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METAL DEMAND FOR RENEWABLE ELECTRICITY GENERATION IN THE NETHERLANDS

Navigating a complex supply chain

COLOPHON

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INDEX

SUMMARY

The current global supply of several critical metals is insufficient to transition to a renewable energy system. Calculations for the Netherlands show that additional wind turbines and PV panels already require a significant share of the annual global production of some critical metals.

Looking at the global scale, scenarios in line with the Paris agreement goals require the global production of some metals to grow at least 12-fold towards 2050, compared to today's output. Specifically, the demand for neodymium, terbium, indium, dysprosium, and praseodymium stand out. This calculation does not include the demand for these specific metals in other applications, such as electric vehicles or consumer electronics.

Safeguarding critical metal supply

The global energy transition requires a rapid and global roll-out of renewable energy technologies. Safeguarding the supply of the required critical metals needs greater attention, since supply and demand cannot be guaranteed through a free market. Mining of the required ores takes place in a few select countries, and refining of these ores is concentrated in even fewer countries. Geopolitical powers will shift from oil-dominated countries to critical metal-dominated countries.

A second important issue is the slow rate of scaling of critical metal production: opening a new mine takes 10 to 20 years, and large capital investments. A rapid increase in global demand will therefore be hard to meet with a rapid increase in global supply. Mining corporations require a global, long-term investment assurance to be able to fund new mining and refining activities.

Complex supply chains

The supply chain of critical metals is extremely complex. Not all theoretical reserves are technically (or economically) extractable, and with decreasing ore grades, mining requires an increasing amount of water and energy. Furthermore, mining is often associated with significant environmental and social costs.

Scarcity in supply will lead to increased competition, both among applications and among countries. Due to increased use globally in all these applications, interdependencies will further increase every year. Shortages or hiccups in the supply chain could hamper the energy transition: a delay we cannot afford from a climate science perspective.

Directions for solutions

To ensure a sufficient metal supply, a global and robust climate policy needs to go hand-in-hand with circular economy strategies to reduce critical metal dependence.

To avoid future scarcity, three directions for solutions are identified:

- **Reduce critical metal use through substitution:** increase substitution efforts, to be able to produce renewable electricity with a smaller need for critical metals. Substitution alone is however not sufficient and might shift the burden to other metals.
- **Increase circular design and recycling efforts:** include circular design principles in the production of wind turbines and PV panels, to enable future reuse of components and materials after the technical lifetime. Also, increase recycling efforts (technology and knowledge) to be able to retrieve metals for which physical disassembly is not possible.
- **Consider a European mining industry:** Europe is almost completely dependent on foreign supply of critical metals, although the continent has some reserves. Mining in Europe will be confronted with administrative and social hurdles, but high-tech solutions can help overcome these.

Towards a truly sustainable energy system

Implementing the Paris Agreement, global efforts are made to move towards a renewable energy system. Sustainable use of resources, required for this energy system, should be part of that effort. The construction of a renewable energy system and the transition towards a more circular economy are therefore part of the same agenda: working towards a truly sustainable energy system, that enables humanity to thrive for the decades to come.

INTRODUCTION

In 2015, all countries agreed to limit the global warming to a maximum of two degrees Celsius. The national contribution of the Netherlands is currently being determined in the *Klimaatakkoord* (hereafter: Climate Agreement). This agreement includes an increase in the production of renewable energy. A large share of this renewable energy will be renewable electricity, produced by solar panels and wind turbines.

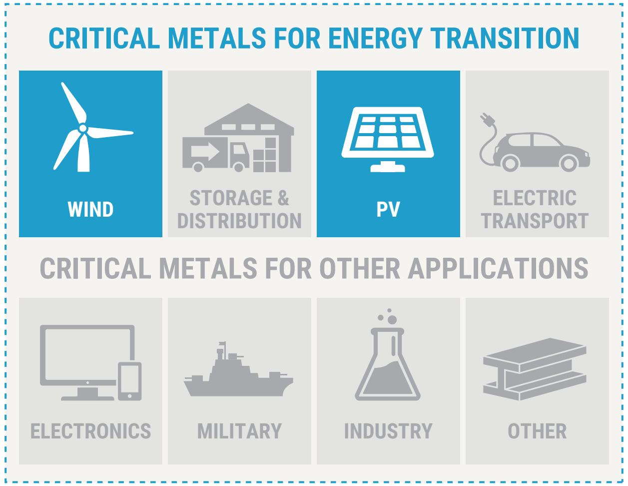
Main issues

A number of important issues need to be solved in order to achieve the energy transition at the speed necessary to reach renewable energy targets. Examples of these issues include spatial planning (where can we place our wind turbines and solar panels?), operational execution (do we have sufficient technicians to install and maintain the installations?), and the financial challenge (who is going to finance the renewable energy supply?).

Perhaps the most significant issue, however, is related to materials: how do we source the materials we need to build the renewable energy production capacity? The world is increasingly dependent on a group of specific rare earth elements and other minor metals that are required for nearly all renewable energy technologies: for example, neodymium in wind turbines, tellurium in solar panels, and platinum in fuel cells.

Scope: critical metals for wind & solar

In this research, we focus on the demand for rare earth elements and other critical minor metals (which we henceforth will collectively refer to as critical metals), for renewable energy in the Netherlands. We will limit ourselves to **solar** and **wind** technologies, since these are expected to provide the bulk of the electricity in the future according to the Climate Agreement. We take the goals for 2030 from the Climate Agreement outlines (in Dutch: *Hoofdlijnen Klimaatakkoord*).[1]



This research focuses on critical metal demand for renewable electricity production through solar panels and wind turbines.

Out of scope: storage, transport and infrastructure

A renewable energy system requires more than just renewable electricity production. The inherently intermittent nature of energy sources, such as PV and wind, require a significant amount of buffering. The material requirements of the energy-buffering infrastructure will be very significant.[2] Additionally, the transport sector will have to move to zero-emission vehicles, which also includes significant critical metal use. Finally, a stronger and more resilient electricity grid is needed to ensure a stable power supply: for this, critical metal needs increase as well.

All these aspects (storage, transport, infrastructure) are left out of scope for this study. Not because these aspects are not important for the future energy system, but because a lack of targets and high uncertainties in technological developments. This makes it hard to determine accurate estimates, and would lead to unwanted inaccuracies. The application of more common metals (e.g. iron) is out of scope for this study as well. In general terms one can expect that the problem of metal scarcity will only grow when these other applications and other metals are also considered.

A new age

The road to renewable energy supply leads us out of the oil age. This is good news for everyone who thinks we should be less dependent on fossil fuel-producing countries. What many don't realize however is that with this transition we enter a new age, one where geopolitics is at least as important as now – the age of critical metals.

Acknowledging how little we know of the new dependencies facing us is an important first step. With this publication we primarily want to contribute to that awareness. We also provide some directions for solutions.

ENERGY TRANSITION AND CIRCULAR ECONOMY IN THE NETHERLANDS

The Netherlands has a goal to be almost climate neutral in 2050; the aim is to emit 95% less CO_2 compared to 1990. In 2030 the country aims to lower CO_2 emissions by at least 49%, and possibly as high as 55% – depending on the ambition of the rest of the EU. This requires enormous efforts in many areas: industry, built environment, agriculture and land use, transportation, and electricity supply. At present, negotiations are being held with key stakeholders in these five areas to deliver the national Climate Agreement.

