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TOWARDS A CIRCULAR ENERGY TRANSITION

Exploring solutions to mitigate surging demand for critical metals in the energy transition

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SUMMARY

Concern continues to grow regarding the availability of critical metals. Such rare or scarce metals, like lithium or cobalt, are not only vital to the world's major economies. They are also crucial for a transition to a renewable energy system in the Netherlands. At current levels, the global supply of these metals is insufficient, and the Dutch demand for them is no exception. This study serves to provide insight into the demand of critical metals domestically over the next few decades, offer perspectives on how to reduce this demand, and demonstrate the opportunities these new measures present to industry in the Netherlands.

Metals scarcity is threatening the transition to a renewable energy system. To achieve the Netherlands' goal of a net climate-neutral energy system by 2050, in accordance with the Paris Climate Agreement, a consistent supply of critical metals is needed for the production of green energy, sustainable transport, and storage technologies. For example, the Dutch renewable energy transition calls for a projected lithium demand of roughly 12-15% of current global production between 2040 and 2050. Similarly, the country's demand for neodymium, dysprosium, praseodymium, iridium, cobalt, and platinum is projected to rise to well above 5% of the global production of these resources. This is significantly more than the Dutch share of global GDP (1.0%), final energy consumption (0.5%), or number of inhabitants (0.2%).

A rapid growth in demand could intensify the metals shortage, both globally and nationally. In the face of a shortage, we cannot assume that simply ramping up mining can provide immediate relief to the increase of demand. Technically, an increase in mining production is possible, but scaling up and opening new mines often involves long lead times (10 to 15 years). In addition, mining is associated with a negative social and environmental impact. Metal concentrations in ores are slowly but surely decreasing. In addition, mining and refining takes place in a limited number of countries, with China having a dominant role in the supply chains of several critical metals.

Current Dutch policies on both the renewable energy transition and circular economy do not adequately factor in the availability of materials. Energy transition measures currently focus on support, spatial embedding, and affordability, while taking for granted the availability of materials. The various circular economy initiatives in place need a coherent and long-term approach, in which the use and availability of materials also becomes one of the criteria driving choices for the energy transition. The greater the scarcity, the more sustainable technologies hang in the balance.

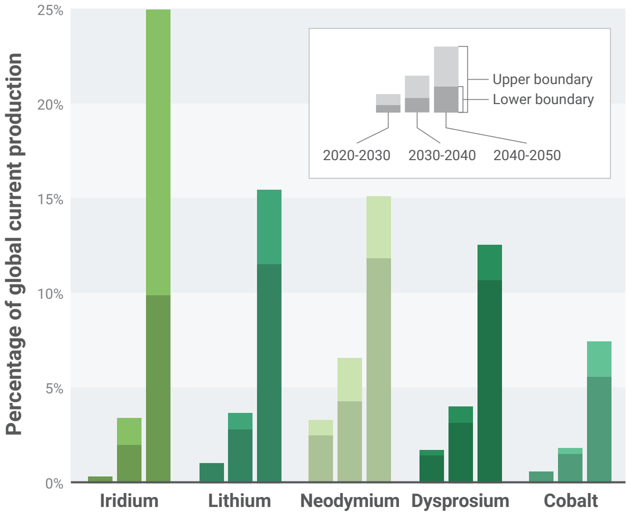

Figure 1 Expected average annual demand of metals needed for the Dutch energy industry, as percentage of current global supply.

Climate-neutral energy scenarios that model for greater self-sufficiency in the Netherlands are projecting a higher risk of insufficient sustainable technology supply. This deficiency is a result of the large demand for metals for both systems batteries as well as generation capacity for both wind and solar energy. Nevertheless, some demand will continue to be outsourced, so the country will still have dependency on supply from outside the country's borders. For example, in the energy scenarios that model for importing more energy (especially hydrogen), that demand shifts to sources abroad.

We propose four circular strategies that can mitigate a future shortage of materials. These strategies focus on both reducing the demand for critical metals and increasing their supply. Note that implementing only one of the strategies is not enough, so it is crucial to apply a combination of all four:

Rethink: adopting methods that save energy on a large-scale and, where necessary, redesigning the energy system in a way that reduces the required sustainable generation, transport, and storage capacity of electricity.

Reduce: shifting towards new technologies that contain less critical metals, such as in wind turbines or system batteries.

Repair, refurbish & repurpose: extending the life of products and parts, such as reusing solar panels or batteries for electric vehicles.

Recycle: recovering raw materials at the end of a product's life cycle.

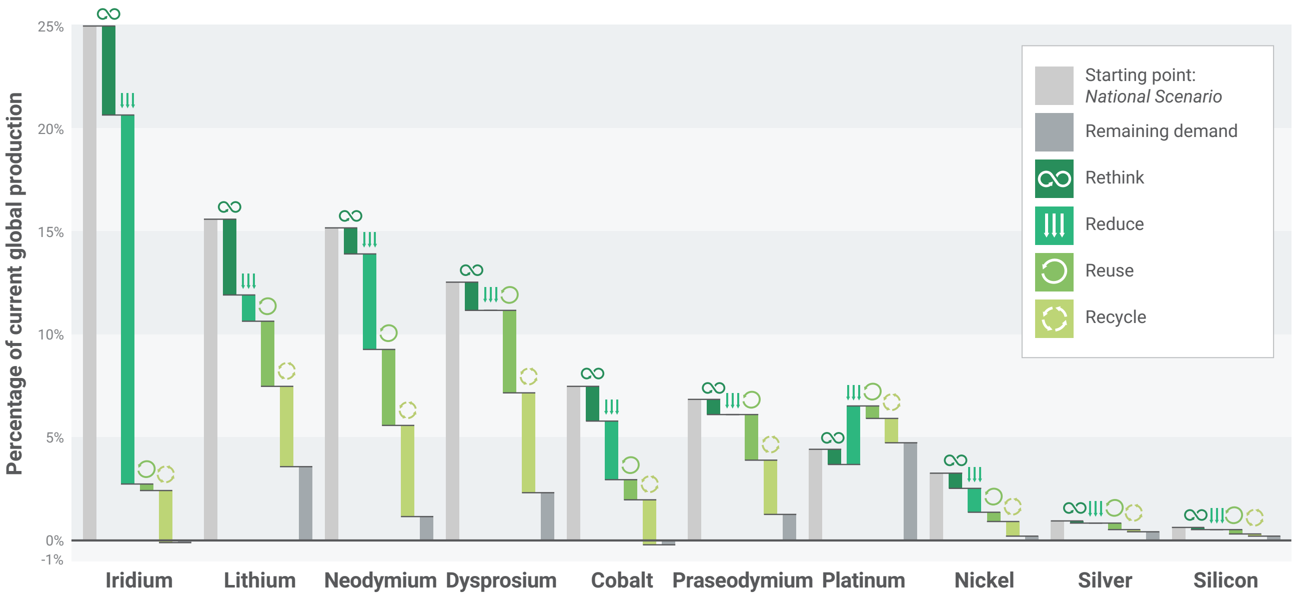

Figure 2 Potential of different circular strategies to reduce the average annual critical metal demand for the Dutch sustainable energy system in 2040-2050.

The Netherlands' position in the supply chain of critical metals is limited. The Netherlands does hold a position in the manufacture of end products, especially in the field of electric cars. It also maintains a position in recycling (in parts) as well as logistics. However, domestic mining is nearly non-existent, and the country hardly has any refining and production capacity for critical metals. It's repair and life extension activities are also limited. Economic opportunities present themselves particularly in the areas of recycling and lifespan extension, due to their respective growth and the potential impact. However, these opportunities can only be realized after an industry is built around them first.

Four preconditions must be met to guarantee security of supply. While work is being done on each of these preconditions, additional efforts are required:

A. Setting up **permanent monitoring and continuous knowledge development** to update knowledge and advance insights about critical metals and other raw materials, for example through a government-affiliated knowledge institute

B. Increasing **supply chain transparency**, to gain better insight into the environmental and social impact of critical metals in the supply chain and thus to be able to reduce that impact

C. Developing a **long-term industrial policy**, that serves as a solid foundation for investment decisions upon which industry can develop. In drawing up that policy, intensive cooperation between the government and industrial stakeholders is essential, as is the relationship between activities in the Netherlands and elsewhere in Europe

D. Strengthening **laws and regulations** to enable and promote high-quality reuse, including tightening product legislation, such as Ecodesign Directive guidelines, and reinforcing Extended Producer Responsibility policy

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INTRODUCTION

The Netherlands, Europe, and the world face the task of significantly reducing CO_2 emissions. To prevent serious climate change, global emissions must be halved over the next ten years. This requires the large-scale application of sustainable technologies such as solar panels, wind turbines, electric cars, electricity storage, and hydrogen. These technologies require critical metals such as nickel, neodymium and platinum. The amounts of metals needed pose an enormous challenge to the transition to a renewable energy system.

A worldwide transition to a clean energy system will not succeed without a structural focus on the required materials.[1] Critical metals are meanwhile also crucial for military applications, digital infrastructure, and consumer electronics, among other things. Combined with a growing world population and a growing global middle class, the pressure on existing stocks is already increasing, even without the transition to a sustainable energy system.[2] The application of these metals therefore creates competition not only between countries, but between applications as well.

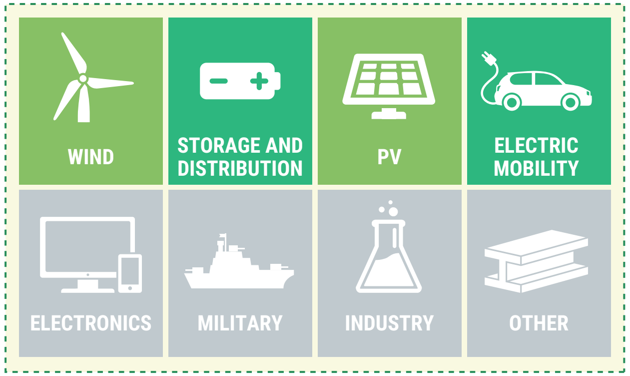

Figure 3 Overview of various applications of critical metals

GROWING FOCUS ON CRITICAL METALS

Attention to the challenges surrounding these critical metals is growing. At the European level, the required metals have been delineated by the European Commission.[3] Previous studies for the Netherlands focus on the economic vulnerabilities[4] and, more specifically, on the metal demand for solar panels, wind turbines[5,6], electric vehicles[7], and hydrogen.[8] We are increasingly recognizing the consequences of a geopolitical dependence on China[9], as well as a wide range of social and environmental impacts on the entire production chain.[10,11]

Preventing serious climate change will only succeed if all nations make sufficient short-term progress toward both a reduction in energy demand and the transition to climate-neutral energy production. This requires a rapid roll-out of sustainable technologies, both in the Netherlands and abroad. To enable their implementation quickly, it is important to map out our dependence on critical metals and the associated economic, environmental, and geopolitical risks. We can then take steps to limit those risks and create opportunities for the Dutch economy.

TWO OBJECTIVES

The challenge surrounding critical metals is a formidable one. The supply chains are long, complex, and international, which means that we must find solutions on a technological, political, and social level. Through this study, we want to achieve two objectives:

1. Provide insight into the Dutch demand for critical metals between 2030 and 2040, with a further projection to 2050
2. Offer a perspective on how to reduce critical metal demand, including the associated risks surrounding the security of supply, environmental impact, and geopolitical dependency

The Dutch version of the report also goes deeper into opportunities for Dutch industries.

IEA: The Role of Critical Minerals in Clean Energy Transitions

The International Energy Agency (IEA) recently put the need for critical metals for a renewable energy system on the agenda.[1] In doing so, it builds on scientific literature and previous reports from the World Bank, among others.[2] In its report, *The Role of Critical Minerals in Clean Energy Transitions* (May 2021), the IEA provided a general perspective of three aspects of critical metals:

- Critical metals needed for the global renewable energy supply
- Supply chain of critical metals
- Sustainable mining and production of critical metals

This study is in line with international IEA findings and provides insight into the metals required for the Dutch energy transition. In addition, we propose what actions should be taken at the national (and European) level.

The figure below illustrates the required production growth of five critical metals in the IEA-Sustainable Development Scenario (SDS) and the main production and refining locations of these metals (see Figure 4).

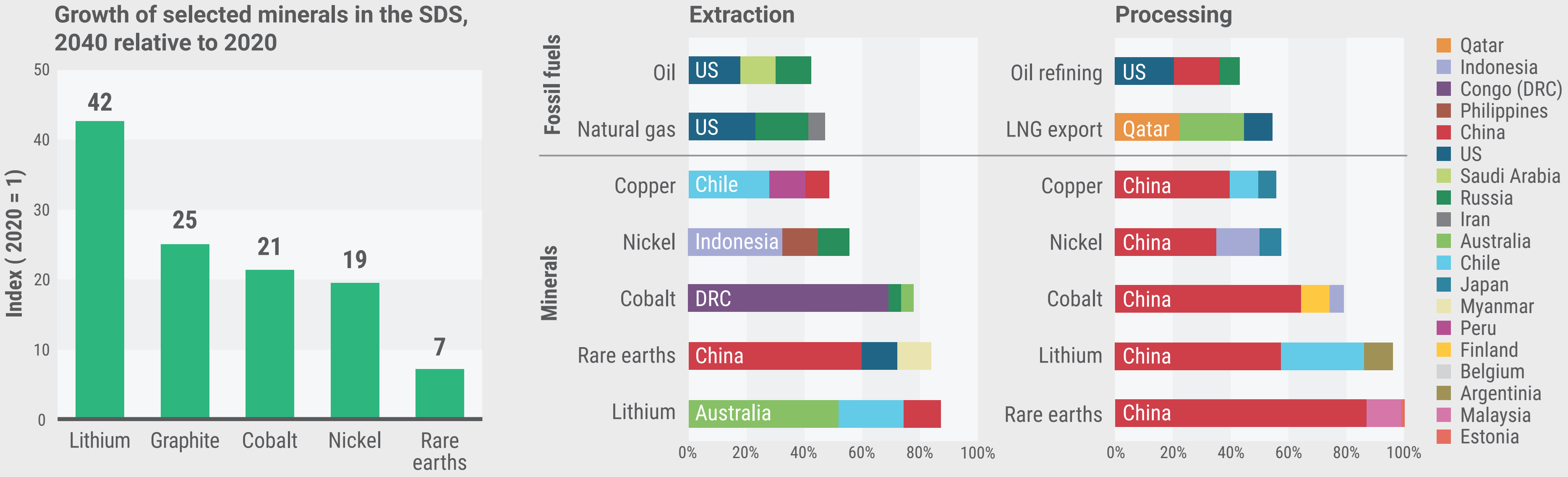

Figure 4 Source: IEA (2021)[1], The Role of Critical Minerals in Clean Energy Transitions, All rights reserved.

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OBJECTIVES & POLICIES

The direction of both European and national policy is clear: working towards a climate-neutral and circular economy. However, the discourse in existing policy on the availability of critical metals for the future transition to renewable energy is inadequate. Consequently, the climate targets seem infeasible. This chapter describes the current policy on climate and circular economy.

The Netherlands and Europe are working on both a climate-neutral and circular economy. Europe recently tightened its climate targets to a 55% CO_2 reduction by 2030 and a 'climate-neutral continent' by 2050. For the time being, the Netherlands has agreed on a CO_2 reduction of 49% (2030) and 95% (2050) in its Climate Agreement, which could tighten in the future to align with European targets.

In addition, both the Netherlands and the EU are working on a more efficient and smarter use of raw materials, based on transitioning toward a circular economy. Manufacturing and construction account for around 45% of global emissions[12]. To combat those levels, a circular economy that extends the life cycle of raw materials should lead to less dependence on primary raw materials, often sourced from outside Europe, and at the same time reduce the environmental impact of resource consumption. In addition, this should create new jobs. The Netherlands is therefore working towards a 'fully' circular economy by 2050, including a 50% reduction of primary raw material consumption by 2030[13].

CURRENT POLICY FALLS SHORT OF STATED AMBITIONS

Building this climate-neutral energy system requires critical materials. On this issue, both climate and circular economy policies however fall short. Today's focus is mainly on studies to understand the magnitude of the problem, and to map risks and dependencies.[3,9,14] Actual measures to safeguard our supply of critical materials are not taken.

Policy initiatives tend to focus on only one part of the problem: making mining activities more sustainable, re-designing products, or organising materials collection for reuse. They lack a structural and coherent approach to the supply chain as well as an associated raw materials policy, both at the national and European levels. They offer no quantitative picture of the various industries and their material flows. Ultimately, these shortcomings will only lead to an infeasible set of climate objectives.

EUROPE FOCUSES ON PRODUCT DESIGN & RESEARCH

The European Commission does emphasize the need for stable access to critical metals and related technologies.[3] Its recent Circular Economy Action Plan aims to minimize the export of raw materials to outside the EU[15], especially the critical metals used for battery production and electric car engines. To tackle this problem, the action plan focuses on the Ecodesign Directive guidelines and on setting up a European market for secondary materials.

To increase the security of a supply of critical metals, there is also a strategy aimed at materials resilience.[14] (However, this strategy still offers few concrete points of reference). In order to provide an unambiguous picture of the criticality of metals, the EU has developed a Critical Raw Material List which is updated every three years.[16] In addition, the EU is committed to responsible sourcing within trade agreements negotiated EU-wide with countries outside the bloc. As part of this, the EU's Conflict Minerals Regulation entered into force in 2021 to oversee sustainable mining of tin, tantalum, tungsten, and gold (also referred to as '3TG')[14].

Based on the strategies, public and private sector efforts within Europe focus on two pillars:

1. **Joint research,** financed by EU funds for research and innovation, for example through *Horizon Europe* and the *Raw Materials* partnership spearheaded by the European Institute of Innovation & Technology (EIT). However, this research focuses mainly on the development of technologies and not enough on their actual application.
2. **Joint agreements,** in which, for example, efforts are aimed at the further development of Ecodesign Directive guidelines and European legislation. In addition, various platforms and partnerships provide input to the European Commission.

Various European partnerships drive the activities within these pillars. The partnerships which are specifically aimed at critical metals are summarised in the box *Key European Initiatives* (page 10). It might be no surprise that Dutch parties are relatively well-represented in those partnerships focusing on wind energy, but the pioneers from the battery industry are mainly from France, Spain, Germany, and Scandinavia.

Overview of critical metals

In order to gain insight into which metals are critical at a European level, the European Commission maintains a list of *Critical Raw Materials*.[16] The fourth version of the list, published in 2020, contains 30 critical raw materials. In this report, we use the same definition of critical (a metal that is very important to major industry and which supply is or could become problematic), but since we research at a different scale and application than the European Commission, we arrive at a different selection of metals. Figure 5 shows which metals are considered critical by the EC and in this report.

