GLOBAL ENERGY TRANSITION AND METAL DEMAND

- AN INTRODUCTION AND CIRCULAR ECONOMY PERSPECTIVES

TNO innovation for life

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KEY CONCEPTS AND FIGURES

KEY-CONCEPTS BRIEFLY EXPLAINED

- **Carbon budget:** the amount of CO_{2eq} that the world can emit before a certain increase in average global temperatures is reached compared to pre-industrial level. Uncertainty margins do apply
- **Wp:** Watt peak, theoretical maximal power output of energy capital stock
- **Load factor:** the percentage during a period of time that the energy capital stock is actually producing power
- **Beyond 2 Degree or B2D:** the energy scenario of choice, aiming for well-below 2C, published by the International Energy Agency
- **Renewable energy capital stock:** PV panels installations, wind turbines, geothermal installations, storage capacity directly related to renewables etc.

Kilo (k)	A thousand	10^3
Mega (M)	A million	10^6
Giga (G)	A billion	10^9
Tera (T)	A thousand billion	10^{12}
Peta (P)	A million billion	10^{15}

Power requirement examples
1 W = 1 J per second
Car-size mining crusher machine (40cm rocks): 55KW
Four 747 engines maximum power (around four times 48 MW): 192 MW

Energy requirement examples
1 kWh = 1000 x 3600 J = 3.6 MJ
Electricity use of a German standard house of 100m^2: 6500KWh/year
Expected electricity production at the Tesla Gigafactory in 2019: 35GWh/year

Energy (electricity and power) totals for the world economy (per year, source IEA 2017c, beyond 2 degrees scenario)

	Power demand (GW)	Renewable power, part of demand (GW)	Electricity demand (TWh)	Renewable electricity, part of demand (TWh)	Energy demand (PJ)	Renewable energy, part of demand (PJ)
2014	5 962	1 723	23 819	5 398	401 817	29 187
2030	9 637	5 190	30 959	14 467	398 207	85 918
2050	16 107	12 646	44 321	32 945	377 310	208 034

"Renewable" includes biomass, hydro, geothermal, wind, solar and ocean (tidal).

Primary mining production in tons and actual metal content, not ores (source BGS 2018; BMNT 2018)

	World production (ton) 2014		World production (ton) 2014
Silver (Ag)	25 700	Magnesium (Mg)	846 451
Aluminium (Al)	46 777 653	Manganese (Mn)	19 599 190
Gold (Au)	2 797	Molybdenum (Mo)	271 499
Cadmium (Cd)	25 500	Neodymium (Nd)	22 391
Boron (B)	4 527 471	Nickel (Ni)	1 750 000
Cerium/Lanthanum (Ce/La)	86 528	Lead (Pb)	5 006 405
Cobalt (Co)	134 000	Praseodymium (Pr)	6 514
Chromium (Cr)	5 879 482	Platinum/Palladium (Pt/Pd)	397
Copper (Cu)	18 600 000	Selenium (Se)	2 697
Dysprosium (Dy)	1 357	Silicium (Si)	2 288 199
Iron (Fe)	1 596 304 130	Tin (Sn)	358 449
Gallium (Ga)	337	Tantalum (Ta)	931
Gadolinium/Samarium/ Terbium (Gd/Sm/Tb)	5 428	Tellurium (Te)	142
Indium (In)	699	Titanium (Ti)	7 191 245
Lithium (Li)	27 349	Vanadium (V)	71 026
		Zinc (Zn)	13 137 570

Global GHG emissions, combination of several scenario's/pathways (IPCC 2018)

	Gton CO_2 equivalent/Year	Remarks
1980	21 Gt CO_{2eq}	
2016	53.4 Gt CO_{2eq}	2Gt uncertainty range (PBL 2017)
2030	52 – 58 Gt CO_{2eq}	Current pledges under Paris agreement
2050	-10 – 10 Gt CO_{2eq}	Bandwidth Global emissions pathway characteristics

WHY PRICE INFORMATION MATTERS MOST AND THEREFORE IS EXCLUDED

Metrics involving specific product prices are ultimately most relevant when analysing renewable energy capital stock build-up. The best example are so-called learning curves, that display the ratio between MWh and $ over time. However, market prices will not be part of our analysis, as there are too many factors influencing market prices for us to make credible predictions. In this study, we will use unit definitions like TWh, GDP and kg metal content. We will refer to prices only in an economic sense, not in a financial sense.

PREFACE

This report was born out of our long running concern about the long-term availability of raw materials for our society, especially metals. Back in 2008 the potential strategic threat caused by the EU's import reliance for raw materials resulted in the Raw Material Initiative. The 2010 conflicts between China and Japan that caused a temporary delay of rare earth export to Japan made this reliance highly visible. The EC (stimulated by Germany) became highly active after 2008 issuing their first report on critical materials in 2010.

The concern was broad and not specifically aimed at raw materials for energy transition issues. The situation in 2010 was self-evidently different than at the time of writing of this document. A broadly supported COP21 Paris agreement was not signed yet and urgency was felt at a very different level. In 2018, concerns about the future of our climate are felt within societies around the world. The challenges to come up with policies are evidently enormous.

In the heat of those debates, there is understandably much less attention for issues concerning the physical implementation of energy technologies. One of these issues is the timely availability of the metals essential for renewable energy technologies. That is the topic of this report.

The logic that we follow starts with the relevance of findings from climate research on the time scale of metal supply. It then discusses energy and economy scenario's, renewable technologies, metal requirements, supply & demand, to end with a discussion about what circular strategies can and can't contribute to safeguard metals for the renewable energy capital stock build-up.

On the basis of this logic we want to provide an introduction into these ands associated issues. We are aware that any of the questions raised in this document may require years of study for an appropriate answer. But we hope that addressing these issues in one report will provide a compelling introduction in to the complex matter and will spur further research an discussion.

We would like to express are gratitude to René Kleijn, Arjan de Koning, Paul Behrens (University Leiden). They have introduced us to vital information and data, based on their own work.

Within TNO, the following persons have provided background information and specific expertise in certain fields: Ton van Dril (energy & macroeconomics), Niels van Loon (solar), Ton Veltkamp (wind), Maurice Hanegraaf (CCS & geothermal), Tom Mikunda (CCS & geothermal), Richard Westerga (grid management), Robert de Kler (industry & hydrogen), Bob Ran (ICT & Energy System Modelling), Frits Verheij (urban heating).

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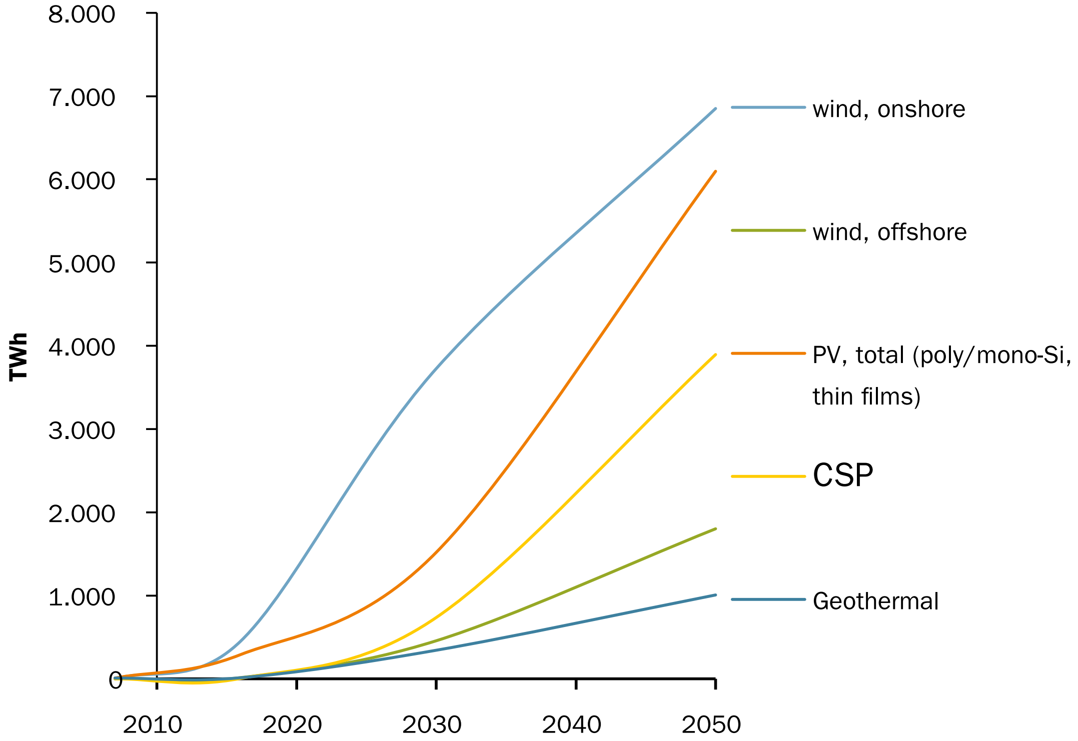
The Hague/Utrecht, December 2018

EXECUTIVE SUMMARY

The global climate action requires a significant clean electricity production. To achieve the Paris Agreement, the vast majority of this production capacity needs to be realized within the next three decades. This production capacity requires a significant amount of critical metals to, amongst others, build wind turbines and PV panels. We find that, by focusing on electricity, we capture the most important part of metal demand for the worldwide energy transition.



Global renewable electricity production capacity (B2D scenario; source: IEA)

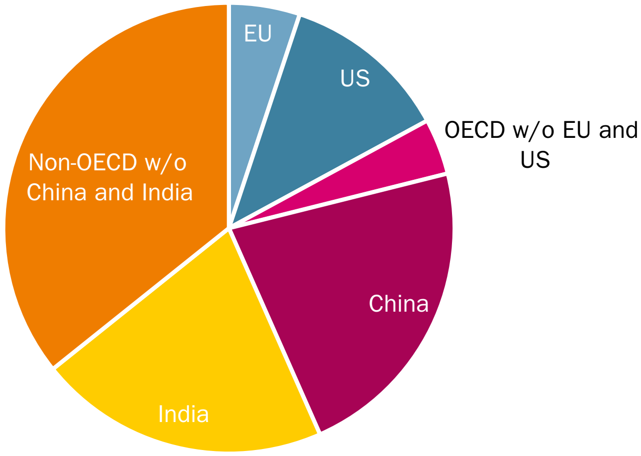
FINAL ENERGY DEMAND WITHIN THE EXPANDING GLOBAL ECONOMY

Some of these critical metals are also required for energy transition related technologies, e.g. batteries in electric vehicles. Besides, it is self-evident that the metal demand for renewable energy capital has to compete with metal demand from other parts of the global economy.

The major concern that we want to address in this report is the impact that the energy transition will or may have on the global demand for metals. We can only assess the risks associated to this transition if we take into account the development of the demand from all other parts of the economy all over the globe. It is not possible to assess metal demand from the global economy without macroeconomic forecasts. The creation of macroeconomic and/or social scenarios is a widespread practice among businesses, governments and NGOs. The World Energy Outlook (WEO) also contains these forecasts. This forecast addresses the observation that emerging economies in the world will demand greater amounts of metals and energy. Apart from demands from new technologies all over the world, emerging economies do need to invest in infrastructure and the built environment that match their standard of living.

METAL DEMAND OF RENEWABLE ELECTRICITY CAPITAL STOCK

Geography matters when deploying renewable energy technologies. For instance, yields of PV installations in Chile, Australia or the Middle East are two to three times higher than in Northern or Middle Europe. Geothermal resources for electricity generation depend on heat exchanges in specific areas of the earth crust. There are several maps online that show average wind speeds and solar insolation around the world. The ETP scenario of the IEA is therefore geographically specified. The geography and the latitude of regions in the world is taken into account in the capacities and market shares of renewable energy types.



Installed PV capacity in 2050 (B2D scenario; source: IEA)

The geography and the resulting lay-out of renewables has an effect on metal use. Densely populated areas may require more adjustments to the existing grid and more storage capacity. Distributed Energy Resources (DER) in emerging economies can benefit from a green field advantages and off-grid energy production. And last but not least the metals required for energy technologies are not evenly spread across the globe, but are in many cases subjected to quasi-monopolies (with China having a very high share of many metals relevant for the energy transition).

THE WORLD'S SUPPLY OF METALS

Given the growth of the energy supply and the (metal) requirement trends of renewable energy capital stock, we can try to estimate the metal demand in a Beyond 2 Degree scenario. This scenario is made for the world economy. The most common way to account for metal demand in renewable energy technologies, is to use coefficients that express the amount of required metal per installed capacity/peak performance: the unit is therefore kg/MWp (or ton/GWp).

Metal demand for renewable energy capital stock build-up takes place in a world economy that is growing autonomously. This growing economy has a metal demand of its own, from infrastructure in Bolivia to packaging in Pakistan to household electronics in Vietnam. For this, we applied the Environmentally Extended Input-Output database (EE-IO) EXIOBASE. This model assumes material efficiency gains between 40 to 60% in 2050 compared to base year 2011, indicating that the same amount of GDP is generated with 40-60% less material. There is evidence that this material efficiency is relevant for renewable energy technologies as well.

Demand for neodymium comes from all three contributions. It is one of the metals that has the greatest relative share to enable the Beyond 2 Degrees renewable energy capital stock build-up, depicted in orange. At the same time, permanent magnet demand in EV's make storage a significant source of Neodymium demand as well.

	Observed Mine production growth 1998-2016	Required annual growth rate with renewables & batteries 2011-2050	Speed-up production compared to last 20 years?
Silver (Ag)	2.86%	3.0%	uncertain
Aluminium (Al)	5.37%	2.8%	safe space
Gold (Au)	1.48%	2.8%	speed-up
Cadmium (Cd)	0.20%	2.7%	speed-up
Boron (B)	2.32%	3.2%	speed-up
Cerium/Lanthanum (Ce/La)	0.00%	3.2%	speed-up
Cobalt (Co)	8.07%	4.1%	safe space
Chromium (Cr)	5.33%	2.8%	safe space
Copper (Cu)	2.92%	3.4%	speed-up
Dysprosium (Dy)	0.00%	5.2%	speed-up
Iron (Fe)	6.55%	3.0%	safe space
Gallium (Ga)	-0.77%	3.1%	speed-up
Gadolinium/ Samarium/Terbium (Gd/Sm/Tb)	0.00%	3.8%	speed-up
Indium (In)	5.41%	3.6%	safe space
Lithium (Li)	4.61%	6.2%	speed-up
Magnesium (Mg)	5.58%	2.7%	safe space
Manganese (Mn)	5.40%	2.7%	safe space
Molybdenum (Mo)	3.85%	3.0%	safe space
Neodymium (Nd)	0.00%	4.5%	speed-up
Nickel (Ni)	3.22%	3.3%	uncertain
Lead (Pb)	2.43%	2.7%	speed-up
Praseodymium (Pr)	0.00%	3.9%	speed-up
Platinum/Palladium (Pt/Pd)	0.02%	2.8%	speed-up
Selenium (Se)	3.30%	3.0%	safe space
Silicium (Si)	5.66%	3.3%	safe space
Tin (Sn)	2.05%	3.1%	speed-up
Tantalum (Ta)	5.20%	3.4%	safe space
Tellurium (Te)	4.54%	6.9%	speed-up
Titanium (Ti)	2.00%	2.7%	speed-up
Vanadium (V)	2.75%	3.2%	speed-up
Zinc (Zn)	2.70%	2.8%	uncertain

To enable the required growth in renewable electricity production, three circular strategies are needed:
- Substitution of critical metals in renewable electricity stock: critical metal use should be decoupled from capacity growth
- Circular design strategies for PV panels and wind turbines: modular design to enable future remanufacturing
- Clear end-of-life criteria in the building contract enable higher recycling yields in the future

Apart from circular strategies, we see other recommendations to be made based on our analysis. We suggest to use the Paris Rulebook. Authorities should make sure that metal markets can supply renewable energy stock manufacturing, using current free market principles.

Moreover, political leaders across the world should use the leverage they have. They can demand circular strategies when procuring and permitting renewable energy capital stock.

IMPACT OF CIRCULAR STRATEGIES ON RENEWABLE ENERGY CAPITAL STOCK

It is one thing to build the capital stock that can provide the world with the renewable energy needed to meet the Paris Agreement. It is another to make renewable energy actual sustainable energy. This requires to think about the anticipated end-of-use-cycles of metals, and their consequences for demand from of renewable energy capital stock. A recovery rate of around 50% can be challenging, even for modular designed electronics.

Apart from recycling techniques, there is the aspect of the size of the so called “urban-mine” that can be also referred to as “stock in use”. The annual amount of products that are offered and collected for recycling are, even at a recycling rate of 100%, not sufficient to meet over 5% of the demand for metals in the coming 15 years. So, recycling can deliver a contribution to the metal markets for renewable energy stock. Supplying a share larger than 3% of the metal demand for the energy transition before 2030 seems to be infeasible though.

Other circular economy strategies show more market potential, e.g. enabling shared use, repair, and refurbishment. For renewable energy capital stock, these circular concepts are highly relevant. Moreover, given the interdependency between renewable energy and a stable economy, circular strategies are relevant for all products in society.

Lifetime is a sensitive parameter in renewable energy modelling. Doubling a lifetime basically reduces the amount of metal needed to deliver the power output by 50%. This fact is as trivial as it sounds. Every percentage of increase in the lifetime of renewables basically reduces the amount of metal needed to deliver the power output with the same percentage.

The recent market success of the renewable energy products has a downside. The substitution of metals for other metals is more difficult for mature products that have a market penetration of over 1%. This metal-for-metal type of substitution, if made necessary by metal prices, is mostly relevant for renewable technologies that are not yet tied to market contracts.