In addition to becoming climate neutral, the Netherlands aims to be circular. Goals have been set for this ambition as well: the country wants to be 100% circular in 2050. Although it is difficult to find a clear measure for ‘circularity’, the goal is to reduce primary raw material use by 50% in 2030. The growing dependence on raw materials was one of the reasons for this agenda, as well as the rapid increase in raw material use. According to the nation-wide national circular economy program,[3] “of the 54 critical materials for Europe, 90% is imported, mostly from China. The Netherlands imports around 68% of its raw materials from abroad.”

The two transitions, energy and circular economy, are intertwined: both are required for a sustainable and prosperous world in the future. They are also conditional for each other’s success: sustainable resource use is required for meeting the material demand of the energy transition, and renewable energy is required for reusing and recycling materials in a truly sustainable way. Circular economy can make a contribution to the climate agenda, among others by reducing raw material use and the associated production processes.

Electricity production in Climate Agreement

In a baseline scenario, the Climate Agreement outlines set the ambition of 49 TWh of renewable electricity production through offshore wind in 2030. This implies a total amount of approx 1,460 wind turbines at sea, assuming the use of 8MW turbines. Moreover, there is a 35 TWh goal for renewable electricity production on land, a load which will be shared between PV and wind turbines. Note that these are intermediate goals; renewable electricity production will need to further increase by 2050.

In addition to this base scenario, there are possibilities for even higher renewable electricity demands. Should a harder push for electrification arise, for example in the heavy industry, the 84 TWh production target would increase to 110 TWh. A higher emission reduction target of 55% requires no less than 120 TWh of renewable electricity in 2030. This implies a significant need for critical metals.

Circular agenda for manufacturing industry

The *Transition Agenda* for the manufacturing industry[4] outlines plans to move towards a circular manufacturing industry, developed by stakeholders in the sector. This agenda focuses both on different product design, increasing recycling efforts and changing incentives and regulations to increase product performance and extend lifetimes. Regarding critical metals, the agenda aims to develop an estimate of future critical metal demand and develop a multi-year program on substitution of these metals. These are important steps in the light of this study.

When estimating our critical metal demand, it is important to realize that the Netherlands is a net importer of many components, including for wind turbines and solar panels. Critical metals are often already contained within these components. The Netherlands is and will remain dependent on other countries for the production of these components, even when it manages to build up its own assembly industry for renewable electricity technologies.

METAL DEMAND FOR WIND TURBINES AND SOLAR PANELS

Both wind turbines and solar panels use a variety of critical metals for a range of specific functions. This research therefore focuses on three aspects:

1. **Demand:** What is the volume of critical metals required by the Netherlands for its renewable electricity production?
2. **Origin:** Where are these metals originally mined?
3. **Technologies:** Which metals are used in the various technologies, and at what ratios will these technologies be deployed?

Total metal demand

To realize the electricity production targets set for 2030, the Netherlands would require some 2.4 to 3.2 million tonnes of metal. For the final situation in 2050, that demand quadruples to 8.6–11.7 million tonnes. The vast majority of this demand –about 87% – consists of iron and steel for the foundation and shaft of wind turbines. Elements such as silicon, copper, lead, and zinc will also see a significant demand increase in absolute terms. However this increase is limited in relative terms because these elements have been used in large quantities for decades, and therefore have sufficient reserve and supply.

Critical metal demand

In this study we focus on the 22 most common metals in wind turbine and solar technologies. Most of these metals are either rare earth elements or minor metals, and as such are subject to possible supply constraints. The figures on the following pages bring to light four aspects of critical metal application in renewable electricity production:

- Figure 1 shows the required annual demand of these 22 metals for the Dutch energy transition, compared to their global annual production.
- Figure 2 shows the future global demand for six specific critical metals, required for wind and PV, compared to their present annual production.
- Figure 3 shows the origin of these metals, focusing specifically on the location of the mining activities (or to the refinery location, in the case of by-products).
- Figure 4 shows the metal demand for specific technologies.

Competition with other applications

Critical metals have many applications besides solar and wind energy. For example, neodymium, dysprosium, and praseodymium are also crucial in electric vehicles. Moreover, neodymium is used in various electronic equipment, e.g. hard drives and loudspeakers. A minor metal like indium, which is used in solar panels in the form of Indium Tin Oxide (ITO), is also used for other common applications such a LCD-screens.

We have purposely excluded other applications of these metals in the calculations of this report. Despite this choice of scope, it is crucial to include this metal demand to determine a yearly metal demand. When other applications are included, it becomes even more clear that metal availability will become a key issue on the short term. As an illustration, consider that if electric vehicles were included in the scope of this study, the combined annual neodymium demand would almost double to 4% of the global annual production.

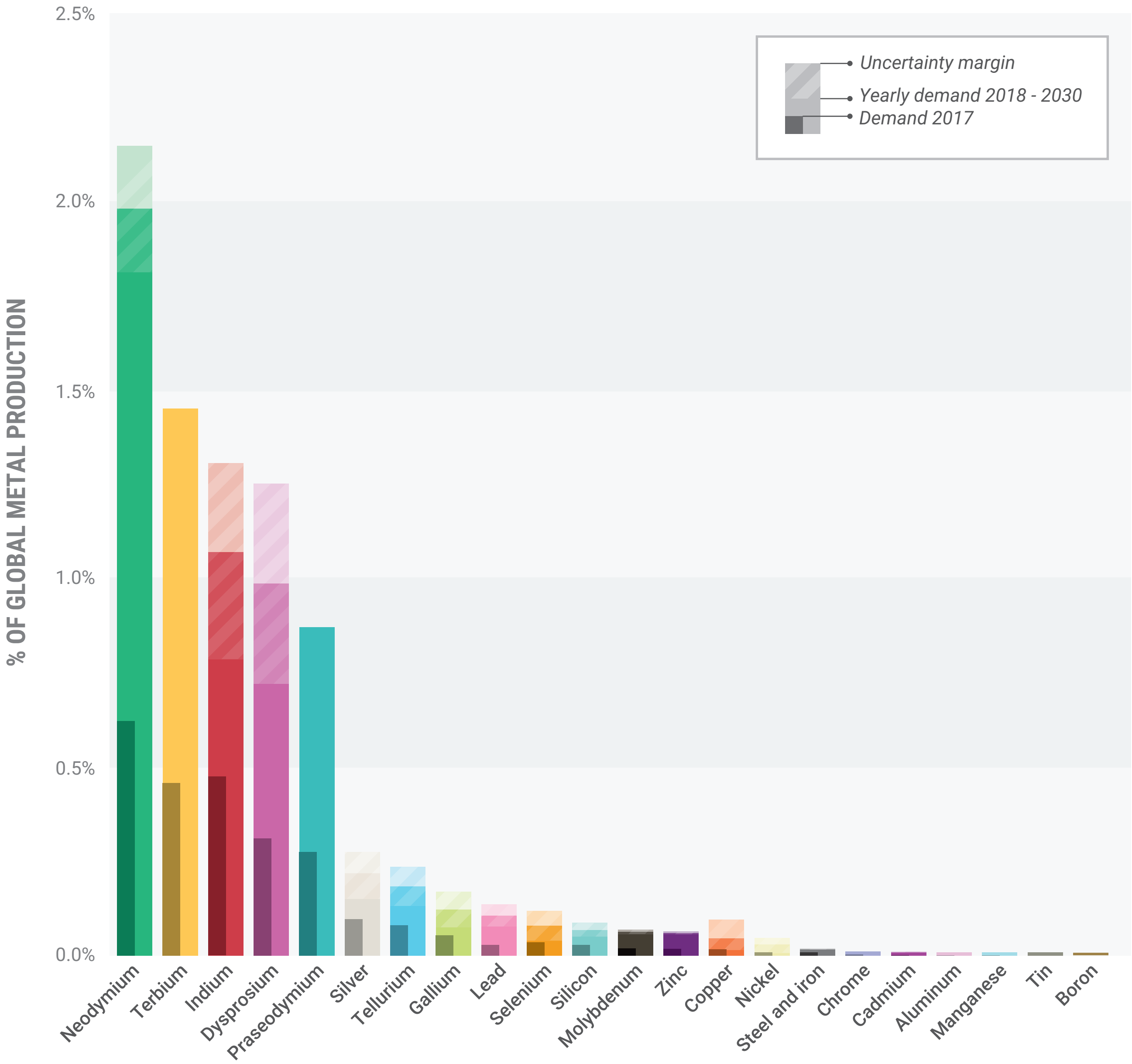
Scarcity will eventually lead to competition between different technologies; and therefore, between companies and countries. This is a serious risk for the transition towards a clean and sustainable energy supply, both within Europe and the rest of the world.

