Climate Neutrality
Foundation

Securing Germany‘s sovereignty

Resilient supply chains for the transformation to climate neutrality by 2045

prognos

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In addition, technical events were held with company and industry representatives from the fields of renewable energies, automobility and green steel.

We would like to thank everyone involved for sharing their expertise and experience. This professional exchange provided important impetus for the preparation of this study.

The study participants Prognos, Oeko-Institut and Wuppertal Institute as well as Climate Neutrality Foundation are solely responsible for the contents of this study.

Securing Germany's sovereignty

Resilient supply chains for the transformation to climate neutrality by 2045

With this study, we would like to draw attention to key priorities, strategies and political measures for "resilient supply chains" in order to secure the transformation to climate neutrality.

Dear Readers,

The past years have been characterized by far-reaching changes that have underscored the need for an accelerated and resilient transformation to climate-neutral economies. One such change is the fact that the impacts of the man-made climate crisis are becoming increasingly noticeable around the world. In addition, the Russian invasion of Ukraine has provided a particularly clear demonstration of the vulnerability of Europe's economy and society as a result of its dependency on fossil fuels, as well as the negative implications of one-sided import dependencies on certain countries. With the introduction of the Inflation Reduction Act (IRA) in the United States, it has also become very evident that the competition for establishing business locations for the key future technologies that are driving the transformation is in full swing. And there is China, which has been working successfully for more than a decade to become the world market leader in green technologies.

The European Union and Germany must ensure that the necessary transformation to climate neutrality takes place in a resilient way. In the context of this study, resilience is understood as the ability to withstand external shocks or upheavals within the social, economic or political framework, in particular with regard to international embedding, as well as the ability to adapt to the new conditions. For key technologies along the entire supply chain, this means possessing the necessary technologies and components, securing the key raw materials, implementing appropriate diversification strategies and establishing a recycling economy at an early stage. Only if these measures succeed will the European Union and Germany be able to implement the transformation, play a strong role on the global market in the future and provide future-proof jobs at home, thereby securing national and European sovereignty. Ultimately, Europe will only enjoy the necessary political leeway for sovereign action if the European Union and its Member States cannot be unilaterally blackmailed when it comes to central issues of economic prosperity. When it comes to transformation, the issue of resilient supply chains is more than an economic question or challenge, it is rather a highly political question of security and sovereignty.

With this study, we will address the various dimensions of the formulated challenges in order to help decision-makers quickly and effectively implement strategies and measures that will advance a resilient transformation.

- We will identify the key technologies, intermediate products and raw materials which are of key relevance in the transformation to climate neutrality, and which should be prioritized and secured by the respective political stakeholders.
- We will analyze the central supply chains and point out individual areas of weakness. The technologies required for the transformation can only be considered to be secure and available if all parts of the supply chain are robust. That is what is meant by resilience.
- We will recommend solutions for each of the key technologies and formulate recommendations for initial political decisions.

The study presented here pertains first and foremost to Germany, thus providing concrete recommendations for action for a key EU Member State on the one hand, while on other hand charting a viable approach to complex questions that must also be addressed at the wider EU level. With this study, we would like to draw attention to key priorities, fields of action, strategies and political measures for "resilient supply chains" in order to secure the transformation to climate neutrality and thereby strengthen the political sovereignty of Germany and the EU. We look forward to continuing our exchange with you.

Yours sincerely,
Regine Günther

Key findings of this study

1. A number of **key industries play a strategic role** in the transformation to climate neutrality. The strategic significance of these industries is central to the success of climate protection strategies, the political sovereignty of Germany and Europe as well as the securing of industrial locations. Among the particularly relevant key technologies are the following:
    - Photovoltaics
    - Wind power
    - Lithium-ion batteries for electromobility
    - Permanent magnets for electromobility and wind power
    - Electrolyzers
    - Heat pumps
    - Green steel plants (DRI shaft furnaces)

2. When assessing the level of resilience, it is necessary to **always take the entire supply chain into consideration**. The resilience of the supply chain as a whole is only as robust as that of the weakest link.

3. For the key technologies, **seven raw materials are rated as highly critical** with respect to extraction and processing as understood by the study objectives. The criticality is manageable through decisive political action. They are: ***graphite, iridium, cobalt, lithium, manganese, light and heavy rare earths.*** In addition, *nickel* and *polysilicon* should receive special attention as additional medium critical (processed) raw materials. Particular importance arises here for the transformation phase up to 2030/35.

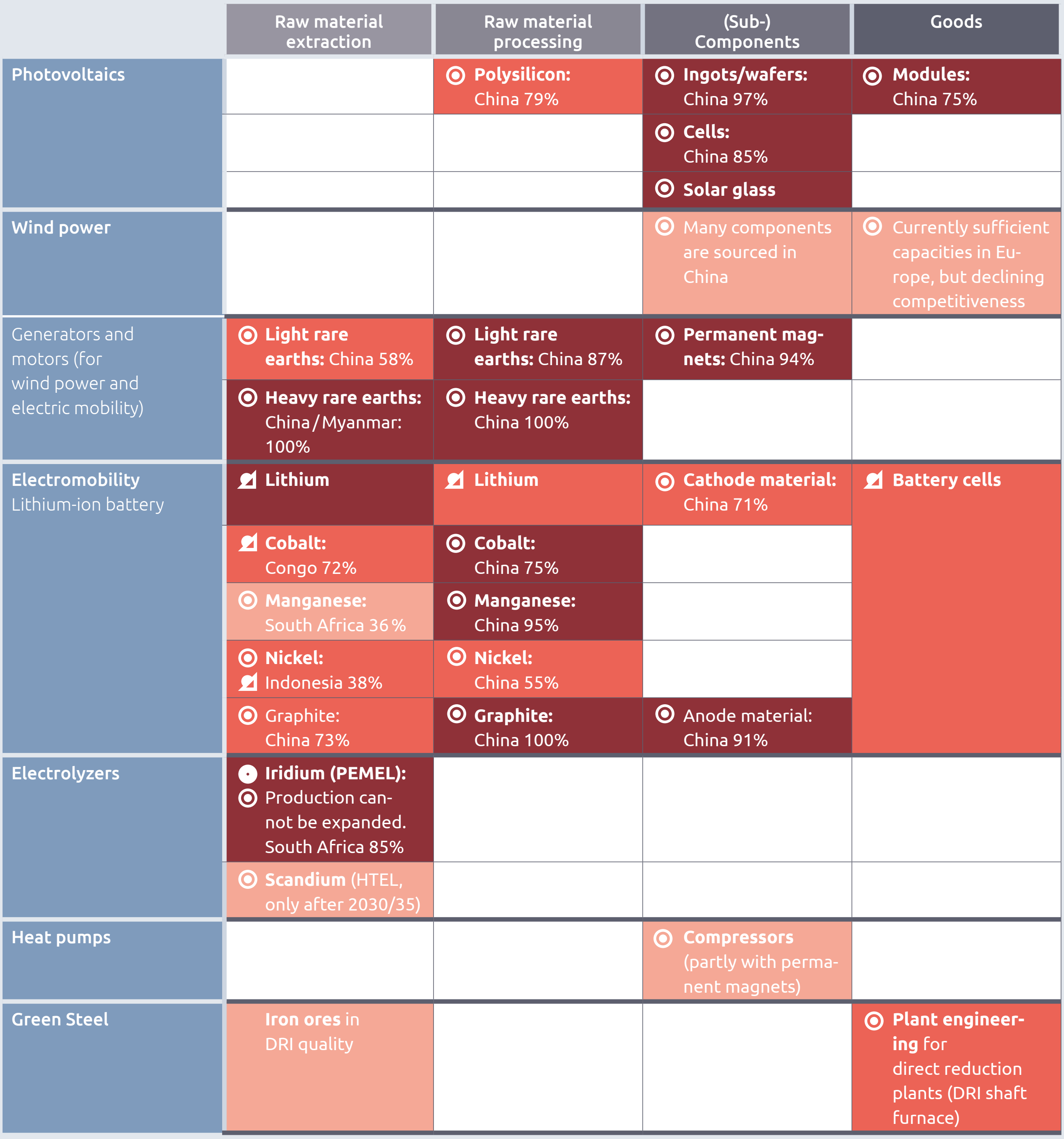
4. **Targeted investments in domestic transformation industries and the locating of particularly critical parts of the supply chain in Germany or Europe enable the successful and resilient transformation to climate neutrality.** Of particular relevance in this context are the PV industry (specifically ingots / wafers, solar glass, PV cells / modules), the manufacturing of permanent magnets and their preliminary products (especially for wind turbines and electromobility), the complete supply chain for lithium-ion batteries (electromobility), and the development of a lead market for green steel.

5. **The international diversification in the procurement of critical raw materials, components and strategic goods** can be decisively supported by building transformation-oriented partnerships, thereby reducing market concentrations and dependencies.
   It is also especially important to establish and promote the further development of new trade relations. The following countries outside the EU are of particular interest for transformation-oriented partnerships: Australia, Brazil, Canada,Chile, Colombia, Ghana, Indonesia, Madagascar, Malawi, Mozambique, Namibia, South Africa, Zimbabwe.

6. A **significant contribution from raw material recycling to building resilience is not to be expected before the early 2030s.** At that point, however, the recycling of raw materials will begin to play an increasingly crucial role. It is essential, therefore, that efforts are already begun in the areas of recycling-friendly design of the relevant goods, **timely investments in recycling capacities, and the development of a conducive industrial ecosystem**.

7. Last but not least, **the reduction of raw material intensities and the development of alternative technology options** is an important pillar of a resilience-oriented transformation policy.
   To this end, it is essential to develop a corresponding environment for innovation in Europe.

FIG./ES 01 **Supply risks for strategic key technologies along the supply chain by criticality**
Risks vary by severity and cause of potential supply shortages.



	Raw material extraction	Raw material processing	(Sub-) Components	Goods
Photovoltaics		⦿ **Polysilicon:** China 79%	⦿ **Ingots/wafers:** China 97%	⦿ **Modules:** China 75%
			⦿ **Cells:** China 85%	
			⦿ **Solar glass**	
Wind power			⦿ Many components are sourced in China	⦿ Currently sufficient capacities in Europe, but declining competitiveness
Generators and motors (for wind power and electric mobility)	⦿ **Light rare earths:** China 58%	⦿ **Light rare earths:** China 87%	⦿ **Permanent magnets:** China 94%	
	⦿ **Heavy rare earths:** China / Myanmar: 100%	⦿ **Heavy rare earths:** China 100%		
Electromobility Lithium-ion battery	◩ **Lithium**	◩ **Lithium**	⦿ **Cathode material:** China 71%	◩ **Battery cells**
	◩ **Cobalt:** Congo 72%	⦿ **Cobalt:** China 75%		
	⦿ **Manganese:** South Africa 36 %	⦿ **Manganese:** China 95%		
	⦿ **Nickel:** ◩ Indonesia 38%	⦿ **Nickel:** China 55%		
	⦿ Graphite: China 73%	⦿ **Graphite:** China 100%	⦿ Anode material: China 91%	
Electrolyzers	● **Iridium (PEMEL):** ⦿ Production cannot be expanded. South Africa 85%			
	⦿ **Scandium** (HTEL, only after 2030/35)			
Heat pumps			⦿ **Compressors** (partly with permanent magnets)	
Green Steel	**Iron ores** in DRI quality			⦿ **Plant engineering** for direct reduction plants (DRI shaft furnace)

KEY ⦿ Concentration and market power ◩ Short/medium-term excess demand ● Permanent shortage

Criticality: ▬ Very critical ▬ Medium critical ▬ Moderately critical

SOURCE Own representation

NOTE Copper, titanium, gallium, germanium, yttrium and platinum: According to the investigations that this study is based on, these raw materials are strategically relevant for the transformation to climate neutrality by 2045, but are not critical.

Prognos, Öko-Institut, Wuppertal Institut, 2023

Key strategies and instruments for bolstering resilience

1. **Introduce and institutionally anchor comprehensive resilience monitoring.** The regular analysis of raw material availability and supply relationships with critical dependencies along strategically relevant supply chains form the basis for policy decisions regarding necessary adjustments. Options for shaping institutional anchoring should be reviewed.

2. **Create stable domestic sales markets for transformative key technologies.** This can succeed by securing a stable political framework and reliable funding instruments in Germany and the EU. Funding for critical raw materials within the EU must be prioritized.

3. **Establish resilient-content requirements.** This can be achieved by setting standards, for example on environmentally and socially acceptable criteria for funding measures and regarding the import of goods.

4. **Facilitate purchasing groups for strategic raw materials and goods as well as the bundling of supply contracts.** This can be achieved through a review and reform of antitrust law, as well as through bundling and securing procurement agreements through the public sector.

5. **Support an assertive approach to domestic business location policy in the area of strategic resources and goods.** This can be achieved through compensation measures for European transformation industries with a view to creating a level playing field vis-à-vis subsidized competitors outside of Europe. In this area, investment should be promoted and state aid for operational expenditures be made possible for a limited period.

6. **Expand and strengthen transformation partnerships on equal terms.** This can be achieved by strengthening economic cooperation beyond existing raw material and technology partnerships, by strengthening value creation in partner countries and by intensifying cooperation in education and research.

7. **Early-phase capacity building in the recycling industry.** This can be achieved by passing design requirements, export restrictions for secondary raw materials and primary products, and through the robust implementation of the EU Battery Regulation and the EU Critical Raw Materials Act.

We understand resilience as the ability to withstand external shocks or upheavals in social, economic or political framework conditions, in particular with regard to international embedding, and the ability to adapt to new conditions.

TABLE/ES 02 **Potential partner countries for building and deepening transformative industrial and investment partnerships,** to securing and processing key raw materials for the transformation to climate neutrality.

Potential partner countries	Raw materials	Comments
Australia	Lithium, Light and Heavy Rare Earths, Nickel, Cobalt	Already extensive lithium extraction and mining of rare earths
Brazil	Graphite, Lithium, Manganese	Already mining or exploitation (lithium) of tailings
Canada	Lithium, nickel, cobalt, rare earths	Lithium extraction, which has been very low to date, is to be expanded. Rare earth mining projects planned/under construction
Chile	Lithium, Copper	Already extensive lithium and copper extraction, lithium production to be expanded.
Colombia	Rare earths, nickel	Expansion of nickel extraction planned, reserves for rare earths
Ghana	Lithium	No mining yet, mining project in the planning stage
Indonesia	Copper, nickel, cobalt	In particular, existing nickel and cobalt extraction is to be expanded robustly.
Madagascar	Graphite	Existing extraction by mining
Malawi	Light and heavy rare earths	No mining yet, mining project in the planning stage
Mozambique	Graphite	Existing extraction by mining
Namibia	Light and heavy rare earths, lithium	No extraction by mining yet, projects planned/under construction
South Africa	Manganese, iridium, platinum	Most important mine producer for the three raw materials
Zimbabwe	Iridium, platinum	Existing extraction by mining; however, significantly lower production compared with South Africa

SOURCE Own compilation by Öko-Institut based on (U.S. Geological Survey, 2023)

Öko-Institut 2023

Table of contents

1. Motivation, goals and methodology

Germany has embarked on the path to achieving climate neutrality by the year 2045. This is transforming entire industries and their supply chains — from raw material extraction to solar modules or electric vehicles. Resilient supply chains are gaining importance not only for successful transformation, but also for securing political sovereignty. Russia's invasion of Ukraine has not only heralded a turning point in foreign and energy policy. It has also highlighted the economic dangers of overdependence or insufficient diversification of energy imports, raw materials, and strategic goods. The global supply chain disruptions caused by the anti-Covid measures in China confirm this risk assessment.

Besides companies, policymakers also have a key responsibility to define the supporting framework for accelerating the development of future industries and resilient supply chains for the key technologies of transformation and thus future prosperity.

Achieving climate neutrality in Germany by 2045 will require immense investments in new technologies in many areas for this comprehensive transformation. Against the backdrop of current geopolitical events, this study aims to identify where dependencies on foreign countries for the supply of raw materials, components and strategic goods are today or will be in the foreseeable future, and to what extent these could be critical for the success of climate neutrality in 2045. The study aims to identify which measures can reduce the greatest dependencies and substantially increase resilience.

The proposal for the "European Critical Raw Materials Act" published by the European Commission on March 16, 2023 (COM, 2023a) illustrates the urgency and relevance of addressing critical raw materials and strategic goods for the success of climate neutrality in Germany. With this approach, the European Union (EU) is emphasizing its strategic efforts along the various stages of the supply chain (from extraction to recycling) to secure the safest and most sustainable access possible to the necessary raw materials through projects and initiatives. As the implications for German climate policy will be considerable, this current EU activity underlines the explosive nature and topicality of the issue addressed in this study.

This study is based on the fundamental study "Klimaneutrales Deutschland 2045" – KNDE2045 (Prognos, Öko-Institut, Wuppertal-Institut, 2021) and builds on the sectors dealt with intensively there, such as buildings, transport, energy, etc., and the technologies relevant for the transformation of these sectors. The basic assumptions of the previous study were retained and only where current developments had arisen (e.g. in the transport sector through the targets of the coalition agreement of the new German government in the fall of 2021) were details of the underlying assumptions and starting points adjusted and updated. However, it also becomes clear that a resilience-oriented policy should not only focus on raw materials, but also take strategic goods and components into account.

The core target "Climate-neutral Germany 2045" remains unchanged. This study examines in detail the ramp-up over time of the raw materials, components and strategic goods required for the transformation of the respective sectors, and places them in relation to the current supply-side situation of the supply chains and their scalability in five-year steps from 2020 to 2045. This condensed version of the study presents the key findings in condensed form. A characteristic feature is the challenge of bringing about and securing the transformation toward climate neutrality by 2045. Therefore, the medium-term time perspective (from today to 2030/2035) is essential. We will only be successful in making Germany climate-neutral by 2045 if the key obstacles and bottlenecks on the strategic supply chain side are identified in this decade and adequately addressed. This study aims to make a substantial contribution to this time-critical objective and to initiate appropriate strategies, actions and initiatives.

Methodology

The quantitative basis for the study is the “Climate-Neutral Germany 2045” scenario. Here, integrated modeling was used to show which specific technical actions could reduce greenhouse gas emissions by 65 percent by 2030 compared to 1990 levels, and how the energy system could become climate-neutral by 2045. Based on this scenario, the first step in this study was to identify around 30 transformation technologies that are of particular importance for the decarbonization pathway. We calculated what would be required in terms of new construction over time to build up the necessary capacity. As a second step, the supply chains for the individual technologies were filtered in an initial screening for possible critical aspects in the individual value creation steps. In the case of raw materials, the focus was on those classified as critical by the European Commission as part of the CRM list (Critical Raw Material). The results were discussed with subject matter experts.

It is a central concern of this study to develop a focused action plan for those technologies that have a particularly high strategic importance and at the same time a high criticality. When assessing the associated risks, the time component is the most important aspect. For example, a possible bottleneck by 2030 requires faster action in contrast to supply risks, which can only become relevant from 2040 onwards, and is consequently to be classified as more critical.

The seven key technologies and components considered in this study are characterized by the fact that they enable particularly high greenhouse gas savings, especially in the short to medium term, have a steep ramp-up path, have few alternatives in the short term, and have a high supply concentration for raw materials, components, or even the production of whole goods:

- Photovoltaics
- Wind power
- Lithium-ion batteries for electromobility
- Permanent magnets for electromobility and wind power
- Electrolyzers
- Heat pumps
- Green steel plants (DRI shaft furnaces)

In the fourth step, the supply chains of these key technologies were examined in detail. Here, all supply chain steps — from raw material production and processing to the production of (sub)components and finished goods — were examined for critical supply bottlenecks for the individual technologies. In addition, the demand for critical raw materials was quantified over time. In the final step, political recommendations for action were developed for the specific challenges. The results for the remaining transformation technologies are presented in the appendix.

In risk assessment, the time component is particularly decisive: A possible bottleneck by the year 2030 requires faster action.

This study is structured as follows: In Chapter 2, the main technologies and measures for reducing greenhouse gas emissions are explained by sector. Chapter 3 provides an introduction to criticality in climate change technologies along supply chains and prioritizes the seven relevant key technologies. Chapter 4 shows the specific annual expansion path for the key technologies up to 2045. Since the individual key technologies can sometimes have different manifestations — in the case of water electrolysis, for example, there are three other key technology manifestations in addition to alkaline electrolysis — the advantages and disadvantages are explained and it is shown how high the assumed share of each technology manifestation is each year. In chapter 5, the supply chains are examined and supply risks are classified as "very critical," "moderately critical," "moderately critical," and "not critical[1]. The demand for each of the identified critical raw materials is quantified in five-year increments through 2045. Chapter 6 then shows what supply-side and demand-side measures can be taken to reduce these risks. Third countries qualifying as diversification options for critical raw materials and components are also identified. Chapter 7 recommends specific strategies and policy instruments to implement the technical measures.

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[1] This categorization is project-specific in terms of the objectives of this study. A direct comparison with other studies that make categorizations regarding the criticality of raw materials etc. (in particular the EU Critical Raw Materials List) is is not useful in this context, since the focus of this work is more specific than that of other publications.

2. Technologies to achieve climate neutrality in 2045

“Climate-neutral Germany 2045" (KNDE 2045) scenario as the basis for this study

Germany has set itself the goal of becoming climate-neutral by 2045. In addition, greenhouse gas emissions are to be reduced by 65 percent in 2030 compared to 1990. Decarbonizing the energy system is one of the biggest industrial policy challenges for the coming years. How this transformation succeeds has been the subject of extensive research in various studies over the past two years. One of the first studies on this topic, published in 2021, is the study “Klimaneutrales Deutschland 2045” (Climate-Neutral Germany) (Prognos, Öko-Institut, Wuppertal Institut, 2021). The transformation of the German energy system is essentially based on the following pillars: Expansion of renewable energies, energy efficiency, extensive electrification of the building and transport sectors, and use of hydrogen in areas where electrification is not possible. Studies published thereafter, such as the "Climate Paths 2.0" (BDI, 2021) for the Federation of German Industries or the "Long-term Scenarios" (Fraunhofer ISI et al., 2022) for the Federal Ministry of Economics and Climate Action (BMWK), also show similar transformation paths.

Focused update of the scenario

Since the publication of the study "Klimaneutrales Deutschland 2045" (KNDE2045) in June 2021, important energy policy directions have been set for the next few years, which further concretize and in part also accelerate climate policy targets for the coming years:

Following the decision of Germany’s Federal Constitutional Court on April 29, 2021, the then black-red government amended the Climate Protection Act (KSG), which then came into force in August 2021. This brought forward the target year for achieving climate neutrality to 2045 and raised the reduction target for greenhouse gases in 2030 by ten percentage points to 65 percent. In addition, specific reduction paths have been defined for the individual sectors up to the year 2030. Greenhouse gas emissions reduction targets were also reaffirmed in the 2021-2025 coalition agreement of the new government elected in the fall of 2021. In addition, the German government’s coalition agreement sets the goal of having at least 15 million fully electric passenger cars on Germany’s roads by 2030. With regard to the expansion of renewable energies, the target has been set to cover at least 80 percent of the national electricity demand (680 to 750 TWh) with renewable energies in 2030. In the Renewable Energies Act (EEG) 2023, these targets were made concrete by specifying actions and the expansion targets for renewable energies were raised significantly. These new goals were incorporated in the study.

In addition, new trends are emerging in the different sectors, such as significantly greater expansion in photovoltaics and heat pumps due to the energy cost crisis in 2022. For this reason, we made updates for specific key technologies to reflect current developments. However, no new energy system scenario was modeled, nor was an integrated view taken across all energy sources and sectors.

The following outlines the challenges facing the sectors and the technologies and technical measures required to achieve the climate targets — and which transformation technologies are of outstanding, strategic interest and are thus the particular focus of the studies. For reasons of security of supply, the short- to medium-term ramp-up path of the technologies to 2030 and 2035 is of particular interest, as political action should be taken particularly quickly due to the short time available.

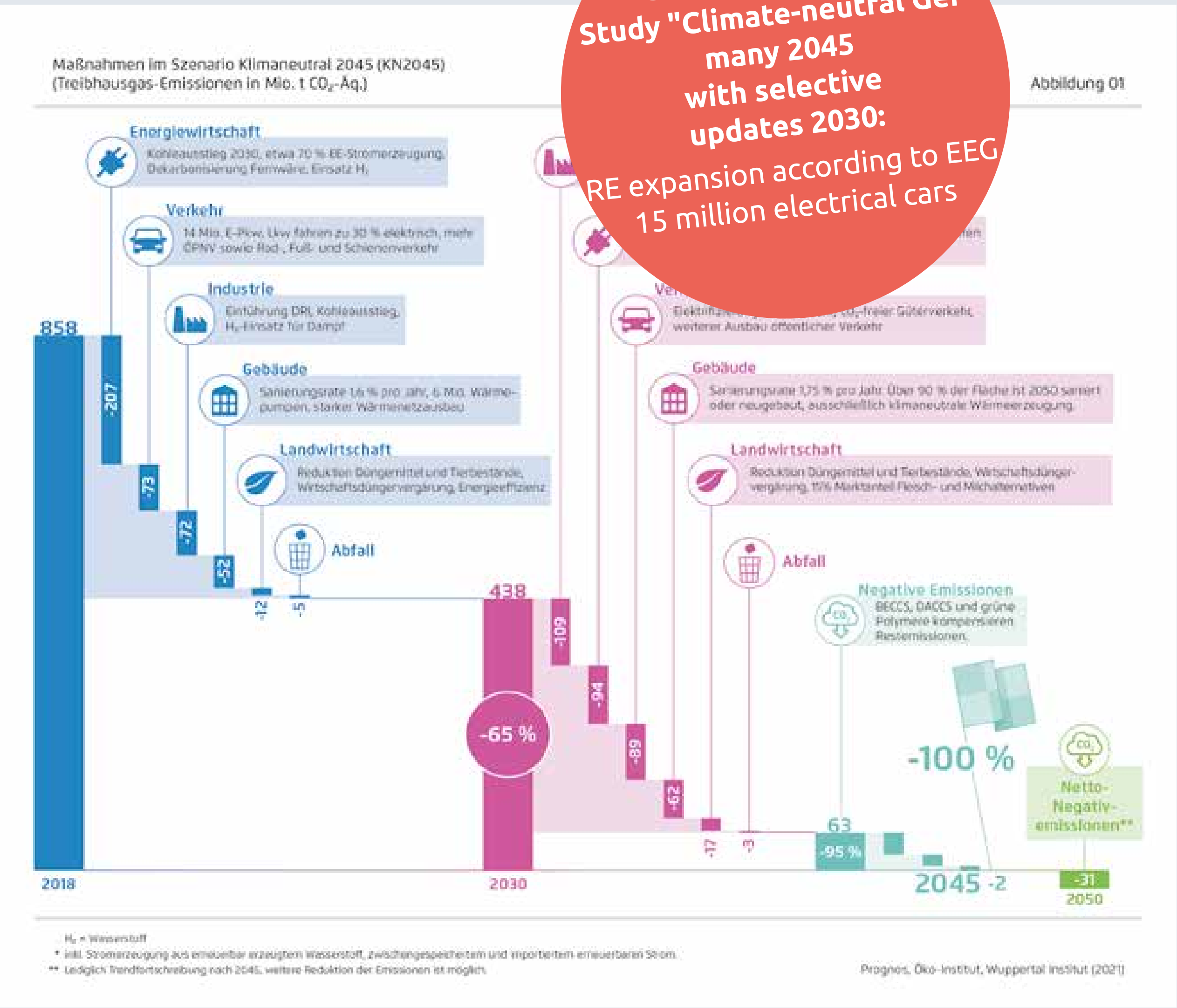
The scenario shown here is the starting point for the prioritization of strategic key technologies and components in chapter 3 and the quantification of critical raw materials for decarbonizing the German energy system in chapter 4.

Energy industry

The energy industry remains the sector with the highest emissions, with 256 million metric tons of CO_2 equivalents in 2022. In order to achieve the German Climate Protection Act target of 108 million metric tons of CO_2 equivalents in 2030, a major expansion of wind power

FIG. 01 **Climate neutrality in the scenario "Climate-neutral Germany 2045 (KNDE2045)"**
The rapid expansion of renewable energies, electromobility and heat pumps as well as the production of green hydrogen with water electrolysis are of central importance for achieving the climate protection targets.

Scenario from the Study "Climate-neutral Germany 2045 with selective updates 2030:
RE expansion according to EEG
15 million electrical cars



SOURCE Own representation based on the study "Climate Neutral Germany 2045" (KNDE2045). The quantity structure is based on the KNDE2045 study, with selective updates for some technologies.

Prognos, Öko-Institut, Wuppertal Institut, 2021 Climate-Neutral Germany 2045

and photovoltaics is required in addition to phasing out coal-fired power generation. The quantity structure assumed here is based on EEG 2023 and envisages a capacity of 215 GW of photovoltaics, 115 GW of onshore wind power and 30 GW of offshore wind power by 2030.

Bioenergy power plants based on solid or gaseous biomass support the balancing of electricity supply and demand as controllable power plant capacity.

The further expansion of renewable energies until the year of climate neutrality (2045) largely corresponds to EEG 2023. In the case of photovoltaics, however, the installed capacity from 2040 onwards was not kept constant, but a stable expansion of 20 GW was continued, as there is still further potential for expansion in roof systems and open-space photovoltaics, in contrast to wind power. By 2045, a total of 480 GW of photovoltaics, 160 GW of onshore wind, and 70 GW of offshore wind will have been installed. In total, renewables generate nearly 1,100 TWh of electricity per year, which is then used to electrify demand sectors and produce green hydrogen. The expansion of photovoltaics (PV) and onshore and offshore wind power thus plays a key role in the decarbonization of the German economy and is therefore a particular focus of this study.

Flexibility options are also needed to meet electricity demand at all times. In addition to gas-fired power plants, which will start using the first quantities of hydrogen as early as 2030 and, above all, bridge longer dark periods, battery storage can compensate for intraday fluctuations in renewable energies. Additional potential arises from shifts in demand — especially for charging electric vehicles or heat pumps in the warmer months, supporting the system. Via directional charging and discharging, the batteries in the vehicles can also be used as direct electricity storage. In addition, cross-border electricity trade can be used to take advantage of imbalances in electricity demand or renewable electricity generation in neighboring countries.

In order to transport and distribute electricity from generation centers to demand centers, both transmission and distribution networks must be expanded. Local and intelligently controlled home storage in conjunction with rooftop PV systems can be supportive here.

A variety of technologies are available for decarbonizing district heating compared to the electricity sector, with different characteristics. Which technologies can be used as base-load heat and which can be used to cover medium and peak loads depends not only on the heat profiles but also, and above all, on the specific conditions in the approximately 800 heating networks in Germany. Geothermal energy, waste heat from industry and waste incineration are suitable for covering the basic heat load. If sufficient areas are available for solar thermal power, much of the summer and transitional months can be covered. Rivers or lakes provide comparatively stable initial temperatures throughout the year, which can be used to generate energy through the use of large-scale heat pumps. In addition, during periods of high renewable electricity generation, electric and electrode boilers can convert excess electricity into heat. Hydrogen-fueled CHP plants can be used to cover the medium load. If only individual consumption peaks need to be additionally served, hydrogen-powered boilers can be used. In addition, heat storage facilities ensure the short and medium-term balance between heat demand and supply.

In addition, green hydrogen must be provided by the energy industry using water electrolyzers. Since the potential for green electricity and thus for domestically produced hydrogen is limited, about two-thirds of the demand will be imported from abroad.

Depending on whether natural sinks from forests and peatlands are counted in the calculation of GHG emissions, negative emissions may also be necessary for full decarbonization. In addition to biomass CCS in the energy sector or industry,CO_2 can also be taken directly from the air (Direct Air Capture – DAC). However, in the "Climate-neutral Germany 2045" scenario assumed here (KNDE2045) this technology will not be applied on an industrial scale until the 2040s.

Transport

The transport sector was responsible for around 20 percent of Germany's greenhouse gas emissions in 2019, with 164 million metric tons ofCO_2 equivalents. Compared to 1990, emissions have thus actually risen slightly. According to the Climate Protection Act (KSG), the transport sector may only produce 84 million metric tons of CO_2 equivalents in 2030. This corresponds to just under half of today's emissions. Private motorized transport plays a particularly important role, accounting for around 60 to 65 percent of greenhouse gas emissions. (Öko-Institut et al., 2022)

To achieve this goal, the expansion of electromobility in particular is of paramount importance. The scenario presented here assumes that a total of 15 million e-cars (BEV – Battery Electric Vehicle) will be on Germany's roads in 2030 (KoaV, 2021). From 2035, only fully electric drives will then be newly approved (Council of the European Union, 2023a). In addition to electrification, the KNDE2045 scenario includes a significant shift in passenger trans port to climate-friendly modes of transport — this leads to a doubling of rail transport by 2045 (KoaV, 2021). As a result, the number of passenger cars in Germany will fall from around 50 million at present to around 40 million in 2045.

For freight transport, analogous to the assumptions of the KNDE2045 scenario, it was assumed that one third of the mileage is electric by 2030 (Harthan, R. et al., 2019). Furthermore, under the European Commissions' proposal, GHG emissions from the heavy-duty vehicle fleet in the EU will be reduced by at least 45 percent from 2030, and by 65 and 90 percent from 2035 and 2040, respectively (COM, 2023b). It also took into account the federal government's agreement to increase rail freight transport to 25 percent by 2030. (KoaV, 2021)

In addition to the described shift of the modal split in passenger and freight transport to rail, the climate protection targets in transport can only be achieved by a very steep ramp-up of electrification of all road vehicles (passenger cars, light commercial vehicles, heavy commercial vehicles, etc.) by 2030/2035. This will require a steep ramp-up in new registrations of battery electric vehicles, with a corresponding impact on the corresponding supply chains; the entire supply side here will have to keep pace with a massive increase in demand over the next ten to twelve years.

Industry

The industry sector emitted 164 million metric tons of CO_2 equivalents in 2022, one-fifth of Germany's total emissions. In the previous years of 2021 and 2019, which are more typical in terms of production activity in Germany, the emissions level was just over 180 million metric tons. To achieve the target under the Climate Protection Act, the level must be reduced to 119 million metric tons by 2030, a reduction of 27 to 35 percent depending on the reference year.

According to the definition in the Climate Protection Act, the industry sector includes both energy-related emissions from the combustion of energy sources by industrial companies and so-called process-related emissions. The latter, in turn, also include emissions that are not associated with production processes but occur only during the use phase of products.

The large individual emitters are particularly relevant for a rapid reduction in emission levels: the steel mills and the large chemical parks. In order to quickly achieve emission reductions in the steel sector, blast furnaces that use large quantities of coking coal to reduce iron ore to iron, producingCO_2, must be replaced first. The KNDE2045 scenario which is the basis for this study, like the industry's own plans, envisions replacement of blast furnaces with DRI (direct reduction) shaft furnaces and electric steel mills, where the shaft furnaces can use both methane and pure hydrogen to reduce ore.

In the chemical industry, the replacement of natural gas in steam generation and the associated operation of CHP plants in line with the electricity system constitute the greatest fast-acting lever for noticeably reducing emission levels. This can be achieved by using high-temperature heat pumps (up to about 180°C), and for the temperature level above this, up to 500°C, the less efficient electrode boilers offer a solution, provided that they are also used in a way that is beneficial to the power system, i.e. only during periods of high feed-in of renewable energies or low electricity prices. The necessary backup can be operated with co-products from chemical production as well as further with natural gas, whereby the latter in particular can also be replaced by hydrogen.

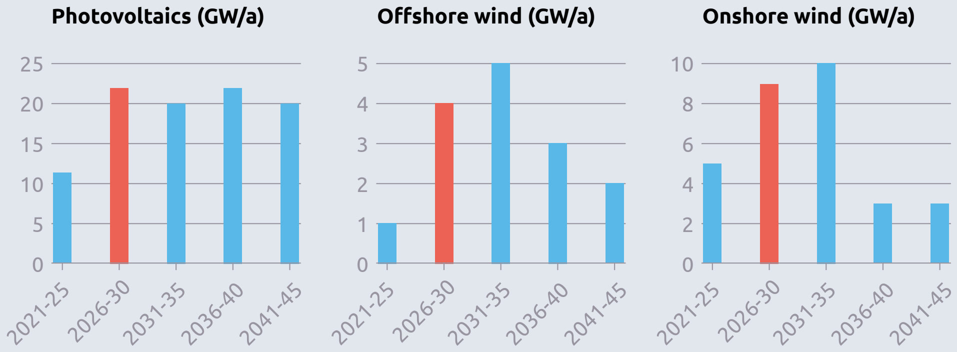
As soon as the infrastructural possibilities for CO_2 removal and storage are available, the mineral industry, and here in particular the cement industry, will also come into focus, where investments in new clinker kilns or retrofits would be necessary in order to also address

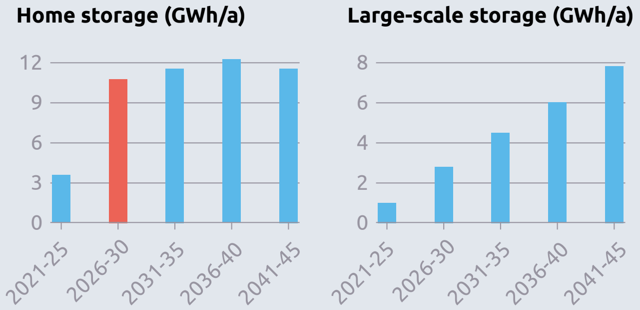
FIG. 02 **Necessary expansion of individual transformation technologies over time to 2045**

Rapid additions by 2030 are required primarily for the key technologies of photovoltaics, wind energy, heat pumps, electric cars (battery electric BEV), and DRI shaft furnaces for the production of steel.

A. **Energy industry ***

For photovoltaic and wind power on land and at sea, 2 to 4 times more installations will be added annually by 2030 than in the recent past.

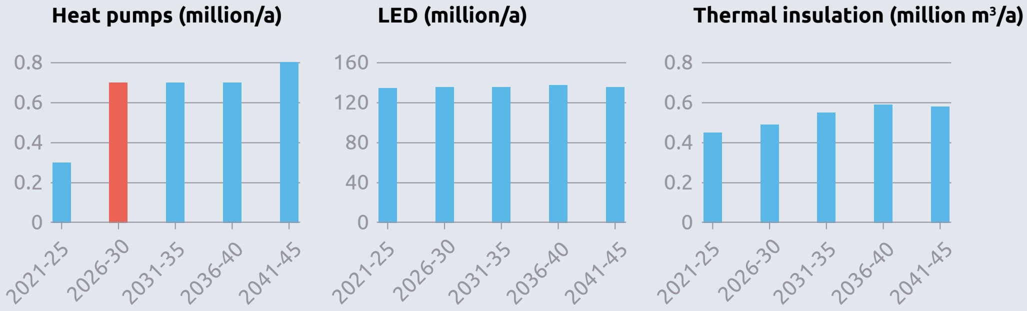




* In addition, replacement investments in bioenergy plants (biogas and solid biomass) are needed in the power sector. By 2028, a total of 2.4 GW will be put out to tender in order to partially compensate for decommissioning of existing plants. The performance target for 2030 is 8.4 GW (2022: 9 GW). Gas-fired power plants that can use hydrogen are also needed to back up power. To this end, the BMWK is currently developing a power plant strategy. Furthermore, biomethane processing plants are needed as well as additionally in district heating solar thermal plants, boilers, large-scale heat pumps, geothermal plants, e-boilers and storage tanks.

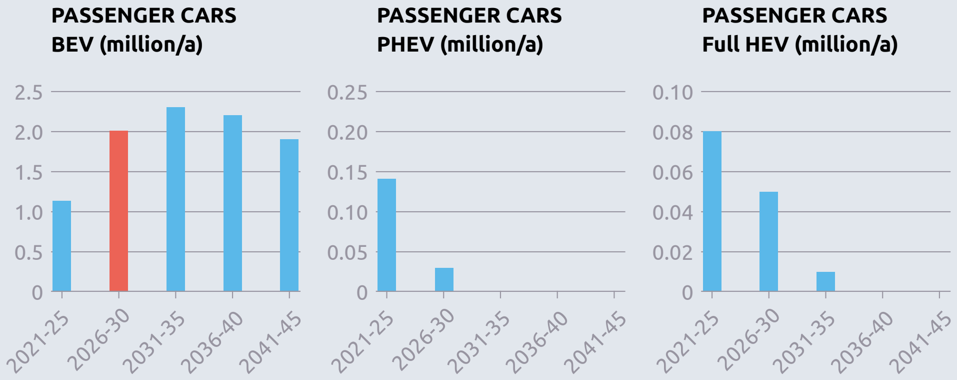
B. **Buildings**

Strong increase in new heat pump installations from 2025 to 2030 to an average of about 700,000 units per year. This is roughly equivalent to today's gas heater sales. In 2022, the gross build was around 240,000 units.



C. **Transport**

By 2030, there will be a large increase in new registrations of battery-powered electric cars (BEV) and light and heavy commercial vehicles (LCV and HCV – BEV) in particular.

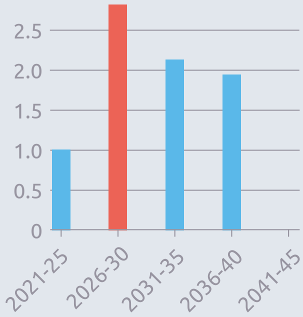


Prognos, Öko-Institut, Wuppertal Institut

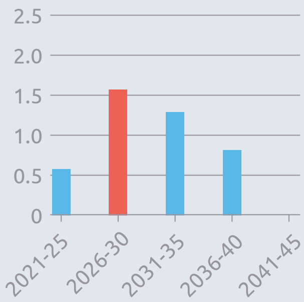
D. Industry

Fast ramp-up to 2030 mainly in decarbonization of steel using DRI shaft furnaces (direct reduction) and electric arc furnaces (EAF).

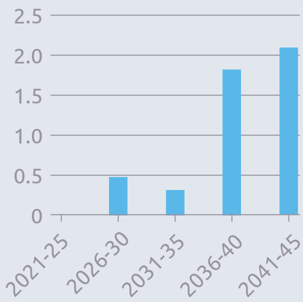
Electric arc furnace (million tons of crude steel per year)



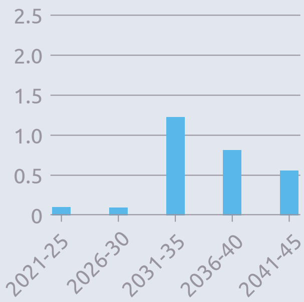
DRI shaft furnace (million tons of DRI/year)



Oxyfuel CCS clinker kiln (million tons of clinker/year)



Industrial heat pumps (GW_{el})



E. Other Conversion

Rapid ramp-up of electrolyzers domestically and internationally to provide the required hydrogen volumes by 2030

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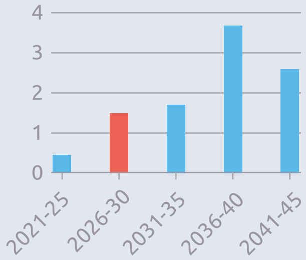
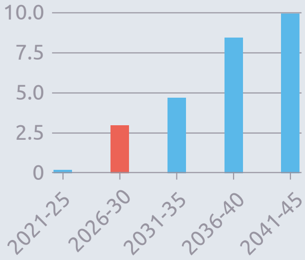
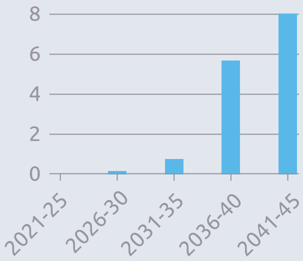
Electrolyzers (GW_{el}/a)



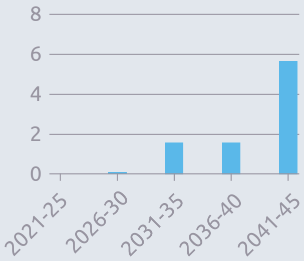
Electrolyzers Abroad (GW_{el}/a)



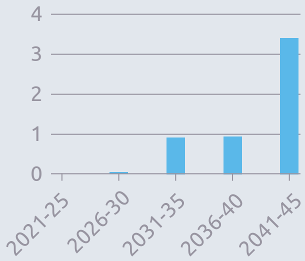
DAC (million tons of CO_2/year)



DAC Foreign (million tons of CO_2/year)



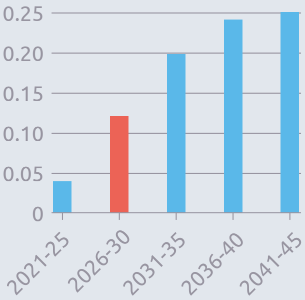
PtL * Abroad (GW_{PtL}/a)**



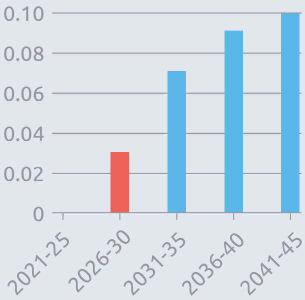
** capture of CO_2 abroad for import of PtL.

*** PtL (synthetic fuels: power-to-liquid) mainly as methanol and naphtha.

LCV BEV (million/a)



HCV BEV (million/a)



SOURCE Own representation based on the KNDE2045 study and own calculations

ABBREVIATIONS BEV: Battery Electric Vehicles; PHEV: Plug-in hybrids; full HEV: Full hybrid; LCV: Light Commercial Vehicles, HCV: Heavy Commercial Vehicles; CCS: Carbon Capture and Storage; DAC: Direct Air Capture (CO_2 capture from the air); PtL: Power2Liquids (synthetically produced liquid fuels) the process-related emissions. On a broad scale, this would not be the case until after 2030 according to the KNDE2045 scenario. However, accelerating the development of CO_2 networks as part of the implementation of the federal government's carbon management strategy currently being developed could also speed up the investment cycle.

Building

The building sector was responsible for 15 percent of Germany's greenhouse gas emissions in 2022, with 112 million metric tons of CO_2 equivalents. Under the federal Climate Protection Act (KSG), the building sector may only produce 67 million metric tons of CO_2 equivalents in2030, a necessary reduction of around 40 percent compared with today.

GHG emissions in the building sector are predominantly generated by the generation of space heating and hot water. Process heat and mechanical energy are of secondary importance. Decarbonizing heat generation and reducing heat demand are therefore the main levers for achieving a carbon-neutral building stock.

For the decarbonization of heat generation, one of the most important measures, in addition to an expansion of district and local heat supply, is the rapid expansion of heat pumps from one million today to around six million by 2030.[2] To achieve this, the number of heat pumps installed annually must be increased from around 200,000 units in 2022 to around 700,000 units. The upcoming Building Energy Code (BEC) is expected to allow more leeway and time for fossil-fuel heating replacements than the original plans. This makes the achievement of the heat pump expansion target more dependent on the development of other instruments such as CO_2 pricing. To achieve climate neutrality, a total of 14 to 16 million heat pumps will have been installed by 2045. A second key measure is the expansion and decarbonization of local and district heating networks. Wood heating systems play a minor role due to the limited availability of biomass.

Strengthening energy efficiency is necessary for the reduction of heat demand in buildings: New buildings with low heating requirements, more energy-efficient renovations in existing buildings, and the use of efficient electrical appliances and lighting. In the KNDE2045 scenario, the annual building area renovated increases by more than 50 percent by 2030 compared to the 2015 to 2020 period. As a result, demand for insulation materials grows markedly through 2030 and remains at this elevated level after 2030. For lighting, only lamps with LED technology will be used in the scenario in the medium and long term. Sales of LED lamps and lights continue to grow.

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[2] The accelerated expansion is to be stimulated in particular by the amendment of the Building Energy Act (GEG) with a minimum share of renewable energies of 65 percent for newly installed heating systems, as well as by the attractive subsidies under Germany's Federal Support for Efficient Buildings programme.

3. Risks along the supply chain and prioritization of key technologies

Risk factors for securing the Security of supply

Whether raw materials, components, and goods needed to achieve climate protection goals are to be classified as critical depends on two factors. First, they must have high economic importance (Bobba, S., Carrara, S., Huisman, J., et al., 2020). Secondly, a risk to security of supply exists or is foreseeable. For the transformation of the energy system, the technologies that lead to high or very high greenhouse gas emission savings are of particular economic importance.

Factors that may jeopardize security of supply in the production or procurement of raw materials, components or strategically important goods can be demand overhangs, supply concentrations, political tensions through to war situations or even natural disasters in important supplier countries and, increasingly, environmental and social risks.

Demand overhang: Technologies that have a large contribution to reducing greenhouse gas emissions often require a particularly rapid ramp-up of technologies and associated supply chains within a few years. Some of these technologies are largely mature and often already have substantial manufacturing capacity, such as photovoltaics and wind power. But there are also technologies that are only now being scaled up to an industrial production level, such as PEM electrolysis. If the supply cannot be expanded quickly enough, this causes excess demand.

For the rapid ramp-up of all technologies, the key challenge is that supply must be established and expanded simultaneously across all stages of the value chain. For example, it is not enough just to vigorously expand the capacities of the gigafactories for battery cell production; at the same time, the capacities for the production of upstream components, such as the anode and cathode material, must grow accordingly. Any supply chain is only as resilient as its weakest link.

The mining of raw materials in particular, as the first stage of the supply chain, can become a bottleneck. The realization time for new mines is usually five to 15 years. The reasons for this are the complex planning and approval processes, the uncertain outcome of environmental impact assessments, the involvement of the local neighborhood, and not infrequently political uncertainties in the respective country due to changes in government. Above all, mining is very capital-intensive. Investments in such projects require a lot of venture capital. Highly fluctuating raw material prices are an additional special challenge for financing and thus also critical for a fast implementation of the projects. The risk that a mining project will not materialize is very high due to the various uncertainties.

Market power and supply concentration: Many raw materials are concentrated in very few countries or are only mined by a few companies. This typically has both geological and historically-rooted reasons. Particularly in the case of raw materials for strategically important key technologies, a high concentration in a few countries can be seen. For lithium, 91 percent of mining in 2021 was in Chile, Australia and China, according to United States Geological Survey (USGS) data. More than 70 percent of cobalt, which is important for cathode material used in the production of lithium-ion cells, is mined in the DR Congo. The mining of natural resources does not always take place in China, but Chinese companies are often involved in the mining process and export the ores and concentrates to China for further processing. Accordingly, one must look beyond the localization of the extraction of raw materials when it comes to depicting dependencies on specific countries.

