Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets

Resource constraints in successful climate policy

Key constraints and bottlenecks, and some solutions

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LIST OF ABBREVIATIONS

BAU	Business as usual
BRICs	Brazil, Russia, India, China
BX	BRIC countries plus Turkey, Indonesia and South Africa
CCS	Carbon capture and storage
CSP	Concentrated Solar Power
EU	European Union
GDP	Gross domestic production
HI	High Income countries
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
OECD	The Organisation for Economic Co-operation and Development
PV	Photovoltaics
RCP2.6	Representative concentration pathway leading to a 2.6 W/m^2 radiative forcing which has a high probability to limit global mean temperature increase to 2°C.
RoW	Rest of World
TS	Techno scenario
WP	Work package

Executive summary

Aim and method

The study specifies potential bottlenecks in the supply of material resources due to effective climate policy in the longer term towards 2050, but indicates longer duration developments as well. A second part of the analysis is about how such bottlenecks may strategically be overcome. The focus is on the metallic elements. Demand for climate related technologies is additional to rising demand due to economic growth in general and the build-up of infrastructure in developing countries specifically. Growth is not neutral as to shares of different metals, but increasingly shifts to smaller amounts of much larger numbers of metals, as related to ICT developments. This tendency is also present in climate and energy technologies. The question which metals will be required, and in which quantities, depends on the technologies being used, their metals-specific composition and the volumes involved. Neither of these variables can be specified with any certainty. Most electric cars use neodymium permanent magnets but Tesla uses variable field copper electromagnets. Similar holds for wind power. Which of these will be the dominant magnet metals in 2050 is substantially open.

However, there are substantial similarities between groups of technologies in their metals demand to make scenarios based on specific technology assumptions relevant, as representative for the broader but mostly unknown domain of future technologies. So we used one of the most technology specific scenarios for 2050 now available, see Koning et al 2014. It is a detailed input-output specification of the economy in 2050. The metals requirements to be met can be specified as flows per year. In the build-up stage of stocks of metals in products and installations, recycling does not yet play a role. So it is not just flows per year but also the stock requirements for having the installations functioning which play a role in assessing bottlenecks in metals demand for the coming decades. Of course such bottlenecks are additive to the ones coming up due to general economic development. All metals demand is global, with production, spatially concentrated or not, for such global markets.

The match between supply and demand is not a mechanical one, or simply linking economic supply and demand curves. It is long term market expectations which determine production development and expected production constraints which influence demand development and hence expected demand. In these somewhat soft surroundings strategies are to be developed to avoid bottlenecks, especially where price peaks do not lead to relevant supply increases as for example due to long gestation periods in opening up new mines. Such strategies partly are public policy oriented, but partly also based on well-founded analysis, such knowledge directing technologies and markets in directions with low supply risks.

Quantification of climate policy related resource demand

The quantification of resource demand focuses on a number of key sectors: electricity production; energy transformation and transport systems; road transport; and Carbon Capture and Storage (CCS).

Potential bottlenecks

Potential bottlenecks will be there where growth rates starting from current production levels towards "2050" production are to be high, in the order of more than 2 or 3%. When current production is still negligible, as is the case with several rare earths, this growth rate is however not meaningful. Also metals coproduced with a major bulk metal can pose different kind of bottlenecks: expanding production of the main product, like copper, iron or zinc, is hardly possible economically for trace metals in the order of less than a percent of the major metal. Also metals where opening up new mines takes up to decades, like for copper, cannot substantially respond to market signals in economically relevant time periods.

Global demand and supply for metals resources

Global demand will rise generally due to economic growth and specifically for new technologies as in IT related developments. The build-up stage of infrastructure in developing countries will require substantial amounts of metals and other minerals in the coming half century, with recycling playing hardly a role. Effective climate policy will require additional resources, both related to bulk materials, like iron and copper; intermediate materials like lithium; alloying materials like nickel and chromium; and specialty materials available in small quantities, like rare earth elements, and really rare elements like indium, and tellurium.

Demand development, including demand related to effective climate policy, must reckon with overall supply limitations: there is more iron available for mining than gold in this world; no technology can change that.

Insight in these constraints is a most basic strategic issue, where governments can contribute through research funding.

Demand for climate technologies detailed

Demand for climate policy related development depends on the technologies that will be implemented. A distinction can be made as to major technologies for emission reduction being used. An emphasis on CCS related developments will require substantial transport infrastructure for CO_2, with demand for iron and alloying metals like nickel, and chromium increasing substantially.

A more renewables oriented developments would require a broad set of elements from the periodic system. Specifics depend on the choice from a set of known technologies in wind

and solar power and on as yet unknown technologies, specifically for PV which in the long term is likely to provide the bulk of renewable energy.

Both systems would require substantial electrification, including that of most transport, as decentralized use of carbon containing fuels will have to be reduced to near zero. However, the intermittent nature of most renewables will also lead to substantial energy buffering and storage requirements. Current developments cannot yet indicate winning technologies in this arena, so precise demand predictions are hardly possible. However, low carbon energy certainly will substantially increase materials demand per MJ, for a broad range of metal resources.

Detailed technology scenarios, more and more detailed than now are used in this analysis, would help create insight in demand requirements for effective climate policy.

Market related supply constraints for climate technologies

Market related supply constraints first relate to the unavoidable limitations in geological resource availability. Within these boundaries, supply constraints depend on the cost of extraction and processing, to be matched by price. Depletion of the most rich and easily approachable ores will increase costs while technology improvement reduces costs. The net effect will differ per resource and groups of combined resources, like rare earths. A complicating factor is that many elements are produced as minor co-products. When such co-production is not fully exploited yet this will make upscaling production easy, involving the processing stage only. Once this option is fully exploited upscaling of production will be extremely expensive. Predictions are hard to make in specific cases. There has been an often exponentially rising trend in almost all metals produced, without a clear direction in price development in the last century. That is the situation to reckon with: substantial uncertainty and no clear tendency in price.

However, climate policy adds a new uncertainty. How sure can miners be that climate policy indeed will be successful? An extreme but important example can clarify the importance of this uncertainty. Relevant miners assume policy success and start opening up copper mines to deliver the required amounts. Demand will rise in the next decades. The new copper mines invested in will come to full production after in the order of up to 25 years. The match is perfect. If however climate policy is delayed, the demand expansion will not occur and copper prices will collapse. Most copper miners will then write red figures till the most costly mines and least financially viable companies will have closed down.

The high uncertainty on climate policy makes any investment for that future supply a high risk investment, with a substantial chance on loss. This implies that if successful climate policy would come about, there nearly certain will be a shortage of copper supply, with prices then spiralling. For metals where production can be expanded more easily and fast, like lithium, this is much less the case.

The most basic issue in having the supply needed in successful climate policy is to reduce demand uncertainty: make effective climate policy really credible.

Recycling and substitution

Long term demand for virgin resources is not absolute per resource. Improved recycling reduces primary demand. This factor can become important only after the build-up stage has been substantially completed. For much fixed and mobile infrastructure, including ships, trains and airplanes, this build-up stage can take half a century and or more.

Substitution is a major route to avoid specific depletion. The supply problems with neodymium (due to political constraints) for ultra-strong magnets can be avoided by using electromagnets instead. This choice has been made by Tesla, but not by other car builders, accepting a slightly lower efficiency of the electromotor' s/dynamo's, but avoiding supply risks. It seems that such considerations, not to rely on resources with possibly restricted supply, is being broader adopted now in technology development. However, in deeper innovations as for example in near-zero resistance electricity transport, public research seems required, then avoiding reliance on possibly too expensive copper.