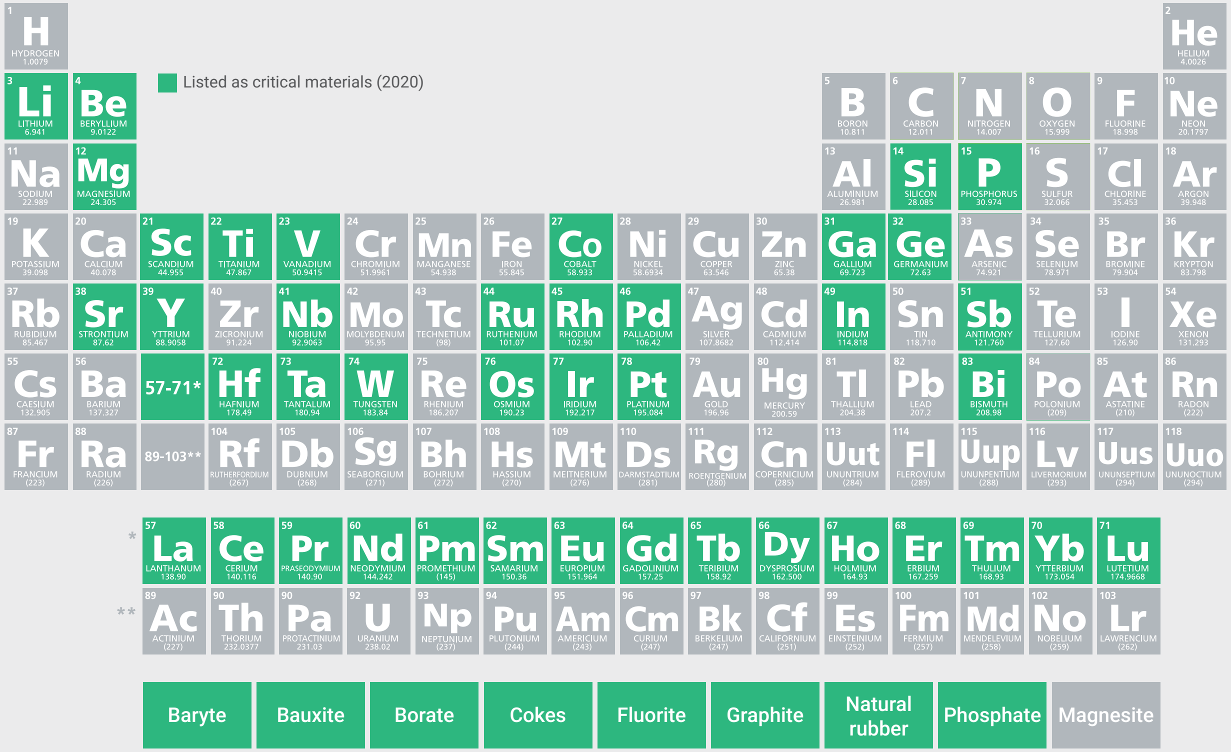

Figure 5 Overview of the elements identified as critical by the European Commission.

Key European initiatives

European Raw Material Alliance (ERMA): a group of parties that formulate recommendations for the European Commission on research and investment projects and the drafting of Ecodesign Directive guidelines.

European Battery Alliance (EBA): a partnership between industrial and innovative parties committed to creating a strong European battery industry. The EBA does this by financing sector-wide initiatives to further develop this industry.

European Institute of Technology (EIT) Raw Materials: a partnership between educational and research institutes that focuses on critical metals, among other things. The EIT facilitates education and research programmes, acts as a secretariat for the ERMA, and advises the European Commission.

European Innovation Partnership (EIP) Raw Materials: a stakeholder platform between industries, knowledge institutions, governments, and NGOs, which advises the European Commission.

European Platform for Responsible Mining (EPRM): a partnership with the aim of increasing the percentage of responsibly-produced materials and supporting local initiatives and communities in making mining more sustainable.

European Energy Research Alliance (EERA) Energy Storage: a collaboration between research institutions that focuses on developing energy storage solutions.

DUTCH EFFORTS TOWARDS A CIRCULAR ECONOMY ARE INCIDENTAL AND SMALL-SCALE

There is a clear snapshot of policy in the Netherlands, as well, with various initiatives to reduce dependence on critical metals. Both TNO and HCSS, Dutch research organizations, recently drew attention to the subject by issuing reports.[17,9] The most important policy framework is the *Transition Agenda Circular Manufacturing Industry*, which is part of the government-wide Circular Economy Programme.[18] A *National Battery Strategy* was launched to identify five important battery-related themes.[19] And a few years ago, the Resources Scanner was developed to create insight into supply chain risks and the impact of raw materials. It can be difficult to use for two reasons. First, the underlying method of this scanner focuses on product groups instead of chain relationships. Second, recent innovations are missing or inaccurate, so data can be outdated.

Het Versnellingshuis Nederland Circulair (The Netherlands Circular Acceleration House) is an organization working on various breakthrough projects that establish national collaborations for circular supply chains. Two of these touch on the need for critical metals for the energy transition:

- **Circular copper chain** focuses on creating new supply chain collaborations between parties to use less primary copper.
- **Circular windmills** proposes a different design for wind turbines and organising future reuse.[20]

There are also various regional initiatives, but their impact on international supply chains is often not yet clear. For example, the Province of South Holland is building a regional network of Circular Solar Panels, aimed at creating local supply chains and initiatives and building knowledge.[21,22] Finally, knowledge institutes such as CML, HCSS, Clingendael, and TNO regularly conduct research to outline the latest state of affairs regarding critical metals.

For the most part, however, these initiatives are incidental and small-scale. Long-term commitment and financing are often not guaranteed, which poses obstacles to ongoing involvement and limits knowledge development. The initiatives often also have a technical focus and, for example, there is hardly any focus on alternative product use or changes in behaviour. These activities have a long way to go before they can make real contributions to national policy objectives.

CRITERIA FOR THE ENERGY TRANSITION DO NOT YET INCLUDE AVAILABILITY OF MATERIALS

Current national policies on the energy transition are based on three criteria: affordability, a support base, and spatial embedding. The strong focus on affordability stems from the desire of the central government to limit public spending. Support is crucial to prevent local resistance to aspects of renewable energy, for example the existing opposition to wind turbines. Spatial embedding mainly focuses on conflicts arising from other aspects with agriculture, nature, or climate adaptation, for example.

Implementation of measures solely on the basis of these criteria has led to certain shifts in technologies. For example, the Regional Energy Strategies mandated a shift in renewable energy from onshore wind to solar farms, because fewer wind turbines on the Dutch landscape means less noise and visual pollution for local residents.

However, this shift leads to a higher demand for critical metals used in the construction of new solar panels.

To ensure future-proof choices, it is necessary to add the availability of materials as a fourth criterion. In doing so, we reduce the risk that plans set in place now prove infeasible in the long term because of any shortage of critical metals or a disruption in the production chain.

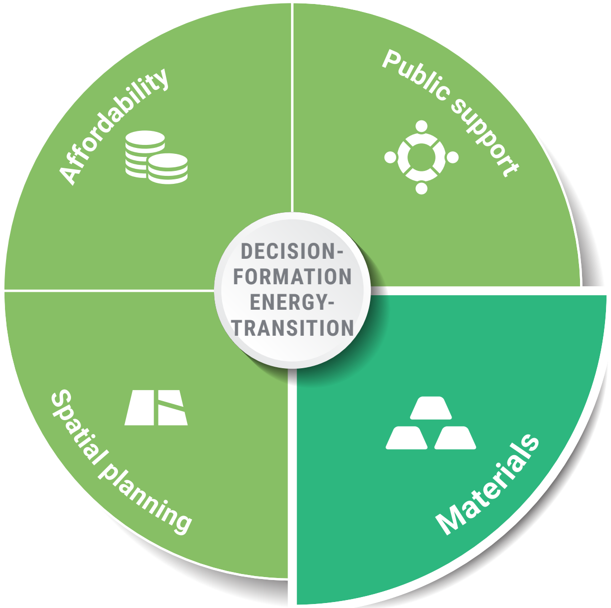

Figure 6 To ensure future-proof choices, materials must be included as a criterion too.

03

GEOPOLITICS, SUPPLY CHAIN COMPLEXITY & IMPACT MINING

In order for sustainable energy technologies to replace conventional natural gas or coal-fired generators, critical metals are needed. These metals are considered ‘critical’ when they are important to the economy and there is a relatively high probability of disruptions in the supply chain. In doing so, geopolitical dependence shifts from the Middle East to the Far East, supply chains lack transparency and mining is, by definition, associated with a social and environmental impact. This chapter discusses these aspects as a context for working with critical metals.

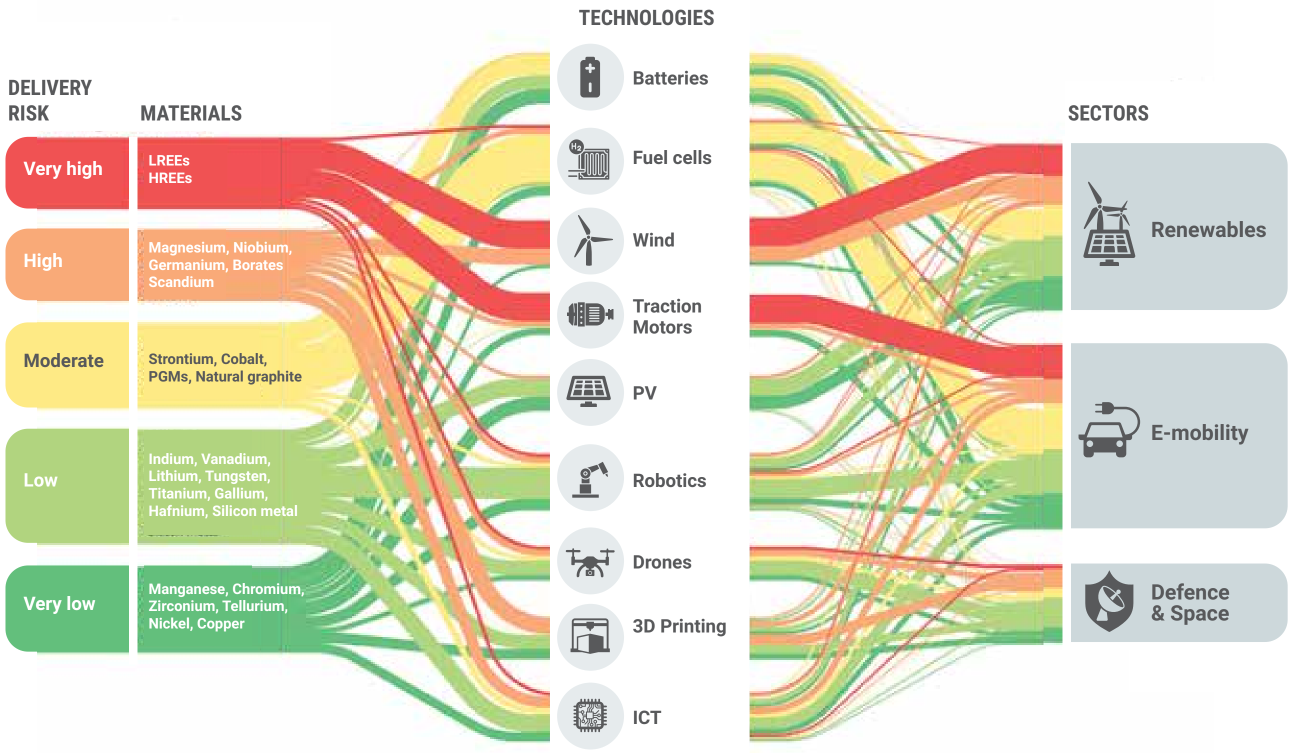

Figure 7 Overview of the different critical metals needed for the various technologies, based on the expected development of these technologies within the EU (source: European Commission).[23]

More and more products in our world use critical metals: mobile phones, laptops, batteries, electric motors, solar panels, and wind turbines. Many of these critical metals involve long, international supply chains running through many different countries. This makes it difficult to influence these chains with a singular approach, and so a thorough understanding of the risks and dependencies surrounding them is key to controlling their complex supply chain.

Not only can a critical metal’s supply chain present challenges within the energy field, the energy transition also contends with other applications that require the same materials. In absolute terms, the demand by the sustainable energy system is the greatest. Figure 7 provides an overview of which critical metals are needed for which technologies.

THE LIMITATIONS OF EXTRACTION

The materials we need to transition to a clean energy supply are also important to other aspects of the economy. Because they are so sought after across industries, the extraction limitations of some of the metals create a considerable risk of a disruption in supply. This makes them by definition 'critical metals'. Disruptions can have various causes, both on the demand side (strong growth) or on the supply side (supply chain disruption).

In an absolute sense, Earth contains more than enough metal ores, including 'critical' metals. The main question is to what extent these can actually be extracted on time, in an economically viable way, and without causing enormous environmental and social impact. This is explained in box *The stock of metal ores.*

GEOPOLITICAL CHALLENGES: SHIFT FROM THE MIDDLE EAST TO THE FAR EAST

Europe is geopolitically dependent in terms of its energy supply. Historically, we have seen a disruption in fossil fuels during the oil crisis in 1973 and of gas supplies from Russia in recent years. These well-known examples of geopolitically motivated disruptions foreshadow a future dependence, but this time, on critical metals.

The dependence on critical metals gained public attention after China's export ban on 'rare earth elements' in late 2010, following a heated argument with Japan over the Senkaku/Diaoyu islands. Since 97% of total global production originated from China at the time, prices shot up by more than 1,000%.

The stock of metal ores

A common question about critical metals is whether sufficient stocks are available. In general, global ore reserves are more than sufficient to meet expected demand. However, the actual production capacity and its scaling up has a number of limits:

- **Technical limits:** what can be extracted with current technology?
- **Economic limits:** what is profitable to extract?
- **Social limits:** what is the social and environmental impact?

Both scaling up existing production locations and opening new mines are time-consuming and capital-intensive processes. Exploration, permit applications, and the construction of an infrastructure, among other things, mean that the opening of a new mine and associated refining capacity can take 10 to 20 years. This alone makes producing enough metals for the renewable energy technologies we need now and up to 2030 challenging.

CHINESE DOMINANCE OF SUPPLY CHAINS

The Chinese dominance of economically and militarily important rare earth elements is the result of a clear vision and consistent Chinese industrial policy originating in the 1960s.[24] This strategic focus on critical metals from China will remain for the foreseeable future. China's industrial plan *Made in China* 2025 aims to advance the country's position in the global manufacturing value chain and reduce China's economic dependence on foreign countries.[25] In recent years, therefore, China has taken dominant positions in the supply chains of almost all critical metals, both in mining and in refining capacity of metals extracted elsewhere.[9]

Since the 2013 inception of the Belt and Road Initiative, China has been investing in logistics infrastructure (ports, roads, and rail) in nearly 70 countries. The 'Belt' in the title is short for the 'Silk Road Economic Belt', an appropriate term, because, in addition to its own extraction and refining capacity, the country also influences the flow of products, including ores and metals, not directly owned by Chinese companies.

China sees investing in supply chains of critical metals as a way to maintain control over these supply chains in the future. Not only does this concern extraction and metal production, but also the production of parts and products that contain these critical metals. In September 2020[26], partly as a result of growing dependence and increasing trade conflicts with China, the US declared a presidential emergency over critical metals and recently announced

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[I] *To clarify:* rare earth elements *is a collective name for 17 metallic elements, including neodymium, dysprosium, and praseodymium, used to enhance batteries, computers, weapons systems, among other applications. Contrary to what the name implies, these are in fact not rare.*

a task force to strengthen its supply chains of critical metals.[27]

Some countries have developed an explicit strategy to deal with this dependency. Europe and the Netherlands recognise the importance of cooperation[28], but any substantive strategy has yet to form. This appears to be mainly due to an insufficient sense of urgency. However, this urgency is being felt in Japan and the US, among other countries. A number of initiatives by these countries are summarised in the text box.

Example: initiatives from Japan and the US

Japan became aware of its dependence on third parties for raw materials well before World War II. In 1963, the Metallic Minerals Exploration Financing Agency of Japan was established with the mission of supporting Japanese businesses in accessing raw materials. In 2004, it was transformed into the Japan Oil, Gas and Metals National Corporation (JOGMEC). JOGMEC maintains expertise in the field of raw materials, coordinates cooperation between government and the private sector, and invests in reducing risks for businesses. It also has the financial means to do so. In addition, Japan has had since 1983 a national stockpiling programme with the goal of holding quantities of petroleum, natural gas, and rare metals that could last the Japanese economy for a few weeks. The government maintains a 48-day reserve and the business community is expected to always keep enough stock for at least 18 days.

The United States has for decades been equally aware of its dependencies on critical metals. Since 1947, the Defense Logistics Agency (DLA) manages a national strategic stock of raw materials deemed critical, valued at approximately $1.5 billion.[29] This year, as in previous years, the United States military spends a significant amount to maintain this stock. For example, in 2021, the (DLA) wants to purchase 600 Mt of neodymium and approximately 15 kt of tantalum. In 2013, the Critical Materials Institute was founded to help develop technical innovations from the laboratory to the pilot phase. This partnership of research institutions currently has a direct budget of approximately $24 million, in addition to all research paid through regular funding streams and through military research budgets.

DLA STRATEGIC MATERIALS
ANNOUNCEMENT

October 1, 2020 DLA-SM-21-3183

ANNUAL MATERIALS PLAN FOR FY 2021

The Defense Logistics Agency-Strategic Materials today announced the Fiscal Year 2021 Annual Materials Plan (AMP) for potential acquisitions. The FY 2021 AMP is effective October 1, 2020 and will expire September 30, 2021.

Annual Materials Plan for FY 2021 (Potential Acquisitions)

Material	Unit	Ceiling Quantity
Antimony	MT	1,100
Boron Carbide	MT	1,000
Carbon Fibers	MT	72
Carbon Fibers	LBS	5,000
Cerium	MT	500
Dysprosium	MT	20
Electrolytic Manganese Metal	MT	5,000
Lanthanum	MT	1,300
Neodymium	MT	600
Praseodymium	MT	70
Rare Earth Magnet Block	MT	100
Rayon	MT	600
RDX/HMX/IMX/TNT	LBS	7,000,000
Samarium Cobalt Alloy	MT	50
Silicon Carbide Fibers	LBS	875
Tantalum	LBS Ta	33,990
Tungsten Rhenium Metal	KG	5,000
Yttrium	MT	600

Materials listed are Potential Acquisitions and quantities listed are ceilings.
www.dla.mil/hq/acquisition/strategicmaterials

Figure 8 Overview of potential purchases of strategic material supplies by the US military.

CHAINS LACKING TRANSPARENCY

In addition to geopolitical risks, the long and complex supply chains present other risks, especially when they lack transparency. Each step of the supply chain is characterised by its own complexity. For example, at the very beginning of the chain, the mining of one type of metal can depend on the mining of a different metal, and a shift in demand can create wild price fluctuations. The text box on the following page, elaborates on the unpredictable nature of extraction of *companion metals* from *major metals*. Refining is another complex industrial process that requires metallurgical knowledge, which has almost completely disappeared in the Netherlands. At the production stage, risks can arise because many different materials are often sourced from different countries, compounded by the myriad parts that complete a finished or semi-finished product. Figure 9 illustrates such complexity surrounding just one part of the circuit of a solar panel.

Well-functioning global logistics are crucial for these complex chains, but when those fail, the world feels the repercussions. Consider the disruptions in the global supply chain when the COVID-19 pandemic caused production restrictions, or when the Suez Canal was blocked for six day by a container ship, as recent examples.

Supply chains are so long and complex that it is virtually impossible to map out all risks. As a result, chain risks are systematically underestimated. A lot of research is conducted into *supply chain resilience*, but due to pressure on efficiency and *just-in-time* management, investments in maintaining stock and thus increasing the resilience of these chains are limited. As a result, customers in the Netherlands can hardly anticipate disruptions.

