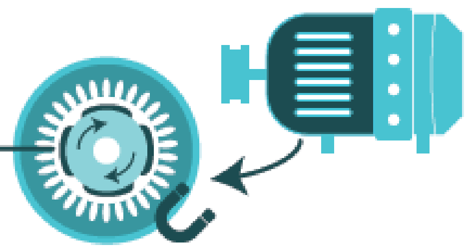
Raw materials used in traction motors



B – **Boron**: in composition of neodymium–iron–boron (NdFeB) magnets

Dy – **Dysprosium**: important additive of neodymium–iron– boron (NdFeB) permanent magnets

Nd – **Neodymium**: in NdFeB permanent magnets in the motor's rotor for providing strong magnetic field

Pr – **Praseodymium**: together with neodymium in permanent magnets

Fe – **Iron**: as cast iron or in steel composition for casings and in NdFeB magnets

Si – **Silicon**: Electronics grade silicon in semiconductors, control electronics; alloying element in Al-alloys and silicon steel

Al – **Aluminium**: in casings and as lightweight material in other metallic parts

Cu – **Copper**: widely used in windings, cables, inverters, control systems

Cr – **Chromium**: in the composition of stainless steel and alloys resistant to corrosion in various motor components

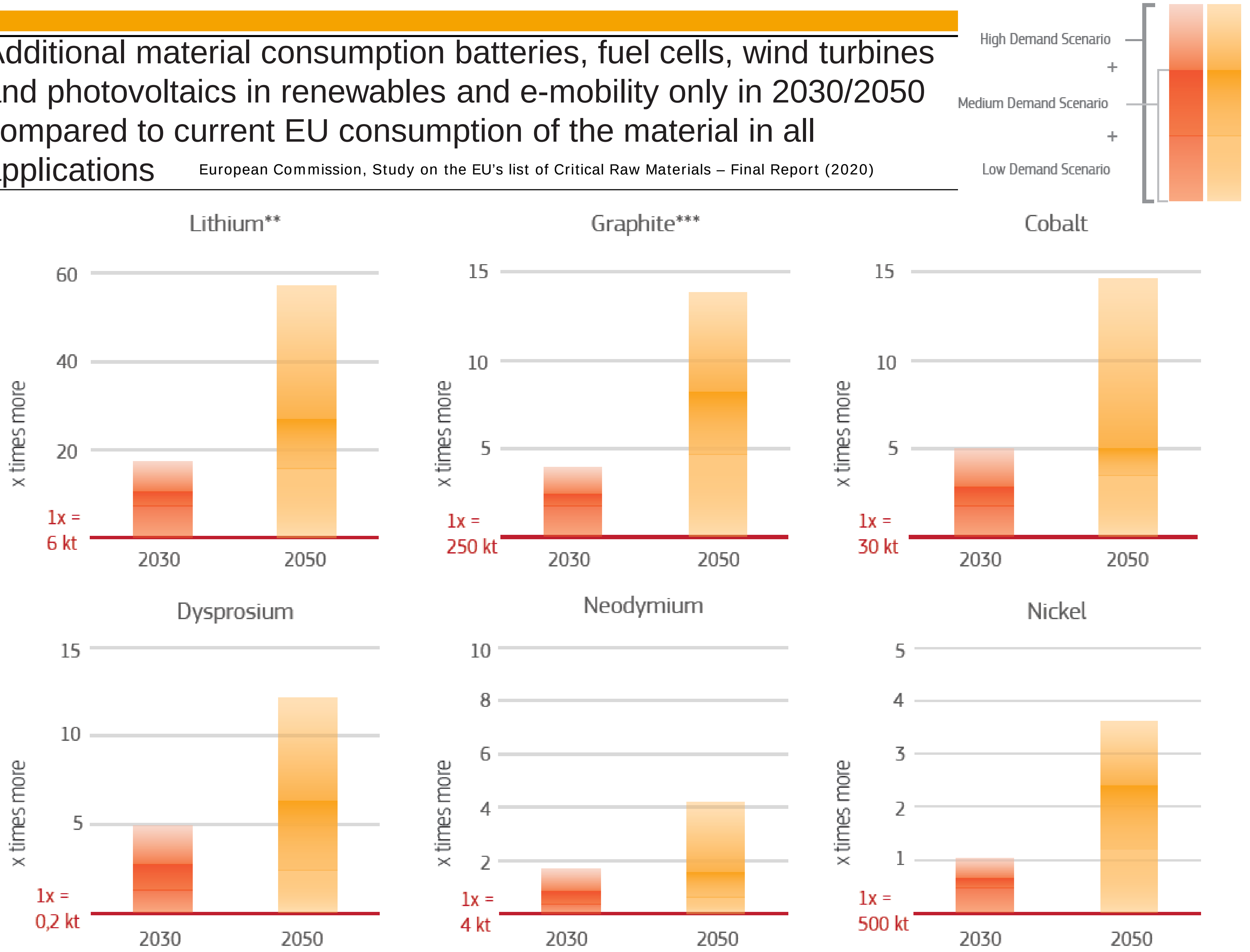
Mo – **Molybdenum**: in the composition of stainless steel and alloys for electric motor's housing and shaft