Setting up relevant recycling systems, including product requirements like demountability, are essential now already for shorter life time applications, but in the long run for all products and installations.

Political and monopolistic supply constraints

Monopolistic behaviour is possible with one producer dominating the global market. It also is possible through state action, where one country has an overarching position in supply, as in the case of export restrictions of rare earth elements by China, especially neodymium. There are two mutually exclusive routes to keep such actions at bay. One is to make long term bilateral arrangements with the producer or producer country. If all user countries do so, an inflexible system results, with extreme price volatility for the tiny open market left. With prices in the open market rising to a manifold of the contract prices, contractual supplies just will not be met, seems a safe prediction from past experience.

The other option is to prevent private monopolies and bring the supply of resources more forcefully in the open market domain, as organized in the WTO. This will not function fully and not always. Especially smaller countries don't have other options than this one. Defeating short term actions by near monopolist countries could be countered by building up strategic reserves by consumer countries of the metals involved. The cost of setting up, which will drive up prices, and of maintaining such reserves are substantial. If that action is successful and monopolistic behaviour does not occur, the full costs of having the reserve are for the organizing party as a full loss, with additional profits for the producer country. Bringing the reserves on the market will depress prices. The experience with the UNCTAD resource funds have not been positive. The strategic stock building in the US in 1950s has led to the collapse of domestic mining as domestic markets were taken over by foreign

producers. Private speculation with silver by the Hunt brothers has proven that costs of maintaining reserves can be very high: they lost their fortunes.

Monopolistic misbehaviour is to be reduced by antitrust policies, and where countries are involved by clarifying WTO rules and developing most direct sanctions. For all metals with monopolistic risks research for substitution is to be publicly supported.

Key conclusions

- Uncertainty on supply and demand of metals has always been substantial and will remain so.

- Successful climate policy would require substantial additional supply, which could be part of the usual investment considerations on metals and mining firms.

- The high uncertainty on having successful climate policy will lead to substantial though temporary shortages.

- Substitution can to some extent avoid reliance on metals with supply uncertainty.

- Shortages, as severe price peaks with limited supply reaction, will be most severe for metals:

  - where increasing the mining and processing capacity takes a long time, with copper as a prime example (>20 years)
  - with a low concentration metals co-produced with bulk metals like some rare earths, and indium and tellurium in some iron, zinc and copper ores
  - where near monopolistic supply makes disturbance possible.

- Monopolistic behaviour can best be approached through antitrust policy where firms are involved. Where governments can play that role strengthening of WTO rules seems the only direct policy option, combined with research to create substitution for the metals or products containing that metal.

- When capacity can be increased with short lead times and without substantial price rises, such shortages will hardly play a role, as for lithium.

- Avoiding the reliance on metals with potential shortages seems a key strategy for avoiding bottlenecks in the development of climate technologies.

1 Introduction

Key elements of an effective climate policy require that by 2050 the energy production and consumption systems are substantially changed relative to the current energy production and consumption systems. These possible future low carbon energy systems require different amounts and different types of materials than the current existing energy production and consumption systems. For instance the amount of materials associated with the production of electricity with a wind turbine is much larger than the production of the same amount of electricity with a conventional coal power plant. The sheer size of the energy production and consumption system means that a change of this system might be limited by the supply of the materials needed for the low carbon energy systems. To be able to limit average global warming to about 2 °C above pre-industrial levels, a 80% reduction of GHGs may be required (IPCC, 2014) by 2050, a figure adopted by the European Union in established policies. Thus the change in energy systems must not only be substantial, it is also to be accomplished in about 35 years' time. The speed by which new resources are discovered and new mines can come into operation might therefore be a bottleneck for the energy transition as well. Well-founded expectations on the certainty of future demand for metals are important for investments in new mines to take place.

In this report it is investigated if resource constraints can be a bottleneck for formulating successful climate policies. If there are bottlenecks, policy measures that might alleviate future resource problems are investigated. Resources that will be investigated are metallic resources like bulk metals such as iron and aluminium. Of specific interest are rare earth metals (Kleijn et al., 2011) that play a large role in many high efficiency low carbon energy technologies such as batteries and electromagnets. An overview of these rare earth metals and their applications in energy technologies can be found in (Eliseeva & Bu, 2011). A successful climate policy is assumed to be a policy in which there is a high change that average global warming is limited to 2 °C above pre-industrial levels, requiring emission reductions up to 80% by 2050.

Not investigated are bottlenecks of minerals resources such as sand, clay, stone. Sand, clay and stone are ubiquitous available and are locally mined and used mostly. There might be local resource constraints (e.g. when building a dam) but it seems unlikely that the supply will become a global problem. Another resource problem not investigated is the supply of fertilizer minerals (phosphate minerals) and biomass for energy production. These two issues are of utmost importance because many of the 2 °C GHG emission scenarios rely more or less on the use of biomass for energy production, potentially competing for land that is also used for food, feed and fibre production (Tilman et al, 2009), and for nature. However the biomass supply constraints need to be studied with a different analytical framework and requires separate study.

Answering the main question of this study is difficult to say the least. The following issues are at play:

o   How a successful climate policy scenario looks like in 2050 is not known. Different scenarios, with different sets of energy technologies can be envisaged.

o   It is uncertain how energy technologies will develop the coming 35 years' time and what their metal requirements will be.

o   It is unknown if new metal substitution possibilities will become available the coming 35 years.

o   While absolute supply of metals can be inferred from concentrations in the earth mantle the supply that matters is the metal that can and will be mined economically. The actual supply of metals is highly dependent on the prices that can be paid, the investments that are made to open up mines, and political constraints.

Given the above it is likely that there will be order of magnitude uncertainties when it comes to establish demand as well as supply of metals in scenarios of successful climate policies. Nonetheless it might be possible to examine if there are possible metal resource constraints that need to be taken into account when formulating successful climate policy by examining boundary cases.

To make an assessment of the possible metal resource bottlenecks the following research questions will be addressed:

o   What might be an educated guess for the demand for metals in the year 2050. Preferably the guess should err on the high side.

o   What would be a ballpark figure for the total demand for metals to build up the new energy production and consumption system from 2000 until 2050, i.e. the cumulative amount of metals needed until 2050 in case of successful climate policy is implemented. Again the guess should err on the high side.

o   What is the current rate of metal extraction and how does it compare the current actual demand and expected demand for metals in 2050.

o   What are the current economic reserves and how does it compare to the expected total metal demand until 2050.

o   In how far can substitution between materials and recycling solve possible conflicts between supply and demand taken a 35 years' time technological progress.

o   Are there bottlenecks in the speed by which the mines can be scaled up both from a technical as well as business/investment point of view.

o   Are there specific political supply risks where the supply of a single metal is controlled by a single country or single firm, a key issue in criticality (EC, 2014).

The report starts with a description of the methodological framework used to make an educated guess of the metal demand until 2050. Then the results of this analysis are confronted with the values on available metal resources and metal supply rate. These results are discussed in the light of other important factors that might influence the long term supply and demand of metals.