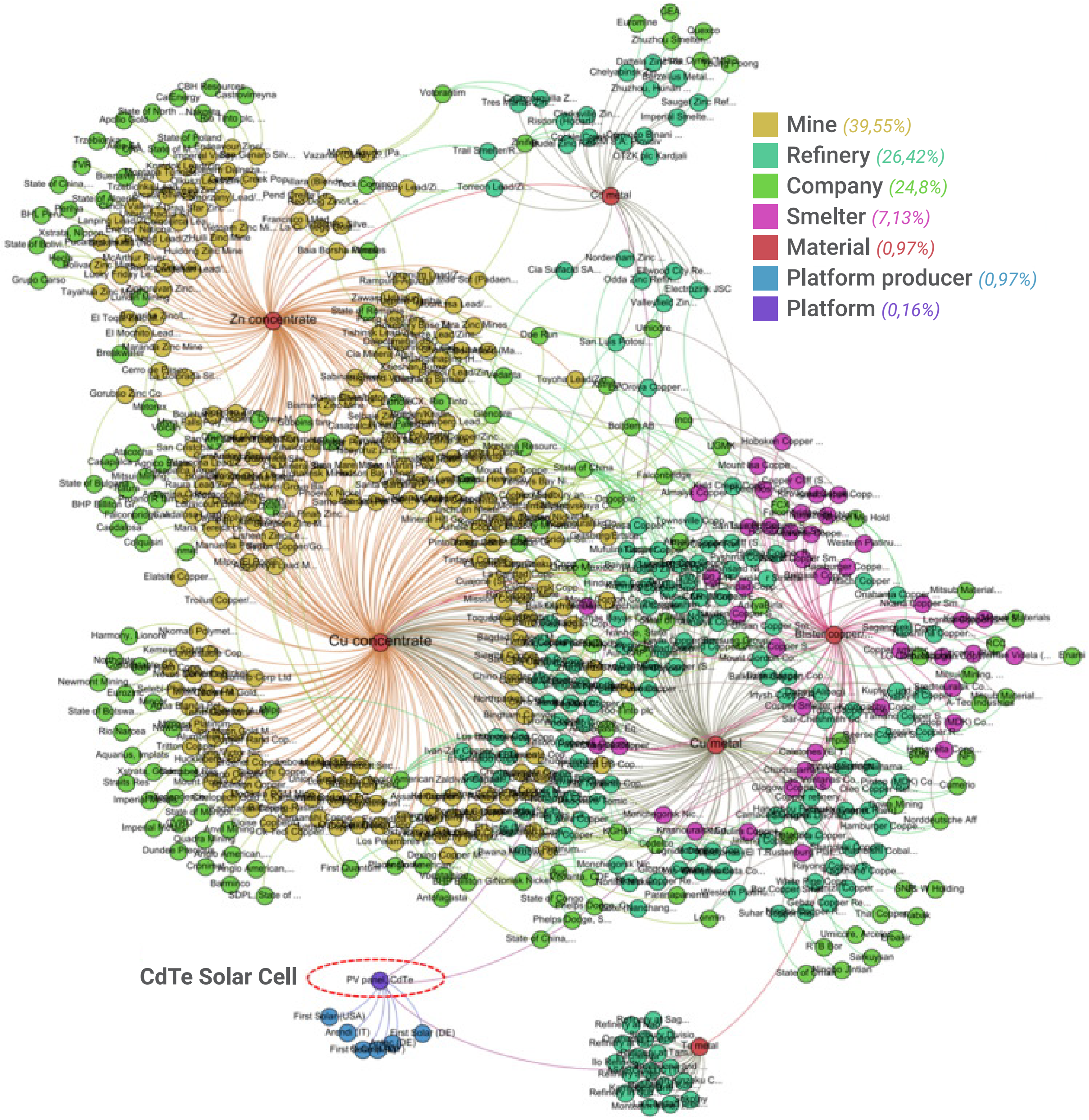

Figure 9 The network of companies involved in the production of a Cadmium-Tellurium solar panel, as far as the researchers have been able to map it out. This visual representation illustrates the complexity of a supply chain (source: Nuss et al.)[30]

Mining Production: *majors* and *companions*

The production of most critical metals is particularly unpredictable, because they are a by-product (*companion metal*) in the extraction of other metals such as copper, iron, and zinc (*major metals*). By way of illustration, more than 90% of global cobalt production is a by-product from sites such as the Katanga mine (the Congo), which produces one tonne of cobalt per 55 tonnes of copper.

If the demand for a companion metal rises, production can often be increased relatively easily in the first instance. However, when the reserve production capacity has been fully utilized at a mine, the price first has to rise suddenly and sharply to make the increase of production as a whole viable, only after which the demand for the companion metal can be met. Since there is hardly any information available on unused production capacity, predicting prices of *companion metals* is extremely difficult.

Not all critical metals in this report are companion metals: lithium and nickel, for example, are extracted independently. Rare earth elements (REEs) and cobalt are often by-products, but not always. To illustrate this, China's Bayan Obo mine, which accounts for most of the world's production of rare-earth elements, was originally an iron mine that also happened to produce REEs. The combination of soaring REE prices and the fall in concentrations of iron in the ore turned Bayan Obo into a mine that mainly profits from the production of REEs, with iron as a by-product.

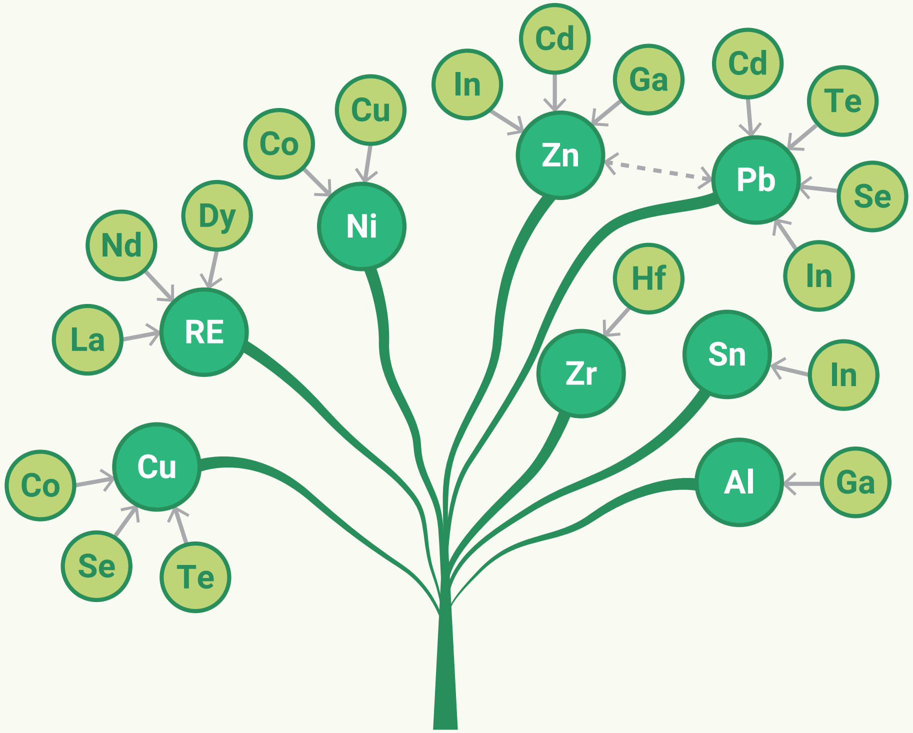

Figure 10 Correlation between major metals and companion metals in ore mining (source: Graedel et al.).[31]

MINING HAS AN ENVIRONMENTAL AND SOCIAL IMPACT

Mining by definition has a negative impact on the environment surrounding a mine, such as deforestation or pollution. Impact is evident both during the exploitation of a mine and after production has ended, when a mining site is not properly decommissioned. Despite agreements, mining companies regularly evade these obligations, for example, by selling the mine to a small company several years before exhaustion, which then goes bankrupt before it can meet the obligations to clean the area and remove equipment. Risks of damage to the natural environment sometimes prevent mines from opening, such as the recent decision not to open a new mine for REEs in Greenland.

Dilemmas at a public and social level

Mining also regularly leads to dilemmas and conflicts at a public and social level. Examples include the high level of water use in nickel production in areas in Australia, which already struggles with major water shortages, and damage to the natural landscape caused by lithium production from salt lakes in South America. Mining is sporadically associated with child and forced labour, such as in cobalt mining in the Congo or the extraction of rare earth elements in the interior of China.

On the other hand, a mine can also make a positive contribution. Often, a mining company is the largest local employer and sometimes better organised than the local government. These companies can play a crucial role in emergency situations. For example, during the 2014-2015 Ebola outbreak, mining companies in Guinea, Liberia, and Sierra Leone took rapid action to help employees and nearby communities with health and safety training. This allowed the mines to remain open.

Yet the negative effects of mining critical metals are negligible, compared to the damage caused by the extraction and combustion of fossil fuels.[32] Nevertheless, the environmental and social impact of mining poses a risk to the renewable energy transition, because negative reporting can reduce public support.

This is illustrated by the many indignant and critical responses to recent articles in Dutch newspapers: on child labour in the Congol in a newspaper called *Trouw*[33], Uyghur forced labour in China in the *Financieel Dagblad*[34], and on the environmental impact of mining in Greenland in the *Volkskrant*[35]. Also, many international media have reported on these issues. A moral issue is also at play here: to what extent will a sustainable energy supply exist at the expense of people and the environment? A focus on responsible mining and production chains across the globe is therefore crucial.

> ***Appendix II contains an overview of some important metals for the energy transition, their main properties, and the impact in the chain.***

ATTENTION TO SUSTAINABLE MINING IS LIMITED, BUT GROWING

However, the focus on more sustainable mining is still limited, globally. Despite the fact that many mining companies indicate that the additional costs to make the shift are relatively limited, working toward sustainability is difficult due to competition, corruption, and the pressure from shareholders on short-term returns. Western mining companies often compete with parties that do not attach value to social conditions. Consequently, negotiations that emphasize sustainable mining and call for the exclusion of corruption can lead to the loss of a contract.

To contribute to reducing the impact of mining, the World Bank, launched the *Climate Smart Mining* programme. In addition, the European Certification of Raw Materials (CERA) project is a developing universal certification scheme specially developed for metals[36] with the aim of standardising the 32 certification schemes already in circulation. However, these types of non-binding initiatives are not sufficient to reduce the negative impacts of mining.

04

METAL DEMAND DUTCH ENERGY TRANSITION

The future sustainable energy system in the Netherlands requires large amounts of renewable production capacity, storage, and transmission and distribution infrastructure — all of which require critical metals in their production. This chapter models scenarios that offer insight on future metal demand for the Dutch energy transition, forecasting a demand for some metals in the Netherlands that will grow to reach 10-25% of current global production.

FOUR SCENARIOS FOR A CLIMATE-NEUTRAL ENERGY SYSTEM

An energy system that adheres to the Paris Climate Agreement requires major adjustments to the current energy system. The Netherlands has several options to reach its own commitment to climate-neutral energy by 2050. Deciding which to choose requires various considerations: Should the nation build toward self-sufficient energy produced domestically, or import energy instead? Would that come in the form of central, or decentralised electricity production? And what about electrification versus scaling sustainable fuels? To clarify the consequences of these choices, scenario studies are being conducted at both a national and regional level. This study is based on the scenarios produced in April 2021 by Netbeheer Nederland, the association representing all gas and electricity system operators nationwide.[37] The main characteristics of each scenario has been summarized in Table 1, and they serve as starting points for calculating the metal demand for the Dutch energy transition.

Table 1: Features of the four climate-neutral energy scenarios for the Netherlands (source: Netbeheer Nederland)[35]

SCENARIO	ENERGY CONSUMPTION[II]	RENEW-ABILITY	SELF-SUFFICIENCY	INDUSTRY	GENERATION	FLEXIBILITY
Regional management	**Reduction:** 40%	95%	73%	**Contraction:** 1% per year *(to 73% of current level)*	125 GWh 20 GWh 31 GWh	400 GWh 42 GW
National management	**Reduction:** 25%	95%	71%	**Stable** *(equal to current level)*	107 GWh 20 GWh 52 GWh	400 GWh 51 GW
European CO_2 management	**Reduction:** 0%	69%	33%	**Growth:** 1% per year *(to 136% of current level)*	59 GWh 10 GWh 30 GWh	200 GWh 19 GW
International management	**Growth:** 2%	59%	32%	**Growth:** 1% per year *(to 136% of current level)*	58 GWh 10 GWh 28 GWh	200 GWh 16 GW

Solar PV   Wind onshore   Wind offshore   Batteries   Electrolysers

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[II] Compared to 2015, and including the use of energy as an industrial raw material.

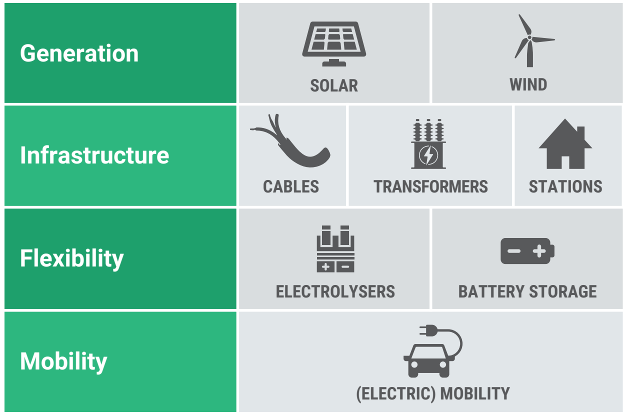
The four scenarios represent 'realistic extremes', showing the different directions in which the energy system can develop. The purpose of the scenarios is to provide insight into the bandwidth of the needs for flexibility resources (energy storage, matching supply and demand) and infrastructure. They range from a focus on self-sufficiency to a more import-oriented perspective. They also range from significant contraction to significant growth in the energy-intensive industry. In addition, the technologies, energy sources, and carriers vary within the scenarios.

A more detailed description of these scenarios is included in Appendix III.

Delineation of the system

This study focuses on the elements of the energy system that (may) contain critical metals. These are mainly technologies for the generation, transport, and storage of electricity.

While we include the demand for metals for electric vehicle production, the production, transport, and storage of heat and gas has been omitted because that process requires hardly any critical metals. Material losses in the production chain have not been included either, mainly because they are difficult to quantify. As a result, total metal demand could be even higher than indicated here.



Generation	SOLAR	WIND	
Infrastructure	CABLES	TRANSFORMERS	STATIONS
Flexibility	ELECTROLYSERS	BATTERY STORAGE	
Mobility	(ELECTRIC) MOBILITY		

Absolute versus relative demand

The absolute demand for metals (critical or non-critical) gives an idea of how much of these metals is needed. However, the production volumes of these metals differ enormously and offers little comparative insight: for example, in 2020, approximately 1,800,000,000 tons of iron was produced worldwide, compared to only 120 tons of platinum.

To gain a better insight of how significant the demand for various critical metals is, the annual required amount of metals for the Netherlands is plotted as a percentage of worldwide annual production. Since future mining production is difficult to predict, these calculations use production levels from 2020 as a reference.

When determining this relative demand, it is important to place the Netherlands within a global perspective:

The GDP of the Netherlands is about 1.0% of the global GDP — BNP 1.0%

Dutch final energy consumption is about 0.5% of global energy consumption — 0.5%

The Dutch population is about 0.2% of the global population — 0.2%

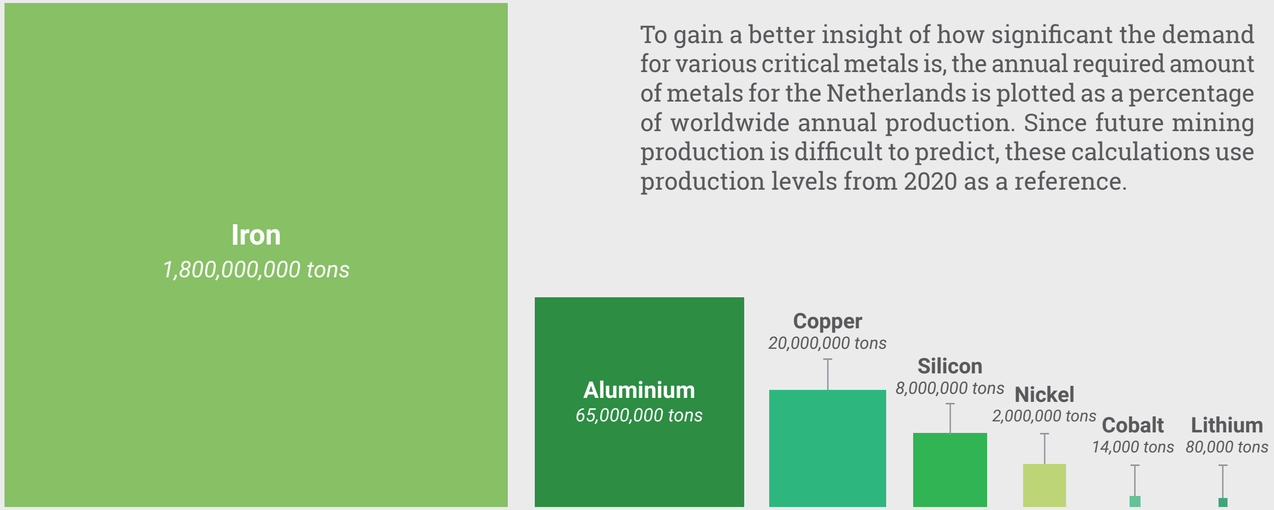


Figure 11 Global production (2020) of a number of important metals for the energy system (source: USGS).[54]

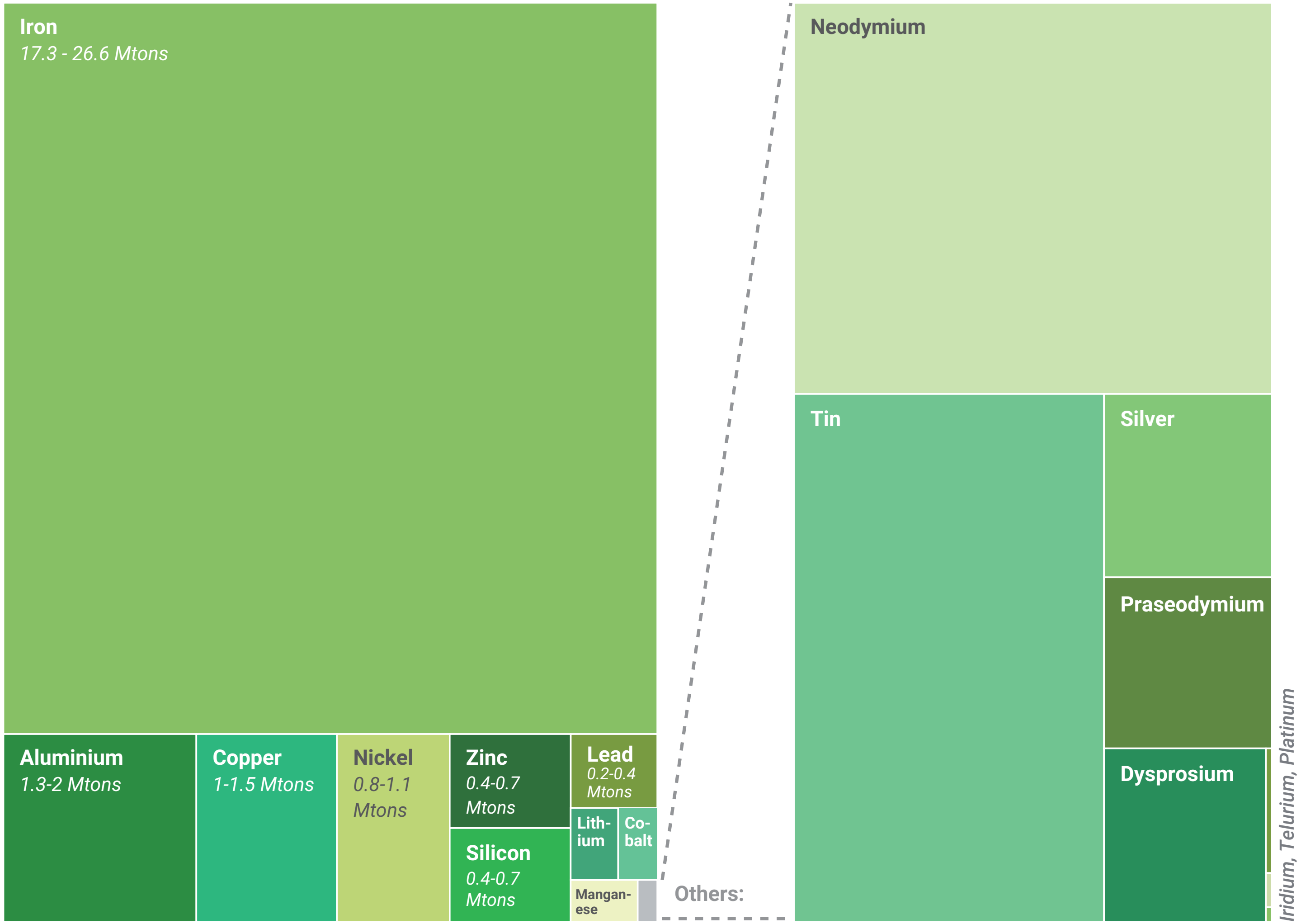


Figure 12 Amount of metals needed between 2020 and 2050 (in Mt) to build the sustainable energy system, based on an average of the four scenarios.

