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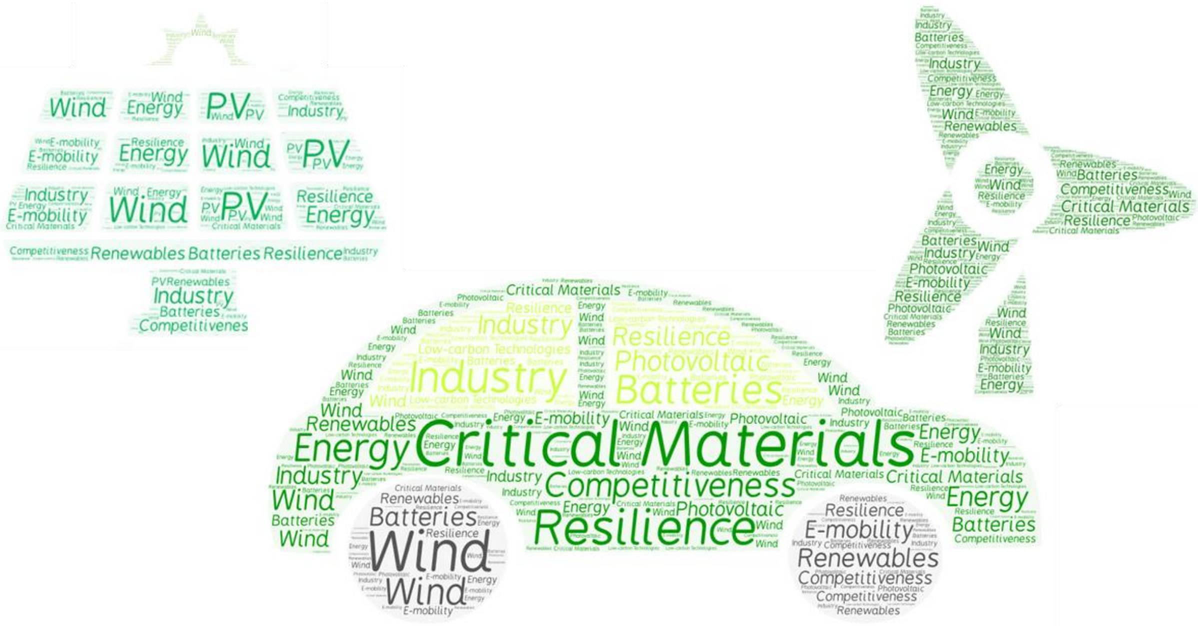
Materials impact on the EU's competitiveness of the renewable energy, storage and e-mobility sectors

Wind power, solar photovoltaic and battery technologies

Pavel, C. C., Blagoeva, D. T.

2017



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Materials impact on the EU's competitiveness of the renewable energy, storage and e-mobility sectors

In the context of the decarbonisation of the European energy system and achieving the long-term climate change mitigation objectives, this study assesses the impact of materials on the competitiveness of the EU's clean energy technology industry, taking into account several factors such as security and concentration of materials supply, price volatility, cost intensity in the technology, etc. These factors, together with the EU's resilience to potential materials supply disruptions and mitigation possibilities, have been analysed for three technologies, namely wind turbines, solar PV panels and batteries. Wind power was found to be the most vulnerable technology in relation to materials supply, followed by solar PV and batteries. From the materials perspective, several opportunities have been identified to improve the EU's industrial competitiveness with regard to the deployment of these technologies, such as boosting recycling businesses in the EU, promoting research and innovation, diversifying the supply and strengthening and increasing downstream manufacturing in the EU.

Contents

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Authors

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Executive summary

This report presents an analysis about materials impact on the competitiveness of EU industry in relation to three technologies: wind energy, solar photovoltaic energy and battery technology. The proposed methodology is used to evaluate the EU's resilience to potential supply shortages of raw, refined and processed materials and to identify a series of opportunities to strengthen the EU's industrial competitiveness regarding these technologies.