A high concentration of supply in a few countries or companies entails the potential risk of abuse of market power. An example of this is the crisis in rare earths in 2010 to 2012, when China drastically reduced its export quotas for rare earths as a result of political tensions with Japan, plunging the market into a severe crisis due to its great market power. Rare earth prices surged, and many industries that relied on them had an acute interest in diversifying their supply chains. When China relaxed its quotas after a few years and prices dropped significantly again, industry and policymakers initially lost the motivation to push ahead with supply chain diversification.

FIG. 03 **Causes of supply risks** in addition to the “classics” of economic significance and supply risks, dynamics are considered in the study.

Economic significance

- High savings of greenhouse gas emissions
- Quantity relevance
- Strategic importance (e.g. no substitutability)

Supply risks

- Demand overhang
- Market concentration, Country risks
- Sustainability

Time and dynamics

- Climate neutrality requires rapid transformation
- Supply ramp-up and demand difficult to synchronize

SOURCE Own representation

Prognos, Öko-Institut, Wuppertal Institut, 2023

FIG. 04 **Causes of supply risks**
Critical supply situations can arise at various levels.

⚠	**Demand overhang**	Insufficient synchronization of supply and demand at dynamic ramp-up
⚠	**Market concentration**	Political risks (country risks) Market power of individual companies
⚠	**Sustainability**	Environmental protection Human rights, social standards

SOURCE Own representation NOTE Environmental and social risks, such as insufficient compliance with social standards and human rights, are not the subject of this STUDY.

Prognos, Öko-Institut, Wuppertal Institut, 2023

Only Japan stuck to its principles and promoted the further processing of rare earths outside China in order not to be completely dependent on China.

In addition, **environmental pollution** and **lack of or low social standards** are major challenges. In many resource-rich countries, environmental protection regulations are inadequate, which can lead to catastrophic conditions. Extraction of raw materials is the step in the supply chain with the greatest impact on nature and, at the same time, the greatest burden on workers and the local population.

In addition, new mining projects face strong opposition if environmental impacts and social participation are not considered from the outset. It is necessary for local people, politicians and the mining industry to work together at the development stage in order to open up new mines in the future, including in the EU. Again and again, there are examples of mining projects that did not come to fruition due to resistance from the population, or were at least temporarily interrupted. One example is the Jadar mine lithium project in Serbia, which was temporarily halted by the government due to protests from the population (TAZ, 2023). In Myanmar, only recently, protests against ongoing rare earth mining led to the concession by mine operators that production would be temporarily halted, but with an unclear outcome (Benchmark Source, 2023a). Chile is exploring the possibility of nationalizing its lithium deposits to have more say in the future and to benefit more overall (MiningScout, 2023). However, the issue of environmental impacts and social issues are not part of this study, as the focus is on the demand and supply situation and they have been explicitly and extensively addressed in various studies before. (Re-Sourcing, 2020), (STRADE, 2016), (Öko-Institut, 2021)

Supply chains: from the extraction of raw materials to the production of whole goods

A critical supply situation can arise along the entire supply chain: In the mining and processing of the raw materials, the production of the (sub)components up to the production of the individual goods. The individual steps are presented in the following sections (cf. FIG. 05).

Raw material extraction The extraction of raw materials from natural deposits in mining is the starting point for the supply chain.[3] Mining from the deposits can take place in open-pit or underground mines. In open-pit mining, extraction takes place on the surface in open pits. The raw materials are usually extracted in the form of ores after the removal of layers of earth and are treated in initial processes, e.g. blasting, dredging, grinding or leaching. In underground mining, the deposits are located deep below the Earth's surface. The raw materials are then extracted in mines and tunnels.

Very few commodities are actually rare in the strict physical sense. Rather, the shortages arise for other reasons: Many raw materials are only mined as by-products, such as iridium, which is also mined in small concentrations during platinum mining. In addition, raw materials are often only available in low concentrations in the natural deposits, which are not economically or technically viable to extract. A huge problem with strong growth in demand is the usually long lead times and financial risk associated with developing and building new mining production capacity. This can very quickly lead to at least temporary shortages in supply.

Raw material processing Raw materials must first be enriched and prepared for further processing. This includes the removal of unwanted accompanying substances and an overall increase in concentration. The processes for processing and refining the individual raw materials not only differ greatly between the various materials, but also according to their occurrence and subsequent application.

For example, batteries require raw materials to be of very high purity, which is not essential for other applications. Also, certain impurities are tolerable for some applications and not for others. The initial enrichment often takes place on site in the mining countries, while the actual refining and achievement of very high purity sometimes takes place after transport over long distances in other countries (tending to be the sites for production of the final products). Depending on the raw material and process, the preparation for further processing into certain components requires a high level of technical know-how, which is not always widely available in the EU.

Production of (partial) components: It is not sufficient to master only the mining and refining of raw materials, or to have the capacity to do so, if the components to be made from the raw materials can only be manufactured elsewhere. Components are, for example, the components of lithium-ion batteries, i.e. anode and cathode material, conductor foils, cell housings, etc. A good example of an existing dependency is the production of cathode material for lithium-ion batteries. Most of this takes place in China, South Korea and Japan, although one of the world's largest cobalt refineries is located in Finland, for example.

Production of goods: The last key step is the production of the actual goods or equipment itself. Often, this is where most of the value creation lies. For this study, goods should be understood as the end products that in turn make other technologies possible. Examples of goods are solar panels, batteries or permanent magnets and electrolyzers. Of course, in these cases production and independence from other countries must also be strengthened. However, it must be noted that without

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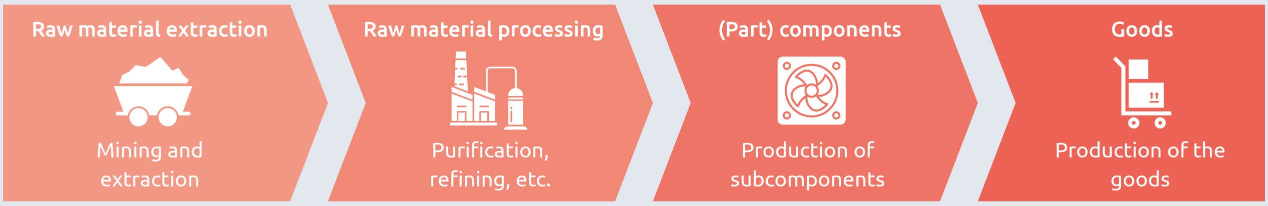
[3] Depending on the intermediate or end product, different proportions of secondary raw materials from recycling processes may also be integrated into the supply chain.

FIG. 05 **Stages of the supply chain**
Critical supply situations can occur along the entire supply chain.



SOURCE Own representation

the previous steps, independence is not possible. Although the previous steps should not be underestimated, the production of goods usually involves a high proportion of the crucial technology that determines the quality of the product. Only with excellent processes, for example, can a lithium-ion battery cell be produced in high volumes and consistent quality from high-quality components. However, the high-quality components are a minimum requirement. The overall process is very material-intensive and the supply chains must therefore be very well coordinated. Even small changes in individual components can lead to cell failure.

Prioritization of strategically important key technologies

To focus the analysis on central key technologies, all transformation technologies were evaluated in terms of the factors that can lead to both high strategic importance (high greenhouse gas emission savings) and high risk in terms of security of supply: rapid ramp-up to 2030, little to no alternatives in the short term, and high concentration in raw materials, components, or even the production of whole goods (see FIG. 06 Seven goods or components in particular were identified as of outstanding importance:

- Photovoltaics
- Wind power
- Lithium-ion batteries for electromobility
- Permanent magnets for electromobility and wind power
- Electrolyzers
- Heat pumps
- Green steel plants (DRI shaft furnaces)

In addition to these goods or components, various chemical process technologies, a wide variety of infrastructures, and information and communication technologies — hardware and software for digitalization — are also of particular importance for the transformation to climate neutrality. Because of the particular specifics in these areas, they are not addressed further in the research presented here, but they are of great importance with regard to resilience and sovereignty.

FIG. 06 **Criteria for the selection of prioritized key technologies**

Wind power (incl. permanent magnets for generators), photovoltaics, battery electric vehicles (incl. permanent magnets for electric motors and lithium-ion battery), heat pumps, water electrolyzers, and direct reduction plants for decarbonization of steel play a key role in reducing greenhouse gases. Due to the very fast ramp-up, the non-existing or hardly existing technological alternatives and the high concentration in manufacturing for raw materials, components or whole goods, these technologies are prioritized key technologies in this study.

	Technology	Very high GHG reduction by 2030/35	Strong ramp-up by 2030/35	Few short-term alterna-tives	Currently, high concentration in raw materials (R), (part) components (K) or goods (G)	
Energy industry	Wind power	X	X	X	X (x)	K: **Permanent magnets for generators**, K: Individual components
	Photovoltaics	X	X	X	X	R, K, G: **Entire supply chain**
	Gas-fired power plants H_2-ready	(x)	X	X		
	Bioenergy	(x)				
	Home storage up to 100 kW	(x)	(x)			
	Large-scale storage	(x)				
	Geothermal energy					
	Solar thermal		(x)			
	Large heat pumps		(x)			
	Electric heaters					
	Electrolyzers	X	X	X	X	R: **Iridium**
Transport	Battery electric vehicles (BEV, incl. passenger cars, light and heavy commercial vehicles)	X	X	X	X	R: **Lithium**, manganese, cobalt, nickel, graphite, **Rare earths**, K: Lithium-ion batteries, **Permanent magnets for electric motors**
	Passenger cars (PHEV)					
	Passenger cars (full HEV)					
Building	Heat pumps	X	X	X	(x)	K: Compressors
	Thermal insulation	X	(x)	X		
	LED					
Industry	Electric arc furnace (steel)	X	X	X		
	DRI shaft furnace (steel)	X	X	X	(x)	Plant engineering
	Oxyfuel CCS clinker kiln (cement)	(x)	(x)			
	Industrial heat pumps	(x)	(x)	X	(x)	Plant engineering (especially for high-temperature HP)
Oth-ers	DAC					
	PtL plants (methanol, naphtha)					
Infra-structure	Hydrogen network	(x)	(x)	X		
	Power grid	(x)	(x)	X		
	CO_2 network	(x)		X		

KEY X: very relevant; (x): limited relevance

ABBREVIATIONS BEV: Battery Electric Vehicles, PHEV: Plug-In Hybrids, Full HEV: Full Hybrid, CCS: Carbon Capture and Storage, DAC: Direct Air Capture (CO2 capture from the air). PtL: Power2Liquids (synthetically created liquid fuels)

SOURCE Own calculations based on the KNDE2045 study and own calculations

4. Expansion paths for key technologies in Germany up to 2045

Chapter 4 takes a closer look at the prioritized key technologies. On the one hand, the expansion paths assumed here are outlined; on the other hand, the concrete technology paths are described and the assumptions are presented in order to calculate which raw materials are contained in each technology and in what quantity:

- **Gross capacity increase:** or demand describes the annual gross capacity increase per technology. In the case of photovoltaic systems, for example, this will average around 22 GW from the mid-2020s, which will have to be added each year in order to achieve the targets set out in EEG 2023.
- **Technology Pathways:** The respective technologies have different technology paths, which have an impact on the raw material requirements. In the ramp-up paths of photovoltaics, the decisive factor is how the shares are distributed between silicon-based wafer cells and thin-film cells. In the case of wind power, it is interesting from a raw material point of view how high the proportion of synchronous generators with permanent magnets with and without gearboxes is. For lithium-ion batteries, the need for critical raw materials determines which cathode technologies are used. For electrolyzers, the crucial question is how quickly PEM electrolyzers (proton exchange membrane, with the very critical raw material iridium) will diffuse into the market and whether and when high-temperature electrolysis — with the raw materials scandium (moderately critical) and yttrium (strategically relevant, but not critical) — will reach market maturity.
- **Raw material intensity:** The third influencing variable is the amount of raw materials per unit of the manufactured good. Specific raw material requirements can be reduced through research and development or through economies of scale in increased production. A sharp drop in raw material intensity can lead to a decline in material requirements over time despite an increase in new production. The assumptions made in this regard are therefore important for the interpretation of the results. In the longer perspective, the role of recycling is growing. The details of the development of raw material intensity is shown in the appendix in Annex A.

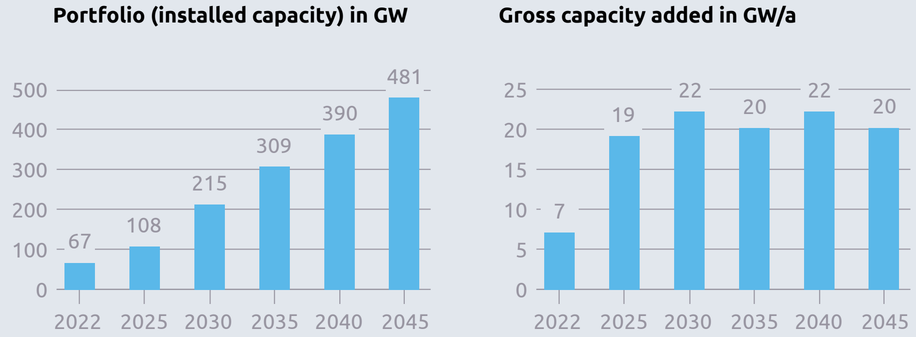
From these three assumptions, the demand for critical raw materials for Germany is determined following the analysis of the supply chains in Chapter 5.

4.1. Photovoltaics

Demand: New capacity increases rise before 2030 to 22 GW per year

Alongside wind energy, photovoltaics is the most important source of climate-neutral electricity and thus essential for the transformation of the German energy system, with low electricity generation costs and high expansion potential. In line with the targets of the Renewable Energies Act (EEG) 2023, the expansion will accelerate significantly in the next few years. Starting from an average of five GW per year in the last five years (BMWK, 2023a), additions are expected to reach twelve GW as early as 2023, rising to 22 GW per year by 2027. By 2045, installed capacity will grow to around 480 GW (cf. FIG. 07) Photovoltaics will thus generate about 450 TWh of electricity and account for about 40 percent of Germany's electricity generation.

FIG. 07 **Photovoltaics**



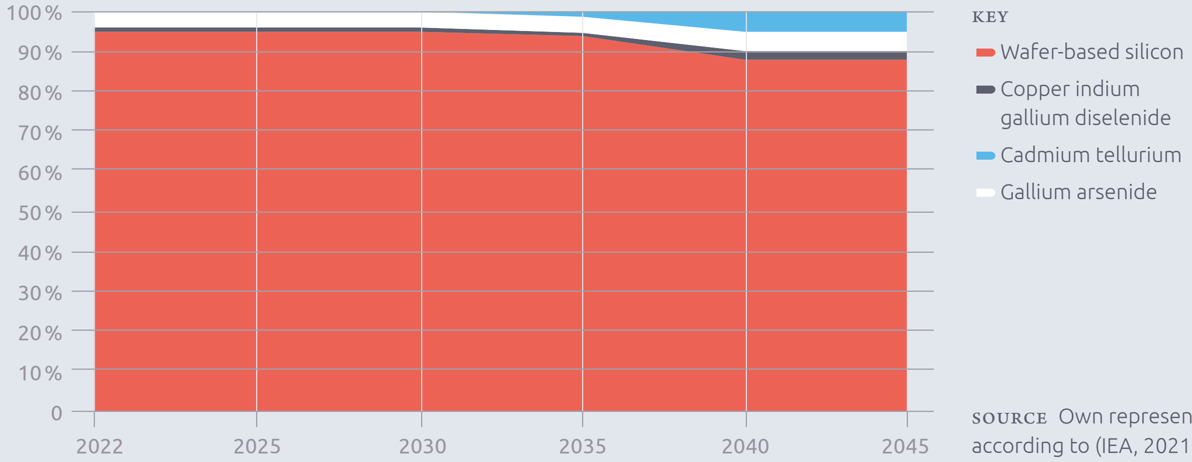
The expansion is based on the EEG 2023 until 2040. From the mid-2020s, annual additions will rise to around 22 GW.

SOURCE own presentation based on EEG 2023 and own calculations

Prognos, 2023

FIG. 08 **Photovoltaics technology mix**

Wafer-based PV technology will continue to dominate the market in the long term.



SOURCE Own representation according to (IEA, 2021a)

Prognos, 2023

Components

A photovoltaic system consists of various components:

- Photovoltaic modules in which direct current is generated
- Inverter for converting the direct current into alternating current and for feeding the current into the grid
- Substructure
- Wiring
- Remote monitoring system
- Radio control unit
- Electricity meter (smart meter)

The photovoltaic modules themselves form the heart of the system and consist, among other things, of several solar cells connected in series or parallel, a glass pane to protect against hail and dirt, a transparent plastic layer in which the solar cells are embedded and thin silver wires to transport the electrons. The modules are framed by a profile frame.

Technology Mix: Wafer-based photovoltaics will remain dominant, also in the long term

There are two main technology strands for solar cells, which differ, among other things, in the thickness of the cells and the semiconductor used: Wafer-based solar cells are thick-film cells with crystalline silicon as the semiconductor (c-Si) and dominate the global market with around 95 percent. This contrasts with thin-film cells, in which other semiconductors are also used. These include, for example, copper indium gallium diselenide (CIGS), cadmium tellurium (CdTe), gallium arsenide (GaAs) and amorphous silicon (a-Si). Thin-film cells currently have a market share of around five percent. (IEA, 2021a) In addition, there are other cell forms, such as perovskite cells, some of which are in the development stage.

The technology strands come with different advantages and disadvantages. Crystalline silicon cells are characterized in particular by their higher efficiency (Solarserver, 2021), a more robust design and a longer service life (solarenergie.de, 2021a). Disadvantages are the increased production costs, the higher weight and their reduced material flexibility (solarenergie.de, 2021a). Due to their low thickness, thin-film cells have a reduced raw material requirement (Photovoltaik.org, n.d.). They are flexible (solarenergie.de, 2021a) and achieve a high electricity yield even in diffuse light (Photovoltaik.org, n.d.). On the other hand, they are less efficient (solarenergie.de, 2021a). In the scenario assumed here, it is assumed that although there will be a slight shift in market share toward thin-film PV by 2040, wafer-based technology will continue to account for the majority of PV modules used, at over 85 percent (IEA, 2021a).

4.2. Wind power

Demand: Annual additions until 2035 of up to eight GW of offshore wind and eleven GW of onshore wind

Wind energy represents the most important pillar in terms of volume for the generation of climate-neutral electricity. In the calculations of this study, around 600 TWh, or a good 60 percent of the electricity in Germany, will be generated with onshore and offshore wind energy in 2045. From about 125 TWh of wind power generation today, electricity generation is expected to more than quadruple by 2045.

The current EEG 2023 provides for ambitious expansion paths for wind energy. Especially in the years 2026 to 2035, this will result in a high annual expansion demand of up to eight gigawatts per year for offshore wind and eleven GW for onshore wind. By comparison, the highest annual addition achieved to date was 5.5 GW in 2017. Although the increasing turbine sizes in the onshore and offshore sectors are reducing the number of turbines required for the same capacity addition, ensuring a stable supply chain remains a key challenge, particularly with regard to the next ten to 15 years.

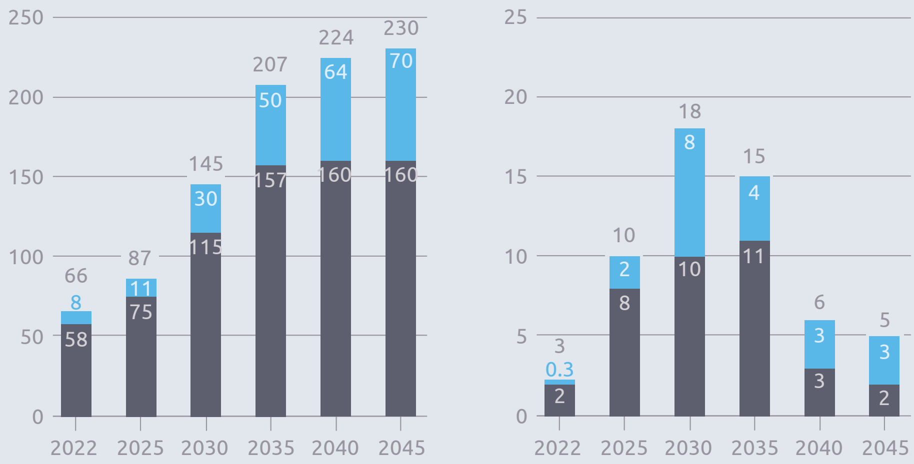
Components

Wind turbines are complex machines. The two most important components are the rotor with hub and the rotor blades, with which the kinetic energy of the wind is converted into motion energy, and the generator, which converts the motion energy into electric current. The generator itself consists of copper coils and magnets — either made of electromagnets or permanent magnets with rare earths. Some wind turbines have a gearbox. It is located between the rotor and the generator and converts the slow motion of the rotor into faster rotary motion. This means that the generator can be smaller than in systems without a gearbox. With regard to the use of rare earths as critical raw materials, this is a relevant factor. In ad-

FIG. 09 **Wind power**

Portfolio (installed capacity) of onshore and offshore wind in GW

Gross additions of onshore and offshore wind in GW/a



The strongest additions per year will take place in the next ten years. In order to implement the targets set out in the Renewable Energy Sources Act (EEG) and the Wind Energy at Sea Act, a lower level of expansion will be necessary from 2030 onwards.

KEY
- ▬ Onshore
- ▬ Offshore

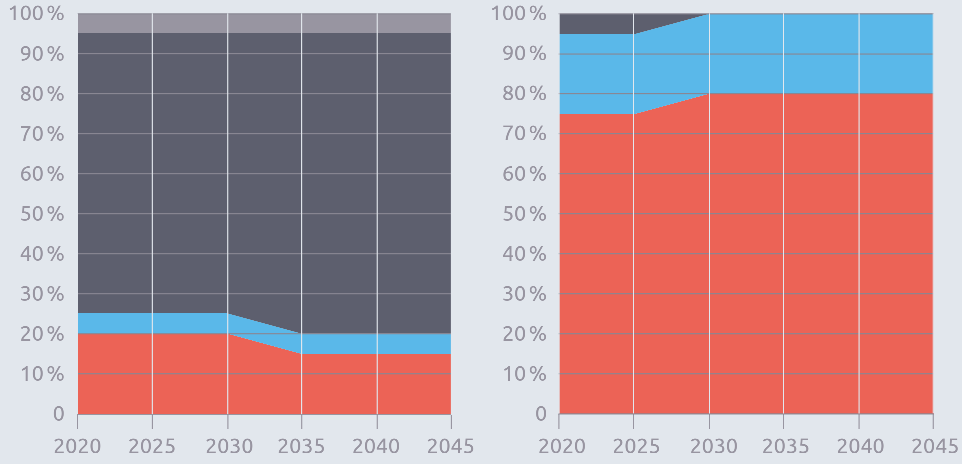
SOURCE Own presentation based on EEG 2023 and Wind Energy at Sea Act as well as own calculations

Prognos, 2023

FIG. 10 **Technology Mix Wind Power**

Wind onshore

Offshore wind



80 percent of offshore wind turbines and 20 percent of onshore wind turbines use generators (DD-PMSG), which have a particularly large permanent magnet with rare earths. By using gearboxes (GB-PMSG), the permanent magnet can be significantly reduced in size. This reduces the demand for rare earths.

KEY
- 🟥 **DD-PMSG**: Synchronous generator with permanent magnet, without gearbox (very high demand for rare earths)
- 🟦 **GB-PMSG**: Synchronous generator with permanent magnet, with box (medium demand for rare earths)
- ▬ **GB-DFIG**: Induction generator with gear (low demand for rare earths)
- ▬ **DD-EESG**: Electrically excited synchronous generator without gearbox (low demand for rare earths)

SOURCE Own representation according to (IEA, 2021a)

Prognos, 2023

dition, a wind turbine includes a tower, foundation and grid connection. In total, a wind turbine consists of more than 50,000 individual parts.

Technology Mix: 80 percent of offshore plants and 20 percent of onshore plants use generators (DD-PMSG) that require particularly large permanent magnets made of rare earths

For the purpose of evaluating criticality in required raw materials and subcomponents, wind turbines in use today can be divided into several basic types that differ in terms of the type of generator used and the use of gearboxes. The impact of technology choice has implications for the use of rare earths.

Basically, four different types of equipment are used:

- with permanent magnet generator and gearbox (GB-PMSG),
- with permanent magnet generator without gearbox (DD-PMSG),
- with induction generator and gearbox (GB-DFIG)
- with electrically excited synchronous generator without gearbox (DD-EESG).

The decisive difference lies in the structure of the magnetic field in the generator. Plants with permanent magnet generators (DD-PMSG and GB-PMSG) use rare-earth-based permanent magnets, while plants with induction generators or synchronous generators (GB-DFIG and D-EESG) use electromagnets or electromagnetically induced magnetic fields. Consequently, the demand for rare earths in the former types of plants is significantly higher than in the latter.

By using gears, a higher speed can be achieved in the generator, reducing the generator size and thus the use of magnetic material. Although the use of rare earths is higher in plants with permanent magnets and without gears (DD-PMSG), these types offer technological advantages that are particularly significant in offshore applications. Permanent magnets enable high efficiencies and efficient energy conversion, and the gearless drive concept reduces nacelle weight, which is particularly advantageous for large turbine outputs and difficult installation conditions. Today, therefore, 75 percent of offshore turbines and 20 percent of onshore turbines are built as DD-PMSG. In addition, onshore plants in China are also mainly built as DD-PMSG. The rest of the offshore turbines are built as generators with permanent magnets and gearboxes (GB-PMSG). That is, they also have a permanent magnet, but it is much smaller due to the use of the gearbox. GB-DFIG accounts for a very small share. However, this technology is dominant in onshore plants. They are not based on permanent magnets and therefore require very little use of rare earths. For the calculation of raw material requirements in Chapter 5, it is assumed that the current market shares in the technology paths will not change significantly in the future.

4.3. Batteries for electromobility

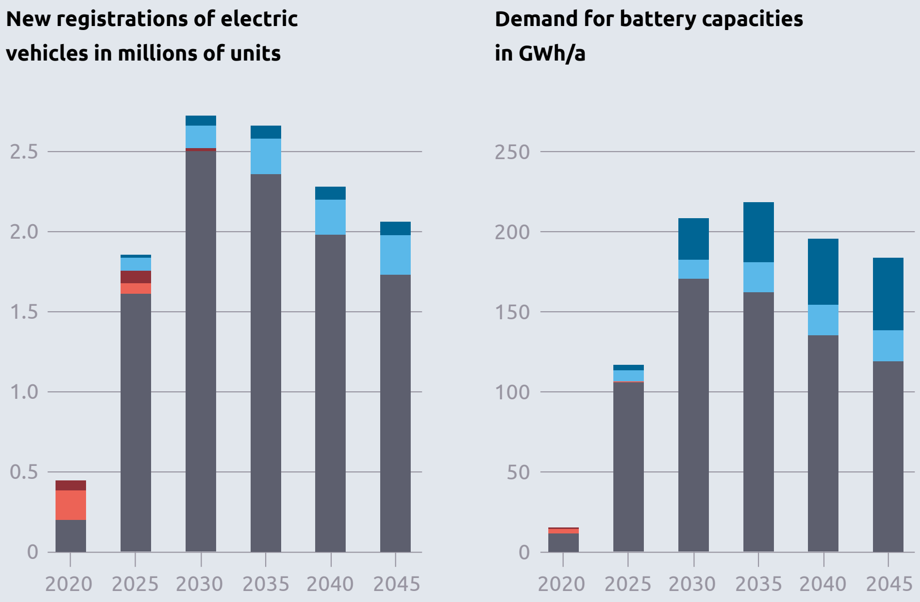
Shifting from internal combustion engine-based mobility to electrically powered vehicles is a key step toward climate neutrality. This is based on battery-powered vehicles, which are equipped with a traction battery and an electric motor[4] (usually with permanent magnets, cf. Ch. 4.4). The lithium-ion battery has become established as the drive battery. This will continue to dominate the market in the coming years. Alternatives, such as the sodium-ion battery, are still in early development. It remains to be seen what market shares they will take over. The demand for lithium-ion batteries is mainly driven by the electrification of vehicle fleets[5].

---

[4] Quite a few battery-electric car models are equipped with multiple electric motors.

[5] Lithium-ion batteries are also used for other applications (portable devices, stationary storage, etc.). However, the rapid ramp-up of electromobility means that applications in vehicles account for an overwhelming share of the market. Therefore, these other applications are not considered further in this study; (cf. for an overview regarding battery applications: Stahl, H., Mehlhart, G., Gsell, M., et al, 2021)

FIG. 11 **Electromobility**



New registrations of electric vehicles in millions of units

Demand for battery capacities in GWh/a

Demand for electric vehicles will be rising steeply through 2030. Battery demand is dominated by passenger cars.

KEY
- ▬ Heavy commercial vehicles (BEV)
- ▬ Light commercial vehicles (BEV)
- ▬ Passenger cars (full HEV)
- ▬ Passenger cars (PHEV)
- ▬ Passenger cars (BEV)

SOURCE Own modeling based on the KNDE2045 scenario

ABBREVIATIONS
EV: Electric vehicle,
HEV: Hybrid electric vehicle,
BEV: battery electric vehicle,
PHEV: Plug-in hybrid electric vehicle,
full-HEV: Full hybrid

Öko-Institut 2023

Demand: Compared to 2020, the Battery demand in the KNDE2045 scenario grows by a factor of almost 14 by 2030

The updated "Climate Neutral Germany 2045" scenario – KNDE2045 scenario — takes into account the interim targets of 15 million e-cars in the stock in 2030 (KoaV, 2021) and of 100 percent electric drives in new registrations from 2035 (Council of the European Union, 2023a). In addition to electrification, the scenario includes modal shifts to climate-friendly modes of transport (public transport, rail, etc.) to reduce GHG emissions from existing fleets in line with targets. As a result, the number of passenger cars in Germany will fall from around 50 million at present to around 40 million in 2045 (cf. FIG. 58 in the Appendix). For a robust estimate of battery requirements, the scenario assumes a complete switch to battery-electric drives in all vehicle segments in the future.

The modeled development of new registrations in Figure 11 shows a rapid increase in sales of battery electric vehicles by a factor of five by 2030. As of 2025, more than 90 percent of new electric vehicles are battery electric (BEV) passenger cars. The importance of plug-in hybrids (PHEVs) and full hybrids (full HEVs) will decline continuously until 2030. Among heavy-duty vehicles (HCV) with a gross vehicle weight of 3.5 tons or more, only BEVs are newly registered in the scenario from 2040. Compared with passenger cars, heavy and light commercial vehicles (LCV) have much lower unit sales.

Demand for batteries will increase rapidly by 2030 in line with the ramp-up of electric vehicles (see FIG. 11. Despite the larger battery storage of electric trucks, whose capacity is significantly higher than for electric passenger cars, the high number of new passenger car registrations is decisive for the overall demand for batteries[6]. Overall, demand for battery capacity for electric vehicles will increase by a factor of almost 14 between 2020 and 2030. For a detailed estimate of battery and raw material requirements from small cars to semitrailer trucks, cars and trucks were divided into size classes (cf. TABLE 11 in the Appendix). In a comparison of size classes, demand is dominated by large passenger cars, i.e. cars in the mid-size class or larger.

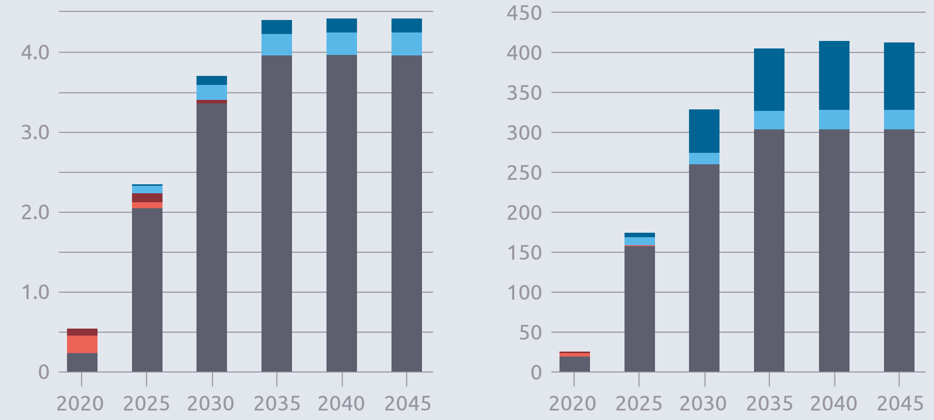
---

[6] The scenario also accounted for battery requirements for other vehicles such as pedelecs, electric buses, and battery-electric powered trains.
Due to their marginal relevance to battery demand and the associated demand for raw materials, these vehicles are not considered further in the context of this study.

FIG. 12 **Domestic production scenario**

Domestic production of electric vehicles in millions of units/year

Demand for battery capacities in GWh/year



Domestic production of electric vehicles is accompanied by a rapid increase in battery demand through 2035.

KEY

- Heavy commercial vehicles (BEV)
- Light commercial vehicles (BEV)
- Passenger cars (full HEV)
- Passenger cars (PHEV)
- Passenger cars (BEV)

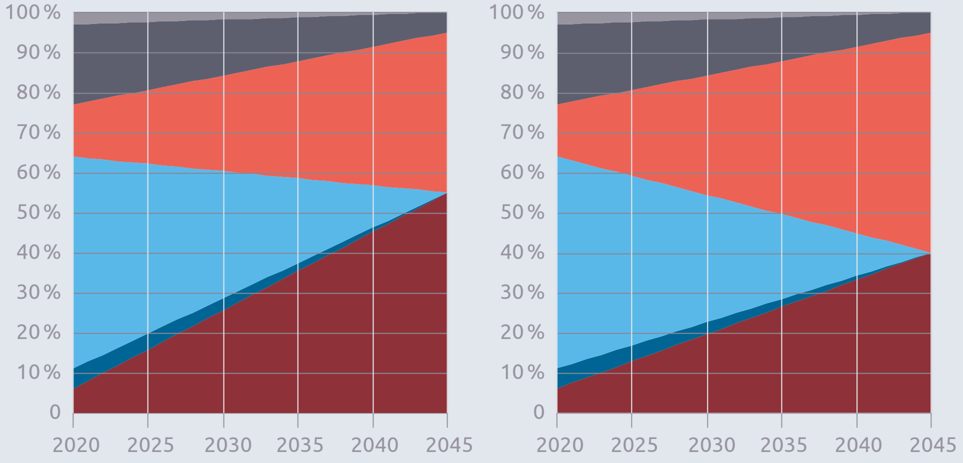
SOURCE own modeling based on the "Domestic production" scenario

Öko-Institut, 2023

FIG. 13 **Market shares of battery types for**

A. SMALL PASSENGER CARS

B) **Medium-size cars**



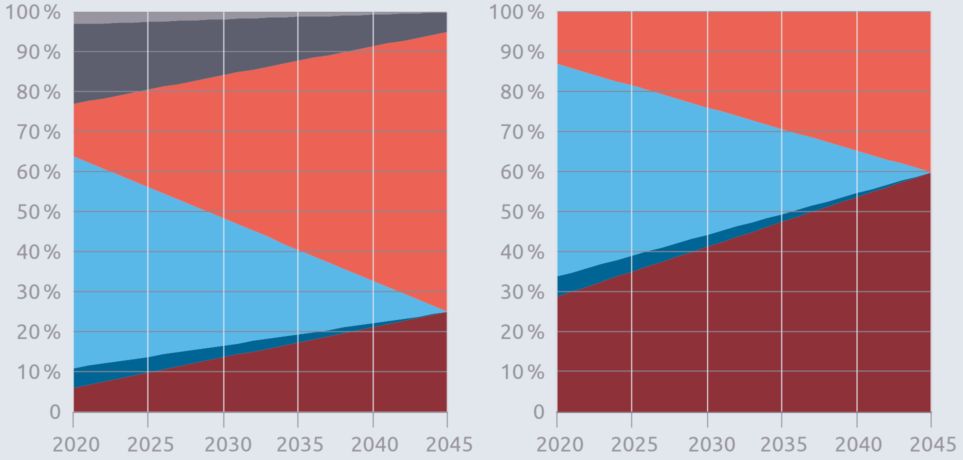
The shares of nickel-rich battery types (NMC 811) and nickel- and cobalt-free battery types (LFP) are increasing.

KEY

- LMO
- NCA
- NMC622
- NMC111
- NMC811
- LFP

C. **Large passenger cars**

D. **Light commercial vehicles**



SOURCE Own forecast based on current market shares and data from Benchmark Minerals

Öko-Institut, 2023

“Domestic production” scenario

The automotive industry is a central pillar of Germany as a business location. Overall, around seven percent of all employment subject to social security contributions in Germany is directly related to the automotive industry (Agora Verkehrswende, 2021). The question of raw material requirements for the domestic production of vehicles in Germany is therefore of high importance and is addressed in an additional scenario.

In the "domestic production" scenario, the development of the drive mix from the modeled new registrations is retained. With regard to the volume framework, it is assumed that once the coronavirus crisis has been overcome, passenger car production will recover and absolute unit passenger car sales will again approach the level of the pre-crisis period (around four million passenger cars produced per year in Germany)[7]. Thus, Germany will continue to act as a net exporter of passenger cars. Moreover, production is predominantly characterized by large passenger cars (mid-size and above), which gives these segments an even greater weighting in terms of raw material demand than for the raw material demand of new registrations.

Figure 12 shows a rapidly growing number of e-vehicles that will be produced in Germany in the future. As in the development of new registrations, passenger cars dominate both the unit numbers of domestic production and the demand for battery capacity. The latter is around 80 percent higher than the demand for new vehicle registrations for domestic production in 2035.

Components

Lithium-ion batteries have established themselves as the standard for the drive battery of electric vehicles. In addition to so-called peripheral components (battery housing, cables, battery management system/electronics), they are primarily composed of often hundreds of individual lithium-ion cells. The lithium-ion cell, as the actual heart of the lithium-ion battery, consists in each case of various individual components such as cell envelope, cathode and anode material, current collector (arrester), electrolyte and separator. The anode and cathode materials are the active materials and thus the heart of the battery. The chemical reactions of the cathode and anode enable the absorption and release of energy. The anode and cathode materials are also relevant in terms of the need for critical or strategic raw materials. For their production, most of the central raw materials lithium, nickel, cobalt, manganese (cathode material) and graphite (anode material) are used. Copper is not a component of the cathode and anode material. However, copper is relevant in other components (current collectors, cables, etc.) of lithium-ion cells.

---

[7] The forecasts for domestic production are based on VDA data and estimates.

Technology Mix

Lithium-ion batteries have clearly prevailed technologically over alternatives (e.g. nickel-metal hydride batteries) for traction batteries for cars, trucks, etc., due to their properties, and will dominate the global markets for this rapidly growing area of application for the foreseeable future (at least until 2030 or even beyond). Possible market shares of technological leaps such as solid-state electrolytes (SSE) or sodium-ion-based batteries[8] (Hopf, E., 2023) are deliberately not considered in this study. Their possible market shares, especially for the demanding German car and truck market (need for high ranges, comparatively high price segments, etc.), cannot yet be seriously estimated today, and in all likelihood alternatives for the lithium-ion battery will not be able to play any role, or at best only a subordinate one, in the medium term (up to 2030) in Germany.

Concomitant with and fundamental to the increasing electrification of the vehicle fleet is the technological advancement of lithium-ion batteries. The cathode active materials used are of particular importance here[9]. They have a decisive influence on the battery's properties, which is why the type of cathode material is used to distinguish between different lithium-ion batteries. In addition, the choice of cathode material affects the critical raw materials needed for the battery.[10] The quantities per car, depending on cathode material, are shown in Table 13 in the Appendix.

Depending on the requirements profile, different battery types are used in different vehicle types in relation to the cathode material. Based on the current distribution of the cathode materials used, the following graphs forecast which cathode materials will be used in which proportions in the future. International comparisons, (announced) production capacities and an assessment of technology developments are taken into account. It should be noted that estimating the technologies that will be used in the future in such a dynamic field as lithium-ion batteries is associated with great uncertainties.

As previously described, the amount of critical raw materials is directly related to the battery type. In the future, according to experts, NMC 811[11] (low in cobalt and manganese, high nickel content) and LFP batteries[12] (cobalt, manganese and nickel-free) will dominate the market. In comparison, LFP is currently significantly cheaper because it does not contain any of the expensive raw materials cobalt, nickel, or manganese. However, the energy density in NMC-based batteries is higher. That is, cars with the same battery size have reduced range with LFP than with NMC 811. LFP is therefore particularly interesting for small cars and smaller commercial vehicles. NMC 811, on the other hand, is used mainly for mid-range and especially upper-range vehicles (large passenger cars). Nevertheless, according to announcements, LFP is gradually gaining ground in this area as well, driven in particular by vehicle manufacturers from China.

---

[8] Sodium-ion batteries in particular have recently received a great deal of attention as a result of developments, especially in the People's Republic of China. However, the estimated production ramp-ups are still manageable, at least at present; for example, the source assumes a global capacity of over 100 GWh/a for sodium-ion batteries in 2030—with a total demand of 4,700 GWh/a at that time. This would only correspond to a market share of less than three percent in 2030.

[9] Currently common cathode materials are lithium-nickel-manganese-cobalt oxide in various compositions. ($LiNi_xMn_yCo_zO_2$, with x+y+z=1, e.g. NMC 111, NMC 622 or NMC 811), lithium-nickel-cobalt-aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, NCA), Lithium-iron phosphate ($LiFePO_4$, LFP), Lithium-Manganese oxide ($LiMn_2O_4$, LMO)

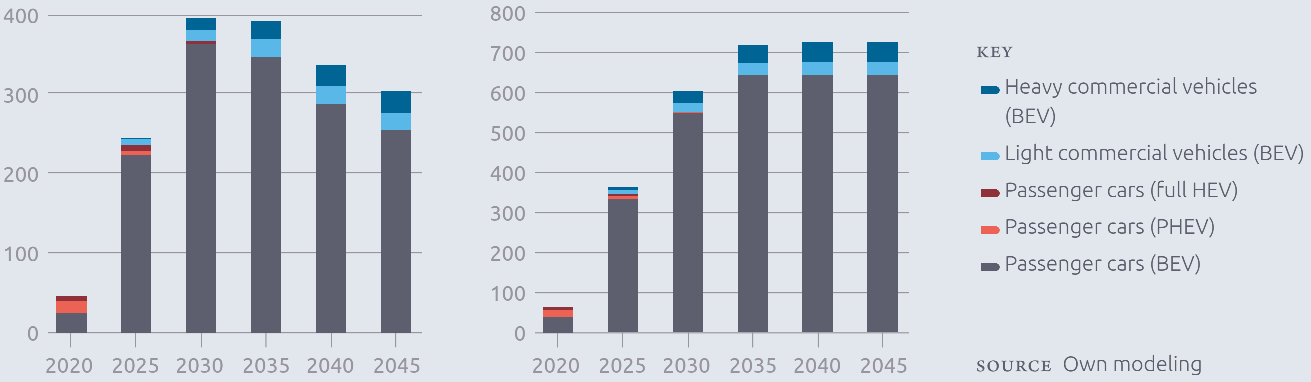
[10] As anode material in lithium-ion batteries, graphite has become the standard, with a small share of other materials (lithium titanium oxide, LTO, other carbon-based anodes, graphite anodes with a share of silicon). For the focus of this study, these other anode materials are not relevant in terms of quality or quantity and are therefore not considered further here.

[11] As previously explained, NMC stands for lithium-nickel cobalt-manganese oxides. The number behind it gives the ratio of nickel, cobalt and manganese. While NMC 811 stands for a large excess of nickel ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) , NMC 111 means equal proportions of cobalt, nickel and manganese ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$). Accordingly, NMC 622 has the composition $LiNi_{0.6}.Mn_{0.2}Co_{0.2}O_2$.

[12] LFP stands for lithium iron phosphate ($LiFePO_4$).

FIG. 14 **Annual demand for electric motors (in GW) for vehicle drives**

Passenger cars almost entirely determine the demand for motors for electric vehicles.


KNDE2045 scenario

Domestic production scenario

SOURCE Own modeling

Öko-Institut, 2023

In the small car size class in particular, a strong increase in LFP is forecast in terms of market share (see fig. 13). The share of NMC (NMC 111, NMC 622, NMC 811) is decreasing overall in small passenger cars and is increasingly dominated by NMC 811, while the market share of NMC 622, which is much used today, is decreasing sharply. In the medium-size car category, the share of LFP does not increase quite as much. For this, the nickel-based systems NMC 811 and NMC 622 play a greater role. According to the assumptions, this trend is even more pronounced in the large car size class. In light commercial vehicles (LCV), LFP is already used a lot and will continue to have the largest share in the future. NMC 622, which currently accounts for the largest share of batteries, is decreasing significantly and is being replaced by NMC 811.

In the case of trucks, economic factors but also higher requirements for storage capacity and robustness against a large number of loading operations play a role. Despite the cost advantages of LFP cells, industry experts therefore expect the importance of NMC cells to remain high, especially for heavy trucks and semitrailers. Since temporal trends for the nascent electrification of commercial vehicle fleets are difficult to estimate from today's perspective, no temporal change in the technology mix of battery chemistries is included in the assumptions (cf. TABLE 14 in the APPENDIX). The proportion of LFP was assumed to increase the lighter the truck (from 50 percent to 100 percent LFP proportion).

4.4. Permanent magnets for electromobility

Permanent magnets are used both for electric vehicles in electric motors and in wind turbines in the generators (cf. CH. 4.2.). Since the basics of generators have been described previously, this chapter focuses on the use of permanent magnets in electric vehicle drive motors. In vehicles, permanent magnets are required not only for the drive[13] (Rizos, V. et al., 2022). However, in electric vehicles the demand for the drive motors dominates by far.

Demand for drive motors

The demand for electric drives and the permanent magnets installed in them is derived from the annual number of new registrations of electric vehicles (cf. CH. 4.3.) and the type, number and drive power of the motors. Information on the assumed engine technologies and power classes of the vehicles is provided in the section "Technology mix". Figure 14 shows the annual demand for propulsion power calculated on this basis for new registrations in Germany according to the KNDE2045

---

[13] Other applications include power steering, window regulators or loudspeakers. Therefore, conventional vehicles are also a relevant area of application for neodymium-iron-boron magnets. A comparison of the shares of different applications can be found, for example, in (Rizos, V. et al., 2022). According to this, there is broad consensus that electric vehicle drives and wind turbines are the two fastest-growing applications for neodymium-iron-boron magnets.

scenario and for the production of vehicles in Germany based on the "Domestic Production" scenario (cf. CH. 4.3.).

It is clear that, as with batteries, demand for drive power from the electromobility sector is dominated by passenger cars, with cars from the upper vehicle segment accounting for a good 50 percent of total demand in new registrations; in domestic production, the figure is as high as around 70 percent. The addition of engine power is about a factor of 1.5 higher for the "Domestic production" scenario until 2030; in the long term, new passenger car registrations in Germany decline in line with the KNDE2045 scenario, while constant volumes are assumed until 2045 for the "Domestic production" scenario (cf. 4.3. Batteries for electric mobility). The share of light- and heavy-duty vehicles does not reach relevant proportions until 2030, rising to 16 percent of total demand in the KNDE2045 scenario and 11 percent in the "Domestic Production" scenario by 2045. LCV and HCV are in the same order of magnitude for the KNDE2045 scenario. Both scenarios are based on complete electrification of new registrations in freight transport from 2040 (passenger cars already from 2035), with only very small numbers of internal combustion trucks between 2035 and 2040.

Technology Mix

Permanent magnets are used in electric drives only in permanently excited synchronous motors (PMSM). However, their market share in the passenger car sector is currently 95 percent (ERMA; Gauss et al., 2021), as they are characterized by a higher power density, both in terms of weight and volume, compared with other engine types (REIA, 2022). The main commercial alternatives are currently separately excited synchronous motors and asynchronous motors (ASM), which avoid the use of rare earths by using more copper. In addition to a slightly higher weight and volume, the efficiency is somewhat lower.[14] Reluctance machines are being investigated as further alternatives, but these are currently still in the development stage and possible market potential for the future cannot be seriously assumed today (Agamloh, E. B. et al., 2020).

In principle, permanent magnets can be made of various metal alloys, the main representatives being neodymium-iron-boron (NdFeB), samarium-cobalt, aluminum-nickel-cobalt (AlNiCo) and ferrite. In electric drive motors for vehicles, however, the neodymium-iron-boron magnet has clearly prevailed despite its dependence on rare earths, as it most reliably meets the high requirements due to its particularly high energy density (VACUUMSCHMELZE GmbH & Co. KG, 2014), (Arnold Magnetic Technologies, 2023), (Rizos, V. et al., 2022).

Therefore, for this study, a current share of 95 percent PMSM with neodymium-iron-boron magnets is assumed for the passenger car sector, and based on (Gielen, D.; Lyons, M., 2022) and discussion with experts from the magnet and automotive industry, it is assumed that their share will continuously decrease moderately to 80 percent by 2045. Since efficiency and power density play an even greater role in trucks in terms of battery size, range and high mileage, it was assumed that 100 percent permanent magnets will continue to be used in the drive motors here in the future. To simplify matters, this assumption was also adopted for light commercial vehicles (LCV) and for hybrid vehicles[15] in the passenger car sector.