METAL DEMAND FOR THE DUTCH ENERGY SYSTEM

Absolute demand for metals is millions of tons

Depending on the energy scenario, the Dutch energy transition will require 22 to 33 million tons of metals between 2020 and 2050. Of this, 94% of the total amount is accounted for by iron (processed into steel), aluminium, copper, and nickel.

Most of these metals are needed for the production of solar panels and wind turbines. By way of illustration: General Electric’s new Haliade wind turbines, which were installed in Rotterdam, have a capacity of 12 MW per turbine and weigh more than 1,500 tons. The scenarios show that there will be between 38 and 72 GW (38,000 - 72,000 MW) of wind turbine capacity by 2050. Because the *Regional management* and *National management* scenarios model for more solar panels and wind turbines being installed by 2050, the metal demand in those scenarios is also significantly higher.

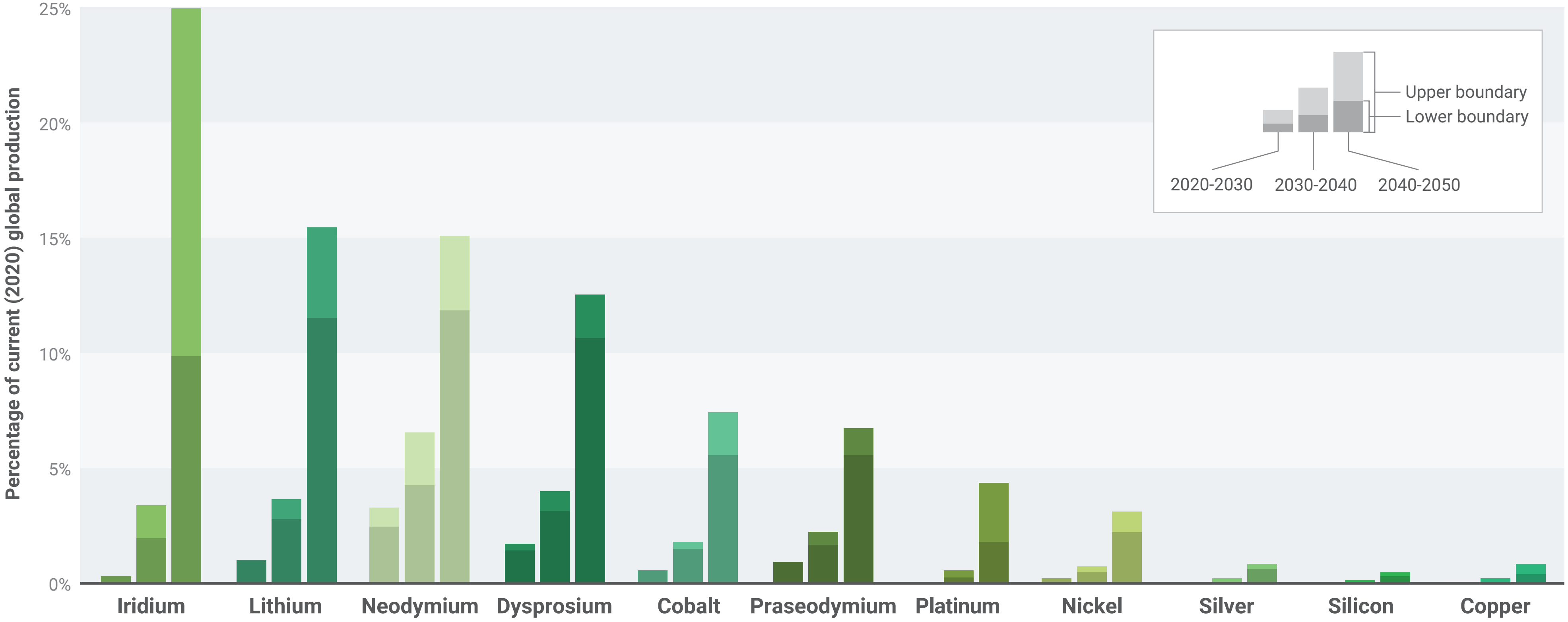


Figure 13 Expected annual demand for a number of critical metals as a percentage of current global production, for the periods 2020 to 2030, 2030 to 2040, and 2040 to 2050.

Relative demand exceeds supply by factors in the next thirty years

When comparing the Dutch demand for critical metals needed for the energy transition with the relative share of current global production of some metals, demand appears to be disproportionately high for a country the size of the Netherlands. The demand is greatest for iridium, lithium, cobalt, platinum, nickel, and rare earth elements, relative to current production. Metal demand of the Dutch energy transition for the period between 2020 to 2050 is visualized in Figure 13.

Demand for most metals will steadily increase between 2020 and 2050 because the largest growth in installed capacity in the scenarios is expected to be concentrated during the last two decades. For iridium, lithium, neodymium, and dysprosium, the average expected demand will rise above 10% of current global production, even in the lowest scenario. The difference between supply (from mining production) and demand from the transition to a sustainable energy system is therefore not expressed in percentages, but in factors.

- In the future, Dutch annual demand for iridium will rise by 10-25% of current production levels when using polymer electrolyte membrane (PEM) technology, which contains platinum, in addition to alkaline electrolysers. TNO recently calculated that in 2050, total Dutch iridium demand for electrolysers will be 122% of current global production.[8]
- The annual demand for lithium is increasing to 12-15% per year due to the use of batteries to buffer the electricity grid and the switch to electric transport.

- The demand for rare earth elements increases: neodymium demand grows to 12-15% and dysprosium demand to 10-12% of global production in the period 2040-2050. Both metals are used in permanent magnets, required both for wind turbines and electric vehicles.

Major differences between scenarios due to varying degrees in self-sufficiency and in share of renewable energy

The demand for metals differs greatly per scenario. In the *National management* scenario, metal demand in the Netherlands is highest, whereas in the *International management* scenario, amounts of critical metals required are the lowest. The lower primary energy demand in the *National management* and *Regional management* scenarios is negated by the fact that the Netherlands is largely self-sufficient, which means the percentage of renewable energy is much higher than in the *European management* and *International management* scenarios. A considerable amount of hydrogen is imported (235 -291 TWh in 2050) in the *International management* scenario, which will have to be produced elsewhere by means of electrolysers and (renewable) electricity. This scenario then will call for a higher metal demand elsewhere for the production that meets the demand for energy in the Netherlands.

GROWING RISKS PERTAINING TO AVAILABILITY

Although relative demand in the scenarios only grows strongly between 2030 and 2050, considerable risks already arise in the short term. In the next 10 years, the average Dutch demand for neodymium, lithium, and dysprosium will already be more than 1% of current global production. As many other countries, including the United States, are accelerating their own climate action efforts, the demand will increase internationally as well.

Considering that opening a new mine takes between 10 to 15 years and that scaling up refining capacity involves significant lead times, there is a real risk that the short term demand will grow faster than supply. In addition, with increased reliance on certain countries for metals, there is a growing risk of disruptions in the availability of raw materials, which can lead to delays in product manufacturing. If this is not addressed in time, the energy transition can slow down or become more expensive.

Extraction is limited to a number of countries

The extraction of critical metals necessary for the renewable energy transition is limited to a number of countries. The world market is therefore for the majority of its demand dependent on production in those countries. The main producer of rare earth elements is China (62%). Lithium production is mostly in Australia (52%), Chile (22%) and China (13%). For nickel, the main producers are Indonesia (30%) and the Philippines (16%). Cobalt is mostly produced in the Congo (69%), and platinum mainly comes from South Africa (82%). The extraction of the required metals per technology is shown in Figure 14.

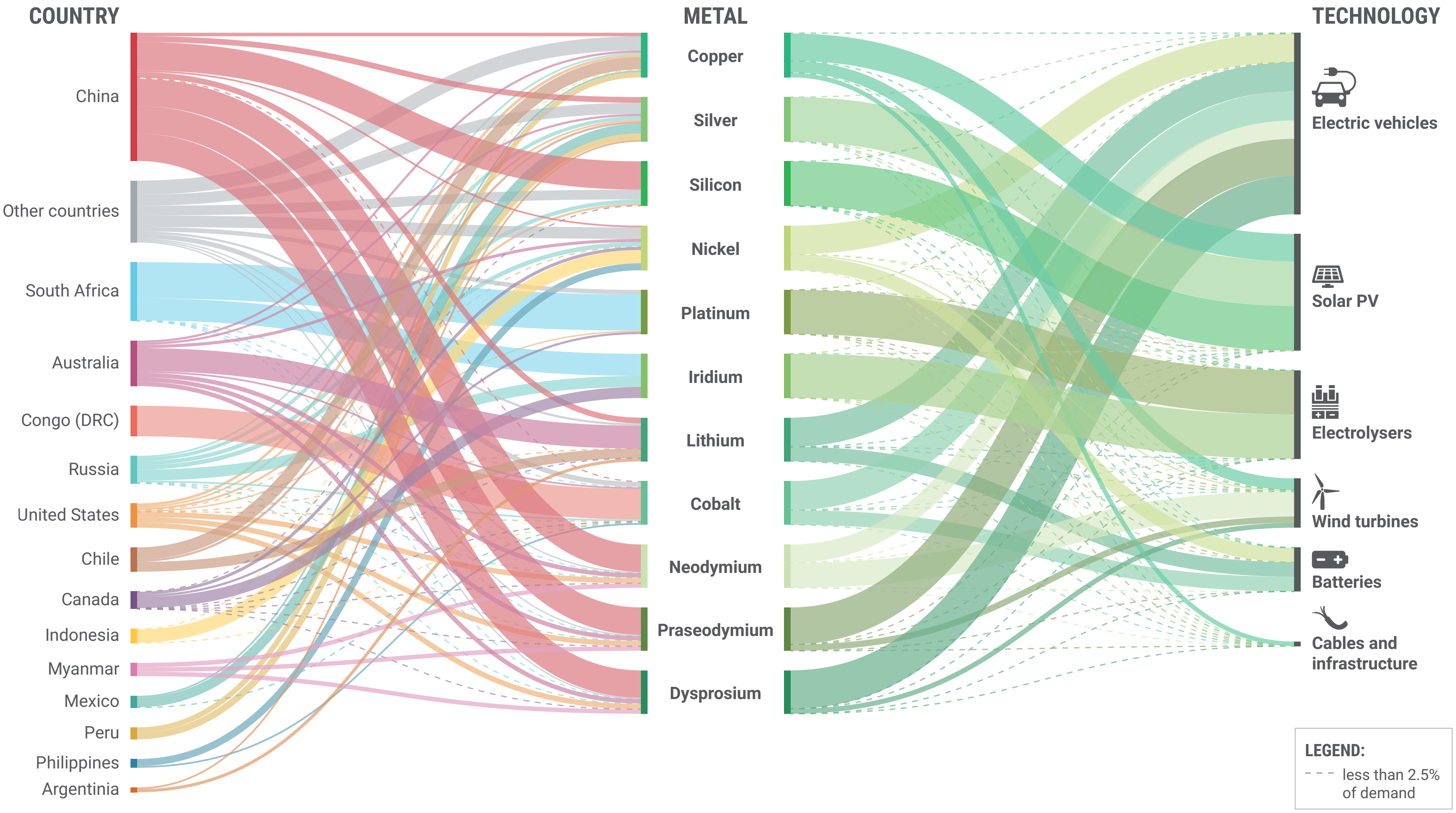


Figure 14 Extraction of critical metals needed for a sustainable energy system.

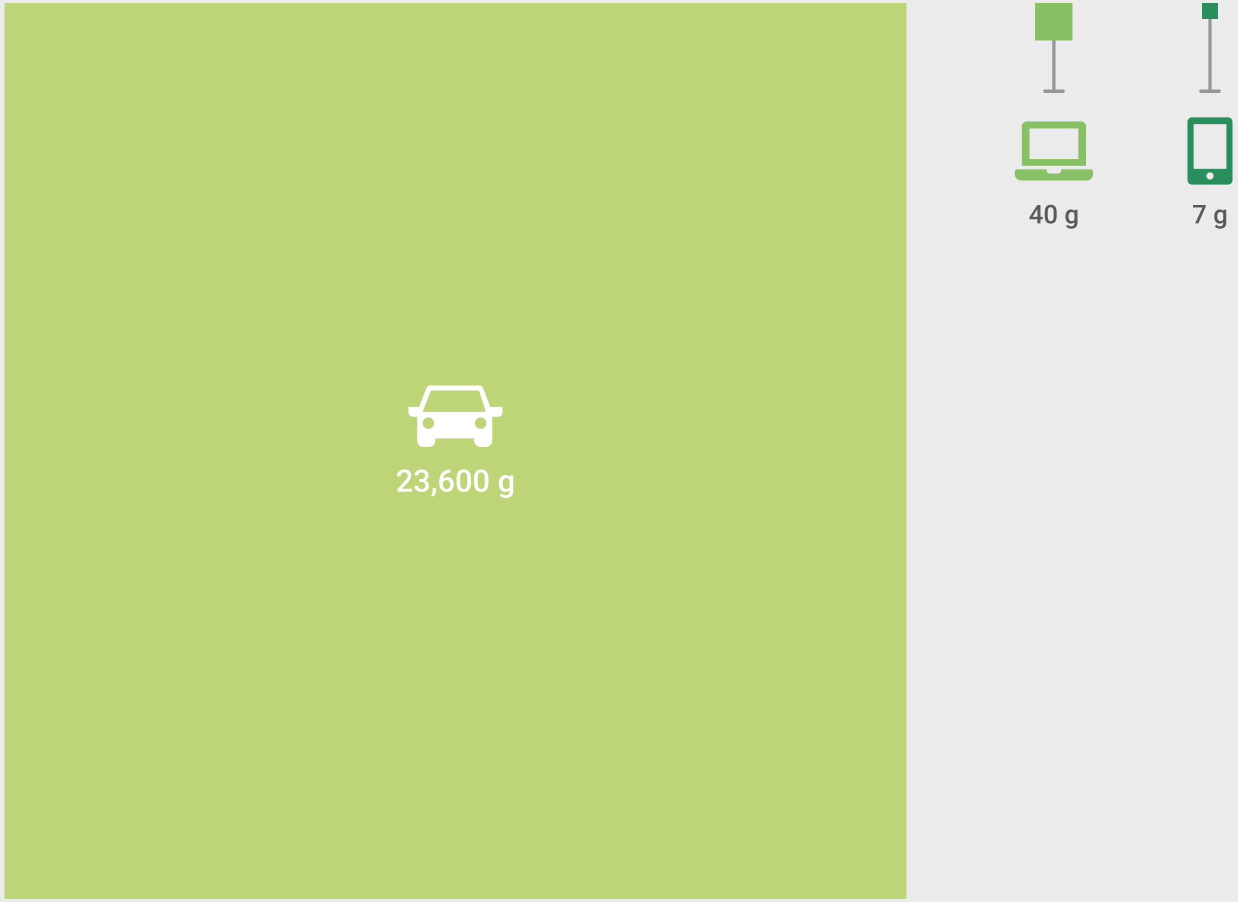
Metal demand by energy transition in relation to other technologies

Critical metals are not only needed for the energy transition, but also for other technologies. Billions of electronic devices have already been produced using batteries that also contain lithium, cobalt, and nickel. Neodymium magnets are also used in headphones and in hard disk drives (HDD). In an absolute sense, however, the demand for sustainable energy technologies is many times higher than the demand for electronics, such as mobile phones, laptops, and sensors. This is illustrated in figure 15.

The quantities of critical metals required for the energy transition are many times greater than for current applications. For example, an iPhone 6 contains about 7 grams of cobalt and 0.9 grams of lithium. The battery (NMC111 60 kWh) of an electric car contains 23,600 grams of cobalt and 8,300 grams of lithium.[38] The cobalt demand of one electric car is therefore equal to that of 3,300 iPhones.

Even in the International management scenario, the energy scenario with the lowest metal demand, the expected lithium demand between 2020 and 2050 is 130 to 178 kt. That equates to 144,000,000,000 iPhones, or nearly 8,500 iPhones per person.

Figure 15 Amount of cobalt in an iPhone, a laptop, and an electric car.



05

POTENTIAL OF CIRCULAR ECONOMY STRATEGIES

Fulfilling the commitment to a global, climate-neutral energy supply by 2050 is not feasible from a materials perspective, based on current mining production (supply) and sustainable energy technologies (demand). Global efforts will have to be made in terms of both increasing mining production and reducing the metal demand for renewable energy technologies. Since mining is not an option within the Netherlands, and the country has limited influence on mining companies, this chapter focuses on four circular strategies to reduce the demand for critical metals: *Rethink, Reduce, Repair,* and *Recycle.*

FOUR CIRCULAR STRATEGIES TO LIMIT METAL DEMAND

One way of limiting our demand for critical metals is to apply circular economy principles. The circular economy is aimed at preserving value in our economic system by limiting the demand for (primary) raw materials and reducing the associated negative effects on people and the environment.

Along with focusing on energy efficiency as much as possible, various circular strategies are available that preserve the value of products, parts, and materials for as long as possible and serve to lengthen their lifespan. This limits demand for new generation, transport, and storage capacity, which at the same time reduces the amount of critical metals required for each process. Figure 16 describes the four circular strategies.

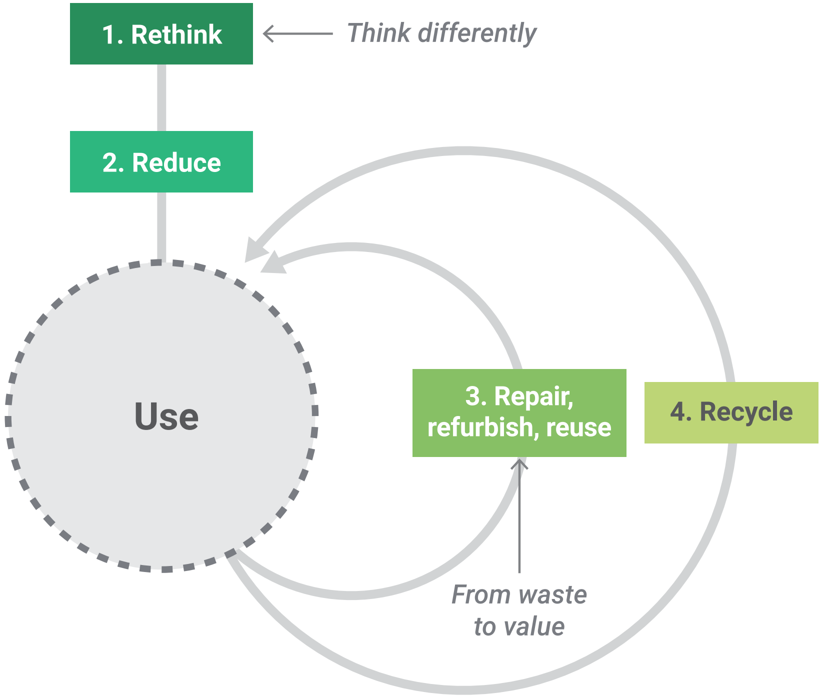


Figure 16 Circular strategies for reducing critical metal demand.