Policy context

The fight against climate change and making EU industry stronger and more competitive are top priorities of the current Commission. Moreover, the EU's transition to a low-carbon economy implies, among other things, the large-scale adoption of renewable systems such as wind turbines and solar panels, more advanced grids and the development of battery technologies to store electricity to power the increasing fleet of electric vehicles. This inevitably leads to an increasing demand for certain materials in the medium and long term. The European Union is highly dependent on imports of materials in different forms: raw materials, refined metals, processed materials, compounds, etc. The supply of different materials required for the production of renewable energy technologies is often highly concentrated from just a few countries, some of which even obstructing trade. This makes the EU vulnerable to potential materials supply bottlenecks. Big countries such as China, USA, Brazil, India and Russia are also promoting ambitious decarbonisation policies, meaning that the deployment of renewables and electrification of transport will increase globally. Competition for the same material resources, the likelihood of rapid global demand growth and limitations on ramping up production capacity for certain materials are several factors that may greatly affect the EU's resilience and competitiveness on the global renewables production and storage scene.

Key conclusions

The study shows that materials can greatly affect the competitiveness of the EU industry engaged in clean energy generation and storage sectors through several factors. Wind technology using permanent magnets is found to be the most vulnerable technology in relation to materials, followed by solar PV and batteries.

Main findings

Several opportunities to strengthen the EU's competitiveness have been identified for wind power, solar PV and battery technologies with regard to materials required for these technologies. In the medium term (2025 horizon), recycling can become a viable solution to decrease the EU's reliance on imports of materials. Extending and building new recycling capacity in the EU is essential, in particular to recover critical rare earth elements from wind turbine generators and electric motors, the potential for which appears to be high but not currently fully exploited. A large amount of related research is already being carried out in Europe, including recycling of materials from wind turbine blades. The new solutions should be adopted widely by industry in the coming years, supported by proper EU regulation. As most solar panels and batteries are still in use, the recycling of materials from these technologies is currently limited due to insufficient stock of end-of-life products. However, the recycling potential is high and it is expected to increase significantly after 2025, especially for lithium-ion batteries originating from decommissioned electric vehicles and from stationary electricity storage.

Innovation is another worthy opportunity for the EU to stay competitive in the global context. Through innovation the EU will be able to find smart solutions and improve manufacturing processes at different stages of the materials supply chain, i.e. from raw-materials excavation and processing, to manufacturing of components, to recycling and finding alternative materials.

A diversified materials supply is a tangible way to increase the EU's resilience to potential materials supply shortages. The EU is very dependent on supply of materials from beyond Europe, and in particular from China. China is the global supplier of about half of the raw materials needed in wind energy, solar photovoltaic energy and batteries technologies. Although significant secondary materials flows might be generated in the future through recycling, it is unlikely that recycling alone can cope with the rapidly increasing demand for materials. Mined primary supply will always be needed to fill in the expected materials-demand gap. Therefore, stimulating the mining sector in the EU and increasing domestic production of raw materials, along with becoming partners in ongoing and future global exploration projects, could ensure a continuous and adequate supply of raw materials. Securing access to non-EU countries' resources via trade agreements would represent an additional solution.

The competition for refined and processed materials is even stronger than that for raw materials due to highly concentrated supply. With a few exceptions, China is the major supplier of all refined and processed materials analysed in this study. The EU has no or only a minor share in the global production of processed materials required in wind turbines, photovoltaic solar panels and lithium-ion batteries. Improving downstream manufacturing capacity could make EU Member States more competitive by ensuring viable access to refined and processed materials. This can eventually support and facilitate standardisation and recycling activities in Europe. Establishing long-term cooperation with China within the framework of EU–China cooperation on energy, resources and climate security is another option for the EU to remain competitive and achieve the renewables deployment targets.

In the long term (after 2030), the substitution of critical and scarce materials with other more available materials or substitution at the technology level could play a significant role in improving the EU's resilience and thus strengthening its competitiveness.

Related and future JRC work

In a recent study (EUR 28192), the European Commission's Joint Research Centre (JRC) evaluated the potential bottlenecks in the materials supply chain that may be encountered by the EU on the road to achieving the 2030 targets related to low-carbon energy and transport technologies. The EU's resilience to supply bottlenecks was assessed for three technologies: wind, photovoltaic energy and electric vehicles. The present report takes stock of the previous study and goes further by identifying opportunities in order for the European Union to be competitive in the global market for wind, photovoltaic energy and batteries for energy storage.

Quick guide

This study investigates the impact of raw, refined and processed materials on the EU's competitiveness with regard to deployment of wind power, photovoltaic and batteries technologies in the EU by 2030. Four key opportunities to enhance the EU's industrial competitiveness in these three technologies are identified, namely: boosting recycling business; promoting research and innovation; diversifying supply; and strengthening and increasing downstream manufacturing. Substitution is also found to be a tangible opportunity for the EU in the long term — beyond 2030.