● Critical Raw Material

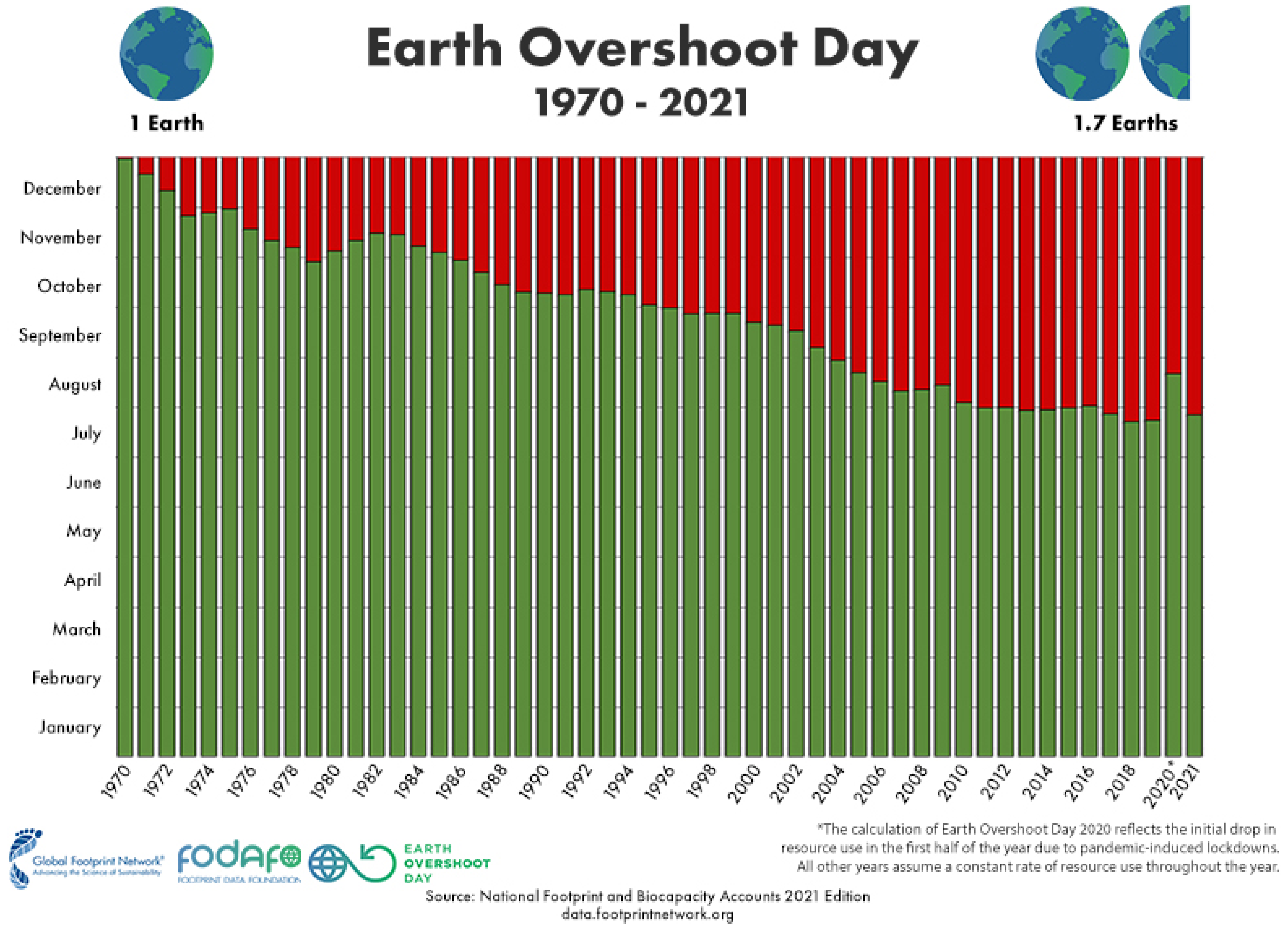
European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)