THE WAY FORWARD

The market for mined resources has competition from other resource needs, such as the need for productive arable land, water and the built environment. Together with the time pressure associated with the carbon budget, the resource nexus – dependencies of people, planet and prosperity – explains why the energy transition is different from any preceding transition. Never before did the economic system change over virtually every part of the globe. Never before was there a transition that had such a clear and present time pressure. Never before was there a transition that delivered no direct increase to the quality of living, which is the case for most westernized countries. And never before were so many decision makers involved. The NDC’s can’t be pursued by any country on its own. This is what the Common But Differentiated Responsibilities (CBDR) philosophy in the Paris agreement represents.

We conclude that it can’t be taken for granted that metal markets supply will meet metal demand including renewable energy capital stock build-up. Market interventions might be justified and need to be explored to safeguard metal supply for the energy transition. Furthermore, these interventions are no exception when it comes to ensuring supply of basic needs for society like energy. Markets for energy are already highly regulated in the EU and throughout the world. Given the regulation of energy markets over the last decades, it would be unacceptable that any possible macroeconomic headwind in the future should diminish perspectives for renewable energy capital stock investment.

Keeping an eye on metal demand is needed. The global society can’t afford to let metal demand frustrate our common climate challenge. An annual or even a more frequent exchange of information between worldwide authorities will allow to monitor metal demand for the renewable energy capital stock. This ensures that a path leading away from catastrophic climate change remains open. To limit the impact of energy transition on metal demand, TNO recommends the following:

1. Circular economy strategies can make the renewable energy investments more sustainable in the long term. Therefore the following is demanded:
   a. Substitution of critical metals in renewable electricity stock
   b. Circular design strategies for PV panels and wind turbines, e.g. applying modular design
   c. Clear end-of-life criteria in the building contract to enable higher recycling yields
   d. Set up a list of universal standards for procuring energy capital stock, regardless if these investments are made by public or private bodies.
2. Use the contents of the so-called Paris rulebook to an explicit investment portfolio, expressed in metal needs

3. Establish a set of key-indicators for twenty metals or metal groups most relevant for renewable energy technologies like solar PV, wind energy, and batteries, and exchange analyses made by organizations applying these indicators
4. Set international standards to be used by institutions responsible for market oversight and governments responsible to safeguard investments in light of the Paris agreement
5. Monitor the impact that supply chain due diligence has on procurement practices of manufacturing industries. Under pressure from legal enforcement, or even social media, supply disruptions can occur that are unprecedented to procurement professionals involved
6. A trivial, yet every bit as sensible, last recommendation is to continue to challenge all these assumptions by publicly available research.

CLIMATE CHALLENGE AND OUR CURRENT GLOBAL SOCIETY

WHAT IS THE IMPLICATION OF THE "WELL-BELOW" 2°C SCENARIO FOR THE CARBON BUDGET ?

The carbon budget is a concept that quantifies the climate policy challenge for the world. The carbon budget is the amount of CO_{2eq} that the world economy can emit while still having a certain chance to limit temperature rise to a certain level.

The IPCC 1.5 calculates a carbon budget of 770Gt CO_{2eq} to limit temperature rise below 1.5 degrees, with a 50% probability. IEA assumes the carbon budget to be 980 Gt CO_{2eq} (IEA 2017c).
The current annual global greenhouse gas emission in CO_{2eq} (2016) (including Agriculture, Forestry And Other Land-use) is estimated at 54.3 Gton (PBL 2017). Just as with the carbon budgets, the goal of the Paris agreement is subject to uncertainty. In the public debate, the "well-below" prefix before the 2 degree goal is *sometimes* not mentioned.

For comparison, the amount of carbon left in the crust of the earth is probably well over 15 000 Gt given current fossil fuel known resources.

The carbon budget "sets the clock" for the energy transition. If the carbon budget is correct, there will be a deadline set for the worldwide energy transition to stay below the cumulated tonnage emissions. This includes sectors that are not part of the Paris agreement. This resulting time pressure makes energy transition different from major transitions (transport, healthcare, housing, food etc.) in recent centuries.

WHAT ABOUT THE EMISSION OF NON-CO_2 GREENHOUSE GASES?

There is more than one relevant greenhouse gas emission. The most important one is CO_2 or carbon dioxide. The other gases are referred to as non-CO_2 and comprise CH_4 (methane), N_2O (Nitrous oxide) and fluorocarbons. To account for the greenhouse effects of these gases, one may calculate CO_2 equivalents, so that emissions can be expressed in one single number. We will refer to this number as GreenHouseGas (GHG) emissions. In 2017, globally, the combined share of non-CO_2 (CH_4, N_2O and F-gas) gases in total greenhouse gas emissions was about 28% (19%, 6%, and 3%, respectively). This means that 72% of the total greenhouse gas emissions can be attributed to CO_2.

The emission of greenhouse gases in the future has uncertainties arising from climate change accelerating feedback loops and also so-called singular events. Examples of climate change accelerating feedback loops are melting of permafrost, that results in additional GHG emissions. Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_{2eq}$ over the course of this century *(medium confidence)* (IPCC 2018). Examples of singular events are melting ice sheets in Greenland or Antarctica, possible grave events that however do not result in additional GHG emissions.

The implication of these future uncertainties is an increase in time pressure. This increased pressure reduces the tolerance even further for delays in the build-up of renewable energy capital stock. The consequence of this share of non- CO_2 to the total emission of GHGs is that even a world that emits no CO_2 emission from combustion, would still emit in ten years what the world currently emits in three years (Peters et al. 2012) due to non-CO_2.

DO WE HAVE AN IDEA HOW THE GLOBAL ECONOMY WILL DEVELOP TOWARDS 2030 AND 2050?

It is self-evident that the metal demand for renewable energy capital has to compete with metal demand from other parts of the global economy. The willingness-to-pay of the consumer for new electronics and vehicles might be higher than investments in renewable energy to replace conventional energy sources. Metal demands for products like smart clothing, robotics, drones or gesture operated electronics are assumed to be part of the long term prospects.

The major concern that we want to address in this report is the impact that the energy transition will or may have on the global demand for metals. We can only assess the risks associated to this transition if we take into account the development of the demand from all other parts of the economy all over the globe. It is not possible to assess metal demand from the global economy without macroeconomic forecasts. The creation of macroeconomic and/or social scenarios is a widespread practice among businesses, governments and NGO's. The World Energy Outlook (WEO) also contains these forecasts (IEA 2017a). This forecast addresses the observation that emerging economies in the world will demand greater amounts of metals and energy. Obviously, the world is not only transitioning to renewable energy supply, it will continue to develop. Apart from demands from new technologies all over the world, emerging economies do need to invest in infrastructure and the built environment that match their standard of living (Halada 2007).

	2030	2050	Index 2030 compared to 2010 (=100)	index 2050 compared to 2010 (=100)
Population (million #)	8 480	9 714	122.9	140.7
GDP (Billion $)	144 520	252 761	219.1	382.3

***Table 1** Assumed growth of population and GDP (Sources: IEA World Economic Outlook (2017a); UNDESA (2015))*

The relation between metals and economic growth can be expressed in kg metal extracted divided by world GDP (expressed in thousand $ at 2005 prices to correct for inflation). This ratio started at "126" in 1980, peaked at "156" in 1988, had a "97" low in 2002, to be back at "112" in 2012 (IRP 2018). This demonstrates that there is no clear decoupling observed between metal demand and economic growth.

WHAT IS THE FINAL ENERGY DEMAND FOR THIS EXPANDING GLOBAL ECONOMY IN 2030 AND 2050?

Given the economic growth, the final energy demand can be mapped as well. We take the International Energy Agency Beyond 2 Degree scenario ("B2D") (2017c) as the basis of our analysis. The world is becoming more energy efficient. The relation between global energy use and global GDP can be expressed in Joules/$. This metric has shown that for every $ increase of GDP in 2018, 25% less energy expressed in Joule is needed compared to 1980 (IRP 2018). In contrast, the relation between raw material extraction and economic growth has not shown an evident decline between 1980 and 2015 (IRP 2018).

	2014	2030	2050
Total Final Energy Demand (PJ)	401 817	398 207	377 310

***Table 2** Development of final energy demand (IEA B2DS) - IEA 2017c, Beyond 2 Degree*

The decrease in final energy demand in the B2D scenario is similar to the one published by (Paltsev 2018). The scenario IEA B2D scenario is 30% to 60% below average of many scenarios that together make up the Shared Social Pathway scenarios of the IPCC (IPCC 2013). The average IPCC Shared Social Pathway assumes an energy demand of around 667 000 PJ and 842 000 PJ in 2030 and 2050 respectively. We don't use any forecast from any SSP's in this study.

When considering energy demand, it is helpful to discern between five stages of energy supply. There is energy production, energy storage, transportation/transmission, conversion and final demand (EDSL 2018). The difference between primary and final energy demand is relevant. Primary energy includes efficiency factors (i.e. losses) of fossil fuels and losses during transportation. Final energy is the energy that is actually useful for the consumer. When energy is increasingly produced on a local level, like distributed solar energy, the difference between primary and final demand will decrease as a result of "loss of loss".

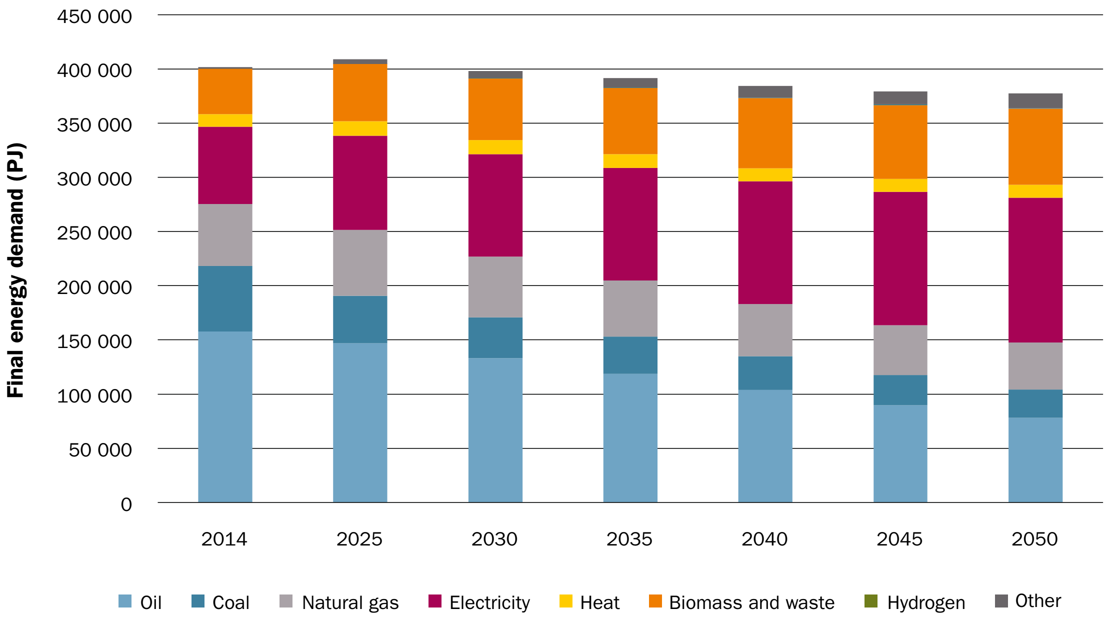


Figure 1 *Development of final energy demand (B2D scenario)*

The IEA scenario also indicates where this final energy demand comes from in Figure 2: 25% from transport, 32% from industry, 2% from agriculture, 22% from residential consumption ("households"), 8% from services ("offices and shops") and 11% from non-energy purposes like the production of plastics.

The most remarkable change assumed up to 2050 is the growth of electricity in the final energy demand: this level grows from 18% in 2014 to 37% in 2050.

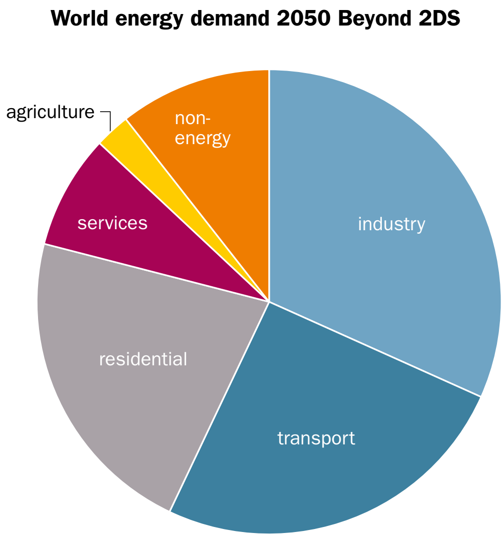


Figure 2 *Distribution of final energy demand in 2050 (B2D scenario) (source: IEA 2017)*

THE RENEWABLE ENERGY CAPITAL STOCK AT HAND

WHY LOOK ONLY AT THE METAL DEMAND FOR THE GENERATION OF ELECTRICITY?

The remainder of this study discusses (the growth of) metal demand as a consequence of the development of technologies for generating and employing electricity from renewable sources.

There are other developments that we will not consider for further analysis at this moment, though their implications may be large and may be worth similar analyses.

Creating heat (or cold) from electricity is straightforward, although not always sensible in a situation where you can harvest heat. This is because electricity is superior to heat from a exergy point of view. However, in a renewable energy future, heat or cold are not only delivered by electricity sources. Countries like France demonstrate that depending on electricity for heat can make a region dependent on others during cold periods (RTE 2018). It is likely that for instance half of heat or cold related energy demand can be delivered by thermal exchange. This means that heat or cold can be taken from masses that retain temperature over long (weeks, months) periods of time. These masses can be water, gravel containers on the surface or several meters below, for instance pockets of water (“aquifers”) that can lie over hundred meters deep into the ground. Combining technologies that enable exchange of this thermal energy can avoid electricity peaks during weeks with extreme temperatures in winter and summer (ETIP SNET 2018).

Carbon neutral hydrogen can meet certain transport demands. By deciding to ignore transport fuels, we ignore metal demand associated with the non-electricity part of hydrogen production. There are several aspects of the hydrogen technology that are worth observing (Kleijn & vd Voet 2010). Use of hydrogen to fire industrial plants is being explored, possibly substituting use of natural gas directly using parts of existing industrial infrastructure. The use of hydrogen in fuel cells is part of the automotive strategy of several countries, including Japan. The use of hydrogen in synthetic fuels (Ridjan et al. 2016) adds another option for heavy transport, jet fuel and ocean transport.

Biomass is also left undiscussed in this document. The low Energy Return On investment (EROI) of biomass needs to be dealt with preparing it for transport fuel. For most biomass technologies, EROI of under 2 are reported (Hall et al. 2014). Biomass is relevant for niche solutions and specific fuels (de Jong et al. 2017). The possibility of BECCS is another reason to research biomass applications beyond 2030.

We find that, by focusing on electricity, we capture the most important part of metal demand for the worldwide energy transition. A possible omission from leaving hydrogen out of the analysis, is the requirement of Platinum Group Metals. These might be needed as catalysts in hydrogen production and conversion. The metal content, expressed in kg/Mw, of thermal exchange units is factors of ten lower (Nitkiewicz & Sekret 2014) than the technologies discussed later in this study.

WHICH PART OF THE GLOBAL FINAL ELECTRICITY DEMAND IS EXPECTED TO BE MET WITH RENEWABLE ENERGY?

The IEA estimates the electricity demand (in a Beyond 2 Degree scenario) in 2030 and 2050 for the world, and provides an estimate of what part of this demand will be met with renewable energy technologies. The following renewable energy technologies are part of the IEA scenario: biomass and waste (with and without Carbon Capture and Storage), hydro, geothermal, wind onshore, wind offshore, solar PV, solar Concentrated Solar Power (electricity, not thermal) and ocean (tidal). See Figure 3 and Figure 4.

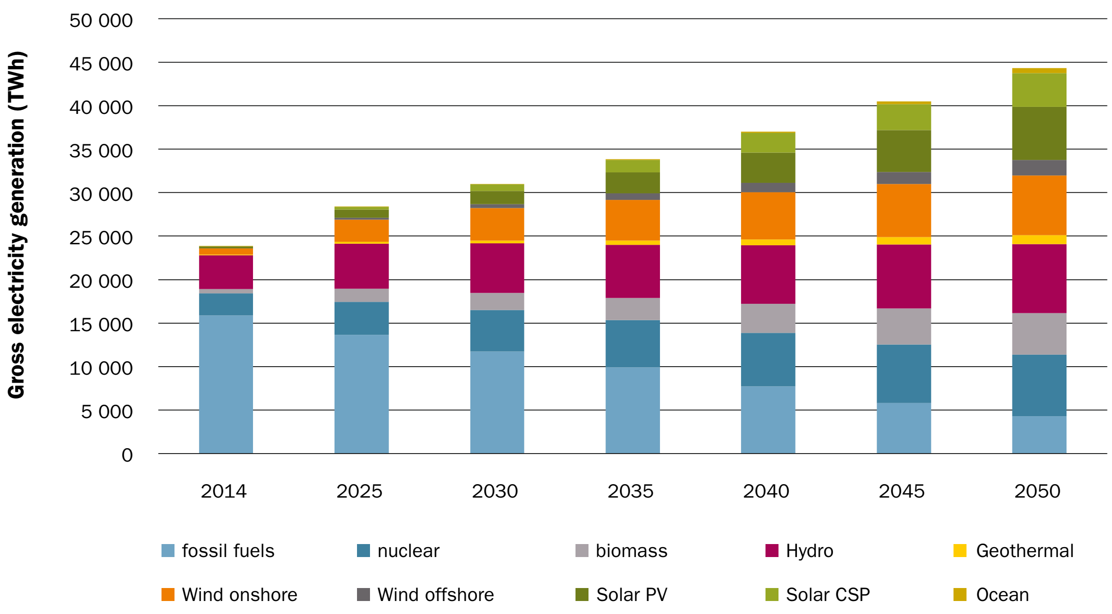


Figure 3 *Development of gross electricity generation in a B2D scenario (source: IEA)*

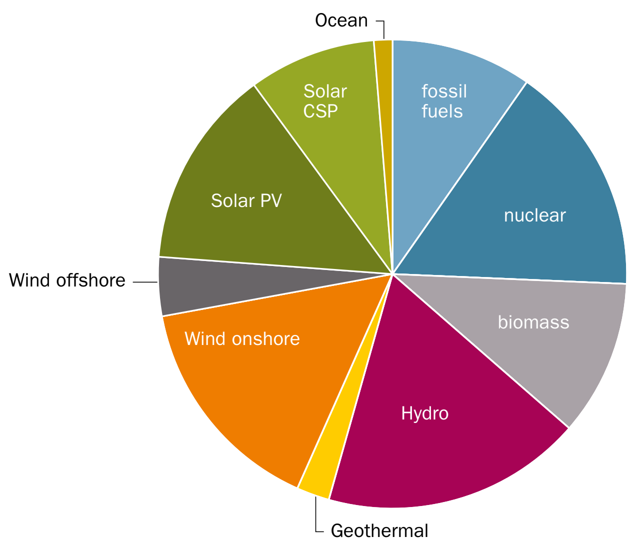


Figure 4 *Distribution of electricity generation in 2050 in a B2D scenario (source: IEA)*

It shows that almost 64% of the electricity in 2050 is expected to be generated from renewable sources. Out of the other 36%, almost half (16% of the total electricity) is expected to be generated by nuclear power. The remaining part of electricity will still be provided by fossil fuels.