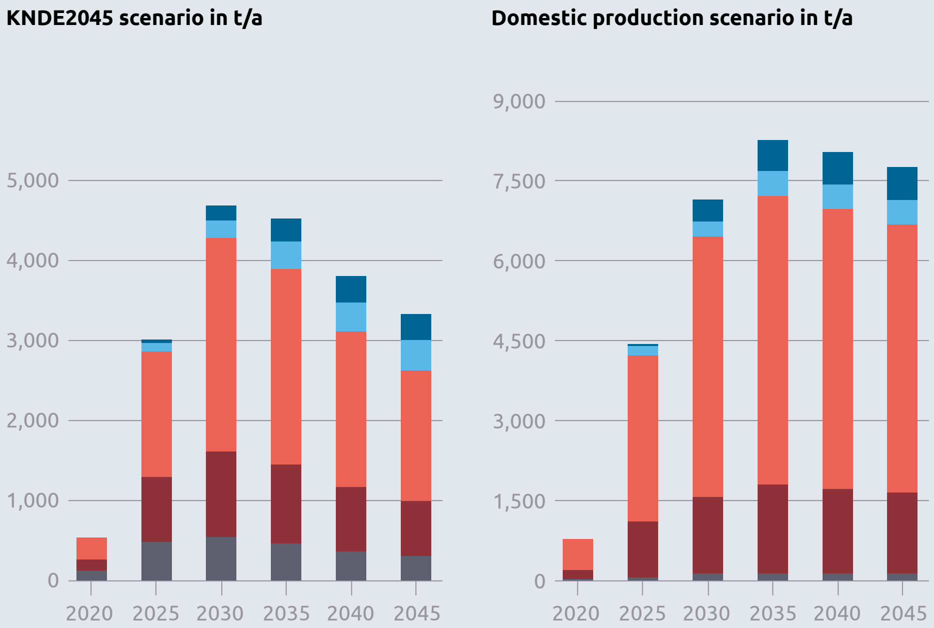
Based on the drive power for the various vehicles considered in this study (see TABLE 17 in the APPENDIX) and a permanent magnet demand of approx. 12-13 g/kW (Nordelöf et al., 2017), this results in the demand shown in Figure 15.

---

[14] According to experts in the field of electric motor development (10th Annual Advanced E-Motor Technology 2023, Munich, Germany), ASMs are about 10-20 percent heavier than PMSMs, and operating efficiency is about 90 percent (ASM) versus 95 percent (PMSM). FESM lie in between.

[15] No new registrations from 2035

FIG. 15 **Annual demand for permanent magnets for vehicle drives**



The main driver of the steeply increasing demand for permanent magnets is the production of "large" passenger cars

KEY
- ▬ Small car
- ▬ Medium-size car
- ▬ Large car
- ▬ LCV (BEV)
- ▬ HCV (BEV)

SOURCE Own modeling

Öko-Institut, 2023 and (Nordelöf et al., 2017)

As with propulsion power, it can be seen that demand for the "Domestic Production" scenario is about twice as high in the medium term as for new registrations under the KNDE2045 scenario. In terms of new registrations, the peak will be reached as early as 2030 due to the very rapid ramp-up of electromobility to achieve the climate protection targets set out in the coalition agreement, among other things, after which they will fall in line with new registrations and the use of alternative engine concepts. In the "Domestic Production" scenario, maximum demand is reached in 2035 and permanent magnet demand declines slightly only due to the shift to alternative motor concepts such as separately excited synchronous motors or asynchronous motors (ASM).

The calculations are based on a power density of a good 2kW/kg engine. Based on interviews with experts, the achievable power density has increased significantly in recent years due to the optimization of various physical parameters[16] so that today approx. 4kW/kgengine can be achieved, which includes a corresponding reduction in the specific magnetic material input. However, implementation is also a question of cost. In addition, there is a trend on the market towards increasing motorization, i.e. higher outputs. In the upper passenger car segment in particular,[17] some cars already have outputs well in excess of 200 kW. The services used in this study for the different vehicle types are listed in the Appendix — Annex A. Since the effects of the opposing developments of material efficiency and increasing motorization could not be quantified, they were not taken into account for the present calculations. However, there appears to be potential through engine development both in terms of reducing specific material use and in terms of possible savings in the use of heavy rare earths (see following paragraph). However, this raises the challenge of meeting the specifications of car manufacturers, who demand small, compact and low-cost motors with the highest possible performance. There also seems to be little leeway for suppliers in terms of design optimization. OEMs (original equipment manufacturers) usually specify the available space in which an electric motor, for example, can be installed.

---

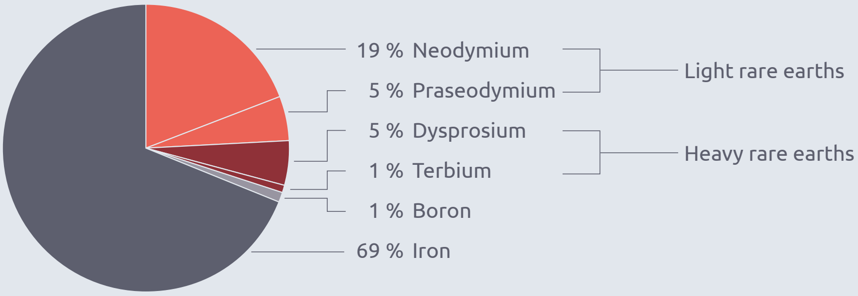
[16] e.g. circuit voltage, motor speed, cooling system, magnetic flux path

[17] Approx. 50 percent share of demand for new registrations (KNDE2045 scenario) and approx. 70 percent share of demand for production (scenario "Domestic production")

FIG. 16 **Composition of neodymium-iron-boron magnets in permanently excited synchronous motors for electric vehicles**

Iron makes up the largest proportion of permanent magnets, but the rare earths are crucial.

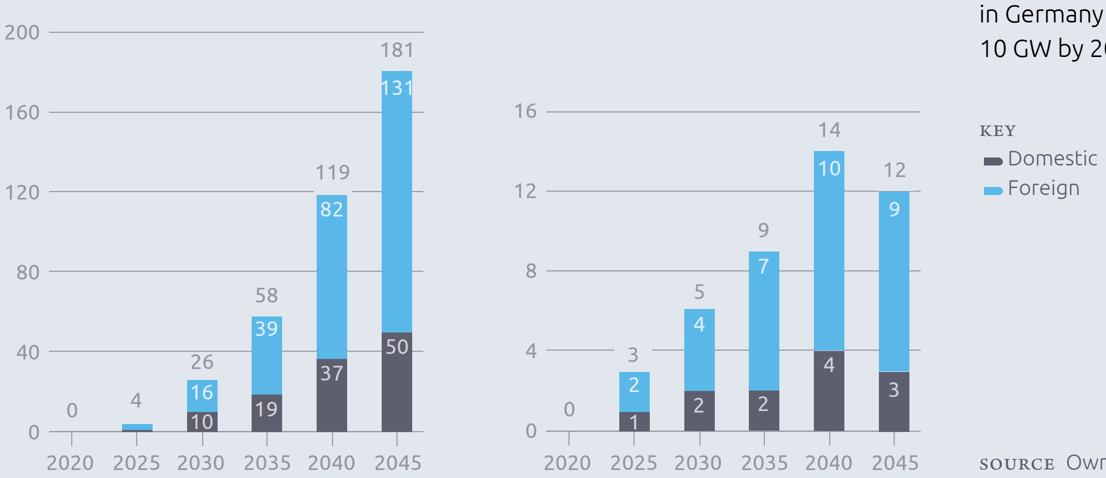
NOTE composition of "present value" in the KNDE2045 scenario according to (Buchert, 2019) and expert survey



SOURCE Own representation

Öko-Institut, 2023

FIG. 17 **Electrolyzers**



Stock of electrolyzers at home and abroad in GWel

Gross construction of electrolyzers in Germany and abroad in GWel/year

Expansion of electrolysis capacity in Germany to 10 GW by 2030.

SOURCE Own calculations

Prognos, 2023

Components

In addition to rare earths, neodymium-iron-boron magnets consist of a good two-thirds of iron and a small amount of boron (about one percent by weight). The remaining portion is divided into light and heavy rare earths, with the ratio varying depending on the application. In addition to neodymium, praseodymium is also used as a light rare earth (LRE), since both occur together in natural deposits and energy-intensive separation is not necessary. The same applies to the heavy rare earths (HRE) dysprosium and terbium. The proportion of heavy rare earths is necessary for the temperature resistance of the magnets and can still be up to 10 percent by weight of the permanent magnet.[18] According to experts, permanently excited synchronous motors with very low proportions of HRE (~0.4 percent by weight in the permanent magnet) could already get by in vehicle drives with good cooling if they had to be built less compactly, i.e. larger volumes and/or lower outputs could be implemented. REIA (REIA, 2022) assumes 28 percent LRE and 3.5 percent HRE. For the present study, the composition shown in Figure 16 was taken as a realistic current mean value.[19]

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[18] Expert testimony at the 10th Annual Advanced E-Motor Technology February 2023 in Munich, Germany

[19] According to (Buchert, 2019) and expert* survey.

Since the use of permanent magnets in BEVs is expected to remain at a high level due to the advantages associated with them (high efficiency and compactness with somewhat lower weight), research is also continuing on the optimization of neodymium-iron-boron magnets. The proportion of heavy rare earths (HRE) was already significantly reduced in the last decade through technical optimization, triggered by the Chinese export ban and the associated drastic price increase in 2011. For the future, manufacturers of permanent magnets for electric motors assume that realistic optimization potential for reducing the proportion of HRE still lies at around 25 percent reduction compared to today.[20] This was taken into account for the present study by considering a corresponding linear reduction of the dysprosium fraction until the target year 2045. For the year 2045, this results in shares of 4.8 percent HRE, with a correspondingly increased share of 25.2 percent LRE.

4.5. Electrolyzers and Hydrogen infrastructure

Green hydrogen is a central pillar for achieving climate neutrality and is used wherever electrification is not possible or where hydrogen is needed for chemical reactions. The heart for the production of green hydrogen is the water electrolyzer. Hydrogen is produced here with the help of renewable electricity and water.

Demand: 10 GW electrolysis capacities by 2030

The demand for electrolysis plants grows strongly with the use of green hydrogen from 2025. In greenhouse gas-neutral Germany, hydrogen is mainly used to safeguard the power (and district heating) systems and in the steel and chemical industries. The demand for hydrogen (without directly used derivatives) grows in the scenario calculated here to about 265 TWh (calorific value) in 2045. It is assumed that about one-third of the hydrogen can be produced domestically and about two-thirds must be imported. In addition to direct use as an energy carrier, hydrogen is also used for the synthesis of power-based hydrocarbons (power-to-liquid, PtL), which according to the KNDE2045 scenario will have to be fully imported in 2045 to the tune of 158 TWh in the form of methanol, green naphtha and other Fischer-Tropsch-based hydrocarbons.

The ramp-up of the required electrolysis capacity results from the assumption of average electrolysis full utilization hours of 3,000 h at home and 4,500 h abroad. For the KNDE2045 scenario, the ramp-up and annual additions are shown in Figure 17.

According to this scenario, the first gigawatt of electrolysis capacity for domestic hydrogen production will be installed in Germany in 2025, and ten GW by 2030. This value corresponds to the target of the national hydrogen strategy (BMWK, 2023b). By 2045, installed capacity in Germany grows to 50 GW in this scenario. To produce the hydrogen and PtL imports, an additional approximately 130 GW of electrolysis will be needed abroad in 2045, including about 60 GW for hydrogen direct use and about 70 GW for PtL production.

To build these capacities, average growth rates in the order of 2.5 gigawatts of electrolysis capacity per year in Germany and 6.5 gigawatts abroad will be needed from 2025 to 2045, with growth rates reaching their maximum in 2040 to 2045.

Components and technologies

There are several types of water electrolyzers: Alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEMEL), high temperature electrolysis (HTEL) and anion exchange membrane electrolysis (AEM). However, the basic principle is the same for all of them: By applying a DC voltage to two electrodes, water is split into hydrogen and oxygen. However, the technologies differ in terms of stage of development, structure, use of materials and technical properties:

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[20] Expert testimony at the 10th Annual Advanced E-Motor Technology February 2023 in Munich, Furgeri (2021)

- **Alkaline electrolysis (AEL):** AEL is the oldest electrolysis technology, established for decades, available on a scale of several MW and ready for the market. Alkaline electrolysis does not require critical materials and is therefore comparatively inexpensive[21] and is therefore comparatively inexpensive, but also requires a lot of space (low power density), is comparatively sluggish and has only limited partial load capability, and is therefore less suitable for responding to flexible electricity supply.
- **Polymer Electrolyte Membrane Electrolysis (PEMEL):** PEMEL, also known as proton exchange membrane electrolysis, is the second electrolysis technology to reach market maturity[22] but still significantly younger than AEL. On the anode side, PEMEL is highly oxidative and therefore corrosive. The anode is therefore coated with corrosion-resistant iridium oxide as a catalyst. In addition, platinum is used on the cathode side and as a thin layer on the bipolar plates to reduce electrical resistance. Due to the platinum metals, PEMEL is comparatively expensive, but has a higher power density due to higher current densities and the caustic-free process. It also has a more flexible load behavior.
- **High-temperature electrolysis (HTEL):** also solid-state oxide electrolysis[23]. It contains the elements yttrium and/or scandium. High-temperature electrolysis is already in its third decade of development and various pilot plants are undergoing industrial trials, so that development to market maturity can be expected in the short term. The main advantage of HTEL is its high efficiency. However, due to the need for high-temperature heat of over 700 °C, the areas of application are limited and the cold start as well as partial load behavior are probably not optimally suited for combination with renewable power generation.
- **Anion exchange membrane electrolysis (AEM)** is a young electrolysis technology and still in the research and development stage. It promises to combine the advantages of PEMEL and AEL, i.e. high flexibility and power density with high long-term stability, low cost and without the use of critical materials. AEM is essentially the same as PEMEL, with the crucial difference that an alkaline solid electrolyte allows the transport of hydroxide ions (OH-).[24] AEM does not require critical materials, but still needs further development work until it is ready for the market, including catalyst development to reduce energy requirements.

Table 1 compares the characteristics of the different technologies.

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[21] In AEL, potassium hydroxide is used as an electrolyte, providing hydroxide ions (OH-) as charge carriers. Nickel-based cathodes and anodes are separated by a diaphragm (zirconium oxide materials) impermeable to hydrogen and oxygen. When voltage is applied, hydrogen and hydroxide ions are formed at the cathode, which can pass through the diaphragm and recombine to form water at the anode, producing oxygen.

[22] PEMEL uses a polymer-based solid electrolyte membrane that is permeable to protons (positively charged hydrogen ions, H+) but not to the gases hydrogen and oxygen. Electrical voltage generates oxygen gas at the anode, the hydrogen ion migrates through the membrane to the cathode side, where hydrogen gas is formed

[23] An oxygen-conducting solid electrolyte is used in HTEL. Due to the high temperature level at which the electrolysis operates (>700 °C), the electrical energy input for water splitting can be reduced and thus very high electrical efficiencies can be achieved. The electrical voltage causes water vapor to decompose into protons and oxygen ions at the cathode. The oxygen ions migrate through the solid electrolyte to the anode, where they form oxygen by donating electrons, and the protons form hydrogen at the cathode by accepting electrons.

[24] The electrical voltage causes hydrogen to be formed at the cathode, which is discharged through the gas diffusion layer. (OH-) ions migrate back through the membrane to the anode, where they recombine with hydrogen atoms to form water again, producing oxygen, which is discharged through the gas diffusion layer.

TABLE 01 **Overview of the four central electrolysis processes**

PEMEL has the decisive advantage over today's common AEL that it is very efficient and can be run very flexibly. This is particularly crucial in power systems with fluctuating renewable energies. The disadvantage is the need for iridium.

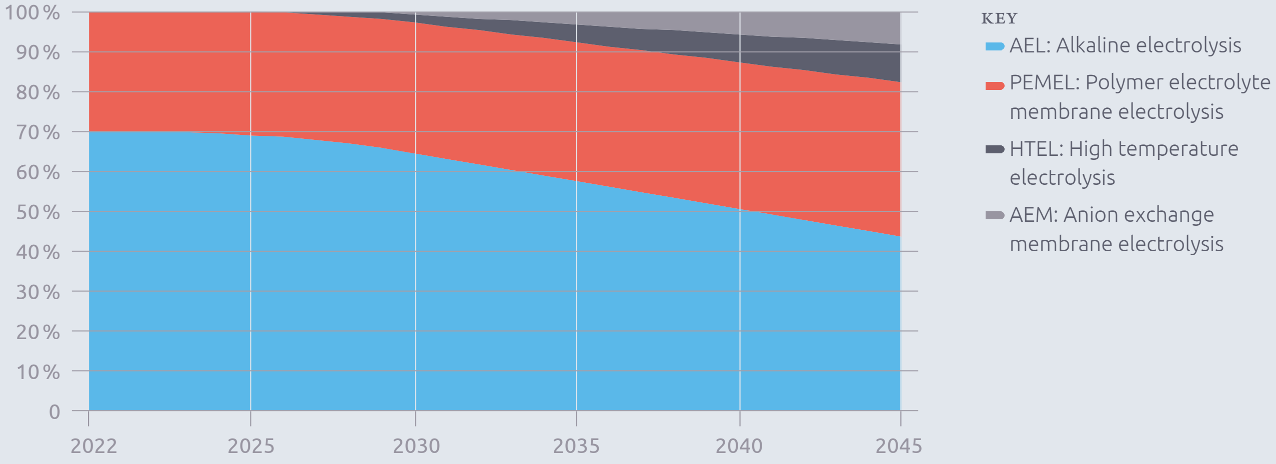
Electrolysis process	Technological maturity	Advantages	Disadvantages
Alkaline electrolysis (AEL)	mature	relatively inexpensive, no critical raw materials, high long-term stability	low power density, inertia, partial load behavior, caustic potash as electrolyte (corrosive, caustic)
Polymer Electrolyte Membrane Electrolysis (PEMEL)	mature	high flexibility and large power density with high efficiency, high gas purity	requires platinum group metal **Iridium** (very critical) as well as titanium and platinum
High temperature electrolysis (HTEL)	Pilot status	very high efficiency with availability of high temperature heat	Rare earth metals **Scandium** and yttrium, high temperature heat requirement (>700 °C) is not suitable for all applications
Anion exchange membrane electrolysis (AEM)	Development	combines advantages of AEL and PEMEL, no critical materials	not yet ready for the market, lack of empirical values, energy requirements still too high

SOURCE Own calculations

Prognos, 2023

FIG. 18 **Technology mix of electrolyzers**

Around 70 percent of today's electrolyzers are AELs. The share of PEMEL today is 30 percent and is gradually increasing. PEMEL require Iridium.



SOURCE Own calculations

Prognos, 2023

Technology Mix: Share of PEM electrolyzers rises slowly

In the scenario calculated here, an assumption is made regarding the development of technology distribution, based on today's technology availability and the prospects for further development. Figure 18 illustrates the assumed development of the technology share in the annual electrolysis increase.

Currently, only AEL and PEM electrolysis with relevant and growing manufacturing capacities are available on the market, with about 70 percent of manufacturing capacity for AEL and about 30 percent for PEMEL, the latter with a growing trend. This trend will continue. In addition, slowly growing shares of high-temperature electrolysis from 2026 and, from 2028, anion exchange membrane electrolysis are assumed in the electrolysis additions, so that by 2045 the annual additions run up to the following distribution of electrolysis technologies: 41 percent AEL, 39 percent PEMEL, 11 percent HTEL, and 9 percent AEM.

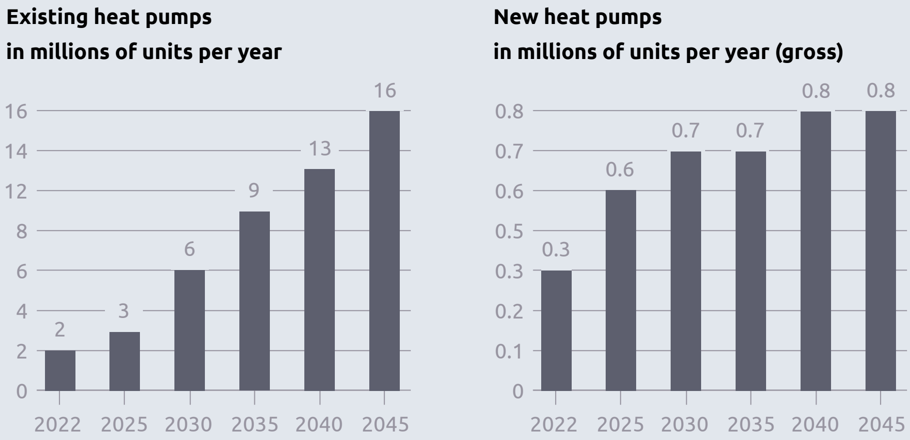
Hydrogen (infrastructure)

For many sectors, such as steel, the use of hydrogen is a key decarbonization measure. How to provide the required quantities in time is a key challenge. The topic is tackled by the German government via the "National Hydrogen Strategy" and examined in various studies and is therefore not the subject of this study.

It should be noted that in addition to the provision of hydrogen, the development of the infrastructure for the distribution and intermediate storage of hydrogen quantities is a key prerequisite for the establishment of a hydrogen economy. This includes a transmission network for supraregional distribution, a distribution network to connect the relevant consumers, compressors to apply the transport energy, cavern storage facilities for intermediate storage, as well as import terminals and connections to import pipelines yet to be built.

Bottlenecks may arise primarily due to the timing of the ramp-up, such as the capacity to build new cavern storage facilities or the build-up of generation, transport and import capacity. Bottlenecks could arise with compressors, since compressors for transporting such large quantities of hydrogen do not yet exist and current natural gas compressors are not suitable for 100 percent hydrogen (Adam, Engelshove, Thiemann, Heunemann, & von dem Bussche, 2020). The criticality of building hydrogen infrastructure needs to be studied in more detail.

FIG. 19 **Heat pumps**



Existing heat pumps in millions of units per year

New heat pumps in millions of units per year (gross)

Around six million heat pumps are expected to be installed in 2030. To achieve the targets, 700,000 new heat pumps per year are needed after 2025.

SOURCE Own calculations

Prognos, 2023

4.6. Heat pumps

Demand: annual capacity increases must reach 700,000 turbines from 2025

Alongside local and district heating, heat pumps are the essential key technology for achieving climate protection targets in the building sector. Around 75 percent of the 43 million homes in Germany are currently heated with natural gas or oil. The existing 1.3 million or so heat pumps for heating only account for three percent of the building stock. The federal government's goal is to increase the number of heat pumps to six million by 2030. During the 2nd Heat Pump Summit at the end of 2022, an alliance of politicians, scientists, tradespeople and the heating industry committed itself to the goal of installing 500,000 new heat pumps by 2024. Starting in 2025, an average annual increase of about 700,000 units is needed to reach six million units in use by the end of 2030. This would be a significant increase over the previous market ramp-up, from 236,000 units in 2022 and under 100,000 units on average over the past decade.

Components

A heat pump consists of the following main components:

- Compressor with electric motor (incl. control and regulation)
- Heat exchanger
- Circulating pump with electric motor
- Pipelines
- Valves
- Housing
- Refrigerant

Technology mix

There are several heat pump technologies. Air-to-water heat pumps have the largest share of the market at over 90 percent. In the case of the less frequently used water-brine and groundwater heat pumps, environmental heat is tapped via surface heat exchangers (brine) or boreholes (groundwater).

In addition, heat pumps are distinguished by the motors in the compressors and by the circulating pumps. A distinction must be made here between asynchronous motors and synchronous motors, whereby the latter build up the magnetic field either current-induced or with the aid of a permanent magnet. The use of permanent magnets leads to higher efficiency of the equipment. This means that less electricity is required to cover the heat demand with these systems. A number-based breakdown of motors by technology is not available. However, it can be assumed that the share of heat pumps with permanent magnets will increase for efficiency reasons.

4.7. Steel

Demand

In Germany, demand for semi-finished steel products has averaged between 35 and 40 million tons per year over the past 20 years. These are mainly rolled steel, cast steel and forged products which are processed by industrial sectors in Germany such as the construction and automotive industries. The corresponding demand for crude steel is slightly higher due to the losses incurred during forming and is roughly on a par with production in Germany, i.e. Germany's net trade balance in steel products is roughly balanced. By contrast, other EU countries are now running significant import surpluses in some cases, with the result that the balance sheet for the EU as a whole has been showing a trade deficit since the mid-2010s.

70 percent (28 million metric tons) of the steel produced in Germany comes from the primary steel route, where today iron is produced in blast furnaces from iron ores and coking coal and further processed — with the addition of up to 20 percent scrap — into steel using the oxygen steelmaking process. The remaining 30 percent (12 million tons) is accounted for by the electric arc furnace (EAF) route, through which steel is produced by melting scrap steel. To compensate for impurities in the scrap, around just under one million tons of direct-reduced iron (DRI) is already being used to achieve higher steel grades in EAF as well. Hamburg currently operates the only commercial DRI facility in Europe. In addition, Germany and other countries (especially Italy and Spain) already import DRI from countries outside the EU (in the past mainly from Russia).

There are four companies in Germany that produce primary steel. These include thyssenkrupp steel, Salzgitter and Saarstahl, three German companies that are among the smaller companies on a global scale. ArcelorMittal is the only global player to be[25] represented in Germany. With their 13 blast furnaces, these companies have a combined production capacity of 27 million tons of pig iron and 29 million tons of crude steel per year (EUROFER, n.d.). The majority of the blast furnaces were built in the 1970s and 1980s and will reach the end of their so-called blast furnace journey in the next five to ten years, after which at least the lining would have to be renewed, which would involve a plant shutdown of several weeks and an investment in the two or three-digit millions, depending on the size of the blast furnace. This investment window should be used to convert iron production to DRI shaft furnaces, which will use climate-neutral hydrogen (or temporarily still natural gas) instead of coke and coal. This technology conversion also includes the construction of EAFs or so-called melters, which are used to further process the intermediate product (sponge iron, HBI) produced in DRI plants.

According to current analyses by Agora Industrie and the Wuppertal Institut, just under 40 percent of German blast furnace capacity would be up for reinvestment by 2029, and the remaining 60 percent by 2035, which would mean a further acceleration of the reinvestment cycle compared with the KNDE2045 scenario shown in Figure 20. Currently, DRI capacity of just under 15 million tons per year is planned in Germany by 2030 (Agora Energiewende, n.d.), which corresponds to six plants in the current world-scale format and is even slightly higher than the blast furnace retirements of 13 million tons per year by 2030. Also, due to the possibility of reducing sponge iron or HBI demand through higher scrap content, it is at least questionable whether this project volume can be fully realized by 2030. Even in the event of a very successful transformation of the industry and continued stable steel production in Germany, a volume of between seven and eleven million tons per year by 2030 is more likely. In order to maintain steel production capacities in the same way, additional electric arc furnace capacity of around 25 million metric tons per year will have to be installed at German locations by 2035.

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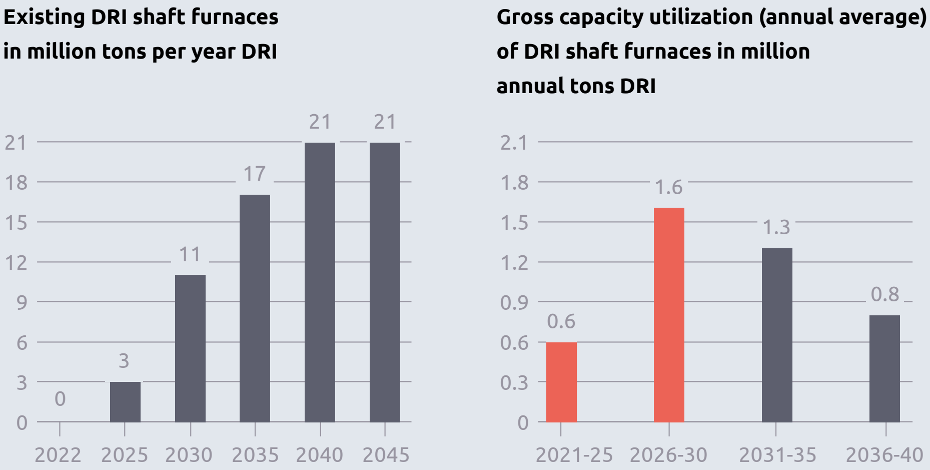
[25] In the secondary steel production sector, there are also several medium-sized companies, some of which also have an international presence and are based abroad.

FIG. 20 **DRI shaft furnaces**

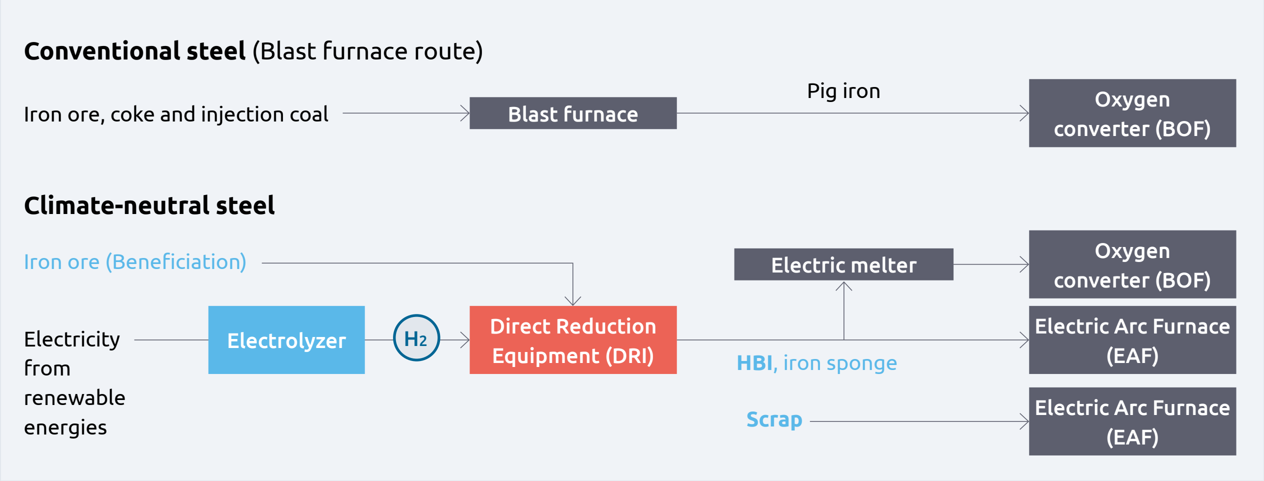


Most of the addition of DRI shaft furnaces will occur by 2030, as many blast furnaces from the 1970s and 1980s will reach the end of their blast furnace journey during this period.

SOURCE Own calculations

Wuppertal Institut, 2023

FIG. 21 **Processes for the production of conventional and climate-neutral steel**
Direct reduction plants (DRI shaft furnaces), in which iron ores are reduced using hydrogen (or natural gas), are the starting point for the production of green steel



KEY Beneficiation: Enrichment of low-iron ores and pelletization; HBI: hot briquetted iron – sponge iron that is heated and briquetted. It can be easily transported and stored.
SOURCE Own representation

Wuppertal Institut, 2023

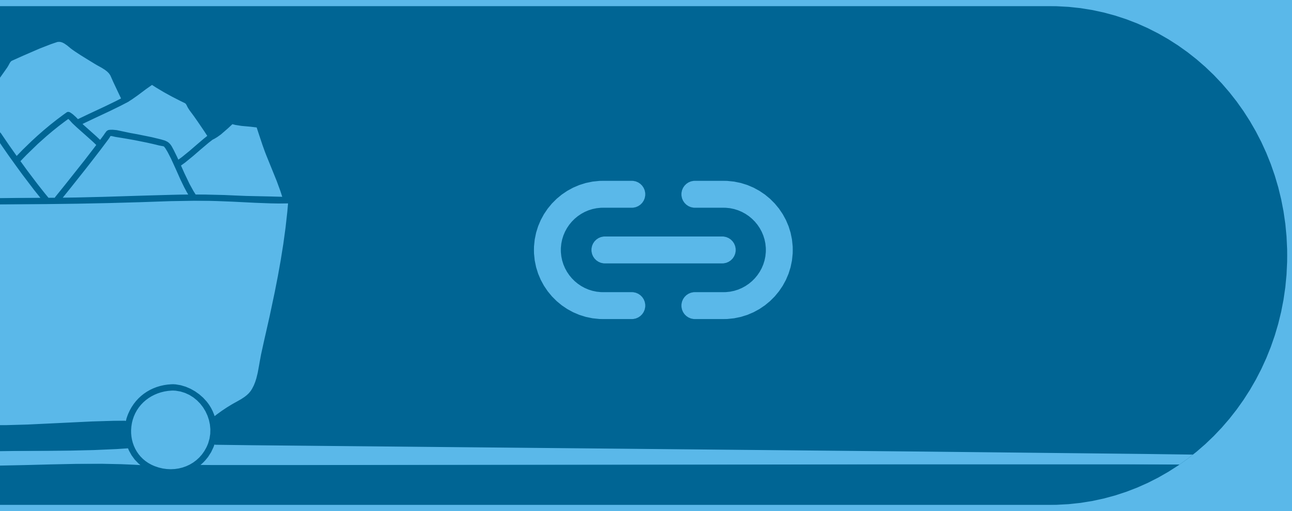
Components and plants

Since the 1960s, primary steel in Europe has been produced mainly via the so-called blast furnace LD converter route. In this process, pig iron is initially produced from iron ores in the blast furnace. To achieve this reduction, coke and injection coal are used as reducing agents; their oxidation essentially produces CO and CO_2. The blast furnace coke must first be produced in coking plants from particularly high-quality, i.e. high-carbon, coal. In the blast furnace, the pig iron is melted by the very high temperatures and then (while still in the liquid phase) processed into steel in the L/D converter with the addition of oxygen and alloyed during or after this process. Up to 20 percent (usually high-purity) production scrap is also used for cooling. After steel production in the converter (or also in the EAF), the steel is cast directly into slabs, billets or ingots, depending on the further processing required. Most of the further processing is done by forming in hot rolling processes into sheets, beams, wire or bars. In particular, thin sheets and wire place high demands on the purity of the steel with regard to low copper tolerance. As copper is increasingly contained in steel scrap due to the relatively coarse sorting, virtually copper-free primary steel is mainly used to produce the semi-finished products thin sheet and wire.

To produce primary steel in a climate-neutral way, the reducing agent coke or coal is replaced by hydrogen. In the so-called direct reduction of iron ore with hydrogen, the oxygen-containing iron ore reacts with hydrogen in the so-called DRI shaft furnace to form sponge iron and water (see FIG. 21). Sponge iron is a porous material with an iron content of over 92 percent. If this is heated and briquetted, it can be easily transported and stored as HBI (hot briquetted iron). However, sponge iron and HBI still contain undesirable gangue as well as sometimes carbon. In order to remove these, a further preparation step is necessary: Either the sponge iron can be melted directly in the electric arc furnace and refined into steel, or alternatively first liquefied and enriched with carbon in an electric melter and then processed into steel in the converter. The second route via the converter has the advantage that the existing equipment from the blast furnace route can still be used and thus the entire product range of today's steels can also be produced. In addition, lower-grade ores can be used because some post-reduction in the electromelter is possible, at the price of an even higher carbon requirement. This is also the central disadvantage of the converter route: To achieve climate neutrality, a relatively complex carbon management is required with a use of biogenic sources, carbon recycling or evenCO_2 captureand storage (CCS).

German steel producers have a clear picture of the first wave of the transformation. While thyssenkrupp intends to retain the oxygen-blown steel process in the converter to serve all existing steel grades, electric arc furnaces are to be used at the other sites. Alternatively, up to 100 percent scrap can be used in both processes.

5. Critical supply chains



5.1. Photovoltaics

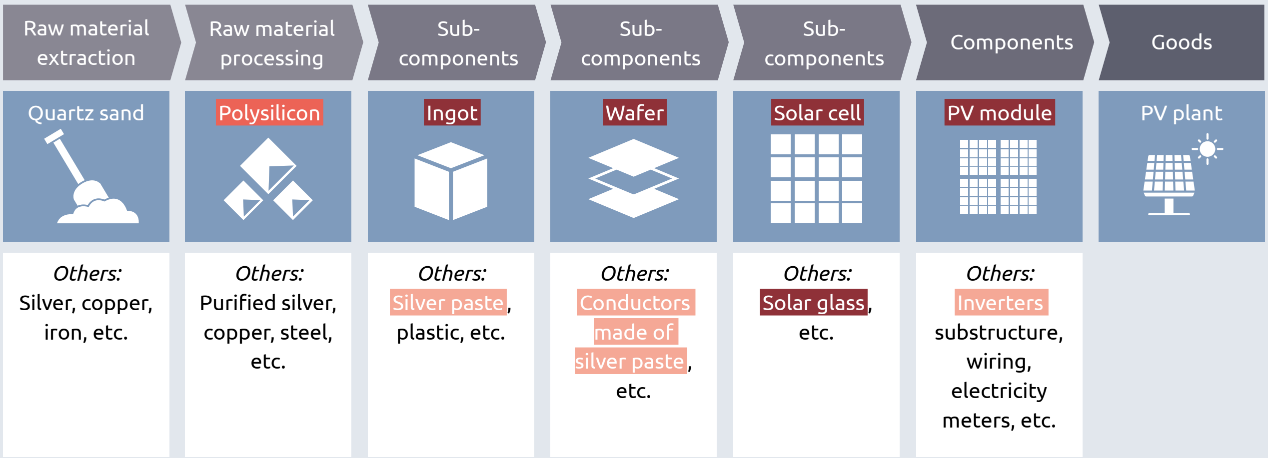
- The production of wafer-based silicon photovoltaic modules is dominated by China along the entire supply chain. Polysilicon, ingots, wafers, solar glass, cells, inverters and modules: In all stages of the supply chain, China has a market share of at least 73 percent.

- In the production of polysilicon, China's market share is about 79 percent, however, *Wacker Chemie* in Germany is the only European producer with a production capacity of 20 GW per year.

- Criticality is highest in the production of ingots and wafers. Here, China has a market share of 97 percent. There is very little capacity (less than 2 GW) in Europe. Equally critical is module production, where China has a market share of 75 percent.

- Market concentration is expected to intensify further, as massive manufacturing capacity is currently being built up along the entire supply chain in China.

FIG. 22 **Supply chain for manufacturing wafer-based photovoltaic systems**
Very high criticality for ingots, wafers, solar glass, solar cells and PV modules.



KEY Criticality: ▬ Very critical ▬ Medium critical ▬ Moderately critical SOURCE Own representation

Prognos, 2023

Chapter 5 now examines the supply risks for the prioritized key technologies. Supply risks arise, on the one hand, from a high concentration of supply in a few supplier countries or companies. On the other hand, supply bottlenecks can result from short and medium-term excess demand (cf. CH. 3). The analysis here focuses not only on the raw materials required for this purpose, but also on the entire supply chain — from the extraction of raw materials, through their processing, to the production of subcomponents, components and entire goods.

This chapter also shows how high the identified demand for critical raw materials is for the transformation of the German energy system from today to 2045.

From quartz sand to photovoltaic systems

The starting point for the production of wafer-based PV systems is the raw material quartz sand (silicon dioxide). This is first melted and cleaned. The resulting high-purity polysilicon is drawn into a colum-shaped block, a so-called ingot, which is then sawn into thin slices (wafers). Further processing of the wafers into solar cells, including the application of conductive tracks made of silver paste, is followed by the final module production. (IEA, 2022a; solarenergie.de, 2021b) Solar glass, support structures and inverters including cabling are used here (DENA, 2022). Figure 22 shows an overview of the most important steps in the supply chain.

Supply chain: Very high criticality for ingots, wafers and cells and modules

For photovoltaics, with exceptions such as silver, the criticality is not so much in the raw materials used, but in the downstream supply chain of the (sub)components. Along the entire chain, China currently dominates world market production. Currently, the market share of Chinese companies at all stages of the supply chain is between 73 and 97 percent (IEA, 2021b; Statista, 2022). Country concentration could increase even further as China invests massively in new manufacturing capacity. A total of 800 gigawatts of manufacturing capacity is expected worldwide in 2023, and capacity could reach 1,000 GW in 2024 (Sánchez Molina, P., 2023). This contrasts with significantly lower current demand forecasts. According to the World Energy Outlook 2022, the average annual global increase by 2030 is about 250 GW in the Stated-Policy scenario and 500 GW in the Net-Zero-by-2050 scenario. Even with significantly higher global demand, from today's perspective we do not expect an excess of demand, but rather an excess of supply and possible further price competition for the plants.

Raw material extraction

Wafer-based photovoltaic cells consist mostly of silica sand (silicon dioxide) (Carrara, Alves Dias, Plazzotta, & Pavel, 2020). Quartz sand is one of the most common elements on earth. It is literally a dime a dozen. The raw material itself is therefore not critical, but the downstream value-added steps, from preparation into polysilicon to completion of the PV modules, must be assessed very critically, as they are almost exclusively carried out in China. Due to its economic importance, the raw material is therefore classified as critical by the European Commission in the list of Critical Raw Materials. (Grohol, M., Veeh, C., 2023)

For thin-film cells, gallium (CIGS, GaAs) and germanium (a-Si) are used in addition to silicon (a-Si), depending on the technology (Carrara, Alves Dias, Plazzotta, & Pavel, 2020). China is the most important global supplier of these raw materials, which is why they are also included in the European Commission's list of Critical Raw Materials (Grohol, M., Veeh, C., 2023).[26] The market share of thin-film modules is very low (IEA, 2021a). Due to their lower efficiency, it is assumed that they will continue to serve only a niche market in the future. Thus, they have only a comparatively low economic importance and criticality and are not the focus of this study.

A photovoltaic system is further composed of steel or aluminum for the support structure, silver for silver paste, copper for wiring/cabling, and special low-iron glass (Carrara, Alves Dias, Plazzotta, & Pavel, 2020). Currently, about 15 percent of the world's silver production is used in photovoltaic production. Due to competing uses with other technologies, such as electromobility or 5G technology, and the high price of the precious metal, the supply of silver should also be considered. (Fraunhofer ISE, 2022a) According to the EU Commission, copper is strategically relevant, but the supply risk here is significantly lower than for the other raw materials examined here.

Photovoltaics in Germany: Demand for key raw materials up to 2045

Figure 23 shows the demand for silicon, gallium and germanium for the scenario calculated in the study. These raw materials are classified as critical in the European Commission's Critical Raw Materials List (Grohol, M., Veeh, C., 2023). It should be noted here that in the assumptions made here, thin-film modules containing gallium and germanium will continue to play a niche role in the future due to their lower efficiency. The demands for gallium and germanium are therefore not classified as critical in this study.

The demands presented here result from the annual gross growth of photovoltaics (cf. FIG. 07 in CHAPTER 4.1. Photovoltaics), the assumptions made for the breakdown of the growth between wafer-based photovoltaics and thin-film cells (cf. FIG. 08 in CHAPTER 4.1. Photovoltaics), and the assumptions for the reduction of material intensities (cf. TABLE 10 in ANNEX A: Technical details).

Due to the high market share of crystalline silicon cells, the demand for silicon far exceeds the demand for gallium and germanium. After today's demand doubles to around 50,000 metric tons, demand falls again in the following years — despite constant high annual growth. The main reason for this is the sharp decline in material intensity. The demand for germanium at the times considered is between 0.6 and 1.4 tons per year. Due to the assumed increase in the market share of GaAs technology to five percent, the demand for gallium increases after 2035 and reaches a level of about 23 tons per year.

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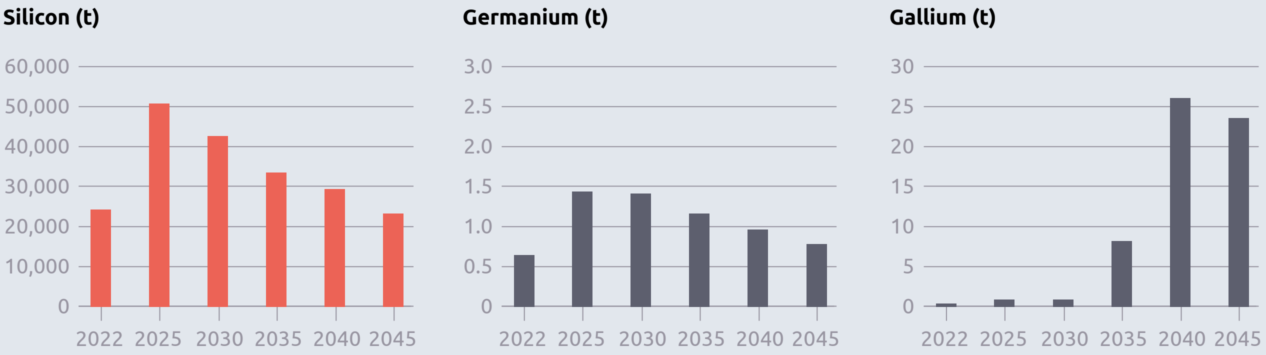
[26] Note: Up to 2020, indium was also identified as critical.

FIG. 23 **Demand for key raw materials for expansion of photovoltaics in Germany**
Silicon demand decreases from 2030 onwards due to the sharp drop in material intensity, despite a constantly high addition of silicon-based wafer cells. The demand for gallium and germanium is small due to the low market share of thin-film modules and is not considered critical here.



SOURCE Own calculations

Prognos, 2023

Raw material processing Polysilicon

Chinese companies account for around 80 percent of the production of polysilicon, the starting material for crystalline modules (IEA, 2021b). The only remaining German or European company, Wacker Chemie, the global market leader three years ago (Enkhardt, S., 2022), has now fallen to fifth place (Bellini, E., 2023). Wacker Chemie's manufacturing capacities currently amount to around 20 GW (SolarPower Europe, 2023). In addition to manufacturing in China, there are other small-scale production facilities operated by various companies in North America and the Asia-Pacific region (excluding China), which together provide just under 12 percent of global annual production (IEA, 2021b). Estimated annual global production capacity is currently around 500 GW and could rise to 975 GW in 2023, according to press reports. However, actual production is expected to be lower. (Santos, B., 2022) The four largest producers of polysilicon (Tongwei, GCL-Poly, Daqo, and Xinte) are from China (Bellini, E., 2023). The two market leaders are planning further huge capacity expansions this year (Enkhardt, S., 2022). It can therefore be assumed that there will be further concentration of the market by Chinese companies in the future.

Part components: Ingots, wafers, cells, and solar glass

The market concentration of Chinese manufacturers is very high, especially in ingot and wafer production, at 97 percent (IEA, 2021b). Due to the strong growth in demand for PV modules in the future, a large number of companies are planning capacity expansions. For example, in the spring of 2023, Trina Solar announced plans for a new manufacturing facility with an annual ingot production capacity of 35 GW (Shaw, V., 2023a). JinkoSolar already opened a new 20 GW ingot plant last year (Shaw, V.; Hall, M., 2022). For comparison: The total production capacity of the three remaining ingot and wafer producers in Europe (the Norwegian companies NorSun and Norwegian Crystals and the French company Photowatt) is less than two GW per year (Hall, M., 2021). Currently there is no ingot or wafer production in Germany (SolarPower Europe, 2023).

There is also a clear market concentration of around 85 percent in China for cell production (IEA, 2021b). The current Chinese annual production capacity is estimated to be around 600 GW (Bellini, E., 2022). The remaining Asia-Pacific countries produce just over twelve percent of the cells (IEA, 2021b). With Meyer Burger, 3SUN, EcoSolifer and Valoe, there are currently four companies in Europe that can provide less than 2 GW of cumulative production capacity. Meyer Burger's ca-

FIG. 24 **Production capacity and supply chain of wafer-based PV modules by region in 2021**

The production of ingots/wafers, cells, solar glass and modules is very critical due to the high dependence on China.

		Highest production capacity	Second highest production capacity	Third highest production capacity	Europe	
Raw material (processed)	Polysilicon	China 79.4 %	Germany 8 %	Asia-Pacific 6 %	Germany 8 %	Rest of Europe -
Sub-component	Ingots / wafers	China 96.8 %	Asia-Pacific 2.5 %	Europe 0.5 %	Germany -	Rest of Europe 0.5 %
	Solar cell	China 85.2 %	Asia-Pacific 12.2 %	India 1.2 %	Germany 0.2 %	Rest of Europe 0.4 %
Component	PV modules	China 74.6 %	Asia-Pacific 15.3 %	India 3.1 %	Germany 0.4 %	Rest of Europe 2.4 %
	Inverters	China 73 %	Europe 15.7 %	RoW 11.8 %	Germany 6 %	Rest of Europe 9.8 %

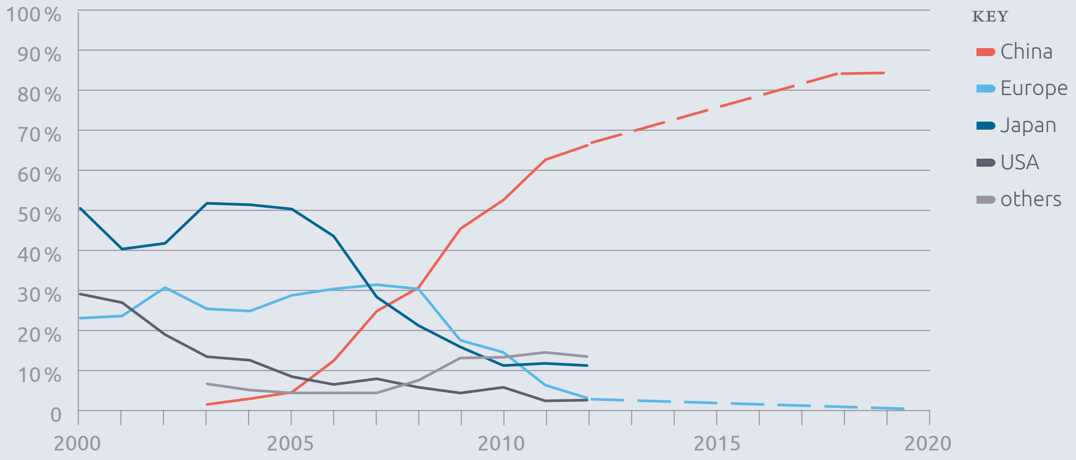
NOTE Solar glass: no comprehensive data is available on this. It can be assumed that China's share is similar to that of other components due to the high transport weight. Germany's share of the world market is less than 0.5 percent.

KEY 🟥 China 🟦 Other countries SOURCE Own representation according to (IEA, 2021b; Statista, 2022)

Prognos, 2023

FIG. 25 **Global PV shipments between 2000 and 2019 by region**

China was able to establish a quasi-monopoly within a few years in the 2000s.



SOURCE Own representation according to (Beneking, C., 2023). This is a work derived by Prognos from the work of the author Claus Beneking with data from Timur Ergen, among others.