Additional material consumption batteries, fuel cells, wind turbines and photovoltaics in renewables and e-mobility only in 2030/2050 compared to current EU consumption of the material in all applications

European Commission, Study on the EU's list of Critical Raw Materials – Final Report (2020)



A COUPLE OF FINAL THOUGHTS



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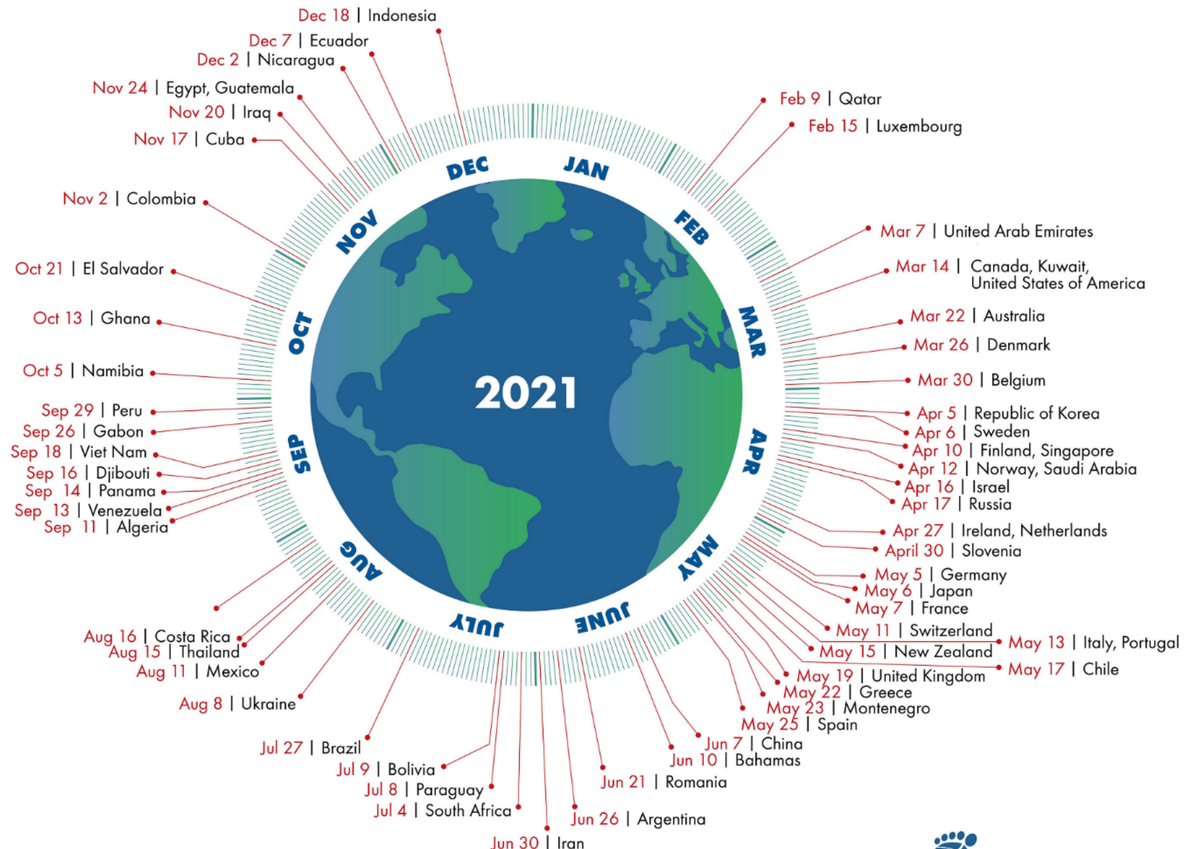
Country Overshoot Days 2021