2 Materials and Methods

2.1 Analytical framework

The research framework is as follows. First two ball park figures for the demand for metals in 2050 are estimated on the basis of two scenarios. One scenario is a business as usual (BAU) scenario until 2050. This BAU scenario is a scenario in which historical developments, including efficiency improvements, are extrapolated until 2050. This scenario has been described in De Koning et al. (2014, 2015). GHG emissions in the BAU scenario are on a trajectory towards an 8 °C global warming, similar to the RCP8.5 BAU scenario (De Koning et al., 2015; IPCC 2014). The second scenario is a Techno Scenario (TS) in which all probable and possible technical CO_2 emission reduction measures currently envisaged have been implemented in 2050. It is a techno-optimistic scenario that for instance includes CCS on all the remaining fossil fuel power plants, widespread introduction of electrical vehicles and complete electrification of household heating. It is important to note that this TS does not yet correspond to a scenario where the average global warming is limited to 2 °C. Instead the TS brings us on a trajectory of about 4 °C average global warming similar to the RCP4.5 scenarios (IPCC, 2014). GDP growth in the BAU scenario and TS follows projections made by the OECD (2012). The TS is not an example of successful climate policy as we defined successful climate policy which realises a 2 °C temperature rise at the maximum. According to our analysis, only our techno-optimistic scenario in combination with a rate of economic growth slower than those predicted by the OECD (2012) can keep global emissions within a 2 °C limit. Instead of an yearly average global GDP growth of 2.3%, the growth rate would need about 1% per year. A truly successful climate policy would therefore entail a TS with a reduced growth rate, lowering the demand for products and energy and hence associated metal resources compared to the TS. The estimate of the metal resources needed in the TS are therefore a high mark for the demand of metals. Another option would be to believe in as yet unknown technologies saving us. Fundamental innovations can however hardly be available in full quantity within 35 years.

The yearly demand for metals required in the BAU and TS in 2050 is estimated using data about metal requirements of different energy sources, coupled to scenarios of the energy market and together with expected growth scenarios of other sectors such that an overall expected demand of the most relevant metals is obtained. How the metal requirements of different electricity generation technologies, road vehicles, buildings and other infrastructure are taken into account is discussed in Section 2.2 - 2.5.

The high mark yearly metal demand results of the TS 2050 are subsequently compared with the current yearly metal demand and supply. These TS 2050 results can next be used to

make get a high mark ball park figure for the total amount of metals to be extracted until 2050 which can be compared to available reserves.

2.2 Electricity generation technologies

In this section the metal requirements of photovoltaics, wind, hydropower, fossil fuel and concentrated solar electricity generation technologies are described. The cradle-to-grave metal requirements of these technologies are taken from a wide range of literature sources and LCA databases. It should be noted that these are the metal requirements of the technologies as they currently exit. By 2050 the metal requirements of the technologies have likely decreased in general due to ongoing technological progress. For specific metals and specific applications material use might increase.

2.2.1 Photovoltaics

Moss et al. (2011) was used as a basis for the metal requirements of PV panels. Moss et al. give an extensive overview for the metal requirement of several energy sources and also give an inventory of different forms of PV panels and which are currently under development. Common metals with low scarcity like aluminium and iron are not accounted for in in the research of Moss et al. (2011). These data were taken from Laleman et al. (2013).

To convert the data from Moss et al. (2011) to the metal requirements per MWh, the data was corrected for the lifetime of the PV panels (25 years), yearly energy production and the capacity factor (20%) both based on (EIA, 2014).

The requirements of aluminium and iron for PV were obtained from Laleman et al. (2013). This source was chosen because it focuses on metals required for installing the modules and different types of PV modules are included. The data is presented as the amount of iron and aluminium per m^2 of module. To determine the metal requirements per MWh the yearly energy production was calculated using the data given in the article. For the yearly irradiation 1300 kWh/m2/year was used, because this is an average of the irradiation at different locations, however it is very well possible that PV panels will be mainly used in areas with higher or lower irradiation levels. Additionally a lifetime of 25 years was assumed (EIA, 2014) and data from the Ecoinvent LCA database was used if multiple data sources were presented. Finally the metal requirements were adjusted for the assumed technology mix of different types of PV panels in Moss et al. (2011).

2.2.2 Wind

For the metal requirements of wind energy Moss et al. (2011) was also used. The data was converted to the requirements per MWh in the same way as described for PV. A lifetime of 25 years was assumed (Wilburn, 2011) and a capacity factor of 30% (EIA, 2014). The

requirement of iron and aluminium was obtained from Wilburn (2011). This research also focuses on the future developments of wind turbine technology and the effect on the average metal requirement, in contrast to a single type of turbine. The same method and assumptions were applied as for the Moss et al. (2011) data to convert the figures to kg/MWh. In the total aluminium demand is 1% of the iron requirement, therefore the aluminium requirement is set to 1% of the iron requirement.

2.2.3 Hydroelectricity

For the metal requirements of hydroelectricity data from da Silva et al. (2013) was used. This however is a case study, but the number of studies on the metal requirements of hydroelectricity is very limited. However, the authors compare their results to results of other studies and find they are in the same order of magnitude.

2.2.4 Natural Gas, Coal & CCS

The metal requirements for natural gas and coal electricity generation with and without CCS have been adopted from van der Giesen (2008).

2.2.5 Nuclear

For nuclear electricity the metal requirements have been obtained from Moss et al. (2011) and calculated in the same way as described for PV. A capacity factor of 90% and a lifetime of 60 years are assumed (Keppler and Cometto 2012). Additional sources are needed for assessing the requirements of iron and aluminium but these have not been found. Iron and aluminium are currently not considered for nuclear power generation.

2.2.6 Concentrated solar power

The metal requirements for Concentrated Solar Power (CSP) electricity is based on a case study of two different advanced solar technologies, parabolic through and tower (Pihl et. al. 2012). The metal requirements per MWh are calculated with the yearly energy production per installed capacity and the given lifetime (30 years), combined with the requirements for maintenance. Parabolic Through is currently the most deployed form of advanced solar power (CSP today, n.d.), therefore only this form of CSP is taken into account in the final metal demand. However it is possible that other forms of CSP will become a significant part of the market in the near future, and then the metal requirements need to be corrected for the market share of the different CSP technologies.

2.2.7 Electricity production mix

Scenarios developed in WP3 by De Koning et al. (2014, 2015) are used. In this work two scenarios are presented with 2000 as base year. An extrapolation of current trends (BAU) and a techno scenario (TS) that assumes the large-scale implementation of probable technologies that will substantially reduce greenhouse gas emissions. For this work the initial energy data from the scenarios had to be specified further, as to which energy technology will produce which amount of electricity. This was done for the TS by taking the total energy production from the mix calculation table and combining that with the specified data of the energy mix.

For the base year a more specified dataset was created. This data was used to calculate the more specified requirements for BAU scenario by calculating the distribution of the different energy technologies and combining that with the total energy demand in that scenario.