∞ ***Rethink:*** aiming for energy savings and redesigning the system so that fewer products are needed

⇊ ***Reduce:*** increasing the material efficiency of a product and replacing critical metals with less critical metals (substitution)

Repair (+ refurbish & repurpose): extending the life of products or components

Recycle: recovering materials

Starting point: the *national management* scenario

One of the four possible energy scenarios has been used as a reference point to gain more concrete insight into the potential of the circular strategies. The national management scenario was chosen because this involves the least amount of energy being generated outside national borders. As such, the indirect use of metals required abroad to meet the Dutch energy demand is reduced to a minimum. Table 2 provides an overview of the four circular strategies, along with potential results when applying each one.

Note that these results assume the potential of the different strategies. These assumptions require further elaboration regarding the technical and social feasibility. An integrated system study should be conducted, especially on the subject of the *Rethink* strategy, to investigate whether and with what consequences this circular strategy is feasible.

Table 2: Elaboration & assumptions of the four circular strategies

STRATEGY	DESCRIPTION	ASSUMPTIONS
Rethink	• Limiting the generation, transport and storage capacity of electricity • Limiting the number of electric cars	• **50% reduction of battery storage capacity** • **25% reduction in the number of passenger cars** • **20% reduction in installed solar and wind capacity** • **20% reduction in infrastructure (cables, transformers)** • **20% reduction of electrolysers**
Reduce	• Improving the efficiency of technologies • Applying technologies using fewer critical metals (substitution)	• **100% battery technology without cobalt or nickel (such as LFP)** • **100% wind turbine technology with less neodymium (gearbox)** • **100% hydrogen technology without Iridium**
Repair	Extending the lifetime of technologies	• **25% extension of the average lifespan of generation, storage technologies, and electric transport**
Recycle	Recovering and reusing materials at the end of their life	• **95% material recovery at end of life**

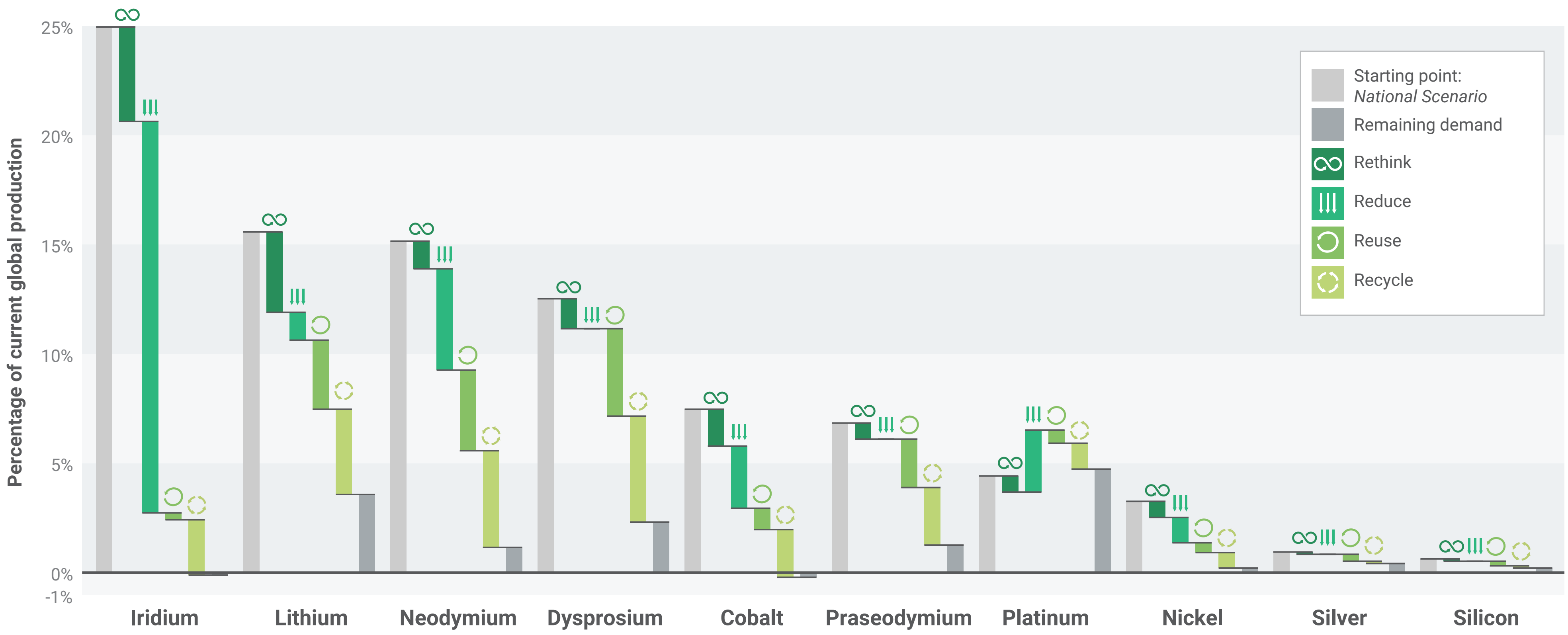


Figure 17 Potential effect of the combination of the four circular strategies on the annual metal demand (period: 2040 to 2050) for the ten metals with the highest relative demand.

CIRCULAR POTENTIAL OF COMBINED STRATEGIES

The combined implementation of the different circular strategies can significantly reduce demand for critical metals from 2040 to 2050, when demand will be highest. The primary demand for iridium and cobalt could even disappear altogether.

According to these scenarios, the combination of strategies leads to the following results for average demand for the period 2040 to 2050:

- The demand for lithium, which is required for electric vehicle batteries and battery storage, drops from 25% to about 3.5% of current global annual production.
- Neodymium demand drops from 15% to 1.1% of current global annual production, especially for use in permanent magnets used in wind turbines and automotive electric motors.
- Platinum demand, which is needed for the production of hydrogen, rises from 4.5% to 6% of current global annual production. The increasing demand for platinum as a result of the *Reduce* circular strategy calling for the replacement of iridium in the production of hydrogen, in which PEM is no longer used for electrolysis (instead, only alkaline).
- As regards iridium and cobalt, supply could, in theory, outperform demand in the Netherlands towards 2050, because new technologies contain fewer critical metals (*Reduce*) and metals from previous technologies are recovered (*Recycle*).

Focusing efforts on a single circular strategy produces insufficient effect

To achieve this reduction, it is necessary to aim for a combination of *Rethink* (alternative energy system), *Redesign* (redesigning technologies), *Repair* (extending life), and *Recycle* (recovering materials at end of life). We note that focusing on just one of these four strategies is insufficient because for example, demand must be reduced and meanwhile, supply from recycling must also be increased. Therefore, all four strategies must be employed for the best results. Figure 18 shows the annual average demand for metals when only the individual strategies have been applied during the decade from 2040 to 2050. Metal demand is in many respects still significant relative to current production.

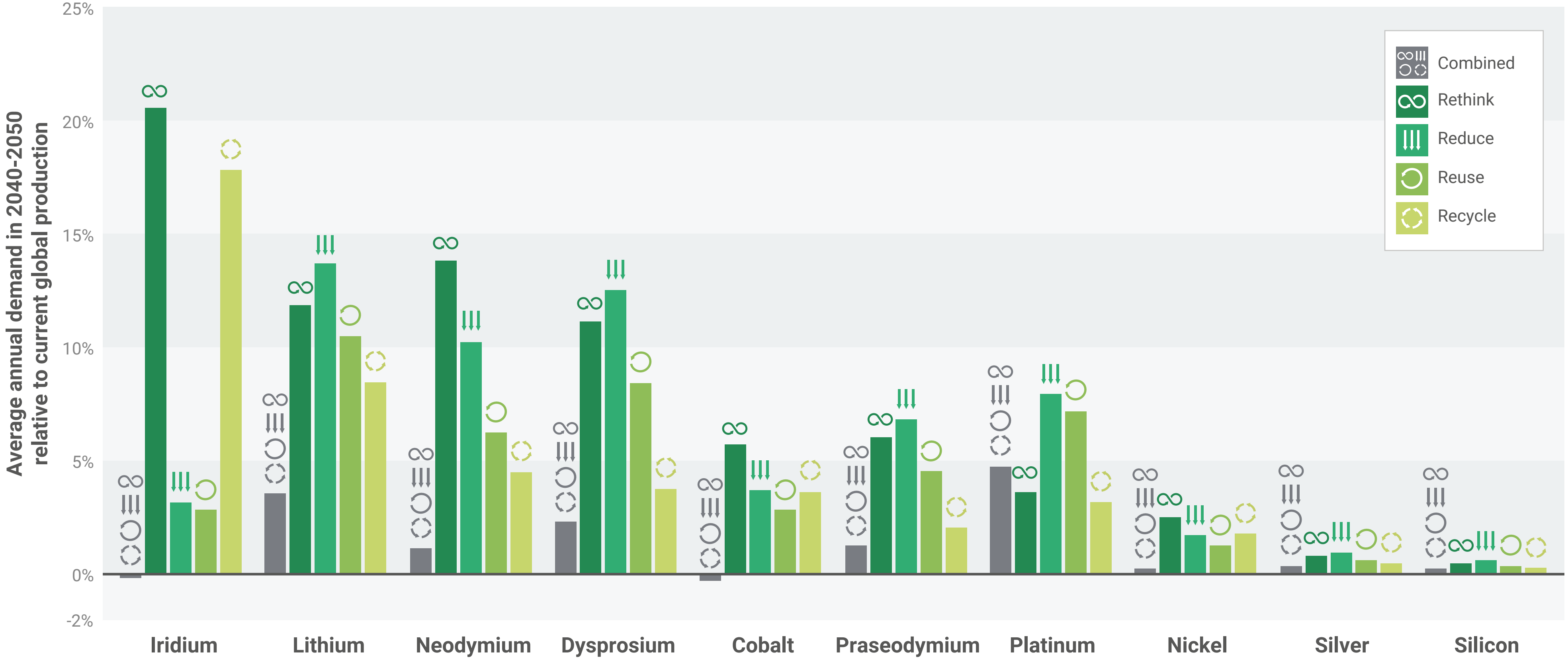


Figure 18 Average annual metal demand for individual strategies (period: 2040 to 2050).

Focusing on circular strategies now is needed for future benefits

Many of these strategies cannot be realized overnight and require the necessary preparation time. Therefore, to realize the future potential of the circular strategies, it is important to take steps in the short term. This involves, for example, including the materials perspective in the design of the energy system (*Rethink*), investing in the development of technologies using fewer critical metals (*Reduce*), implementing legislation and tax schemes for life extension and repair (*Repair, refurbish,* and *repurpose*) and investing in building sufficient recycling capacity (*Recycle*).

Scaling up mining production still remains necessary

Even if all circular strategies are applied, there will still be a residual critical metal demand that exceeds the Dutch share in global GDP (1.0%), energy consumption (0.5%) and population (0.2%). Therefore, responsible scaling up of global mining production remains necessary to be able to make the transition to a sustainable energy system across the globe and thus prevent serious climate change.

The next section breaks down the four circular strategies into greater detail.

Illustration: Lithium reduction 2020 to 2050

The reduction in critical metal demand is not instantaneous, but grows over time. A distinction can be made between the reduction in demand at one point in time (for example, in 2050) or the cumulative reduction in demand (over the period 2020 to 2050). The graph in figure 19 shows the potential reduction in lithium demand over time as a result of the different circular strategies. The effects of life extension (*Repair, refurbish,* and *repurpose*) start to manifest themselves as early as 2035. The effects of a different design of the energy system (*Rethink*) will only follow later, because battery storage systems are not expected to start playing a more significant role until 2040.

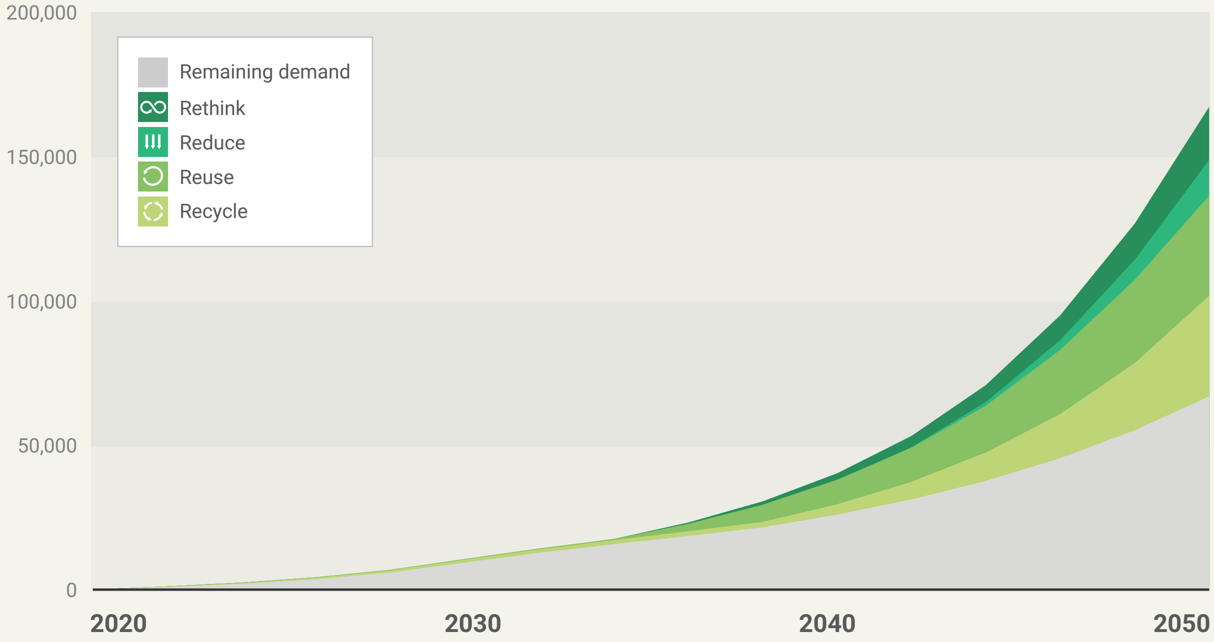


Figure 19 Cumulative lithium demand between 2020 and 2050, including the reduction potential of the different circular strategies.

RETHINK: INCLUDING THE MATERIALS PERSPECTIVE IN ENERGY SYSTEM DESIGN

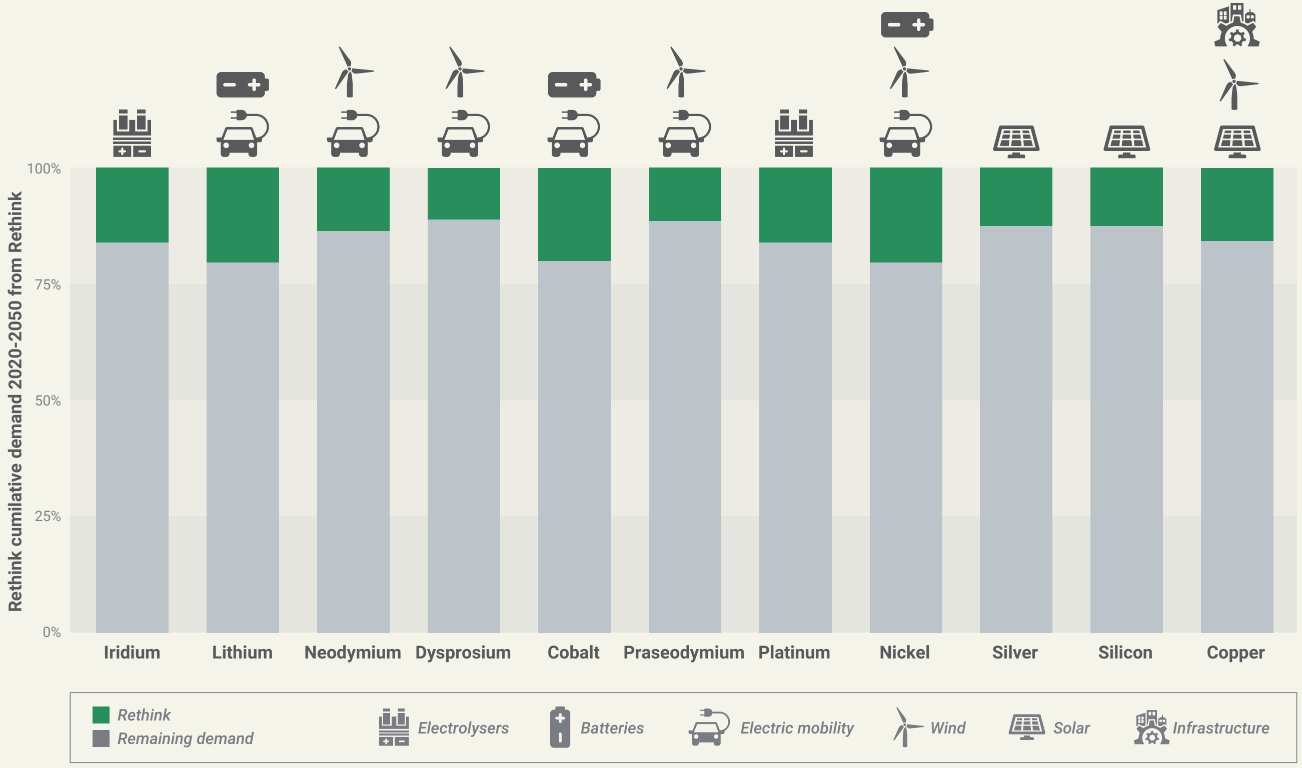


Figure 20 Reduction potential of the *Rethink* strategy for the 10 most commonly used metals, per technology in which these metals are incorporated.

The first circular strategy, *Rethink* focuses on reducing the required generation, transport, and storage capacity of electricity. This can be achieved by saving energy and focusing on increased grid interconnectivity within the energy system. In addition, this strategy is based on a mobility system with fewer vehicles, meaning less battery capacity will be required. Figure 20 illustrates the reduction potential for the 10 most commonly used metals.