1. Introduction

The possible implications of materials for the successful future deployment of wind, solar photovoltaic (PV) and battery technologies in the EU are analysed in this study. The analysis strives to identify the issues that might affect the EU's competitiveness on the global market. Both raw materials and processed materials are considered in the analysis. Different factors, such as geopolitics, supply security, prices, future demand, materials recycling and substitution potential, are taken into account when assessing materials-related implications.

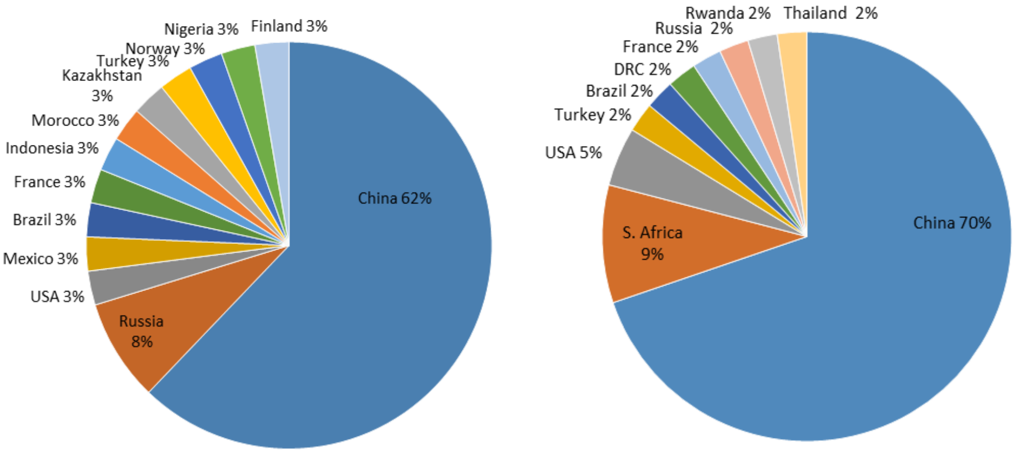
How could materials influence the competitiveness of European industry in renewable technologies?

Competition in the global wind and solar energy market is fierce, as many companies are competing for a share of the world's leading market. Materials can offer European players a competitive edge, hence producing technologies for the generation and storage of renewable energy at a more competitive price.

Several factors could provoke implications when addressing materials and their potential impact on the competitiveness of the clean energy sector.

- **Geopolitics.** The suppliers of materials needed for wind, solar and battery technologies are different from the suppliers of fossil fuels. The EU is strongly reliant on supplies of raw materials from non-EU countries. For some materials near to monopoly supply situation is observed, often from politically unstable countries, sometimes having history of applying export quotas. A European Commission study (European Commission, 2017a) indicates that 62 % of the raw materials identified as critical for the EU economy are supplied from just one country — China (Figure 1, left side). The EU countries supplying Critical Raw Materials (CRMs) are Finland and France, each of them supplying 3 % of the materials needed for the EU economy. On a global scale China is delivering 70 % of CRMs (Figure 1, right side).

Figure 1. Main suppliers to the EU (left) and global suppliers (right) of CRMs



Source: European Commission, 2017a.

- **Competitiveness of the EU's mining sector.** The companies are stimulated to invest in mining activities only in view of a clear business case: if they can sell the product while garnering a certain profit. Opening or extending mining capacity is capital intense and in some cases may require up to 10 years. Therefore, new mine projects and processing facilities are often planned to be developed in countries that are already suppliers. Many of the existing suppliers are currently located in developing countries, where in general the environmental standards and labour/energy costs are low. Since it is very likely that these countries would remain the major future suppliers, no significant change in the security of supply is to be expected. Mining raw materials in the EU at a competitive cost can be a challenge due to strict environmental restrictions and high labour costs, which can often slow the process down and make it more expensive compared to mining activities in developing countries.