2.3 Land vehicles

2.3.1 Number of vehicles

To determine the effects of the electrification of the transport sector the number of the different types of vehicles in the different scenarios needs to be estimated. The current analysis is limited to passenger cars. The basic data is taken from the motor vehicles production sector in the different scenarios. This is monetary data not corrected for inflation. The total production of motor vehicles (not sold vehicles) in 2000 was 41 million (OICA n.d.). Combination with the monetary data gives an average of k€40 per car. In fact this figure is a simplification and does not give the actual production cost of a car, since the value represents the total value of the sector and the sector also consists of production of other goods such as trailers and trolleys or more expensive types of cars such as SUVs or hybrids. This number will be used as a rough estimation that is used to calculate the future production of vehicles in 2050 but only after it is corrected for the relative price difference for different types of vehicles in comparison to a fossil fuel driven vehicles, based on EPRI (2004). It is assumed that gasoline and diesel vehicles have the same relative price. However, in EPRI (2004) different types of cars (Passenger and City car) are compared in the sections on hybrid and electric vehicles (EV), so the relative price of hybrid and EV is determined according to the type of vehicle that they are compared to in the article.

In De Koning et al. (2014) the market share of gasoline, diesel, battery-electric, hybrid-electric and plug-in hybrid vehicles are specified for the base case and the Techno scenario. The share of the different types of vehicles is assumed to be the same for the business as usual scenario (BAU) and base year. Together with the monetary data of the sector in the different scenarios and the relative price of the vehicles the number of the different types of vehicles is determined.

2.3.2 Metal requirements

Data from Burnham (2012) is used to determine the metal demand per type of vehicle, since Burnham (2012) focuses on the metal demand of all the vehicle types specified in our scenarios. Data on the amount and distribution of the different metals in the vehicles and batteries are used to determine the requirements of the different types of metals per vehicle.

However for the electric engine no data is given for the requirements of metals such as neodymium that are sometimes present in the permanent magnets in electric motors. Therefore, Hawkins et. al. (2012) is use to determine the more specific metal requirements for electric engines. This data is converted to the metal requirements per weight of the electric engine and together with the data of the weight of the electric engines the requirements of the metals that are not specified in Burnham (2012) are determined.

Some additional assumptions have been made to obtain the metal demand. It was assumed that metal categories copper/brass (in the vehicle weight) and electronic parts (in the Li-ion battery) consisted of mostly copper. Additionally for the materials of which the chemical formula is given the requirements of the specific elements are determined according to their molecular weight.

2.4 Infrastructure and building construction

By far the largest amount of mineral and metal resources in the world are used in the construction sector. The construction sector provides such diverse products as bridges, motorways, canals, airfields, private houses, and factory buildings, including all wiring, plumbing and other building products that are needed to make a complete building.

The calculation of the amounts of metals used in the current worldwide construction work is problematic because such diverse products are produced by the construction sectors. A bottom-up analysis where detailed data for specific construction products are collected and subsequently scaled up to world level will likely be unsuccessful.

Instead a top-down approach has been used to make a rough estimate of the current and future rates of metal resource use. The same data and models used to make the different GHG emissions scenarios (De Koning et al., 2014, 2015) were exploited to calculate cradle – to – grave metal resource use associated with construction. To do so the EXIOBASE supply-and-use tables (SUTs) which form the basis for specifying the GHG scenarios where extended with information about metal ore extraction data. Similar to the calculation of GHG emissions associated with the consumption of specific products, also the metal ore extraction associated with the consumption of products could be calculated.

The number of metal ores that could be distinguished by this approach is limited. These metal ores categories are shown in Table 2-1. The estimated metal content of the ore has

based on an overview of average metal content of ores presented by Philips and Edwards (1976).

Table 2-1 Metal ores that could be associated with construction work in the top – down analysis

Ore	Element	Me content (kg Me/kg ore)
iron ores	Fe	0.147
bauxite and aluminium ores	Al	0.111
copper ores	Cu	5.21×10^{-3}
lead ores	Pb	5.11×10^{-2}
nickel ores	Ni	3.88×10^{-3}
tin ores	Sn	6.76×10^{-3}
uranium and thorium ores	U	5.65×10^{-4}
zinc ores	Zn	2.82×10^{-2}
precious metal ores	?	?
rare earthes ores	?	?
other metal ores	?	?

Bulk metal use in EXIOBASE is well represented but precious metals and rare earth metal use of the construction work cannot be estimated.

Using the data in Table 2-1 the global metal resource use in the actual year 2000 could be calculated and the metal resource use per unit of construction work output. The global metal resource use in the BAU 2050 scenario and TC 2050 were subsequently calculated by multiplying the output of the construction sector taken from the BAU 2050 and TC 2050 with the metal use per unit of output as calculated for the actual year 2000. Thus we assume that there is no change in the amount of metals being used in construction work in 2050.

2.5 Transmission & buffering

The amount of additional transmission and storage that is required depends on the share of intermittent renewable energy technologies, such as wind, CSP and PV. Buffering can be provided by either getting electricity from other areas with long distance transmission or more local storage. However, since the share of renewable technologies that require additional transmission or buffering is only 0,20% for the BAU scenario and 6% for the techno scenario, buffering is provided from the remaining 94-99% of the production.

3   Results

3.1 Metal resource use by energy generation technologies

In Table 3-1 the metal requirements of the different energy technologies investigated are presented.

Table 3-1 Life cycle metal requirements for the different energy technologies expressed in kg/MWh.

Elem.	PV	Wind	Hydro	Natural Gas	Natural Gas+CCS	Coal	Coal +CCS	Nuclear	CSP
Sources	Moss et al., 2011 Laleman et al., 2013	Moss et al., 2011 Wilburn, 2011	da Silva et al., 2013	van der Giesen, 2008	van der Giesen, 2008	van der Giesen, 2008	van der Giesen, 2008	Moss et al., 2011	Pihl et al., 2012
Fe	4.65	1.46	0.138	1.11	1.46	1.34	2.14	0[*]	8.07
Al	3.69	1.46E-02		8.00E-03	1.00E-02	3.20E-02	4.70E-02	0[*]	6.98E-03
Cu	0.370	1.74E-02	2.45E-03	6.00E-03	8.00E-03	1.20E-02	1.80E-02	1.26E-04	2.92E-02
Ni		1.01E-02		2.60E-02	4.30E-02	3.10E-02	6.60E-02	5.40E-04	8.59E-03
Cr		1.37E-02		7.00E-03	1.30E-02	6.00E-03	1.70E-02	9.02E-04	2.01E-02
In	1.03E-04							3.38E-06	
Nd		6.18E-04							
Dy		4.26E-05							
Cd	1.39E-04							1.06E-06	
Ag	4.38E-04							1.75E-05	1.23E-04
Mo		2.08E-03		1.00E-03	1.00E-03	4.00E-03	7.00E-03	1.50E-04	1.83E-03
Mn		1.23E-03			1.00E-03	4.00E-03	7.00E-03		1.83E-02
Pb	9.36E-02							9.09E-06	
Ga	2.74E-06								
Se	7.42E-05								
Sn	1.06E-02							9.72E-06	
Te	1.07E-04								
Hf								1.01E-06	
W								1.06E-05	
Y								1.06E-06	

Elem.	PV	Wind	Hydro	Natural Gas	Natural Gas+CCS	Coal	Coal +CCS	Nuclear	CSP
Nb								4.23E-06	0
Zr								6.45E-05	
V								1.27E-06	1.74E-05
Ti								3.17E-06	2.28E-04
Zn					1.00E-03	1.00E-03	3.00E-03		5.94E-03
Mg									2.83E-02

* The cradle to gate metal requirements are not known and set to zero

The metal requirements of the different energy production technologies given in Table 3-1 can be combined with the production volumes as specified by the different scenarios. The energy production volumes are given in Table 3-2. The energy production mix and volumes for the year 2050 are largely based on EMF-21 scenario study described by Jakeman and Fisher (2010).