Example: Neodymium in electric vehicles

Neodymium demand is expected to increase dramatically. Neodymium is used for permanent magnets in wind turbines, but also in electric vehicles. Strong demand for neodymium from electric vehicles could influence neodymium supply for wind turbines, and vice versa.

As an example: we assume – conservatively – that the Netherlands will have about 1.2 million electric cars in 2030, resulting in an average demand of 100,000 electric cars per year. With a neodymium demand of 1.46 kg per car, that results in a total demand of 146 tonnes per year. In addition to the results within the scope of this study, the Dutch demand for neodymium - only related to the energy transition - would amount to 4% of the global annual production.

Besides neodymium, electric vehicles will also need large amounts of lithium and cobalt for their batteries. The total lithium and cobalt demand for electric vehicles is expected to increase by a factor of 25 towards 2050.[5]



Metal demand for Dutch renewable electricity production

This chart shows the average annual metal demand (for 22 metals) required for the installation of new solar panels and wind turbines. This assumes a linear installation of capacity. The annual metal demand is compared to the annual global production of these specific metals, resulting in an indicator for the share of Dutch demands for renewables in global production.

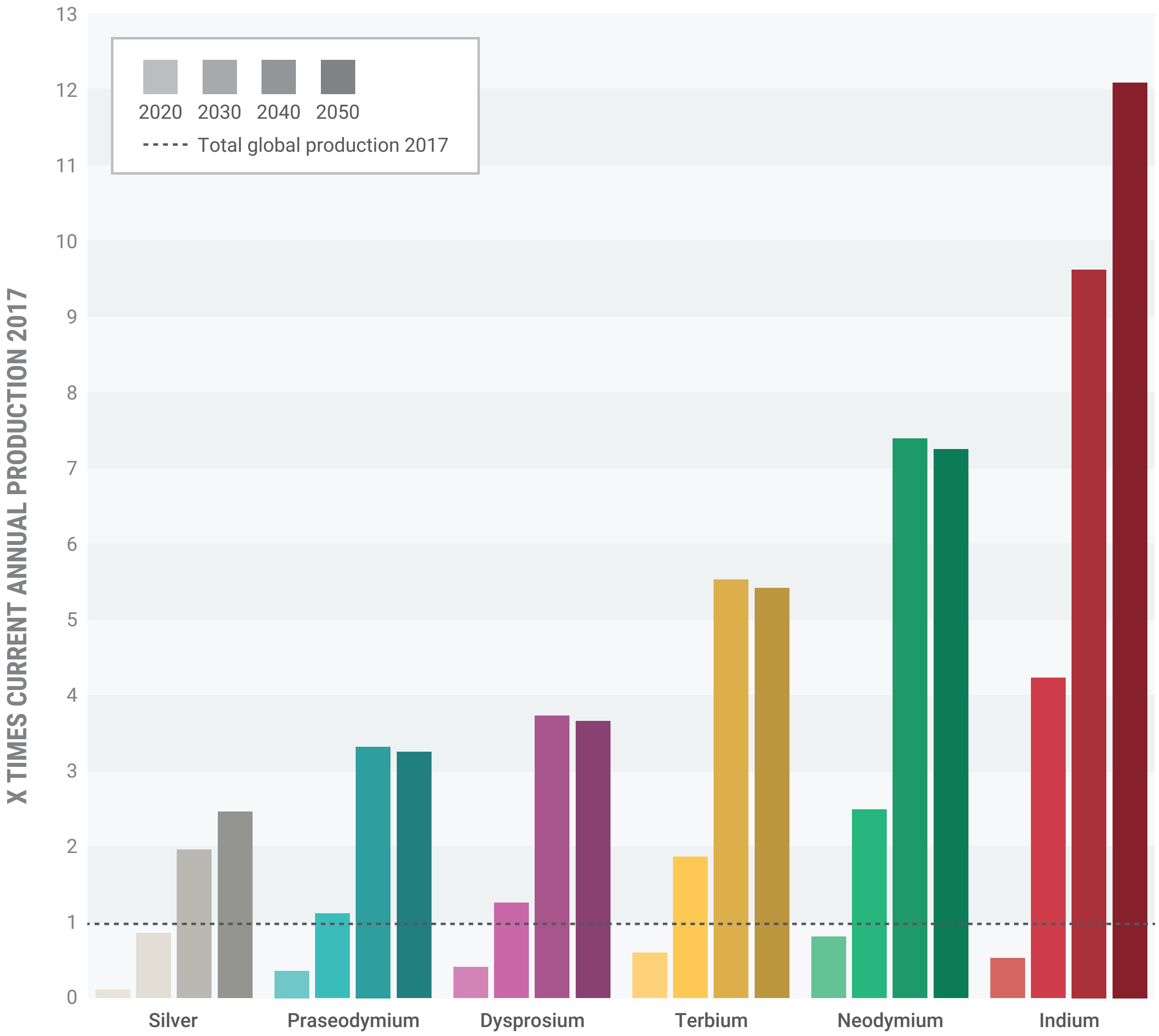
Conclusions

- For five of the metals, the required demand for renewable electricity production capacity is significant: neodymium, terbium, indium, dysprosium, and praseodymium.
- If the rest of the world would develop renewable electricity capacity at a comparable pace with the Netherlands, a considerable shortage will arise.
- When other applications (such as electric vehicles) are also taken into consideration, the required amount of certain metals would further increase.

Method

The renewable electricity targets for 2030 serve as the starting point for the calculations. Based on these targets, the annual installed capacity is calculated. The metals required for this capacity are shown as a percentage of the annual global production.

Figure 1: *The average annual Dutch metal demand for wind turbines and solar panels for the period 2018-2030, compared to the annual production in 2017.*



Global critical metal demand for wind and PV

When considering a global perspective, the critical metal demand for our future renewable electricity production is significant. This graph shows the annual metal demand for the six most critical metals, compared to the annual production. The dotted line represents present-day annual production.