- **Material use intensity.** Wind power, solar PV and battery technologies are significantly more material intensive than traditional fossil-based energy-generation and electricity-storage systems. Since renewable and battery-storage technologies are expected to be deployed more broadly in the coming decades, their share of global materials consumption is expected to grow rapidly. Thus, the supply of certain critical materials may not be sufficient to meet the increased demand in a timely manner.
- **Price volatility.** Driven by global fluctuations of supply and demand, the price volatility of materials can greatly influence the production cost of a technology, and therefore the competitiveness of a manufacturing industry. A typical example is the four- to ninefold increase in the price of rare earth elements (REEs) during 2011/2012 due to export restrictions imposed by near-monopolistic China. As a result, the cost of products containing REEs, such as wind turbines, has increased. Since the beginning of 2017 the price of some materials used in batteries has surged as a result of electric vehicle (EV) industry growth, raising concerns among manufacturers.
- **Specific technology share.** The future demand for materials for renewable technologies will depend on how many wind turbines, solar panels and batteries are deployed in the coming years. Uncertainties are created by the fact that the demand for materials will be determined by technology type and share, for example if permanent magnet-based wind turbines are to be more widely deployed in future, the EU’s dependence on China for REEs will increase due to the near-monopolistic supply of such materials and magnets. Deploying more thin-film PV technology will introduce higher dependence on indium rather than on silicon, the reference material for common crystalline silicon PV. Therefore, the chosen specific technology will affect the EU security of supply in a different way due to different geopolitics related to the supply of the required materials.
- **Supply chain integration.** To deal with the increasing effects of globalisation and fiercer competition worldwide, some companies/countries are adopting a so-called supply chain competitiveness strategy. China is a good example. An important element of its success is the integration of the entire supply chain (end to end), from raw materials to final systems. Having undistorted access to raw materials is a necessity, but is not a sufficient condition to be competitive. Better integration of materials sourcing, processing, manufacturing and delivering processes are equally important in improving the overall industry competitiveness.
- **Inter-sectoral competition.** Several emerging technologies and sectors could require the same materials. For example, wind turbines require the same materials as EVs and other non-energy sectors, such as ICT, defence, etc. Therefore, materials demand for renewable technologies should be also assessed in a multi-sectoral context.

Box 1. Materials can significantly influence the competitiveness of EU industry related to renewable generation and storage technologies through a combination of factors, among which rapidly growing demand, security and concentration of supply, price volatility and materials cost intensity of the technologies.

2. Methodological approach

In this study, the competitiveness of European industry in wind power, solar PV and battery technologies from a materials perspective is addressed in relation to the EU's resilience to materials supply issues. In this study resilience is considered to be a key element of industry competitiveness. The EU's overall resilience to potential supply bottlenecks of materials used in wind turbines, solar PV and batteries is assessed as a combination of the EU's resilience at several levels of the value chain: raw materials, processed materials and technological level (Figure 2). The latter is influenced by various mitigation measures.

- **Raw materials**: includes material criticality, cost, key suppliers and associated supply risk, along with recycling and substitution potential.
- **Processed materials**: analysis of key suppliers and associated supply risk.
- **Technological developments**: evaluation of the effect of selected mitigation measures on the technologies under consideration in the 2030 timeframe.

Figure 2. Methodological approach followed in the analysis

Source: JRC representation.

The EU's resilience at the level of raw materials is estimated by a semi-quantitative assessment of seven parameters: materials criticality; cost impact; price evolution; EU import reliance; major production countries and associated supply risk; recycling; and substitution potential.

The average value is then used to determine the EU's resilience for each technology in relation to raw materials required for this particular technology.

The estimate of the EU's resilience at the level of processed materials is based on major countries and EU production shares, taking into account the concentration of supply and political stability of the supplier countries. Details on the calculations of this parameter were provided in a recent JRC study (Blagoeva et al., 2016).

The estimate of the EU's resilience at the technology level is based on four elements: regulation; research and innovation; existing capacity; and future potential of the selected mitigation measures by 2030. More details are given in Section 6.

All parameters used for the assessment of resilience are assigned scores ranging between 0 (red) and 1 (green). The results are presented in a traffic light assessment matrix, with red indicating potential problems and green indicating no issues.

The overall resilience for each technology is estimated as the average of resilience over three steps of the supply chain — raw materials, processed materials and technological developments, the later influenced by the most effective mitigation measures. The EU's resilience for wind technology is calculated as follows:

$$EU\ Resilience_{wind} = [EU\ Resilience\ (Raw\ Materials)_{wind} + EU\ Resilience(Processed\ Materials)_{wind} + EU\ Resilience(Technological\ developments)_{wind}]/3$$

The EU’s resilience for solar PV and batteries is calculated in a similar way:

$$EU\ Resilience_{PV} = [EU\ Resilience\ (Raw\ Materials)_{PV} + EU\ Resilience(Processed\ Materials)_{PV} + EU\ Resilience(Technological\ developments)_{PV}]/3$$

and

$$EU\ Resilience_{batteries} = [EU\ Resilience\ (Raw\ Materials)_{batteries} + EU\ Resilience(Processed\ Materials)_{batteries} + EU\ Resilience(Technological\ developments)_{batteries}]/3$$

The resilience assessment is finally used to identify potential opportunities to improve the EU’s competitiveness in the context of the analysed technologies from a materials perspective.