When would Earth Overshoot Day land if the world's population lived like...



EARTH OVERSHOOT DAY

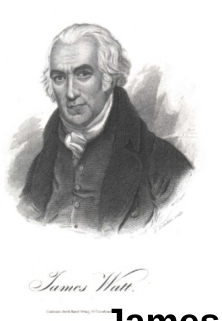
Source: National Footprint and Biocapacity Accounts, 2021 Edition
data.footprintnetwork.org

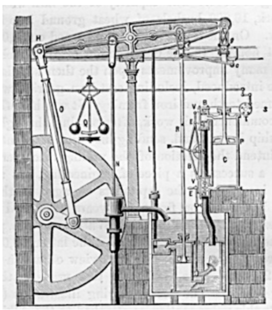
Global Footprint Network
Advancing the Science of Sustainability

FUNKTIONALE MATERIALIEN

The EFFICIENCY PARADOX

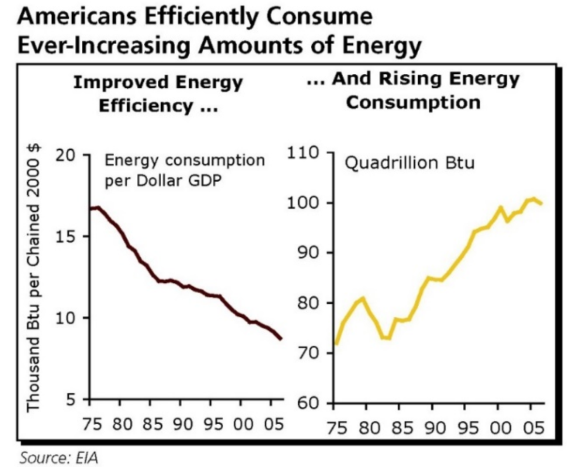
William Jevons observed this way back in 1865





James Watt (1769)

Jeff Rubin and Benjamin Tal,
"*Does Energy Efficiency Save Energy?*"
CIBC World Markets, InC. StrategEcon
November 27, 2007



Inside Climate News

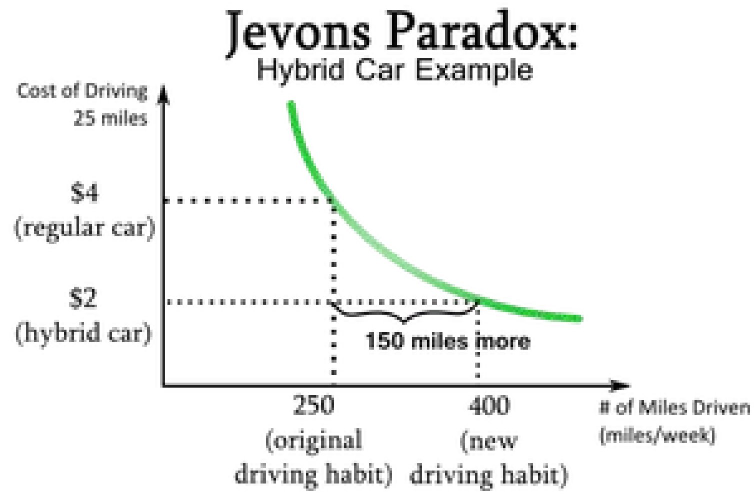
Pulitzer Prize-winning, nonpartisa
on the biggest crisis facing our plai