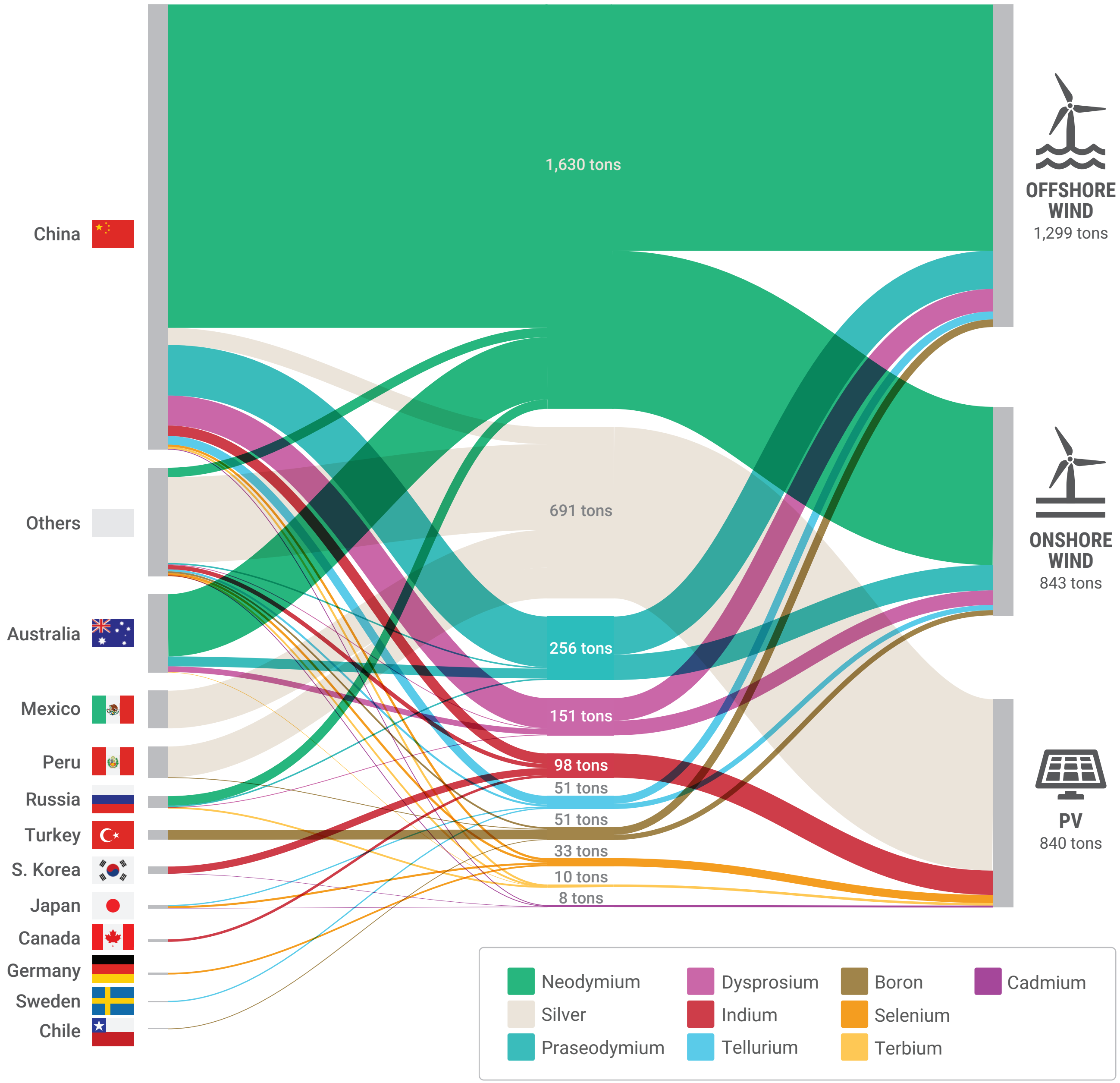
Conclusions

- Future annual critical metal demands of the energy transition surpass the total annual critical metal production.
- An exponential growth in renewable energy production capacity is not possible with present-day technologies and annual metal production. As an illustration: in 2050, the annual need for Indium (only for solar panel application) will exceed the present-day annual global production twelvefold.
- To be able to realize a renewable energy system, there is a need to both dematerialize renewable electricity production technologies and increase global annual production.

Method

The growth curves of global wind and PV capacity are based on the IPCC SR15-models which project a temperature rise below two degrees.[10] Averaging these models results in a projected capacity for both wind and PV. Subsequently, per unit of installed capacity, the critical metal demand was calculated.

Figure 2: *Annual global critical metal demand for wind and PV, between 2020 and 2050, compared with the annual metal production index (2017 = 1).*



Origin of critical metals

This diagram shows the origin of the metals required for meeting the 2030 goals. The left side of the diagram shows the origin, based on today's global production of metals. The right side shows the cumulative metal demand for wind and solar technologies until 2030.

Conclusions

- The Netherlands is entirely dependent on countries outside of Europe - and mainly on China - for its critical metals.
- Not only is the main share of current production located in China, the country also hosts refinery facilities for many metals.
- Australia and Turkey are also important countries for the extraction of specific metals, particularly neodymium (Australia) and boron (Turkey).

Method

The renewable electricity capacity required is calculated from the goals in the Climate Agreement outlines. This capacity is then translated to a metal demand. The ratio of world production is based on the annual production statistics of 2017.[6]

Note: *This diagram shows the mining origins of metals. Four metals (indium, cadmium, tellurium and selenium) are extracted as a companion metal and are refined as a byproduct of another metals refinery process. For these the location of refinery is shown.*

Figure 3: *The cumulative demand for a selection of critical metals until 2030, showing the origin (left) and technology (right)*