Table 3-2 Energy production of different energy technologies for the year 2000 and BAU and techno scenario (De Koning et. al. 2014)

Region	Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050
	EJ	EJ	EJ
Nuclear	9.3	31.7	31.5
Solar PV	0.0	0,0	1.9
Advanced Solar			3.9
Wind	0.1	0.4	3.6
Bio-energy (including waste for 2000 & BAU)	4.6	15.8	0.0
Coal	21.5	73.2	18.4
Gas	9.9	33.8	19.6
Coal + CCS			15.1
Gas + CCS			15.2
Bio-energy + CCS			4.4
Hydro (Including Geo-thermal for Techno)	9.3	31.6	48.2
CHP	0.0	0.0	
Total	54,8	186.6	161.9

Notice that the introduction of CCS on bio-energy leads to removal of CO_2 from the atmosphere in the TS.

3.2 Metal resource use by new cars

In Table 3-3 the number of produced vehicles in the different scenarios and the base year is presented, based on the final consumption volume of cars as available in the scenarios developed by De Koning et al. (2014). Additionally the relative price of the different vehicle types is presented based on EPRI (2004).

Table 3-3: The relative price of different vehicle types and the number of the vehicles produced in the actual year 2000, the 2050 BAU scenario, and 2050 techno scenario

Type of vehicle	Relative price	Number of new cars (million)		
		Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050
Gasoline	1.00	31.45	69.06	2.38
Diesel	1.00	8.66	18.88	5.85
Full-electric	1.36	0.00	0.00	43.58
Hybrid-electric	0.97	1.08	1.89	7.98
Plug in Hybrid-electric	1.01	0.00	0.00	41.77
Total		41.18	89.83	101.57

The metal requirements of the different vehicle technologies taken from the literature as discussed in Section 2.3.2 are presented in Table 3-4. Both batteries and engines have been taken into account.

Table 3-4 Material requirements of different vehicle technologies for passenger cars in kg/vehicle.

Element	Internal Combustion Engine Vehicle	Hybrid Electric Vehicle	Plug-in Hybrid Electric Vehicle	Electric Vehicle
	kg/vehicle	kg/vehicle	kg/vehicle	kg/vehicle
Fe	964	1016	1047	1295
Al	92	105	119	244
Cu	26	66	79.4	166
Mg	0.27	0,29	0.30	0.39
Ni	0.00	0.00	0.00	0.00
Pt	0.01	0.00	0.00	0.00
Pb	11.3	6.89	6.89	6.89
Li		0.21	1.09	8.43
Mn		3.05	16.0	125
Nd		0.01	0.01	0.03
B		0.01	0.01	0.03

3.3 Metal resource use in construction

The calculated metal resource use in construction work in the actual year 2000, the BAU scenario and TC in 2050 are given in Table 3-5.

Table 3-5 Metal requirements for construction work in kg/year

Metal	Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050
Fe	3.23×10^{10}	7.91×10^{10}	7.93×10^{10}
Al	2.97×10^{9}	8.00×10^{9}	8.02×10^{9}
Cu	2.16×10^{9}	5.95×10^{9}	5.97×10^{9}
Pb	3.69×10^{8}	1.02×10^{9}	1.02×10^{9}
Ni	1.47×10^{8}	4.30×10^{8}	4.31×10^{8}
Sn	2.38×10^{8}	7.10×10^{8}	7.12×10^{8}
U	1.88×10^{6}	5.94×10^{6}	5.96×10^{6}
Zn	1.31×10^{9}	4.10×10^{9}	4.12×10^{9}

3.4 Total metal resource use

The total yearly metal resource use, summing up the use of metals by land vehicles, new construction work and energy systems is given in Table 3-6. Because a limited number of metals could be taken into account when calculating the amount of metals in construction work (see Section 2.4), the total yearly metal resource use could be calculated for a limited number of metals only. The values given for chromium, indium, neodymium, dysprosium, and lithium are based on the metal use of electricity generation technologies and land vehicles only.

Table 3-6 Total global yearly metal demand for the actual year 2000, BAU 2050 scenario and Techno 2050 scenario for the electricity production sector, construction work and land vehicles together. The supply data for Fe, Al, Cu, and Ni have been taken from EXIOBASE for the year 2000. The supply data for Cr, In, Nd, Dy and Li have been taken from the USGS for the year 2000.

	Total metal demand from electricity production construction work and land vehicles (kg)			Annual mine production 2000/2008 (kg)	requirement/production-2000		
	Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050		Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050
Fe	8.35×10^{10}	2.05×10^{11}	2.38×10^{11}	1.60×10^{11}	0.52	1.28	1.49
Al	6.99×10^{9}	1.70×10^{10}	2.77×10^{10}	2.29×10^{10}	0.30	0.74	1.21
Cu	3.35×10^{9}	8.66×10^{9}	1.77×10^{10}	9.15×10^{9}	0.37	0.95	1.94
Ni	4.05×10^{8}	1.31×10^{9}	1.21×10^{9}	4.36×10^{8}	0.93	3.00	2.79
Cr	5.75×10^{7}	1.96×10^{8}	2.40×10^{8}	6.98×10^{9}	0.01	0.03	0.03
In	8.78×10^{3}	2.99×10^{4}	8.41×10^{4}	5.73×10^{5}	0.02	0.05	0.15
Nd	1.34×10^{4}	2.35×10^{4}	2.80×10^{6}	1.80×10^{7}	0.00	0.00	0.16
Dy	0	0	4.66×10^{4}	1.00×10^{5}	0.00	0.00	0.47
Li	2.22×10^{5}	3.88×10^{5}	4.14×10^{8}	3.82×10^{8}	0.00	0.00	1.08

As can be seen in Table 3-6 the sum metal use as calculated from the use by the electricity generation technologies, land vehicles and construction work does not equal yearly mine production in 2000/2008. The technologies that are explicitly taken into account use a large share of the mined bulk metals iron, aluminium, copper and nickel. However that cannot be said for the metals chromium, indium, neodymium, dysprosium, and lithium. Only a very small fraction of the mining supply is taken up by electricity generation technologies, land vehicles and construction work. Likely most of these metals are used in electronics, glass and

ceramics and these applications are not accounted for in the calculation of the demand of metals in Table 3-6.

Notice the very large increase in the demand for neodymium and lithium in the TS, considering the electricity production sector, building sector and land vehicles together. Expected increase in the use of neodymium is a factor 200 and for lithium the demand is even 2000 times higher in the electricity production sector, construction work and land vehicles applications. However, while looking at these sectors only the rise in demand seems dramatic, the overall rise in demand (see Table 3-7) is much less pronounced, something like a factor 3-4.

To make an assessment of the demand for metals in products that have not been taken into account explicitly, we assume that yearly metal mining supply and demand are by and large in balance, and that recycling can be neglected. The gap between mining supply and demand as shown in Table 3-6 is assumed to be fully taken up by other products such that the supply and demand in 2000 is in balance. Subsequently the use of metals in these other products has been scaled proportionally to GDP to make a rough estimate of the use of metals in 2050. The calculated total metal use is shown in Table 3-7. Also shown for reference is GDP growth (OECD, 2012).