3. Selection and assessment of raw materials

3.1. Selection of raw materials

Different sub-technologies were considered in order to select the relevant raw materials for wind turbines, solar PV and batteries, as described below.

Wind turbines. Today a mix of wind turbines differing by generator type are used to meet the various specific onshore and offshore site conditions, for example: doubly fed induction generators, electrically excited synchronous generators, squirrel-cage induction generators and permanent magnet synchronous generators (PMSGs). While the onshore market is dominated by traditional doubly fed induction generators, with capacities up to 6 MW, the offshore wind market mostly uses Siemens 3.6-MW turbines, which operate with a high-speed transmission and a squirrel-cage asynchronous generator. Manufacturers of wind power technology have focused on enhancing turbine performance in terms of energy production, reliability, operation, maintenance, capital cost and transportation. The direct-drive turbine with permanent magnet synchronous generators (DD-PMSG) offers certain advantages in terms of efficiency, weight, dimension and maintenance. However, this type of turbine is associated with a high demand for REEs. About 2 tonnes of permanent magnets are used in the 3 MW DD-PMSG turbine (low-speed design), or approximately 650 kg of REEs. In 2015 the global market share of DD-PMSGs was estimated at 19 %. Based on their technical advantages, the global market share of PMSGs is expected to increase in the future, especially for offshore applications — up to 29 % by 2020 and 44 % by 2030 (Lacal-Arántegui and Serrano-González, 2015). The future deployment of wind power generation may be affected by potential disruptions in supply and the rising price of critical REEs.

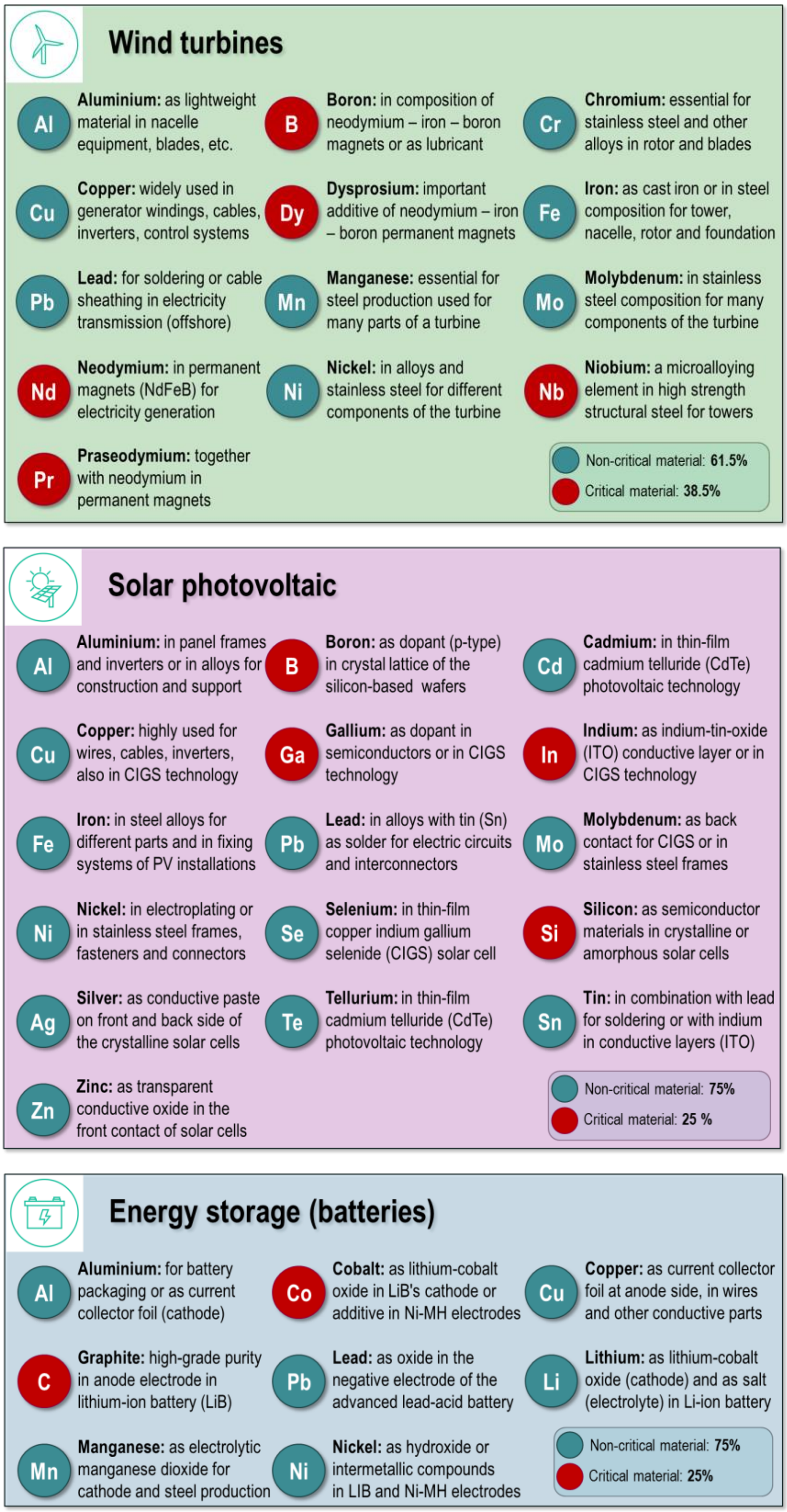
Solar PV. Crystalline silicon solar panels currently account for about 96 % of global installed PV capacity. Since the deployment of thin-film PV technologies, namely copper-indium-gallium-selenide and cadmium telluride, is expected to increase in the future, these sub-technologies are also taken into consideration in the analysis.