Prognos, 2023

pacity in Germany is less than 1 GW. (SolarPower Europe, 2023)

Chinese companies also appear to dominate the world market in the production of the solar glass required for the modules. Due to incomplete data, no valid concentration value can be given for Chinese production at this stage of the value chain. However, it can be assumed that the market concentration is similar to that at the other levels. According to their own statements, the two Chinese market leaders Xinyi and FGG account for more than 50 percent of global production. Together, the two companies produce nearly 40,000 tons of solar glass per day. (Xinyi Solar, 2022; FGG, 2022) The only company remaining in Germany, GMB Glasmanufaktur Brandenburg in Tschernitz, currently produces 300 tons per day and was sold to the Indian group Borosil in 2022. The total European production capacity for solar glass is currently sufficient to manufacture modules with an estimated capacity of 3 to 4 GW per year. (Photovoltaics, 2022)

Components: Modules and Inverters

Chinese market concentration within module production is at a high level of 75 percent, but is somewhat lower compared to the other stages of the value chain (IEA, 2021b). China's estimated annual production capacity is equivalent to about 600 GW (Bellini, E., 2022). The remaining 25 percent is distributed in particular among the Asia-Pacific countries as well as India, Europe and North America (IEA, 2021b). In Germany and Europe, there are many companies producing PV modules, but their production capacities are very limited and only some of the companies are currently implementing capacity expansions (Fuhs, M., 2023a). Currently, there is a total capacity of just under ten GW in Europe for the production of PV modules, of which Germany accounts for around 3.5 GW (SolarPower Europe, 2023). The majority of the cells required for this come from outside Europe — especially China, which is why the criticality is also rated as particularly high. At the same time, Chinese companies are planning significant capacity expansions. For example, a subsidiary of China's third-largest manufacturer, Jinko Solar, is aiming to build new production lines with an annual capacity of 56 GW, with implementation of the first two phases totaling 28 GW of capacity to be completed in mid-2024 and the other two phases in 2025 (Ernst, R., 2023).

Other components required for the operation of PV systems are inverters. Here, too, there is currently a strong concentration on Chinese companies, at around 73 percent (Statista, 2022). However, inverters are electrical devices that can be manufactured anywhere in the world. SMA, one of the best-known manufacturers of inverters, is based in Germany. Although the company has lost market share to other producers in recent years, there are many companies in Europe and the rest of the world that produce similar quantities (Diermann, R., 2019). The market for inverters is also growing due to the increasing global PV demand. For example, SMA plans to double its production capacity in Germany to 40 GW by 2025 (Enkhardt, S., 2023). The authors consider the market concentration on Chinese manufacturers to be less critical compared to wafer or cell production.

China as a success model

Figure 24 illustrates that China has been able to establish a quasi-monopoly in the PV market within a few years. PV expansion will also be completely dependent on China in the short to medium term in Germany and worldwide.

Production capacities in China currently exceed domestic demand many times over. For example, nearly 90 GW of photovoltaic systems were installed in 2022 with an estimated 600 GW of module manufacturing capacity (Shaw, V., 2023b). Due to already planned expansions of Chinese production capacities for the next years, there will continue to be a significant oversupply along the entire supply chain. Given their enormous production capacities, Chinese PV manufacturers have a significant cost advantage over other companies. The International Energy Agency (IEA) estimates that Chinese companies can produce ten percent cheaper than Indian companies, 20 percent cheaper than American companies, and up to 35 percent cheaper than European companies. These differences can be explained, among other things, by divergent energy, labor, investment, and operating costs. (IEA, 2022a) For the expected development and expansion of PV production outside China, the major challenge remains achieving a similar cost level. Chinese companies took the technology lead in many areas of the supply chain in recent years. Corresponding patents and the necessary know-how are not only available for the individual production steps, but also for the manufacture of the equipment necessary for the various steps. To this end, the Chinese government is currently discussing export restrictions on equipment for the production of polysilicon and wafers (Enkhardt, S.; Shaw, V., 2023).

The success of China's PV industry is due in part to very substantial, persistent and reliable government support for the companies. After an initial purely entrepreneurial growth path, the Chinese government developed a variety of incentive programs with various ministries, regional authorities and the National Energy Agency starting in 2011 to increase domestic demand for PV modules. At the same time, companies were able to rely on government support, especially in the loss-making phases of global cutthroat competition, and thus expand their market leadership. (Shaw, V., 2023c; Beneking, C., 2023)

A similar form of government support is currently being sought with the Inflation Reduction Act (IRA) in the USA and Production-Linked Incentives (PLI) in India. One objective of these (climate protection) programs is to provide industrial policy support for companies in order to significantly expand the production of key technologies (e.g. photovoltaics and wind), among others. This is intended to reduce dependence on foreign imports. It is anticipated that the programs in both the U.S. and India may lead to an expansion of the PV industry based there. For example, PV module production capacity in India is expected to increase from 38 GW today to 110 GW in 2026. In parallel, the country plans to establish its own polysilicon and ingot/wafer production facilities and massively expand cell production. (IEEFA, 2023)

5.2. Wind power

- Wind turbines are complex systems consisting of thousands of individual components.
- The very critical components are permanent magnets made of neodymium-iron-boron, which are installed in 95 percent of offshore generators and about a quarter of onshore generators.
- The very high criticality of permanent magnets results from the very strong dominance of China. All stages of the supply chain must be classified as very critical: from the raw material extraction of the rare earths (especially the heavy rare earths), to the processing of the light and heavy rare earths to the production of the permanent magnets (cf. chapter 5.4.).
- In addition, many other components for which there are also suppliers outside China are sourced from Chinese companies for cost reasons.

Thousands of individual components for one wind turbine

Wind turbines consist of many thousands of individual components. Accordingly, many raw materials are needed for this. The largest-volume materials required are iron ore, copper and bauxite (aluminum), which are used in various components — such as steel in the tower, in the machine nacelle and as stainless steel in the gearbox and bearings. The rotors are made of carbon, fiberglass and epoxy resin. Large quantities of copper are needed for the electronics located in the nacelle.

Supply Chain: Very high criticality for permanent magnets

For wind turbines, a high criticality lies in the plants that use permanent magnets in the generators (DENA, 2022). Especially in offshore wind power, these turbines dominate with 95 percent of newly built turbines (cf. CH. 4. The permanent magnets, in turn, require rare earths. These are obtained as oxides in mining, processed into metals in chemically complex processes, and then manufactured together with iron and boron to form permanent magnets. (Neodymium iron boron magnets). The criticality here arises along the entire supply chain — from the mining of rare earths, to further processing, to the production of permanent magnets, since Chinese companies have a market share of over 90 percent at all stages. In the production of permanent magnets, the concentration is as high as 94 percent. In Europe, on the other hand, there is no mining or processing. Figure 26 shows an overview of the most important steps in the supply chain.

Permanent magnets are used not only in generators, but also in synchronous motors installed in electric vehicles and, in some cases, in heat pump compressors and circulating pumps. Chapter 5.4. therefore takes an overall look at the risk situation for permanent magnets.

In addition, as in most industries, many individual parts are purchased from Chinese companies for cost reasons, even though manufacturers outside China also exist for them. Examples here include fiberglass mats and castings. For these components, the criticality is lower because there are other suppliers and there is no concentration of production capacity in China (yet). In the medium to long term, however, there is a risk that other providers will be forced out of the market due to cost advantages and the build-up of capacity, resulting in monopoly-like conditions.

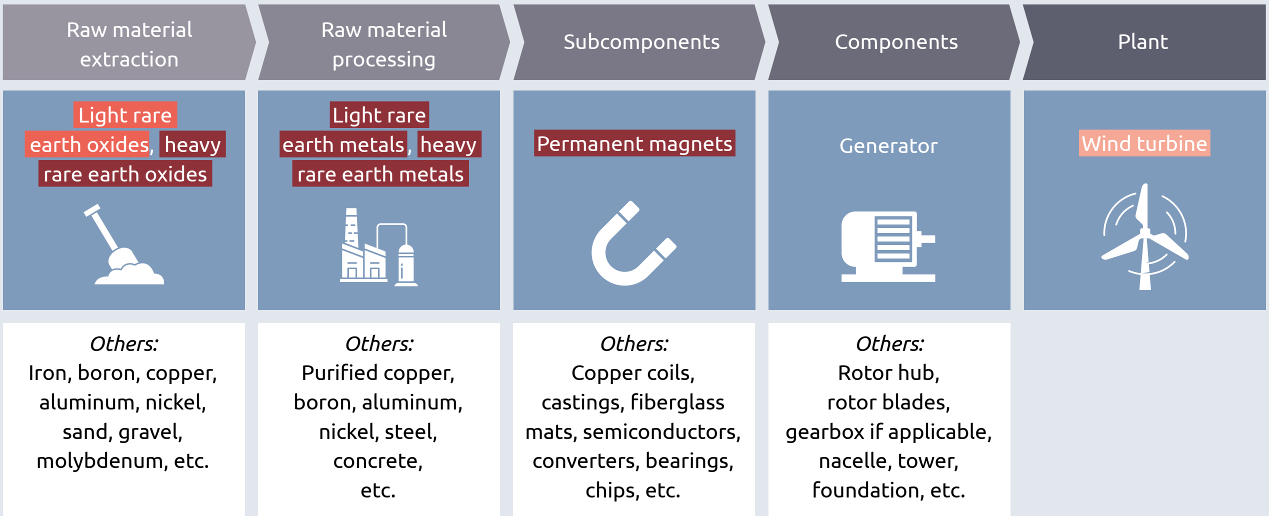
In the area of manufacturers and main component production, there is sufficient production capacity in Europe for onshore wind energy to be able to meet the expansion demand in the medium term as well. In the offshore sector, too, there is currently still sufficient production capacity, although the greatly increased expansion targets throughout Europe for the target year 2030 are creating enormous challenges for ramping up production capacity (see also CH. 6). This applies in particular to the turbine segment with outputs of more than 12 MW. The main manufacturers in the offshore wind turbine sector in the European market are Siemens Gamesa, Vestas and GE.

Wind power in Germany: Demand for critical raw materials up to 2045

Figure 27 shows the demand for light (neodymium, praseodymium) and heavy rare earths (dysprosium, terbium). While the raw material extraction of neodymium and praseodymium is classified as medium critical, the raw material extraction of dysprosium and terbium is classified as very critical. The demand shown here results from the wind power plants built each year — especially offshore wind (cf. FIG. 09), the assumptions made here regarding the distribution of new capacity increases among

FIG. 26 **Supply chain for the production of wind turbines with permanent magnets**

The criticality arises mainly from the manufacturing process for permanent magnets



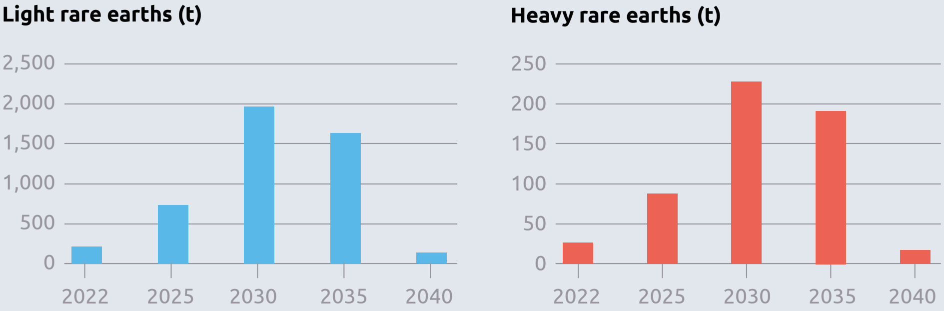
NOTE Extraction of rare earth elements: The raw materials each occur in different compositions. The proportion of rare earth elements in the respective deposits varies greatly. Generators with permanent magnets are mainly installed in offshore wind turbines. Here, the share is almost 100 percent. 20 percent of wind onshore plants also use generators with permanent magnets. (Cf. Chapter 4.2.)

KEY Criticality: ▬ Very critical ▬ Medium critical ▬ Moderately critical SOURCE Own representation

Prognos, 2023

FIG. 27 **Demand for critical raw materials for the expansion of wind power in Germany in tons**

Rare earths are critical as a raw material both in terms of extraction (here especially the heavy rare earths) and processing. The demand for rare earths in Germany is primarily determined by the annual gross construction of offshore wind farms.



SOURCE Own calculations

Prognos, 2023

the individual generator types, and the assumptions regarding the reduction in material intensity (see APPENDIX). Demand for the raw materials is primarily driven by the annual gross increase in offshore plants: after the strong ramp-up until the 2030s, the annual growth and thus the demand for rare earths will decline.

5.3. Lithium ion batteries

- Lithium-ion batteries are produced on a large industrial scale across complex value chains: the main steps are (put simply) raw material extraction, further processing of the raw materials, component production and production of the lithium-ion battery cells ("gigafactories”).

- Due to the rapid growth in demand both in Germany and on a global scale, all stages of the value chain must be massively expanded at a considerable pace.

- For the production of lithium-ion batteries, the first priority in raw material extraction is lithium (very critical), the second priority is cobalt, nickel and graphite (medium critical) and the third priority is manganese (moderately critical).

- In commodities, a global supply gap is expected in the next few years (by 2030), especially for lithium, if global mining capacity is not expanded quickly and in large volumes.

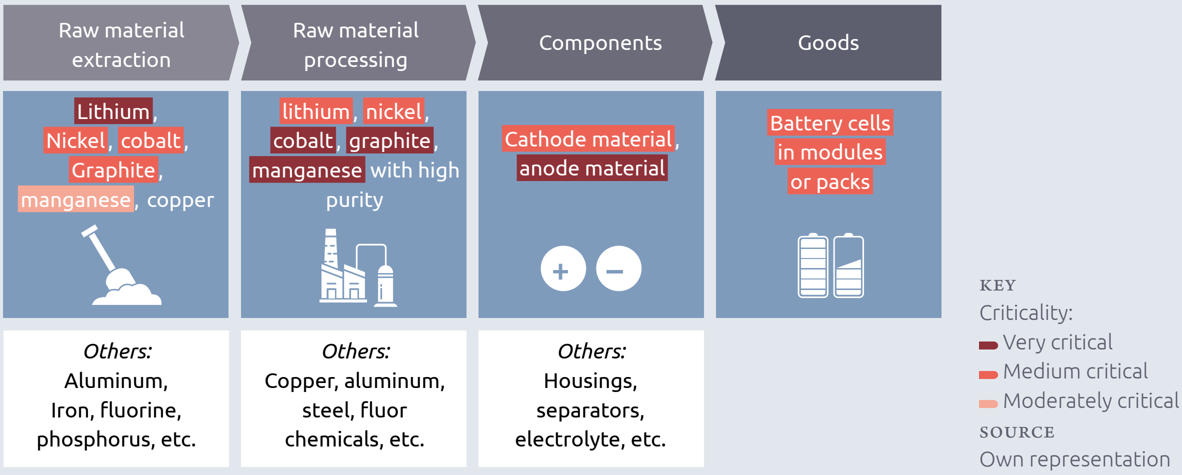
- The PRC dominates in raw material extraction, especially in graphite, in processing for all critical raw materials, and has a very strong position in component and lithium-ion battery cell manufacturing through domestic capacity and globally operating Chinese companies.

- The development of production capacities for gigafactories as well as components and upstream stages has started in Germany and the EU; however, to meet demand, the corresponding capacities must be massively expanded by 2030.

- The development of lithium in the EU and Germany should be accelerated.

FIG. 28 **Supply chain for the production of lithium-ion batteries**

In addition to lithium as a raw material, the processing of cobalt, graphite and manganese in particular and certain components must be classified as very critical



SOURCE
Own representation

Öko-Institut , 2023

Supply Chain: The criticality of the lithium-ion battery supply chain differs from step to step

Of the raw materials contained in lithium-ion batteries, the following key raw materials are examined in more detail in this study: Lithium, nickel, cobalt, graphite, manganese. Additionally, copper is considered for comparison. Other raw materials, such as steel, are also used. The extraction of raw materials is the first stage of the supply chain. In the next step, purification into starting materials (processed materials) for the production of components (anode and cathode active materials, etc.) takes place. The battery cells are then manufactured from the components in so-called "giga factories".

Raw materials and reserves

It is very clear from Figure 29 that the increase in global demand for the battery raw material lithium is particularly strong starting from 2020 through 2030 to 2040. The ramp-up of electromobility is expected to increase demand fivefold by 2030 compared to 2020. The increases in demand for the three raw materials graphite, cobalt and nickel are also significant and their availability must be secured. However, special attention should be paid to the battery raw material lithium. This is also supported by recent DERA publications (Al Barazi, p., 2022). Only minor increases in demand are expected globally for manganese and copper.

Not only excess demand but also high country concentrations in raw material production could lead to a critical supply situation. When looking at global mining production for selected raw materials relevant to lithium-ion batteries (Figure 30), it is noticeable that many of the raw materials are dominated by a few countries in terms of mining production. According to USGS, in 2021 (U.S. Geological Survey, 2023)[27] countries such as Australia and Chile (lithium), Indonesia and the Philippines (nickel) or the Democratic Republic of the Congo (DRC) played a very relevant role. In addition, the environmental and social conditions of artisanal small-scale mining [28] (Al Barazi, S. et al., 2017) in the DR Congo have repeatedly been the subject of detailed reports and studies in recent years. (Schüler, D. et al., 2018), (BGR, 2020)

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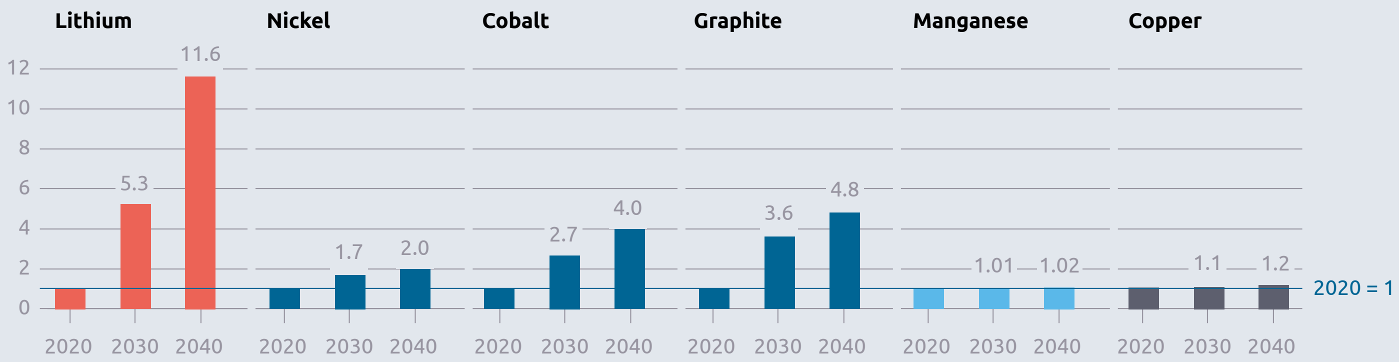
[27] In the case of graphite, only natural graphite was considered, although synthetic graphite also plays a major role in battery production.

[28] Estimates for the share of artisanal small-scale mining in the DRC vary between 15-20 percent of total cobalt production in the country.

FIG. 29 **Increase in world demand for lithium, nickel, cobalt, graphite, manganese and copper due to electromobility compared to world production 2020**

Global demand for lithium in particular will increase by a factor of twelve by 2040



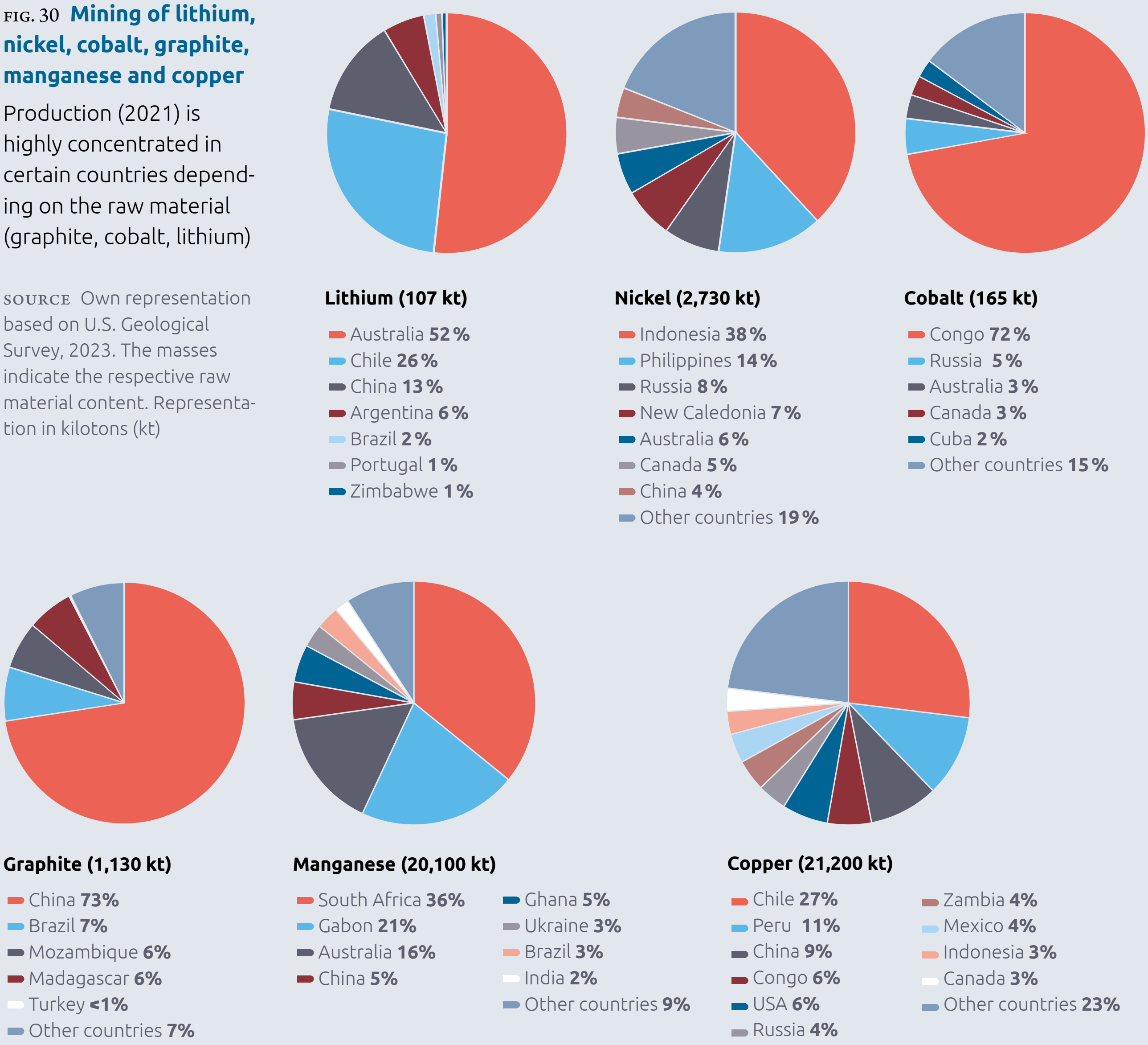
SOURCE Own representation based on the Sustainable Development Scenario (IEA, 2022b)

Öko-Institut, 2023

FIG. 30 **Mining of lithium, nickel, cobalt, graphite, manganese and copper**

Production (2021) is highly concentrated in certain countries depending on the raw material (graphite, cobalt, lithium)

SOURCE Own representation based on U.S. Geological Survey, 2023. The masses indicate the respective raw material content. Representation in kilotons (kt)



Öko-Institut, 2023

The very different quantities of raw materials extracted from mining each year also become clear. The amount of 107 kt of lithium is of a very different order of magnitude from the 21,200 kt of annual copper production. This also relativizes certain requirements for the corresponding raw materials for lithium-ion batteries. In the case of lithium, lithium-ion batteries (and increasingly so in the coming years) are the overwhelmingly dominant application. In the case of copper, many other applications are much more relevant and the increase relative to total production volume is less dramatic.

If we compare the distribution of countries in the production of raw materials to the reserves for 2023 shown in the next graph, some differences become clear. For example, Australia is currently the largest producer of lithium, but Chile has significantly more lithium reserves than Australia. In addition, while Turkey has the largest natural graphite reserves in 2023, it has no production from mining. It should be noted that reserves can change greatly, as they depend not only on knowledge about them, but also on environmental and economic conditions. A resource deposit is only counted as a reserve if it has been fully evaluated and is considered economically viable. (BGS Minerals UK, 2023)

This becomes clear when comparing annual lithium reserve data according to USGS. While reported reserves for lithium were just 9,900 kt in 2010, they have increased more than 2.5-fold to 26,000 kt by 2023 (U.S. Geological Survey, 2010), (U.S. Geological Survey, 2023). It can be seen that there are enough natural reserves for all six raw materials on a global scale and that this is therefore not an obstacle to the ramp-up of electromobility. However, the production and processing of certain raw materials will have to be ramped up considerably and adapted to future requirements. The comparison of the current raw material production in Figure 30 with the natural reserves shown in Figure 31 makes it clear that for certain raw materials there are still many options regarding future producing countries. Broader distribution can reduce dependencies on individual locations and the associated risks.

Lithium-ion batteries in Germany: Demand for critical raw materials up to 2045

The new registrations of the different vehicle types and the battery compositions used in the vehicle types presented in Chapter 4 result in concrete demand ramp-up curves for the individual raw materials (such as lithium, cobalt, nickel, graphite, manganese and copper) up to 2045 for the scenario calculated here. This is contrasted with the demand for the production of vehicles within Germany in order to illustrate the actual demand for Germany as an industrial location.

Some general trends can be derived from this. It is noticeable that manganese and cobalt reach their demand peaks early on in the new registrations scenario (2030 at about 20,000 metric tons per year each), and after 2030 the annual demand volumes drop off steeply again. In the case of manganese and cobalt, this is due to three assumptions in the KNDE2045 scenario:

- The decline in new vehicle registrations after 2030,
- the increasing trend towards low-cobalt and low-manganese lithium-ion batteries (NMC 811) and
- the increasing trend toward cobalt-free and manganese-free LFP batteries.

A combination of political and technological developments thus results in significant easing trends for the demand of the raw materials cobalt and manganese from the transport sector after 2030.

In the "domestic production" scenario, we also see the trend for demand for manganese and cobalt fall. However, this only occurs with a significant delay. Thus, the peak demand for cobalt is in 2035 (33,300 t per year). Demand for manganese also remains high until 2035 (31,800 t per year) and only drops thereafter. This can be explained by the previously described switch to low-cobalt, low-manganese or cobalt-free, manganese-free battery chemistries.

In the case of nickel demand, the peak is also reached quite early (around 90,500 tons per year in 2030) and thereafter there is also a decline to just over 60,000 tons per year in 2045. However, the decline is much less steep compared to cobalt and manganese This is because, with the percentage growth of nickel-rich NMC 811 lithium-ion batteries, an opposite trend (towards lower new registrations and nickel-free LFP) also plays a role here.

In the "domestic production" scenario, nickel demand initially continues to rise after 2030 and only falls slightly after 2035. The reason lies in two opposing trends: both nickel-rich NMC 811 lithium-ion batteries and nickel-free LFP batteries will increase in percentage terms.

Peak demand for lithium, copper and graphite, which are used in all battery types, comes much later. However, after 2030 and until 2039, a plateau is reached with an almost constant level of demand. Lithium, copper and graphite peak in 2039 at 20,800 tons per year (lithium), about 100,000 tons per year (copper), and 200,000 tons per year (graphite). The decline in annual demand for these three feedstocks for transport batteries through 2045, while discernible, is quite moderate compared to the other three feedstocks. This can be explained by the fact that no specific technological changes in battery chemistries have yet come to bear in this scenario.

In contrast to the KNDE2045 scenario, there is no decrease in demand for graphite and copper in the "Domestic Production" scenario. Demand continues to increase slightly after 2035 until 2045. Demand in 2045 would be about 370,200 metric tons per year for graphite, more than double the demand in the KNDE2045 scenario (167,700 metric tons per year). For copper, demand is 203,400 tons per year in 2045, again more than double that in the KNDE2045 scenario (94,200 tons per year).

For lithium, demand in the "domestic production" scenario increases to 38,800 tons per year by 2040, after which a slight decrease is evident until 2045. However, changes in demand are minimal from 2035 onward and are at a nearly constant level between 2035 and 2045.

Regardless of the different developments in the annual demand for the six battery raw materials described here, it is important to note for the objective of this study that a huge increase in demand and thus a phase of short and medium-term "supply stress" for the corresponding supply chains is inevitable for battery raw materials until 2030/2035. The corresponding challenges for the supply side and corresponding solution strategies are discussed in more detail in Chapter 6.

The raw material demand according to the "domestic production" scenario for the domestic production of vehicles with traction batteries, which results from the corresponding increase in the annual demand for lithium-ion batteries, is also shown in Figure 32.

Compared to the KNDE2045 scenario, it is clear that there is no significant decrease in raw material demand after 2035, as the production level of vehicles remains consistently high. Annual demand for lithium, graphite and copper in particular remains stable at a high level. In 2045, almost twice as much graphite would be needed in the "domestic production" scenario as in the KNDE2045 scenario. However, for cobalt and manganese (and to a lesser extent nickel), a decrease in annual demand after 2030 can be seen. This can be explained by the previously described switch to battery chemistries low in cobalt and manganese or free of cobalt, manganese and nickel. As before, recycling is neglected for the time being. As shown below, recycling can have greater potential, especially in later years.

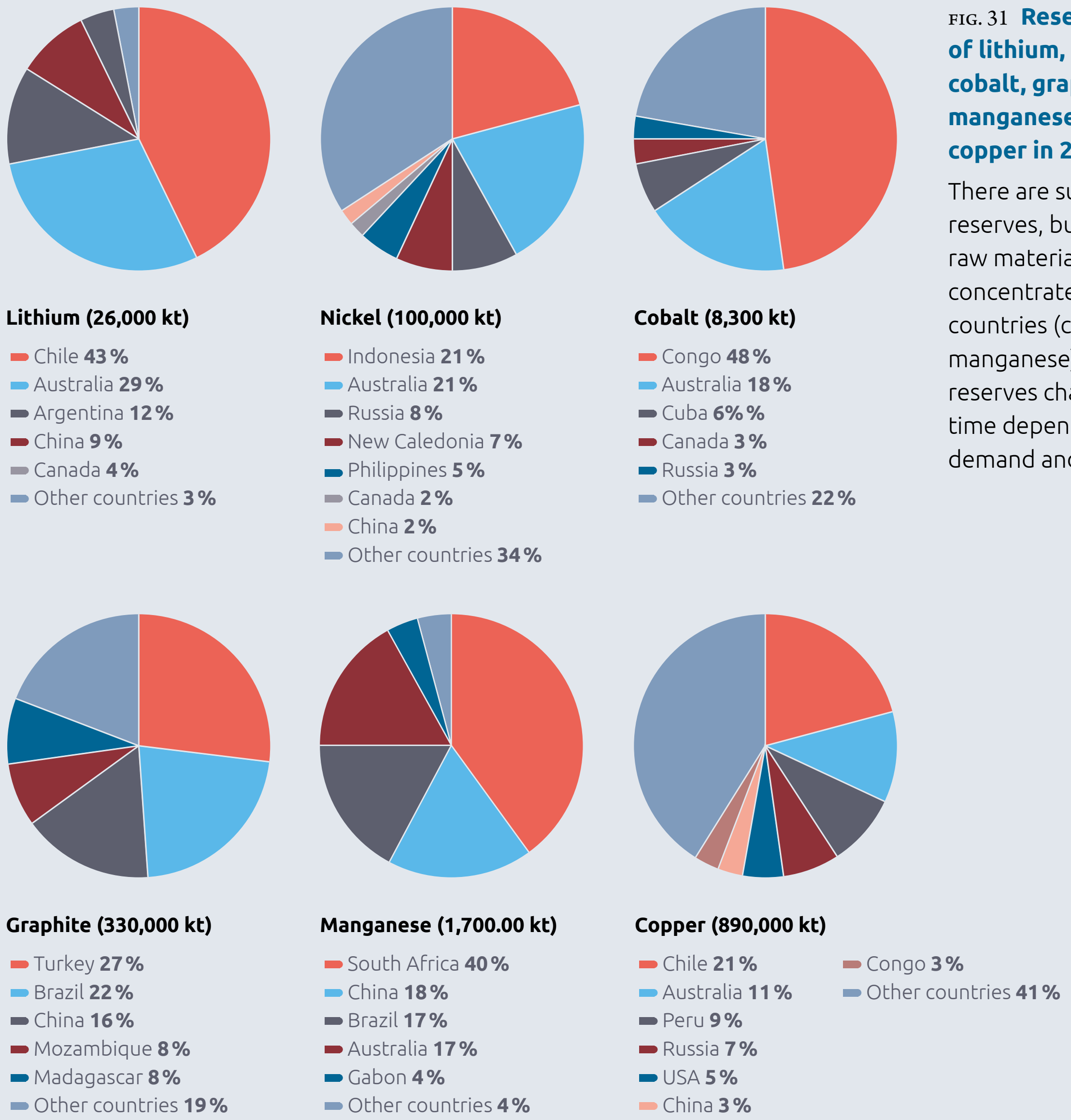


FIG. 31 **Reserves of lithium, nickel, cobalt, graphite, manganese and copper in 2021**

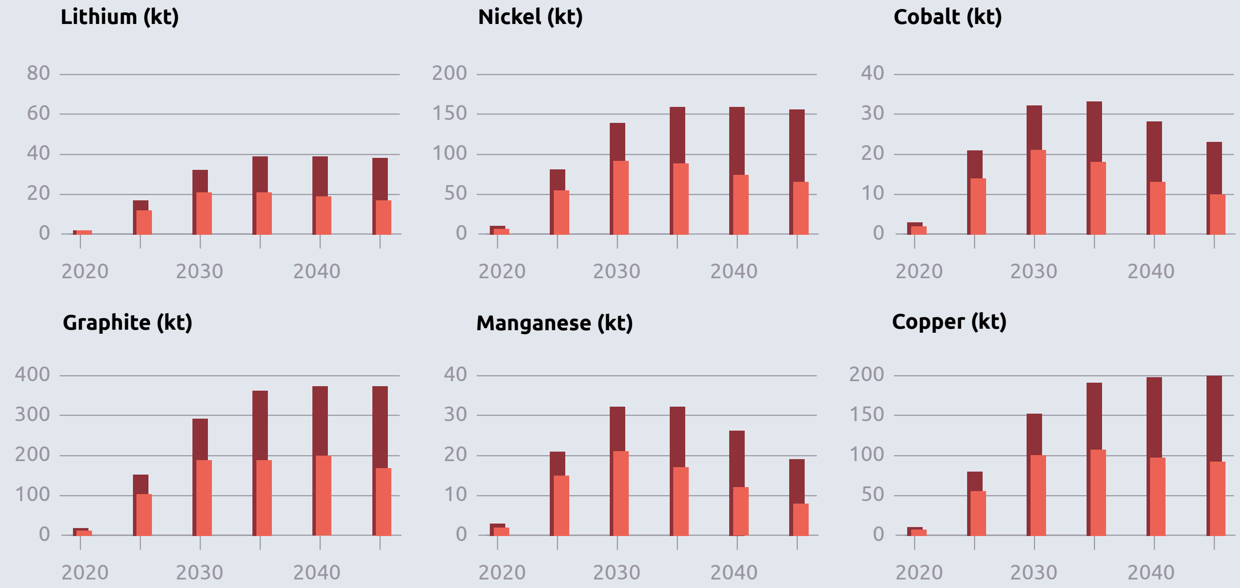
There are sufficient reserves, but for certain raw materials they are concentrated in a few countries (cobalt, lithium, manganese). However, reserves change over time depending on demand and economics.

SOURCE Own representation based on U.S. Geological Survey, 2023. The masses indicate the respective raw material content. Representation in kilotons (kt)

Öko-Institut, 2023

FIG. 32 **Raw material demand until 2045 for lithium, nickel, cobalt, manganese, copper and graphite for lithium-ion batteries in kilotons (kt) for the "Domestic production" scenario and the KNDE2045 scenario**

For all raw materials considered, there is a very strong increase in demand, although this also decreases again due to technological developments, particularly for cobalt and manganese



KEY ▬ "Domestic production" scenario ▬ KNDE2045 scenario

SOURCE Own representation

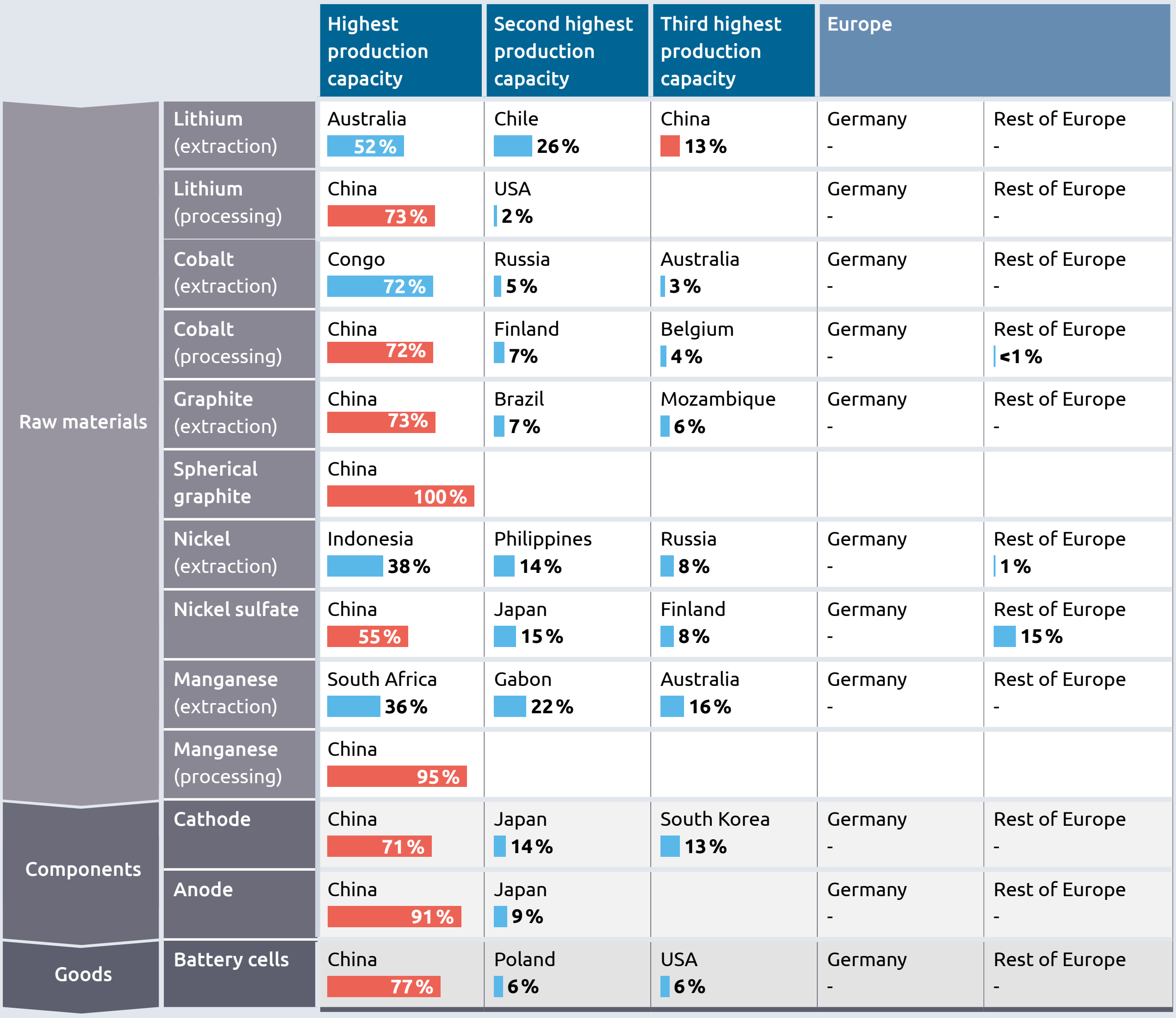
Öko-Institut, 2023

Global supply chain: China dominates all processing steps

Figure 33 below shows a simplified overview of the global supply chain for lithium-ion batteries and the locations of the respective production for 2021. The main location countries for mining the important strategic raw materials for the batteries (lithium, nickel, cobalt, manganese and graphite) in the form of ores, etc., further processing into important intermediate products (e.g. battery-grade lithium compounds, battery-grade cobalt, manganese and nickel sulfate), the production of important cell components (anode and cathode material) and finally the production of the lithium-ion cells in the so-called gigafactories are shown on the basis of their percentage shares of the global supply side.

As shown above, China holds a very dominant position only in graphite for raw material extraction. However, China's dominance is evident in the further stages of the supply chain and here especially in the intermediate products (lithium, nickel, cobalt and manganese compounds, and battery-grade graphite). China also has a very large to overwhelming share in the global production of the strategic components of the cathode and anode material. This is explained further in the following section with reference to the origin of the companies. China is also very dominant in cell production, with battery cells with LFP as the cathode material in particular coming almost entirely from China. For other countries with cell production, the USA is particularly worth mentioning, although the first cell production facilities have now also been opened in the EU (see TABLE 16 in the APPENDIX). Due to their size, these facilities far exceed other previously important production volumes in countries such as Japan and South Korea. Overall, the shares in the global supply chain are subject to major fluctuations due to the strong expansion. Therefore, the

FIG. 33 **Production capacities and supply chain of lithium-ion batteries by region**
The value chain is dominated by China, especially from raw material processing onward.



		Highest production capacity	Second highest production capacity	Third highest production capacity	Europe	
Raw materials	Lithium (extraction)	Australia 52 %	Chile 26 %	China 13 %	Germany -	Rest of Europe -
	Lithium (processing)	China 73 %	USA 2 %		Germany -	Rest of Europe -
	Cobalt (extraction)	Congo 72 %	Russia 5 %	Australia 3 %	Germany -	Rest of Europe -
	Cobalt (processing)	China 72%	Finland 7%	Belgium 4 %	Germany -	Rest of Europe <1 %
	Graphite (extraction)	China 73%	Brazil 7 %	Mozambique 6 %	Germany -	Rest of Europe -
	Spherical graphite	China 100 %				
	Nickel (extraction)	Indonesia 38 %	Philippines 14 %	Russia 8 %	Germany -	Rest of Europe 1 %
	Nickel sulfate	China 55 %	Japan 15 %	Finland 8 %	Germany -	Rest of Europe 15 %
	Manganese (extraction)	South Africa 36 %	Gabon 22 %	Australia 16 %	Germany -	Rest of Europe -
	Manganese (processing)	China 95 %				
Components	Cathode	China 71 %	Japan 14 %	South Korea 13 %	Germany -	Rest of Europe -
	Anode	China 91 %	Japan 9 %		Germany -	Rest of Europe -
Goods	Battery cells	China 77 %	Poland 6 %	USA 6 %	Germany -	Rest of Europe -

KEY 🟥 China 🟦 Other countries
SOURCE Own representation based on (U.S. Geological Survey, 2023), (Benchmark Source, 2022)

Öko-Institut, 2023

figures quickly become outdated and continuous monitoring is necessary to ensure up-to-date knowledge of the supply chains.

Due to the sometimes very large dominance of China in a number of important (intermediate) stages, there is a significant risk for this supply chain in the current constellation with regard to the resilience of supply for countries and economies outside China. The risks to the resilience of the lithium-ion battery supply chain will become even more significant in the short and medium term due to the rapidly growing ramp-up of electromobility in Germany, the EU and worldwide.

Production of components: Ownership of the companies

In addition to the actual locations of production, the ownership of the respective companies is also relevant. According to a recent study by the Fraunhofer Institute ISI, in the case of anodes, the market shares of companies in Chinese hands come to well over 70 percent in 2022, with Japan at over 15 percent and South Korea at under ten percent still clearly outstripping the rest of the world (approx. two percent) (Wicke, T., 2023).

According to this Fraunhofer ISI study, the dominance of Chinese companies in cathode materials is somewhat lower than in anode materials, at over 65 percent. The market shares of South Korean companies are in second place at almost 20 percent, while Japan comes in at around seven percent. It should be noted here that the EU, especially through Umicore as the largest European representative with its headquarters in Belgium, occupies a solid fourth place in 2022 with over 6 percent market share (Wicke, T., 2023). However, Umicore still produced mainly in South Korea and China during the period. However, in the fall of 2022, Umicore started its first cathode material production in Europe in Poland (Schaal, S., 2022). Such location decisions can explain the differences in the figures between the ownership of the firms and the shares of the countries in the actual production.

Differences between the anode and cathode markets can also be seen in the company structure for 2022. While the four largest anode producers with their headquarters in China have a market share of over 50 percent, the cathode market is more diversified in terms of companies. There, the company with the largest market share comes to just about eight percent, closely followed by other companies of similar size (Fraunhofer ISI; Wicke T., 2023). However, this is only a snapshot and may change rapidly and significantly over the years due to massive expansion plans worldwide, but also in Europe. Production of anode material on an industrial scale does not yet exist in the EU (as of June 2023). For cathode material, production is currently being ramped up independently in Poland by Umicore and in Germany by BASF.

5.4. Permanent magnets

- The entire supply chain of permanent magnets is dominated by China. With each stage of the value chain, China's role grows: Raw material extraction of rare earths (60 percent share of China), further processing (87 percent), production rare earth metals (91 percent), production of neodymium-iron-boron magnets (94 percent).

- China currently has a virtual monopoly in the processing of the heavy rare earths dysprosium and terbium (important for the temperature stability of magnets).

- Demand in Germany and globally for permanent magnets (neodymium-iron-boron) will grow strongly up to 2030 and beyond due to applications in wind turbines and electromobility.

- Germany and Europe are currently not represented at all or only marginally (e.g. around one percent of global production of neodymium-iron-boron magnets) at all stages of the value chain.

- The growing demand for neodymium-iron-boron magnets and the extreme dependence on imports call for a rapid strengthening of the value chain within Europe and greater differentiation of supply relationships with non-European countries.

From rare-earth deposit to permanent magnet

Figure 34 below schematically shows the stages of the supply chain for permanent magnets (neodymium-iron-boron magnets). After mining of the rare earths (mostly in oxide form), the ore material is subjected to complex processing involving concentration, purification and separation of the individual rare earths in suitable compounds. Due to the fact that many of the total of 17 rare earths always occur together in natural deposits, this step is very complex and thus involves a high input of chemicals and energy. The next essential step in the supply chain is the production of rare earth metals from the rare earth compounds previously produced in pure form. Finally, the neodymium-iron-boron magnets are manufactured using a sophisticated sintering process. (Pupil, D. et al., 2011)

Currently, there is no mining of rare earths in the EU. In the two subsequent stages, the European share is vanishingly small at about one percent (ERMA; Gauss et al., 2021). There is no production of magnetic rare earth alloys. The only EU country with magnet production is Germany, with all the alloys needed for production being imported from China. At the moment, therefore, there is a very one-sided and thus critical dependency.

Raw materials and reserves

In addition to the pure quantitative availability of raw materials in deposits, the current use and possible requirements for an increase in raw material production to meet future demand also play an important role with regard to the dynamics of criticality. For a rough classification of the development on a global level, Figure 35 shows the demand for rare earths calculated according to the IEA scenarios (IEA, 2021c) due to the worldwide ramp-up of electric vehicles and wind turbines[29] in relation to the total demand in 2020. (Pupil, D. et al., 2011) For light rare earths, this shows a narrow doubling of global demand due to electromobility and wind power in 2030, which remains at about this level in 2040. For heavy rare earths, the increase in the two technologies will lead to a tripling of current total global demand in 2030 and a quadrupling in 2040. From this point of view, the demand for heavy rare earths is more critical, despite lower demand in terms of quantity. This is also confirmed in the following analysis on deposits (lower quantities, stronger country concentration). In contrast to the situation in Germany, the global demand peak according to (IEA, 2021c) has not yet been reached in 2030.

The shares of the most important producing countries (mining production) of rare earths[30] are shown in Figure 36. China (58 percent), the United States (15 percent), Myanmar (12 percent), and Australia (8 percent) provide the largest shares of world production of about 290,000 metric tons per year (rare earth oxide equivalent unit) (U.S. Geological Survey, 2023). An interesting development is the comparison with the data for 2011 — ten years earlier. Here, China accounted for about 95 percent of global mine production, with a global production volume of about 111,000 metric tons in 2011 (U.S. Geological Servey, 2013). On the one hand, this shows the significant increase in global rare earth mining within 10 years, but it also shows that shares of global mining production can shift dramatically.

From Figure 36, it can be seen that as of 2021, there are known global reserves of about 130 million metric tons of rare earth oxide equivalents. On the one hand, this is a huge order of magnitude,[31] but on the other hand, it shows that countries such as Brazil or Vietnam, which had only negligible shares of mining production in 2021, have huge shares of the known global reserves of rare earths. Further changes in country shares of global rare earth mining production are therefore possible for the future.

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[29] This is in addition to the current total demand in 2020, i.e. assuming that the other application areas remain at a constant level.

[30] USGS statistical data are reported only for all rare earths combined in aggregate annually. Scandium is not included in these figures (U.S. Geological Survey, 2023).

[31] It has been known for some time that the historically used term "rare earths" is misleading in terms of quantity.

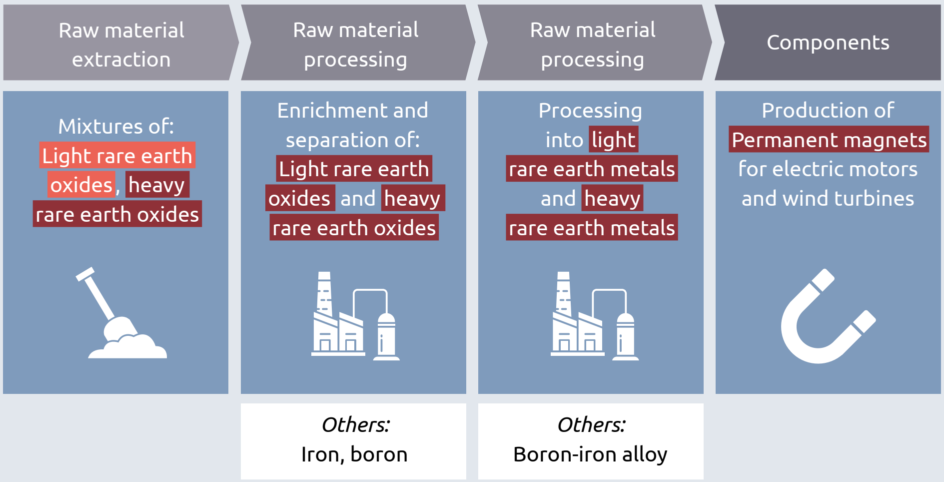


FIG. 34 **Supply chain for the production of permanent magnets**

Rare earths as a raw material for permanent magnets are to be classified as very critical, with criticality tending to increase along the value chain.