Market prices show that natural gas is currently the only traditional electricity source that is a competitive source of electricity compared to renewables regarding power generation. Oil, nuclear and coal are more expensive, expressed in Levelized Cost Of Energy (LCOE). Investing in capital stock for electricity generation from oil, coal and nuclear installations is not attractive based on existing (2018) market prices. At the same time, given the need to reduce emissions as fast as possible, natural gas is hardly a viable long term (beyond 2030) solution for the electricity market, especially if one considers an increasing price of carbon on an Energy Trading System (ETS) market. Yet, it is an unavoidable stepping stone, for instance providing back-up power during long spells of unfavourable weather conditions for renewables.

Every forecast about the uptake of renewable energy over the last decade has proven to underestimate the renewable energy capital stock build-up (Steinbuch 2017). This is explained by the reduction of the so called Levelized Cost Of Energy (LCOE), mostly expressing the cost of electricity in cents per KWh over a typical lifetime (for instance 25 years). The IEA is no exception to this assessment. Given that even an organization like Greenpeace is underestimating the uptake of renewable energy capital stock, the data on which our estimates for metal demand are based can be regarded as modest. The speed of the implementation of renewable energy technologies should be monitored closely and considered as an important uncertainty when assessing metal demand for renewable energy capital stock build-up.

WHERE WILL THESE RENEWABLE ENERGY TECHNOLOGIES BE DEPLOYED?

Geography matters when deploying renewable energy technologies. For instance, yields of PV installations in Chile, Australia or the Middle East are two to three times higher than in Northern or Middle Europe. Geothermal resources for electricity generation depend on heat exchanges in specific areas of the earth crust. There are several maps online that show average wind speeds and solar insolation around the world. (Altestore, Global Wind Atlas). The ETP scenario of the IEA is therefore geographically specified. The geography and the latitude of regions in the world is taken into account in the capacities and market shares of renewable energy types.

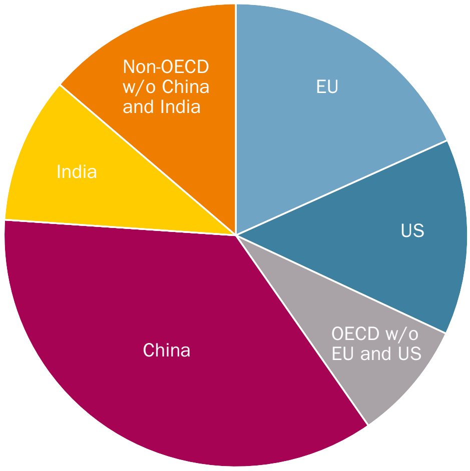


Figure 5 *Installed capacity for wind on-shore in 2050 (B2D scenario; source: IEA)*

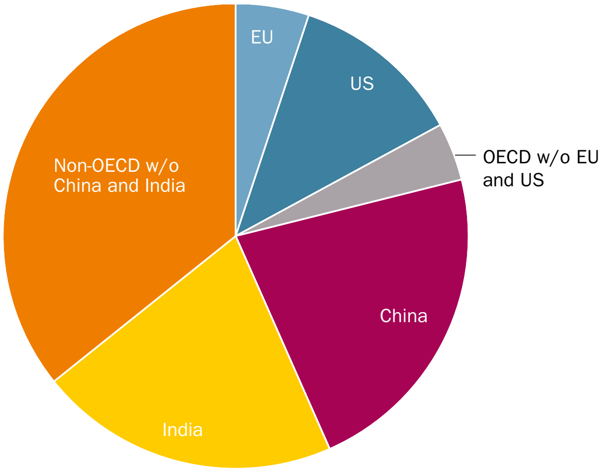


Figure 6 *Installed PV capacity in 2050 (B2D scenario; source: IEA)*

The geography and the resulting lay-out of renewables has an effect on metal use. Densely populated areas may require more adjustments to the existing grid and more storage capacity. Distributed Energy Resources (DER) in emerging economies can benefit from a green field advantages and off-grid energy production.

And last but not least, as we will see later in this report, the metals required for energy technologies are not evenly spread across the globe, but are in many cases subjected to quasi-monopolies (with China having a very high share of many metals relevant for the energy transition): it may be speculated that the local desires for energy transition are more easy to accommodate in case the required metals are locally available, then when all metals (and technologies derived from these metals) have to be imported.

WHAT IS THE EXPECTED DEVELOPMENT OF WIND AND SOLAR ENERGY DEPLOYMENT IN THE NEXT DECADES?

With respect to renewable energy production technologies, we focus in this report on the various types of on-shore and off-shore wind energy and on the various types of PV generated electricity.
Again following the IEA Beyond 2 Degree scenario, the table below shows the energy production for each of these technologies from 2007 until 2050.

In GWh	2007	2016	2030	2050
wind, onshore	92	452 424	3 726 000	6 851 000
wind, offshore	1	14 081	457 000	1 802 000
PV	8 678	290 791	1 519 000	6 097 000
CSP (electricity, not thermal)	479	4 873	736 000	3 895 000
Geothermal	9 144	12 628	343 000	1 007 000

Table 3 *Development of electricity generation from wind and solar - 2007 and 2016 numbers from (IRENA 2017); 2030 and 2050 numbers from (IEA 2017c)*

In terms of installed capacity for PV and wind, the B2D scenario of the IEA expects a growth form just over 500 GW in 2014 to just below 8000 GW in 2050. This represents 16 times the volume in a 35 years period. That will not only impact the economy of the renewable energy sector but also will heavily affect the mining activities.

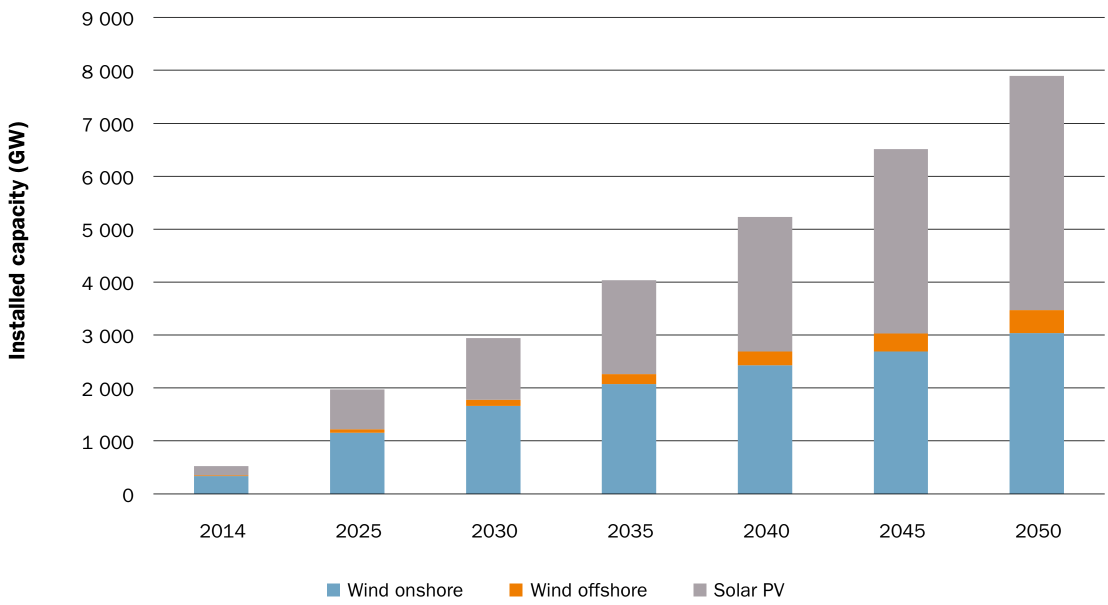


Figure 7 *Installed capacity for wind and PV in 2050 according to B2D scenario*

HOW HAVE WIND, SOLAR AND GEOTHERMAL ENERGY TECHNOLOGIES DEVELOPED OVER THE LAST DECADES?

The renewable technologies for wind, solar and geothermal have had a steep and steady Learning Curve over the last decade. There are many sources on-line, showing the learning curves for these technologies (NREL 2018; DoE 2018). The learning rate of CSP (electricity production, not thermal) has been 18% over the last decade (Haysom et al. 2014), considerably lower than the other renewable technologies that are discussed.

The load factors of renewables have developed rapidly in recent years. Load factors express the amount of time during a 24h period that renewable energy capital stock actually produces energy. The load factors in Europe for both PV and wind have come up from 10% to above 20% for PV and from 20% to well over 40% for wind. This evidently has a direct effect on the amount of renewable energy capital stock that needs to be build. The higher the load factor, the lower the capacity (in Watt peak Wp) of renewable energy capital stock that needs to be built.

It is not without irony that PV development in the nineties of the 20th century was partly spurred by the offshore oil industry. The panels provided the best possible off-grid electricity for drilling platforms (Middelkoop & Koppelaar 2017). Other drivers were space applications and off-grid telecom requirements. Material efficiencies have increased (FhG ISE 2018) in the last ten years, for instance the amount of silicium in both mono and poly crystalline PV cells has dropped from 16 gram to 4 gram per Wp.

The market uptake of thin film technologies such as Copper Indium Gallium Selenium (CIGS) and Cadmium-Tellurium (CdTe) PV films is a development worth noting. They are on the market for over 10 years. Thin film market shares on the total PV market have remained constant between 3-5% each, despite better performance than crystalline PV cells, that had a market share of over 90% (Angerer 2016). The Learning Curve of thin film technologies is similar to the curve of crystalline PV's. The cost rate per square meter is already at the same level, despite the lower (under 10%) produced cumulative volume of thin films in the world compared to crystalline (over 90%). This is promising for future cost developments. Especially CIGS thin-films have shown potential in 2017 and 2018 for cost reduction, following reduction of material requirement and conversion efficiency.

As a rule-of-thumb, we assume in our analyses that about 90% of installed capacity of PV in the world is based on crystalline silicium. Thin film technologies based on cadmium and tellurium (CdTE) are assumed to contribute 6% and CIGS cells contribute 4%. It is unclear how these shares will develop in future years. For the current analyses these distributions are held constant over the period of analysis.

The market uptake of Concentrated Solar Power (CSP) for electricity production has been stagnating in recent years compared to solar PV since CSP is only potentially viable for large (greater than 20MW) projects in areas with the right irradiation from sunlight and land use. Concentrated Solar Power is expected to become more relevant after 2030, given the options to use the thermal component of CSP. The thermal component is about the fact that the CSP can be designed to store and convert heat as well, apart from electricity.

Onshore wind is and will be easier to build from a technical point of view than offshore wind. Spatial planning of onshore wind turbines can represent major societal difficulties. Offshore wind on the other hand, for instance in the North Sea countries, is now profiting from zone planning efforts that have been made since the early nineties. The typical peak performance of a wind turbine has developed in from around 1MW around the turn of the century to 5 to 8MW towers that are installed in 2018, with a prospect of building 10 to 11MW towers in the near future (Pollinder 2013).

With respect to the technology options for wind energy the situation seems to be more complex than with PV: there is not only an assumed distribution of off-shore and on-shore wind (see Table 3) but beyond that, there is a variety of technologies employed for wind turbines, each with a different demand for metals. There are two main types of wind turbine systems in the market: gearbox operated and direct drive. Gearbox operated wind turbines have more components and therefore require more operational expenditures. The market uptake for Direct Drive (DD) has started as early as 2011. The benefit of direct drive compared to a gearbox is low maintenance, leading to a higher market uptake for Direct Drive for offshore wind applications. The permanent NdFeB magnet (Neodymium-Iron-Boron), invented by happenstance in 1983, has enabled the development of direct drive wind turbines. Several efforts are made to reduce the neodymium amount of these permanent magnets (MC 2018), but it is expected that these efforts will contribute to modest (0.5-1%) material efficiency gains only.
The amount of neodymium can currently be shifted between 22% and 31% in permanent magnets (Smith & Eggert 2015), but a share below 22% will affect performance of the magnet too severely for use in a wind turbine.

We conclude that advancements in the most relevant technologies are take decades to develop. The market competitiveness of a technology can emerge in a matter of years. At the same time, the full development of renewable energy technologies seem to usually take decades.

WHAT DEVELOPMENTS FOR THESE RENEWABLE TECHNOLOGIES MAY WE EXPECT IN THE FUTURE DECADES?

The field of renewable energy technology is continuously under development. Some interesting developments are highlighted below. For the sake of the current analysis (i.e. the metal demand for the energy transition) the potential consequences of these developments are not yet taken into account.

For solar PV, progress can be expected by reducing production costs of thin films, reducing layer thickness and improving efficiencies. The development of the Perovskite solar cell is a possible major development in the PV market. When combined with crystalline PV, these Perovskite thin films can be adjusted so that they harvest different wavelengths of light in order to produce electricity. This will allow efficiencies that are higher than the theoretical maximum PV efficiency 33.7%. The potential of Perovskite is large given the amount of "regular" glass windows in the built environment all over the world. Even if only a fraction of regular glass surface would be replaced by translucent Perovskite cells, it would greatly increase PV capacity.

For wind turbines, have (Viebahn et al. 2015) made an extensive assessment of the scenarios with which wind energy will develop in the coming decades, taking into account 4 different types of wind turbines. The conclusions by Viebahn have been used in this paper to assess the 'average' need for metals, among which rare earth metals, of PV. The results in this paper are based on their so-called scenario, that predicted the highest implementation of rare earth containing wind turbines.

	year	asynchronous, gear, high speed, induction	induction, synchronous, DD	PM*, synchronous, gear, high speed	PM*, synchr. , middle speed	PM*, synchr., DD
wind onshore	2012	19	57	22		2
wind onshore	2030	5	16	46	9	24
wind onshore	2050	2	4	40	14	40
wind offshore	2012	100				
wind offshore	2030	31		2	49	17
wind offshore	2050	2			60	38

Table 4 *Scenarios for penetration of on-shore and off-shore wind energy technologies (source: Viebahn)*

** Using NdFeB permanent magnets*

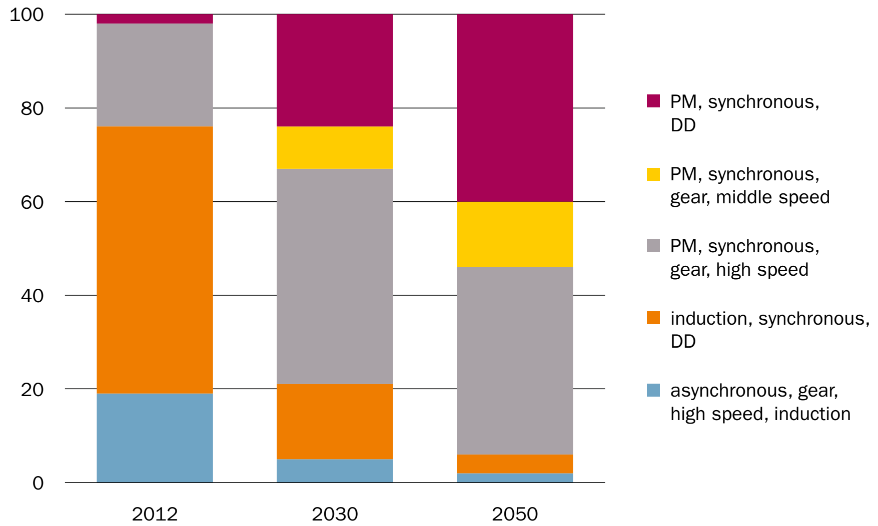


Figure 8 *Scenario for on-shore wind turbines (source: Viebahn)*

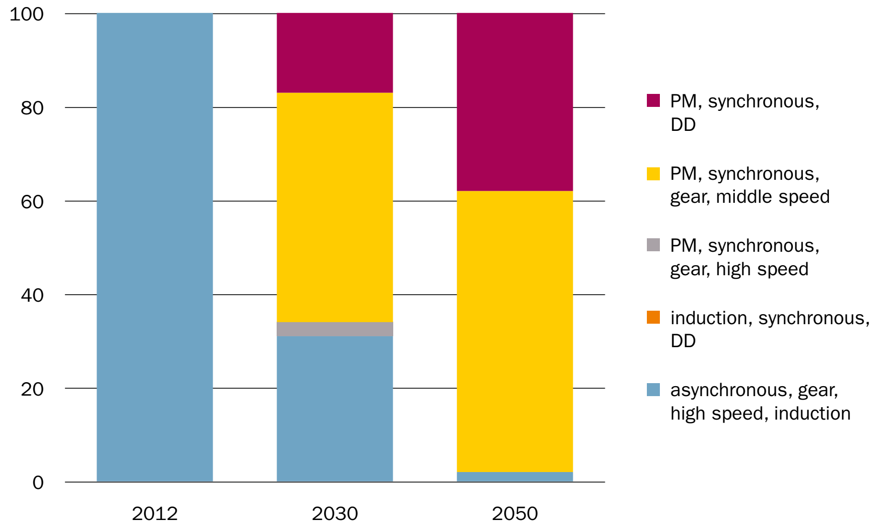


Figure 9 *Scenario for off-shore wind turbines (source: Viebahn)*

These 5 different technologies differ markedly in their metal content, especially in their rare earth content, which is strongly related to the permanent magnet, essential to generate electricity. The direct drive synchronous turbine contains 200 kg Nd (and Pr) per MW; this figure is most often quoted. Given the compositions and the scenarios for penetration of these technologies average compositions of turbines can be calculated. These will be given in a subsequent chapter.