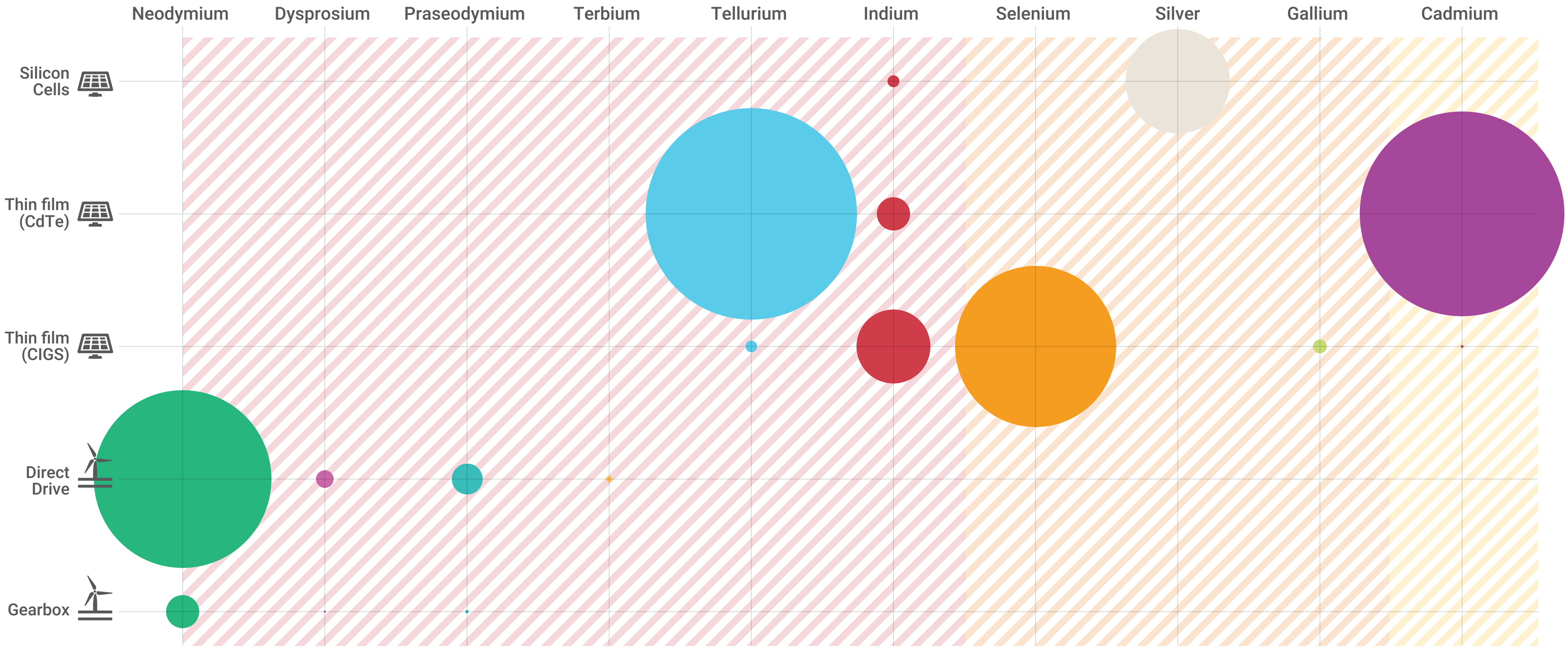


Figure 4: *Metal demand of various renewable electricity technologies per unit of electricity production (kg / MWh). The background colors show the annual demand for the Dutch wind and PV capacity, as percentage of the global annual production*

>1% of global production >0.20% of global production >0.025% of global production

Metal demand per technology

There are various technologies available for the production of electricity through wind and solar. Each technology requires different amounts of critical metals. This figure shows the metal demand for the five most common technologies.

Conclusions

- Newer technologies are often more efficient and cheaper, however, they rely on the properties of critical metals to achieve this.
- Thin film cadmium-tellurium solar PV cells have the best performance in terms of CO_2-emissions and energy payback times. They do however require large quantities of tellurium and cadmium, and tellurium is one of the rarest metalloids.
- Direct-drive wind turbines use neodymium-dysprosium based permanent magnets. They are more expensive to produce, but cheaper in their exploitation phase. Gearbox turbines require less critical metals, but are generally understood to have higher maintenance costs because they have more moving parts. Gearbox turbines also have a shorter energy payback time.

Method

The average metal demand per unit of electricity is calculated based on load hours in the Netherlands.[7–9] The entire lifespan of the specific technologies has been taken into account.

CRITICAL METALS: FIVE PERSPECTIVES ON RESERVES

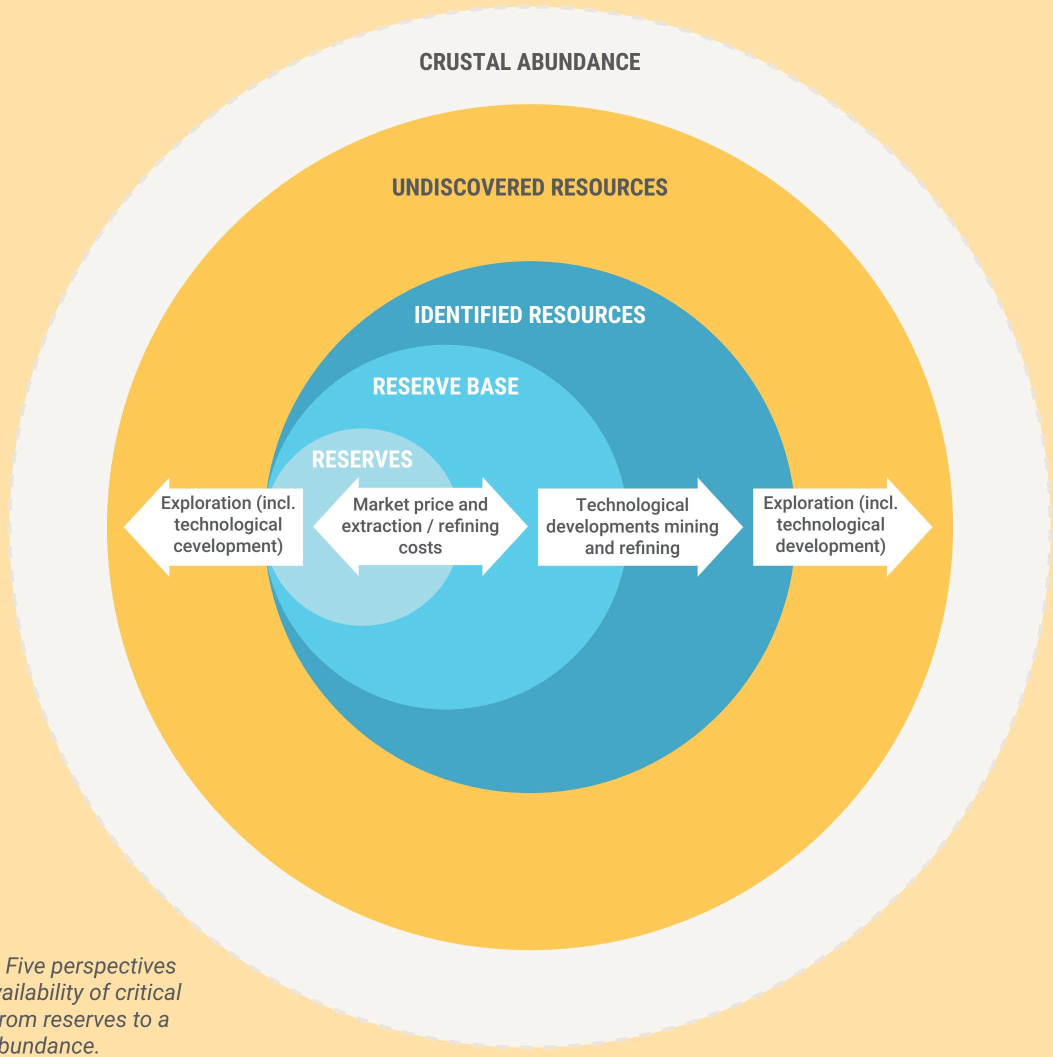


Figure 5: *Five perspectives on the availability of critical metals: from reserves to a crustal abundance.*

One of the most frequently asked questions about mineral resources is: "how much do we have left?" One could start by asking: "how much do we have in the Earth's crust?" Although this question can be answered, it is in fact irrelevant. If one would want to know how much, for example, copper is be available for future generations, the right question to ask is: "how much copper can we still extract from the Earth's crust?"

The American geologist Brian Skinner[11] noted that almost all of the metal that is available in the Earth's crust is embedded in common rock, such as granite atomic substitutes. Commercial mining is aimed at ore bodies in which metals have been concentrated through geological processes. Although the concentration of metals in common rock is very low, the sheer amount of common rocks in comparison to these concentrated ores makes this by far the largest reservoir of metals. For all practical purposes we can exclude this reservoir from the assessment of the remaining resources. The amount of energy required to extract substantial amounts of copper from granite, as well as the environmental impacts, land and water use, will prevent us from using common rocks as a source of less common metals.

Definitions around reserves

If we want to know what quantity of metals we can still extract from the Earth's crust, we need to focus on the amount available in concentrated ores. In general, the amount of ores that are available can be quantified in five different ways:

- **Reserves** are the ores of which we know can be mined under current market conditions.