NOTE Extraction of rare earth elements: The raw materials each occur in different compositions. The proportion of rare earth elements in the respective deposits varies greatly

KEY Criticality: ■ Very critical ■ Medium critical ■ Moderately critical SOURCE Own representation

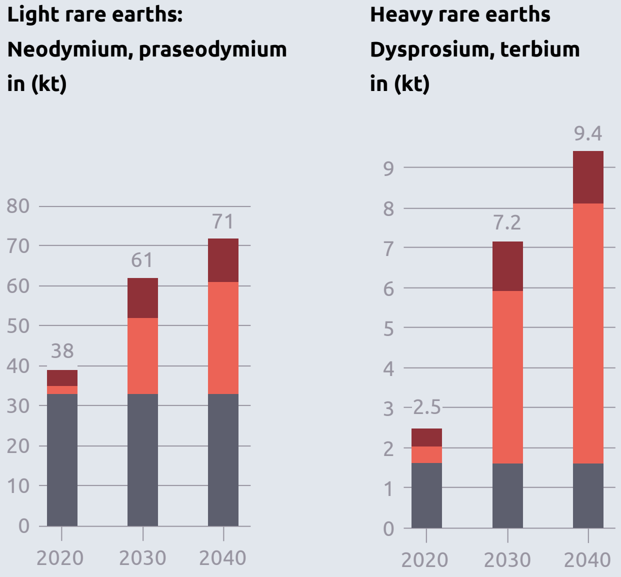
Öko-Institut, 2023

FIG. 35 **Global demand for Rare earths increase significantly due to expansion of wind power and Development of electromobility**

There will be a multiplication of demand for rare earths in 2030 and 2040 due to e-mobility and wind power compared with 2020

KEY
■ Wind power
■ Transport
■ Other

SOURCE Own representation



Öko-Institut, 2023

The production of neodymium-iron-boron magnets requires the light rare earths neodymium and praseodymium and the heavy rare earths dysprosium and terbium. In many natural deposits (e.g. in China, Australia, USA and India), the proportion of neodymium is between 10 - 30 percent of the respective rare earth deposit; in the case of praseodymium, the proportion often ranges between four and six percent. Mining production of 50,000 tons of neodymium oxide has been estimated for 2020. (Gielen, D.; Lyons, M., 2022)[32]

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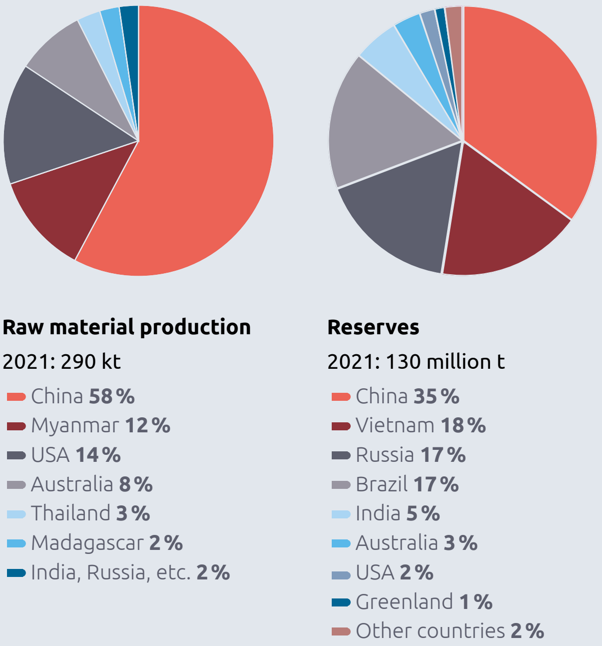
[32] From the value for neodymium oxide, a mining production of approximately 12,500 tons of praseodymium oxide can be estimated for 2020.

FIG. 36 **Production and global reserves of rare earths***

China, USA, Myanmar and Australia currently supply the largest shares of world production. Reserves are also located in other countries, e.g. Vietnam and Brazil

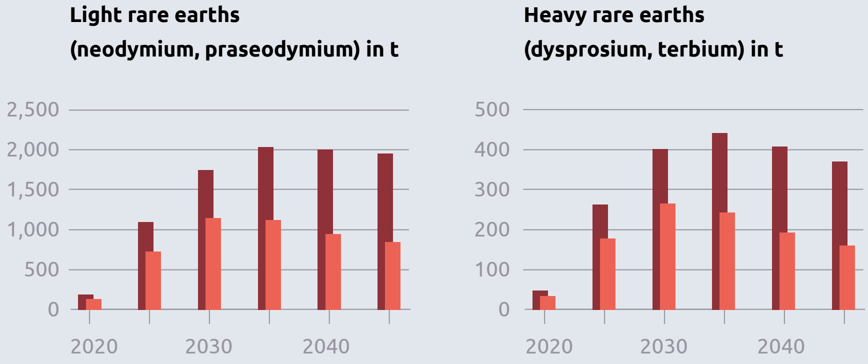


* Scandium, also a rare earth element discussed for high temperature electrolysis (cf. Chap. 4.5. Electrolyzers and hydrogen infrastructure & 5.5. Electrolyzers), is excluded from this listing according to (U.S. Geological Survey, 2023).
** No reserve information is available for Myanmar according to (U.S. Geological Survey, 2023).

SOURCE Own representation based on (U.S. Geological Survey, 2023): Rare earth mine production in 2021 and reserves in 2021. Reserves without Myanmar**

Öko-Institut, 2023

FIG. 37 **Annual demand for light and heavy rare earths for electric vehicles in Germany in the KNDE2045 and "Domestic Production" scenarios**



KEY
- 🟥 "Domestic production" scenario
- 🟥 New registrations – KNDE2045 scenario

SOURCE Own representation

Öko-Institut, 2023

The supply situation for the heavy rare earths dysprosium and terbium, on the other hand, is more critical, as these are currently only extracted from natural deposits in China and Myanmar, and further processing takes place exclusively in China. In addition, the proportions of heavy rare earths in natural deposits are often very small. Dysprosium is reported to have an average value of less than one percent of total rare earth occurrences (Gielen, D.; Lyons, M., 2022). For 2019, (Xiao, S. et al., 2022) indicate a mine production of about 4,000 tons.

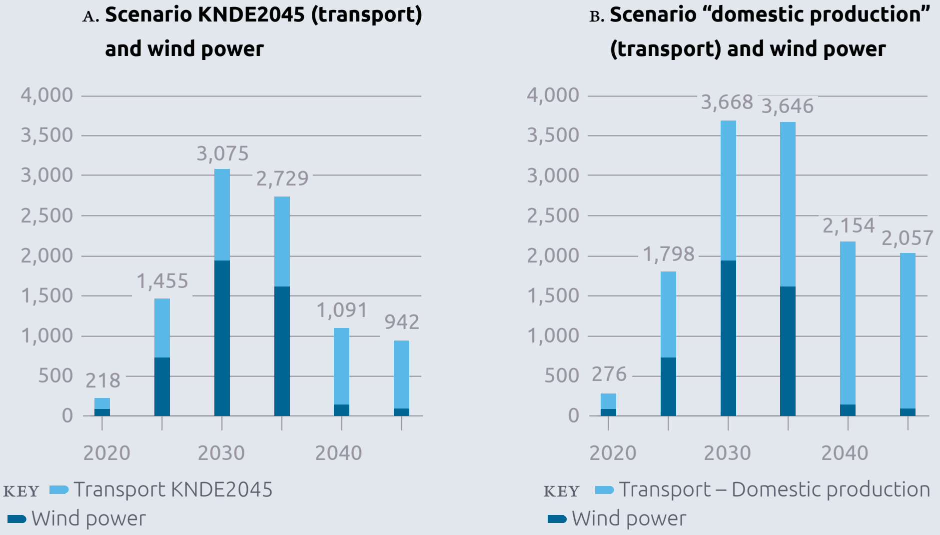
Permanent magnets in Germany: Demand for critical raw materials up to 2045 for electromobility

In Chapter 4.4, the demand for neodymium-iron-boron magnets for vehicle drives was derived. The resulting demand for rare earths up to the year 2045 is shown in Figure 37 for new registrations in Germany (KNDE2045 scenario) and the "Domestic production" scenario. It is evident that demand will increase significantly over the next few years due to the ramp-up of electromobility, peaking at just un-

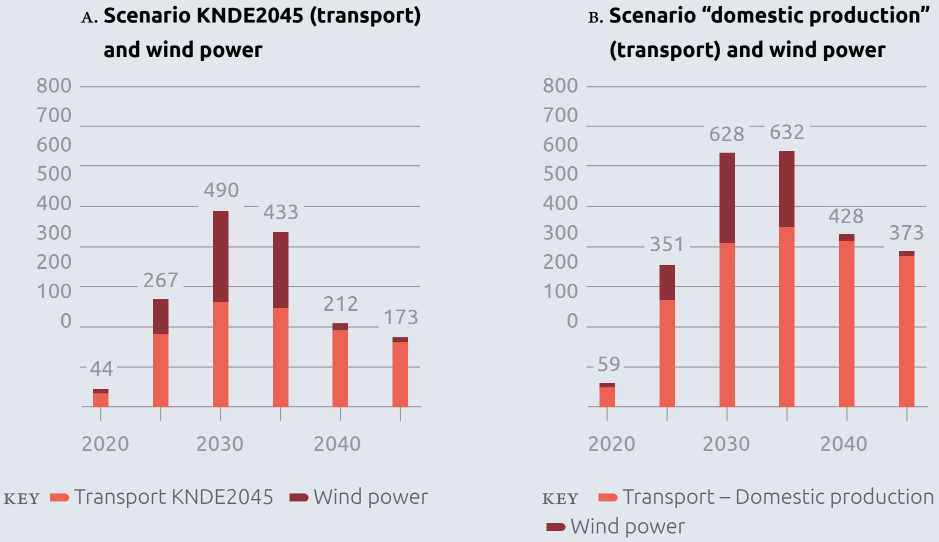
FIG. 38 **Annual Demand for Rare earths for electric vehicles and wind power in Germany in the KNDE2045 and "Domestic production" scenarios**

While demand for permanent magnets from wind power will again decline very sharply by 2040, demand from electromobility will remain at a high level. Demand in "Domestic production" scenario is twice as high in the long term as in KNDE2045 scenario.

Light rare earths (neodymium, praseodymium) in t



Heavy rare earths (dysprosium, terbium) in t



SOURCE Own representation

Öko-Institut, 2023

der 1,500 metric tons in new registrations in 2030. Thereafter, demand levels off slightly, but remains at a total of 1,000 tons in 2045. In the "domestic production" scenario, maximum demand is reached in 2035 with a total of almost 2,500 tons. After that, it remains almost constant for light rare earths until 2045, while it decreases for heavy rare earths due to the savings in magnets and the increasing share of other engine types. [33]

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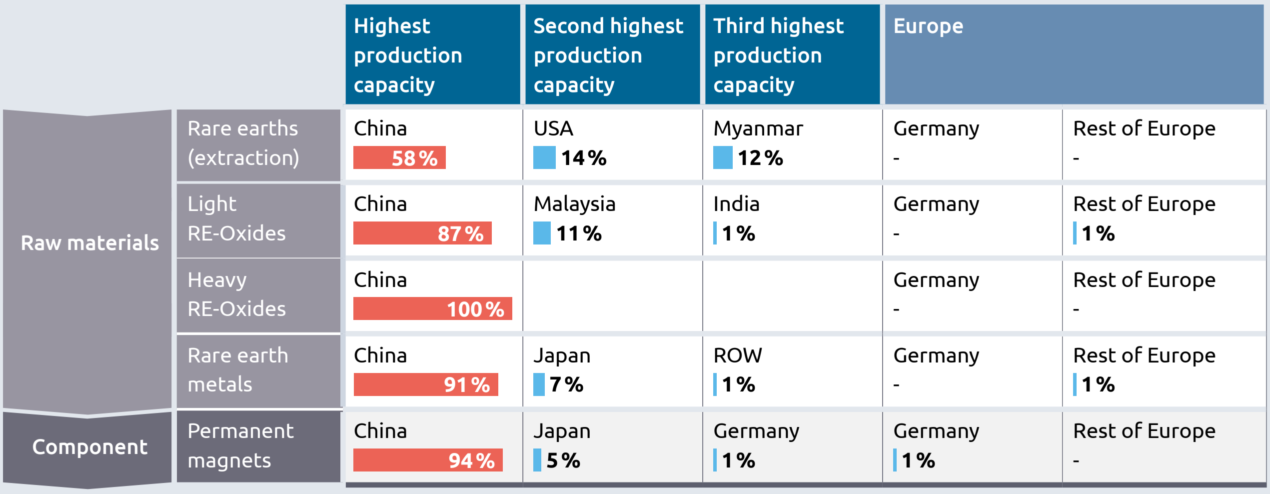
[33] According to the "domestic production" scenario, vehicle numbers are relatively constant in 2035 to 2045 (cf. 4.3. Batteries for electric mobility). In the case of light rare earths, the quantities saved by a higher share of alternative engine technologies are roughly offset by the higher demand for the magnets (savings in SSE are offset by a higher share of LSE) (see 4.4. Permanent magnets for electromobility).

FIG. 39 **Global supply chain of permanent magnets by main countries 2021**

The value creation of permanent magnets is clearly dominated by China across all steps



		Highest production capacity	Second highest production capacity	Third highest production capacity	Europe	
Raw materials	Rare earths (extraction)	China 58 %	USA 14 %	Myanmar 12 %	Germany -	Rest of Europe -
	Light RE-Oxides	China 87 %	Malaysia 11 %	India 1 %	Germany -	Rest of Europe 1 %
	Heavy RE-Oxides	China 100 %			Germany -	Rest of Europe -
	Rare earth metals	China 91 %	Japan 7 %	ROW 1 %	Germany -	Rest of Europe 1 %
Component	Permanent magnets	China 94 %	Japan 5 %	Germany 1 %	Germany 1 %	Rest of Europe -

KEY 🟥 China 🟦 Other countries SOURCE Own representation with data from (ERMA; Gauss et al., 2021)

Öko-Institut, 2023

The comparison of the demand for rare earths from the areas of electromobility and wind power for Germany in the KNDE2045 scenario shows that both technologies are in similar orders of magnitude (cf. ABB. 39. For both wind power and electromobility, this study calculates a peak demand for the year 2030. However, in the case of wind power, demand flattens out more significantly after 2035, reaching the 2020 baseline level in 2040/2045.

Accordingly, the total demand for electric drives and wind power in Germany for the KNDE2045 scenario is a maximum of about 3,000 tons per year of light rare earths (mainly neodymium) and about 500 tons per year of heavy rare earths (mainly dysprosium). In the domestic production scenario, it is somewhat higher. This compares with current global production volumes of about 50,000 tons per year of neodymium and about 4,000 tons per year of dysprosium (see section on raw materials and reserves). Accordingly, in order to increase resilience, in addition to diversification of supplier countries, measures are also essential that enable a reduction in (primary) material demand or a compatible increase in production volumes (cf. Ch. 6.)

Supply chain clearly dominated by China

As previously described, China's share in the extraction (mining) of rare earths has fallen to about 60 percent of global production in recent years. However, this still very much determines the market. In addition, the dominance of China increases with each further step in the supply chain, reaching an outstanding share of about 94 percent in the production of permanent magnets (permanent magnets). Japan takes second place here with a 5 percent market share, while the EU accounts for only about one percent of global production of neodymium-iron-boron magnets.

While according to (ERMA; Gauss et al., 2021) there is minor production of rare earth metals in the EU, no magnetic rare earth alloys are produced (reference year 2019), so the supply chain is completely broken here. However, based on known projects, (ERMA; Gauss et al., 2021) experts expect capacity to increase in the near term to about 10 percent by 2030. According to the same source, about 20 percent is possible in magnet production by 2030, and even about 30 percent in rare earth oxide production for magnets (see 6. Resilience measures).

5.5. Electrolyzers

- Alkaline electrolysis (AEL) and PEM electrolysis (PEMEL) are currently ready for the market and will continue to dominate the market for electrolyzers in the coming years.

- No critical raw materials are required for the AEL; platinum, iridium, and titanium must be considered for the PEMEL.

- Iridium is by far the most critical raw material for PEMEL and for electrolyzers as a whole, as extraction by mining of iridium cannot be expanded (since as a minor metal it is dependent on platinum and palladium production).

- The supply situation for platinum and titanium (titanium sponge) is hardly tight, as material efficiency and recycling options are available for both metals and free supply capacities are still discernible for titanium sponge.

- High-temperature electrolysis (HTEL) is only at the pilot stage and moderate market shares are only expected in the medium term.

- At HTEL, the essential raw materials are scandium and yttrium, both of which belong to the rare earth group.

- The supply of yttrium is not considered critical in view of the small quantities that can be expected; scandium has so far only been produced in very small quantities by a few countries, although supply expansions through additional supplier countries are feasible here in the medium and long term.

Very high criticality for PEM electrolyzers due to the use of iridium

In the case of electrolyzers, criticality results from the use of the critical raw materials. Iridium, platinum and titanium are used in PEM electrolyzers. Scandium and yttrium are required in high-temperature electrolyzers. Iridium is by far the most critical raw material in electrolyzers and is classified as very critical according to the definition of this study. Iridium is one of the few raw materials whose natural occurrences are actually very rare and extraction by mining cannot be easily increased (see below for raw material extraction). In addition, there is a high country concentration of production in South Africa. In addition, platinum and titanium are used in PEM electrolyzers. The supply situation for platinum and titanium (titanium sponge) is hardly critical, as material efficiency and recycling options are available for both metals and free supply capacities are still discernible for titanium sponge.

High-temperature electrolysis (HTEL), which is currently only in the pilot stage, uses scandium and yttrium. They belong to the group of rare earths, but are not threatened by supply shortages in the short and medium term (until 2030) compared to the rare earths needed for permanent magnets. The supply of yttrium is not considered critical for the HTEL against the background of the low quantities that can be expected; scandium has so far only been produced in very small quantities by a few countries, although supply expansions through additional supplier countries are feasible here in the medium and long term.

From today's perspective, the production of electrolyzers and their subcomponents is hardly critical, as Europe currently still has a market share of around 30 percent. However, the decisive factor here is that Europe continues to secure market share, and investments are now being made in plant automation and scaling.

Raw material extraction
PEM electrolyzers: Iridium, platinum, titanium

Iridium, along with platinum, is one of the so-called platinum group metals (PGMs)[34]. It is highly corrosion-resistant and thus an important metal for the market ramp-up of PEM electrolyzers in the future. Today, iridium is mainly used for spark plugs, crucibles and in electrochemistry. It is one of the few raw materials that are actually rare. Each year, only 6 to 10 tons are extracted. In addition, it is very critical that iridium occurs in natural deposits exclusively as a so-called "minor metal" in very low concentrations[35] and is therefore only mined as a by-product of platinum production (DERA, 2022). Thus, the production of iridium is entirely dependent on the development of platinum production. Platinum production will not be increased further in the future. This is because platinum is needed primarily for exhaust catalysts in diesel and gasoline engines. Due to the decline in fossil combustion technologies in transport and the good recycling potential of platinum from old car catalytic converters (cf. CH. 6), it can be assumed that platinum and thus iridium production will not be expanded. Expanding production only for iridium would not be feasible from an economic and environmental standpoint.

Moreover, the extraction of iridium is concentrated in just a few countries and companies[36]: South Africa is the largest single producer in absolute terms, with a share of 85 percent. Zimbabwe accounts for a further seven percent of extraction. The remaining eight percent

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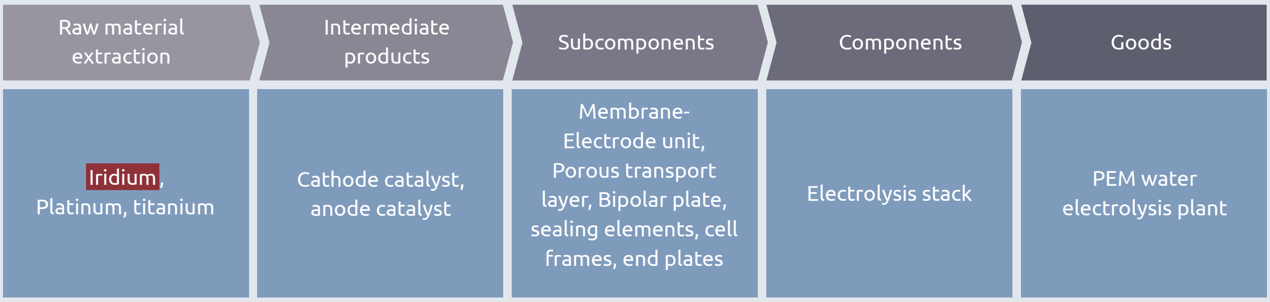
[34] The PGMs include the elements platinum, palladium, rhodium, ruthenium, iridium and osmium.

[35] The iridium content in natural ores is only 0.02 – 0.1 g/t ore.

[36] According to the (DERA, 2022), PGMs are extracted by only a few companies and fed directly into the first stages of the supply chain in the producing countries, which is justified by their high value. Except for intra-company transfers, there are no pure exports of ores and concentrates.

FIG. 40 **Supply chain for the production of PEM electrolysis plants (PEMEL)**
In PEMEL, the use of iridium is very critical because production cannot be expanded. Platinum and titanium are strategically relevant, but are not considered critical in this study.

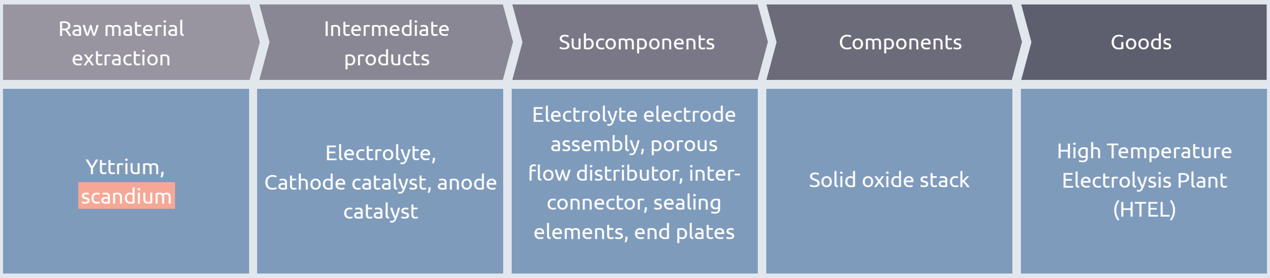


Raw material extraction	Intermediate products	Subcomponents	Components	Goods
Iridium, Platinum, titanium	Cathode catalyst, anode catalyst	Membrane-Electrode unit, Porous transport layer, Bipolar plate, sealing elements, cell frames, end plates	Electrolysis stack	PEM water electrolysis plant

KEY Criticality: ■ Very critical ■ Medium critical ■ Moderately critical
SOURCE Own representation based on IndWedE and (U.S. Department of Energy, 2022a)

Prognos, 2023

FIG. 41 **Supply chain for the manufacture of high-temperature electrolysis equipment (HTEL)**
scandium is used in the HTEL and is classified here as moderately critical. Yttrium is not classified as critical.



Raw material extraction	Intermediate products	Subcomponents	Components	Goods
Yttrium, scandium	Electrolyte, Cathode catalyst, anode catalyst	Electrolyte electrode assembly, porous flow distributor, inter-connector, sealing elements, end plates	Solid oxide stack	High Temperature Electrolysis Plant (HTEL)

KEY Criticality: ■ Very critical ■ Moderately critical ■ Moderately critical
SOURCE Own representation based on IndWedE and (U.S. Department of Energy, 2022a)

Prognos, 2023

is mined in the USA, Canada and Russia[37] (see FIG. 42. In addition, no new players and options are emerging because the world's reserves of platinum group metals are located in the current producing countries.

So far, the critical dependence on iridium is still low because the global ramp-up of PEM electrolyzers is still in its early stages. However, since they can be operated in a particularly flexible manner compared to the alkaline electrolysis (AEL) currently in use and can thus respond better to volatile power generation from renewable energies, their market share will increase significantly in the future (cf. CH. 4.5.)

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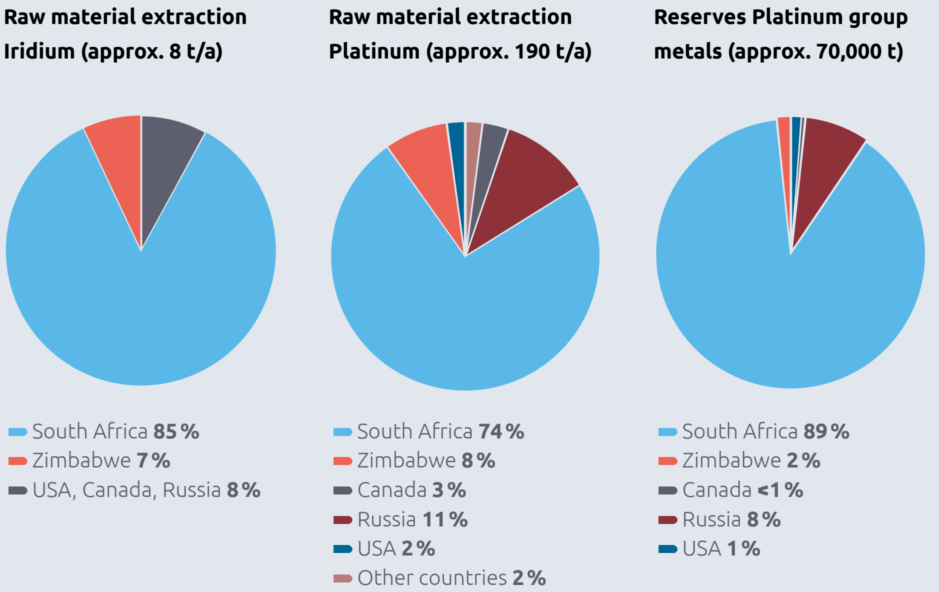
[37] Platinum group metals, such as iridium and platinum, occur mostly with sulfidic nickel and copper. In Russia, nickel and copper dominate the deposits, so platinum group metals are a by-product of nickel and copper production here and therefore also dependent on their demand. In South Africa, on the other hand, platinum group metals dominate the deposits, and there are only small proportions of nickel and copper. According to (Dera 2022), for example, platinum grades in South Africa are 1.26 to 3.25 g/t, but iridium grades are only 0.02 to 0.1 g/t.

FIG. 42 **Extraction and global reserves of iridium and platinum**

High country concentration for iridium and platinum due to high market share of South Africa in production and reserves.

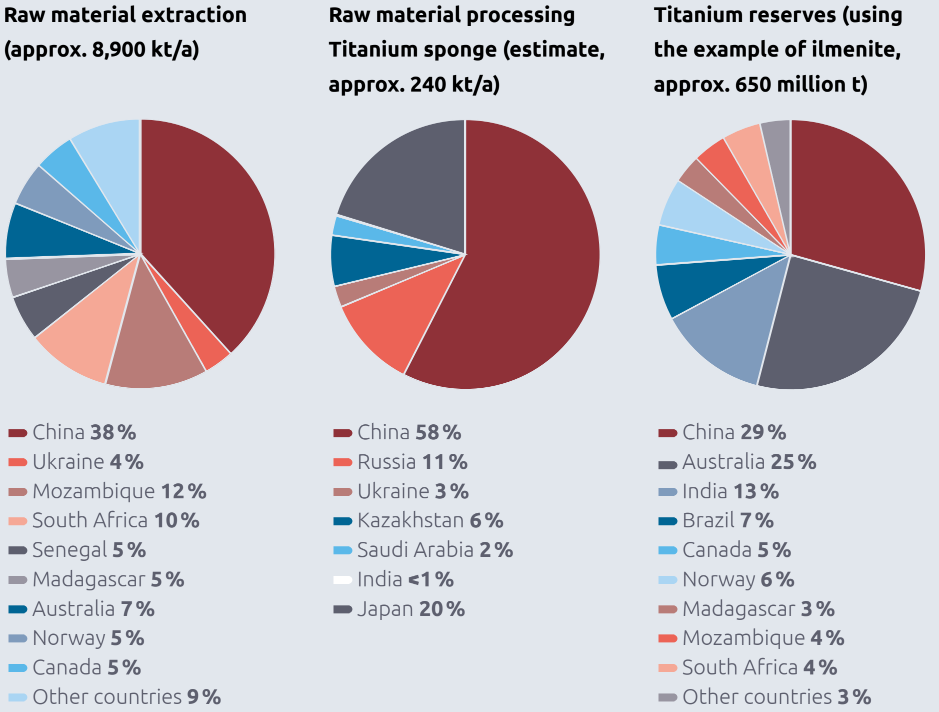


SOURCE Own representation according to (JM, 2022): Mine production of iridium in 2021, and (U.S. Geological Survey, 2023): Mine production of platinum in 2021 and reserves of platinum group metals (including platinum, iridium) in 2023.

Öko-Institut, 2023

FIG. 43 **Extraction and global reserves of titanium**

In the case of titanium, there is less market concentration in terms of extraction and reserves.



SOURCE Own representation based on (U.S. Geological Survey, 2023). Production of titanium (extraction using the example of ilmenite, plus 600 kt/a rutile, and titanium sponge production) in 2021, and reserves of titanium minerals using the example of ilmenite (plus 50 million t of rutile) in 2023, breakdown by country. Raw material processing to titanium sponge based on own estimate. Representation in kilotons (kt)

Öko-Institut, 2023

Platinum is listed as a critical raw material on the European Commission's Critical Raw Material list. The reason for this is the high country concentration on South Africa of around 75 percent of world production. In terms of the supply/demand ratio, however, supply bottlenecks are not expected. Therefore, while platinum is strategically relevant, it is not critical for the purposes of this study. Today's global platinum production is 200 tons per year. Additional demand from expansion of PEM electrolyzers worldwide is limited[38]. In addition, the decline in new registrations of vehicles with combustion engines, which is the main application of platinum, will free up substantial volumes in the market in the future. Furthermore, platinum can also be used very well as a secondary raw material through the established recycling of old car exhaust catalysts.

In addition to iridium and platinum, titanium is also used in PEM electrolyzers. Titanium is mined worldwide primarily from the minerals ilmenite and rutile, with ilmenite production clearly predominating: about nine million tons per year versus 0.6 million tons per year (U.S. Geological Survey, 2023, Figure 43). However, only a very small portion (2.5 percent) of the titanium mined is processed into metallic titanium in the form of titanium sponge. By far the largest quantities are processed into titanium dioxide and used as a pigment. Today, metallic titanium is mainly used for titanium alloys, especially in aircraft construction.

While the production of titanium minerals is spread over more than ten countries, titanium sponge is produced in seven countries worldwide. China leads in both cases, followed by Japan, Russia, Kazakhstan, and Ukraine for titanium sponge (U.S. Geological Survey, 2023). After China, ilmenite is mined mainly in African countries, but also in Australia, Norway, Ukraine and Canada.[39] A comparison of today's global titanium sponge production — around 240,000 metric tons in 2021, of which around 20 percent is in Japan — with the demand in the KNDE2045 scenario (in the worst case, i.e. without material efficiency gains) of a maximum of around 2,000 metric tons per year shows that the supply situation for titanium sponge (and even more so for titanium minerals) is orders of magnitude less critical compared with the platinum group metal iridium, which is essential for PEM electrolyzers.

High temperature electrolyzers: Yttrium and scandium

For HTEL, the essential raw materials are scandium and yttrium, both of which belong to the rare earth group. For yttrium, the maximum annual demand calculated here is only a very manageable 6 metric tons — without taking material efficiency gains into account and only in the very long term from 2040. This compares with a magnitude of annual global yttrium production of 8,000 to 12,000 metric tons in 2021 (U.S. Geological Survey, 2023). The additional demand — even when scaled up to world demand — is to be considered marginal compared to this current production volume. So far, mining production of yttrium is almost exclusively concentrated in China and Myanmar. However, natural yttrium reserves are estimated at more than 500,000 metric tons — and this figure does not yet include significant reserves in Myanmar, which have not yet been quantified (U.S. Geological Survey, 2023). Natural reserves of yttrium are also reported for Brazil, Australia, Canada and India but also for Sweden.

Scandium has been recovered only in the range of 15 to 25 metric tons annually as a byproduct of processing titanium, zircon, cobalt, and nickel ores (U.S. Geolog-

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[38] For the expansion of PEM electrolyzers in the scenario calculated here, depending on the material intensity, between 1.7 (at current material intensity) and 0.2 million metric tons (at possible future material intensity) will be required annually for Germany from 2040. Since the plants have so far only been produced on a small scale and there is a high potential here for reducing the use of raw materials through economies of scale, a significant reduction in material intensity is realistic. Assuming that 100 to 200 times as much capacity is built worldwide as in Germany, the demand would be between 20 and 40 tons per year at low material intensity. That's ten to 20 percent of current extraction.

[39] Ukraine also has a relevant share of rutile production; it is on par with South Africa here at 95,000 t/a, and other relevant producing countries are Australia, Sierra Leone, and Kenya (U.S. Geological Survey, 2023).

ical Survey, 2023). China has a share of more than 75 percent here (DERA, 2022), followed by Russia and the Philippines. With a maximum demand of a good eleven tons of scandium per year (approx. 2040), the supply for scandium from today's perspective shows resilience issues for the KNDE2045 scenario. DERA also rates the future demand/supply relationship for scandium as significantly more relevant than for yttrium, platinum and titanium — but significantly less relevant than for iridium — against the backdrop of the expected ramp-up of electrolyzer capacity for hydrogen.

No global reserve data are reported for scandium, but (U.S. Geological Survey, 2023) emphasizes that natural resources for scandium are abundant — there are greater resources than for the bulk metal lead. These resources cover more than 100 different minerals present in several countries, including Finland and Norway. However, scandium occurs only as a concomitant element in concentrations of 0.5-100 ppm in, for example, zircon, tin, nickel, and bauxite deposits (DERA, 2022). This fact makes the extraction of scandium relatively complex and expensive.

Electrolyzers in Germany: Demand for key raw materials up to 2045

With the ramp-up of electrolysis production, the demand for technology-relevant metals is also increasing. These are in particular very critical iridium (platinum and titanium are strategically relevant but not critical) used in PEM technology, as well as moderately critical scandium[40] and non-critical yttrium in HTEL, which are currently indispensable for the functionality of the corresponding technologies. Figure 44 below shows two possible ramp-up curves of the critical materials for the KNDE2045 scenario assuming the technology distribution in the annual electrolysis build-up (cf. CH. 4.5.) The upper trajectory results if the current material intensity of the technologies is taken as a basis, the lower trajectory if a significantly reduced specific material input can be realized on the basis of the scientific literature (continuous reduction from today's level to approx. -90 percent in 2040).

However, the reduction of material intensity has an important role to play for all metals analyzed — but here especially for iridium — with regard to increasing the resilience of supply chains. These and other necessary measures are presented in Chapter 6.

Of the technology metals for electrolyzers, iridium is by far the most critical for the resilience of the supply chain, as already mentioned. In the case of iridium, it is impressively demonstrated that the required ramp-up is not feasible with the current loads of the catalysts. The demand for this would be around three tons per year between 2030 and 2045 for Germany alone. This contrasts with a world production of currently about eight tons per year as a by-product of other platinum group metals, which cannot be expanded. Future platinum demands for electrolyzers, on the other hand, can be easily met from well-established recycling structures.

Scandium has so far only been extracted globally as a by-product in the order of 15 to 25 tons per year. In contrast to iridium, an expansion of primary extraction is perfectly possible here. The supply situation for titanium sponge and yttrium is not classified as critical.

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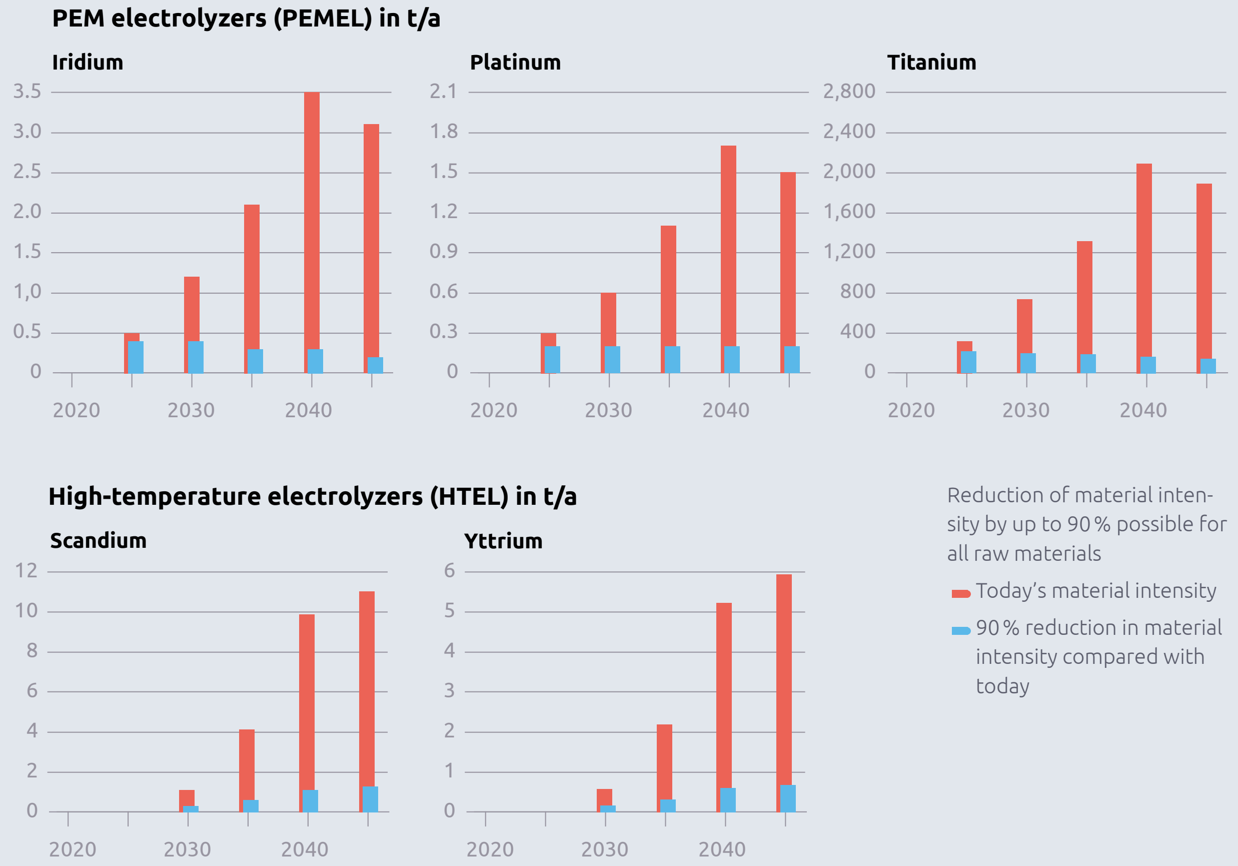
[40] Scandium is discussed, for example, in (Kiemel, S. et al., 2021) as a possible substitute for yttrium.

FIG. 44 **Demand for relevant raw materials for the expansion of electrolyzers in Germany**
Iridium is by far the most critical element in electrolyzers (PEMEL). It is estimated that material intensity could be reduced by 90 percent. This is the key lever for increasing resilience.



SOURCE Assumed reduction in scenario based on (Kiemel, S. et al., 2021) (assumption: literature value for 2035 will not be reached in the market until 2040). Platinum, indium and titanium considered as additive to PEM technology, yttrium and scandium for HTEL as an alternative.

Prognos, Öko-Institut, 2023

Production of components and plants

The technological core of the electrolysis technologies are the respective electrolysis stacks. Here, the central subcomponents are catalysts, electrodes and ion exchange material (electrolytes or membranes, depending on the technology), as well as structures for fluid transport (porous transport layers) and structural plates (bipolar plates) and sealing elements. Industrialization of manufacturing is currently under intensive development for PEM electrolyzers.

Currently, the manufacturing capacities for electrolyzers are distributed between the core regions of Europe and China (43 percent each) and the USA and India (7 percent each) (IEA, 2022c). A compilation of 66 global electrolysis producers based on various sources (see TAB. 18 in the Appendix) provides similar figures: 42 percent of the companies found in this research are located in the EU, 35 percent in Asia and 23 percent in North America. Due to the high dynamics in the field of electrolysis production and technology development, this list can only be classified as a snapshot, which nevertheless shows that technology development in Europe currently has a good basis.

The vertical range of manufacture varies depending on the company and technology. For example, there are companies that manufacture only individual components (membranes, catalysts) and companies with high vertical integration (U.S. Department of Energy, 2022a).

In addition to the electrolysis stack, the following components of the entire plant are of central importance, depending on the electrolysis technology:

- Fluid management: Pipes, pumps and compressors, gas and water separators, valves, etc.
- Thermal management: Heat exchangers and heat circuits with pipes, pumps, valves and heat transfer medium for heat supply (HTEL) and removal (waste heat, recooling)
- Power electronics (rectifiers) and electronic system control

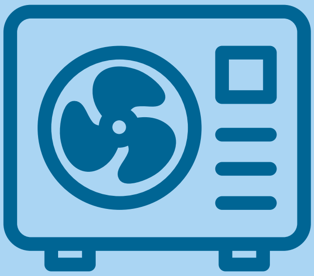
All these components can be obtained from a broad supplier market and are also known from other applications in the field of water or gas technology, so no criticality is expected.

In summary, apart from the critical raw materials for the PEMEL and HTEL technologies, the supply chain for the electrolysis technologies is currently estimated to be non-critical for the following reasons:

- Various electrolysis technologies are ready for the market (AEL, PEMEL) or in development (HTEL, AEM) that can contribute to the successful ramp-up of hydrogen production.
- The technological ramp-up is only just beginning, and the transition to highly automated, serial production processes will only be realized as capacities increase.
- It is difficult to forecast the criticalities that will arise in the future ramp-up, but Europe's starting position can be considered solid in terms of its current share of know-how in the form of production capacity and companies.

However, the central task for the ramp-up of green hydrogen production is the sufficiently rapid build-up of production capacities for electrolyzers and their actual commissioning. In addition, the emergence of structural dependencies similar to PV technology should be avoided with foresight.

5.6. Heat pumps



- Due to the high proportion of manufacturing in Europe, the strategic dependency for heat pumps is primarily at the level of imported components, primarily compressors and the high-performance magnets used in most electric motors
- Compared to the other key technologies considered, the manufacturer market for heat pumps is significantly more diverse, small-scale, and thus more resilient.

Supply Chain: High complexity due to many components

Heat pumps consist of several hundred individual parts. In terms of volume, the most relevant materials are steel (including compressors and housings), copper (piping, heat exchangers, cables), aluminum (castings, partly for heat exchangers), nickel and plastics. Additionally, electronic modules are required for the control systems. The heart and drive of the heat pump is the compressor, which is usually driven by an electric motor (see FIG. 45).

Raw material extraction

Nowadays, some heat pumps use permanent magnets (neodymium-iron-boron magnets) in the electric motors of the compressors, which consist of the very critical heavy rare earths (dysprosium and terbium) and the medium critical light rare earths (neodymium and praseodymium). In both raw material extraction and processing, supply chains are dominated by China (cf. CH. 5.4).

Components

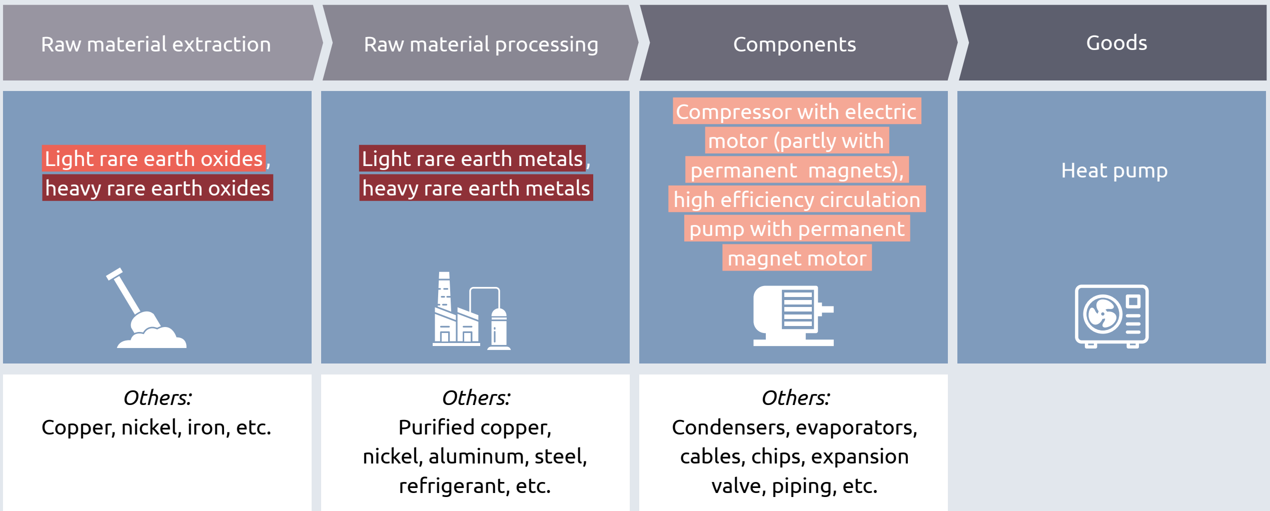
According to the current EU status report on heat pumps (Lyons, L. et al., 2022), most compressors of air-to-water heat pumps commonly used in Germany are manufactured in Europe, e.g., by Danfoss (Denmark, France), Bitzer and GEA (Germany), and Tecumseh (France). In interviews with manufacturers, however, a high level of dependence on imports from China and other Asian countries was repeatedly mentioned, even in the case of compressors.

The current development pressure towards compressors that use more climate-friendly refrigerants (such as propane) creates a window of opportunity for European manufacturers, who are often technologically well positioned, to regain market share in compressor manufacturing.

The heaviest components of heat pumps in terms of mass are the heat exchangers. These are not considered critical due to the flexibility to use different materials such as steel, aluminum or copper and because European manufacturing companies are strongly positioned. Here, it is important to be able to map the scaling up of production volumes with the market in Europe, which is still growing in total.

There is a high dependence on imports for electronic components, which, as with almost all other technologies, are mainly procured from Asia (Taiwan, South Korea, Japan, China).

FIG. 45 **Supply chain for the manufacture of heat pumps**
The criticality only arises with increased use of permanent magnets in the compressors and circulators. Technical alternatives are available.



Raw material extraction	Raw material processing	Components	Goods
Light rare earth oxides, heavy rare earth oxides	Light rare earth metals, heavy rare earth metals	Compressor with electric motor (partly with permanent magnets), high efficiency circulation pump with permanent magnet motor	Heat pump
Others: Copper, nickel, iron, etc.	*Others:* Purified copper, nickel, aluminum, steel, refrigerant, etc.	*Others:* Condensers, evaporators, cables, chips, expansion valve, piping, etc.	

KEY Criticality: Very critical Medium critical Moderately critical SOURCE Own representation

Prognos, 2023

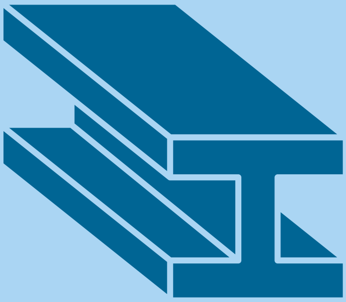
Goods

According to the EU status report, there are many factories in Europe where heat pumps are manufactured or assembled: 170 factories in total, 24 of which are in Germany.

Compared to the other key technologies considered, the manufacturer market for heat pumps is significantly more diverse, small-scale and thus also more robust. Thus, there are several dozen manufacturers. Currently, both German and foreign manufacturers are greatly expanding their capacities in Europe through plant expansions and the construction of new production halls, especially in Poland, the Czech Republic and Slovakia.

Due to the high proportion of manufacturing in Europe, the strategic dependency for heat pumps is primarily at the level of imported components, primarily compressors and the high-performance magnets used in most electric motors (see Chapter Permanent magnets for electromobility). Compared to electric mobility, the quantities required are more than one order of magnitude lower, due to the smaller number of heat pumps compared to electric vehicles and the smaller power of the motors.

5.7. Steel



- Shaft furnaces are required for the production of climate-neutral steel in the DRI route. Other technologies (such as fluidized bed processes) are not yet available on an industrial scale. There is a risk in the construction of shaft furnaces, as there are only two technology providers, with a strong increase in demand worldwide.

- For climate-neutral steel, iron ores with an iron content of 67 percent and more are preferred. Only about 3 percent of the ore traded worldwide today has such a grade. However, technical processes for ore enrichment are already in use today and could be further expanded, especially in the case of magnetite due to the simpler (magnetic) processes.

From iron ore pellets to steel products

The starting point for the production of primary steel is iron ore pellets. These are reduced with the aid of hydrogen — i.e. oxygen is removed and processed into sponge iron (direct reduced iron, DRI) in shaft furnaces by means of direct reduction (DR) plants. If the sponge iron is briquetted, HBI (hot briquetted iron) is produced, which can be transported because it does not oxidize on contact with air or water. HBI can be processed into steel in the same way as DRI in an electric arc furnace or melted in a melter and enriched with carbon to be processed into steel in a converter.