Table 3-7 Total global yearly metal demand for the actual year 2000, BAU 2050 scenario and Techno 2050 scenario all products. The supply data for Fe, Al, Cu, and Ni have been taken from EXIOBASE for the year 2000. The supply data for Cr, In, Nd, Dy and Li have been taken from USGS for the year 2000.

	Total metal requirements (kg)			Annual mine production 2000/2008	requirement/production-2000		
	Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050		Actual Year 2000	BAU Scenario 2050	Techno Scenario 2050
Fe	1.60×10^{11}	4.50×10^{11}	4.80×10^{11}	1.60×10^{11}	1.00	2.82	3.01
Al	2.29×10^{10}	6.83×10^{10}	7.83×10^{10}	2.29×10^{10}	1.00	2.98	3.42
Cu	9.15×10^{9}	2.73×10^{10}	3.62×10^{10}	9.15×10^{9}	1.00	2.99	3.95
Ni	4.36×10^{8}	1.41×10^{9}	1.31×10^{9}	4.36×10^{8}	1.00	3.23	3.01
Cr	6.98×10^{9}	2.25×10^{10}	2.23×10^{10}	6.98×10^{9}	1.00	3.22	3.19
In	5.73×10^{5}	1.85×10^{6}	1.88×10^{6}	5.73×10^{5}	1.00	3.22	3.28
Nd	1.80×10^{7}	5.80×10^{7}	6.00×10^{7}	1.80×10^{7}	1.00	3.22	3.33
Dy	1.00×10^{5}	3.22×10^{5}	3.65×10^{5}	1.00×10^{5}	1.00	3.22	3.65
Li	3.82×10^{8}	1.23×10^{9}	1.63×10^{9}	3.82×10^{8}	1.00	3.22	4.26
GDP					1.00	3.21	3.21

In Table 3-7 it can be seen that in the BAU scenario the demand for iron, nickel and chromium grows approximately as fast as GDP. The growth in nickel and chromium is for a large part coupled to that of iron as alloy elements in steel and stainless steel.

In the TS the introduction of all kinds of CO_2 emission reduction technologies raises the demand growth of aluminium, copper, indium, neodymium, dysprosium and lithium above the level of economic growth but not very much. The largest growth is seen in lithium where the demand growths a factor 4.3 in 35 years' time (4.25% p.a.). Please notice that while the specific application of lithium in car batteries increases 2000 times, the overall demand growth of lithium is only a modest factor 4 (4% p.a.). The increase in lithium in car batteries is in reality likely less pronounced because our estimate of lithium use in car batteries for the actual year 2000 is very low compared the values reported by the lithium manufacturers (Roskill, 2009). It is reported that about 10% of the lithium is used in batteries. According Gruber et al. (2011) in 2007 about 25% of the lithium is used in batteries. In contrast to those number we calculate that about 0.1% if the produced lithium is used in batteries. In the overall picture the yearly demand growth is between 2.2% for iron and 2.9% for lithium.

4 Discussion

4.1 Metal resource use in 2050

The ball park high estimates for total metal use in 2050 as shown in Table 3-7 are rough guesses at best. The estimates are for a large part dominated by linear extrapolation of GDP growth and constant metal composition of general products. They incorporate for small part specific information on changing technology and associated metal content. It is therefore not a big surprise that the total estimated metal use increase closely follows expected GDP projections. The estimated increase in demand for metals is between 2–3% per year, which is well within bounds that can be met by suppliers, and this increase in demand is even a high estimate. These are rather modest growth percentages that are not out of the ordinary and it has been demonstrated in the past that such demand growth can readily be met by supply over longer times (Kleijn et al., 2012). Historical data on supply of iron, aluminium and copper (Kleijn et al., 2012) show that in the 20 years from 1995 and 2014 supply grew yearly between 20% - 28%. From this viewpoint, it seems that metal supply will in general be able to keep up with metal demand driven by a successful climate policy.

However because of the generality of our assessment, for metals that are going to be used in an application for which there is going to be a large demand, supply constraints may apply. A small hint of this issue can be seen in the analysis made. For energy technologies that will see much larger application in the future and contain specific metals, the amount of metal going into the application grows quickly. We see this effect for the metals neodymium in energy technology and lithium in land vehicles. The application of neodymium in energy technology increases a factor 1800 (16% p.a.), the application of lithium in land vehicles increases a factor 162 (10% p.a.) from 2000 to 2050. These large increases of these specific metals in specific technologies are masked by the general use in other applications as shown in Table 3-7.

4.2 Metal resources used until 2050

Using our assessment of the yearly metal demand in 2050 in the TC, a simple assessment can be made of the total amount of metals needed until 2050 by linear interpolation of the metal demand in 2000 and 2050. The estimates are highly dependent on the estimated use of metal in 2050 in the TC. Given that the TC is high mark for metal use in 2050, the total amount of metal reserves used until 2050 is a high mark as well. The estimated total cumulative demand for metals is given in Table 4-1. These amounts can be compared to the economic reserves that exist today. Economic reserves is defined that part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative (USGS,

2015). The economic reserves that are available today can be seen as the amount of resource that for sure can be extracted until 2050 from a technical and economic point of view. Investment uncertainties and rate of opening these economic reserves might still be an issue. There might also be regulatory or political barriers that make exploitation problematic. The economic reserves are probably a low mark for the reserves that are available until 2050. Increasing metal prices, new technologies and new discoveries can only increase the amount of economic reserves. The economic reserves of the different metals have mostly been estimated based on figures given by the USGS (2015). Indium reserves were taken from USGS (2007) and neodymium reserves were based on estimates of rare earth ores (USGS, 2015) and assuming that the rare earth ores contain 18.5% neodymium (Bastnasite from Bayan Obo, Inner Mongolia, China (Zhang et al, 1982)).

Table 4-1 Total global cumulative metal demand from 2000 until 2050 in the TS 2050. The cumulative demand was calculated by linear interpolation between the yearly demand for these metals in the actual year 2000 and the yearly demand for these metals in the TS 2050. The data on the economic reserves were mostly based on data given by the USGS 2015. The data on Indium reserves were taken from the USGS (2007). Economic reserves for neodymium were based on aggregated rare earth reserves (USGS, 2015) and a rough estimate of the neodymium content of the rare earth ore currently processed in China (Zhang et al, 1982), the main supplier of neodymium.

Element	Unit	Cumulative demand until 2050 – TS 2050	Economic reserves ≈ 2014	Demand/reserve
Fe	kg	1.63×10^{13}	8.70×10^{13}	0.19
Al	kg	2.58×10^{12}	7.41×10^{12}	0.35
Cu	kg	1.16×10^{12}	7.00×10^{11}	1.65
Ni	kg	4.46×10^{10}	8.10×10^{10}	0.55
Cr	kg	7.46×10^{11}	1.64×10^{11}	4.54
In	kg	6.25×10^{7}	2.80×10^{6}	22.33
Nd	kg	1.99×10^{9}	9.56×10^{9}	0.21
Li	kg	5.13×10^{10}	1.35×10^{10}	3.80

Interestingly the high mark for cumulative demand of iron, aluminium, nickel and neodymium until 2050 can be met by the currently know economic reserves of metals. It does not mean that no further development of mines is necessary but mines can probably provide these metals at roughly the same price as of today, because future demand can be satisfied by current known economic reserves. A more precise analysis can be made if supply curves are available but has not been carried out within the scope of this study. For copper, chromium, indium, and lithium the current economic reserves as known today are not sufficient to provide the cumulative demand for metals until 2050. Metal prices have to increase or improvements in mining and refining technology have to be made to be able to expand the economic reserves to be able to satisfy cumulative demand until 2050 for these

metals. These economic reserves have to double for copper and increase twenty times for indium.