Clean Energy

The Lighting Paradox: Cheaper, Efficient LEDs Save Energy, and People Use More

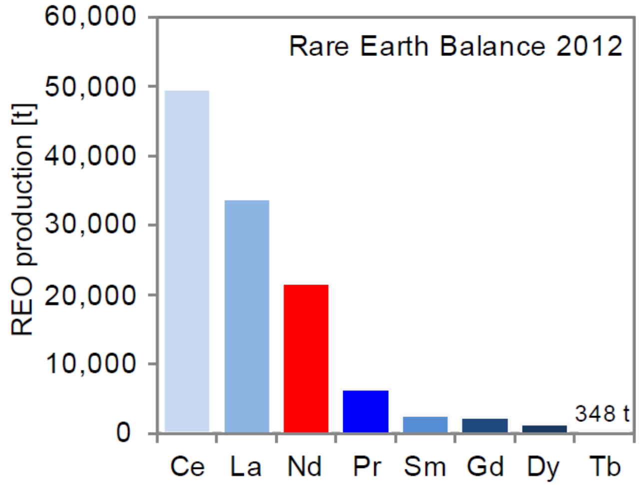
The effort to replace current bulbs with LEDs gets a boost from cheaper materials, but it only feeds society's addiction to light.

By Phil McKenna
August 21, 2015



Mitigation strategies to address REEs criticality

- **Diversify** primary mining and make it sustainable
- **Reduce the utilization** of critical materials by Material Science advances (GBDP and AM)
- **Recycling** will make use of the urban mine (technosphere)
- **Substitute** strategic metals by (more) earth abundant elements