Supply Chain: Medium risk for DRI shaft furnaces and moderate risk for higher grade iron ores

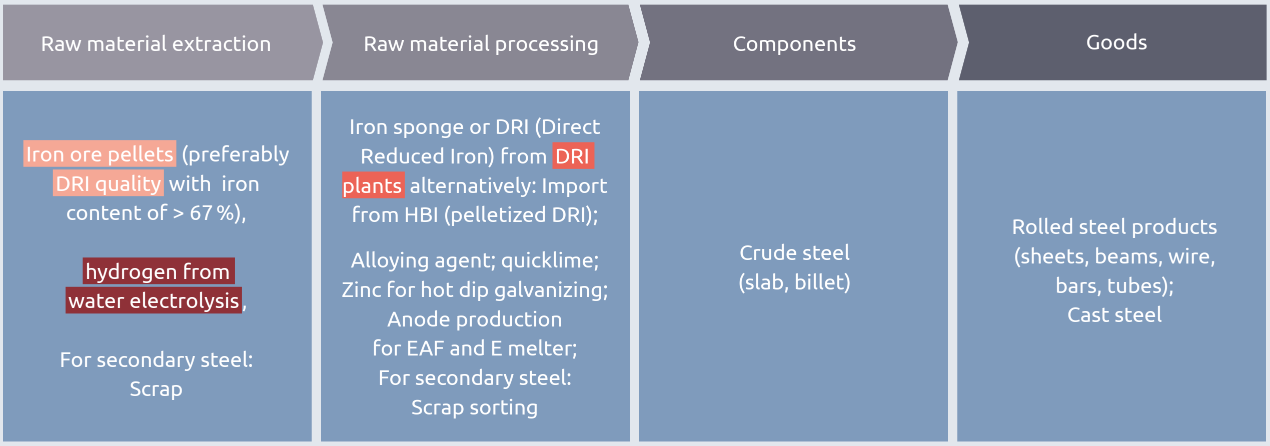
For the production of climate-neutral steel, there is a medium risk for the construction of the DRI shaft furnaces, as there are only a few suppliers in this area and at the same time there will be a high demand. In addition, another possible bottleneck could be the supply of ores that have a sufficiently high iron content (moderate risk). However, there are already technical solutions for this.

Raw material extraction: Higher grade iron ores

The starting point for steel production is iron ore. Iron ores are found all over the world. The main producing countries are Australia, Brazil, South Africa and Canada. Depending on their occurrence, the ores differ in particular in their iron content and the composition of the gangue. For use in the production of DRI with EAF as the target, the iron content of the pellet used in the shaft furnace should be at least 67 percent ("DR-grade"); otherwise, high slag quantities must be accepted in the EAF, which is associated with efficiency losses. However, due to the existing demand structure with a focus on blast furnaces, most suppliers today mainly offer lower ore grades. Only very few ore producers offer grades with an iron content of more than 67 percent. These higher-grade ores are mainly offered from Sweden, Brazil, Russia and Canada, where there are relatively large deposits of magnetite. Magnetite is often more impure than hematite, but is easier to purify by magnetic methods. For a ramp-up of DRI capacity — in conjunction with the electric arc furnace (EAF) — new mines would therefore have to be developed for higher-grade ores on the one hand, and additional capacity would be needed for beneficiation of the ores on the other. Another solution is the use of electric melters, as already outlined, which is a possible insurance against supply problems in the DR-grade pellet market. From a resilience point of view, it is also possible to use ore of lower quality, but this involves higher production costs in the further process.

Alongside iron ores, hydrogen is a key starting material for the production of climate-neutral steel. The timely development of a hydrogen infrastructure and the provision of green hydrogen in the coming years is important for the transformation of the steel sector. Possible supply bottlenecks can be cushioned by the use of natural gas on a transitional basis and especially in the initial phase of the transformation, since direct reduction in the DRI plants can be carried out with both natural gas and hydrogen.

FIG. 46 **Supply chain for green steel production**
Medium critical with availability of DRI shaft furnaces and moderate critical with ores with very high iron content.



Raw material extraction	Raw material processing	Components	Goods
Iron ore pellets (preferably DRI quality with iron content of > 67 %), hydrogen from water electrolysis, For secondary steel: Scrap	Iron sponge or DRI (Direct Reduced Iron) from DRI plants alternatively: Import from HBI (pelletized DRI); Alloying agent; quicklime; Zinc for hot dip galvanizing; Anode production for EAF and E melter; For secondary steel: Scrap sorting	Crude steel (slab, billet)	Rolled steel products (sheets, beams, wire, bars, tubes); Cast steel

KEY Criticality: ▬ Very critical ▬ Medium critical ▬ Moderately critical SOURCE Own representation

Prognos, Öko-Institut, Wuppertal Institut, 2023

Raw material processing: The bottleneck is the construction of DRI plants

For raw material supply, the following section focuses on the reduction of iron ore to DRI.

Iron ore and hydrogen react in the so-called DRI shaft furnace. DR plants have been used since the 1970s, but with natural gas as the reducing agent. More precisely, at least in the most common midrex process, the methane itself is not used as a reducing agent; it first reacts in a reformer to form carbon monoxide and hydrogen, which are then used as reducing agents in the shaft furnace. In the second most common Hy/L process, on the other hand, the methane is used in the shaft furnace itself, reacting in part directly with the ores to form iron carbide and indirectly via carbon monoxide and hydrogen. The processes experienced a certain boom in the USA and in the Middle East, where natural gas is available at very low cost. In the USA in particular, DRI has helped to make steel markets more flexible, as it has enabled the electric arc furnace to become much more widespread and manufacturers to achieve much higher quotas for scrap use than European producers.

What is new, however, is that hydrogen is to be used here instead of natural gas. However, there are currently only a few projects that plan to run DRI (almost) exclusively on hydrogen from the start, all of them located in Sweden: LKAB is planning a DR plant at its mine site in Gällivare, start-up H2GreenSteel is currently building a completely new site in Boden, and established steelmaker SSAB is planning to replace its blast furnace in Lulea with a DR plant. Other projects, such as those of German manufacturers, are planning at least a temporary partial use of natural gas. Here, too, more than 60 percent of GHG emissions can already be saved compared to the blast furnace route; these bridge concepts thus address the foreseeable shortage in the development of electrolysis hydrogen capacities.

A greater threat to rapid transformation is the scarcity of engineering capacity and the scarcity of competition to date, with only two technology providers offering DR technology. Agora Industrie and Wuppertal Institut (2023) estimate current annual capacities at a plant volume of six to eight million tons per year. The Italian-Mexican manufacturer Tenova, which built the pilot plant in Sweden, and the U.S. company Midrex, which is the leading technology provider for direct reduction plants worldwide, are the only technology providers. While Tenova has so far built the plants itself, the Midrex plants will be built by licensees, although Midrex will remain involved in the planning of the plants. Midrex is owned by Kobe Steel of Japan, a licensee for the construction of such plants. Another important licensee is the German company SMS. While Tenova plants can run on 100 percent hydrogen, the same is not true for existing Midrex plants. However, the manufacturer promises that the newly built plants can be converted to 100 percent hydrogen.

Together with the concentration on a few technology providers, the rapidly growing demand could contribute to a critical supply situation in plant engineering and jeopardize the timely completion of projects.

The race to build new DRI plants is necessary from a climate policy perspective, and it has long since spread to other countries. The H2GreenSteel Group is planning a plant on the Iberian Peninsula and is looking into projects in Brazil. Brazilian iron ore miner Vale is planning a joint venture with companies in the Middle East to act as future DRI hubs. And Australia, which is privileged in terms of iron ore deposits and renewable energies, has also recognized the potential that can be achieved domestically by refining its raw materials. The main focus here is on serving East Asian markets (Japan and Korea). Not all of the projects cited as examples are intended to be hydrogen projects from the outset, but the enormous DRI project volume focuses attention on a potential bottleneck at technology suppliers Midrex and Tenova.

Especially in the coming years, green steel is likely to be a commodity in high demand and German steelmakers do not want to lose their anchor customers, particularly from the automotive industry, which has set ambitious targets for its upstream emissions. However, as an alternative to domestic production of green DRI, companies in Germany could consider importing pre-processed sponge iron or HBI. Especially because the costs for production in Australia, for example, are likely to be significantly lower than in Germany. There are indications that these options are under active consideration. However, companies are currently publicly sticking to the first wave of investment, which will replace the blast furnaces in Germany that will be decommissioned by 2030. With their own plants, they avoid the risk of non-supply of HBI by competitors or potential price extortion by monopolists. However, HBI imports can be used to supplement the company's own production. It must also be pointed out that HBI imports lead to an overall higher energy demand than the further processing of hot DRI material on site ("hot-link")

Raw products: Raw steel in the form of slabs or billets

With the new processes (DR plants), the advantages of vertical integration at integrated sites are diminishing. It would therefore also be conceivable for rolling mills in Germany to import steel slabs or billets, i.e. that the steelmaking production stage also migrates.

While DRI and HBI are a very homogeneous commodity and therefore well suited for future trading or even storage in a world market, crude steel is not a homogeneous commodity. Steel is produced to customer specifications in terms of dimensions and alloys and is therefore not generally produced in stock, as this would entail very high revenue risks for producers in the volatile steel market. And steel is still predominantly traded only regionally, because short delivery routes and times are what make an efficient supply chain with on-demand production possible in the automotive industry, for example. From the point of view of a resilient supply chain for steel products, the continued existence of steel locations in Germany is therefore clearly preferable, as the energy cost disadvantages are kept within clear limits for this less energy-intensive stage (EAF, E-melter).

5.8. Summary

- Very critical in the extraction of raw materials: Lithium (lithium-ion batteries for electromobility), heavy rare earths (for permanent magnets in electric motors for electromobility and generators for offshore wind power) and iridium (PEM electrolyzers).

- Medium critical in the extraction of raw materials: Nickel, cobalt and graphite (lithium-ion batteries for electromobility), light rare earths (for permanent magnets).

- Very critical in terms of raw material processing: Light and heavy rare earths (permanent magnets) and cobalt, manganese and graphite (lithium-ion batteries. This puts the development of electromobility in transport and the expansion of wind energy (especially offshore) at risk.

- Very critical in the manufacture of components: Ingots, wafers, cells for photovoltaics, permanent magnets as well as anode material for lithium-ion batteries

- Very high criticality for PV module production and medium criticality for battery cell production.

- Medium risk of rapid ramp-up of DRI shaft furnaces for steel production in Germany.

The challenges and critical dependencies vary widely across technologies, both in terms of the cause of criticality (cf. Ch. 3. country concentration, demand overhang) and also severity. In addition, the factors specifically relevant for the decarbonization of the German energy system are when the concrete technologies ramp up and what concrete technology characteristics prevail. Technologies with a particularly strong short or medium-term ramp-up to 2030/35 are in particular focus — as the scope for action to increase resilience is significantly more limited here than for risks that do not become apparent until 2040.

Copper, titanium, gallium, germanium, yttrium and platinum: According to the research in this study, these commodities are strategically relevant, but not critical, to the 2045 transformation to carbon neutrality.

Overview: Criticality for key technologies

- **Photovoltaics:** For wafer-based photovoltaics, the actual raw material extraction is not vulnerable, but significant challenges to the resilience of the value chain through the further processing stages become apparent. Especially the production of ingots, wafers, solar glass and PV cells as well as modules is very critical because it is significantly dominated by China and the EU has very little own capacity here.
- **Wind power:** For wind power (especially offshore), as for electromobility, the key challenge is the resilience of the supply chain for rare earth permanent magnets. This is very critical because China dominates nearly all stages of the supply chain.
- **Electromobility:** For electromobility, large areas of the lithium-ion cell value chain are also to be classified as very critical in the sense of this study.
- **Electrolyzers:** For electrolyzers, the main challenge is in the area of PEM electrolyzers. Here, the future supply of sufficient amounts of iridium is very critical.
- **Heat pumps:** The main challenge with heat pumps, as with electric cars and offshore wind turbines, is the use of permanent magnets made of rare earths, some of which are installed in the electric motors of the compressors and the circulation pumps.
- **Steel:** In the case of steel, there is a medium risk for the rapid ramp-up of DRI shaft furnaces in Germany, as there are only a few suppliers here. A moderate risk exists in the availability of iron ores with very high iron content.

In the following section, the raw materials, components and goods examined in this study are categorized according to their degree of criticality. For the raw materials, a distinction is made between raw material extraction and raw material processing.

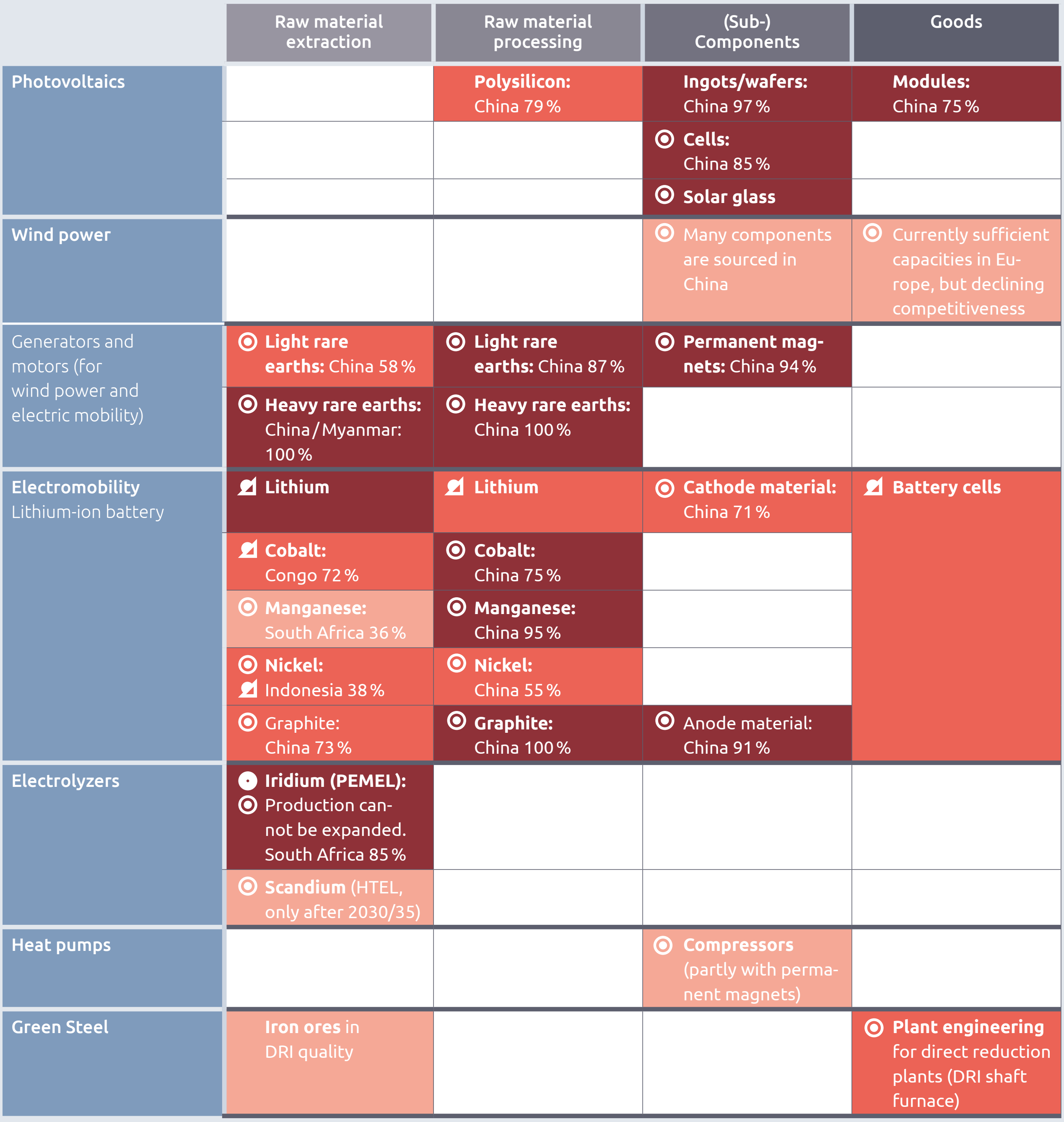
Criticality in raw material extraction

Very critical: lithium, heavy rare earths and iridium

Very critical at the level of raw material extraction (mining) are, among all the technologies studied in depth, the raw materials lithium (lithium-ion batteries), heavy rare earths (permanent magnets for offshore and electromobility) and iridium (PEM electrolyzers).

- **Lithium:** In the case of lithium, the main challenge is the rapid ramp-up of global demand (excess demand). The expansion of existing mines and the opening of new mines – or extraction from salt lakes – requires relatively long lead times. Therefore, for lithium, the time dimension is crucial for classification.
- **Heavy rare earths:** Heavy rare earths, such as dysprosium and terbium, are currently mined exclusively in China and in smaller quantities in Myanmar. This very narrow country concentration is the main reason for this categorization, compounded by the fact that in many (but not all) natural deposits around the world, heavy rare earths occur only in very low concentrations.

FIG. 47 **Supply risks for strategic key technologies along the supply chain by criticality**
Risks vary by severity and cause of potential supply shortages.



	Raw material extraction	Raw material processing	(Sub-) Components	Goods
Photovoltaics		**Polysilicon:** China 79 %	**Ingots/wafers:** China 97 %	**Modules:** China 75 %
			◎ **Cells:** China 85 %	
			◎ **Solar glass**	
Wind power			◎ Many components are sourced in China	◎ Currently sufficient capacities in Europe, but declining competitiveness
Generators and motors (for wind power and electric mobility)	◎ **Light rare earths:** China 58 %	◎ **Light rare earths:** China 87 %	◎ **Permanent magnets:** China 94 %	
	◎ **Heavy rare earths:** China / Myanmar: 100 %	◎ **Heavy rare earths:** China 100 %		
Electromobility Lithium-ion battery	↗ **Lithium**	↗ **Lithium**	◎ **Cathode material:** China 71 %	↗ **Battery cells**
	↗ **Cobalt:** Congo 72 %	◎ **Cobalt:** China 75 %		
	◎ **Manganese:** South Africa 36 %	◎ **Manganese:** China 95 %		
	◎ **Nickel:** ↗ Indonesia 38 %	◎ **Nickel:** China 55 %		
	◎ Graphite: China 73 %	◎ **Graphite:** China 100 %	◎ Anode material: China 91 %	
Electrolyzers	● **Iridium (PEMEL):** ◎ Production cannot be expanded. South Africa 85 %			
	◎ **Scandium** (HTEL, only after 2030/35)			
Heat pumps			◎ **Compressors** (partly with permanent magnets)	
Green Steel	**Iron ores** in DRI quality			◎ **Plant engineering** for direct reduction plants (DRI shaft furnace)

KEY ◎ Concentration and market power ↗ Short/medium-term excess demand ● Permanent shortage
Criticality: ▬ Very critical ▬ Medium critical ▬ Moderately critical

SOURCE Own representation
NOTE Copper, titanium, gallium, germanium, yttrium and platinum: According to the investigations that this study is based on, these raw materials are strategically relevant for the transformation to climate neutrality by 2045, but are not critical.

Prognos, Öko-Institut, Wuppertal Institut, 2023

- **Iridium:** Mining production of iridium cannot be expanded because it is extracted exclusively as a minor metal, primarily in platinum mining (very high country concentration on South Africa). Because a future increase in platinum extraction is not realistic, no increase in iridium supply is to be expected. Other natural occurrences of iridium can also be ruled out as a source of increased supply.

Medium critical: nickel, cobalt, graphite and light rare earths

According to the investigations carried out in this study, nickel, cobalt, graphite and light rare earths are categorized as medium critical with regard to raw material extraction (mining extraction). Significant growth in demand can be expected for all of these raw materials in the coming years. However, in contrast to the raw materials assessed as very critical in the section above, there are various reasons (see below) that justify this categorization here as medium critical – despite the great importance of these raw materials:

- **Nickel:** Global mining extraction is relatively widely distributed, although Indonesia is currently in the process of expanding its leading position. The increase in nickel demand can be at least partially mitigated by the increasing market share of nickel-free lithium-ion batteries (LFP batteries).
- **Cobalt:** The DR Congo is responsible for a very large share of global cobalt mining. However, Indonesia, which will soon become the second largest mining producer, is meeting market demand by expanding extraction (as a minor metal in nickel extraction). In addition, the growth in demand for cobalt is expected to slow down in the medium term due to the increasing use of cobalt-free and low-cobalt lithium-ion batteries.
- **Graphite:** China plays a very dominant role in mining production of natural graphite. However, the use of synthetic graphite opens up an alternative field here. In addition, the natural graphite reserves are distributed across various countries, making increases in supply possible from these sources.
- **Light rare earths:** Although China is still the country with the largest mining extraction of light rare earths, there has been a clear downward trend in recent years. Light rare earths occur naturally in many countries (Australia, United States, Canada, etc.) and are increasingly being mined in those countries to meet the strong growth in demand.

Moderately critical: manganese, scandium, iron ores in DRI quality

Moderately critical at the raw material extraction level (mining extraction), for the purposes of this study, are the raw materials manganese and scandium, as well as iron ores in DRI. There are various reasons for this, which are explained in the respective sections.

Investigations have found the raw materials copper, titanium, gallium, germanium, yttrium and platinum to be not critical, although strategically relevant for the transformation to climate neutrality by 2045. The details of this can be found in the corresponding chapters in this study.

Criticality in raw material processing

Very critical: Processing of light and heavy rare earths, cobalt, manganese, graphite

For raw material processing, the categorizations scheme into very critical, medium critical and moderately critical differs from that for raw material extraction. The processing of light and heavy rare earths as well as cobalt, manganese and graphite is categorized as very critical. The reasons for the categorization are the same in all cases, namely the very strong to total dominance of China against the background of steep growth in global demand.

Medium critical: processing of polysilicon, lithium and nickel

For polysilicon, lithium and nickel, [41] raw material processing is classified as medium critical. Although China has a leading position here too, other countries also have relevant market shares.

Criticality in the manufacturing of (sub-) components

Very critical: Ingots, wafers, cells for photovoltaics, permanent magnets for offshore wind power and electric motors, as well as anode material for lithium-ion batteries in electromobility

In terms of (sub-) component production, the production of ingots, wafers and cells for wafer-based photovoltaics, the production of permanent magnets for wind power and electromobility, as well as the production of anode material (for lithium-ion cells) for electromobility must be categorized as very critical. In all cases, the reason is China's extremely high to overwhelming market power.

Medium critical: Cathode material for lithium-ion batteries

Furthermore, for the level of (partial) component production, the production of cathode material (for lithium-ion cells) is classified as medium critical. Although China is the market leader here too, South Korea, Japan and, to a certain degree also the U.S. and the EU play relevant roles as well.

At the processing level, lithium refers specifically to lithium carbonate and lithium hydroxide hydrate, and nickel refers to nickel sulfate.

TABLE 02 **Demand for critical raw materials by 2045 for Germany according to KNDE2045 scenario**

For almost all strategic goods, the peak demand for critical raw materials is between 2030 and 2035.

Goods	Raw material	Unit	2020	2025	2030	2035	2040	2045
Lithium-ion batteries in vehicles	**Lithium**	kt/a	2	12	21	21	19	17
	Nickel	(kt)	7	55	91	88	74	65
	Cobalt	kt/a	2	14	21	18	13	10
	Graphite	kt/a	13	104	187	198	179	168
Permanent magnets								
Vehicles	**Heavy rare earths**(dysprosium, terbium) in	t/a	34	180	267	245	194	162
Wind power		t/a	10	86	223	187	17	12
Vehicles	**Light rare earths** (neodymium, praseodymium**)**	t/a	134	730	1153	1127	954	850
Wind power		t/a	84	725	1923	1602	138	92
Electrolyzers in EN (with material reduction)	**Iridium**	t/a	0	0.4	0.4	0.3	0.3	0.2

SOURCE Own representation and calculations

Prognos, Öko-Institut, Wuppertal Institut, 2023

Criticality of goods

At the product level PV modules are categorized as very critical. While China's market share of global production is somewhat lower here than in the upstream stages, and there is currently more production capacity in Europe than is the case for cells, due to the fact that modules manufactured in Europe are largely dependent on imported Chinese PV cells, this study also categorizes module production as very critical. The production of battery cells is also categorized as medium critical due to the strong growth in global demand and China's strong position. Furthermore, the plant construction of direct reduction plants is classified as medium critical due to the concentration of suppliers.

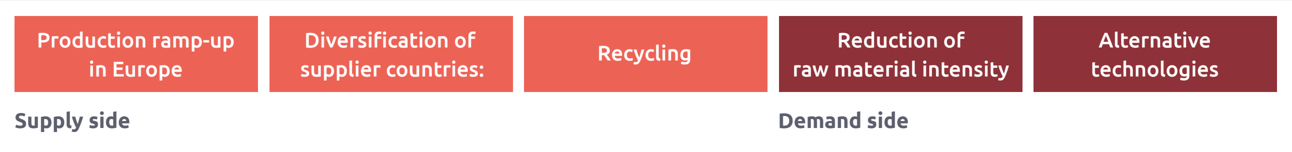
Demand for critical raw materials up to 2045

Table 2 shows the annual demand from today to 2045 in 5-year intervals for the very critical raw materials lithium, heavy rare earths and iridium as well as the medium critical raw materials nickel, cobalt, graphite and light rare earths classified in the study. For almost all very critical and medium-critical commodities, the next five to ten years in particular are decisive, as not only a very steep ramp-up in demand is observed here, but most commodities also reach their demand peak.

6. Measures to increase resilience

FIG. 48 **Measures to increase resilience**

The study examined five supply-side and demand-side measures for key technologies.



SOURCE Own compilation Öko-Institut

Öko-Institut, 2023

After the analysis in Chapter 5 of the strategic key technologies and at which stages of the supply chains the greatest supply risks are to be found, Chapter 6 now presents possible measures to increase supply security and strengthen resilience.

These include, in particular, the following demand-driven and supply-side measures:

1. **Production buildup in Europe**: This measure basically applies to all stages of the value chain. Due to the limited geological availability of most critical raw materials, the strengthening of European mining is only possible for isolated raw materials. This measure therefore applies primarily to downstream stages of the value chain.

2. **Diversification of supplier countries:** This measure is particularly effective in the case of supply risks on the raw materials side. The proposals for prioritizing countries are made on the basis that the analysis reveals realistic opportunities for raw material and technology partnerships with Germany or the EU. Essential criteria for this are:
   - **Reserves:** relevant reserves exist and, at best, projects for mining have already started on site or are at least at an advanced stage (time component),
   - **Experience:** Countries with mining and processing experience, such as Canada, Australia, Brazil, Chile, are particularly advantageous, as projects can be implemented more quickly there in case of doubt: local authorities have more experience, more potential skilled labor is available, etc.
   - **Infrastructure:** Sufficient transport infrastructure is in place or under construction: Ocean ports with corresponding capacities are particularly relevant for this. This makes storage facilities near the coast and with good connections to existing road and/or rail infrastructure particularly attractive.
   - **Relationships:** The countries under consideration already have good political relations with Germany and the EU or are at least open to strengthened economic ties,
   - **Not a war or crisis zone:** These are not countries that include designated war or crisis zones.

3. **Recycling of critical raw materials:** these measures — with a few exceptions, such as the recycling of battery production scrap — only have an effect in the longer term in particular, as many technologies remain on the market for several decades after the initial ramp-up in some cases before they are available for recycling.

4. **Reduction of raw material intensity:** This is achieved mostly through research and development or through automation and setting up industrial production. This measure reduces domestic demand, usually only takes effect in the medium to long term.

5. **Alternative technologies:** Shifting to technologies with lower demand for critical raw materials — e.g. use of nickel, manganese, and cobalt-free LFP batteries.

6.1. Photovoltaics

- Dominance of Chinese companies along the entire supply chain of wafer-based PV equipment (especially in the production of ingots and wafers) as one of the biggest risks to the decarbonization of the power sector.

- Production expansion in Europe as the most important measure. Target under *Net-Zero Industry Act:* 40 percent domestic production is possible, the biggest obstacle being cheaper production costs in the USA and China (up to -30 percent) — mainly due to subsidies (IRA in the USA).

- Diversification potentials are difficult to forecast as capacities are just being built up (USA, India).

- Recycling: Larger potentials only from 2035/2040 due to the longevity of the modules. Recycling processes for the recovery of polysilicon and solar glass is currently still being developed and tested.

- Alternative technologies: Lower efficiencies for thin-film modules argue against high market shares. Perovskite or organic cells are still under development.

- Reducing material intensity works on the raw material side, but does not solve the problem of market power in the downstream supply chain.

TABLE 03 **Current production capacities for wind power in Europe and targets for 2030**
There are hardly any production capacities for ingots, wafers, cells and solar glass today.

Raw material / component	Status 2022	EU target 2025	EU target 2030 according to Net-Zero Industry Act*
Polysilicon	~ 21 GW	30 GW	40%
Ingots and wafers	< 2 GW	30 GW	40%
Cells	< 2 GW	30 GW	40%
Modules	< 10 GW	30 GW	40%
Solar glass	3 to 4 GW	30 GW	40%

* According to targets set by the Net-Zero Industry Act, 40 percent of Europe's buildout demand should be manufactured in Europe in 2030. In total, installed capacity is expected to reach 600 GW by 2030.

SOURCE Own representation according to (COM, 2022a; COM, 2023c; SolarPower Europe, 2023; Photovoltaik 2022)

Prognos, 2023

Production ramp-up in Europe

In Europe, the European Solar PV Industry Alliance has set a target of building 30 GW of European production capacity along the entire PV supply chain by 2025 (COM, 2022a). For the year 2030, the EU Commission plans that at least 40 percent of the annually installed PV modules come from European production (COM, 2023c). Furthermore, according to the EU Solar Energy Strategy, which is a part of the REPowerEU plan, 320 GW of PV modules should be installed in 2025 and 600 GW in 2030 (COM, 2022a).

The discussion on (re)building a European PV industry has gained intensity, not least because of the Ukraine war. However, such a development and expansion is associated with enormous challenges and would only be conceivable with correspondingly extensive and ongoing support from the European Union and its member states. The revival of an integrated European PV industry would have to face ongoing competition from Chinese manufacturers. Furthermore, a European investment program would compete with programs in the USA and India.

Establishing and expanding European production capacities would be a major challenge, especially for energy-intensive processes (production of polysilicon, ingots & wafers and solar glass), as energy prices for energy-intensive industries in Europe are significantly higher than the international average. The relevant manufacturers complain that under the Net-Zero Industry Act and the Temporary Crisis and Transition Framework (TCTF) possible extensive investment grants or subsidies are currently being discussed, but it is so far unclear whether operating subsidies will also be provided. These would be necessary especially for the electricity-intensive process steps as long as the industrial electricity price is significantly above the level of other regions, especially China (Fuhs, M., 2023b). In the long term, a European PV industry must be able to be competitive in the long term even without subsidies. Support from the EU and the member states should therefore only serve as bridging assistance.

Table 3 shows the current European production capacities for the value-added stages polysilicon, ingots and wafers, cells and modules, and for the component solar glass.

Achieving the 30 GW target by 2025 at all levels would require timely, joint, and landmark decisions at the highest political levels of the EU and its member states. All stages of the value chain would have to be scaled up to the target value at the same time. An expansion on only single levels would not be purposeful. For example, building up 30 GW of production capacity for ingots & wafers would only make sense with simultaneous expansion at the upstream and downstream stages of the value chain. There are currently announcements by individual European companies to expand their production capacities. For example, the Italian energy company Enel plans to expand the production capacity of 3Sun's Sicilian module factory from 200 MW to 3 GW by the summer of 2024 (Romano, V., 2023). The Swiss company Meyer Burger aims to increase cell production in Germany to 3 GW by 2024 (Diermann, R., 2023). Major challenges in implementing projects to expand manufacturing capacity lie in existing cost structures and the subsidies available abroad.

Diversification of supplier countries:

Another way to reduce the heavy dependence on China is to diversify the procurement of the required (sub) components. However, this poses major challenges in the short to medium term. Market concentration along the entire supply chain is so high in some cases that there are practically no alternatives in procurement. Even if India and the USA were to succeed in achieving their production expansion targets in the next few years, and were thus able to successfully set up their own fully integrated production chains, it would remain questionable whether the volumes produced there would be sufficient to supply the global market or would be needed entirely for their own PV expansion.

However, should countries succeed in producing high-quality PV modules in sufficient quantities and at costs similar to those in China for the world market, it would be advisable to promote procurement from these regions in the interests of diversification. In order to realize such country diversification, the required production capacities would first have to be built up and then compete with manufacturing in established companies. Building such capacity depends heavily on the design and implementation of government support programs.

Recycling

Only a few gigawatts of PV capacity will be retired by 2030. The low deconstruction can be explained by the fact that the service life of even older PV modules is around 25 to 30 years. Thus, the deconstruction quantities, at least in the case of rooftop systems for private households, largely result from modules that were installed 25 to 30 years ago. Consequently, larger amounts of deconstruction will not be available until the 2040s.

In the case of industrial plants, the current adjustments in the EEG 2023 with regard to repowering could lead to plants being replaced not only before the end of their technical service life, but also before the expiry of the EEG subsidy and thus being recycled earlier (Herz, S., 2023).

The recycling of end-of-life modules is currently still concentrated on the recyclable materials aluminum, glass and copper. In addition, initial development-scale approaches exist in which high-purity silicon could be recovered and subsequently processed into solar cells. However, these cells have so far exhibited significantly lower efficiencies than current cell generations (Fraunhofer ISE, 2022b). Therefore, to produce competitive recycled solar cells, further research and development work is needed to increase efficiency.

Also, the solar glass from old modules cannot be used for the production of new photovoltaic modules at present (Rueter, G., 2021). In recycling, it represents the largest share of components by mass, at around 70 percent (BDEW, 2022). So far, only low-quality glass wool can be obtained from the recycled solar glass because of impurities in the recyclate due to the combination of the glass with adhesives, coatings and heavy metal pastes (Scherhaufer, Part, & Beigl, 2021). Here, too, further research and development work is necessary.

Reduction of raw material intensity

As shown in the previous sections, the problem with photovoltaics is less a raw material problem than a problem of market concentration along the supply chain. For this reason, a reduction in material intensities would not directly lead to a reduction in market concentration in China. However, it could have a positive effect on the units produced at the respective stages of the value chain, as the available starting products (e.g. ingots for the production of wafers) could be used more efficiently. However, this cannot be assessed across the board at this point in time.

In principle, a reduction in material intensity, especially with regard to the reduction of raw material use, makes sense and can enable cost savings.

Alternative technologies

In addition to the expansion of European PV production, alternative technologies could help to reduce the dependence on Chinese manufacturers. Wafer-based PV technology is clearly dominated by China. In addition to thin-film modules already in use, other alternative PV technologies, such as perovskite cells, tandem solar cells or other novel cell technologies, exist in varying degrees of maturity.

Perovskite cell technology currently appears to be the most promising alternative. It has a very high efficiency because several areas of the light spectrum can be used to generate energy. At the same time, scientific experts assume lower production costs. However, the use of materials with respect to various pollutants (e.g., lead in water-soluble form) and, in particular, the durability of the technology must be improved (at least 20 years lifetime) to provide a competitively attractive alternative (Fischer, A., 2022). It is currently difficult to predict when the technology will reach market maturity. Initial manufacturers plan to start production lines from 2024 with the aim of commercialization from 2026 (Hannen, P., 2023). It remains to be seen whether or how quickly and to what extent perovskite technology will gain market share over conventional silicon-based modules.

Increased use of the thin-film technology already in use could also reduce dependence on China. The lower efficiencies and the use of critical raw materials are major challenges here. According to (Fraunhofer ISE, 2023), there are contradictory statements for the long-term availability of tellurium and indium for CdTe modules. However, the use of thin-film modules in large-scale projects has been increasing in the U.S. recently (NREL, 2022).

6.2. Wind power

- Currently still strong manufacturing industry in Germany and the EU, which can meet growing expansion needs even in the medium term.
- The EU targets from the Net-Zero Industry Act of 85 percent European manufacturing share can probably be achieved.
- The most important measure for maintaining a high share of European production is providing support for the upscaling of production facilities,as well as in the ramp-up of capacities, especially in the power range above 12 MW (for the offshore sector).
- This could be helped in particular by expansion paths coordinated at European level, which would lead to continuity in production orders, and by tendering rules that reward the use of European equipment.
- The most critical dependency is on the purchase of permanent magnets from China.
- A reduction in criticality through alternative technologies hardly seems possible and would be associated with high side effects, possibly even to the point of supporting the massive market entry of Chinese manufacturers.

TABLE 04 **Current production capacity for wind power in Europe and targets for 2030**
Projected production capacity in 2030 could likely meet 100 percent of incremental demand by increasing turbine output.

Raw material / component	Status 2022	Projected capacity 2030	Targets 2030 according to Net-Zero Industry Act: min. 85 %*
Rotor (hub, blades)	18 GW	~ 30 GW	36 GW
Generator	36 GW	~ 65 GW	36 GW
Gearbox	22 GW	~ 40 GW	36 GW
Nacelle	22 GW	~ 40 GW	36 GW

* According to Net-Zero Industry Act goals, at least 85 percent of new equipment should be manufactured in Europe by 2030. This corresponds to a manufacturing capacity of 36 GW.

SOURCE Own representation according to (Telsnig, Georgakaki, & Letout, 2022)

Prognos, 2023

Production ramp-up in Europe

According to the EU Climate Target Plan, around 40 GW of onshore wind power is expected to be added annually in the EU by 2030. Under the goals of the Net-Zero Industry Act, at least 85 percent of newly installed equipment in 2030 is to be manufactured in Europe. This will require a manufacturing capacity of 36 GW. The expected European production capacities for the main components of wind turbines (cf. TAB. 04) could even exceed this target (Telsnig, Georgakaki, & Letout, 2022). The reason for this assumption is the continuous development of production towards larger turbine capacities. Put simply, the trend towards plants with more capacity would also increase production in GW for the same number of plants produced. This also applies accordingly to the other plant components, such as rotors or towers.

However, when considering the production capacities for wind energy components, the size class of the turbines manufactured also plays an increasingly important role in the assessment. The reason for this is that turbine components of a higher MW class cannot easily be manufactured in a production facility for turbines of the 3 MW class.

Especially in the area of offshore turbines with outputs greater than 12 MW, there are therefore the greatest risks of shortages in the European supply chain. Currently, there is only a manufacturing capacity of about two to three GW per year for the production of turbines with a capacity of more than 12 MW in Europe. However, the annual demand for new capacity in this segment in Europe is expected to rise to more than 20 GW per year by 2030. The challenge is to build up production capacities accordingly or to expand existing production facilities accordingly.

In contrast to photovoltaics, there is still a strong domestic manufacturing industry for onshore wind in the EU, which is also able to meet the strong increase in expansion demand in the medium term. The aim of all measures in this area must therefore be to maintain these existing capacities and to enable capacity expansions at existing locations so that the strong future growth in demand for turbines in the largest power class in the offshore sector can also be met.

As already described, wind turbines consist of numerous subcomponents, many of which are also currently sourced from China. The dependency on rare earths and the permanent magnets made from them for generator production is very critical, as is also the case in electromobility. Significant import shares can also currently be observed for iron castings, electrical sheets and glass fiber mats, although these are due to price advantages of foreign manufacturers rather than a lack of production capacity in the EU. The dependency on electronic components, chips and individual control elements from the Asian region is more critical. However, the issue is by no means specific to wind energy and must be considered in the context of potential shifts in global supply chains against the backdrop of the current geopolitical situation.

Chinese wind turbine manufacturers have achieved significant reductions in manufacturing costs in recent years. For onshore turbines and offshore turbines, they are up to 40 percent lower than the manufacturing costs of European manufacturers, driven in particular by lower raw material and labor costs (Totaro, P., 2022). However, due in particular to the high transport costs associated with large plants, this has not yet led to any noticeable market entry by Chinese manufacturers into the German market. Nevertheless, the cost situation in an international comparison must always be kept in mind for all measures.

Reduction in raw material intensity and alternative technologies

Reducing the material intensity of the use of rare earths as the main component of permanent magnets can probably only contribute to a very limited extent to reducing the criticality of the dependence on the supply of these subcomponents from China.

A significant reduction in the use of permanent magnets in wind turbines could be achieved by a technological focus in the expansion on those types of turbines that use gearboxes and/or no permanent magnets. The use of gearboxes alone, and thus a reduction in generator size, can reduce rare earth material intensity by 65 to 90 percent.

In the offshore sector in particular, however, wind turbines with permanent magnets are used almost exclusively, although there is currently a clear trend towards gearless turbines. This is due in particular to the dominance of very large plants (with outputs of currently up to 15 MW). The power increases per turbine significantly reduce the overall cost of a wind farm by decreasing the number of foundation structures required. Interference in the choice of technology would therefore probably lead to severe distortions, especially in the offshore sector. Against the background of the already existing advantages of non-European equipment manufacturers in terms of manufacturing costs, this would even result in the risk that the additional advantages in terms of total costs when using larger and more efficient equipment (based on (gearless) permanent magnet equipment) would additionally severely weaken the market position of European manufacturers.

Diversification and recycling

As in the case of electromobility, measures that lead to a diversification of the supply chains for rare earth metals and permanent magnets or that further reduce the need for imports through recycling are therefore crucial for the reduction of criticality in the expansion of wind energy (cf. CH. 6.4). In the wind energy sector, however, significant decommissioning of offshore plants that offer significant recycling potential for rare earths is not expected until the years 2030 to 2035.

6.3. Lithium ion batteries

- The ramp-up on the demand side is a major challenge on the supply side for raw materials, especially with regard to the lithium supply chain for Germany and Europe.

- In addition, nickel, cobalt, graphite and also manganese are relevant in the processing of raw materials, and in the case of (sub)components, it is essential to accelerate the ramp-up of anode and cathode material production within the EU, among other things.

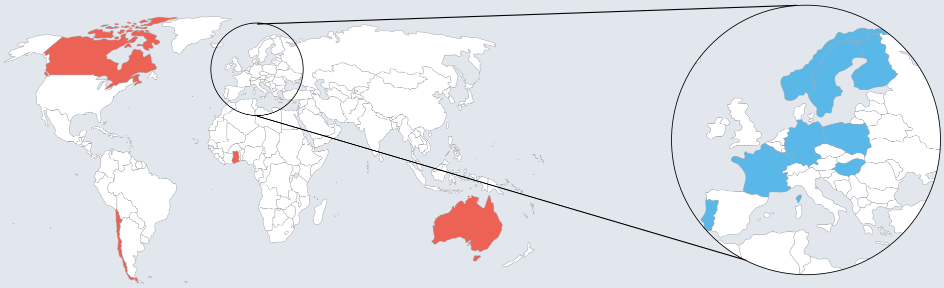
- The extraction and processing of lithium compounds in Germany and Europe is a strategic task: This concerns mining, lithium refineries, cathode material production, gigafactories, etc.

- For battery raw materials, active materials and battery cells — especially lithium iron phosphate (LFP) cells — greater differentiation of supply countries is necessary and also possible.

- The recycling of lithium-ion batteries will become increasingly relevant for supply in five to 15 years (see specifications of the new EU Battery Regulation).

FIG. 49 **Measures to increase the resilience of the lithium-ion battery supply chain**

Short-term priority: increased country diversification and strengthening of value chain within Europe. Recycling becomes very relevant after 2030.



Establish production in Europe *(short/medium term)*

- 🟦 Mining *(medium-term from 2026+)* Lithium: Germany, Finland, France, Portugal Nickel / Cobalt: Finland Graphite: Norway
- 🟦 Refining lithium: Germany, Poland, Finland *(medium term from 2024+)*
- 🟦 Cathode material: Germany, Poland *(from 2023)*
- 🟦 Gigafactories for lithium-ion cells in Germany, France, Poland, Hungary, Sweden *(current, short term from 2023+)*

Country diversification *(short term)*

- 🟥 New commodity partnerships and collaborations with: Australia, Canada, Ghana, etc.
- 🟥 Strengthening existing partnerships with Chile

Recycling *(medium-term from 2030)*

- Until 2030: low potential, thereafter strongly increasing due to end-of-life of vehicles
- All raw materials are highly recyclable: 80 to 90 %
- Expeditious approval procedures necessary

Prognos, 2023

For the lithium-ion battery supply chain, there is an urgent need for action in the short and medium term to identify and deploy effective levers to significantly strengthen resilience. The key levers are:

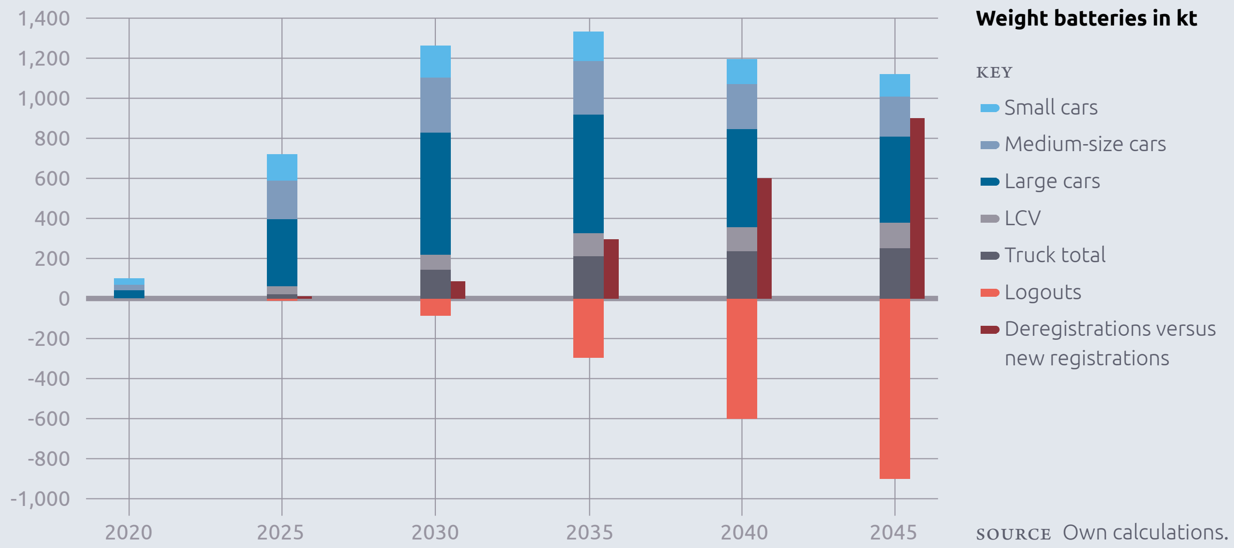
- The robust establishment of intra-German or intra-European production across the entire supply chain,
- Greater diversification in terms of partner countries for supply at key levels of the supply chain (raw materials, key intermediates, strategic goods and components),
- The consistent development and upscaling of the infrastructure for industrial-scale recycling of lithium-ion batteries.

Figure 49 shows some examples of these levers for increasing the resilience of the lithium-ion battery supply chain in concrete terms using a world map. Reducing the material input of critical raw materials through smaller batteries and fewer and smaller vehicles is already part of the very ambitious KNDE2045 scenario on which this study is based, and is only considered here in passing. The development of gigafactories for the production of lithium cells within the EU is currently being strategically pushed by the EU and member states such as France and Germany. There are many large-scale projects in the short and medium term that can help strengthen supply chain resilience for Germany or for the EU. Important examples of projects in Europe, each often involving investments in the range of several hundred million or several billion euros, are:

- **Mining:** mainly mining projects for domestic production of lithium compounds in Germany, Finland, France, Portugal, etc.; plus mining projects related to nickel and cobalt in Finland and graphite in Norway and Sweden,
- **Intermediates:** there are several projects for so-called lithium refineries for the production of battery-grade lithium compounds in Germany, Finland, Poland in planning or even already in the construction phase,
- **Cathode material**: new plants for the production of cathode material are under construction or recently already in production in Finland (also precursors), Germany and Poland,
- **Anode material:** there are recent plans to build larger production capacities in Sweden (Benchmark Source, 2023b),
- **Gigafactories:** large plants for the production of lithium-ion cells are in planning, construction or already in operation in numerous states of the EU (Hungary, Poland, Germany, France, Sweden, etc.).

FIG. 50 **Total weight of lithium-ion batteries for new registrations and deregistrations in Germany according to the KNDE2045 scenario**

The potential return volumes of end-of-life batteries grow massively after 2030



SOURCE Own calculations.

Öko-Institut, 2023

Recycling

Recycling of lithium-ion batteries is already practiced on a small scale[42] in Germany and other EU countries. So far, the processes have mainly been aimed at recovering copper as well as nickel and cobalt compounds. Processes for the recovery of lithium compounds — and possibly also manganese compounds — are close to industrial realization. The sophisticated recovery of graphite is currently still being attempted in a number of research and development projects. To answer the question of the extent to which secondary raw materials (lithium, cobalt, nickel, etc.) from the recycling of lithium-ion batteries can play a relevant role in the future, Figure 50 shows the total demand for lithium-ion batteries in Germany (in tons of total weight of batteries incl. housing, etc.) for new vehicle registrations and the respective theoretical potential from deregistered vehicles in Germany between 2020 and 2045 for the "KND2045" scenario.

According to the KNDE2045 scenario, the total demand for new vehicle registrations in 2030 is around 1.26 million tons of lithium-ion batteries — this quantity compares with around 86,000 tons of lithium-ion batteries from deregistered vehicles in the same year. The enormous dynamics in this system (new registrations vs. deregistrations) can already be seen five years later — i.e. in 2035: here, 1.33 million tons of lithium-ion batteries for new registrations are already compared with around 297,000 tons of lithium-ion batteries from deregistered vehicles. This potential becomes somewhat smaller in the medium-term perspective, considering the increased quantities of raw materials required for the "domestic production" scenario.

Furthermore, for various reasons (secondary uses of batteries, exports of used vehicles abroad, etc.), it cannot be assumed that the potential of lithium-ion batteries will be available for recycling in its entirety. However, recycling capacities for lithium-ion batteries are also increasingly being built in other EU countries and beyond (fortum, 2023). Nevertheless, the shifts in the ratio of tonnage of new registrations versus tonnage of deregistrations over time are significant — especially as the ratio of magnitudes continues to converge after 2035 to 2045.

Figure 51 shows the respective tonnages for the strategic raw materials lithium, manganese, cobalt, graphite, nickel and copper between 2020 and 2045 for new vehicle registrations and vehicle deregistrations in Germany.