Possible major developments in wind energy may come from floating wind turbines. These turbines can be placed in sea areas that are farther away from shore and/or are not prime fishing territory. Recent projects in Norway have delivered load factors of 65%, higher than natural gas or coal electricity generation observed since 2008 in the United States and Europe (Equinor 2018).

Conventional geothermal applications can only be viable where there is ample heat, fluidity and permeability at a certain depth. To reduce dependency on naturally-occurring geothermal reservoirs, it has been proposed that such reservoirs be created artificially (Olasolo et al. 2016). These so called Enhanced Geothermal Systems represent the potential upscaling of geothermal technologies, and justify the over 1TWh of energy expected to be harvested in 2050.

Storage on the grid may require additional investments and metal supply. There are positive by-effects of storage that have become apparent in recent years. Grid storage has created ancillary services like frequency regulation and responsiveness (“adding power to the grid in an instant”). A typical discharge is 50kW per powerpack. A powerpack is a block that measures roughly 1 by 2 meters. The Hornsdale power reserve in south Australia is a famous grid battery storage example, operational since late 2017. Battery storage on the grid of this size (100MW, 129MWh) has improved the stability of wholesale electricity prices (ARENA 2018). This signals an important general need. Storage will prevent renewable energy to be curtailed (“wasted”) during renewable peak production hours. It will prevent high CO_2 footprint electricity to be better priced during hours of low renewable production. It should be noted that the full range of storage technologies could, and probably will, be needed to solve the challenge to store electricity long enough for a period up to 72 hours to meet peaks in demand or supply. This range of technologies includes hydrogen production.
Non-metals will contribute to innovation in the coming years as well. Carbon fibre is already used in renewable energy capital stock, for instance in manufacturing rotor blades of wind turbines. Carbon fibre has excellent strength-to-weight ratio’s. Even though the first carbon fibre applications were invented over 50 years ago, prices of manufacturing carbon fibre have not come down. Though carbon fibres may reduce any dependence on the secure supply of metals, we can’t expect disruptive price changes from innovations in manufacturing carbon fibre. The use of graphene in carbon fibre can be a promising technological development. Graphene production has seen a major breakthrough in 2004. The global market size of Graphene has reached 250 tons in recent years (2016, 2017).

A different look on build-up of the current renewable energy technologies is the total GHG emission associated of the capital stock build-up. Several studies have determined the carbon footprint (in kg CO_{2eq} per kWh) of energy technologies. If we use the coefficients found by (Gibon et al. 2017), the “GHG footprint” of the renewable capital stock build in the IEA B2D scenario is between 140 to 180 kT of CO_{2eq}. in 2030 and 400 kt to 700 kt of CO_{2eq}. in 2050. Please mind that these are summations over a period of time, not single year emissions. This means that GHG claims made in the past about embedded GHG of renewables are no longer valid. These claims suggested that renewable energy capital stock could never prevent GHG emissions over their lifetime (replacing fossil fuel technologies) than the GHG emissions associated with the building-up of the stock. Even an emission of 700 kt of CO_{2eq} (as a total emission between now and 2050) would represent only 5.1% of global annual emissions from electricity production in 2014.

WHAT ARE MARKET-READY APPLICATIONS FOR STORAGE, POWER TRANSPORTATION AND CONVERSION?

Apart from generation and consumption, the three other distinct elements of the electricity system are transportation, storage and conversion. The need for investments on the grid for transportation, storage and conversion is self-evident in a future with renewable energy production. The sun is not always shining and the wind is not always blowing. Moreover, over the last decades grid management already has developed steadily to increase the operational quality.

Storage

Storage on the grid was long perceived as the missing link in the renewable energy transition. In recent years, several alternatives have presented themselves. The storage system of choice is not yet determined and will be made of several different technologies, that in any case depend on the circumstances of the specific characteristics of the region it serves. For instance, the grid has short term (seconds) and long term (hours) storage, like pumping-up water in a lake to let it flow down later on the day (a process called “pumped storage”). The deployment of nuclear energy has demanded storage on the grid since the 1970s, since power production from nuclear installations continued more or less throughout the day and therefore had to be stored during periods of low electricity demand in the night.

Besides grid management, storage will be dominant in the innovation of the automotive industry. Metal demand from the automotive sector will be discussed this in section “What will be the metal demand for battery storage that comes with renewable energy?”

Storage technologies are often classified in a Ragone chart, showing energy storage capacity (Wh/kg) versus and specific power (W/kg).

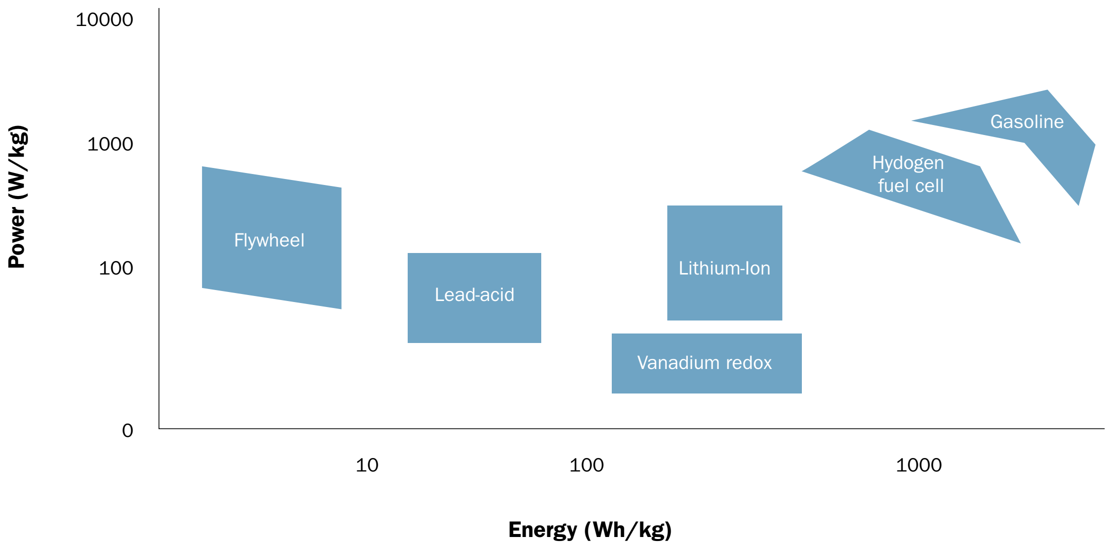


Figure 10 *Ragone chart: storage capacity vs. specific power*

The storage technology characteristics are important in order to decide which storage properties are optimal. Examples of these properties are power density ("how much power from how much battery weight", especially relevant for vehicles), production costs (CAPital EXpenditures), environmental impacts, operational costs (OPerational EXpenditures), number of loads (every time a battery is charged, there is some permanent quality loss), reliability etc. The most important examples of electricity storage technologies deployed over the last years are listed below. Several more technologies can be found at (Enipedia 2018).

– **Pumped storage.** The grand old classic on the storage market. This type of storage suitable for long term periods, many hours or even days. More recent types of pumped storage feature tall towers combined with wind energy (EE 2018)
– **Compressed Air (CAES) & Fly wheel,** classic technologies on the market, suitable for short term storage (minutes and a few hours). Most applications of this storage technique can be found on a local level.
– **Lead Acid,** the classic battery with moderate properties in terms of power output or storage capacity.
– **Vanadium Redox Flow Battery,** a currently yet possible dominant option for storage on the grid. It has poor power to weight ratio makes it an unlikely candidate for vehicles. It reacts slower to power demand changes than lithium-ion batteries. For grids, its durability and controlled power output (due to the flow of the electrolyte) are attractive characteristics
– **Lithium ion:** the most well-known class of batteries. Types that are considered in this study are named after the cathode material. These types are Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP), Lithium Cobalt Oxide (LCO), Nickel Cobalt Aluminium (NCA) and Nickel Manganese Cobalt (NMC) in 111 ratio. The NMC in ratios 532, 622, 811 are less proven on the market and therefore deemed too uncertain to count on significant market uptake. In general, lithium-ion are the leading battery. They have the highest "ramp-up" speed ("how fast can you deliver power"), highest energy density and highest power output.

The exact amount of storage needed in the future, compared to the installed capacity, is uncertain (Denholm 2016). Uncertainties come from several possible developments: the development of demand response mechanisms that coordinate the electricity demand of homes, the development of Distributed Energy Resources (production on site, for instance PV panels on a roof of a home) or the development of "behind the meter" storage such as the Tesla Powerwall. We will estimate the amount of non-pumped storage based on IEA (2017b). For a nice overview of the latest developments on storage technology, see (IRENA 2017; Research interfaces 2018).

In this study we decided to model the metal need of batteries, given the specific and authoritative sources available to predict demand from the International Energy Agency.

Transportation
Connecting electricity networks on a continental scale is expected to take place in North-America (NREL 2018). Large parts of continental Europe are already connected in an electricity grid. The existing network is mainly based on High Voltage Alternating Current (HVAC), visible in the landscape as powerlines. New connections on a continental scale or below sea can also be designed as High Voltage Direct Current (HVDC). Since 2011, there is a cable connecting the United Kingdom and the Netherlands (350Kv, 1430mm2 copper cable). Other studies have explored the connection of the northwest European area, especially the North Sea zone (Kleijn 2012). The purpose of these links is not only to send electricity from A to B. It is possible that renewable, so variable, electricity production in countries around the North Sea can store excess power through pumped storage facilities in Norway. The inventory data of the Windspeed project provides a list of metal needs of a single offshore project (Arvesen 2014). Such a study could be used as building block of a greater network.

However, in this study we decided not to model investments in grid cables separately, given the uncertainty of the timing and scale of these investments.

Conversion
Conversion is the least discussed element of operating electricity grids suitable for renewable but variable generation. The main capital stock associated with conversion of electricity are (super)capacitators, transformers and inverters. Transformers are used to change the voltage of alternating currents in electricity power applications. The transformers that operate next to High Voltage Direct Current have the size of a car. Capacitor banks or even supercapacitors are increasingly needed to supply reactive power on local circuits. This is something that fossil fuelled generators did in the past for large parts of the grid, but this is not supplied by the current renewable electricity capital stock. Inverters change (“invert”) direct current (DC) into alternating current (AC) and vice versa. Inverters are usually an expensive part of a PV installation.

In this study we decided not to model investments in conversion hardware separately, given the uncertainty following the specific requirements of transformers, inverters and capacitors.

WHICH TECHNOLOGIES ARE NOT DISCUSSED FURTHER IN THIS REPORT?
A series of possible relevant renewable energy technologies are not part of the analysis in this document. In general, these technologies are excluded because the uncertainty involved in the type and scale of their application is deemed too great.

The metal demand of **hydro** is not assessed. The growth of hydro in the Beyond 2 Degree scenario is significant, expecting to grow from 3895 TWh in 2014 to 7965 TWh in 2050.

Existing technologies for storage facilities on the grid (pumped hydro, Lithium-Ion, batteries, flywheels, compressed air) are discussed. However, new storage technologies might come on the market in the coming years. Innovations could be expected in technologies like **Sodium-Sulphur based batteries or solid state batteries** (with an electrolyte made of a polymer or ceramic).

Tidal energy provides a viable renewable alternative for locations with the right geography. A recent project in Scotland has produced 3GWh in its first year (Independent 2018). The application of this renewable technology depends heavily on the circumstances. Scaling-up of this technology first has to manifest itself at places with high potential for tidal technology.

The metal demand of **nuclear energy** is not taken into account in this study. The main objection from a technological point of view of this technology are the cost overruns and planning delays encountered in projects on various continents. Some examples are the Olkiluoto 3 reactor in Finland, the Hinkley Point reactor in England, the Flamanville reactor in France or the VC Summer reactor in the United States. It should be noted that nuclear energy still is part of the IPCC and IEA scenario’s (IPCC 2013; IEA 2017c).

(Grubler et al. 2018) has deeply looked into five major drivers for energy demand reduction. Reducing demand could be a viable alternative to meet the 1.5C IPCC scenario without use of Carbon Capture and Storage (CCS). Examples of these drivers are servitization (consumers pay for use, rather than ownership of a physical product), ICT innovations (e.g. blockchain, big data) and influencing consumer behaviour. **Demand reduction** is not part of our analysis. Solutions on the energy demand side in order to realize climate policy have great potential nonetheless.

The current market applications for **CCS** have the potential to capture 30 Mt CO_2, although actual capture is estimated to be around 9 Mt (IEA 2017b). Application of CCS technologies that are competitive on the market are mostly deployed to enhance oil recovery. If the increase of carbon dioxide level in the atmosphere develops as expected, it is likely that CCS technologies will (have to) become an essential part of the world's economy at some point. Capturing carbon would become a tradable commodity just like carbon extraction is. The implication for future CCS technologies for raw material demand may be related to the additional need for specific minerals. For instance, a mineral carbonation with a 1 to 1.6-3.7 ratio is possible for olivine minerals (IPCC 2018, chapter 7). Carbonation means that CO_2, can be captured by this mineral to form solid carbonates using the chemical energy of the minerals.

The state in physics where current can run without resistance is called **superconductivity**. It was first observed in 1911. Superconductors would completely change the behaviour of the existing grid, a truly disruptive technology. However, there have been no recent innovations that justify quantification of metal needs in this study. The same goes for **sodium/thorium nuclear reactors**, Solar Radiation Management ("sunscreen for the planet"), space mining on the moon, or Mars, and nuclear fusion.
On-line sources like the MIT technology review (MIT 2018) can be used to put potentially disruptive innovations in a context and time frame.

THE METAL DEMAND OF RENEWABLE ELECTRICITY CAPITAL STOCK

WHAT IS THE BILL-OF-MATERIALS REQUIRED FOR THE CAPITAL STOCK BUILD-UP FOR RENEWABLE ENERGY PRODUCTION?

Given the growth of the energy supply and the (metal) requirement trends of renewable energy capital stock, we can try to estimate the metal demand in a Beyond 2 Degree scenario. This scenario is made for the world economy. The most common way to account for metal demand in renewable energy technologies, is to use coefficients that express the amount of required metal per installed capacity/peak performance: the unit is therefore kg/MW_p (or ton/GW_p).

We show the extensive table below to be transparent about the numbers used. The sources used for this table are given in the “inventory” section of the references. If one thing is certain, it is that these kg/MW coefficients are uncertain, and that numbers in literature vary markedly. One uncertainty factor is the watt peak numerical value that is used as a denominator.

	Wind turbine with gearbox	Wind turbine with direct drive	PV cristalline-Si module	PV CIGS	PV CdTe	Concent. Solar Power	Geothermal energy	2030 annual extra need (ton) compared to BAU	2050 annual extra need (ton) compared to BAU
Ag			20	10	10	16		2.338	4.482
Al	1000	400	10 000	100	100	740		1.264.953	2.258.795
Au								0	0
B	0,8							63	41
Cd				1	95			706	1.354
Ce/La								0	0
Co								130.406	212.753
Cr	850					2 200	64 405	413.623	537.401
Cu	2 000	2 500	2 500	20		3 200	3 604	5.725.971	12.430.557
Dy	4	15						2.742	4.861
Fe	100 000	100 000					600 000	27.442.308	36.504.780
Ga				5				25	47
Gd/Sm/Tb	0.8	3						2.149	4.169
In				35	15			283	543
Li								114.509	189.104
Mg				54				0	0
Mn	55	50				2000	4325	36.368	48.075
Mo	125	125				200	7209	53.215	67.401
Nd	50	200						27.141	47.109
Ni	600	500				940	120 155	768.764	1.058.675
Pb								26.640	27.200
Pr	4							4.196	6.175
Pt/Pd								0	0
Se				40				197	377
Si			5 000					553.692	1.061.533
Sn			500	6	21			55.554	106.507
Ta							64	344	491
Te					95			701	1.345
Ti						25	1 634	8.783	12.527
V								2.081	2.125
Zn	5500	5500		30				636.672	534.081

Table 5 *Metal demand for renewable energy production technologies*

The precious metals platinum, palladium and gold are present in the selected renewable technologies as catalyst in the production of biofuels and hydrogen. They therefore play a modest or non existent role in the table above, because hydrogen technologies are excluded. Metal demands of Cerium, Cobalt, Lithium, Lanthanum and Vanadium will be discussed when we discuss storage on the grid.

WHAT WILL BE THE METAL DEMAND FOR BATTERY STORAGE THAT COMES WITH RENEWABLE ENERGY?

You can think of two types of batteries that are an essential part of renewable energy generation: batteries for Electric Vehicles (EV) and storage on the electricity grid. Since well-developed assumptions for future energy storage are available we calculate this metal demand separately, just as we did for renewable energy capital stock build-up.

Several recent publications have looked into the metal demand associated with the expected market penetration of Electric Vehicles, for instance (McKinsey 2018). We take our expected metal demand for EV batteries from (Marscheider-Weidemann 2016). This study shows the demand for non-energy applications for the future in 2035. For simplicity, we have assumed linear trends to calculate this demand in 2030 and 2050. We have excluded all non-EV related metal demands discussed in this study. It must be noted that the demand for cobalt in our analysis is between 1.5 and 5 times lower than more recent studies on the subject of metal demand for EV’s. The investments made in China into EV, for instance city buses, are not taken into account (Citylab 2018).