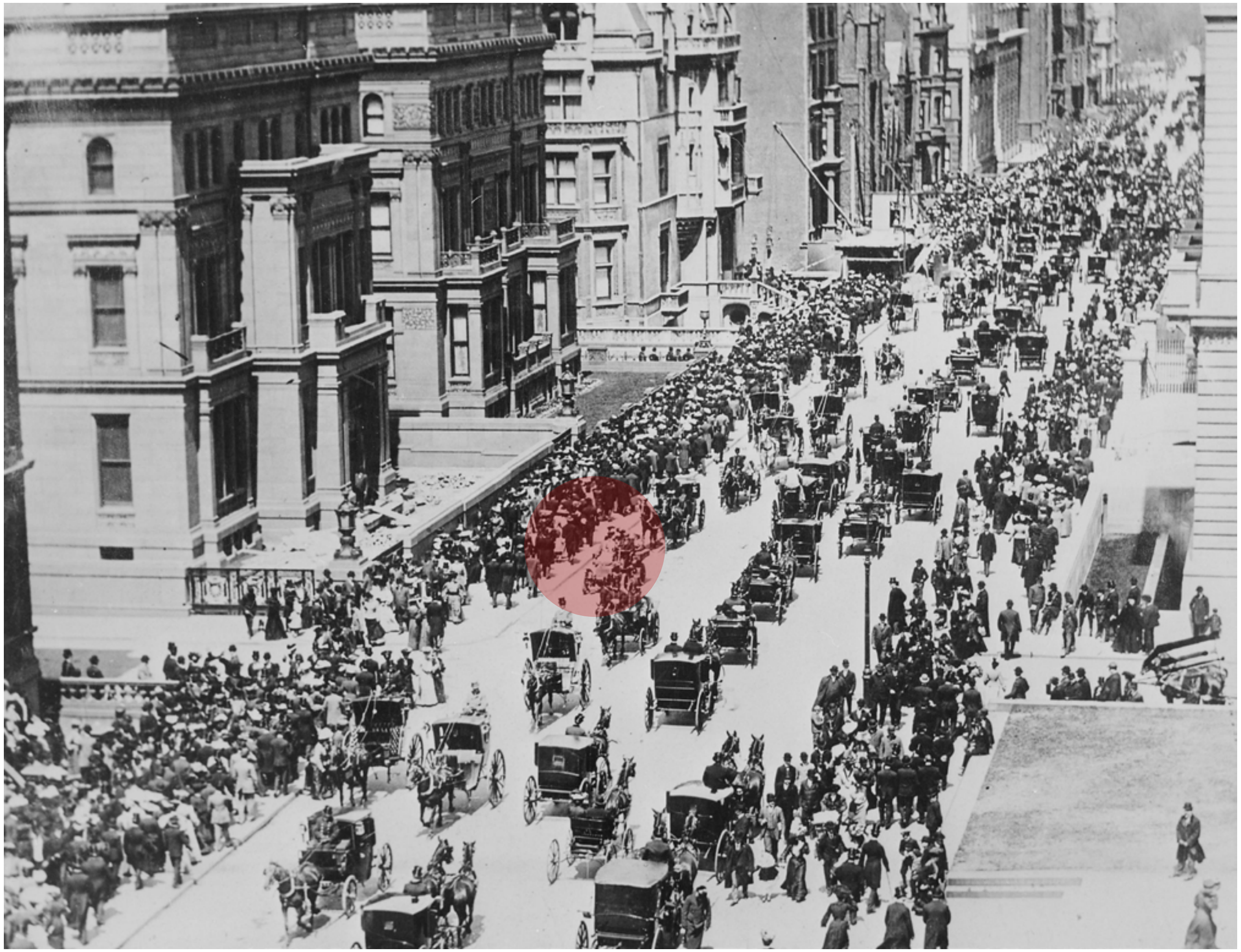
Summary

→ **exit from nuclear and fossil-fuel energy aggravates our dependencies on strategic metals**

→ **how "green" are our metals for green technologies and what ecological footprint are we willing to pay for?**
Or going further:
what is the real price of a metal, of energy, who defines this price, who is paying the price, now and in the future?

→ **the great transformation**
post-fossil society is not possible without rare metals

5th AVE NYC
Easter morning
Year 1900



From: Tony Seba, 2016: Clean Disruption! Why current energy and transportation will be obsolete by 2030

US National Archives

Radical, disruptive innovation!

TECHNISCHE UNIVERSITÄT DARMSTADT

5th AVE NYC
Easter
Year 1913

From: Tony Seba, 2016: Clean Disruption! Why current energy and transportation will be obsolete by 2030

George Grantham Bain Collection

FUNKTIONALE MATERIALIEN

Acknowledgements

- **University Duisburg-Essen**
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- **Ames National Lab.**
- **HZDR and IFW Dresden, ESRF**
- **Universities Danube and Uppsala**
- **Max-Planck-Institut für Eisenforschung**

- **Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient**
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- **Towards high performance PMs w/o REs**
  J. Phys.: Condens. Matter **26** (2014) 064205;
  Scripta Mat View point (2018)
  Nature Com. 8:54 (2017)
  Phys. Rev. Mat. 4, 094402 (2020
- **Mastering hysteresis**
  Phil. Trans. R. Soc. A **374** (2016), Review in Energy Techn. 2018, Nature Com. (2018) 9:2680
  Nat Commun 11 (2020) 4849, Advanced Materials (2020) 2006853
- **Shaping and Additive manufacturing**
  J. Appl. Phys. 114 (2013) 043907, Adv. Mat. 22 (2010) 3735, Acta Materialia 127 (2017) 389
  Advanced Functional Materials (2021)