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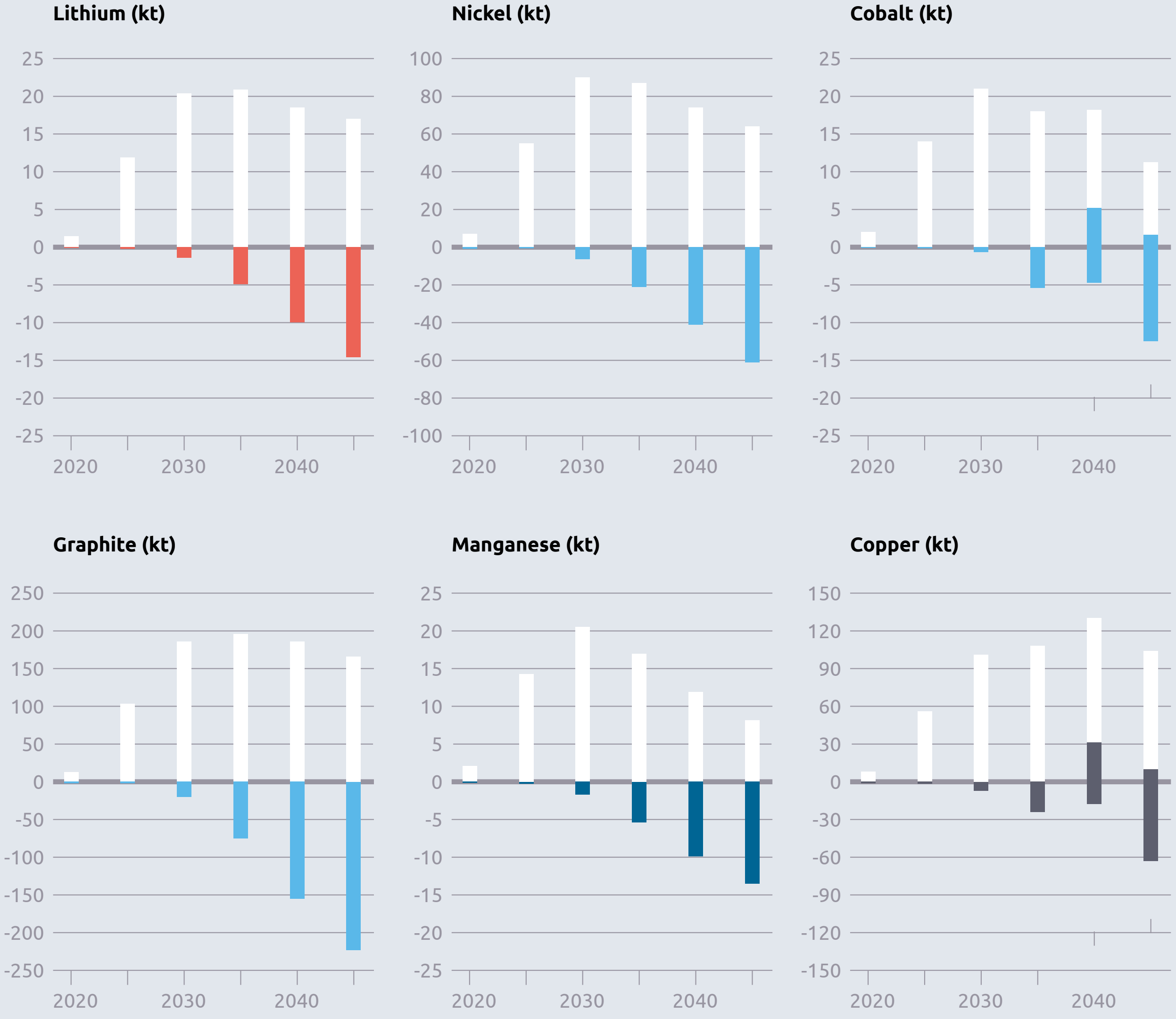
[42] The current plant capacities for recycling lithium-ion batteries in Germany and the EU are mostly in the four-digit annual ton range or in some cases in the lower five-digit annual ton range (based on the input flow of the plants).

FIG. 51 **Annual raw material requirements for lithium-ion batteries for new vehicle registrations and theoretical raw material potentials from vehicle deregistrations in Germany according to the KNDE2045 scenario**

Especially for lithium, cobalt, nickel and copper, recycling potentials show considerable growth from 2030 onwards.



KEY ▭ New registrations ■ Deregistrations (colored bars)

SOURCE Own representation

Öko-Institut, 2023

In detail, the developments of the volume ratios of the individual raw materials differ between new registrations and deregistrations. These differences in detail reflect the changes in lithium-ion battery cell chemistries over the scenario timeline described earlier. For the strategic raw material lithium, new registrations for 2030 show a demand of around 20,500 metric tons of lithium; this compares with a theoretical potential in 2030 from deregistrations of around 1,400 metric tons of lithium. The ratios shift rapidly in the following years: already in 2035, the ratio of new registrations and deregistrations for lithium is about 21,000 tons (new registrations) versus about 4,900 tons of lithium (deregistrations). If, after deducting losses in the recycling chain (during collection, in the treatment and recycling processes themselves), only 50 percent of the theoretical potential for lithium in 2035 could be tapped, more than ten percent of lithium demand would nevertheless already be able to be supplied from secondary sources.[43]

In the case of cobalt, the recycling potential is developing even more steeply than in the case of lithium. Here, new registrations for 2030 show a demand of around 20,900 metric tons of cobalt; this compares with a theoretical potential in 2030 from deregistrations of around 1,700 metric tons of cobalt. The ratios shift rapidly in the following years: as early as 2035, the ratio of new registrations to deregistrations for cobalt is around 18,000 metric tons (new registrations) versus around 5,400 metric tons of cobalt (deregistrations). If, after deducting losses in the recycling chain, only 80 percent of the theoretical potential for cobalt could be tapped in 2035, about 24 percent of cobalt demand would still already be supplied from secondary sources.[44]

In this context, it should be noted that the new EU Battery Regulation, which is scheduled to come into force before the end of 2023, will maintain the following secondary metal input quotas for lithium-ion batteries newly placed on the EU market (Council of the European Union, 2023b):

- Eight years after coming into force: six percent each for lithium and nickel, 16 percent for cobalt,
- 13 years after coming into force: twelve percent for lithium, 15 percent for nickel, 26 percent for cobalt.

As can be seen from Figure 51, secondary metal input rates in the order of around 50 percent (lithium) and around 70 percent (copper) from the lithium-ion battery cycle are quite possible in the long term (2045). In the case of nickel and cobalt, it is even calculated that by 2045 there will be almost full supply from secondary raw materials from the battery cycle. The same applies mathematically for manganese — however, manganese is not specifically addressed in the upcoming new EU Battery Regulation and so far the economic incentive in the recycling industry for the recovery of manganese is still low due to the specific relatively low manganese prices. However, it is quite possible that with the development of a recycling economy for lithium-ion batteries in the EU on a large industrial scale in the medium term, manganese will also be recovered and recycled as "by-catch".

In all cases, the increased demand of the German automotive industry must be taken into account in the "domestic production" scenario. If only German vehicle deregistrations are compared with the total vehicle production as recycling potential, this potential drops sharply. However, here too, the view must be extended to the EU, where vehicles are also produced and recycled, but where automobile production usually plays a lesser role than in Germany.

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[43] Higher recovery rates are also expected for lithium in the medium and long term. The new EU Battery Regulation provides for strict collection targets and, in a second stage, recovery rates for lithium from the reprocessing and recycling processes of > 80 percent.

[44] The new EU Battery Regulation provides for strict collection targets and, in a second stage, recovery rates for cobalt from the reprocessing and recycling processes of at least 95 percent. Exports from the EU, however, are neglected.

Production ramp-up in Europe

The development of gigafactories for the production of lithium cells within the EU is currently being strategically pushed. There are many large-scale projects planned and existing in the short and medium term for different stages of the supply chain: from mining to lithium-ion cells (see Tab. 15 and Tab. 16 in the appendix). The focus is on the time horizon from today to 2030 due to the steep short to medium-term demand ramp-up for lithium-ion batteries. However, they differ greatly among themselves in their concrete details. Partly the mentioned projects are already completely established and producing, partly they are only vague announcements. At the same time, this shows very large potentials for a future supply of raw materials and materials partly extracted or processed in the EU until the year 2030, shown in Table 5.

In this context, reference should be made to published estimates by DERA on the possible self-sufficiency of Europe with regard to lithium in 2030. According to two different scenarios, DERA sees a range of 27 percent to 34 percent as possible for self-sufficiency in terms of lithium demand in Europe. In this context, both domestic mining of lithium and recycling (Schaal, S., 2023a) contribute to this estimate of potential (Al Barazi, S., 2022). If all the projects announced in the above table can be realized by 2030, this share could even be exceeded. However, this is rather unlikely.

The different importance of the raw materials is also illustrated again by the amount of copper already mined in the EU today (>500 kt/a) and in comparison the demand of the battery industry during the absolute ramp-up. In this context, demand is clearly exceeded by the available supply. However, it is important to keep in mind that lithium-ion batteries are only one of very many applications that require copper, and the additional demand for copper in particular could lead to challenges in the future. However, compared to the other raw materials, such as lithium and cobalt, the battery market is less decisive for this.

The stated battery cell production capacities in the EU (up to 2030) as of today (May 2023) are listed in Table 16 in the Appendix. This market is also characterized by strong changes and the quantitative developments are highly dynamic. The large numbers of announced capacity for lithium-ion cell production (totaling over 1.5 TWh) also indicate that the EU could meet its own demand for cells (about 1 TWh)[45] in the future (for the year 2030) from production within the EU. However, this ignores the demand for different battery cell chemistries, which may only be met by other companies outside the EU.

In addition, it must be noted that most projects have been delayed to date and some are still subject to major uncertainties overall. Especially in the case of announcements without a launch year or with a long lead time, the future must show to what extent these projects can be realized. The subsidies from the US side (Inflation Reduction Act) have currently contributed to the uncertainty. Moreover, experience to date has shown that, particularly at the beginning, the announced capacities of the so-called gigafactories will in all probability not be reached and will only be increased gradually. Therefore, everything must now be done to ensure that the announced gigafactories are actually realized in practice in a timely manner and that this ramp-up is supported.

Diversification of supplier countries:

The proposals for prioritizing countries are made on the basis that the analysis reveals realistic opportunities for raw material and technology partnerships with Germany or the EU. The general criteria for this are listed at the beginning of this main chapter.

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[45] Benchmark Minerals January 2023

TABLE 05 **Current lithium-ion battery supply chain capacities in the EU and previously announced capacities and targets until 2030**

For most raw materials and further steps, there are no or hardly any production capacities in the EU today.

	Status 2022	Announced Capacities	EU target 2030
Raw materials	Lithium: 0 kt Cobalt: 0 kt Copper: >500 kt Nickel: approx. 30 kt Graphite 0 kt	Lithium: >50 kt Cobalt: < 1 kt Copper: >500 kt Nickel: approx. 30 kt Graphite 19,5 kt	10% *
Processed materials	Lithium: 0 kt Cobalt: 0 kt Copper: >500 kt Nickel: approx. 30 kt Graphite 0 kt	Lithium: >50 kt Cobalt: < 1 kt Copper: >500 kt Nickel: approx. 30 kt Graphite 19,5 kt	40% *
Components	Anode: 0 kt Cathode: 20 kt	Anode: 77 kt Cathodes: 300 kt	not available
Battery cells	approx. 35 GWh	>1500 GWh	90% **

* Target of the Critical Raw Material Act on strategic raw materials based on the share of total EU capacity in annual consumption

** EU sector target

NOTE see Table 15 and Table 16 for data, targets according to (COM, 2023a) and (Bloss, M., 2022)

SOURCE Own representation

Öko-Institut 2023

Despite the massive increase in investments in the development of the intra-European supply chain for lithium-ion batteries, the rapid ramp-up of electromobility in the EU requires additional diversification[46]. The rapid ramp-up of electromobility in the EU also requires a strengthening of diversification with existing or potential new supply countries outside the EU for important raw materials, intermediates, and strategic goods of the lithium-ion battery supply chain. Examples regarding the important battery raw materials are the strengthening of existing supply relationships with Chile regarding lithium compounds and new supply relationships with companies that are active in classic major mining countries such as Australia, Canada or Brazil (especially regarding lithium, cobalt, nickel). Furthermore, potential partner countries in the global South should also be increasingly considered here. For lithium, for example, the West African country of Ghana could offer itself as a future economic partner.

Reduction in raw material intensity

A better material intensity in terms of critical raw materials for batteries can be achieved through smaller batteries and fewer or smaller vehicles with reduced energy consumption. However, these measures are already partly included in the ambitious KNDE2045 scenario and therefore play only a minor role here in reducing demand even further. Nevertheless, it is essential that they be taken into account in any political regulation if the goals of climate neutrality by 2045 are to be achieved at all. A technology shift to a different battery chemistry that uses no, or at least moderately critical, raw materials can also ease the burden on supply chains. However, these come with their own challenges in terms of recyclability and possibly increased GHG emissions per kWh in production and use. This must be taken into account when developing the political framework. In addition, technologies such as sodium-ion batteries will still take several years before they could reach significant production volumes, provided they reach the necessary level of technological maturity.

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[46] See further information on specific projects in the EU in Table 15 and Table 16 in the Appendix

6.4. Permanent magnets

- Germany and the EU should massively expand the European value chain and the differentiation of supplier countries in the short and medium term in order to reduce considerable dependencies caused by China's strong dominance.

- China's strong current dominance in key intermediates, such as rare earth separation and neodymium-iron-boron magnet production, poses a significant risk ahead of the steep ramp-up in demand.

- The USA in particular is therefore vigorously pursuing the development of its own supply chain: Processing plants for light rare earths as well as heavy rare earths, establishment of own magnet production (GM/VAC) in the USA (mine production in USA; Australia, Canada etc.).

- The EU is also trying to catch up here with a time lag, but European players in the supply chain need investment security for new plants and production regardless of short-term changes.

- Recycling of rare earths or permanent magnets is strategically relevant in the medium and long term (material with 30% by weight of the desired rare earths) for greater European independence: the few industrial players in Europe should definitely be strengthened here.

The most efficient electric motors and generators (wind turbines) contain permanent magnets (neodymium-iron-boron magnets) based on rare earths, i.e., light rare earths (LSE) neodymium and praseodymium, and heavy rare earths (SSE) dysprosium and terbium, which are currently classified as the most critical raw materials of all (JRC, 2021).

Figure 52 shows important examples of planned projects to strengthen the supply chain in Europe (incl. recycling) and to increase diversification with regard to supplier countries from outside the EU. All of these projects, if successful, can help increase the resilience of the neodymium-iron-boron magnet supply chain.

Production ramp-up in Europe

Interesting perspectives for strengthening the supply chain of neodymium-iron-boron magnets within the EU and neighboring countries such as Norway and Great Britain have emerged in recent years from various activities (see also the overview table in the Appendix). Thus, there are concrete plans in Estonia to realize several important stages of the supply chain at once (separation of rare earths, production of rare earth metals) up to the production of neodymium-iron-boron magnets (from recycled magnets, among others, Antea Group, 2023, Turovski, M., 2022). A corresponding project has recently been launched with the start of construction of a plant for the production of neodymium-iron Bo magnets (initially 2,000 tons per year from 2025; with an envisaged phase 2 up to a total of 5,000 tons per year) with EU funding (neomaterials, 2023).

In Sweden (mining) and Norway (separation) there are investment plans in the time horizon up to 2026 drawn up by a Swedish-Norwegian consortium (see TAB. 18 in the appendix). In France, in turn, Solvay, a company familiar with the processing of rare earths, is planning to expand separation specifically for rare earths needed for magnet production (SOLVAY, 2022). Material from magnet recycling is also expected to play a role as an input stream in this project (SOLVAY, 2023). Finally, concrete plans for a rare earth separation plant in the UK are also reported.

In the EIT Raw Materials report "Rare Earth Magnets and Motors: A European Call for Action" (ERMA; Gauss et al., 2021), it is estimated that by 2020 the production of neodymium-iron-boron magnets could be significantly expanded from today's 500 tons per year to 7,000 tons per year by 2030. This means that 20 percent of European demand could be met from domestic production in 2030 (see TABLE 06).

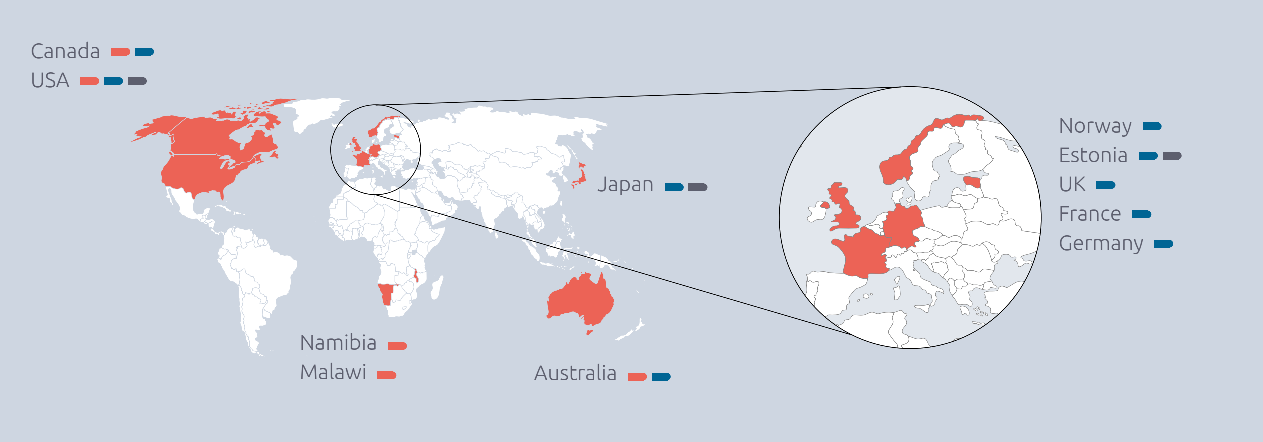
Recycling

Recycling of neodymium-iron-boron magnets and the rare earths they contain is still in its infancy at the global level — and even more so in Germany and the EU. However, in recent years, due to the extremely vulnerable supply chain for neodymium-iron-boron magnets described above (cf. CH. 5.4.), the recycling of these magnets and thus the securing of rare earths for the production of new permanent magnets is strongly in the focus of science, economy and politics in many countries and also in the EU and in Germany (van Nielen, S. et al., 2023). The need for diversified material supply and improved manufacturing capabilities is clearly described in a European Commission study on critical raw materials (Bobba, S., Carrara, S., Huisman, J., et al., 2020). The EC's current draft legislation on the supply of critical raw materials (COM, 2023a) (proposed Critical Raw Materials Act) targets a recycling rate of more than 15 percent by 2030. So far, however, there is no industrially developed recycling of rare earths in the EU.

FIG. 52 **Overview of short- and medium-term alternatives for increasing the resilience of the Supply chain Permanent magnets**

Short-term activities: Country diversification, medium-term production expansion Europe. USA, Canada, Australia, UK, EU, Japan are currently pushing to build their own "western" supply chains.

KEY 🟥 Mining 🟦 Processing and production of rare earth metals ⬛ Permanent magnets



Country diversification
(short term)

- New raw material partnerships and cooperations with Namibia, Malawi, Canada, Australia and USA

Raw material recycling
(medium term from 2030)

- So far only marginal in China
- First small plants planned in Germany and the UK.
- 2030: moderate potential from the return of e-motors: growing strongly from 2035 onward
- Revision of the EU ELV (End-of-Life Vehicles) Directive: Dismantling and appropriate disassembly of electrical motors

Establish production in Europe
(short/medium term)

- Further processing of rare earth oxides: Norway, Estonia
- Rare earth metal production: Estonia, Great Britain
- Production of permanent magnets: Germany*, Estonia
- ERMA Plan: 20% self-sufficiency of the EU in 2030

* VAC in Germany has a production capacity of about 1000 t: more than 5 times the demand is necessary for Germany alone until 2035.

SOURCE Own representation, see table 14 and table 15 for data, targets according to (European Commission, 2023) and (Bloss, 2022)

Öko-Institut, 2023

TABLE 06 **Current capacities of the supply chain of permanent magnets in the EU in tons and targets for 2030**

The supply chain in the EU is only just being established.

Raw material / component	Status 2022	EU target 2030
Rare earths	0 t	not available
SE-oxides	< 1000 t	6.000 t
SE metals	0 t	5,000 t
Permanent magnets	1,000 t	7,000* t

* corresponds to 20% of forecast demand

SOURCE Own representation according to (ERMA; Gauss et al., 2021)

Öko-Institut 2023

The strategic potential of recycling results on the one hand from the fact that neodymium-iron-boron magnets contain around 30 percent by weight of the rare earths (neodymium and praseodymium as well as dysprosium and terbium) required for the production of new high-performance magnets, whereas in natural deposits, the total rare earth content is usually only between 0.5 – 1.5 weight percent, and large amounts of other rare earths such as cerium and lanthanum always have to be separated at great expense (Gielen, D.lyons, M., 2022. On the other hand, the results of this study for the KNDE2045 scenario also show the medium- and long-term strong growth in potential from electric vehicles that are then decommissioned — and, somewhat later, from dismantled wind power plants.

The analysis of the scenario results (cf. FIG. 53) shows that for the electric vehicle sector in Germany, a ratio of rare earths used in new registrations to the material content in deregistered vehicles of a good 10:1 can be expected in 2030. Just five years later in 2035, this ratio is around 4:1 and approaches the same proportions by 2045. In comparison, demand for the "domestic production" scenario is significantly higher (cf. CH. 4 and 5), so that the ratio will still be around 2.5:1 in 2045. Even if not all vehicles deregistered in Germany are scrapped immediately[47], this overview impressively shows that the recycling potential of neodymium-iron-boron magnets and the rare earths they contain will grow massively from today's very small dimensions in the next seven to twelve years. The EU has now recognized this and, in its proposal for the Critical Raw Materials Act, places a special focus on the recycling of permanent magnets in order to get the necessary framework conditions and investments underway in a timely manner.

The Critical Raw Materials Act proposal explicitly highlights relevant ongoing revisions to key directives focused on permanent magnet recovery (COM, 2023a): "A joint review of Directive 2000/53/EC on end-of-life vehicles in conjunction with Directive 2005/64/EC on the type-approval of motor vehicles is currently underway with regard to their reusability, recyclability and recoverability in order to reduce waste from end-of-life vehicles and their components and to increase the recyclability of both conventional and electric vehicles, which contain significant amounts of critical raw materials. The legislative initiative based on this review will complement the horizontal recyclability requirements contained in this regulation by introducing more specific requirements to improve the recyclability of permanent magnets in vehicles, thereby facilitating waste treatment and recycling."

Furthermore, the draft regulation already envisages prescribing specific quotas in the future (cf. the EU Battery Regulation soon to come into force) to support the recycling of magnets (COM, 2023a): *"In order for the recycling of magnets to be economically viable, permanent magnets in products placed on the Union market should contain an increasing amount of recycled raw materials over time. While transparency on recycled content is provided in a first stage, a minimum recycled content should be set after a specific assessment of the appropriate level and impact."*
The political discussions on the supply chain of neodymium-iron-boron magnets, their importance for the energy and transport transition, and completed and also ongoing research and development projects on the recycling of neodymium-iron-boron magnets (SUSMAGPRO, 2023) have led to the fact that the first recycling plants for neodymium-iron-boron magnets are now under construction in the UK and also in Germany and are expected to be commissioned in 2023 and 2024 respectively (Mining Magazine, 2022). Under the EU's proposal for the Critical Raw Materials Act, a recycling rate of more than 15 percent is required by 2030. (COM, 2023a)

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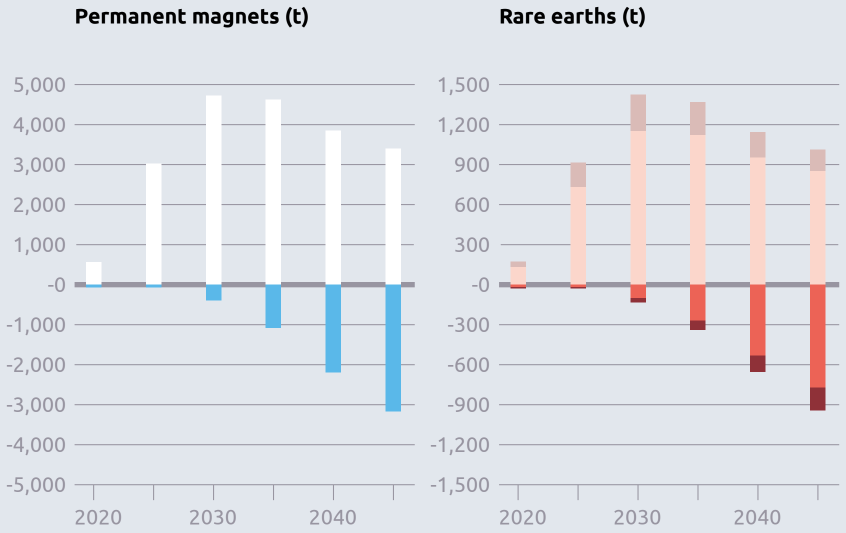
[47] On the one hand, it is likely that electric vehicles, like today's combustion engine vehicles, will be exported in part (especially to other EU countries) and will continue to operate for some years to come. In addition, with regard to the e-motors, which have a much longer service life than the batteries, the possibility of continued use is being discussed.

FIG. 53 **Annual demand for permanent magnets or rare earths for electric motors for Vehicle drives (new registrations) and deregistrations from the German fleet**

After 2030, the recycling potential for permanent magnets and rare earths is growing rapidly.



KEY
- new registrations (white, pastel)
- Logouts (solid colors)
- Permanent magnets
- Heavy rare earths: Dysprosium, terbium
- Light rare earths: Neodymium, Praseodymium

SOURCE Own modeling based on the KNDE2045 scenario and (Nordelöf et al., 2017)

Öko-Institut, 2023

In summary, it can be stated for the development and strengthening of a European supply chain for neodymium-iron-boron magnets that with political and financial support from the EU, among others, a number of projects (from mining, recycling and across all steps of the supply chain) have in fact been launched in recent years. In comparison with corresponding projects in the lithium-ion battery supply chain, it is clear that there is an urgent need to catch up both in terms of concretization (capacity and time schedules are often not yet known) and maturity of the projects in the case of the European supply chain for neodymium-iron-boron magnets. The strong focus on permanent magnets in the EU's proposal for the Critical Raw Materials Act indicates that the EU has now recognized this shortcoming. Regardless, even if some of the above projects succeed, Europe will continue to rely on supplies from outside the EU of raw materials, intermediates and strategic goods in 2030. It is therefore essential to pursue greater diversification of supply countries in order to reduce the very heavy dependence on China for this supply chain.

Diversification of supplier countries:

In addition to traditional Western countries with strong mining sectors, such as Australia and Canada, a number of countries in the Global South have also come into focus for diversifying the supply of raw materials to Europe and Germany with rare earths or corresponding intermediate products. The following countries, among others, are known to have natural deposits of rare earths and should be considered for raw material and technology partnerships:

- Brazil (BMBF, n.d. a), (BMBF, n.d. b),
- Kenya (Kenya News Agency, 2023),
- Colombia (Mining.com, 2023), (auxico resources, 2023),
- Malawi: Heavy rare earths (Mining Technology, 2023a),
- Namibia: Heavy rare earths, yttrium (Nyaungwa, N., 2022), (Innovation News Network, 2023)

In addition to questions of political stability and good governance, issues of logistics and infrastructure (road links, connections to deep-sea ports, valid power grid, etc.) also play a key role in the selection of potential partner countries. This is considered positive for the countries mentioned above.

Reduction in raw material intensity

There have been and still are efforts to reduce the content of the very critical heavy rare earths in the magnet material, to reduce the specific magnet weight by intelligent design of the electric motors, or even to use other electric motors for electric vehicles that do not have permanent magnets, i.e. that operate without any rare earths. However, experts agree that material efficiency and substitution will not decisively slow down the rapid increase in demand for rare earths for neodymium-iron-boron magnets in the foreseeable future[48] and that contributions to increasing resilience will therefore only have moderate effects.

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[48] Expert testimony at the (Automotive IQ, 2023) 10th Annual Advanced E-Motor Technology February 2023 in Munich.

6.5. Electrolyzers

- Reducing the specific material requirement of iridium for PEM electrolyzers is by far the most important strategic task for the electrolyzer complex.
- Alkaline electrolyzers (AEL) and PEM electrolyzers (PEMEL) are crucial for the medium-term market ramp-up.
- High-temperature electrolyzers (HTELs) are only at the pilot stage: their supply chain is therefore uncertain in the short and medium term.
- AELs do not contain critical raw materials; for PEM electrolyzers, iridium is primarily relevant, with platinum and titanium in subsequent priority.
- Iridium is the very critical raw material for electrolyzers: its mine production can hardly be increased. Low-iridium electrolyzers and recycling will therefore be very important for the supply in the future.
- The platinum supply can be fed today and increasingly in the future from recycling (especially automotive catalytic converters).
- For the supply of titanium metal via titanium sponge, cooperation with producing countries such as Japan can be intensified.
- For high-temperature electrolyzers, the supply of scandium must be taken into account; here, diversification of supply from countries such as the USA, Canada, but also from the EU (Finland, Sweden, Greece) is possible.

The analysis of the critical raw materials necessary for the ramp-up of the different technologies of electrolyzers for the production of hydrogen (cf. CH. 5.5) has resulted in a clear prioritization in terms of relevance and temporal urgency. This prioritization is expressed in the following order:

- **Iridium:** very relevant, as supply quantity can only be expanded slightly,
- **Scandium:** relevant, as only a few suppliers so far and offer must (and can) be significantly expanded in the future,
- **Platinum:** relevant due to demand growth, but large easing due to recycling potential (see below),
- **Titanium and yttrium:** only moderately relevant due to large supply in terms of volume and realistic options for demand moderation through increase in material efficiency

Iridium

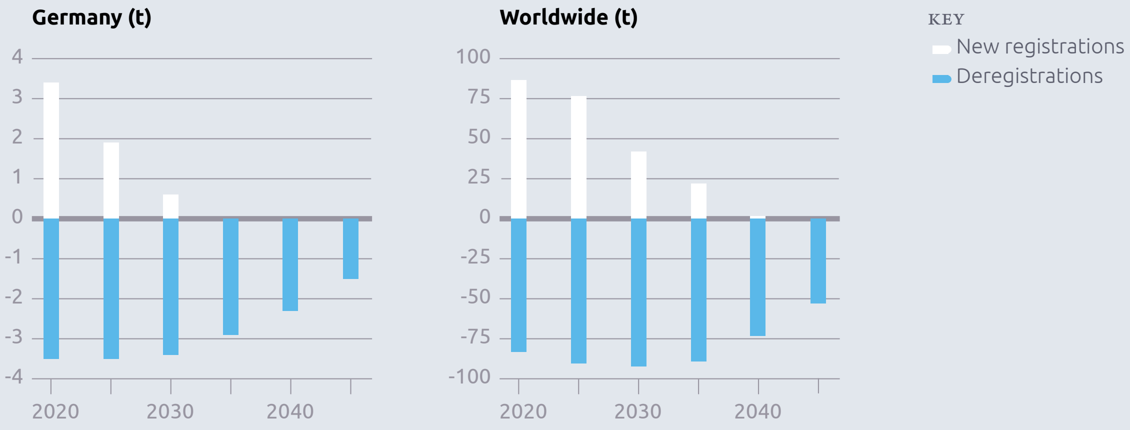
From the ramp-up of PEM electrolysis according to the KNDE2045 scenario, current iridium loadings result in a demand of up to 3.5 tons per year for Germany only. This underscores the relevance of development efforts in this direction, especially in the case of iridium. The technology company Heraeus, for example, reports that their "next generation" catalysts already require 75 percent less iridium — 0.1 g/kWel instead of the current approximate 0.4 g/kWel (Heraeus; Walter, Ph., 2022). In the short term, however, the demand for iridium is still high even if the path of reduced material intensity is followed (cf. FIG. 44) at about 0.5 metric tons per year and drops to 0.2 metric tons per year by 2045, which corresponds to a share of six or 2.5 percent of current global iridium production for Germany alone.

Since the supply quantity of iridium from natural deposits can hardly be increased (cf. CH. 5.5), the only option left for increasing resilience, in addition to increasing material intensity, is forced recycling as a second relief option. European companies such as Umicore and Heraeus are already recovering iridium from various end-of-life materials. The German company Heraeus claims to already recycle more than two tons of iridium annually (Heraeus; Walter, Ph., 2022). Another potential source of relief for iridium comes from the future decline in production of vehicles with internal combustion engines. Here, iridium is used in spark plugs — on a global scale of about one ton per year (JM, 2022), (Heraeus; Walter, Ph., 2022). This amount of iridium should be available for the production of PEM electrolyzers in the future.

Platinum

Although 74 percent of the supply of platinum from mine production to world markets is concentrated in South Africa (U.S. Geological Survey, 2023), the recycling of platinum from various applications such as jewelry, electronics, but especially from spent industrial and exhaust catalysts has been a technologically and logistically very efficient and well-established system for decades (Hagelüken, C.; Buchert, M. et al., 2005) and, with recovery rates of well over 90 percent, makes a high contribution of around 50 percent to the global platinum supply (Graedel, T. E. et al., 2011). The supply of future technologies such as fuel cells or PEM electrolyzers is therefore far from being solely dependent on mine production. The electrification of the vehicle sector will also make a very large secondary platinum potential available in the future from decommissioned vehicles with internal combustion engines, which can be used not least in PEM electrolyzers. The scenario results in Figure 54 demonstrate the high supply potential for platinum from end-of-life catalysts from the automotive sector.

FIG. 54 **Platinum in exhaust catalytic converters of internal combustion vehicles in Germany and worldwide: New registrations and deregistrations per year**



SOURCE Own modeling based on the KNDE2045 scenario and the IEA's Net Zero scenario

Öko-Institut, 2023

TABLE 07 **Titanium sponge: Production capacities and capacity utilization in 2021**

Production facilities are only partially utilized

Country	Plant capacity	Utilization 2021
China	181.000 t/a	77%
Japan	68.800 t/a	72%
Russia	46.500 t/a	58%
Kazakhstan	26.000 t/a	58%
Ukraine	12.000 t/a	51%
Saudi Arabia	15.600 t/a	37%
India	500 t/a	50%

NOTE Utilization results from the produced quantity per capacity

SOURCE Own representation according to (U.S. Geological Survey, 2023)

Öko-Institut, 2023

The amount of platinum contained in the exhaust catalytic converters of vehicles with internal combustion engines was estimated under the assumption that about four grams of platinum group metals are used in the catalytic converters per vehicle, with a platinum content of 28 percent (Buchert, M. et al., 2019). Overall, a return of around 3.5 metric tons per year can be expected from the German fleet in the coming years, whereas the demand for new vehicles with internal combustion engines will be around two metric tons per year in the short term and fall to 0.6 metric tons per year as early as 2030. In the KNDE2045 scenario, no more internal combustion vehicles will be registered from 2035. Accordingly, the return volumes also decrease with a time lag, but are still at three tons per year in 2035 and over one ton per year in 2045. On a global level, the return rate is constant at around 90 tons per year until 2035. From 2025, the demand for new registrations of vehicles with internal combustion engines falls below the value of the return of vehicles; from 2030, it is already 50 metric tons per year below the expected return, according to this scenario, due to the ongoing electrification of the global vehicle fleet. The large platinum potential from decommissioned vehicles can be tapped for the most part in practice due to the excellent recycling rates of over 90 percent.

The explanations and scenario results make it clear that, with regard to future platinum supply, the transformation through the vehicle sector is winning, since the future platinum demand for electrolyzers can be covered many times over from secondary potentials (especially automotive exhaust catalyzers). Therefore, no special new levers for increasing the resilience of the supply chain are to be identified with regard to platinum supply — rather, the existing professional recycling structures for platinum and other precious metals in Europe but also worldwide must be maintained. The high economic revenues from platinum recycling provide strong incentives for economic actors here.

Titanium

As shown in section 5.5, the market ramp-up for PEM electrolyzers will indeed increase the demand for titanium sponge. However, other demand sectors such as the aircraft industry are much more relevant. In addition, titanium sponge production capacities exist in a number of countries, which were only utilized between 37 percent (Saudi Arabia) and 72 percent (Japan) or 77 percent (China) in 2021 (see Tab. 07: Accordingly, there is still great potential to increase supply volumes globally simply by increasing the utilization of existing capacities. For Germany and Europe, it would be particularly useful to intensify cooperation with Japan, which has the largest production capacities after China.

Finally, there are also positive developments regarding the recycling of titanium scrap in Europe. In 2018, for example, a new titanium scrap recycling plant was commissioned in France, which can recycle up to 4,000 tons of titanium scrap annually when fully operational (Knight, Ch., 2018).

Scandium and yttrium

In the case of the two rare earths yttrium and scandium, both of which could play a role in future high-temperature electrolyzers, the focus should mainly be on scandium with regard to the resilience of the supply chains (cf. ch. 5.5 The scenario results in this project and the analysis of the supply side clearly show a need for action for future supply assurance in the event that scandium is relied upon in HTEL. This is also supported by recent work by DERA (DERA, 2022).

For scandium, the following levers are important for increasing supply-side resilience:

- Exploiting the enormous potential for material efficiency in the stacks: this results in a high R&D requirement for reducing the specific scandium demand,
- Diversification of supplier countries

To date, China, Russia, and the Philippines dominate for scandium supply (U.S. Geological Survey, 2023). However, reserves of scandium are found in many countries of the world — always in quite small concentrations associated with other raw materials such as bauxite, nickel, titanium and zirconium ores (cf. Ch. 5.5 Recently, several projects have been launched in the USA, Canada and Australia.

More focus should also be placed on the supply of scandium from European countries. Current projects reported here are from Greece (recovery of scandium from bauxite processing residues) and Finland (U.S. Geological Survey, 2023). Completed and ongoing EU collaborative projects such as SCALE (DERA, 2022) and (HARARE, 2021) should be pushed and supported in this context to ensure an entry into European contributions to scandium supply. Due to the early stage of the projects, it is not yet possible to quantify the potential for the future supply of scandium to Europe.

Reduction in raw material intensity

A key lever for increasing resilience is reducing the specific material requirements of critical materials. Figure 55 shows the significant reduction in critical electrolysis materials to the order of 90 percent by 2040 that underlies the determination of the lower limit of demand for the electrolysis ramp-up in the scenario. It is based on literature values (Kiemel, S. et al., 2021). These potentials are also confirmed by the companies. The first manufacturers of PEM anode catalysts are advertising the greater competitiveness of their products thanks to significantly reduced iridium requirements of 50 to 90 percent (Heraeus, 2020). The realization of this potential is dependent on success in research and development, but is also an important prerequisite for the further ramp-up of PEMEL technology.

Approaches to reduce the material requirement exist, for example, by combining the critical material with less expensive substrate materials by applying the critical component only to its surface and/or substituting some of the metals with others. Other approaches pursue the continuous reduction of layer thicknesses by means of innovative automated processes (e.g. vapor deposition of nanolayers) and enlargement of the active surface area with simultaneous material reduction of the critical material.

Alternative technologies

Critical materials concern only the PEMEL and HTEL. The established AEL and the AEM under development are largely independent of critical materials, so that substitute technologies for electrolysis are available in the event of raw material shortages due to critical materials.

Production ramp-up in Europe

Only 1.4 GWel of electrolyzers have been built worldwide to date (IEA, 2023). For the KNDE2045 scenario, 26 GWel of electrolysis capacity (of which 10 GWel is domestic) is required by 2030 for German demand alone (see CHAPTER 4.4).

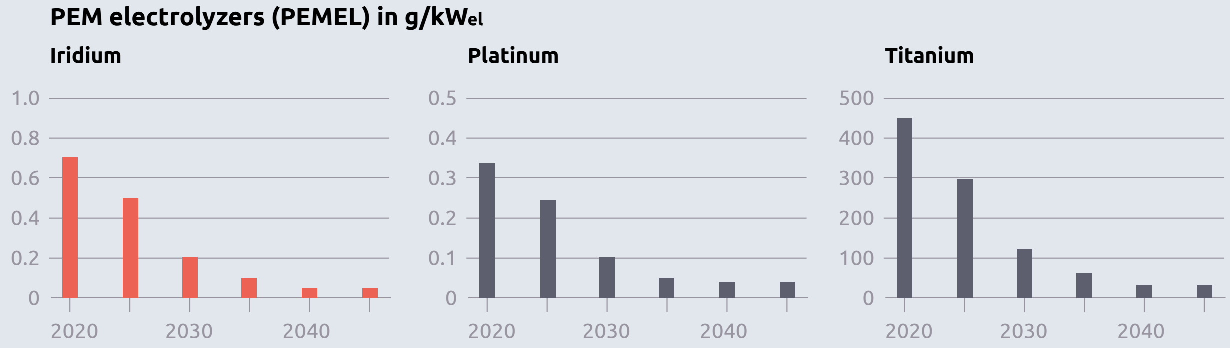
The low demand that has so far existed for water electrolysis systems has been met in the manufacturing sector and in small series production. In order to meet the rapidly increasing demand, it is essential to develop a gigawatt electrolysis industry with serial production, to achieve a high degree of automation and to make use of economies of scale. The expected increase in production capacity is already becoming evident. It must now be ensured that the announced projects are implemented and further expanded.

Compared to the output of electrolyzers built, the production capacity for building electrolyzers was significantly higher. In 2021, manufacturing capacity worldwide was around eight GWel, almost double the figure for 2020. Compared to the annual realization of electrolysis projects in the order of several hundred MW in recent years, it is evident that production capacities are not being utilized.

Based on company announcements, the IEA projects that by 2030, manufacturing capacity to build the electrolyzers could grow to about 60 GWel. Of these, 19 GWel — around one third — are located in Europe (see FIG. 56).

In May 2022, as part of RePowerEU, the EU had issued a target of achieving manufacturing capacities for the construction of electrolyzers in the amount of around 25 GWel by 2025. According to the current IEA estimate, this target will still be missed by seven GWel.

Moreover, the IEA's expansion scenario presented here is not ambitious enough. Based on the optimistic assumption that these manufacturing capacities will produce at 90 percent capacity utilization from 2024, this would mean that around 250 GWel of electrolyzers could be built globally by 2030. According to the IEA's



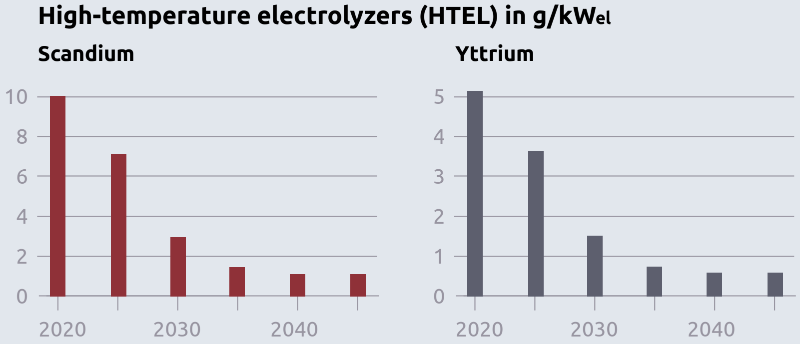


FIG. 55 **Reduction of specific material intensity for raw materials of electrolyzers**

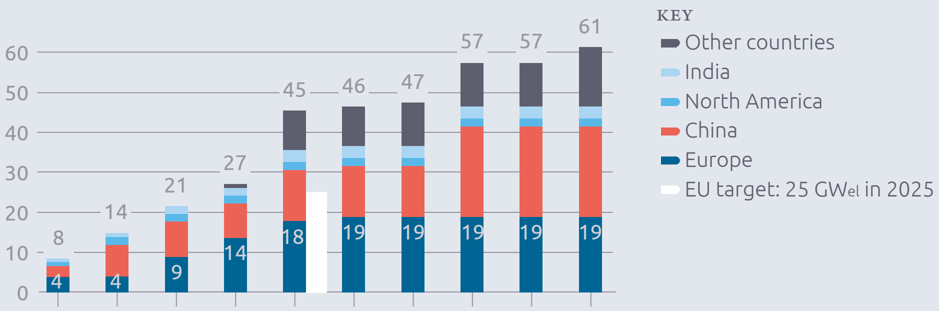
Reducing the specific material intensity is the central lever for reducing the raw material requirement for electrolyzers (PEMEL and HTEL).

ASSUMPTION Literature value for 2035 will not be reached in the market until 2040
SOURCE Assumed reduction in scenario based on (Kiemel, S. et al., 2021)

Prognos, Öko-Institut, 2023

FIG. 56 **Estimate of the development of global electrolysis production capacity in GW_{el}**

The EU's manufacturing target of 25 GW_{el} will be missed by 7 GW_{el}, according to IEA estimates.



SOURCE Prognos based on IEA 2022, currently known projects

Prognos, Öko-Institut, 2023

Net Zero scenario, however, 720 GWel of electrolyzers, almost three times as many, would have to be built worldwide by 2030 (IEA, 2022d). It can be deduced from this that global manufacturing capacities must be further increased.

PEM electrolyzers (PEMEL) in t/a

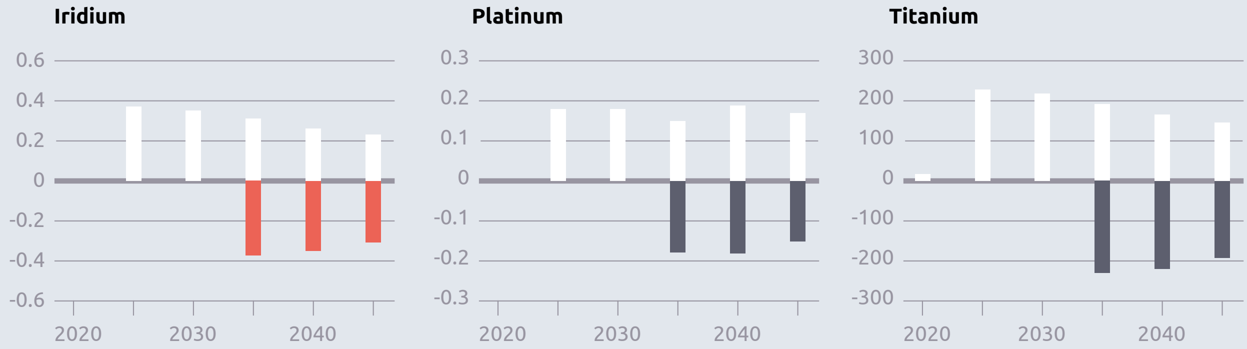
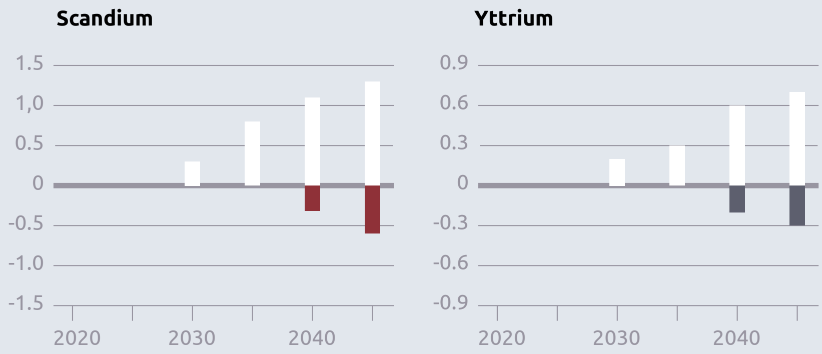


FIG. 57 **Additions and potential Return flow of metals (electrolyzers) in the KNDE2045 scenario**

Return flows from recycling only become relevant from 2035 onwards.

High-temperature electrolyzers (HTEL) in g/kW$_{el}$



KEY
□ annual demand
🟥 potential return (colored bars)

ASSUMPTION Stack life of ten years. Quantities with assumed continuous reduction of material intensity (see section on material intensity) SOURCE Prognos based on (IEA, 2022d), currently known projects

FIG. 57Öko-Institut, 2023

Recycling

Returns of metals at the end of life of the electrolyzers start to become relevant at the earliest from 2035 onwards, assuming a stack lifetime of ten years (conservative derivation from 45,000 operating hours (Smolinka, T. et al., 2018) and full load hours of 4,500 h/a,) (Figure 57). In the case of platinum, however, the quantities are far below the level of the current return flow from catalytic converters of internal combustion engines. However, less platinum is also needed for the expansion of new electrolyzers (despite still increasing capacities, due to decreasing material intensity), so that the quantities are already in the range of the quantities needed for the annual capacity expansion. In the case of iridium and titanium, the return values are even higher. The situation is different for the rare earths relevant for high-temperature electrolysis, as the ramp-up of this technology will not start until later and thus no return volumes are expected until 2045 that could offset the volumes for the expansion.

The recycling of valuable metals from electrolyzers is currently still an absolute field of research and development worldwide due to the still relatively new technology and the very low installed capacities to date. Therefore, recycling potentials cannot yet be reliably concluded from the return quantities. A comparison with established and mature recycling processes such as those used for automotive catalytic converters is therefore out of the question for the foreseeable future.

However, a key aspect in the commercial development of electrolysis plants is that recyclability is already being considered so that the potential can be tapped as fully as possible in the future. In Germany, the potential recycling processes for electrolyzers are currently being investigated via a comprehensive joint project funded by the BMBF, which, however, will run until 2025 (DECHEMA; Peuker et al., 2021).

6.6. Heat pumps

- Compared to other key technologies and their components, the supply risks for heat pumps are significantly lower.
- A stable domestic market is necessary for the expansion of manufacturing capacities — and thus a reliable regulatory framework for reducing emissions in the building sector.

TABLE 08 **Current production capacities for Heat pumps in Europe and targets for 2030**

To meet the goals of the Net-Zero Industry Act, today's manufacturing capacities in Europe must increase by 50 percent.

SOURCE Own representation

	Status in 2021	Targets for 2030 under Net-Zero Industry Act: 85%
Heat pumps	19 GW	31 GW

Prognos, 2023

Production ramp-up and keeping production in Europe: Today, production capacity in Europe is already at 19 GW.

Based on the targets of the Net-Zero Industry Act, at least 85 percent of newly installed systems are to be manufactured in Europe by 2030. This corresponds to a manufacturing capacity of 31 GW and a necessary increase of 50 percent compared to today. In Europe as a whole, and especially in countries with a large pent-up demand for climate-neutral heating systems, such as Germany and the UK, manufacturers are expecting significant market growth and are expanding their capacities accordingly.

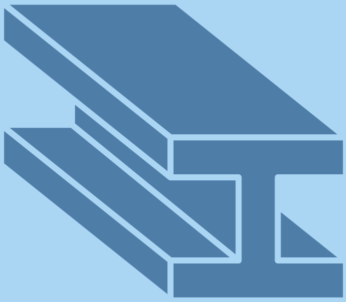
In order to cover this ramp-up as well as the necessary investments, there must be reliable framework conditions in place for bringing about a reduction of greenhouse gases in the building sector. The energy price crisis caused by the Russian war of aggression and the resulting shortage prices for natural gas have led to a significant increase in demand for heat pumps in recent months and thus to clear investment signals for the heat pump industry. The Building Energy Act in particular is crucial for the further perspective up to 2030.