From (IEA 2017b), we estimate that 37GW of storage will be needed in 2030, and 85GW in 2050. A total of around 160GW pumped storage was in place in 2015, a number that is expected to grow at a slower pace, i.e. around 500MW to 1000MW per year.

The figure below (IEA 2017b) shows the market share of non-pumped storage between 2011 and 2016, to estimate what types of batteries will be used to provide electricity storage on the grid.

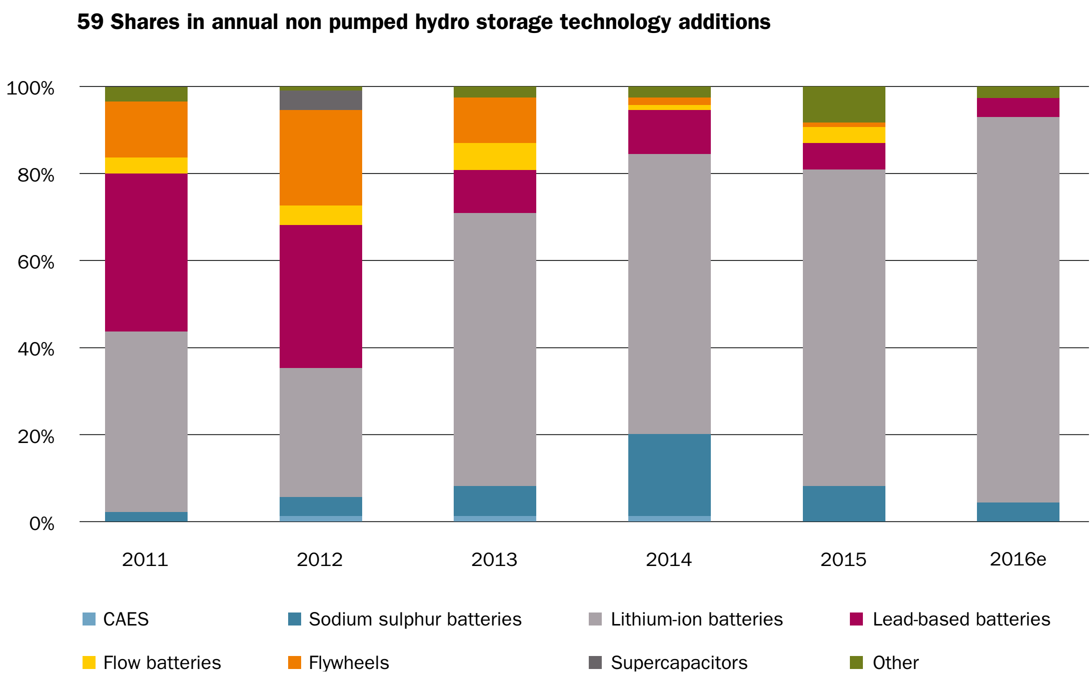


Figure 11 *Market share of battery types between 2011 and 2016 (source: IEA)*

The types of lithium-ion batteries that are used for storage on the grid are LFP, NCA and NMC. If we consider the metal use in (Peters & Weil 2018; Unterreiner et al. 2016; Georgi-Maschler 2012), we can assume the following table, expressed in kg/MW.

	Lithium-ion LFP	Lithium-ion NCA	Lithium-ion NMC	Lead-acid battery	Vanadium Redox Flow Battery	CAES & flywheel	2030 total metal extra need (ton)	2050 total metal extra need (ton)
Market share (100% in total)	25%	25%	25%	8%	5%	12%		
Al	30	7.5	16.5	0	0	No metal demand modelled	449 500	1 147 500
Ce/La	0	0	0	7	0		5 000	13 000
Co	0	3	6	0	0		83 250	191 250
Li	1.25	1.2	1.2	0	0		36 075	82 875
Mn	0	0	6	0	0		55 500	127 500
Ni	0	24	6	0	0		277 500	637 500
Pb	0	0	0	72	0		213 120	489 600
V	0	0	0	0	9		16 650	38 250

***Table 6** Metal demands for battery technologies*

The numbers above relate to the pure metal content of Lithium in batteries. The lithium is part of batteries both as concentrated metal (>99.9% Li) or as lithium salt like $LiPF_6$. This makes the resulting demand of Lithium high compared to other metals in this analysis. Therefore it should be remembered that a Lithium salt (containing Lithium metal particles) is not the same substance as almost pure Lithium metal.

WHAT IS THE METAL DEMAND OF AUTONOMOUS ECONOMIC GROWTH IN GENERAL?

Metal demand for renewable energy capital stock build-up takes place in a world economy that is growing autonomously. This growing economy has a metal demand of its own, from infrastructure in Bolivia to packaging in Pakistan to household electronics in Vietnam. For this, we applied the Environmentally Extended Input-Output database (EE-IO) EXIOBASE. This approach and methodology are explained in a technical annex of this report.

It is important to note that in this exercise, the metal coefficients related to wind, solar, CSP and geothermal are “set to 0”. This means that they are not accounted for in this analysis in order to avoid a double counting with the calculation made in the previous section.

The EXIOBASE model also assumes material efficiency gains between 40 to 60% in 2050 compared to base year 2011, indicating that the same amount of GDP is generated with 40-60% less material. There is evidence that this material efficiency is relevant for renewable energy technologies (Viebahn 2014). It remains to be seen if these efficiency gains will reflect in metrics such as metals/GDP, available at (IRP 2018). The metal/GDP ratio has been fluctuating around 110 kg/thousand $ since 1980. Emerging countries will, after all, need the metals to build-up there built environment to match their increase in prosperity (Halada 2007).

	2030 annual extraction given autonomous economic growth	Index 2030 (2011 = 100)	2050 annual extraction given autonomous economic growth	Index 2050 (2011 = 100)
Ag	42 150	164	73 035	284
Al	78 901 211	169	129 275 220	276
Au	4 779	171	7 923	283
B	7 681 138	170	12 654 401	280
Cd	47 028	184	83 832	329
Ce/La	159 580	184	284 465	329
Co	237 056	177	406 286	303
Cr	9 974 288	170	16 431 315	279
Cu	31 970 704	172	53 323 987	287
Dy	2 503	184	4 461	329
Fe	2 849 513 960	179	4 925 440 746	309
Ga	592	176	1 009	299
Gd/Sm/Tb	10 011	184	17 845	329
In	1 232	176	2 106	301
Li	46 380	170	76 380	279
Mg	1 435 967	170	2 365 564	279
Mn	33 255 451	170	54 793 701	280
Mo	460 853	170	759 610	280
Nd	41 294	184	73 610	329
Ni	2 973 315	170	4 905 179	280
Pb	8 438 617	169	13 817 188	276
Pr	12 013	184	21 414	329
Pt/Pd	674	170	1 112	280
Se	4 736	176	8 058	299
Si	4 017 213	176	6 835 597	299
Sn	613 230	171	1 018 274	284
Ta	1 648	177	2 824	303
Te	262	184	467	329
Ti	12 198 709	170	20 094 309	279
V	130 989	184	233 500	329
Zn	22 193 813	169	36 416 471	277

Table 7 *Metal demand caused by autonomous growth*

The economic growth is assumed to be 4.2% until 2030 and to be 2.2% between 2030 and 2050.
The annual growth of metal demand in the world is found to be in the same order of magnitude.

ADDING UP, HOW FAST DOES METAL PRODUCTION NEED TO GROW TOWARDS 2030 AND 2050 TO KEEP UP WITH THE DEMAND?

In the previous chapters we have analysed how the metal demand grows for renewable energy capital stock, batteries and general economic growth. We can therefore indicate how fast metal production needs to increase in the coming decades to meet demand.
The table below no longer shows the bill-of-materials in absolute amounts. It is hard to understand the context of a total metal need of over 6 kilotonnes of Dysprosium in 2030 or close to 20 Mt of Nickel in 2050.

Instead, Table 8 shows the observed Compound Annual Growth Rates (CAGR) of the mining production between 1998 and 2016 and of the required growth, every year, to meet total metal demand in 2030 and 2050. For all CAGR calculations, linear growth is assumed, opposed to possible S-shaped growth curves or other growth trends. The comparison made in this table indicates whether the required growth asks for unprecedented growths in production capacities (indicated by a red cell in the column “Speed-up…?”).

	Observed Mine production growth 1998-2016	Required annual Growth rate 2011-2030 BAU	Required annual growth rate with renewables & batteries 2011-2030	Required annual growth rate 2011-2050 BAU	Required annual growth rate with renewables & batteries 2011-2050	Speed-up production compared to last 20 years?	Index 2050 (2011= 100)
Ag	2.86%	2.8%	3.1%	2.8%	3.0%	uncertain	305
Al	5.37%	2.7%	3.0%	2.7%	2.8%	safe space	281
Au	1.48%	2.8%	3.0%	2.8%	2.8%	speed-up	28
B	0.20%	2.7%	3.0%	2.7%	2.7%	speed-up	280
Cd	2.32%	3.2%	3.5%	3.2%	3.2%	speed-up	334
Ce/La	0.00%	3.2%	3.5%	3.2%	3.2%	speed-up	329
Co	8.07%	3.0%	5.8%	3.0%	4.1%	safe space	462
Cr	5.33%	2.7%	3.2%	2.7%	2.8%	safe space	291
Cu	2.92%	2.8%	4.0%	2.8%	3.4%	speed-up	354
Dy	0.00%	3.2%	7.8%	3.2%	5.2%	speed-up	687
Fe	6.55%	3.0%	3.3%	3.0%	3.0%	safe space	311
Ga	-0.77%*	2.9%	3.4%	2.9%	3.1%	speed-up	313
Gd/Sm/Tb	0.00%	3.2%	4.6%	3.2%	3.8%	speed-up	406
In	5.41%*	2.9%	4.4%	2.9%	3.6%	safe space	379
Li	4.61%**	2.7%	10.3%	2.7%	6.2%	speed-up	971
Mg	5.58%	2.7%	3.0%	2.7%	2.7%	safe space	280
Mn	5.40%	2.7%	3.0%	2.7%	2.7%	safe space	280
Mo	3.85%	2.7%	3.7%	2.7%	3.0%	safe space	308
Nd	0.00%	3.2%	6.4%	3.2%	4.5%	speed-up	539
Ni	3.22%	2.7%	4.3%	2.7%	3.3%	uncertain	341
Pb	2.43%	2.7%	3.0%	2.7%	2.7%	speed-up	277
Pr	0.00%	3.2%	5.2%	3.2%	3.9%	speed-up	424
Pt/Pd	0.02%	2.8%	3.0%	2.8%	2.8%	speed-up	280
Se	3.30%	2.9%	3.4%	2.9%	3.0%	safe space	313
Si	5.66%**	2.9%	3.9%	2.9%	3.3%	safe space	345
Sn	2.05%	2.8%	3.5%	2.8%	3.1%	speed-up	314
Ta	5.20%***	3.0%	4.3%	3.0%	3.4%	safe space	356
Te	4.54%	3.2%	11.2%	3.2%	6.9%	speed-up	1 275
Ti	2.00%	2.7%	3.0%	2.7%	2.7%	speed-up	280
V	2.75%	3.2%	3.5%	3.2%	3.2%	speed-up	332
Zn	2.70%	2.7%	3.1%	2.7%	2.8%	uncertain	281

Table 8 *The Compound Annual Growth Rate (CAGR) for past and future mining production. Source BGS (2018)*

** denotes a CAGR of between 2006 and 2016*

*** denotes CAGR found in (Buchholz & Brandenburg 2018)*

**** denotes a CAGR based on (Mancheri et al. 2018)*

Is the glass half-full or half-empty? For a majority of the metals, production needs to speed-up, between a few tenths of a percent to 5%. On the other hand, major metals like iron and aluminium have apparently grown strong enough in the last two decades.

Yet, it is important to remember that the percentages above refer to physical units. Though there is no known upper bound to economic growth, value or utility, there is however a limit to what can be extracted from the planet at acceptable market prices and acceptable GHG emission levels. It is no foregone conclusion that the required growth percentages for metals will be realised with the same ease in the coming years, as they have been over the last two decades. For this reason, we add three “yes, but....” type of questions later on.

The following three graphs (for Lithium, Neodymium and Nickel) show the contribution of the metal demand originating from economic growth (blue), from the Beyond 2 Degrees scenario and from the need for storage. Lithium clearly has a strong growth in metal demand from storage. Other renewable technologies do not require significant amounts of Lithium. Therefore, the ‘beyond 2C’ does not show up in de graph.

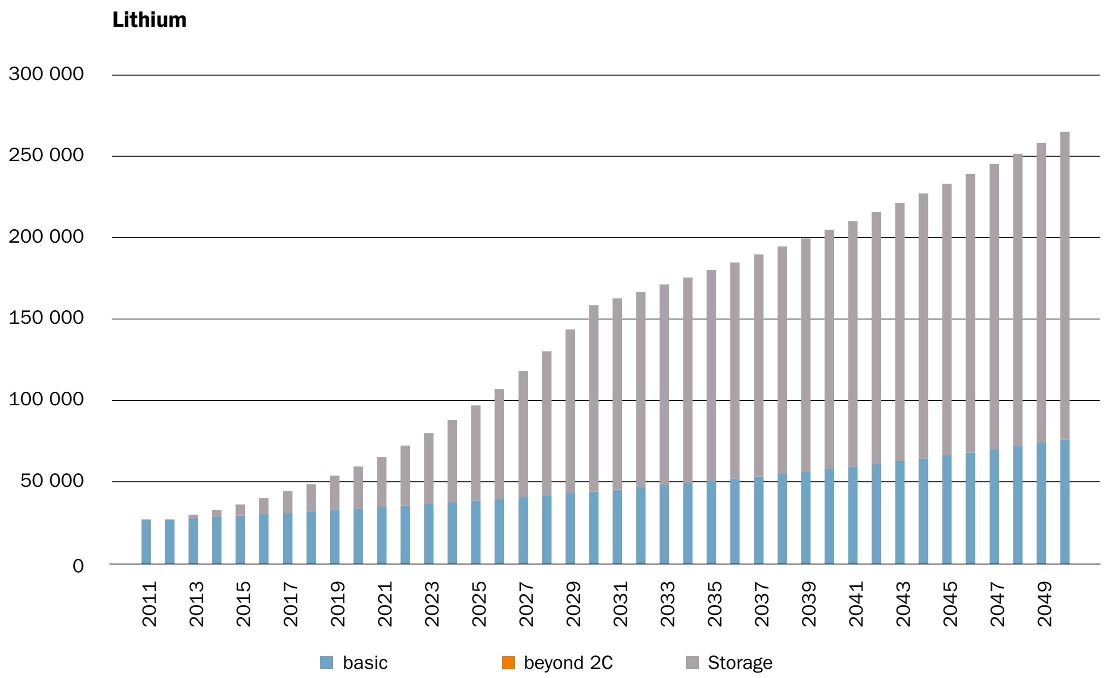


Figure 12 *Required growth of lithium*

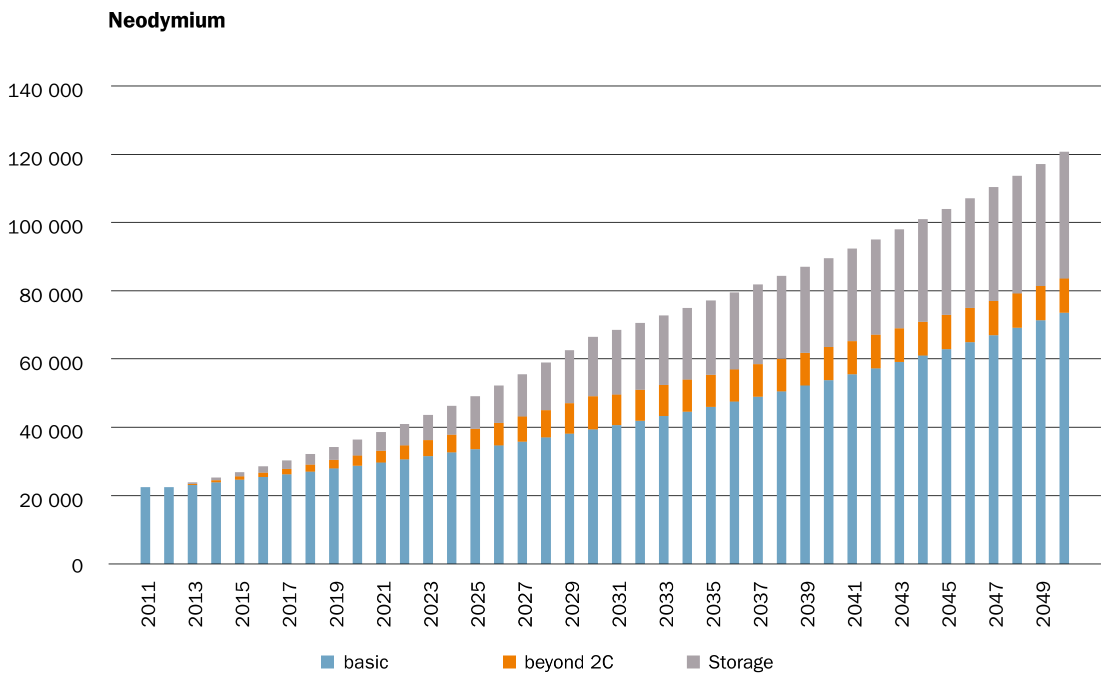


Figure 13 *Required growth of neodymium*

Demand for neodymium comes from all three contributions. It is one of the metals that has the greatest relative share to enable the Beyond 2 Degrees renewable energy capital stock build-up, depicted in orange. At the same time, permanent magnet demand in EV's make storage a significant source of Neodymium demand as well

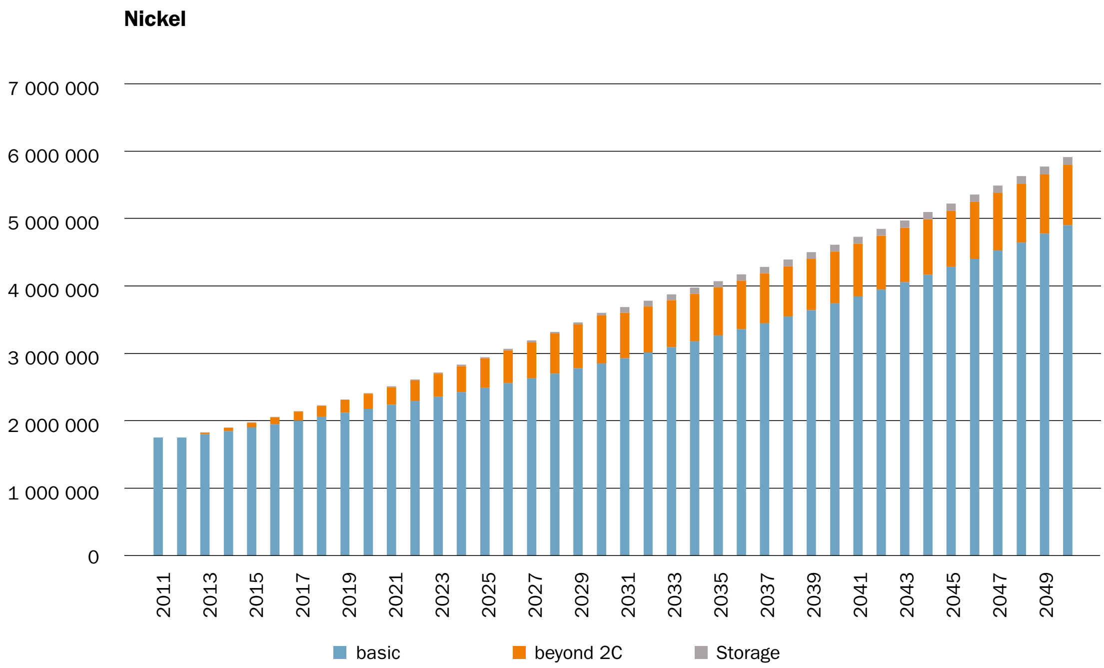


***Figure 14** Required growth of nickel*

Demand for Nickel is mostly based on the business-as-usual demand from economic growth in general, not so much from growth caused by the energy transition.