This yearly expansion rate of the economic reserves of copper, chromium and lithium by technological progress and/or price increases, needed to be able to satisfy cumulative demand until 2050 is modest, between 1.4% and 4.3%. However for indium this increase is 9% per year. Indium is a special case however. It is only produced as a by-product of zinc refining. Most zinc refineries do not yet extract indium in their process while they might do so if the price of indium increases, then expanding their supply.

The cumulative demand/economic reserve ratio given in Table 4-1 is based on our uncertain but likely high mark for metal demand in 2050 and uncertain but probably low mark for economic reserves available in 2050. All in all it suggests that the availability of metals is not an essential bottleneck for the development of successful climate policies. A previous study on future supply and demand of lithium reported by Gruber et al. (2011) conclude, like we do, that lithium availability will not constrain the electrification of the automobile during the present century. Moreover it seems likely that iron, aluminium, nickel and neodymium can be supplied in 2050 at the same price as of today. Nonetheless these results are not a reason for complacency; mines have to be developed, and for some metals the economic reserve has to be expanded. There might be substantial challenges to expand the supply in a timely manner or there might be regulatory, political or market barriers to do so which will be further discussed below.

4.3 Supply rate constraints

As discussed in Section 4.1 the demand for metals increases up to a factor 4.2 for Lithium which is likely a high estimate. In Section 4.2 we saw that current economic reserves are sufficient for the supply of iron, aluminium, nickel and neodymium. For copper, chromium, indium and lithium the economic reserves have to be expanded. While the yearly increase in the supply needed to satisfy the demand are quite modest compared to recent historical data, there are reasons not to be complacent.

o   The opening up of a large deep open-cast mine can take decades. If the metal supply has to increase in a decades time, investments have to take place now while the return on investment is uncertain.

o   Expanding mines, even if it is to exploit current economic reserves, has negative local environmental consequences. Especially if these reserves are located in fragile environments.

o   For some metals new resources have to be found, possibly with lower metal ore concentrations than are currently available. Extracting metals from ore bodies with lower metal concentration means that more energy, water and auxiliary materials are needed to extract the metal leading to higher environmental impacts associated with

the mining of these new resources. In addition there will be extra local environmental impacts as well. Efficiency increases will counter these effects, more, or less.

How fast mining capacity can be expanded is difficult to envisage. Although in general the rate of expansion needed to keep up with supply is similar to historical rates of expansion as found for aluminium and iron, short term imbalances between demand and supply may occur, see also Section 4.4 and 4.5.

The uncertainty about return on investment will mean that mining corporations will be very cautious opening up new mines, especially in case of long gestation periods to full production. Uncertainty can be reduced, although very partially, by providing convincing long-term climate policy pathways. However as we have seen the demand for metals is for a large part driven by changes in infrastructure and ICT and not by changes in the energy system.

Providing high quality public information on the coupling between climate policy pathways and expected demand for metals is essential for mining companies. Only by reducing the uncertainty about their return on investment, can they react to future changes in the demand for metals.

4.4 Regulatory and political barriers

Opening up new mines by definition means additional environmental impacts. These range from severe local environmental impacts as well as upstream impacts in the form of additional use of energy, water etc. Large open cast mines will forever change the way the landscapes look like. To keep the local environmental impacts within acceptable limits, governments may restrict the development of resources, driving up the price of the mining activities. On the other hand governments, in the search for extra revenues, might push the development of new mines, giving less attention to environmental and labour issues.

The links between resource extraction, energy use and water resource use has been called the mineral-energy nexus (Giurco et al., 2014). Future regional food and water stress and political instability might make (economic) reserves unavailable creating a bottleneck in the supply of metals. Bleischwitz et al (2013) made an analysis of resource-rich countries with relevant reserves of strategic reserves that are politically unstable and where future food and water stress is likely. In these countries resource-driven conflicts that may be triggered by food and water shortages might escalate into socio-economic breakdowns with subsequent interruption of the supply chain of metals (Bleischwitz et al., 2013). An example of such a situation can be found in the Niger delta. The results of the analysis by Bleischwitz et al., indicates that the likelihood of such interruptions is quite large. About 15 countries are at high risk of supply chain interruptions which might affect lithium, copper, nickel, cobalt, bauxite, iron and platinum.

To be able to better get to grips with the long-term mineral – energy nexus and broader sustainability issues surrounding resource use, Giuarco et al. (2014) proposes a research agenda that includes (1) taking a longer-term perspective (2) really take the linkages between resource extraction energy use and water use into account (3) responsible mining initiatives (4) mastering recycling technology in countries where the end use takes place.

It is highly uncertain how regulatory and political barriers might influence the supply rate of metals. A level playing field for all mining operations seems to beneficial as it will make sure that the resources that can be developed with the least environmental impacts are brought into operation first.

4.5 Markets and corporations

Commodities that can only be produced with large upfront investments, investments that are only recouped in decades time, are naturally produced by a few global firms. Only these very big corporations are able to bear the large upfront investments in uncertain markets. Computer chips, fossil fuels and metal resources are examples of such commodities. Thus there is a natural tendency to form oligopoly or even monopoly market forms. By creating an oligopoly or monopoly market form uncertainty about future market prices are reduced because they can be influenced more or less by reducing or increasing supply.

It is important to note that many basic commodity suppliers are state-owned or are closely tied to the state. The behaviour of the mining corporations might therefore not be influenced by market forces alone but also by political interests. Political interests might try to stifle foreign competition or create more favourable market conditions for their own industries.

The natural tendency to form oligopolies or monopolies, although beneficial for the mining corporations, has its drawbacks. First of all, the corporations will seek out the best return on investment which will likely drive up prices for metals needed in the energy transition. Moreover metal supply might be supplied to certain industries creating barriers to a low carbon economy.

In a competitive market with multiple suppliers, metal prices will likely fluctuate strongly.

4.6 Substitutability

4.6.1 Elemental and resource substitution

There are two reasons to substitute one element for another. One is that the alternative element provides extra functionality. The second is that the alternative element is cheaper but often at the cost of functionality. Innovation often leads to elemental substitution improving the characteristics of materials. As a response to the threat of material scarcity most of today's scientific and engineering research is aimed at elemental substitution.

Elemental substitution holds great promise to alleviate metal resource constraints specially if the alternative element is an abundant element such as carbon.

4.6.2 Functional substitution and dematerialization

Examples of functional substitution are the replacement of photographic film by digital photography and the replacement of paper mail and fax by email (Kleijn et al., 2012). In general the relative importance of materials has changed considerably in the economy some increased and other decreased. However in absolute and per capita terms. the consumption has increased. The amounts of stone and bronze and iron we use now is much higher than in the ages named after these materials. This is the same for energy. Oil and natural gas have not in absolute terms replaced coal. They have just been additional to coal (Kleijn et al., 2012). Thus it seems that functional substitution has not lead to an absolute decrease in metal resource use in the long-term. However it certainly has contributed to a reduced absolute growth in metal resources. Looking at long term global trends of iron, aluminium and copper ore the period after WWII can be characterised as the period in which metal use per capita increased sharply until the oil crisis in the beginning of the 1970s (Kleijn et al., 2012). Of course, absolute ore production increased also because population grew as well. From the beginning of the 1970s until the beginning of the 21st century, the

Dematerialisation is used to describe a process that leads to a decrease in the amount of material to fulfil a certain function. There are several ways to achieve this. Two concepts that might lead to dematerialisation are miniaturisation and the service economy.