The issue of a shortage of skilled workers in the heating sector should also be addressed simultaneously. In addition, the continuation of research and development should help to maintain the technological lead of domestic manufacturers wherever possible.

Alternative technologies, diversification

In terms of raw materials and components, the use of permanent magnets in the motors of compressors and circulating pumps is considered critical. However, there is currently no data available on what proportion of heat pumps use permanent magnets. Further research on this question is required. In addition, it is necessary to investigate which alternative drive concepts are suitable. In addition, it is necessary to build up manufacturing capacities in Europe (production of permanent magnets) and to diversify the supplier countries. Details on this can be found in Chapter 6.4.

6.7. Green steel



- Due to the foreseeable bottlenecks in the construction of DRI plants, speed is critical to ensure that steelmakers secure domestic engineering capacity in a timely manner. Previous investment decisions by companies were based on the promise of government funding.
- Establishing supply relationships to import DRI sponge iron in the form of HBI (hot briquetted iron) and strengthening secondary steel (recycling) create additional security of supply.

Production setup in Germany and Europe

In order to be able to build the shaft furnaces for direct reduction with hydrogen (DRI plants) in Germany, speed is of the essence in view of the impending supply bottlenecks in plant construction. Policymakers can support such a development in particular through forward-looking infrastructure development and financial support — as a complement to the CO_2 border adjustment mechanism (CBAM) and support for the ramp-up of a lead market for green steel.

In terms of infrastructure, the prerequisites are first and foremost the hydrogen grid and — almost more importantly — efficient connections to the extra-high voltage grid. From today's perspective, there is no way around the electrification of the melting units — and this is the prerequisite for keeping the value-adding stage of steel production in the country.

The investments by German companies have so far been decided without exception subject to the proviso of billions of euros in government funding, but so far funding commitments from the German government have only been received for the first plants in Salzgitter and Duisburg. The projects in Sweden, on the other hand, are financed by the companies themselves[49]. As in other areas, the Inflation Reduction Act (IRA) is likely to provide some pull for projects to North America. There, it is also possible to build on a culture where market players already have experience in the interaction between ore, DRI and scrap markets. If the subsidized electrolyzer projects are added, very attractive location conditions for green steel projects are created there.
Securing the construction of DRI plants in Germany would also have the advantage that, thanks to large anchor customers in the steel sector, there is a certain reliability for the purchase of large quantities of hydrogen, which is an important prerequisite as an entry into a hydrogen economy (start-up network). As a fall-back option, in times of scarce hydrogen availability, German companies (unlike their northern Swedish competitors) still have the natural gas option in the medium term.

Diversification of supplier countries:

However, Germany should also have an interest in a secure DRI supply also through HBI imports; this could be supported by flanking the emergence of supply relationships or liquid markets, for example through credit hedging. Fixed supply contracts for green DRI would be possible, e.g. with Sweden's LKAB, which is currently preparing to build a DRI plant at the Gällivare mine to be operational by 2026. In the medium term, opportunities for diversification should arise as soon as projects have made progress on the Iberian Peninsula, in Australia, Brazil and Africa. Liquid world markets for green DRI would be preferable from an efficiency point of view, but it is not certain whether these can emerge robustly in view of the virulent protectionism in the steel sector in particular.

Recycling

A stronger supply of domestic secondary material is, of course, the best insurance against import dependency in the steel sector as well. In order to achieve this, however, scrap sorting must be greatly improved, especially in the automotive sector. On the other hand, in view of a possible cannibalization of DRI production and impending carbon leakage, (net) scrap imports should be subjected to intensive monitoring. However, with continued net exports of steel-containing products such as automobiles, these could also have their place in terms of a circular economy that avoids downcycling.

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[49] In the case of the private companyH2GreenSteel, although the public sector is involved as a lender through the European Investment Bank (EIB), the project is predominantly financed by its customers, who hold shares in the company. The main investors are German companies from the automotive sector such as Mercedes-Benz, Schaeffler and Bilstein, as well as Miele and the aforementioned SMS Group, which is also responsible for the construction of the plants in Boden as the general contractor.

6.8. Summary

Basically, the study identified five different areas of action to increase the resilience of relevant supply chains for the transformation to climate neutrality:

- Production ramp-up in Europe
- Diversification of reference countries
- Recycling
- Reduction of raw material intensity
- Alternative technologies

For all prioritized key technologies, relevant resilience measures could be identified from these five different measure areas. The most important examples are briefly summarized below.

Production ramp-up in Europe

The relocation back to or the establishment of the value chain in Germany and Europe is essential for large parts of the PV value chain. Particular efforts should go toward strengthening the market shares for the production stages of ingots, wafers, PV cells and PV modules for the market-leading technology of wafer-based photovoltaics. Europe currently has very little production capacity in these areas, and a significant increase in production capacity in the EU by 2030 is of strategic importance with an aim to increasing resilience and reducing dependencies. With regard to the value chain for lithium-ion batteries (electromobility), the necessary development of a European value chain through financing (from EU, German government, etc.) of "gigafactories" and upstream stages (lithium refineries, cathode material production etc.) has already begun.

Despite current challenges such as that posed by the United States' Inflation Reduction Act (IRA), these activities must be continued in a consistent manner and expanded to include raw materials extraction within Germany and the EU (the focus here is primarily on lithium). Likewise, groundwork must be laid for building and bolstering relevant production capacities in Europe for the supply chain of permanent magnets (processing of rare earths, extraction of rare earth metals and extraction of neodymium iron boron magnets) as well as for electrolyzers and DRI steel.

Diversification of supplier countries:

The diversification of supplier countries (outside of the EU), especially with regard to the supply of raw materials and intermediate products, is a second important pillar of building resilience. Of absolutely importance is, on the one hand, the strengthening of economic ties with established partners such as Chile (lithium, copper), Canada (lithium, nickel, rare earths), Australia (lithium, rare earths, nickel, cobalt), and Brazil (graphite, lithium, manganese).

On the other hand, with an aim to further expanding the diversification of supplier countries, the development of new raw material and technology partnerships with countries in the Global South is highly recommended. Examples of countries that could enter into possible future cooperation projects are Ghana (lithium), Indonesia (nickel, cobalt), Namibia (rare earths, lithium), Malawi (rare earths, incl. heavy rare earths) and Colombia (rare earths, nickel). Table 9 lists examples of potential supply countries for key raw materials. The table makes no claim to completeness. Furthermore, it is important to note that, following Indonesia's example, more and more countries will not export non-processed raw materials. This allows the respective countries to increase the share of added value in their own country by carrying out the further processing stages of raw materials themselves. It is therefore desirable for partnerships to evolve towards transformation-oriented relationships on equal terms.

TABLE 09 **Potential supply countries for key raw materials for the transformation to climate neutrality**
The table includes both established producers, such as Chile for lithium, and potential new countries for future raw materials and technology partnerships, such as Namibia for lithium and rare earths

Potential partner countries	Raw materials	Comments
Australia	Lithium, Light and Heavy Rare Earths, Nickel, Cobalt	Already extensive lithium extraction and mining of rare earths
Brazil	Graphite, Lithium, Manganese	Already mining or exploitation (lithium) of tailings
Canada	Lithium, nickel, cobalt, rare earths	Lithium extraction, which has been very low to date, is to be expanded. Rare earth mining projects planned/under construction
Chile	Lithium, Copper	Already extensive lithium and copper extraction, lithium production to be expanded.
Colombia	Rare earths, nickel	Expansion of nickel extraction planned, reserves for rare earths
Ghana	Lithium	No mining yet, mining project in the planning stage
Indonesia	Copper, nickel, cobalt	In particular, existing nickel and cobalt extraction is to be expanded robustly.
Madagascar	Graphite	Existing extraction by mining
Malawi	Light and heavy rare earths	No mining yet, mining project in the planning stage
Mozambique	Graphite	Existing extraction by mining
Namibia	Light and heavy rare earths, lithium	No extraction by mining yet, projects planned/under construction
South Africa	Manganese, iridium, platinum	Most important mine producer for the three raw materials
Zimbabwe	Iridium, platinum	Existing extraction by mining; however, significantly lower production compared with South Africa

SOURCE Own compilation by Öko-Institut based on (U.S. Geological Survey, 2023)

Öko-Institut 2023

Recycling

Recycling, as the third important pillar for strengthening resilience, is initially relevant in terms of timeline for the recovery of battery raw materials such as lithium, cobalt, nickel and copper. The first recycling plants have begun operations in Germany and Europe, and the upcoming adoption of the new EU Battery Regulation will lay out an ambitious regulatory framework. Efforts must now be redoubled to continue necessary measures to increase recycling activities in order to exploit the large recycling potential that will emerge starting in 2030 and beyond.

Recycling is also of great strategic relevance for permanent magnets (rare earths). In this area, however, more effort has to be devoted to research and development and towards advancing the corresponding technological innovations for the recycling processes in order to tap into the full recycling potential. The European Commission's proposal for the Critical Raw Materials Act and the revision of the EU End-of-Life Vehicle Directive also creates important regulatory framework conditions that must be supported. The recycling of PV modules and materials from electrolyzers (titanium, iridium, platinum) is also an option — but with relevance only after 2035.

Reduction of raw material intensity

Innovations in the area of reducing raw material intensity by increasing material efficiency in specific components are particularly relevant for future production expansions of PEM electrolyzers. A significant reduction in the specific iridium requirement of PEM electrolyzers is an absolute prerequisite for the successful mass production of this technology, which is crucial for the development of a global hydrogen economy. In the area of permanent magnets, there is at least moderate potential for reducing the content of heavy rare earths through innovations in magnet production. Heavy rare earths are categorized as very critical for the purposes of this study.

Alternative technologies

Alternative technologies are already in sight in the lithium-ion battery product family, and some are already market-ready. These include, on the one hand, the expansion of the use of low-cobalt NMC8111 batteries and, above all, nickel, cobalt and manganese-free LFP batteries. Other alternatives under development that may become relevant after 2030 include solid-state batteries and sodium-ion batteries.

7. Policy recommendations

Based on the investigations into the demand and the supply side for the technologies that are particularly important in the context of this study, the project team has identified the following possible strategies and instruments for increasing the resilience of the relevant supply chains. An in-depth examination of the individual instruments was beyond the scope of this study. Rather, the following initial recommendations are intended to define a framework in which the possible effectiveness and priority applicability can be further explored in subsequent studies, with the aim of achieving a robust strengthening of the resilience of important supply chains for the transformation.

Introduction of comprehensive resilience monitoring

For all value chains or supply chains identified as priorities in this study (PV, wind power, permanent magnets, batteries for electromobility, electrolyzers, DRI steel, and heat pumps), it makes sense to introduce "resilience monitoring" that provides relevant information on the strategic value chains to political and economic decision-makers on a regular basis, e.g. annually. It is important that the entirety of the respective supply chains be analyzed with regard to their vulnerabilities and resilience, that this is carried out from both a German and a European perspective and that the information is quantifiably supported as far as possible. Resilience monitoring requires its own institutional foundation.

Creation of stable markets for transformative key technologies

Creating a reliable domestic market in Germany and the EU is essential for all key technologies, also from the perspective of resilience. Various individual instruments are relevant for achieving this. This includes the creation of attractive framework conditions for markets, i.e. regulatory measures (regulatory law, CO_2 pricing, infrastructure expansion and subsidies) that are as stable and predictable as possible, the support of green lead markets, a foresighted effort to secure skilled workers, expedited planning and approval processes, the reduction of burdensome bureaucracy as well as the development and continuation of clear export strategies (e.g. in the field of renewable energies in offshore wind power).

Establish resilient-content guidelines.

Resilient content includes setting standards and qualities, such as carbon footprint specifications or environmentally and socially responsible supply chains. The new EU Battery Regulation, for example, already includes provisions for specific target years. This instrument could be used to limit the import of goods that are produced under low environmental and social standards.

More in-depth investigations into this relatively sensitive instrument are necessary with regard to the value chains that have been categorized as priorities. Thus, conformity with WTO rules is relevant. The criterion could be used in different ways, for example by way of bonuses in tender procedures or feed-in tariffs (based on the staggered model of the Inflation Reduction Act), or also as a qualitative criterion in corresponding auctions.

In the area of offshore wind power, resilient content specifications could help to establish a long-term perspective for production commissioning, in particular for European-coordinated expansion paths. Tenders should also be designed to prioritize the use of European technology. This could also be an important contribution to the necessary export strategy.

Facilitate purchasing groups for strategic raw materials and goods

Bundled purchasing groups could strengthen the position of German and European companies on the global market thanks to their added purchasing power. Today, antitrust law can prevent the formation of such purchasing groups. In the interest of strengthening supply chains and companies, the possibility of adjusting antitrust law should be examined.

Strong representation of domestic business location policy in the area of strategic raw materials and goods

The basic premise of this overarching supply-side strategy is that creating resilience insurance for future transformations comes at a cost. For strategic supply chains, which are indispensable for a resilient and future-proof economy, domestic market players will have to receive robust support through additional financial means during a transitional period, to protect them from structurally unfair competition coming from outside the EU (market advantages as a result of various state subsidies, taxes and levies, undercutting of environmental and social standards, etc.). This support should continue until a truly level playing field is reached in this area.

Initially, investment subsidies (CAPEX) should be taken into consideration. Well-known examples are IPCEI projects, i.e. investments classified by the EU as "Important Projects of Common European Interest", which are particularly eligible to receive support. Eligibility for funding for the establishment of a business location should be based not only on regional criteria, but also and in particular on resilience factors.

An addition supply-side instrument used by the EU is the "Just Transition Fund", which provides special funding for investment projects for regions particularly affected by transformation. A current example is the funding of a magnet factory in Estonia (construction incl. preliminary stages have recently begun) within the framework of the Just Transition Fund. The Lusatia region, which was particularly affected by the phase-out of coal production, would certainly be a prime example of a region that can present persuasive arguments for receiving corresponding investments.

In addition to CAPEX funding, however, OPEX funding that is at least limited in time may also be necessary. This instrument should take into account all energy-intensive productions for priority value chains that have massive competitive disadvantages in terms of operating costs compared to competitors outside of Europe. This may be very relevant, for example, with regard to battery cell factories, plants for the production of permanent magnets and also certain parts of the value chain for photovoltaics and the production of green steel. One component of such an OPEX funding could be an industrial electricity price that is set for a limited time period, or limited to certain industries or processes.

In principle, a business location policy that is financially supported as outlined above can help strengthen value chains in Europe and also contribute to a more efficient domestic production by giving impetus to economies of scale.

Establish and strengthen technology and raw material partnerships

For a number of products such as lithium-ion batteries, permanent magnets and electrolyzers, analyses have shown how important it is to have more diversified supply relationships with countries outside the EU. Within the context of this study, general criteria have been formulated for a pre-selection of countries in both the Global North and the Global South. These partnerships should by no means only be limited to the procurement of raw materials, but should instead also focus on intermediate products and end products. Establishing so-called transformation partnerships on equal terms is key to ensuring that the diversification strategy is also successful in the long term. Countries of the Global South (e.g., Indonesia, Namibia) in particular will make future economic cooperation dependent on a greater participation in the value chain.

Germany should definitely combine these new partnerships on raw materials and technology with educational and research collaborations that give substance to these partnerships and ensure that they take place on equal terms. One of the recommendations arising from this study is to undertake more in-depth investigations of the proposed countries over the next few months in order to determine their specific suitability for such partnerships.

Early-stage capacity building in the recycling industry

For a number of strategic raw materials such as lithium, nickel, cobalt and copper from batteries, rare earths from permanent magnets, the end-of-life material flows that will increase in the future (e.g. from de-registered vehicles, decommissioned wind turbines) represent an attractive domestic source of supply for strategic raw materials in the medium and long term. The European metals recycling industry operates at a world-class level in some areas (e.g. copper and precious metals). This optimal starting point must be bolstered with suitable regulatory instruments to support "new" or currently growing recycling infrastructures (such as for lithium-ion batteries, permanent magnets, and later also for PV modules and electrolyzers). The EU Battery Regulation, which will soon come into force, has paved the way with collection targets, material-specific end-of-life recycling quotas (for lithium, etc.) as well as recycled content specifications for batteries that are to enter the market in the future. It is now of paramount importance to robustly implement enforcement in all EU countries over the next few years in order to achieve the ambitious goals that have been set.

The draft law of the Critical Raw Materials Act has set important parameters for the future recycling of permanent magnets and rare earths in the EU. Another important set of rules that is currently in the revision process is the EU End-of-Life Vehicle Directive. which also focuses on specifications for dismantling and processing electric motors (permanent magnets).

Other accompanying instruments to support recycling within the EU are design requirements (see EU Design Directive), R&D funding for new innovative recycling processes or even export restrictions for strategic (intermediate) products from recycling processes. A current example is the related discussion regarding restrictions on the possible export of the valuable "black mass", an intermediate product that comes from the recycling of lithium-ion batteries.

Even if recycling will only supply Europe with relevant amounts of strategic raw materials in the medium term (as of 2030) or long term (as of 2035), the instruments for tapping into this potential must be launched within the next three years.

Appendix

Photovoltaics

TABLE 10 **Raw material intensity of photovoltaic systems in kg/MW**

Component	Raw material or subcomponent	c-Si	CIGS	CdTe	a-Si	GaAs
		Crystalline silicon (wafer-based)	Copper-indium-gallium diselenides	Cadmium-tellurium	Amorphous silicon	Gallium-arsenide
Cells	Silicon	3.700 / 2.000 / 1.250*	–	–	146.7 / 130 / 115*	–
Cells	Gallium	–	6.6/4.5/3*	–	–	22.7
Cells	Germanium	–	–	–	45.3/32/23*	–
Silver paste	Silver	18.5/11/6,5*	–	–	–	–
Wiring/ Wiring	Copper	4,600	4,600	4,600	4,600	4,600
Glass		46,400	46,400	46,400	46,400	46,400
Support structure	Steel	67,900	67,900	67,900	67,900	67,900
Support structure	Aluminum	7,500	7,500	7,500	7,500	7,500

* Value 1: 2020, Value 2: 2030, Value 3: 2045

NOTE The raw material intensities from (Carrara, Alves Dias, Plazzotta, & Pavel, 2020) were taken from the High Demand Scenario as part of a conservative estimation of demand. Deviating from this, the values from the Low Demand Scenario were used for the silicon demand of wafer-based cells, due to a comparatively strong decrease in raw material intensity in recent years. There is a justified assumption that, due to technological advances, a strong future expansion of photovoltaics will lead to a further, significant decrease in raw material intensity. In the Medium Demand Scenario, the specific demand for silicon in 2050 is 2,000 kg/MW, twice as high as in the Low Demand Scenario.

SOURCE Own representation based on (Carrara, Alves Dias, Plazzotta, & Pavel, 2020; Jean, Brown, Jaffe, Buonassisi, & Bulović, 2015).

Prognos, 2023

Lithium-ion batteries

Figure 58 below shows the development of the stock of electric vehicles for the KNDE2045 scenario, differentiated by the vehicle types passenger car all-electric (BEV), passenger car plug-in hybrid (PHEV), passenger car hybrid (HEV), light commercial vehicle all-electric (LCV BEV) and heavy commercial vehicle all-electric (HCV BEV) in detail in five-year steps from 2020 to 2045. Passenger cars without traction batteries, which are missing for the total number of passenger cars by 2045, are neglected in this presentation. The steep ramp-up of battery electric vehicles (BEVs) in particular is reflected in the development of existing vehicles, not least in the medium-term time horizon between 2025 and 2035. For the calculation of the demand for lithium-ion batteries, a detailed consideration of the size classes within the vehicle segments was carried out. Table 12 provides an overview of the allocation of the segments to the size classes or the classification according to the permissible gross weight. In addition, the assumptions on the average battery capacity[1] per size class are listed. For passenger cars, the battery capacities in each case represent the market average of currently available models. Only a few models are available for heavy-duty vehicles, and further increases in range are likely. The battery capacities are based on

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[1] In this paper, the term "battery capacity" (unit kWh) is used for the energy content of batteries, as it has become colloquially accepted in many publications.

Wind power

TABLE 11 **Market shares of wind turbines by technology and raw material intensity (rare earths):**
Wind turbines with permanent magnet and without gearbox have the highest use of critical rare earths. Today, they account for around 75 percent of newly built offshore turbines.

Technology	Market share	Permanent magnets	With gearbox?	Raw material intensity	Rare earths [t/GW]
GB-PMSG Permanent magnet synchronous generator with gearbox	**5 percent** of the onshore plants and **20 percent** of the offshore plants	yes	yes	high	Neodymium: 51 Praseodymium: 4 Dysprosium: 6 Terbium: 1
DD-PMSG Permanent magnet synchronous generator with direct drive	**15 - 20 percent** of the onshore plants and **75 - 80 percent** of the offshore plants	yes	no	very high	Neodymium: 180 Praseodymium: 35 Dysprosium: 17 Terbium: 7
GB-DFIG Double-fed synchronous generator with gearbox	**70 - 75 percent** of onshore turbines and up to 5 percent of offshore turbines	no	yes	very low	Neodymium: 12 Praseodymium: 0 Dysprosium: 2 Terbium: 0
DD-EESG separately excited synchronous generator with direct drive	**5 percent** of onshore plants	no	no	low	Neodymium: 28 Praseodymium: 9 Dysprosium: 6 Terbium: 1

SOURCE Own representation according to (Carrara, Alves Dias, Plazzotta, & Pavel, 2020; IEA, 2021a).

Prognos, 2023

the energy consumption assumed for 2030 and take into account a residual charge of 15 percent. The range given shows the range of the four vehicle configurations considered in the modeling for heavy-duty vehicles (trucks > 3.5t) with ranges of 200 km, 400 km, and 600 km.

The choice of cathode material has a decisive influence on the electrochemical properties of the battery, which is why the type of cathode material is used to distinguish between different Li-ion batteries. In addition, the choice of cathode material affects the critical raw materials needed for the battery.[2] The quantities per car, depending on the cathode material, are shown in Table 12. They are derived from the assumptions and calculations made for this study.

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[2] Graphite has become the standard anode material in lithium-ion batteries, with a small proportion of other materials (lithium titanium oxide, LTO, other carbon-based anodes, graphite anodes with a proportion of silicon). For the focus of this study, these other anode materials are not relevant in terms of quality or quantity and are therefore not considered further here.

FIG. 58 **Stock of electric vehicles in millions**

Especially in the period before 2035, the number of electric vehicles increases very strongly in the KNDE2045 scenario.

ABBREVIATIONS HCV: Heavy Commercial Vehicles, LCV: Light Commercial Vehicles, EV: Electric vehicle, HEV: Hybrid electric vehicle, BEV: battery electric vehicle and PHEV: Plugi-in hybrid electric vehicle, full-HEV: Full hybrid

SOURCE Own modeling based on the KNDE2045 scenario

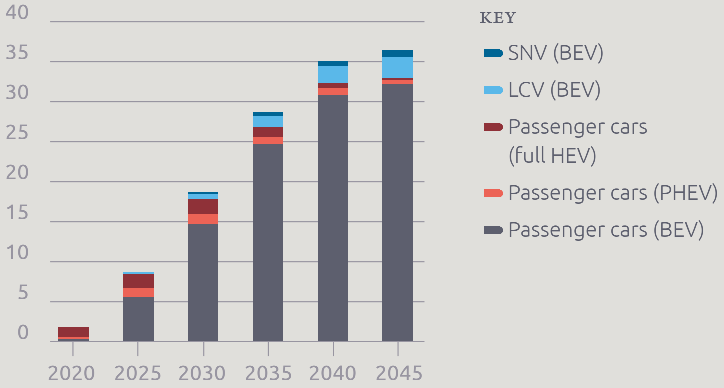

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TABLE 12 **Definition of the modeled size classes and assumption of the average battery capacity in kWh per size class**

The size class of large passenger cars includes very many segments and therefore has a wide range of battery sizes, making it significant based on the number of vehicles.

Size classes	Small car	Medium-size car	Large car	LCV	HCV			
Segments	Mini, small cars	Compact class, mini vans	Mid-size cars, upper mid-size cars, sports cars, SUVs, etc.		Trucks from 3.5 to 7.49 t	Trucks from 7.5 to 11.99 t	Trucks from 12 t	Trucks and semi-trailers
Battery capacity BEV	40 kWh	70 kWh	80 kWh	80 kWh				
Battery capacity PHEV	15 kWh	15 kWh	15 kWh					
Battery capacity HEV	2 kWh	2 kWh	2 kWh					
Battery capacity BEV with 200 km, 400 km and 600 km range					130-380 kWh	210-630 kWh	290-860 kWh	430-1,300 kWh

SOURCE Own assumptions based on KBA registration statistics and vehicle data from ADAC, among others

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TABLE 13 **Material intensities of critical and other raw materials of lithium-ion batteries of different cell chemistries for medium-size cars**

Unlike for the other essential raw materials, the amount of lithium is dependent on battery size but relatively independent of battery chemistry.

Cell chemistry		LFP	NMC 111	NMC 622	NMC 811	NCA	LMO
Total mass	kg / BEV	516	423	403	383	392	508
Battery capacity / energy	kWh	70	70	70	70	70	70
Drive power	kW	125	125	125	125	125	125
Specific energy	Wh/kg	135.6	165.3	173.7	182.8	178.6	137.9
Lithium	kg / BEV	6.2	8.2	7.3	6.5	7.0	6.7
Nickel	kg / BEV		22.5	36.2	43.0	46.2	
Cobalt	kg / BEV		22.6	12.1	5.4	8.7	
Manganese	kg / BEV		21.0	11.3	5.0		88.8
Graphite	kg / BEV	67.0	60.5	60.8	60.8	61.0	56.4
Copper	kg / BEV	49.1	32.8	30.2	27.7	28.5	47.8

SOURCE Own calculation with the BatPaC model of Argonne National Lab

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TABLE 14 **Assumption of the proportion per cathode material for heavy-duty vehicle types**

As energy density becomes more critical for large trucks, a lower LFP content was assumed in contrast to the nickel-rich NMC battery chemistry.

Vehicle type	LFP	NMC 622	NMC 811
Truck – **from 3.5 to 7.49 t**	100 %	0 percent	0 percent
Truck – **from 7.5 to 11.99 t**	80 %	20 %	0 percent
Truck – **from 12 t**	70 %	20 %	10 %
Trucks – **Trucks and semitrailers**	50 %	30 %	20 %

SOURCE Own assumptions, based on interviews with experts

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TABLE 15 **Existing capacities and targets/forecasts for the lithium-ion battery supply chain in the EU***

We are listing facilities that already exist and others that have yet to be constructed. At the same time, certain announcements are still subject to a great deal of uncertainty, while others will be added.

Mining

Raw material	Country	Company	Forecast capacity	Note
Lithium	Germany	Vulcan Energie Ressourcen	4 kt/a Li in 2024, >11.5 kt/a in 2025 (Schaal, S., 2022)	1.120 kt of reserves
	Germany	Zinnwald Lithium	3.5 kt/a Li, no year specified (Zinnwald Lithium, 2023)	
	Austria	European Lithium	3 kt/a from 2025 (European Lithium, 2020)**	Running time: more than 10 years; also Preparation to LiOH
	Finland	Sibanye-Stillwater/ Keliber Oy	4 kt/a from 2025 (Sibanye-Stillwater, 2023a), (Randall, C., 2022)	Term: at least 16 years; plant under construction (Sibanye-Stillwater, 2023b). Also preparation to LiOH
	France	eramet	3.8 kt/a	In planning, pilot completed (eramet, 2023)
	France	Imerys	9.9 kt/a from 2028	In planning (IMERYS, 2022)
	Portugal	Savannah Resources		In planning, no capacity named (savannah resources, 2023)
	Spain	Infinity Lithium	5.7 kt/a (Stockhead, 2021)**	In planning; term: 26 years
	Sweden, Finland	United Lithium		In Exploration (United Lithium, 2021)
	Czech Republic	European Metals	8.5 kt/a (European Metals, 2022)	In planning; term: 25 years
Copper	Sweden, Finland	Boliden	109 kt in 2022 (Boliden, 2023a)	
	Finland	Eurobattery Minerals	0.86 kt/yr (AFRY, 2023) without annual data	
	Poland	KGHM Polska Miedź S.A	392.5 kt in 2022 (KGHM, 2023)	Mining has already started
Nickel	Finland	Eurobattery Minerals	0.9 kt/a (AFRY, 2023) no year specified	
	Finland	Boliden	25-35 kt/a (Boliden, 2023b)	Mining has already started
Natural graphite	Sweden	Talga Resources	Material for 19.5 kt/a anodes	Environmental permit issued (Mining Technology, 2023b)
Cobalt	Finland	Eurobattery Minerals	0.26 kt/a (AFRY, 2023) with no year specification	

* Despite intensive research, the table does not claim to be exhaustive — in this supply chain in particular, there have been constant reports recently.

** Calculated from LiOH quantities

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Further processing

Raw material	Country	Company	Forecast capacity	Note
Lithium	Germany	AMG Lithium	From 2024 >5 kt/a Li, expansion to approx. 29 kt/a planned (IWR, 2023)	Plant under construction
	Germany	Rock Tech Lithium	7 kt from 2025 (cleanthinking.de, 2023)	
	Germany	Livista Energy Europe	Up to 8.5 kt as of 2026	
Cobalt	Finland	Umicore	16 kt/a	Expansion to 21 kt/a planned from 2025 (Coastline, 2023)
Copper	Sweden	Boliden	350 kt in the year (Boliden, 2023a)	
	Poland	KGHM Polska Miedź S.A	586 kt in 2022 (KGHM, 2023)	Of which 381.5 kt from own mines
Nickel	Sweden	Boliden	25-35 kt in the year (Boliden, 2023b)	
	Finland	Terrafame		Already producing, no quantities (Terrafame, 2023)
Cobalt	Finland	Terrafame		Already producing, no quantities (Terrafame, 2023)

Components

Raw material	Country	Company	Forecast capacity	Note
Anode material	Sweden	Putailai	50 kt/a	Synthetic graphite, not yet under construction, no date given (FT, 2023)
	Sweden	Talga Resources	19.5 kt/a	Construction planned from H2 2023 (Mining Technology, 2023b)
	Sweden	Leading Edge Materials	7.4 kt/a (Leading Edge Materials, 2021)	So far only economic analysis, mining and processing over 15 years, natural graphite;
Cathode material	Poland	Umicore	Material for 20 GWh/a 2023, 40 GWh 2024 and 200 GWh/a 2030	Already producing
	Finland	Umicore	20 kt/a	Intermediate products only, expansion to 104 kt/a planned starting in 2025 (Coastline, 2023)
	Finland/Germany	BASF (Zeit, 2023)	Material for approx. 20 GWh/a	Start in 2023
	France	XTC New Energy Materials		Planned from 2026 (Werwitzke, C., 2023b)

SOURCE Own representation with various sources

TABLE 16 **Existing capacities and targets/forecasts for production capacities for lithium-ion cells in the EU until 2030**

The number of announced production capacities and their capacity far exceeds the projected EU demand. However, many of them are subject to a high degree of uncertainty with regard to realization and schedule.

Country	Company	Forecast capacity	Note
Germany	Cellforce	0.1 GWh/a from 2024, later >1 GWh (cellforce, 2022)	
	Northvolt	Up to 60 GWh/a from 2026	
	Leclanché	0.5 GWh/a, planned expansion to 1 GWh/a up to a maximum of 4 GWh/a	Already producing
	SVOLT	16 GWh/a	Planned capacity as of 2025
	SVOLT	6 GWh/a up to a maximum of 24 GWh/a	Planned capacity as of 2025
	Varta	Up to 2 GWh/a from 2026	
	acc	13.4 GWh/a to a maximum of 40 GWh/a as of 2025	
	CATL	8 GWh/a, planned expansion to 14 GWh/a, up to 100 GWh/a as of 2025	Already producing
	Tesla	Up to 200 GWh/a	Planned start before 2030
	Gotion	3.5 GWh/a from 2023, up to a maximum of 18 GWh/a	
	PowerCo/VW	20 GWh/a from 2025 to a maximum of 40 GWh/a	
	QuantumScape	Up to a maximum of 21 GWh/a	Planned start unclear
	Liacon	0.5 GWh/a	Already producing
	UniverCell	1.5 GWh/a	Already producing
Poland	LG Chem	70 GWh/a, planned expansion to 90 GWh/a to a maximum of 115 GWh/a	Already producing
Slovakia	InoBat	0.045 GWh/a, planned expansion to 4 GWh/a up to a maximum of 10 GWh/a as of 2026	
Hungary	Samsung	40 GWh/a	Already producing
	SK innovation	18 GWh/a	Already producing
	SK innovation	30 GWh/a from 2024	
	CATL	Up to 100 GWh/a	Planned start unclear
	EVE Energy	Up to 28 GWh/a	Planned start unclear
Czech Republic	MES	0.2 GWh/a, planned expansion to 1.2 GWh/a up to a maximum of 15 GWh/a	Already producing
Italy	acc	Up to 40 GWh/a from 2026	
	ITALVOLT	Up to 45 GWh/a from 2025	
	FAAM	0.35 GWh/a, planned expansion to 8 GWh/a up to a maximum of 8.3 GWh/a	Already producing
Spain	PowerCo/VW	40 GWh/a from 2026 to a maximum of 60 GWh/a	
	Envision AESC	10 GWh/a to a maximum of 30 GWh/a as of 2025	
	Phi4tech	0.3 GWh/a, planned expansion to 2 GWh/a up to a maximum of 10 GWh/a	Already producing

Country	Company	Forecast capacity	Note
France	acc	13 GWh/a from 2024 to a maximum of 40 GWh/a from 2030 (Schaal, S., 2023b)	
	Envision AESC	9 GWh/a to a maximum of 30 GWh/a as of 2027	
	Blue Solutions/ Bolloré	0.5 GWh/a, planned expansion to 1 GWh/a	Already producing today, time of expansion unknown
	Verkor	Up to 50 GWh/a from 2025	
	ProLogium	Up to 48 GWh/a from 2026	
Sweden	Northvolt	16 GWh/a, planned expansion to 60 GWh/a	Already producing
	Northvolt	Up to 50 GWh/a from 2025	
	Northvolt	0.35 GWh/a	Already producing
Sweden	novo	Up to 50 GWh/a from 2025	
Portugal	CALB	15 GWh/a to a maximum of 45 GWh/a as of 2025	
	Eurocell	Up to 6 GWh/a from 2025	Production site still unknown
	PowerCo/VW	Up to 140 GWh/a	Production site still unknown, time of expansion unknown
	InoBat	Up to 32 GWh/a from 2025	Production site still unknown
	Eurocell	Up to 6 GWh/a from 2025	Production site still unknown

SOURCE Source: Own representation with various sources, primarily (IPCEI Batteries, 2023)

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Permanent magnets

As with traction batteries, the raw material requirements for electric motors are derived from a balance of vehicle size classes. The breakdown of size classes and the assumed engine power per size class are shown in Table 17. The assumed values are based on currently available vehicle models. For "large passenger cars", the range of engine outputs is widest due to the large number of vehicle types in this size class (including SUVs, sports cars) and, as a consequence, the different engine capacities of similar vehicle types. Assuming a growing demand for mid-range models in a mass market of electric vehicles, outstandingly high engine outputs of individual vehicle models have not been included in the averaging. Compared to the values used in this study, the average engine power of new registrations in 2022 was around 145 kW for "medium-size passenger cars" and 240 kW for "large passenger cars". If these values are extrapolated, this would mean a correspondingly higher demand for raw materials, which would, however, be offset by potential for material efficiency in engine development. A quantification of these opposing effects was not possible within the scope of this study. The benefits were therefore set as shown in Table 17 and kept constant over the years.

TABLE 17 **Definition of the modeled size classes and assumption of average Power (in kW) of the drive motors per size class**

In the next few years, the share of electrical motors with permanent magnets for passenger cars will fall from 95 % to 80 %, according to experts.

Size classes	Small car	Medium-size car	Large car	LCV	HCV			
Segments	Mini, small cars	Compact class, mini vans	Middle and upper middle class, sports cars, SUVs, etc		Trucks from 3.5 to 7.49 t	Trucks from 7.5 to 11.99 t	Trucks from 12 t	Trucks and semi-trailers
Engine power, total (number of engines) **BEV**	88 kW (1)	125 kW (2)	180 kW (2)	100 kW (2)	120 kW (2)	170 kW (2)	325 kW (2)	375 kW (2)
Engine output, total (number of engines) **PHEV**	80 kW (1)	80 kW (1)	80 kW (1)					
Engine power, total (number of engines) **HEV**	80 kW (1)	80 kW (1)	80 kW (1)					
Share of permanently excited synchronous motors **BEV**	Current 95 percent, decreases linearly to 80 percent in 2045 in all size classes			Assumption: 100 percent constantly				
Share of permanently excited synchronous motors **PHEV, HEV**	Assumption: a constant 100 percent in all size classes							

SOURCE Own assumptions, based on various sources and experts

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With regard to the permanent magnet demand, a roughly linear dependence on power was assumed according to (Nordelöf et al., 2017). The power density is a good 2kW per kg of motor weight, which corresponds to a permanent magnet quantity of approx. 12-13 g/kW with a magnet content of approx. three percent. Based on the engine outputs in the above table, this results in between 1 and 2.2 kg NdFeB magnet per car[3] approx. 1.6 kg per LCV and between 1.8 and 4.7 kg per HCV (truck).

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[3] Figures are in the range used by other publications cf. (ERMA; Gauss et al., 2021), (REIA, 2022), Furgeri (2021): Design for motors: the way forward. REIA Webinar on Rare Earth Elements in Sustainable Circular Economy.

TABLE 18 **Targets/projects for permanent magnet supply chain in EU/UK/Norway**
Although there are hardly any (announced) productions so far, the value chain of permanent magnets is barely established in the EU.

Mining

Raw material	Country	Company	Forecast capacity	Note
LSE	Sweden	LKAB (High North News, 2022)	4 kt/a Li in 2024, >11.5 kt/a in 2025 (Schaal, S., 2022)	

Further processing

Material	Country	Company	Forecast capacity	Note
SE-oxide	Estonia (euronews.next, 2023)	Neo Performance Materials/Silmet (Turovski, M., 2022)	Not known	Until 2026
	France (SOLVAY, 2022), (FT, 2023)	Solvay	For magnet capacity for millions of EVs (Kinch, D., 2023)	Details such as schedules etc. not yet published
	UK	Pensana (The Chemical Engineer, 2022)	5.000 t/a Nd/Pr oxides	From 2024
	Norway	REEtec (High North News, 2022)	Not known	2024/2026
SE metals	Estonia	Neo Performance Materials/Silmet (Turovski, M., 2022)	Not known	Until 2026
	UK	Pensana (The Chemical Engineer, 2022)	Not known	

Recycling EU Permanent Magnets (SOLVAY, 2023)

	Country	Company	Forecast capacity	Note
Strategic raw materials	EU-27		15 percent of annual consumption: 2030	CRMA (COM, 2023a)

Production of permanent magnets

Material	Country	Company	Forecast capacity	Note
NdFeB magnet	Germany	Vacuum melting	1.000 t/a	Estimated current capacity
	Estonia	Neo Performance Materials/Silmet (neomaterials, 2023)	2.000 t/a	From 2025, expansion later to 5,000 t/a planned (target year not yet known)
	different	Various	7.000 t/a 2030 = 20 percent of Europe’s total. Demand	ERMA Plan (ERMA; Gauss et al., 2021)

SOURCE Own assumptions, based on various sources

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Electrolyzers

TABLE 19 **Global company list electrolyzer manufacturers**

Company	Country	AEL	PEMEL	HTEL	AEM
Acta	Italy				x
Angstrom Advanced	USA	x	x		
Permanent magnet synchronous		x	x	x	x
AREVAH_2 Gen (today Elogen)	France		x		
Asahi Kasei	Japan	x	x		
Auyan	China	x			
Beijing Zhongdian	China	x			
Cawolo	China		x		
Ceres Power Holdings	UK			x	
Cockerill Jingli Hydrogen	China	x			
Cummins	USA		x	x	
Ecolyzer	Germany	x			
Electric Hydrogen	USA		x		
Elogen (previouslyH_2 Gen)	France		x		
Enapter	Germany				x
Erredue	Austria	x			
FuelCell Energy	USA			x	
Green Hydrogen Systems	Denmark	x	x		
GTA Inc	USA		x		
GuofuHee	China	x			
H_2 Core Systems GmbH	Germany				x
H_2 PERIC	China	x			
HIAT Gmbh	Germany		x		
Hitachi	Japan			x	
Hoeller Electrolyzer GmbH	Germany		x		
H-TEC Systems	Germany		x		
Hydrogenics	Canada	x	x		
Idroenergy	Italy		x		
iGas Energy	Germany		x		x
iph Hähn Gmbh	Germany		x		
ITM Power	UK	x			
John Cockerill	Belgium	x			

Prognos, 2023

Company	Country	AEL	PEMEL	HTEL	AEM
Kobelco Eco-Solutions	Japan	x	x		
KohodoH2	China	x			
Kylin Tech	China	x			
Kyocera AVX Group	USA		x	x	
Longi	China	x			
McPhy	France	x			
Millennium Reign Energy	USA	x			
Mitsubishi Power	Japan			x	
NEL	Norway	x	x		
Nel Hydrogen	Norway	x			
Nexceris	USA			x	
Ohmium	USA		x		
ostermeier hydrogen solutions gmbh	Germany		x		
OxEon Energy	USA			x	
PERIC	China		x		
Plug Power	USA		x		
Pochari Technologies	USA	x			
Pro Puls	Germany		x		
Proton Onsite	USA		x		
ShaanXi HuaQin	China	x			
Shandong Saksay Hydrogen Energy	China		x		
Siemens Energy	Germany		x		
SinoHyEnergy	China	x			
SolydEra	Italy			x	
SPIC	China		x		
Sunfire	Germany	x			
Sungrow	China	x	x		
Suzhou Jingli	China	x			
Teledyne Energy Systems	USA	x			
ThyssenKrupp	Germany	x			
TianJin Mainland Hydrogen	China	x			
Toshiba Energy Systems	Japan	x			
Water electrolysis hydrotechnology	Germany	x			
Yangzhou Chungdean Hydrogen Equipment	China	x			

SOURCE Own listing based on (Gallandat, Romanowicz, & Züttel, 2017), (Central Agricultural Commodity Marketing and Energy Network, 2021), (U.S. Department of Energy, 2022b), (BNEF, 2022), (Heuser, R., 2022) and online research

Gas power plants (hydrogen)

Gas-fired power plants that run on greenhouse gas-neutral hydrogen will secure the electricity system of the future with flexible controllable power. Technology options under development include gas turbines (2 to 100 MW class) and gas engines (1 to 10 MW class) for 100 percent hydrogen, and initial models are available on the market. The option of converting to future operation with 100 percent hydrogen is also being offered by an increasing number of suppliers under the name "H_2-Ready". Due to the established natural gas turbine and engine production, no manufacturing bottlenecks are expected for the manufacturers:

For gas engines, there is a wide range of manufacturers with a high degree of vertical integration in Europe. No critical raw materials or materials are known. There are indications that central components such as valves for intake manifold injection of hydrogen are not yet available as series products in the supplier industry.

In gas turbines, there are four global manufacturers — General Electric (USA), Kawasaki (Japan), Mitsubishi Hitatchi (Japan) Power Systems, and Siemens Energy (Germany) — with high vertical integration. Critical elements are sometimes found in superalloys and composites, including as corrosion inhibitors, to increase the strength of highly stressed components such as gas turbine blades: critical raw materials include titanium, nickel, cobalt, chromium, and in some cases molybdenum, tungsten, cerium, hafnium, zirconium, yttrium, niobium, rhenium and ruthenium. According to DERA, the past decades of development show an increase in the proportions of critical elements in superalloys, which, however, are replaced by alternative alloy compositions in case of shortages (Marscheider-Weidemann, F. et al., 2021).

In the absence of hydrogen volume availability and hydrogen distribution infrastructure, further technology development also depends on the ramp-up of hydrogen availability.

Power grid infrastructure

The decarbonization of the German energy system requires a comprehensive expansion of the power grid. According to estimates by Consentec and Agora Energiewende, the transmission grid must be expanded from 35,000 line kilometers today to 50,000 in 2035 (Agora Energiewende, Prognos, Consentec, 2022) and 55,000 line kilometers in 2045[1] be expanded. This also requires more power poles, cables, conductor cables, insulators, transformers, rectifiers, inverters and switchgear.

Since a large part of the renewable energies are connected in the distribution network, extensive conversion and expansion is also imminent here. Whereas distribution networks were originally intended to be more of a one-way street in the direction of the end consumer, a great deal of flexibility and intelligent control is already required today and will be in the future.

In addition to raw materials, components and plant engineering, the issue of cybersecurity is also important when considering the criticality of power grids, especially third-party access, e.g. via rectifiers and inverters. Here, the Chinese company Huawei has high market shares. For PV inverters, the company is the market leader for the seventh year in a row (2021: 22 percent market share). Likewise, there are only a few competitors who can build equivalent DC systems. The issue was not examined in this study, but requires further analysis.

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[1] https://enertile-explorer.isi.fraunhofer.de:8443/open-view/55705/66acc1cfdc47cfea01308bccbdb375f7

TABLE 20 **Components, subcomponents and raw materials in the power grid**

Component	Raw material, subcomponents
Foundation/Foundation	Concrete
Overhead line pylons	Steel frameworks
Overhead lines	Aluminum, steel, zinc
Cable	Copper, insulating oil/adhesive compound, plastics, steel pipe, lead, sand
High temperature cables	Carbon fiber, aluminum, zirconium, steel
Transformers	Iron core, copper coils, oil
Rectifiers, inverters	Silicon, Nickel, Silver
Switchgears	Busbars (aluminum, steel), insulators, transformers

SOURCE Own representation

Prognos, 2023

District heating

In addition to decentralized heat pumps, the climate-neutral generation of district heating and its distribution with the aid of heating networks is an essential component of future heat supply, especially in densely populated areas. District heating systems have the advantage over individual heating systems that they can use a wide range of technologies. In addition to large-scale heat pumps, electric boilers, combined heat and power plants and heating plants using climate-neutral fuels, solar thermal systems, geothermal energy, waste heat from industrial plants or waste incineration can also be used. In the grids, multiple generation plants will complement each other and also use thermal storage to respond flexibly to heat demand and power system signals.

The technologies mentioned are all market-ready and readily available. However, demand for these facilities is expected to increase significantly in the coming years. In addition to creating a stable environment for an economically viable transformation of district heating networks, it is necessary to build up the corresponding capacities and knowledge among manufacturers, planners, approval authorities and heating network operators. Compared to other key technologies, there are fewer strategic dependencies in district heating, as the plant manufacturers are largely based in Germany and Europe and the wide range of technologies means that any shortages can be easily compensated for.

Direct Air Capture (DAC)

Negative CO_2 emissions from technical CO_2 sinks are also necessary to limit global warming (IPCC, 2018). One of the technical options here is CO_2 capture from the atmosphere (Direct Air Carbon Dioxide Capture – DAC). In contrast to CO_2 capture at point sources, direct capture from ambient air captures CO_2 directly from the atmosphere. The captured CO_2 can either be used for the production of synthetic fuels (Direct Air Carbon Dioxide Capture and Utilization – DACCU) or permanently stored geologically (Direct Air Carbon Capture and Storage – DACCS).

In the separation process, fans are first used to direct ambient air to a sorbent. With the help of absorbing or adsorbing substances, the CO_2 is bound from the ambient air. In the final step, heat is added to separate the CO_2 from the sorbent. Depending on the choice of sorbent, the type of regeneration and the required temperature level, different types of plants can be distinguished. The Swiss company Climeworks specializes in the development of the low temperature DAC systems (100° C). The company operates pilot-scale DAC plants in Iceland, Norway and Italy. The Canadian company Carbon Engineering, on the other hand, uses high-temperature DAC plants (900° C) and has set itself the goal of permanently removing 100 million tons of CO_2 from the atmosphere by 2035.

The decisive factor for an industrial ramp-up path of DAC plants is the reduction of the high investment costs and the enormous energy demand. Currently, DAC plants have an electricity demand of 350 - 500 kWhel per ton of CO_2 and a heat demand of 1,500 - 2,000 kWhth per ton of CO_2, depending on the technology and stage of development (Danish Energy Agency, 2021). In addition, water and land requirements are also critical influencing factors.

According to the IEA, there are currently seven DAC projects in Europe with a capture capacity of about 2.6 million tons of CO_2 per year, of which five projects will store CO_2 geologically for the long term and two projects will process atmospheric CO_2 into synthetic energy sources (IEA, 2023).

According to (Deutz & Bardow, 2021), a low-temperature DAC plant, such as Climeworks', consists of the components foundation, building/hall/pipes, adsorbent, container with CO_2 collectors, vacuum system with condenser and CO_2-water separation, and the spare parts. In addition, an area of about 8 km^2 is required to capture one million tons of CO_2 per year. The main raw materials are mainly concrete and steel.

More technologies

In addition to the technologies presented in this study, other facilities are needed to achieve climate neutrality in 2045, such as bioenergy plants (including biomethane processing plants), thermal insulation, CO_2 infrastructure, electric steam crackers, etc. These technologies were not the focus of the analyses because they are either established technologies without critical raw material and component requirements (insulation) or/and because the technologies contribute to comparatively low GHG savings for the critical period until 2030/2035. Further analyses may be required here.

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The transformation to climate neutrality requires a rapid and decisive investment and modernization program in Germany and the EU. A resilient supply with necessary raw materials and strategic goods is an elementary prerequisite to be successful. In this context, new geopolitical challenges must be taken into account in such a way that Europe and Germany do not become susceptible to blackmail and the necessary political freedom for sovereign action is preserved.

The study of the Climate Neutrality Foundation identifies crucial weak points for strategically important transformation industries along the entire value creation and supply chain. It provides answers for politics, business and society on how to increase resilience to exogenous shocks.

The Climate Neutrality Foundation was established to develop robust cross-sector strategies for a climate-neutral and -fair Germany. Based on sound research, the foundation aims to inform and advise — beyond individual interests.

On behalf of the

Climate Neutrality Foundation