Assumptions

Rethink

- a 50% reduction in battery storage capacity
- a 25% reduction in the number of passenger cars
- a 20% reduction in installed solar and wind capacity
- a 20% reduction of net capacity

Potential effects

- The average annual demand (from 2045 to 2050) of the 10 most commonly used metals can be reduced by 9-18%. This reduction is evenly distributed over the different metal types.
- More far-reaching reduction measures seem possible, by focusing on a mobility system with (even) fewer vehicles, among other things. To achieve this, it is necessary to reduce the current number of 8.7 million cars by more than 25%. By focusing more on shared cars, the Dutch transport demand could be met with 5.7 million passenger cars and 240,000 shared cars: a reduction by more than 30%.[39-42]

Required effort

- **Large-scale energy savings** to reduce the total demand for generation, transmission and distribution, and storage capacity
- **More flexibility in electricity demand from (bulk) consumers,** meaning less storage capacity is required, especially during peak times
- **More efficient use of vehicles** by organising a mobility system based on more shared mobility, so that fewer electric vehicles are needed
- **Optimal use of battery capacity** by using batteries in passenger cars for grid balancing as much as possible
- **Design an energy system** in which metal demand is taken into account, in addition to affordability, support, and spatial embedding, among other factors

REDUCE: BOOST TECHNOLOGIES USING FEWER CRITICAL METALS

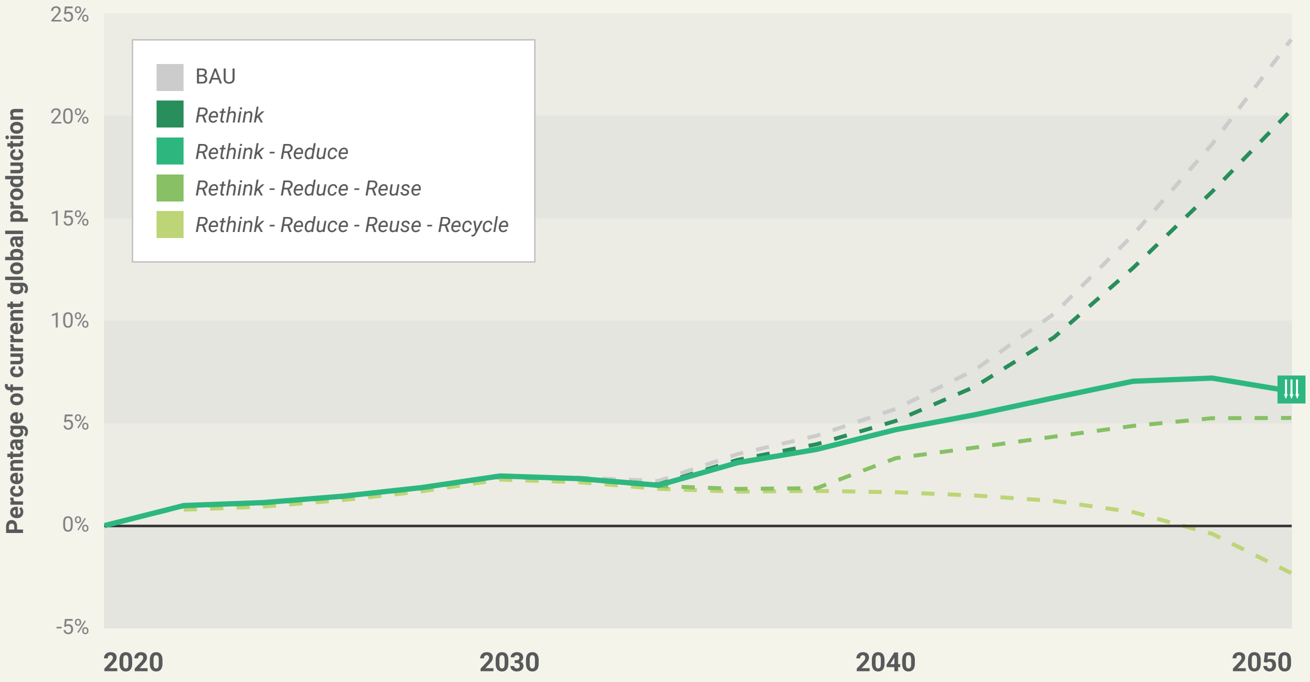


Figure 21 Development of annual cobalt demand as a percentage of current global production.

The circular strategy *Reduce* is based on technologies that contain less or no critical metals, but which have already sufficiently proven their potential and which can be produced on a commercial scale. However, these technologies currently do not always prevail due to higher costs or a lower performance (for example, the energy density of an LFP battery containing no cobalt or nickel is 30-40% lower than an NMC battery).

Assumptions

∞ *Rethink* +

|‖ *Reduce* −

- **100% battery technology without cobalt or nickel (LFP batteries)**
- **100% wind turbine technology with less neodymium (turbines with a gearbox)**
- **100% hydrogen technology without iridium (alkaline technology, with platinum)**

Potential effects

- Demand for the most critical metals falls significantly: from 2045 to 2050, up to 60% less cobalt and nickel is needed and even up to 90% less iridium compared to *Rethink*. Demand for neodymium can also be reduced by more than 30%.
- The total amount of metals needed for the energy transition hardly decreases (-0.7%). This is mainly because of a shift towards metals that are less critical. For example, an LFP battery replaces cobalt and nickel, but requires more iron.
- Since critical metals are often expensive, this strategy reduces the potential value released during recycling. Consequently, the business case for recovering metals may become less favourable.

Required effort

- **Investment in the upscaling** of generation and storage technologies that contain less critical metals (substitution), but that are already market ready (TRL-9)
- **Promoting technologies using less critical metals,** for example, through innovation subsidies and criteria in tenders for wind turbine parks and solar farms.

REPAIR: EXTEND THE LIFE OF PRODUCTS AND PARTS

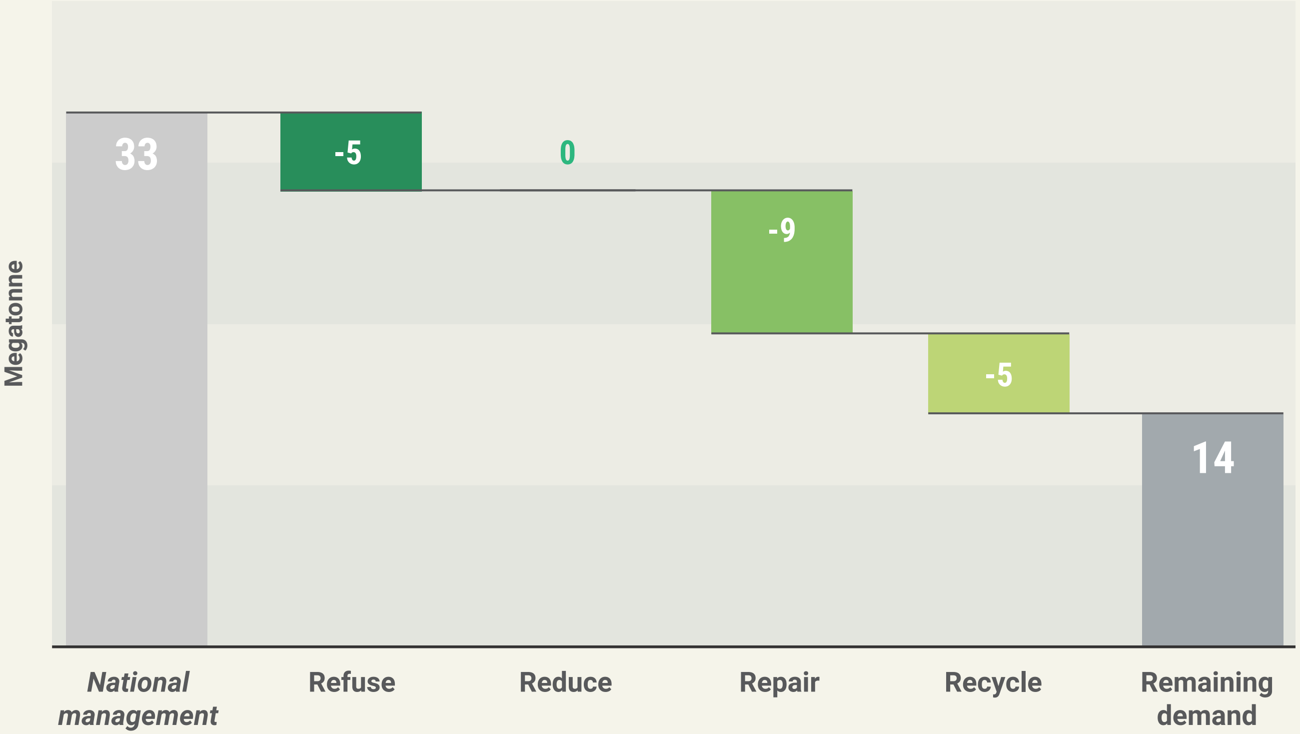


Figure 22 Reduction of the various circular strategies in comparison to the total amount of raw materials needed between 2030 and 2050 for the components included in this study.

The circular strategy *Repair* focuses on extending the life of technologies. Because wind turbines, electric cars, or solar panels last longer, they need to be replaced less often. By focusing on repair and maintenance, the economic value of products and parts is preserved, while it also reduces the demand for products that contain critical metals. Figure 21 shows that this strategy has the greatest effect of the four strategies on reducing total primary metal demand.

Assumptions

∞ *Rethink* +
||| *Reduce* +
○ *Repair* −

- **Extending the average life of technologies by 25%**

Potential effects

- Fewer critical metals are needed because technology needs to be replaced less quickly. Life extension means that demand will drop mainly from 2030 onward, because the large-scale replacement of technologies that have been added since 2010 will commence around that time.
- Cumulative metal demand could fall by nearly a quarter between 2020 and 2050. The largest reduction in material demand is accounted for by extending the life of solar panels and wind turbines.
- As a result of the slower build-up of the sustainable energy system, the increase in the supply of metals for recycling has slowed.

Required effort

- **Tightening legislation and regulations** on the minimum lifespan of products (e.g. based on Ecodesign Directive guidelines), agreements on extended producer responsibility during the lifespan, and legal safeguarding of responsibility when products are reused
- **More technical and service personnel** who can maintain and repair systems
- **Tax shifts** from labour to raw materials and pollution to create a business case for repair and reuse
- **Research** into technical barriers to the reuse (and repurposing) of products or parts, for example, repurposing car batteries for energy storage in the built (human-made) environment

RECYCLE: REUSE OF MATERIALS FROM ENERGY TECHNOLOGIES

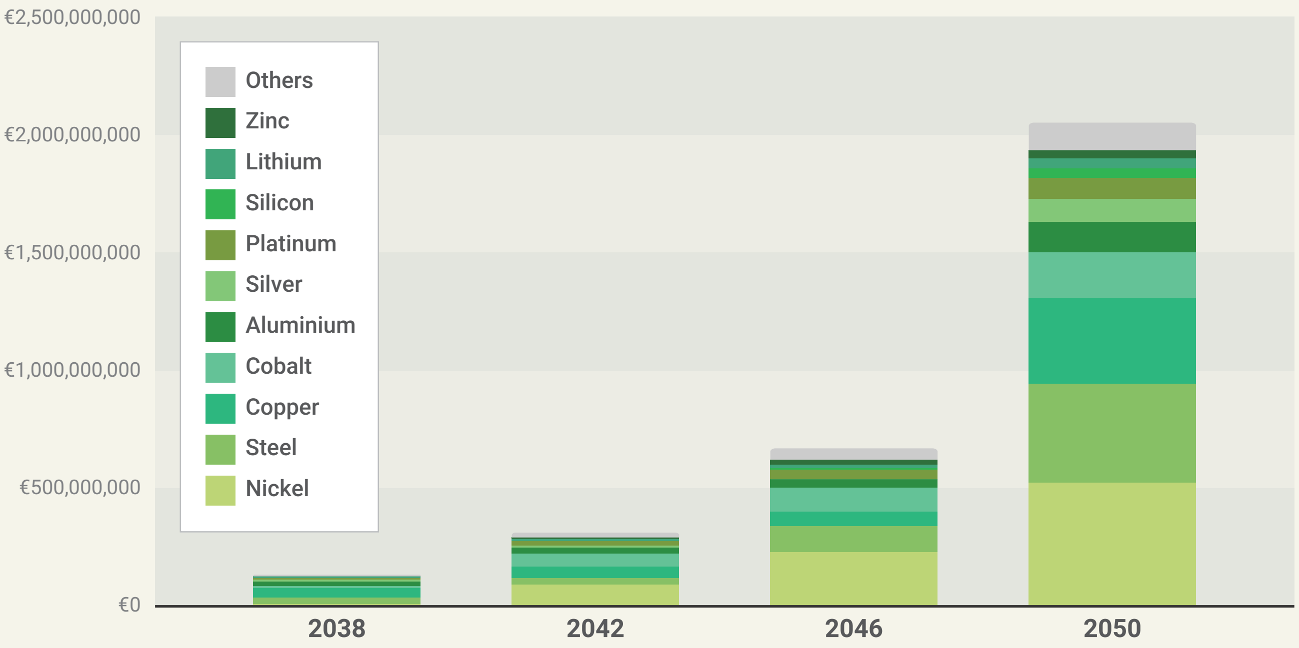


Figure 23 Potential value of materials released from the Dutch energy infrastructure.

The circular strategy *Recycle* focuses on recovering the metals at the end of the lifespan of sustainable energy technologies. This is the lowest-value circular strategy, which becomes suitable when the other strategies have been completed or are no longer possible. However, proper recycling with minimal losses is a requirement. Sooner or later, products will have to be reintroduced to the system at the materials level. Figure 23 shows the value of the released materials, against the current new material price.

Assumptions

Rethink +
Reduce +
Repair +
Recycle −

- **Recycling rate of 95% of all metals, at the end of product life**

Potential effects

- From 2040 onwards, the released mass of used material available for recycling will increase significantly because around that time, many technologies will have reached the end of their lifespan and need to be replaced. At the same time, there is already enough volume being released for reuse well before 2040 to establish recycling technology as soon as possible. Significant volume will already be released earlier, especially in terms of car batteries, solar panels and wind turbines.
- From 2040 to 2050, recycling can lead to a 20-80% reduction in demand of the aforementioned 10 commonly used metals compared to current production levels, in addition to the effects achieved with *Rethink, Reduce,* and *Repair.*
- Theoretically, the Netherlands could become a net exporter of cobalt around 2050. This is because cobalt will disappear from new battery technology and is then released from recycling old batteries.
- The value of metals released annually will rise to more than €2 billion in 2050 (based on current material prices) and is set to increase further after 2050.

Required effort

- ***Design for recycling*** means to design products in such a way that critical metals can be recovered more easily
- **Improving recycling technology** to increase the purity of the recycled metal
- **Investing in recycling capacity and infrastructure** to ensure sufficient scale to decommission, transport, and process sustainable technologies
- **Increasing the level of knowledge** on recycling, which mainly concerns specialist technical knowledge within the industry

PRECONDITIONS FOR INDUSTRIAL DEVELOPMENT

The Netherlands is dependent on foreign producers and suppliers for the production of the vast majority of its generation and storage capacity. As described in Chapter 3, geopolitical dependency is a problem that needs to be resolved mainly at the EU level. This is illustrated by the recent news that one in five factories in the Netherlands is facing production issues due to the growing global scarcity of production resources and materials.[43]

Nevertheless, some Dutch parties can influence the supply chain of critical metals. And opportunities present themselves to play an even greater role in the future, provided industrial stakeholders and the government make the right investments. In a number of interviews (see Appendix I), companies mention requiring three preconditions in order to be able to make the necessary investments:

1. Long-term industrial policy
2. Tightening of laws and regulations
3. Continuous knowledge development

1. Long-term industrial policy

Risks related to commodities partly arise from the absence of a consistent vision and strategy regarding commodities, the lack of a long-term policy, and limited involvement by the government. After all, the Netherlands and its industry compete with strong players such as China, which use the commodity market to pursue geopolitical objectives.

To date, the Dutch (and European) governments have relied on market forces, combined with a few minor legal interventions regarding, for example, recycling and product design. This is in contrast to countries like China, Japan, and the US, where governments take more control, especially in the case of China.

In the future, the Dutch approach based on market forces will prove insufficient. A strong industrial policy is needed to promote and support specific industrial activities. Within the Netherlands, industrial policy can be applied to three phases in the supply chain: the design phase, the use phase, and during processing (recycling):

- The design phase lays the foundation for future reuse of critical metals, for example by focusing efforts on *design-for-disassembly* and *design-for-recycling*. This ensures processable flows at the end of product lifecycles.
- The use phase involves focusing on activities that extend the life of products and parts. This creates new economic activity and at the same time reduces the demand for metal.
- In the recycling phase, it is important to optimally process the metal flows to create the purest possible end product. This requires strong logistical support to sort products and parts and transport them to recycling sites.

In the coming years, as part of the recycling effort, it is important to focus investments on large-scale, 'omnivorous' processes. These can handle different flows and at the same time produce a wide range of materials as output. There are two reasons why this matters:

1. No large volumes of a singular critical metal are expected to be released until 2030. Therefore, focusing on specific flows would not make for a good business case until that time.
2. The supply of critical metals for recycling is expected to remain diverse for the time being, because critical metals come from a wide variety of sources. Recycling processes that can deal with this diversity can therefore offer an advantage by, for example, processing different types of batteries, rather than just NMC 811 batteries.

When volumes subsequently increase after 2030 and the technological uncertainty subsides, the focus can be shifted to more specialist and more efficient processes.

2. Tightening of laws and regulations

Current legislation and regulations are aimed mainly at promoting recycling. Hardly any attention is paid to reuse and repair, and yet these strategies can in fact have a huge impact. This is slowly starting to change, thanks to the tightening of guidelines with the European *Ecodesign* Directive. Guidelines are currently being developed for many new products, including batteries and electronics.[15]

Legislation and regulations concerning product design can also guide the production process. Examples include employing instruments such as minimum material efficiencies and rules regarding the prioritisation of critical metals that will be used for the betterment of society, such as sustainable energy technologies. An example of comparable efficiency legislation includes energy saving measures in industrial processes that must be taken if they pay for themselves within five years. An example of prioritisation is banning helium, which is extremely scarce, for use in party balloons.

In addition, a number of tax rules could be amended to incentivize circular business cases. This applies to two aspects in particular[44]:

- Pricing of external costs, such as CO_2 emissions and environmental pollution, through which parties are financially steered towards sustainable processes. This encourages the industry to reuse critical materials, as the acquisition of new raw materials involves significantly more external costs compared to recovery from a recycling process.
- Reducing taxes on labour, to improve the business case of direct reuse, repair, and refurbishment. A combination with a higher tax on (primary) raw materials provides a financial incentive for extending the lifespan, which in turn lowers future demand for critical metals.

In addition, a certain degree of legislation and regulations to process released materials within Europe is subject to consideration. For example, an export ban on products containing certain critical metals, in line with the current export ban on waste. However, this can also have adverse effects, such as an export ban from other countries to Europe.

3. Continuous knowledge development

Innovations within the industry are generated through the Netherlands' strong R&D infrastructure, often clustered around large industrial players and technical universities. For example, the combination of M2i and Tata Steel Europe, or Metalot with Eindhoven University of Technology and Nyrstar, among others. However, Dutch knowledge is generally limited to the metals that Dutch industry has historically focused on: steel, zinc, tin and, to a lesser extent, aluminium.

The amount of knowledge of all other metals is relatively limited. Knowledge about the supply chain and associated dependencies and risks is also insufficient. As a result, the existing knowledge infrastructure has so far proved insufficient to solve urgent problems surrounding critical metals.

Several other countries have their own research institutes and think tanks dealing specifically with critical metals. Examples include the *Critical Materials Institute* (CMI, in the US), JOGMEC (Japan), and the *Deutsche Rohstoffagentur* (Germany). These institutes are collaborating with each other to maintain the level of knowledge regarding raw materials, even if attention is weakened by a lack of incidents.

Organisations such as CMI and JOGMEC are not only active as think tanks, but have the expertise and budget to make targeted investments. This additional expertise is needed because there are many innovative ideas about product design and recycling, but risk-bearing funding is lagging behind. This is especially true for new and relatively high-risk technologies that have already proven themselves in a lab environment, but which need funding to scale up to pilot level (*Technology Readiness Level* 5-8).

To reach the level of these foreign agencies, development of structural knowledge of critical metals in the Netherlands will involve building technical knowledge within the industry and forming a better understanding of the risks and dependencies discussed earlier in this study. Ideally, this knowledge development would be linked to investment opportunities for research and innovation, for example, in collaboration with European programmes such as *EIT Raw Materials*.

06

RECOMMENDATIONS

With the current metal production and the demand for different metals for each technology, there are not enough critical metals to make the global transition to a clean energy system. However, to prevent serious climate change, a climate-neutral energy supply by 2050 at the latest is vital. To limit these risks in the Netherlands and build a future-proof industry here, a total of four preconditions must be met. This study also calls for additional efforts that put the four circular strategies into practice. This chapter outlines these preconditions, circular strategies, and the recommendations for implementation.

To make the transition to a circular energy system possible, it is important to begin with a solid structural understanding of the materials that are required. The availability of these materials must become one of the factors guiding choices toward building that system. Private parties are not able to resolve this material issue on their own; this would be an example of market failure.

Government interventions are therefore necessary, both at a national and European level. Based on the analysis set forth in this study, there are a total of four preconditions for intervention that will both ensure the security of the required critical metal supply and also lead to further development of industrial activity, which, in turn, enhances the focus on the four circular strategies.