Findings like the required CAGR in Table 8 are in the same order of magnitude as results that can be found in academic papers like (Deetman 2018; Elshkaki et al. 2018). The required annual growth percentages are higher than found in (De Koning et al. 2016), as this study assumed mainly 4C scenarios that are less ambitious for renewable energy capital stock investments than the Beyond 2 Degree scenario. The required amount of iron is around twice as high than the amounts estimated by (Allwood & Cullen 2015). They make assumptions about material efficiency, that leads to estimation about iron demand in 2050 that are just over half amount of iron expected to be needed in this study.

Cobalt is assumed to be in a safe operating space in the coming decades, a statement that can be taken from Table 8. This conclusion is different from many other market reports that estimate the demand for cobalt (Dera 2018). The result of this study is based on the (Marscheider-Weidemann 2016) study. The uptake of EV's was based on the market situation as observed between 2011 and 2015. The fact that this market might have changed illustrates the volatile nature of renewable energy capital stock uptake and the need to closely monitor the demand for metals as a result.

THE WORLD'S SUPPLY OF METALS

WHAT ARE THE CURRENT PRODUCTION TOTALS AND WHAT IS THE HISTORIC GROWTH FOR RELEVANT METALS?

Now we have an idea how much metal we need for investments in renewable energy stock and the rest of the economy, we should take a closer look at the production side. What are the current levels of mining and how has mining production developed over the last few decades? The data are published by the US Geological Survey (USGS) and the British Geological Survey (BGS). In this report we use the BGS data (unless stated otherwise).

	World production 2014		World production 2014
Ag	25 700	Mg	846 451
Al	46 777 653	Mn	19 599 190
Au	2 797	Mo	271 499
Cd	25 500	Nd	22 391
B	4 527 471	Ni	1 750 000
Ce/La	86 528	Pb	5 006 405
Co	134 000	Pr	6 514
Cr	5 879 482	Pt/Pd	397
Cu	18 600 000	Se	2 697
Dy	1 357	Si	2 288 199
Fe	1 596 304 130	Sn	358 449
Ga	337	Ta	931
Gd/Sm/Tb	5 428	Te	142
In	699	Ti	7 191 245
Li	27 349	V	71 026
		Zn	13 137 570

Table 9 *Primary mining production as actual metal (>99.99%) content (tons) (source: BGS 2018; BMNT 2018)*

Whereas in Table 9 the absolute production data are given, for our analysis it is more relevant to look at the development of mining capacity over recent years. This so-called Compound Annual Growth Rate (CAGR) for the metals discussed here is shown in Figure 15.

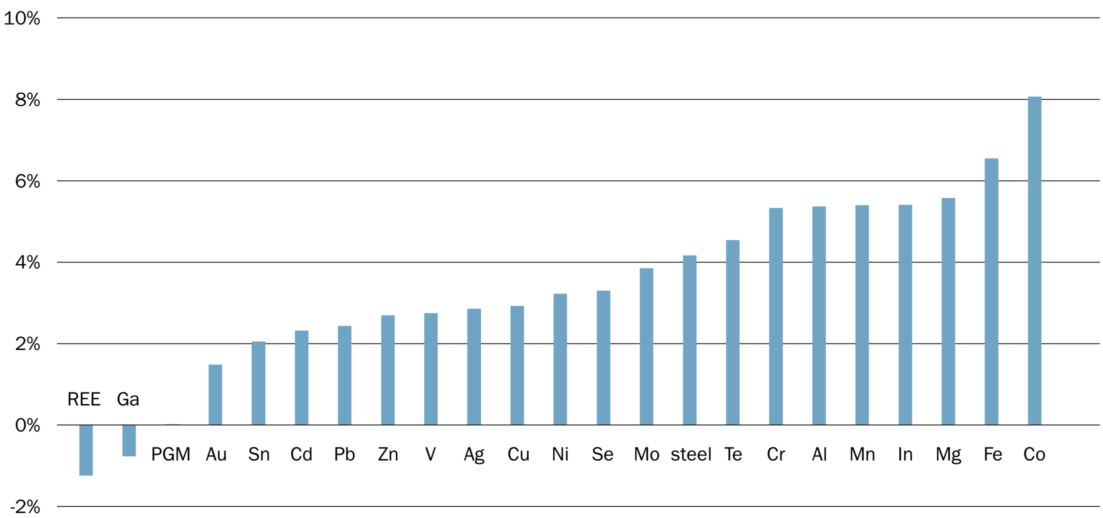


Figure 15 *Average growth (or decline) of mining production between 1998 and 2016*

Most noteworthy here is that the formally reported production data for several metals (Rare earth elements, gallium and platinum Group Metals) show a decline over the last two decades. This will of course play a role in the discussions regarding timely availability of these metals, that will be elaborated in subsequent chapters.

Most of these metals are mined as ore. Exceptions are cobalt (Co), gallium (Ga), lithium (Li), the rare earths (Tb, Nd, Pr), indium (In), selenium (Se) and tellurium (Te), which are not mined but 'harvested' as by-products of their so-called host-metals, usually during the refining stages of those hosts. We will come back to this issue in a separate chapter in this report.

For illustration, we show some typical ores related to mining.

Mineral	Metal as a result of processing mineral		Mineral	Metal as a result of processing mineral	
Cassiterite	Tin		Sphalerite Chalcopyrite	Indium	
Monazite Bastnaesite	REE		Garnierite Laterite	Nickel	
Cobaltite	Cobalt		Over 50, e.g. Argentite, Pyrargyrite	Silver	
Petalite Lepidolite	Lithium		Coltan	Tantalum	

WHERE DO THESE METALS CURRENTLY COME FROM?

Mining takes place at locations that have the right combination of geology and absence of conflicting land-use. Furthermore, mining operations require economies of scale to be profitable. Therefore, the metal mining sector, at least for most metals, is characterized by a high level of concentration. The picture below shows some originating countries that have a high share of the world market (EC 2017).

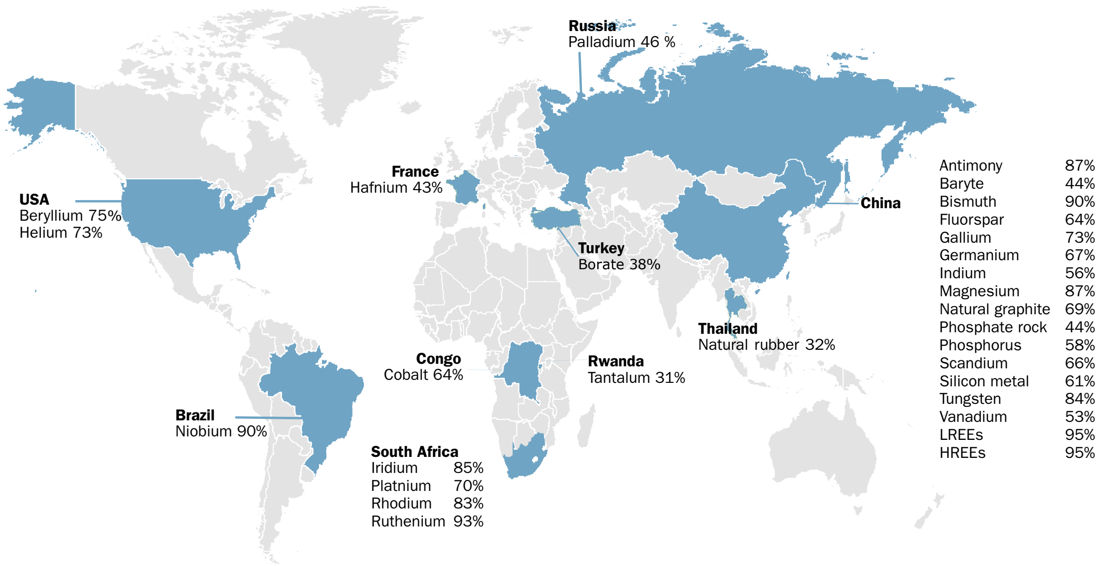


***Figure 16** Overview of countries with dominant metal market shares (source: EC 2017)*

As such, this high level of concentration does not lead to a change of view with respect to the required speeding-up of mining capacity to keep up with demands for energy transition (such as presented in Table 8). However, the existence of monopolies undoubtedly leads to an increase in risks with regard to the security of metal supply. Monopolies lead to greater market power and to the ensuing potential effects on price. Monopolies also lead to portfolio risk (all eggs in one basket). Risks that are not correlated (for example environmental disasters) lead to greater supply risks where regional concentration is greater. Therefore, such monopolies could lead to influences on the price of renewable energy capital stock and to a lower level of implementation of such technologies in parts of the world that rely heavily of imports, like the countries of the EU.

Geopolitical monopoly formation has therefore received ample attention in criticality analyses (see for instance EU 2017, Bastein 2015). The degree of monopoly forming is expressed in most studies using the so-called **Herfindahl-Hirschman Index (HHI)**, which is composed of the total sum of squares of the extraction concentrations per source country. This is an general standard for concentrations in a sector (in this case, source countries). The maximum value is therefore 10,000 (one country produces 100% of the total volume). An overview of the HHI of the metals under attention here is given in Figure 17. A value greater than 2,500 is considered (by the US Federal Trade Commission at least[1]) as highly concentrated.

The HHI is lower than 2500 for just 9 of the 23 metals considered here; all other metals are therefore to be regarded as a highly concentrated.

1 www.justice.gov/atr/public/guidelines/hmg-2010.pdf

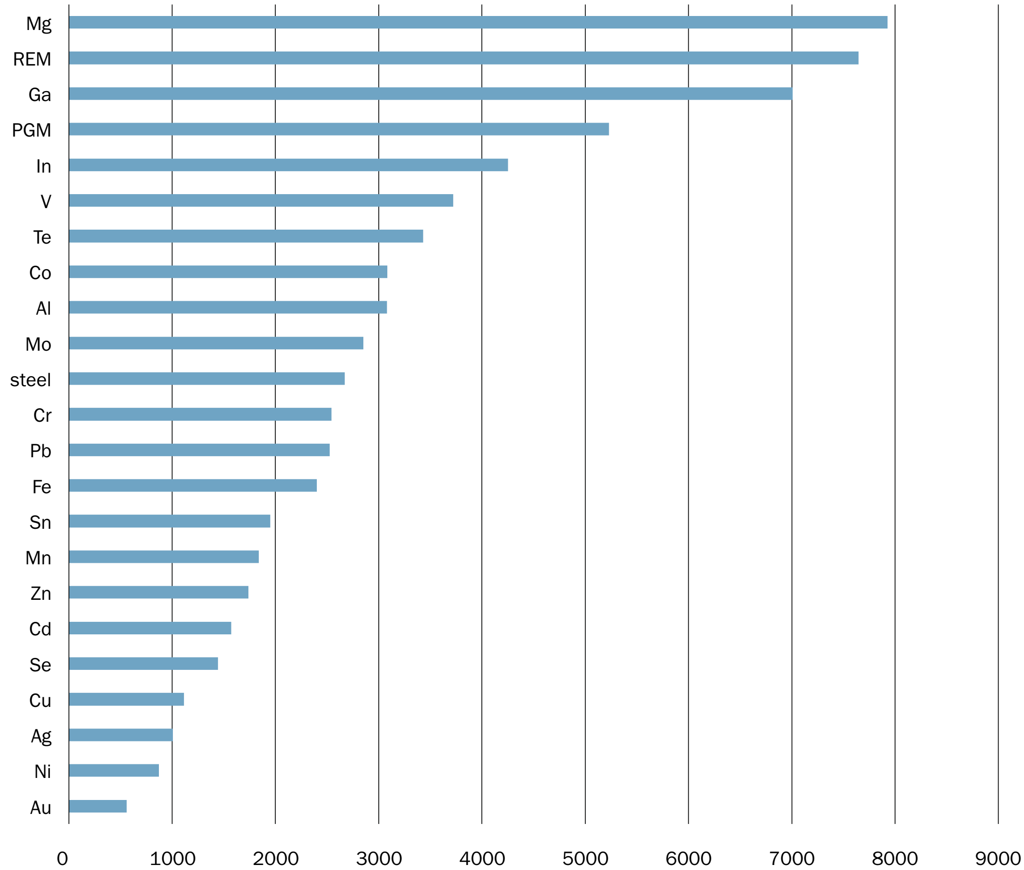


Figure 17 *Monopoly formation for metals, expressed as HHI (source: BGS; data 2016)*

For most of the metals that exhibit a large HHI, this is caused by the dominance of China: the market share of China for magnesium, rare earth metals, gallium, indium, vanadium and tellurium is way above 55%, with magnesium and the rare earths as extremes with a share of production over 95%.
Since speeding-up of the production capacity of several of these metals is required (Table 8), it is relevant to monitor the development of production capacity in China and other quasi-monopolists. Given the high ambitions of China in developing a renewable energy infrastructure (see also Figure 5 and Figure 6) the domestic availability of metals in China may eventually have an impact on the availability of metals elsewhere in the world.

HOW RESPONSIVE WAS MINING SUPPLY AND DEMAND IN THE PAST?

Making a mine operational takes time. The response time to the commodity price surge between 2002 and 2009 was approximately 10 years (Buchholz & Brandenburg 2018). Lead times between discovery of resources and a product on the market for metals like gold, copper and nickel lie between 10 to 15 years. For most other metals, this lead time lies between 5 years and many decades, depending on the mineral, size and grade of the deposit, institutional factors and market prices (Schodde 2014). This response time is rooted in the fact that the mining industry is a sector that takes years to get access to its assets, that can't assess the value of its assets at the time of purchase, that can't predict the selling price of its product and that faces immediate disruption throughout its operation.

A typical example of operational lead-time for mining operations is the Kvanefjeld Rare Earth and Uranium exploration on Greenland. Having started in 2007, the project is in the final permitting phase in 2018 (EURARE 2018). Crude oil extraction faces similar lead times when starting off-shore drilling operations. Oil markets are however provided with flexibility due to tar sands extraction. This source of crude oil can come on-line within months, acting as a balancing mechanism to supply and demand shocks (Middelkoop & Koppelaar 2017).

Natural resources often fall outside WTO following GATT Article 20. These means that even WTO members can install trade barriers without arbitrage if they see fit. A typical example of a trade barrier is the cap on exports of rare earth elements from China. Reversibly, countries can choose to limit imports. The Dodd-Frank act obliges companies to provide evidence that there procured goods are not related to mining operations in the Great Lake Area (notably Congo), that are held responsible for financing rebellious insurgents.

The most famous example of supply disruptions originated from a China-Japan incident in 2010. Fishing boats from both countries collided near the Senkaku islands. As a result, exports of rare earth elements from China to Japan and to the rest of the world were halted for months.

The global mining sector has proven to be prone to unstable prices between 2006 and 2015 (MacDiarmid et al. 2018). This suggests a volatile industry. Price volatility is a market distorting effect in a sector that is, for technical reasons, seldom able to respond to demand surges by opening new production facilities quickly. Mining lead times are hardly reduced by greater financial capital investments. The time to make a mine operational will not reduce from ten years to two years as a result of a five-fold increase in investments. This is why the carbon budget matters. When we want mining production to stay in a safe operating space, we need to understand the lead time of mining operations, combined with price volatility of metal markets.

In general, mining industry can't be regarded as responsive or irresponsive to supply and demand. The presence of complicating factors, ranging from long term geological factors to short term factors such as political opposition or trade barriers determine the rate or responsiveness.

YES, BUT... WHAT IS THE GROWTH SCENARIO FOR BY-PRODUCTS OF MAJOR METALS, SO CALLED COMPANIONS?