- The **reserve base** can be mined with available technologies but is not currently economically viable.
- The **identified resource** is the amount of concentrated ores that we know is within the Earth crust.
- There are expected to be **undiscovered resources**, which are not yet known in present resource data.
- The **crustal abundance** expresses all the material of a certain metal, right down to the lowest concentrations imaginable.

Changing market conditions, mining technologies and exploration efforts will therefore influence the size of reserves, reserve base, and identified resources. Therefore, it is difficult to provide a straightforward answer to the question of how much of a certain element we can extract from the Earth's crust.

Time is the most scarce resource of all

The good news is that, for most metals, enough identified metal reserves are available for the energy transition. However, the lead time for opening new mines is in the range of 10-20 years. Therefore, the much more pressing question is if we can make these metals available in the time we have left for the energy transition: about three decades.

Taking into account this slow upscaling of primary production, it makes more sense to compare the metal requirements of the energy transition with current annual production levels. This will generate insights regarding the required upscaling of current mining activities. Regardless of the exact outcome, this much is clear: the most scarce resource of all is time.

Mining versus recycling

Currently, mining of most metals follows a path of exponential growth. Even a moderate growth rate of 3% would double mining production every 25 years. This is clearly not sustainable in the long run. For major industrial metals (e.g. iron, aluminum, and copper), that are used in relatively concentrated form, losses can be limited and recycling is possible.

Demand for these metals has also been shown to level off when economies and applications are mature. An example: the input of iron has levelled off between 1975-2000, after a period of strong growth related to the buildup of urban infrastructure in OECD countries. Once the cities and infrastructure are in place, recycling and thus secondary production can almost keep up with demand.

This picture is quite different for most minor metals (e.g. indium and neodymium): recycling rates are below 1%.[12] Unless a circular strategy is implemented, the industry will remain completely reliant on mining for its raw material supply. To make recycling the dominant source of raw materials, very high recycling rates will be needed.

CRITICAL METALS: A COMPLEX SUPPLY CHAIN

The availability and applications of critical metals are accompanied with large uncertainties. There are many things we do not know about the evolution of the demand and supply of specific critical metals. This uncertainty manifests in different parts of the supply chain: the reserves, the availability, the application, and the recycling. For each step we summarize the factors which result in uncertainty.

PRODUCTION
- Dependency on other metals
- Slow scaling of production

AVAILABILITY
- Protectionism
- Environmental factors
- Responsible sourcing

APPLICATIONS
- Substitution difficulty
- Speed of growth

RECYCLING
- Technological complexity
- Availability of secondary material

Uncertainty in mining production

The reserves of critical metals are not always clear, and rely on a number of factors.

- **Dependency on other metals:** A number of critical metals - known as minor metals - can only be produced in combination with other, more common metals. Without the production of these common metals, the production of critical metals is not economically viable. For example, tellurium is a byproduct of the refining process of copper and indium is a byproduct of the refining process of zinc.
- **Slow scaling of production:** Opening a new mine takes about 10 to 20 years. This time is required for preliminary research, the construction of infrastructure, and environmental permits, etc. Therefore, if demand rapidly increases, supply cannot quickly follow suit.

Uncertainties in availability

The availability of a reserve of a specific metal does not automatically mean a free availability for the global market. There are three important factors:

- **Protectionism:** Producing countries are dominant players when it comes to availability of critical metals. Especially China has reduced its exports to attract more industry to the country. After all, the transformation from metals into products or components leads to a higher economic output.
- **Environmental factors:** Mining has significant environmental impact to the mining area. Legal standards on health and environment can increase costs, and even prohibit mining activities, for example recently in the Mountain Pass project (California, US).
- **Responsible sourcing:** An important factor in the critical metal supply chain is the labor conditions under which critical metals are won. Supply chains of a number of metals are known to cause displacement of villages, or include forced labor or child labor.[3]

Uncertainty in applications

The demand for nearly all critical metals is growing, caused by our increasing need for applications which include these metals. This growth occurs primarily in three types of applications: electronics (for the consumer as well as in public spaces), military applications (due to technological development as well as quantity of material), and applications for renewable energy supplies. Two factors determine the largest part of the uncertainty, specifically for renewable energy technologies:

- **Substitution difficulty:** All critical metals have unique properties. Therefore, they are difficult to substitute in the specific application they are used in. Due to the high technological complexity of applications, research in the substitution of critical metals is costly and time-consuming (in the order of decades), and the alternative is often the use of a different critical metal – which will also become scarce in time.
- **Speed of growth:** It is unclear how fast the transition to renewable energy technologies will take place in the coming years. In a speedy transition, desirable in the reduction of CO_2-emissions, chances are that production capacities of mines and refineries will not be able to keep up with the growing demand.

Uncertainty in recyclability

Recycling critical metals seems like a good solution to supplement the growing demand. There are two important factors that determine the uncertainty concerning recycling:

- **Technological complexity:** Recycling critical metals is a complex process. Materials are often combined and alloyed to enhance and create functional properties. This in turn makes them difficult to separate and recover. To illustrate, consider that the Belgian company Umicore, a global leader in recycling, manages to recover only 8 of 25 critical metals from a smartphone. Other materials are lost in the process.
- **Availability of secondary material:** In the upcoming 20 years, the material need for new wind turbines and solar panels exceeds the potential supply from recycling: there is simply not sufficient material to be recycled yet. Therefore, even if recycling efforts are increased, a significant need for primary materials will remain relevant in the upcoming years.

KEY INSIGHTS

The consequences of critical metal application are complex. We have identified four key insights, which are important to take into consideration in policy- and decision-making.

1. Use of critical metals saves energy

The applications of critical metals and the energy transition are more intertwined than it seems at first glance. The application of critical metals often increases efficiency of products, and therefore saves energy.

Examples can be found everywhere around us:

- The use of neodymium and dysprosium in permanent magnets in wind turbines makes generators more efficient, because no electricity is required to induce a magnetic field.
- Addition of niobium enhances the strength of steel, as it increases the strength and carrying capacity of a steel component. Therefore, less steel is required, and less energy is used in steel production.
- Indium, gallium, and selenium are required in LED-lights, which have a much higher efficiency than a regular light bulb.

In our aim to reduce CO_2-emissions, the application of critical metals seems like a wise decision: we save energy and materials in the production phase, as well as saving energy in the use phase. However, if we want to limit our geopolitical dependence on critical metals, we will most likely need to use products with less critical materials, which in turn are often more energy intensive to produce.

2. Limited availability and one dominant supplier limit market freedom

At present, the critical metal reserves seem able to meet the demand. The reserves of metals are however not the impeding factor, but annual production is. Being able to rapidly scale up production to meet rising demand – a principle that lies at the root of the neoclassical economy – does not apply here.

Currently, China is the dominant player in the critical metal production – and its dominance is growing. In the past few years, the country has structurally increased the economic value of these metals: first China developed extraction infrastructure, and consecutively internalized the refining of the raw materials. Now, the country is increasing the production of components and products that require critical metals.

In the coming years the demand for renewable electricity production will increase: not only in Europe, but also in other parts of the world. Therefore, critical metal demand will rise. This puts pressure on availability. The key question is whether Europe will be able to get the critical metals it needs, when supply exceeds demand and resource-rich countries determines to whom they sell.

3. Recycling is a long-term strategy, not a short-term solution

Recycling can only significantly contribute to the reduction of the demand for virgin raw materials when demand is stable, and when the life-time of the products is limited. In the case of renewable energy technologies, neither conditions are met: the market needs to grow rapidly if the 1.5 C goal is to be met, and the lifetime of wind turbines and solar panels is long (~25 years).