Preconditions for security of supply and industrial development

The growing demand for critical metals leads to geopolitical dependency on a limited number of countries for mining and refining. This dependency brings certain environmental and social consequences within the supply chain. To realize a climate-neutral energy supply in the Netherlands, it is therefore necessary to guarantee security of supply. We see two preconditions for this:

A Establishing a Dutch system for **permanent monitoring and continuous knowledge development.** This serves to update and maintain the knowledge base and insights surrounding critical metals and other raw materials, for example, through a government-affiliated knowledge institute. This arms the country with a better ability to respond to future developments. Such a knowledge base also helps the private and public sectors make targeted investments in industry and to thus capitalize on economic opportunities.

B Increasing the **transparency of international supply chains**, to gain better insight into the environmental and social impact of critical metals throughout the chain and thus manage the reduction of that impact.

The Netherlands currently deploys little industrial activity where supply chains of critical metals are concerned, such as product and material life extension and recycling. However, there are opportunities to build efforts in the future. To ensure the industry starts investing in this and foster business cases, we identify two additional preconditions:

C Developing a **long-term industrial policy** that directs investment decisions. In drawing up that policy, intensive cooperation between the government and industrial stakeholders is essential, as is the relationship between activities in the Netherlands and elsewhere in Europe.

D Tightening **laws and regulations** that promote high-quality materials reuse, including tightening product legislation, such as Ecodesign Directive guidelines, and strengthening extended manufacturer's responsibility.

Circular strategies for reducing metal demand

This study has emphasized that achieving a climate-neutral energy hinges on reducing the amount of critical metals required to build the energy system. Saving energy is an important first step, because it immediately reduces the need for generation, transport, and storage capacity. Here is the four-part circular strategy, that when applied together, can reshape how the Netherlands uses and recovers critical metals:

1. Rethink: incorporating a materials perspective when designing the energy system, to enable the same functions with less generation, transport and storage capacity. This includes focusing on strong interconnectivity, combining electricity production and use at the same time and place, and actively adjusting and balancing industrial processes in the event of a surplus or shortage of electricity.

2. Reduce: promoting technologies using fewer critical metals to reduce metal demand per technology. For example, promoting innovation and substituting with alternative materials.

3. Repair, refurbish* and *repurpose: extending the lifespan of products and parts to reduce the amount of new materials. This includes encouraging initiatives for high-value reuse and shifting taxation from labour to pollution to help promote the relevant business cases working toward this end.

4. Recycle: recovering materials from decommissioned energy products to create a secondary material flow. This specifically concerns investing in recycling capacity, regionally whenever necessary to ensure optimal logistics.

RECOMMENDATIONS ON THE IMPLEMENTATION OF PRECONDITIONS

PRECONDITION A	RECOMMENDATION	PARTY
A **Establishing a national system for permanent monitoring and continuous knowledge development** Developments in critical metals can surface in rapid succession and are sometimes unpredictable. Permanent monitoring of risks and disruptions in global supply chains and up-to-date knowledge about developments are necessary to be able to make timely adjustments when risks become too great. In addition, thorough knowledge of industrial processes is required in order to both upscale those processes and to be able to make sound investments in innovations. In addition to European programmes, it is important to introduce this nationally as well.	Make structural investments that enhance national expertise in critical metals. Secure this by establishing a knowledge institute that focuses explicitly on this subject. Study successful examples of such organisations already existing abroad. This institute should also be a connecting factor between umbrella organisations such as Metaalunie and FME, universities, knowledge institutes such as TNO, Clingendael, and HCSS; include the central government, in collaboration with R&D departments of industrial stakeholders.	• *Central government* • *Science* • *Business*
	Invest in accelerated development of technical innovations for energy generation and storage, with a focus on practical application. In doing so, explicitly aim for a low use of critical metals to ensure the future-proofing of the production of these generation and storage technologies.	• *Central government* • *Science* • *Business*
	Include the required critical metals for the different energy scenarios in the further development of these scenarios. Remember also the follow-up processes of the Integrated Infrastructure Exploration and the further development of the Energy Transition Model.	• *Grid operators* • *Knowledge institutes*

PRECONDITION B	RECOMMENDATION	PARTY
B **Increasing transparency of international supply chains** The social and environmental impacts of mining and refining are significant. Yet we cannot do without new metals in our efforts to realize a sustainable energy system. Supply chain transparency is an important first step towards reducing negative impacts.	Include supply chain transparency of used materials and products in public tenders for sustainable energy technologies, such as wind farms, solar farms, and possible system storage. Create volume by working with a front-runner approach, possibly within Europe.	• *Central government* • *Provinces* • *Municipalities*
	Support the development of effective and unambiguous certification schemes for materials where these schemes do not already exist. Where possible, use the European CERA certification system under development.[36]	• *EU* • *Central government* • *Producers*
	Include sustainability aspects of mining activities in trade agreements between the EU and the foreign countries where mining takes place. The first steps are already being taken in this respect. Reinforce the efforts on this from the Netherlands.	• *EU*

PRECONDITION C	RECOMMENDATION	PARTY
C **Developing a strong industrial policy to make future-proof choices** A sound and long-term strategy outlining the Netherlands' role in the critical metals supply chain is important as a basis for policy and investment choices. Intensive public and private sector collaboration is vital. After all, the government can support industries with the right infrastructure and possible financing, and in turn, industry can support the government in realising its policy objectives while building future earning potential for the Netherlands.	Develop a joint investment agenda for a critical metals industry. The location of the Netherlands is a distinguishing factor compared to other countries, especially with regard to the recycling of wind turbines from the North Sea. When drawing up this agenda, it is important to align with Europe. Take into account what developments are already taking place in other European countries. In addition, assess the availability of EU funding for investments.	• *Central government* • *Invest-NL* • *Industry*
	When analysing the current stock of critical metals, include metals from industrial waste. In doing so, build on the current development of the Raw Materials Information System (RMIS). Examples are residual streams from TATA Steel and Nyrstar. There are also various 'waste mountains' as a result of former residual streams from industrial processes containing relatively high levels of critical metals, such as the Slufter depot on Maasvlakte.	• *Invest-NL* • *Industry* • *Knowledge institutes*

PRECONDITION D	RECOMMENDATION	PARTY
D **Tightening legislation and regulations to enable high-value reuse** Legislation and regulations determine the scope companies have in their business operations. This concerns their use of energy and raw materials as well as the design and manufacture of their products. Stricter legislation ensures energy savings and supports circular product development.	Tighten legislation on energy savings and increase enforcement capacity. One such example is the current regulation that energy-saving measures must be taken if they pay for themselves within five years, which is enforced to only a limited extent.	• *Central government* • *Environmental services*
	Tighten European and national product standards to secure efficient use of materials. Examples include European Ecodesign Directive guidelines and sector-wide product standards. In addition, critically review existing standards to prevent unnecessary use of critical metals.	• *EU* • *Certification bodies*

RECOMMENDATIONS ON CIRCULAR STRATEGIES

1. RETHINK	RECOMMENDATION	PARTY
Designing an energy system from a material perspective Currently, choices in the energy transition are made on the basis of affordability, support, and spatial embedding. To achieve truly future-proof choices against supply chain disruptions or negative impacts, the necessary critical metals must be included as a fourth design perspective. This reduces the total generation, transport, and storage capacity of electricity.	Make a strategic choice for strong interconnectivity with other countries within Europe. This balances supply and demand and reduces the amount of storage capacity needed. Investigate what is needed to shape this interconnectivity, possibly with a *coalition of the willing* around the North Sea. Deployment of the North Sea Wind Power Hub is one such example.[45]	• *Central government* • *National grid operator*
	Focus on combining demand and production of electricity at the same time and/or location. This limits the required amount of storage and transport capacity. This, for example, can be achieved by setting additional requirements in the subsidy scheme for sustainable energy production.	• *Central government,* • *Developers of wind and solar projects*
	Promote the use of a flexible energy rate, for example, on an hourly basis. This discourages energy consumption when supply is low and encourages use during times of overproduction.	• *Central government* • *Energy suppliers* • *National grid operators*
	Make it possible for major energy consumers, such as industrial processes, to temporarily increase or decrease production in the event of impending congestion on the electricity grid. If necessary, offer financial compensation for this. This means that less transport and storage capacity will be required to continue to meet electricity demand. This can be an alternative to grid reinforcement. Carefully assess which industrial applications are suitable for this. For some processes, this is relatively easy, while for others, it is practically impossible.	• *Central government* • *Provinces* • *Regional grid operators*
	Focus on shared mobility and other forms of collective transport to reduce the total demand for cars, including electric cars and the batteries required for these cars. This can be achieved by means of tax measures (central government), by intensifying high-quality public transport (regional governments), and by reducing the number of parking spaces in cities (municipalities). ▌ ***For further elaboration, see the study Metal Demand for Electric Vehicles***[7]	• *Central government* • *Provinces* • *Transport regions* • *Municipalities*
	Use electric cars as storage capacity, through which extra electricity is available in case of an imminent threat of under capacity as a result of high demand or low supply. Electric cars thus supply electricity from the battery back to the grid. The first large-scale experiment in the Netherlands is currently being carried out in Cartesiusdriehoek (Utrecht).	• *Municipalities* • *Grid operators* • *Energy and flexibility suppliers*

2. REDUCE	RECOMMENDATION	PARTY
Promote technologies using fewer critical metals The amount of critical metals required differs per technology. By targeting technologies with lower metal demand, total demand can be reduced. An important side note is that often, a shift to other metals used as substitutes can in turn become critical as well.	Invest in alternative forms of energy storage with a significantly low demand for critical metals. This could be in the form of underground water reservoirs (example: Dutch OPAC concept), air-based storage (*Compressed Air Energy Storage*) and types of batteries with a lower critical metal demand (such as flow batteries).	• *Central government* • *Regional government*
	Encourage relevant parties to participate in European working groups for the purpose of tightening European guidelines, including Ecodesign guidelines for batteries. On the one hand, this tightening is necessary to create a level playing field for *design-for-disassembly, design-for-repair,* and *design-for-recycling*. On the other hand, this simplifies future recycling.	• *Industry* • *Umbrella organisations*
	In public tenders, extend the focus explicitly on circular product design and possibilities for life extension, basing decisions beyond price alone. Create volume by working with front-runners, possibly within Europe. Where possible, permits for sustainable energy projects should include requirements for (long) service life and disassembly.	• *Central government* • *Regional government* • *Municipalities*
	Set innovation policy that focuses not only on technical performance and costs, but also on scalability based on the availability of materials and the environmental and social impact of certain product choices. Consider these factors when awarding innovation subsidies.	• *Central government* • *Research institutions*

3. REPAIR	RECOMMENDATION	PARTY
Extend the life of products and parts Many renewable energy technologies do not yet have a clear destination at the end of their lifecycle. Extending the service life and reusing products in other functions reduces the number of new products required in the long run.	Offer financial incentives for initiatives aimed at high-quality reuse of sustainable energy technologies. This will be necessary in the coming years, because a business case is currently lacking. Examples include refurbishing and reusing old solar panels.	• *Central government* • *Industry*
	Promote the design of new products and systems with a long lifespan and, where necessary, adjust tax and legal rules to support this shift. For example, extending depreciation periods.	• *EU* • *Central government* • *Business*
	Research how batteries from electric cars can be reused as battery storage after completing their lifecycle, both technically and legally. This significantly extends the service life and prevents environmental impact due to recycling and new battery production.	• *Central government* • *Regional government*

4. RECYCLE	RECOMMENDATION	PARTY
Recovering materials from energy products When sustainable energy products such as solar panels, wind turbines, or batteries can no longer be used, it is important to recycle them and recover the critical materials with maximum preservation of quality. The volumes of such materials that are being released will grow enormously in the coming years. Timely investment can lead to new industrial activity, employment, and a long-term economic revenue model.	Invest in new processing and recycling capacity in the short term to anticipate future volumes. Within a few years, significant quantities of old batteries and solar panels will enter the market. In the first few years, opt for omnivorous recycling processes, to be able to process the diversity of the products that are being released.	• *Central government* • *Investors*

07

APPENDICES

APPENDIX I. FORMATION

This report was produced in collaboration between Metabolic, Copper8, Quintel Intelligence and Polaris Sustainability. The report contains data inventoried by the Centre for Environmental Sciences (CML) of Leiden University, on behalf of the Netherlands Environmental Assessment Agency (PBL).

This research was carried out on the joint instruction of a group of Dutch parties: Invest-NL, the Provinces of South Holland and Flevoland, the three regional grid operators, Alliander, Stedin and Enpuls, and the Directorate-General of Public Works and Water Management.

The translation into English was also made possible by Rijkswaterstaat, the executive agengy of the Ministry of Infrastructure and Water Management.

The research further included five consultations with a steering group from our partners. The broad outlines and scope were determined during these meetings. In addition, interviews were held with various experts to gather background information and to create a perspective of the opportunities for the industry. Finally, the draft report was reviewed by a number of experts. These reviews were included in this final report.

Steering group

- Guy de Sevaux (Invest-NL)
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- Koen Eising (Alliander)
- Dirk Bijl de Vroe (Stedin)
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- Marieke Spijkerboer (Ministry of Infrastructure & Water Management)
- Matthew van de Pol (Ministry of Economic Affairs & Climate)
- Alexander van der Vooren (SER)

APPENDIX II. PROPERTIES OF CRITICAL METALS

Chains of critical metals are long and complex. To illustrate, this appendix explains the main characteristics of some critical metals.

The USGS for production figures[46], reports from the IEA[1] and the World Bank[2] for the dynamics in the chain and a report from TNO on the copper chain[47] and other data has been to draw up this appendix.

REE METAL	APPLICATION	MAIN PRODUCTION	ANNUAL PRODUCTION (2020)
Rare Earth Elements (REE)	**Wind turbines + EV**	**China (58%)**	**240,000 tons**

Extraction & Refining

China is largely responsible for mining the rare earth elements, including neodymium, dysprosium and praseodymium. In addition, production takes place in the US, Myanmar and Australia. China also controls most of the refining (~70%) and increasingly, the production of parts containing these metals. The Australian Lynas Corporation, the largest Western producer, is financed by Japan, on the condition that Japanese industry is given priority of supply in case of scarcity.

Environmental and social impact

In the past, there were many problems with extreme environmental pollution in rare earth production due to the use of hydrogen fluoride in the electrolysis step of the manufacturing process. In recent years, this pollution seems to have improved under pressure from the Chinese government. There are, however, reports of Chinese forced labour in the production of these metals.

Recycling

A lot of research is being conducted into the recycling of REEs, including from the EU. However, this has not yet got off the ground sufficiently because newly produced REEs, despite the geopolitical dependencies, are still too cheap to make recycling commercially feasible. When recycling REE magnets, product design is vital, because these magnets get contaminated quickly, which makes recycling much more difficult.

3 Li LITHIUM 6,941 METAL	APPLICATION	MAIN PRODUCTION	ANNUAL PRODUCTION (2020)
Lithium	**EV + storage**	**Australia (55%), Chile, Argentina**	**82,000 tons**

Extraction & Refining

About half of global production comes from Australia, based on traditional mining of spodumene, a mineral. Most of the remaining production comes from salt lakes in Chile and Argentina. Nearly half of the world's lithium concentrates are shipped to China, where it is used to make a chemical compound (hydroxide or carbonate). The lithium industry is financially weak due to a long period of very low prices and is therefore struggling to scale up quickly.

Environmental and social impact

In South America, production takes place in salt lakes, which consumes a lot of water and leads to conflicts between the local population and mining companies. In addition, the evaporation baths in which the lithium is extracted causes major damage to the landscape.[48] Australia can still considerably expand its production. This too consumes a lot of water, but will probably lead to fewer conflicts with the local population.

Recycling

Lithium can be recycled from existing Li-ion batteries, but recycling rates are very unpredictable (5-50%). Rapid changes in battery chemistry and design and competition from relatively cheap primary production of lithium have so far led to the absence of large-scale lithium recycling plants.

METAL	APPLICATION	MAIN PRODUCTION	ANNUAL PRODUCTION (2020)
28 Ni NICKEL 58.6934 **Nickel**	**EV + storage + stainless steel**	**Indonesia (30%), Philippines**	**2,500,000 tons**

Mining & Refining

Nickel is extracted and used on a large scale. It is, among other things, needed for stainless steel and is one of the largest components of lithium batteries. Batteries require high-quality nickel (*class 1*), which is expected to be in short supply. The extraction of nickel releases a relatively large number of valuable by-products such as cobalt, copper and PGMs. Indonesia, the world's largest nickel producer, recently imposed export restrictions in an effort to bring refineries to Indonesia and preserve more of the value chain.

Environmental and social impact

Nickel is especially problematic because of the environmental damage caused during production and refining. To illustrate, in 2017, 23 mines in the Philippines, predominantly producing nickel, were closed due to the resulting environmental damage.[49] The Russian city of Norilsk, home to one of the world's largest nickel producers (Norilsk Nickel), is also one of the most polluted cities in the world and in 2020, it was the scene of a major natural disaster after a spill of waste material.[50]

Recycling

At 17%[17], the recycling of nickel is relatively limited, because it is incorporated in a wide variety of materials, often as an alloying element. Alloys are complicated to recycle at an equivalent level because they are often difficult to separate and because even very small variations can have a major impact on the quality of an alloy.

METAL	APPLICATION	MAIN PRODUCTION	ANNUAL PRODUCTION (2020)
27 Co COBALT 58.933 **Cobalt**	**EV + storage**	**Democratic Republic of the Congo (70%)**	**140,000 tons**

Mining & Refining

Cobalt mining is for 90% a by-product of copper and nickel production, both in the Democratic Republic of the Congo (DRC) and abroad. This represents a high risk, because the upscaling in the production of cobalt is dependent on the upscaling in the production of these other metals.

Environmental and social impact

While the majority of cobalt production from the DCR is industrially mined, with minimal labour conditions observed, the country is notorious for poor working conditions, child labour and corruption. The fact that this is difficult to prevent is apparent from the fact that even FairPhone, which only wants to use cobalt free from conflict and child labour, has difficulty making this chain transparent.[51]

Investment in additional production elsewhere is difficult, because it is often difficult to compete with African cobalt in terms of production costs. Large companies that supply direct to consumers are wary of the negative associations with cobalt from the DRC.

Recycling

Technically, cobalt is easily recyclable. In practice, however, this is rarely done because it is not yet economically attractive.

METAL	APPLICATION	MAIN PRODUCTION	ANNUAL PRODUCTION (2020)
29 Cu COPPER 63.546 **Copper**	**Cables**	**Chile (30%), Peru**	**20,000,000 tons**

Mining & Refining

Copper is mainly mined in South America, where about 40% of the mining takes place. At 8%, China accounts for a relatively small percentage of mining, but is responsible for 39% of refining. The EU also has a number of copper mines, especially in Poland and Scandinavia, together accounting for ~4.4% of global production. In addition, copper ore often contains relatively little copper: the ore grades have roughly halved over the past century.

Environmental and social impact

The ever-decreasing ore grades mean more and more energy and water is needed for the extraction of copper. Copper ore also contains a lot of sulphur, which leads to mining waste with a high risk of *acid mine drainage*, involving rainwater being strongly acidified before flowing into nature.

Recycling

Technically, copper is easily recyclable. Preventing the mixing of copper with other metals is vital: on the one hand, to maintain its conductive properties and, on the other, because copper contamination is harmful to the quality of steel. Currently, almost half of copper use in the EU comes from recycling.

METAL	APPLICATION	MAIN PRODUCTION	ANNUAL PRODUCTION (2020)
78 Pt PLATINUM 195.084 **Platinum**	**Hydrogen production, catalysts in diesel cars**	**South Africa (70%), Russia**	**170,000 tons**

Mining & Refining

Platinum is one of the platinum group metals (PGMs), which are mined collectively in platinum-containing ores. In addition to platinum, this group also includes osmium, iridium, ruthenium, rhodium and palladium. The last two (Rh + Pa) in particular are widely used in, among other things, catalytic converters in cars. Platinum is mainly mined in South Africa (70%), followed by Russia (12%); the ratios are slightly different for some other elements. Production in South Africa is regularly halted due to strikes. Consequently, the supply chain has learned to deal with these disruptions and maintains buffer capacity at every step.