Many metals are only available in the earth's crust as 'companions' of major ore stocks. A comprehensive overview of these so-called companions and their relation with the major metals is given in the 'metal wheel' reproduced from (Nassar et al. 2015).

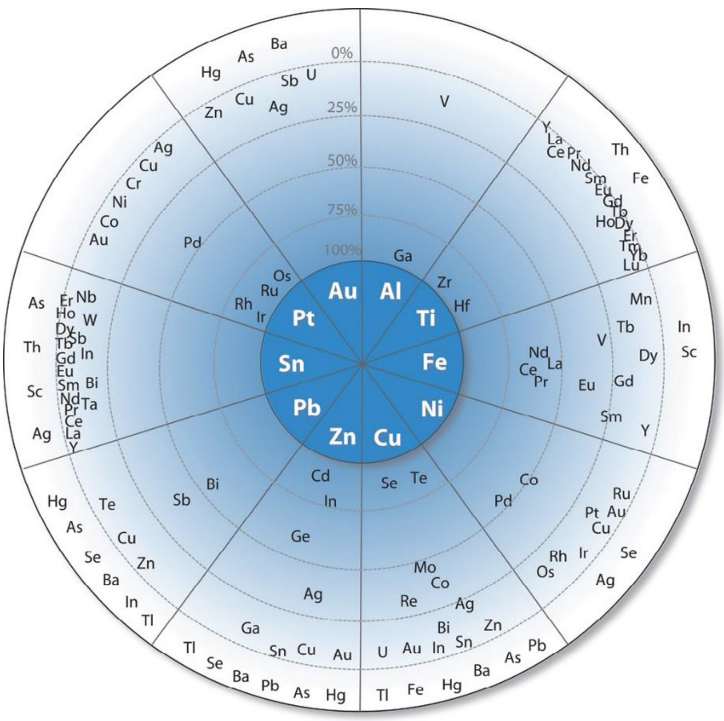


Figure 18 *The metal wheel: overview of host and companion metals (source: Nassar et al. 2015)*

The metals indicated here are harvested as a by-product: the income that they generate is not sufficient to support a mining operation. As a consequence, steep increases in the demand of such by-products can only be accommodated in case enough host material is excavated and/or the full potential of the isolation of the by-product is not reached yet (Afflerbach et al. 2014).

A summary of the relationship between host and by-products for metals in focus here is given in the following table.

Companions	Al	Fe	Ni	Cu	Zn	K
Gallium	95					
Rare earths : Nd, Pr		24-67				
Vanadium		62				
Cobalt			50	35		
Selenium				90		
Tellurium				90		
Indium					80	
Lithium						52

Table 10 *Relationship between hosts and by-products. Displayed are the percentages of by-product metal (rows) are found in hosts (columns)*

For the sake of this report, we illustrate this by looking at the case of tellurium (Te), a byproduct of (mainly) copper refining, and a metal that is essential for one of the PV-technologies that play a role in the energy transition scenarios.

The principal source (more than 90%) of tellurium are anode sludges from the electrolytic refining of blister copper. This sludge contains between 0.5 and 2% of tellurium (USGS 2018), though levels up to 8% are also reported. This route is followed for 84% of copper refining, the remainder increasingly being refined through the SX-EW-route (ICGS 2018). Furthermore, tellurium is also harvested from dusts from blast furnace refining of lead. The USGS state (Bleiwas 2010): National Renewable Energy Laboratory, or NREL, estimated that approximately 900 metric tons of copper sulfide ore extracted from copper porphyry deposits, the largest source of world primary copper, is required to recover 1 pound of byproduct tellurium and that at least 1,000 tons of byproduct tellurium, or roughly ten times the world production in 2008, could potentially be produced annually from mining operations; however, for a number of reasons, chief among them being economics and proprietary technologies, the metal is not recovered at this time. The NREL estimate is relatively close to the 1,200 t of tellurium potentially recoverable from copper anode slimes (George 2009).

Based on such findings, the USGS Mineral Commodity Summaries report reserves for tellurium of 24,000 ton, also based on the assumption that 50% can be recovered from the anode slime. The USGS include in their reserve estimates only tellurium contained in copper reserves. The reserves assumed for copper amount to 790,000 kton. Therefore, the reserve figure for tellurium is about 0.03% of the reserve of copper.

The past development of tellurium production of is shown in Figure 19 (total production). The overall growth rate (CAGR) between 1998 and 2016 for tellurium is 4.5%.

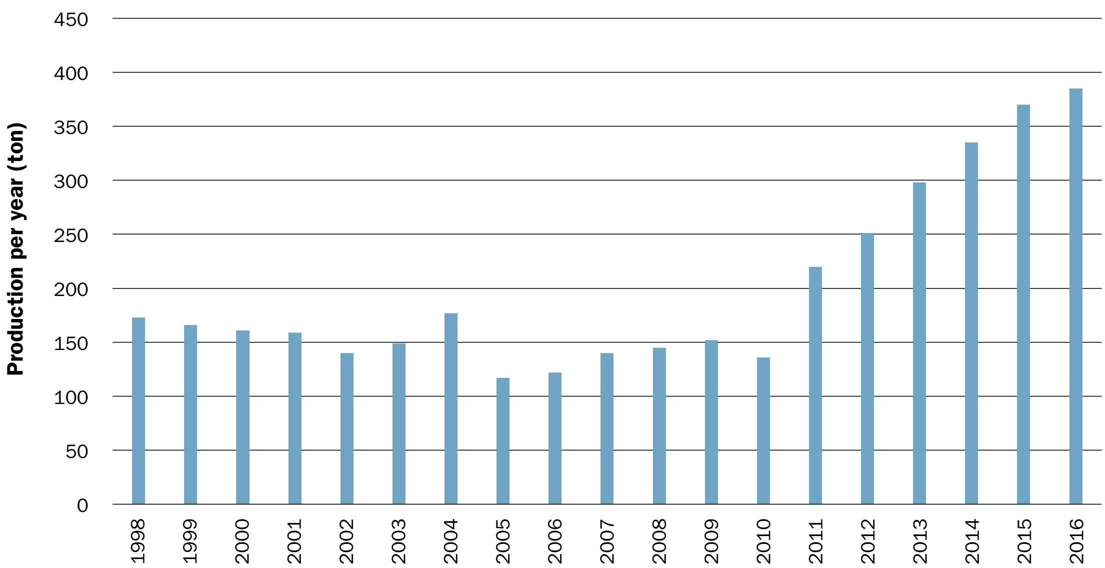


Figure 19 *Production of tellurium between 1998 and 2016 (source: BGS)*

The production of refined copper has grown from approximately 14 Mton in 1998 to appr. 23 Mton in 2016 exhibiting an average growth (CAGR) of 2.9%.

In 2016 (the year of highest tellurium production), the production of tellurium was only 0.0016% of the production of refined copper. The data from USGS presented above suggest that they assume that (given the recuperation rate of 50% from the anodic slime) the reserve for tellurium is 0.03% of the copper reserve. Therefore a doubling of the tellurium production (again using the same recuperation technology) may be feasible if market circumstances demand so.

The global distribution of tellurium in copper ores self-evidently needs to be reflected in the distribution of refined copper production in the world (see Figure 20): again we see an important role for China, Japan, Russia and the USA. Important copper refinery countries like Chile do not appear in the list of top producers for tellurium, whereas e.g. Sweden plays an important role in Te production without significant copper refining. This is related to the fact that the Swedish Kankberg deposit is one of only two areas where tellurium is recovered as a primary ore (in total 15% of world production from these two sites, the other one being in China) (Goldfarb et al. 2017).

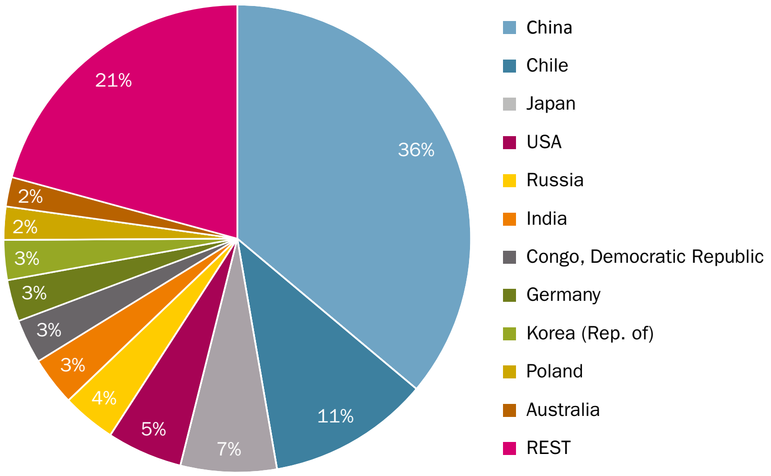


Figure 20 *Distribution of the production of refined copper (source: BGS)*

Since the distribution of refined copper is much wider than for tellurium (characterized by an HHI of 1585 for copper vis-à-vis an HHI of 3430 for tellurium) there seems to an opportunity to diversify the production of tellurium if needed.

Concluding, one may assume that -though the production of tellurium is strongly coupled to that of copper- the maximum production level of tellurium is not reached yet, and that the level of annual growth for tellurium may exceed that of copper. Furthermore, it seems likely that the level of geopolitical dependency for tellurium may decrease from its current level because of the relatively widespread existence of copper refineries in the world.

YES, BUT... CAN WE RELY ON THE PRODUCTION FIGURES OF RARE EARTH MINERALS GIVEN ILLEGAL MINING ACTIVITIES?

The production growth figures for rare earth elements (among which neodymium) are remarkable: formal figures (BGS 2018) report (on average) a small in production over the last 20 years for these metals that play an important role in several energy transition technologies. Commonly, authors (Buchholz & Brandenburg 2018) 'correct' these figures by assuming illegal mining of rare earths to contribute to the production. We have in this document chosen not to adapt the CAGR-data from the BGS-data, because of the following.

Several papers and web-based information report on the importance of illegal mining of rare earths in China as a means to cope with the high) demand for rare earth minerals (Packey & Kingsnorth 2016). This high demand can relate to both domestic demand in China or international demand. It is reported that "the international rare earth market has an uncontrolled illegal market that represents approximately 30–40% of the market". This would lead to an assumed annual production of rare earths in China of about 150 kton instead of the reported approximately 100 kton.

However, the very nature of illegality makes it very difficult to report on the development of the extent of these mining activities. Even as early as 2008, there was already a discrepancy between formal and informal reported production data of up to 30 kton. Furthermore, "China has acted to decrease illegal activities by shutting down more than 600 illegal activities on rare earth exploration and mining. Thirteen mines and 76 smelting separation companies have been ordered to stop production". The restructuring policies of the Chinese government have been reviewed by (Shen et al. 2017).

One may conclude that part of the available rare earth demand has always originated from (semi-) illegal operations and that clear data about the growth (or even decline) of this part are not available. Since we are mainly interested in growth trends (represented by CAGR) we choose to base our analyses on the formally reported production data.

Furthermore, the importance of illegal mining (and the corresponding uncontrolled environmental impact of the damaging extraction processes) and the consequential lack of transparency of production figures of rare earth elements make a future based on rare earth containing technologies rather vulnerable. This calls for increased attention for either more transparency or for technology development less depending on these metals (substitution).

YES, BUT... ARE METALS BECOMING HARDER TO MINE, JUST AS IS OBSERVED FOR OIL?

Between 2000 and 2013, the CAPEX expenditures for crude oil supply almost tripled ("300%"), with crude oil production increasing 16%. This statistic is an example of the increased investments in capital stock to maintain raw material extraction (Lewis, 2014).

The energy demand for the production of a concentrated metal from a metal ore depends on the ore grade. The lower the amount of metal in the ore, the higher the required energy, see for instance (Mudd et al. 2010).

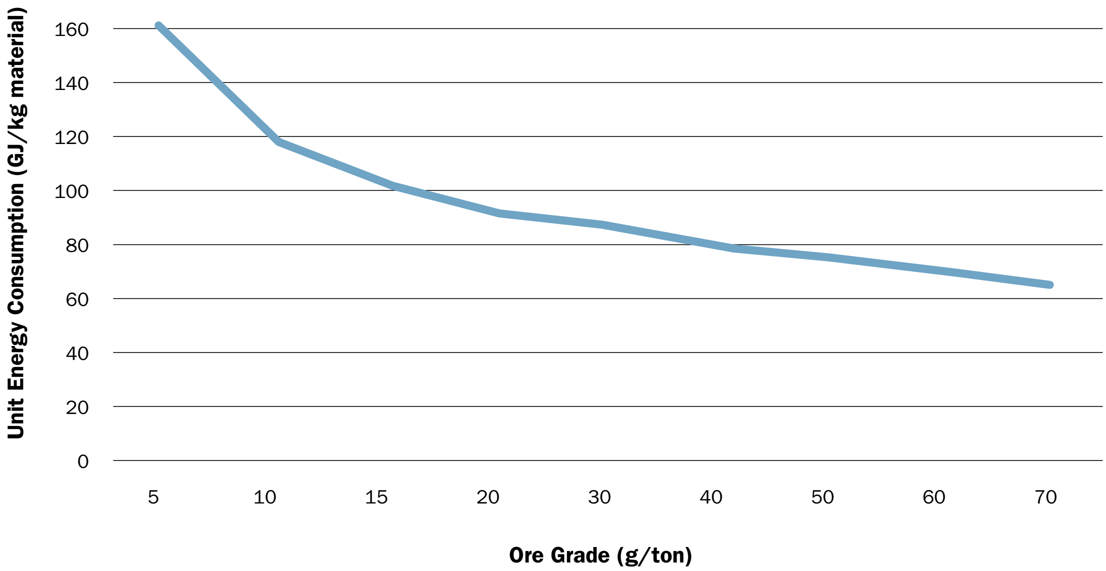


Figure 21 *Energy consumption for copper mining vs. ore grade*

With an assumed 30% increase in energy efficiency in primary copper production, (Elshkaki, 2016) finds that the share of primary energy demand of production of copper doubles compared to the global energy demand in 2050 compared to 2010.

The conclusion is that metals will become harder to mine, meaning that more energy will be needed to produce the same amount of pure metal content. This effect will have an effect on the global metal production and the corresponding price mechanisms.

WHAT EFFECT DO METAL PRICE FLUCTUATIONS HAVE ON THE RENEWABLE ENERGY CAPITAL STOCK?

The manufacturing industries in essence need energy, services and materials as input to make their products, including renewable energy products like PV panels and wind turbines. Most manufacturing sectors in the Netherlands spend between 45% and 60% of their expenditures on the procurement of goods (raw materials, intermediates and final goods). These sectors are the manufacturing of chemical products, plastics, metal products, machinery, automotive, transport equipment. The exception is electronics and electrical equipment, who spend only 19% of their procurement costs ongoods, and 80% on highly valuable services from other sectors (Statline 2018). For the manufacturing of renewable energy products, the average material costs are assumed to amount to 30-40% of the total expenditures, as average between 19% and 60%. The shares of 30-40% are also observed in specific sector reports as well (Greentechmedia 2014).

The effect of metal price fluctuations on manufacturing cost is more complicated than a percentage of 30 to 40% suggests. The cost of goods procured by manufacturing are made up not only of raw material costs. They also have costs of labour, capital stock, energy etc. embedded in the price (Wilting & Hanemaaijer 2014). It is possible that metal (i.e. raw material) prices will only reflect a percentage of 1 or 2%, or even less of the cost of an intermediate good procured by manufacturing.

On the basis of three examples, we show how products react to a price shock of a material that has been processed in that product. An example of a price shock could be: what percentage price increase of a mobile phone can I expect if a metal used in production doubles in price?

Flat panel display
The total cost of a flat panel display (FPD) of 40 inches in April 2011 is around € 600. A FPD contains 2.13 grams of indium per m^2, given that a 40 inch screen has a surface of $0.43m^2$ this amounts to 0.92 grams per screen. With a price of € 486/kg, this amounts to a value of € 1.21 on indium per screen. A doubling of the cost of indium would increase the screen of € 600 by € 1.21, a very small cost increase of 0.2%.

CIGS panel
Solare panels, the so-called CIGS (Copper Indium Gallium Selenide) PV panels, are the previously discussed alternative for silicium panels. The share of the price of indium in the cost price of a CIGS panel is currently 16%. This means that a CIGS panel will be 16% more expensive if the price of indium doubles. This also means that the cost price of the energy produced will increase by about 10%.

Toyota Prius
In the Prius approx. 1-2 kg of neodymium has been processed in the powerful electric motors. Given a cost price of a basic Prius of € 12,000, and a kilo price of 92.5/kg (summer 2010) neodymium thus determines about 0.8% of the cost price. A doubling of the price of neodymium would make a Prius a tight € 100, or 0.8%, more expensive.

From these examples it can be concluded that price shocks of semi-finished products have a very limited (e.g. 0.2%) to moderate (10%) effect on the price of end products.

There is only a rule-of-thumb answer to the effect of metal prices on costs of manufacturing. The effects can be very direct, reflecting the full 30 to 40% of the purchasing cost. In that case, metal prices will lead to a market response of any kind. Yet, the effects can be in the order of 1-2%. In that case, metal prices will have a limited effect on a particular part of the renewable energy capital stock.

IMPACT OF CIRCULAR STRATEGIES ON RENEWABLE ENERGY CAPITAL STOCK

CAN RECYCLING PROVIDE ANY SECONDARY METALS?

It is one thing to build the capital stock that can provide the world with the renewable energy needed to meet the Paris Agreement. It is another to make renewable energy actual sustainable energy. This requires to think about the anticipated end-of-use-cycles of metals, and their consequences for demand from of renewable energy capital stock.

We can explore the contribution of secondary ("recycled") metals to renewable energy capital stock build-up. Based on the (UNEP 2011) report, we can estimate the share of secondary metals worldwide in the economic system. The table below shows the EOL RIR ("the amount of recycling actually replacing primary extraction, not just recycling") for a number of metals, indicating the percentage of recycled metal that actually takes away the need to mine new metal (EC 2017).