This means that recycling can only contribute significantly after the transition is completed to maintain the 'standing stock'. However, since the amount of materials that will be invested is unprecedented, circular design will be required in order of to make sure these materials are not lost at end-of-life.

4. Our dependency increases further every year

Use of critical metals continues to grow at a rapid pace. This is most evident in consumer electronics, military applications, and other technical equipment in industrial applications. The growth of the global middle class from 1 billion to 3 billion people will only further accelerate this growth. Reuse and recycling possibilities will be limited for the next decades as insufficient stocks will become available through recycling of products currently in use: we will therefore remain primarily reliant on new metal production.

In addition, new technologies are being developed around the world, all with unique new functionalities. The fact that most of these new technologies also require critical metals is often not taken into account. New technological developments therefore increase our reliance on critical metals, further increasing long-term supply risks.

DIRECTIONS FOR SOLUTIONS

The application of critical metals is a complex problem. Technical or geopolitical solutions are not easily found. Nevertheless, there are three options to reduce our dependency on other countries, or at least prevent a further increase in dependency.

1. Reduce critical metal use through substitution

If a significant shortage of a metal leads to sustained price increases, products are redesigned to utilize less of the expensive raw metal, or not to utilize these metals at all.

The 2010 price peak of neodymium provides an informative picture of substitution possibilities for renewable energy technologies. Before this price peak, researchers generally assumed that substitution of neodymium magnets was very difficult.[13] After the price peak hit, producers found many ways to either cut down on neodymium use, or substitute it altogether: 20-50% of the neodymium magnet demand was substituted with other technologies.[14] Such substitution also takes place in the wind-turbine market.[15] Wind turbines designed by Enercon feature a novel direct drive mechanism without any neodymium magnets, and manufactures such as Vestas and Gamesa designed hybrid generators containing much smaller magnet-generators coupled to traditional gearboxes.

Besides completely removing permanent magnets through different technological choices, more limited reductions in rare earth element (REE) usage can be implemented: through improved manufacturing processes of REE alloys, and by redesigning wind-turbines so that environmental demands are less stringent. For example, Siemens designed a system to cool the neodymium magnets in the wind-turbine generator, allowing them to reduce heavy REE content from 4.5% to 3%.[15]

While substitution seems a promising solution to material scarcity, there are limits. Using a different technology can completely replace the demand for neodymium magnets, but often leads to suboptimal performance. Improving alloying properties in order to reduce REE need has fewer negative side-effects but seems to be limited to at most ~50% reduction in demand.[14,15]

Using historical substitution rates might also might also overestimate future possibilities. For example, since 2011, improvements in manufacturing processes to reduce process losses have improved yields from 30-60% pre-crisis to 70-85% currently.[15] However, this significant improvement cannot be repeated again if another price shock occurs.

Finally, and perhaps most importantly, substitution does not remove material demand, it merely shifts the burden onto another material. If overall demand is large enough – as seems likely in a global energy transition – then many materials would become scarce simultaneously, which would prove an even more significant challenge.

2. Improve circular design and increase recycling efforts

By applying circular design principles, the lifespan of wind turbines and solar panels can be optimized and components (and metals) can be recycled at high quality.

The first principle of circular design is making products with long lifespans: when wind turbines and solar panels have a longer lifespan, annual metal demand on the long term can decrease. The second principle is modular design, facilitating easy separation of its components. Modular design allows for modifications through easy repairs and upgrades, and also makes high quality reuse possible because components can be renovated at the end of their lifespan. Downcycling or low-grade recycling, where part of the material is lost, is no longer necessary.

For wind turbines, especially for offshore installations, focusing on a longer lifespan seems most important: as turbines keep producing electricity, minimal additional material is required. For solar panels, a focus on modular design seems more relevant: with present technologies, most materials can barely be separated and therefore not be reused. Therefore, recycling technologies are accompanied with significant material losses. Increasing the purity of recovered materials and improving energy consumption related to this recovery are primary areas of improvement in upcoming years.

Reuse of critical metals is still in a state of infancy. High-quality reuse can greatly reduce dependency on virgin sources on the long term: wind turbines and solar panels that are currently being deployed, will provide the materials for the future.

3. Consider a European mining industry

In a world with an ever-increasing hunger for resources, international competition over these resources is inevitable. It is therefore important to think about the security of supply. From this perspective it is of interest to note that, currently, Europe is almost completely dependent on imports of both major and minor metals. An interesting question that has been discussed in the past decade is whether Europe could increase domestic mining and refining activities, as this would be an obvious pathway to security of supply.

If in the future a larger proportion of our ores would have to come from within Europe, we would have to manage the factors that made mining disappear from Europe in the first place: driving down costs while staying within acceptable environmental boundaries. We note that the conditions for mining in the EU are not favorable: deposits are relatively limited, the richest deposits have been depleted in the past, most of Europe is densely populated, public acceptance of mining is low, and labor is relatively expensive. One of the few advantages which could benefit a European mining industry is a relatively strong industry producing high-tech mining equipment.

The European mining industry envisions a future where a mix of remotely controlled and autonomous robots will perform the underground mining, thereby minimizing the required amount of labor, as well as limiting social impacts. It seems, however, that this is still in the realm of aspirations, at least for the next three decades in which we need to make the materials for the energy transition available.

Despite the fact that critical metals are barely extracted in Europe, the continent is home to several reserves: most notably in Greenland and Sweden. *Kvanefjeld* (Greenland) is an area that could supply an annual amount of 31,000 tonnes of rare earth oxides (REO), for a period of 33 years. For comparison: the current annual global production of REO is about 130,000 tonnes. This area contains mainly light rare earth elements (LREE), such as neodymium, but also uranium and zinc. *Nora Kärr* (Sweden), another area with reserves, could produce 6,800 tonnes REO annually, of which 3,600 tonnes would be heavy rare earth elements (HREE). This mine could produce about 15% of the annual global demand of dysprosium.[16]

These mines are currently in the development stage: it could take several years before these mines actually produce any raw materials. Moreover, it is important to not only extract ores, but also develop a refining industry to refine the metals and process them into the technologies we need. This aspect is currently almost entirely done in China.

CLOSING REMARKS

To reach the goals for renewable energy production, as described in the Climate Agreement outlines, the Netherlands requires a significant percentage of the annual global production of five specific critical metals. The case of the Netherlands is illustrative for other countries, both within and outside Europe. As future demand of these metals exceeds the expected supply, the energy transition becomes a vulnerable process. While we are working on reducing our dependence on Arabian and Russian oil, we are creating a new dependency at the same time: a dependency on (Chinese) metals.

This dependency increases risks of future conflict, arising from a growing resource scarcity. These risks further increase when the production of renewable electricity from wind and solar will also scale outside Europe. As we are at present still in an early phase of the energy transition, we are able to take steps to limit our dependency.

There is much that is not yet known about critical metals. By actively stimulating technical research in this area, Europe is able to distinguish itself. It can develop new economic activities, and take the lead in realizing a circular economy for critical metals.

For this research, a number of assumptions have been made and calculations have been carried out. This section explains these steps across a range of four topics:

- Future production capacity of renewable electricity
- Technology ratios for solar and wind
- Critical metal demand per technology
- Current critical metal production

Also, the definitions of terms used are provided here.

Future production capacity of renewable electricity

The goals set in the Climate Agreement outlines have been used as a basis to determine the future production capacity of renewable electricity: 49 TWh offshore wind, and a further 35 TWh of renewable electricity on land – a combination of solar power and onshore wind.