Environmental and social impact

PGMs are notorious for their association with prolonged and violent strikes in South African mines.

Recycling

The recycling of precious metals in general is at a high level. This is because of the relatively very high prices and because components containing PGM, such as catalysts, are relatively easy to remove from products during the recycling process. High-quality recycling is important, because PGMs are very difficult to replace by other metals, although metals can be exchanged relatively easily within the group.

APPENDIX III. EXPLANATION OF ENERGY SCENARIOS

This study uses scenarios for the Dutch energy system drawn up by the collaborating grid operators and various other stakeholders. The scenarios are based on four ‘realistic extremes’. This appendix further explains the energy scenarios plus underlying assumptions.

This method explains three things in more detail:

1. Scenarios *Energy system of the future*
2. Figures used for scenarios & system studies
3. Battery storage assumptions

1. Scenarios *Energy system of the future*

To be able to work towards a climate-neutral energy system, the collaborating grid operators have drawn up energy scenarios. These scenarios make assumptions for, among other things, the development of industry, the installed generation and storage capacity and the method of steering towards emission reduction and sustainable energy production. These are explained in detail in the report Energy system of the future.[37] Table 3 provides a brief summary of these scenarios. Figure 24 provides an illustration of the energy flows in one of the scenarios.

Table 3: Description of the four scenarios for the future energy system (source: Netbeheer Nederland)[35]

Regional management 	Emphasis on management through local communities and citizens, a high degree of autonomy and circularity as spearheads. Onshore solar and wind energy have grown strongly. The industry is shrinking and becoming more sustainable through electrification and green hydrogen. The Netherlands is almost completely self-sufficient in energy. Green hydrogen also plays a role for backup plants. Green gas from local biomass is important for the peak supply of heat networks.
National management 	In this scenario, the national government maintains a strong focus on (almost complete) self-sufficiency. Large-scale national projects are being set up, in particular offshore wind. There is less growth in heat networks, the emphasis is on electrification. The size of the industry remains the same and will be made more sustainable through electrification and green hydrogen. Green hydrogen also plays a role for backup plants and industry in the form of green gas and green hydrogen.
European CO_2 management 	In this scenario, management is mainly based on a European CO_2 tax, which leads to a greater emphasis on green gas in various sectors. There is strong growth in solar and wind energy. The industry is growing and becoming more sustainable thanks to electrification and the use of hydrogen (partly also as a raw material). CCS is used on a large scale, for the production of blue hydrogen, among other things. Hybrid heat supply in buildings means this scenario features a moderate peak in electricity demand. Energy imports are relatively high. Gas continues to play a role in the districts and other sectors, in the form of green gas and a mix of blue and imported green hydrogen.
International management 	In this scenario, the market is decisive and the Netherlands is looking for options internationally, offering the lowest costs. Much hydrogen is imported from countries with a lot of sunshine, where it is easier to produce. There is less use of green gas, but a lot of hybrid heat supply in buildings, especially in combination with hydrogen. The industry is growing thanks to electrification and the use of hydrogen (also as a raw material). By importing hydrogen, the Netherlands needs less wind power to produce hydrogen itself via electrolysis. This scenario therefore has the lowest national electricity production, although that production has grown strongly in 2050 compared to 2030.

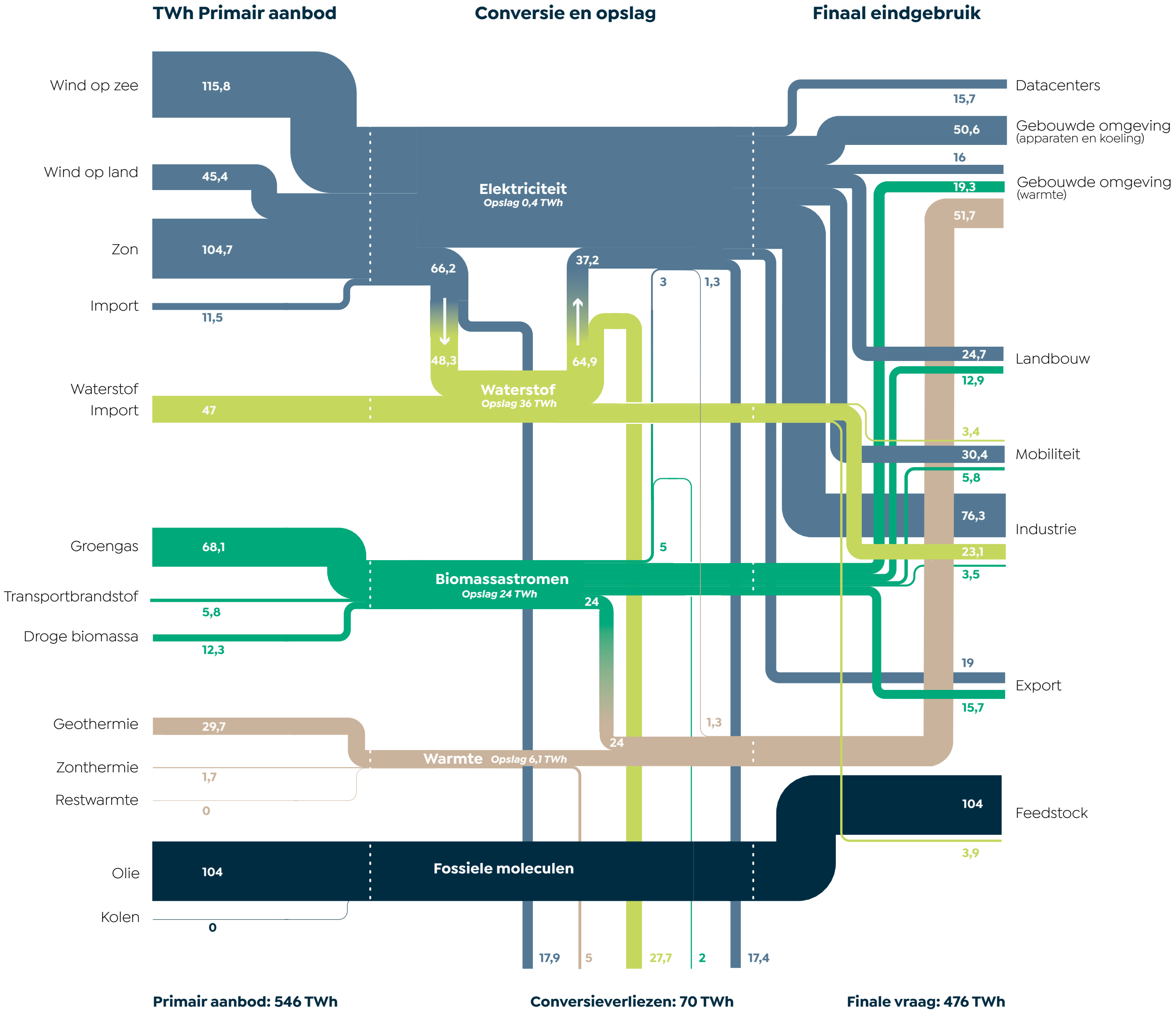

Figure 24 ▶ Visual representation of Dutch energy management, in the national management scenario (source: *The energy system of the future*).[37]

2. Figures used for scenarios & system studies

Chapters 4 and 5 show the metal demand and possible reduction of metal demand in the different energy scenarios. For this, the figures from the four energy scenarios from *The energy system of the future*[37] have been used, which are explained in II.1. The figures for Dutch infrastructure show the required additional infrastructure. Since these have only been determined for 2050, an interpolation has been made for 2030 based on 2020 and 2050.

3. Battery storage assumptions

An important part of the metal demand is driven by battery storage. This includes all batteries available for balance maintenance: home batteries, district batteries and some of the batteries of electric cars[37]. Which part of the batteries of electric cars is available as battery storage has not been specified. In order to form a picture of the required additional battery storage, it is assumed that 10% of car batteries are available for system storage. However, more research is needed on this. The total amount of car batteries is based on the scenarios in the Energy Transition Model used for "The energy system of the future".

The development of market share of battery technology in the base scenario is based on data from IEA (2021).[1]

Table 4: Installed capacities and quantities for the Netherlands in the various scenarios.

NETHERLANDS							
Topic	**Part**	**Unit**	**2030**	**2050 – REG**	**2050 – NAT**	**2050 – EUR**	**2050 – INT**
Generation	Offshore wind	GW	13	31	52	30	28
Generation	Onshore wind	GW	6	20	20	10	10
Generation	Rooftop solar	GW	9	59	49	24	18
Generation	Solar farms	GW	18	66	58	35	35
Generation	Solar thermal energy	GW	1	15	7	6	5
Flexibility	Battery storage	GWh	12	400	400	200	200
Flexibility	Elektrolysers (P2G)	GW	0	42	51	19	16
Flexibility	Power plants	GW	24	33	35	37	35
Infrastructure	HS-MS, HS-TS plants	#	11,700	42,600	40,500	29,400	27,300
Infrastructure	MS, MS-MS, TS-MS plants	#	35,000	117,000	114,000	99,000	90,000
Infrastructure	MS-LS plant	#	2,100	7,200	7,140	5,940	4,500
Infrastructure	220/380 kV	km	200	400	700	500	450
Infrastructure	110/150 kV	km	300	900	1090	880	960
Infrastructure	MS cables	km	13,100	44,400	44,100	35,200	33,600
Infrastructure	LS cables	km	11,000	33,800	38,800	32,000	27,900
EV	Batteries	GWh	117	540	444	396	300

APPENDIX IV. OVERVIEW OF ENERGY TECHNOLOGIES

Different renewable energy technologies exist, each with their own metal demand and their own characteristics. This appendix explains the main technologies and innovations for solar panels and wind turbines, energy storage and cables.

LEGEND

Technology Readiness Level (TRL)

●○○ in development
●●○ potential for application in the energy system
●●● widely applicable in the energy system

Applicability

▨ applicable
✕ not applicable
✱ under investigation
↑ up and coming
? unknown

Generation

The main technologies for the generation of sustainable electricity are wind turbines and solar panels. Both feature different sub-technologies, which are explained in the tables below.

Wind

Wind turbines can be placed on land (*onshore*) or at sea (*offshore*). The advantages of onshore wind are lower metal demand for the infrastructure and easier maintenance. The advantages of offshore wind are the often higher wind speeds and the larger amount of available space. In the case of offshore wind, the demand for copper is higher, because longer cables need to be laid.

TECHNOLOGY	TRL	METALS	ADVANTAGES	DISADVANTAGES
Doubly-Fed Induction (DFIG) (gearbox)	●●●	Boron Chrome Copper Dysprosium Manganese Molybdenum Neodymium Nickel	• Few rare earth elements needed • Cheap • Light-weight	• High wear, high maintenance. Thus less suitable for offshore wind.
Permanent Magnet Synchronous (PMSG) (gearbox + direct drive)	●●●	Boron Chrome Copper Dysprosium Manganese Molybdenum Neodymium Nickel Praseodymium Terbium	• Higher efficiency • The direct drive variant has little wear and maintenance and is therefore very suitable for offshore use.	• High demand for rare earth elements • The direct drive variant comes with a very high demand for rare earth elements, such as neodymium.
Electrically Excited Synchronous (EESG) (direct drive)	●●○	Boron Chrome Copper Dysprosium Manganese Molybdenum Neodymium Nickel Praseodymium Terbium	• High demand for metals, but fewer rare earth elements	• Low market share • Not suitable for offshore wind

Wind turbines feature two 'main streams' in terms of technology: in the case of gearbox wind turbines, a small dynamo is driven via a gearbox; in the case of *direct drive*, the generator is directly coupled to the rotor. Both types use permanent magnets containing rare earth elements, in which the *direct drive* type uses much more of these rare earth elements. In addition, there are different types of generators, which also contribute to the critical metal demand.[1,53]

Solar

Solar panels can be placed on roofs (rooftop solar) or on the ground (solar farms). An advantage of rooftop solar is the combination of generation and consumption at a single location, which reduces grid load. A disadvantage of solar farms is that this can be at the expense of, for example, agriculture or biodiversity. At the same time, with solar farms, it is possible to install generating capacity quicker.

The vast majority of the solar panels installed are c-Si panels. This applies not only in the Netherlands, but worldwide. However, the development of solar panels is going very fast and other types, such as CdTe, CIGS and perovskite panels, may be playing a role in the future as well.

TECHNOLOGY	TRL	METALS	ADVANTAGES	DISADVANTAGES
c-Si	●●●	Silicon Silver (Lead) (Indium)	• Most Efficient Commercial Technology • Development is benefiting from the development of electronics, because the same materials are needed	• Complex production process • Very pure silicon required
a-Si	●●○	Silicon Silver	• Thin • Environmentally friendly production, without cadmium or lead	• Low efficiency
CdTe	●●●	Cadmium Tellurium	• Low CO_2 and water production • Short payback period • Good performance at high temperatures and low light	• Contains cadmium (toxic) • Contains critical metals (tellurium)
CIGS	●●●	Copper Indium Gallium Selenium (Cadmium/ Lead)	• Thin and flexible • Most efficient solar panel on thin foil • Less (or no) cadmium compared to CdTe	• Modules do not yet have economies of scale
Perovskite panels	●○○	Mineral with metals ($CaTiO_3$)	• Potentially very cheap • Can be combined with Si panels for higher efficiency	• Sensitive to humidity • Panels small (for now) • Requires a lot of lead during production (with current technology)

STORAGE

There are different ways of storing energy, depending on the required storage volume, the storage period and the required charging and discharging speed. Not all forms of energy storage can replace each other, because some technologies cannot be placed in cars or can only store energy for a short time. Various sources have been used for the information in this table.[54-61]

In addition to the technological aspects, the costs of the storage technology over the entire service life are also an important factor in the decision for this infrastructure. By 2030, lithium batteries, flywheels, pumped water (PHES), air pressure (CAES) and hydrogen are expected to be the most cost-effective technologies internationally, depending on the application.[54] However, because the Netherlands has an unfavourable geography for pumped water (PHES), batteries, air pressure and hydrogen will play a greater role here.

TECHNOLOGY	TRL	APPLICATIONS				METALS	ADVANTAGES	DISADVANTAGES
		SEC	DAY	SEASON	EV			
Lithium-ion batteries								
LCO (Lithium-Cobalt Oxide)	●●●			×		Cobalt Lithium	• Most advanced battery of its kind • Widely applicable • High energy density	• Risk of combustion • Dependent on cobalt
LFP (Lithium-Iron Phosphate)	●●●			×	↑	Lithium Iron Phosphate	• Less dependent on critical metals (compared to other Li batteries) • Lasts many cycles • Relatively safe	• Low energy density • Less advanced (compared to other Li batteries)
NMC (Nickel-Manganese-Cadmium oxide)	●●●			×		Lithium Nickel Manganese Cobalt (less than LCO)	• Contains less cobalt than LCO • Ratio between metals can be varied • High energy density • Doesn't heat up quickly • Lasts many cycles, so well-suited for EV	• Dependent on cobalt
NCA (Nickel-Manganese-Cadmium oxide)	●●●			×		Lithium Nickel Cobalt Aluminium	• High energy density • Reasonably high capacity • Lasts many cycles	• Safety risks (combustion) • Relatively high costs

TECHNOLOGY	TRL	APPLICATIONS				METALS	ADVANTAGES	DISADVANTAGES
		SEC	DAY	SEASON	EV			
LMO (Manganese Oxide)	●●●			×		Lithium Manganese	• Fast charging and discharging • Relatively cheap • Stable	• Lower energy density than LCO • Can be combined with NMC batteries
LTO (Lithium-Titanate)	●●●	↑	↑	×		Lithium Titanium	• Very safe • Fast charging	• Lower energy density (compared to other Li-ion batteries) • Low voltage
LiPo (Polymer)	●●●	×	×	×		Lithium Other metals	• High energy density • Safer than other lithium batteries	• Relatively expensive (compared to other Li-ion batteries)
Solid state (SSB)	●○○	?		×		Lithium Other metals, depending on design	• High energy density • Safe • Fast charging • Long service life	• Development lags far behind (compared to conventional Li-ion batteries)
Other chemical batteries								
Li-sulphur	●○○			×		Lithium Sulphur	• Very high energy density	• Short service life for now
Li-air	●○○			×		Lithium (Titanium) Other metals, depending on design	• Potentially high energy density	• Not applicable yet • Not stable yet • Air requires continuous purification
Lead-acid battery	●●●			×	×[III]	Lead	• Low purchase price • High capacity compared to weight	• Very low energy density • Toxic (lead) • Risk of explosion due to oxyhydrogen

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[III] *Lead-acid batteries are used in cars as a starter battery, but they cannot propel the car independently.*

TECHNOLOGY	TRL	APPLICATIONS				METALS	ADVANTAGES	DISADVANTAGES
		SEC	DAY	SEASON	EV			
Molten-salt batteries								
Sodium sulphur	●○○			×	*	Sodium Sulphur	• High energy density • High efficiency • Low self-discharge • Long service life • Cheap materials • Very suitable for stationary energy storage	• High production costs • Recycle options needed for sodium
Sodium-ion	●●○	?	*	×	*	Sodium	• Potentially lower cost than Li-ion • Dependent on less critical metals than Li-ion	• Low energy density • Short service life • Too expensive for now to be a realistic option as a battery storage system or car battery
Flow-batteries								
Vanadium	●●○			×	×	Vanadium	• Can stay discharged for a long time • Easily rechargeable • Safe • Can be deeply discharged • Low costs • Modularly expandable • Suitable alternative to Li-ion for intensive use	• Stationary applications only (very low energy density)
Zinc Bromide	●●○	*		×	×	Zinc Bromide	• Can be deeply discharged • Lasts a long time • Modularly expandable	• Stationary applications only (very low energy density) • Needs to be discharged regularly (every few days) • Low power

TECHNOLOGY	TRL	APPLICATIONS				METALS	ADVANTAGES	DISADVANTAGES
		SEC	DAY	SEASON	EV			
Mechanical storage								
Pumped hydro (PHES)	●●●	×			×	Steel for construction	• High storage capacity • Low cost compared to capacity • Few critical metals needed • Suitable for long-term storage	• Disturbs nature, local residents and the water level • Unfavourable geography in the Netherlands, but potential for underground reservoirs (O-PAC)
Air pressure (CAES), large scale	●●○	×			×	Steel for construction	• High storage capacity • Low cost compared to capacity • Probably suitable geography in the Netherlands (salt caverns + gas fields) • Suitable for long-term storage • Modularly expandable	• Customisation required per installation • Low efficiency
Flywheel (FES)	●●○		×	×	×	Composite	• High capacity • High efficiency • Highly versatile	• Only suitable for a very short periods of time
Gravity systems	●○○	?			×	Steel for construction	• Potentially high efficiency • Few critical metals needed	• Low storage capacity
Fuel								
Hydrogen (H_2)	●●●	×				Platinum Iridium Nickel Cobalt	• Suitable for long-term storage • Widely applicable • Suitable for industry • Suitable geography in the Netherlands for underground storage	• Low efficiency • Depending on the application, expensive catalyst required
Other								
Cryogenic storage (CES)	●●○	×			×	Steel for construction	• High capacity • Low investment costs	• Low efficiency

CABLES

As regards power cables, you can choose between copper and aluminium cables, each with its own advantages and disadvantages.

TECHNOLOGY	TRL	METALS	ADVANTAGES	DISADVANTAGES
Copper cables	●●●	Copper	• Low resistance	• Expensive • Heavy • More scarce (compared to aluminium)
Aluminium cables	●●●	Aluminium	• Cheap • Light-weight • Less scarce (compared to copper)	• Higher resistance (x1.6)

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METABOLIC

Copper8

POLARIS SUSTAINABILITY

QUINTEL INTELLIGENCE