Metal	End-of-Life Recycling Input Rate
Lead, Iron	> 70%
Silver, Vanadium, Copper	40 - 70%
Nickel, Tin, Zinc, Molybdenum	30 - 40%
Chromium, Gold, Titanium, Aluminium, Manganese, Platinum	10 – 30%
Palladium, Praseodymium, Magnesium, Terbium	6 – 10%

Table 11 *End-of-life recycling input rates (source: UNEP 2011)*

It should be noted that it is virtually impossible to collect all metals embedded in products (Reuter 2018). A recovery rate of around 50% can be challenging, even for modular designed electronics.

There are signs that increased metal end-of-life recycling input rates are possible. Projects dedicated to permanent magnet recycling are either approved or under way in China (Roskil 2015). Recent improvements for lithium-ion battery recycling are also reported (Huang et al. 2018).

Apart from recycling techniques, there is the aspect of the size of the so called “urban-mine”. The urban mine can be considered to exist in the built environment of the planet, and all products in there. This can be also referred to as “stock in use”. The annual amount of products that are offered and collected for recycling are, even at a recycling rate of 100%, not sufficient to meet over 5% of the demand for metals in the coming 15 years (Deloitte Sustainability 2015). The annual amounts added to landfill in Europe of Silicium (100 Kton), Magnesium (100 Kton) and Cobalt (10 Kton) are reported, as are smaller amounts (around 50 ton) of Dysprosium and Terbium. But these quantities have contamination levels and/or a chaotic configuration that decimates real recycling potential.

It is therefore concluded that recycling can deliver a contribution to the metal markets for renewable energy stock. At the same time, supplying a share larger than 3% of the metal demand for the energy transition before 2030 seems to be infeasible.

WHAT CAN CIRCULAR ECONOMY STRATEGIES, OTHER THAN RECYCLING, DO?

It is important to remember that circular economy concepts go beyond recycling. Enabling shared use, repair, refurbishment show more market potential than recycling. For renewable energy capital stock, these circular concepts are highly relevant. Moreover, given the interdependency between renewable energy and a stable economy, circular strategies are relevant for all products in society. See for instance Figure 12, Figure 13 and Figure 14 to see the ratio between renewables and other products in society.

Lifetime is a sensitive parameter in renewable energy modelling. Doubling a lifetime basically reduces the amount of metal needed to deliver the power output by 50%. This fact is as trivial as it sounds. Every percentage of increase in the lifetime of renewables basically reduces the amount of metal needed to deliver the power output with the same percentage.

In some cases, circular strategies are deployed to renewable technologies directly at the moment a product comes onto the market. This is the case for CdTe PC modules. Worldwide, there is one dominant producer, that has a take-back system in place. This system was developed given the environmental impacts (toxicity) of cadmium.

Mathieux et al. 2017 analyses relevant sectors for the energy transition from a circular economy point of view. The following opportunities are proposed:

- Technical requirements for parts of the energy system that have a long (over 15 years) anticipated economic lifetime. Examples are concrete bases of installation, wiring in the grid, supporting frames of installations. This offers opportunities for remanufacture on-site.
- Performance monitoring and predictive maintenance parts, using for instance remote sensing, blockchain. This offers opportunities for repair.
- Substitution of metals and components of renewables. Stimulating modular designs can enable reduced metal demand. Design decisions relating to material-for-material substitution can improve recycling. Other substitution innovations (product-for-product, process-for-process, use-for-use) offer even greater metal demand reduction potential.

Circular concepts, not only including renewable energy capital stock, can reduce CO_2-emissions by themselves. This relates to the previously discussed technologies for energy demand management. Several studies have shown a potential for CE to reduce GHG around 10 to 30% of the national emissions in westernized countries (TNO 2018, Worell & Carreon 2017; SITRA 2018).

The recent market success of the renewable energy products has a downside. The substitution of metals for other metals is more difficult for mature products that have a market penetration of over 1%. This metal-for-metal type of substitution, if made necessary by metal prices, is mostly relevant for renewable technologies that are not yet tied to market contracts (Blagoeva et al. 2016).

THE WAY FORWARD

TO WHAT EXTENT CAN EXISTING METAL MARKETS HELP TO REALISE THE PARIS AGREEMENT?

A useful concept to assess a market is “safe operating space”. A safe space means that markets can operate and change in a way that they can adhere to the laws of a functional free market. We can think of this safe operating space as a situation without the need for governmental interventions such as significant (>5%) taxation, trade restrictions or violation of the most common labour regulations.

The market for mined resources has competition from other resource needs, such as the need for productive arable land, water and the built environment. The resource nexus is a way to describe the dependencies of people, planet and prosperity (Bleischwitz & Miedzinski 2018). Politics, culture, knowledge, land-use, eco-system services, the availability of metal and mineral resources, business models and the availability of financial capital all influence each other. The need to map the nexus is important for human security and their strategic choices (Bleischwitz 2018). Yet, it is generally accepted that commodity markets do not reflect the true cost of resource extraction (Conde 2017).

Together with the time pressure associated with the carbon budget, the resource nexus explains why the energy transition is different from any preceding transition (scale & time pressure & character & interdependence). Never before did the economic system change over virtually every part of the globe. Never before was there a transition that had such a clear and present time pressure. Never before was there a transition that delivered no direct increase to the quality of living, which is the case for most westernized countries. And never before were so many decision makers involved. The NDC’s can’t be pursued by any country on its own. This is what the Common But Differentiated Responsibilities (CBDR) philosophy in the Paris agreement represents.

There seems to be tailwind from the market: on a worldwide scale, investments in renewable energy capital are higher than investments in fossil fuels and nuclear (Forbes 2018). At the same time, there seems to be headwinds for renewables investments. Even in a period with low interest rates and high economic growth, markets are suffering from a lack of political urgency. For instance, Renewable Portfolio Standards in certain states of the USA are bound to be lowered, representing a setback for renewable energy investments (ENN 2018).

We conclude that it can’t be taken for granted that metal markets supply will meet metal demand including renewable energy capital stock build-up. Market interventions might be justified and need to be explored to safeguard metal supply for the energy transition. Furthermore, these interventions are no exception when it comes to ensuring supply of basic needs for society like energy. Markets for energy are already highly regulated in the EU (Thurmes 2016; DLA 2018) and throughout the world. Given the regulation of energy markets over the last decades, it would be unacceptable that any possible macroeconomic headwind in the future should diminish perspectives for renewable energy capital stock investment.

RECOMMENDATIONS FOR ACTION IN 2019

Some things change in time scales of single years in an energy transition, like the prices to build renewable capital stock or solving a bottleneck related to a technology that was not market competitive for decades. Some things change in time scales of decades, like substitution of a metal for another metal in a technical component or the adjustment of a metal supply chain to permanent shifts in demand. The political will to enable changes can be mobilised in days or can take several decades to gather, adding an overall uncertainty to the energy transition.

Keeping an eye on political developments is, obviously, not the conclusion of this vision document. Keeping an eye on metal demand is. We can’t afford as a global society to let metal demand frustrate our common climate challenge. An annual or even a more frequent exchange of information between worldwide authorities will allow to monitor metal demand for the renewable energy capital stock. This ensures that a path leading away from catastrophic climate change remains open.

Recommendation: demand circular strategies during capital stock build-up
Circular economy strategies can make the renewable energy investments more sustainable in the long term. Extended Producer Responsibilities can set standards for operating expenditures and end-of-economic-life schemes. Investments in renewable energy capital stock on a scale larger than 1 MW almost always have to rely on political support. This provides leverage to public authorities. A **first** recommendation is to demand:

- Substitution of critical metals in renewable electricity stock: critical metal use should be decoupled from capacity growth
- Circular design strategies for PV panels and wind turbines: modular design to enable future remanufacturing
- Clear end-of-life criteria in the building contract: enabling higher recycling yields in the future.
- To set universal standards: set up a list of universal standards for procuring energy capital stock, regardless if these investments are made by public or private bodies.

Recommendation: use rulebook
Societies all over the world are looking for ways to meet their Nationally Determined Contributions to the Paris agreement. The practical details of how the Paris Agreement will be brought to life is known as the Paris "rulebook" (Carbonbrief 2018). Our **second** recommendation will be to use the contents of the Rulebook to an explicit investment portfolio, expressed in metal needs.

Recommendation: exchange and monitor key-parameters among authorities
The metal demand for the global energy transition found in this document shows the need for an unprecedented growth for twenty metals or metal groups. Nonetheless, the path towards the goal of renewable energy capital stock build-up is still open, as far as metal demand is concerned. To safeguard this path, the following organisations need to base their responsibilities on the same data and the same resulting metrics. A **third** recommendation would be to establish a set of key-indicators that need to be exchanged between analyses made by these organizations. Examples of these organisations are

- Climate – IPCC
- Global economy – Worldbank, OECD, IMF
- Energy demand & supply - IEA
- Energy technologies - Renewable energy transparency platform (EU) or NREL (US)
- LCA standards - ISO LCA Standards
- Mining – USGS, GeoERA (in near future)
- World trade – WTO
- Circular Economy – UNEP/International Resource Panel

Recommendation: standards for metal market oversight
To ascertain that markets remain in safe operating space, the current criticality assessment methods (JRC 2016) for metals should be more advertised. A public, comprehensive and transparent framework can signal markets either operating in a safe operating space or markets failing. Examples are reported geological reserves, annual expected demand for metals in a coming year, number of imposed trade

restrictions, production impediments from environmental pressures (transport route reliability, water supply etc.) and obviously (estimated) price developments. A **fourth** recommendation would be to set international standards to be used by institutions responsible for market oversight and governments responsible to safeguard investments in light of the Paris agreement.

Recommendation: monitor impact responsible sourcing
A fifth recommendation would be to monitor the impact that supply chain due diligence has on procurement practices of manufacturing industries (OECD 2016). Under pressure from legal enforcement, or even social media, supply disruptions can occur that are unprecedented to procurement professionals involved.

Recommendation: recommendations for further research
The table below shows the main assumptions made throughout this document. A trivial, yet every bit as sensible, last recommendation is to continue to challenge all these assumptions by publicly available research.

Assumption	Source	Uncertainties involved	Likely to lead to underestimation/ overestimation of metal demand
The 1.5 degree threshold has a 50% certainty to correspond to (GMST method)	IPCC 2018	770 +/-400 Gton GHG	Neutral
Growth of the global economy	Johansson et al. 2012	% annual growth per sector	Neutral
Exclusion of demand for metals for non-energy related disruptive applications like drones	Steinbuch 2017		Underestimate
The energy demand, by technology, in 2030 and 2050	IEA 2017c	% share of energy technologies worldwide and deviation from SSP 2	Neutral
Exclusion of hydro and tidal			Underestimate
Ignoring reported tendency to underestimate demand for renewable energy capital stock			Underestimate
Embedded assumptions in IEA: load factor, efficiencies for energy production and distribution	IEA 2017		Neutral
The GHG emission associated with the of renewable energy capital stock build-up	Gibon et al. 2017		Neutral
The metal needed to build a unit (m^2 of solar panel, a wind turbine etc.) of an energy technology. Including the battery technologies.	See reference subsection	LCI expressing kg	Overestimate
The decision to include demand for batteries as additional bill-of-material	Marscheider-Weidemann (2016) (IEA 20017b)		Underestimate
Linear uptake of non-pumped storage on the grid and assumed technology uptake between types of storage	IEA 2017b		Neutral
Efficiency increases in metal demand per functional unit (€, MW etc.)	De Koning 2016	No evidence that metal/ GDP metric has relatively decoupled over last 25 years	Underestimate
Using different base year for macroeconomic assessment (2011) and renewable energy stock (2014)	Exiobase v3.3 and (IEA 2017a	CAGR can deviate tens of percentages	Underestimate
The global demand for metals given the current worldwide value chains from extraction to final consumption	Exiobase v3.3 (technical coefficients)		Neutral

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TECHNICAL ANNEX

GOAL OF THE EXERCISE BEHIND "WHAT IS THE METAL DEMAND OF AUTONOMOUS ECONOMIC GROWTH IN GENERAL?"

With this project we aim to quantify metal use in 2050 for one specified scenario, using input-output analysis. For this, we need an input-output table for 2050. Obviously, this is not yet available, however it can be approximated using scenario assumptions.

THE MODEL

For the implementation of scenario's in the supply and use tables, the IO scenario model has been used and changed for the purpose of this study[2]. That is, the following changes have been made to the code of the scenario model:

- The IO scenario model code was written in Octave software. This code has been rewritten for Matlab software.
- The scenario model uses supply and use tables from EXIOBASE, year 2000. We have updated this database to supply and use tables from EXIOBASE 3.0, year 2011.
- The scenario model covers the global economy divided in four regions: European Union, other developed countries, fast-developing countries and the rest of the world. We have aggregated the global economy in three regions: Netherlands, rest of the European Union, and rest of the World.
- Scenario assumptions have been updated to the situation for 2011 to 2050. Also, scenario input sources changed depending on the type of change in the scenario. Below we will describe which assumption were taken for the scenario model and which additional assumptions were taken to obtain the results in this report.

The supply and use tables can be transformed into one industry-by-industry input-output table. This is the correct format to perform the IO analysis. Note that the industry-by-industry dimension is important, because the metal physical extensions in EXIOBASE are defined by industry.

SCENARIO ASSUMPTIONS

The IO scenario model requires a selection on inputs. These input all had to be modified to the correct number of industries and product, and the correct number of regions. Where EXIOBASE for year 2000 had 129 products and 129 industries, EXIOBASE 3.0 for year 2011 gives the data for 200 products and 163 industries. When in the table below it is stated that scenario assumptions from CECELIA2050 was taken (i.e. the IO scenario model), a mapping of industries, products and regions between the two databases is required.

	Netherlands	EU	World
GDP projection	NEV 2017	ETP 2017 2DS	ETP 2017 2DS
Efficiency improvement	CECILIA2050	CECILIA2050	CECILIA2050
Electricity mix in production	NEV 2017	ETP 2017 2DS	ETP 2017 2DS
Technological change factor	CECILIA2050	CECILIA2050	CECILIA2050
Change in emissions coefficient	CECILIA2050	CECILIA2050	CECILIA2050
Change in (final) consumption pattern	CECLIA2050 with changes in energy demand from NEV 2017	CECILIA2050 with changes in energy demand from ETP 2017 2DS	CECILIA2050 with changes in energy demand from ETP 2017 2DS
Change in metal coefficient	CECILIA2050	CECILIA2050	CECILIA2050

2 The Octave Source code implementing scenarios and all input data to create the supply and use tables for 2050 can be downloaded from: https://www.universiteitleiden.nl/en/research/research-projects/science/cml-cecilia2050---optimal-eu-climate-policy .

The scenario input that differs from the IO scenario model is given in the tables below:

	GDP change factor for 2050 w.r.t. 2011 (Note that this is a factor and not a percentage. This factor should be multiplied with GDP in 2011)
Netherlands	1.798
Rest of European Union	1.975
Rest of World	3.832

	Electricity mix in production		
	NLD	Rest of EU28	Rest of World
'Production of electricity by coal'	7.0%	0.8%	3.0%
'Production of electricity by gas'	6.8%	2.7%	5.7%
'Production of electricity by nuclear'	0.0%	14.4%	6.9%
'Production of electricity by hydro'	0.1%	10.8%	12.4%
Production of electricity by wind	45.7%	33.0%	14.1%
'Production of electricity by petroleum and other oil derivatives'	2.0%	0.0%	0.2%
'Production of electricity by biomass and waste'	2.1%	9.0%	5.1%
'Production of electricity by solar photovoltaic'	33.8%	21.9%	49.6%
'Production of electricity by solar thermal'	0.0%	0.0%	0.0%
'Production of electricity by tide, wave, ocean'	0.0%	6.3%	1.5%
'Production of electricity by Geothermal'	0.0%	1.0%	1.5%
'Production of electricity nec'	2.6%	0.0%	0.0%

	Change in (final) demand for electricity 2050 w.r.t. 2011 (Note that this is a factor and not a percentage. This factor should be multiplied with the final demand for electricity in 2011)
Netherlands	1.05
Rest of European Union	1.00
Rest of World	2.32

IO ANALYSIS

For the IO analysis, technical coefficients are calculated in matrix A, metal coefficients are calculated and denoted by C_m. Final demand matrix for region r is denoted by Y_r. The footprint for region r (f_r) is found by performing the following matrix calculation:

$f_r = C_m \cdot (I - A)^{-1} diag(Y_r)$.

For the input of this model we have three regions, 163 industries, 19 types of metal. Therefore, C_m is a [19 by 3*163] matrix, A a [3*163 by 3*163] matrix, and the diagonal matrix of column vector Y_r is [3*163 by 3*163]. Footprint f_r is a [19 by 3*163] matrix that provides the metal footprint for 19 types of metals when Dutch consumers purchase goods from one of the 163 sectors in one of the three regions.

This metal footprint calculation is performed for 2011 and 2050.

COMBINING FOOTPRINT FROM IO ANALYSIS WITH EXTERNAL RESULTS

When we aggregate the footprint for all three regions, the global demand for metals is found. However, there is a selection of sectors (the electricity production sectors) for which we are in doubt whether the metal coefficients in EXIOBASE approximates the realistic use of metals by these sectors in 2011. Namely, in 2011, the uptake of renewable electricity sources was still limited, therefore the use of metals in these sectors is only an approximation. We are currently years after 2011, the uptake of renewables made a spurt, and we can therefore make a better projection of metal use in electricity sectors. Therefore, we set the footprint for the electricity sectors from the IO analysis to zero and replace this footprint with external data. The calculations of these “external” results are described in parts “How do you make a bill-of-materials associated with the deployment of the renewable energy capital stock build-up?” and “ And what if we consider demand for battery storage that comes with renewable energy?”. The results of combining the IO analysis is described in “ When we put all metal demand together, how fast does metal production need to grow towards 2030 and 2050?”

November 2019

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