To determine the required capacity of these technologies, the load hours for the Dutch geography have been used:

- 4,200 load hours for offshore wind[7]
- 2,500 load hours for onshore wind[8]
- 875 load hours for PV[9]

The required capacity in 2030 is determined by combining the electricity production and the load hours. We assume a linear growth rate of installed capacity from 2018 until 2030. The starting point for this calculation is the installed capacity at the end of 2017.[17] The total capacity that needs to be installed for 2030 and 2050 is shown in table 1.

	2017	2030	2050
Offshore wind	1	11.7	28.2
Onshore wind	3.2	7.2	16.8
PV	2	19.5	48.0

Table 1. *Assumptions on the total installed capacity of renewable electricity production in the Netherlands in GW*

For both solar and wind technologies, a lifespan of 25 years is assumed. This corresponds with present contracts for offshore wind, and with observed lifetimes for solar panels. Replacement of existing capacity after 25 years is also taken into account - i.e. if 1.3 GW of PV were to be installed in 2020, that same capacity will have to be installed in 2045 on top of the planned capacity increase. Since capacity installation is still ramping up, replacement rate effects will be small until 2030 and will only become more apparent towards 2050.

Technology ratio for solar and wind

Both solar and wind energy can be produced by various technologies, each with their own metal demand per unit of installed capacity. As future technology ratios are difficult to predict, it was necessary to develop a scenario. For the Dutch situation, we have developed a scenario based on a German study,[18] and a European study by the Joint Research Centre.[19] The ratio is shown in table 2.

PV			OFF-SHORE WIND		ON-SHORE WIND	
C-Si	**CdTe**	**CIGS**	**PM-DD**	**PM-Gearbox**	**PM-DD**	**PM-Gearbox**
90%	5%	5%	30%	70%	45%	55%

Table 2: *Scenario for technology ratio between various renewable energy technologies. The percentages indicate the ratios among technologies.*

It is important to note that it is difficult to predict how the ratio of technology deployment will develop. This is particularly difficult for wind energy, as both gearbox (GB) and Direct Drive (DD) have pros and cons.[20]

- DD generators are likely to be more reliable and therefore require less maintenance, but this has not been proven yet.
- Gearbox generators are more efficient than DD generators and have therefore been studied and optimized more extensively.
- The difference in efficiency at different wind speeds is small and is therefore not a deciding factor.

Critical metal demand per technology

To determine the critical metal demand per technology, various sources have been used.[17,18, 20–33] Based on the values from these different studies, a low, medium and high estimate have been made. The low and high estimates were calculated as an average of the lowest and highest three values found per metal. If only three or less values were found, the lowest and highest values applied. The medium estimate was based on the average of all values. All results that use the critical metal demand as input use the medium estimate. The research includes 22 different metals.

Current critical metal production

The production of metals is based on the reports by the United States Geological Survey (USGS). These numbers were also provided by the research by Månberger & Stenqvist[20] for a number of critical metals.

Definitions

Metals are sorted in many categories: mainly on basis of chemical properties, but also on price and abundance. This research uses the term critical metals: a subset of the more often investigated critical materials.[34] We use the term critical metals to collectively refer to metals which are difficult to extract or otherwise subject to supply constraints. Figure 6 shows which metals are included in this study, along with an indication to which group they belong.

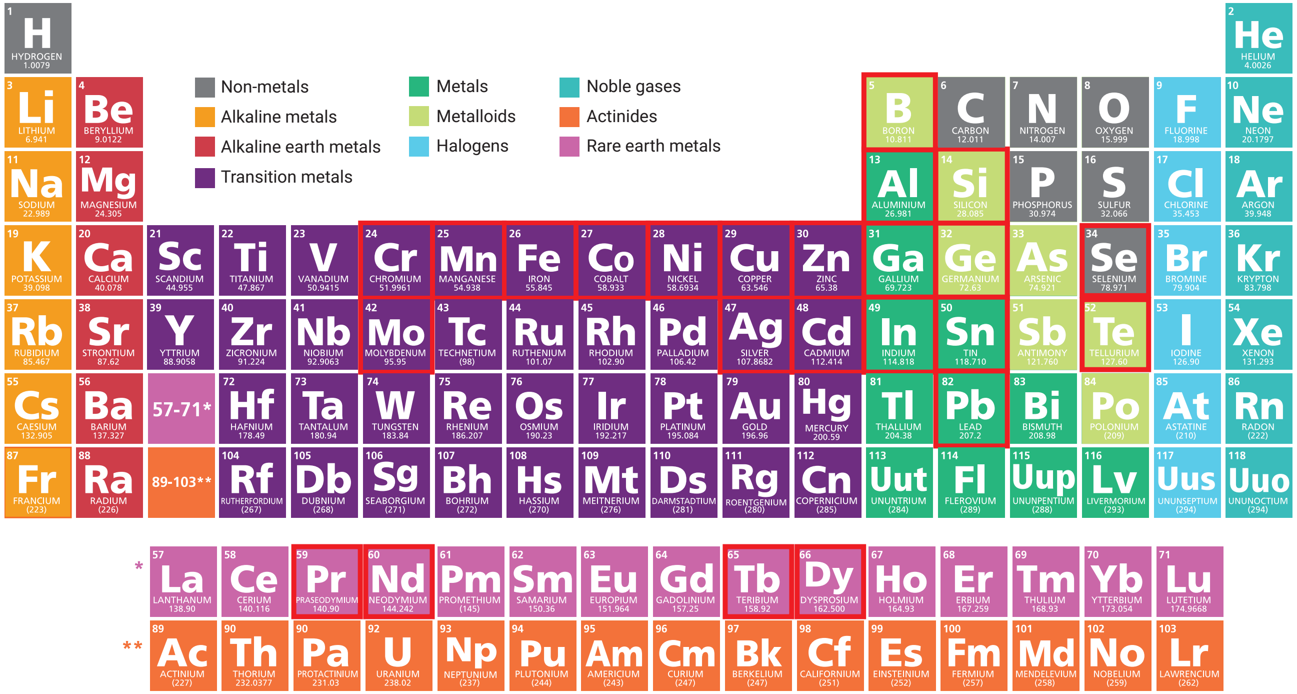


Figure 6: Periodic table of elements, with red frames indicating which elements are included in this study.

Rare Earth Elements (REE)

The term 'rare earth elements' is used as a collective name for a number of elements with similar properties (indicated pink in the periodic table above). These include 'light' rare earth elements (LREE) and 'heavy' rare earth elements (HREE). The elements are extracted from the earth in their oxidized form and are called 'rare earth oxides' (REO). In the refining process these oxides are turned into their pure elemental form: a metal. In this report we do not differentiate between heavy and light REEs.

Minor metals

The term minor metals refers to metals that are produced as a by-product in the refining process of base metals, for example indium and tellurium. Because of their by-product status it is often very difficult to increase production significantly. Therefore, minor-metals are highly susceptible to supply constraints if their demand increases significantly.[35]

Metalloids

Metalloid are metallic elements with a couple of properties similar to metals. It is a group in between metals and nonmetals. There is no exact definition for a metalloid, but the most commonly accepted metalloids are:

Boron (B), Silicium (Si), Germanium (Ge), Arsenic (As), Antimony (Sb), and Tellurium (Te). Selenium (Se) and Polonium (Po) are sometimes also classified as member of this group.

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