Miniaturisation has been very prominent in the form of ever smaller and more powerful computer chips as used in electronics and computers. However it is not so clear if this miniaturisation has led to reduced material use from a lifecycle perspective. The amount of energy and materials to create these ever smaller chips has increased. Another mechanism that reduces the effect of miniaturisation is that these smaller devices can be used in ever more appliances creating additional demand for electronic appliances. Miniaturisation created a market for mp3 players but also brought the need for new infrastructures such as 2G, 3G and 4G networks with all its associated metal resource requirements in the form of millions of cell phone towers, land lines and data warehouses.

The service economy also holds out promise for dematerialisation the economy. Car-sharing schemes is one such example. Another example is the use of e-services where newspapers, magazines or books are delivered in electronic form and read on a e-ink device. Not much is known about the reduced metal resource use of service economy solutions but some solutions might lead to 50% less resource use (Moberg et al., 2010).

4.7 Recycling

Recycling can be seen as a way to expand the economic reserves with the stocks that are available within society, so-called urban mining. However up to 2011 less than 1% of the REEs were actually recycled (Binnemans et al., 2013). Recycling rates of rare-earths are so low because the technology to recycle at a cost effective price is lacking and because of the diffuse application of the rare earths.

For instance recycling of neodymium from magnets in computer hard drives, a high quality concentrated source of neodymium magnets, cannot be made cost-effective (Sprecher et al., 2014). However it has been established that recycling will always be an improvement over primary production, the large losses of material incurred while shredding the material puts serious doubts on the usefulness of this type of recycling as a solution for scarcity. Furthermore, our LCA also shows that technological progress can make a significant difference in the environmental impact of producing neodymium magnets from primary sources (Sprecher et al., 2014). In general REE recycling can reduce the environmental challenges associated with REE mining and processing (Binnemans et al 2013).

For bulk metals that are mainly used in infrastructure such as iron, aluminium and copper current recycling rates are already significant and the build-up of infrastructure (at least in the Europe and America) has for a large part already taken place. Recycling of in these cases can be an important supply source in 2050. Pauliuk et al. (2013) examined steel supply and demand for the 21st century and predicts that secondary steel production will more than double by 2050, and it may surpass primary production between 2050 and 2060. Recycling of iron could therefore lower the demand for iron ore significantly.

In 2010 secondary aluminium could already supply 30% of global demand and it is expected to supply 30% of global demand by 2020 (International Aluminium Institute, 2009) thus lowering the demand for primary aluminium.

In our model we have a poor view on recycling cycles and hence primary demand. However this shortcoming only strengthens our conclusion that supply can keep up with demand because demand is overestimated. Nonetheless for a better insight into future primary supply it is essential to integrate primary and secondary supply in scenarios and to establish inter-linkages with macro-economic modelling.

While recycling does not seem to alleviate rare earth bottlenecks in the near future because so little rare earth waste leaves the economy at the moment compared to demand (rising demand and long life times of products imply that the amount of rare earths in the waste stage is a fraction of primary demand). So the recycling rates are low compared to primary demand. Yet, it is important to invest in the technology. In a steady-state economy, recycling can be an important source of supply while likely having smaller environmental impacts.

For bulk metals, recycling is already important and likely will become a dominant source for metals by 2050. However important issues remain such as the quality of the recycled metals (Nakamura et al., 2012). More research is needed to see in how far secondary sources can provide high quality alloys.

4.8 Missing information

Additional research is needed on the metal requirements of the energy technologies like bio-energy, with and without CCS and combined heat and power (CHP). However the amount of CHP that is required is so low that it will probably not have a significant impact on the results. Additionally data needs to be found for the metal requirements of iron and aluminium of nuclear electricity.

Furthermore, more general data could be found for some of the energy technologies, since some of the metal requirements are based on case studies, such as for advanced solar power and PV iron and aluminium requirements. This can also explain why the requirements for iron and aluminium of PV are so high in comparison to the other energy technologies.

For a lot of rare earth metals the analytical framework could not be fully completed, keeping open the possibility that future supply and demand of these metals are a bottleneck.

In addition the research might not include the data requirements for all subtypes of the types of energy, like the data for iron and aluminium for wind energy, which is based on a research that focuses on onshore wind and does not take into account offshore wind.

Nevertheless, in any investigation the results of the metal requirements are always influenced by the decisions made in the research such as the system boundary, lifetime, location, etc. Because the requirements are based on researches performed by others, there will be a large variation in these assumptions between the different studies.

Another point to be considered is that installing most of the electricity forms require large amounts of metals in the installation and mostly only a little amount of metals during operation. Since the scenarios only look at a single year it is very well possible that the required metals were already necessary during installation earlier than 2050. An alternative to solve this issue is to investigate the required extra electricity capacity.

The results of this research can be used to estimate the global demand of metals if it is combined with the growth and demand of metal requirements of other sectors. As mentioned earlier a development that needs to be considered and is described in the scenarios is the application CCS to other forms of industry. When estimating metal demand in the future, this can then be used to compare with current metal production and how much this needs to be scaled up to fulfil this demand, so that possible metal constraints can be identified.

5 Conclusions

Demand and supply of metals until 2050 under influence of successful climate policy is highly uncertain. By examining corner cases it can be established that for iron, aluminium, nickel and neodymium the supply until 2050 will probably easily keep up with demand. If there are no regulatory and/or political constraints for expanding current mines or exploiting new economic reserves, it is likely that the prices of these metals will not increase substantially in the long run. For several rare earth metals the analytical framework could not be fully completed, keeping open the possibility that future supply and demand of these metals constitute a bottleneck.

Providing high quality public information on the coupling between climate policy pathways and expected demand for metals is essential for mining companies to react to future changes in the demand for metals and might reduce their uncertainty about their return on investment.

A level playing field for all mining operations seems to beneficial as it will make sure that the most attractive resources that can be developed, with the least environmental impacts are brought into operation first.

Oligopolistic or monopolistic market tendencies have to be counteracted to prevent build-up of too much power to influence markets, specifically if the oligopolistic/monopolistic firm has close ties to governments. In a competitive market metal prices will likely strongly fluctuate.

Recycling of the rare earths likely will play a small role in the supply of rare earths. Recycling rates will likely be rather low the coming decades because of the diffuse application of these metals in difficult to separate matrices. Also as long as society is building up stocks in the form of products in use, the return flow can only be modest in comparison with the new supply. For bulk metals, secondary sources are already important and will become more important or even dominant by 2050. It is important to get a better view on the long–term amount and quality of secondary sources, possibly by integrating primary and secondary supply in scenarios and link this to macro-economic modelling.

Elemental substitution can play a large role in diminishing (temporarily) the need for some metals.

- The most policy relevant conclusions are: Predictability of effectiveness of climate policy is a key factor in having adequate future supply, especially for metals where lead time to new mine production is long.
- Public research on substitution options for highly critical metals can reduce constraints.
- Functioning global markets reduce supply risks of critical metals, especially as compared to bilateral contracting.

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