Batteries. Currently, two major battery technologies are used in EVs: nickel metal hydride (NiMH) and lithium-ion (Li-ion). However, NiMH batteries are gradually being replaced by Li-ion batteries (Eurobat, 2016). In the power sector, several battery types are currently used to store electricity, mainly sodium sulphur (~ 400 MW), followed by Li-ion (~ 175 MW), advanced lead-acid (~ 75 MW), redox flow (~ 30 MW) and nickel cadmium (~ 25 MW). The numbers refer to the installed global capacity in 2012 (IRENA, 2015a). Between 2013 and 2014 Li-ion batteries saw the largest increase in capacity (around 33 %), while the other types of batteries had a very marginal increase of about 1-2 %. Germany is Europe’s leader in terms of implementing renewable energy. In 2016, 92 % of the newly installed storage capacity in Germany was Li-ion batteries, and only 8 % lead-acid batteries (Figgener et al., 2017). Such facts would lead it to the conclusion that the future tendency will be a steady increase in the Li-ion battery market in both electro-mobility and stationary electricity storage. Advanced lead-acid batteries are also expected to be present in 2030. Therefore, two battery chemistries were considered in this study: Li-ion and advanced lead-acid (World Bank Group, 2017a; Schmidt et al., 2017).

Two recent studies published by the World Bank Group (World Bank Group, 2017b) and Bloomberg (BNEF, 2017a) were also considered when selecting raw materials relevant to the three technologies analysed.

The materials selected for further evaluation required in wind power generation, solar PV and battery technologies are listed in Figure 3. The materials identified as critical for the EU economy (European Commission, 2017a) are highlighted in red.

Figure 3. Representative materials required in wind turbines, PV and battery technologies analysed in this study ([1])



Wind turbines

🔵 **Al** **Aluminium:** as lightweight material in nacelle equipment, blades, etc.

🔴 **B** **Boron:** in composition of neodymium – iron – boron magnets or as lubricant

🔵 **Cr** **Chromium:** essential for stainless steel and other alloys in rotor and blades

🔵 **Cu** **Copper:** widely used in generator windings, cables, inverters, control systems

🔴 **Dy** **Dysprosium:** important additive of neodymium – iron – boron permanent magnets

🔵 **Fe** **Iron:** as cast iron or in steel composition for tower, nacelle, rotor and foundation

🔵 **Pb** **Lead:** for soldering or cable sheathing in electricity transmission (offshore)

🔵 **Mn** **Manganese:** essential for steel production used for many parts of a turbine

🔵 **Mo** **Molybdenum:** in stainless steel composition for many components of the turbine

🔴 **Nd** **Neodymium:** in permanent magnets (NdFeB) for electricity generation

🔵 **Ni** **Nickel:** in alloys and stainless steel for different components of the turbine

🔴 **Nb** **Niobium:** a microalloying element in high strength structural steel for towers

🔴 **Pr** **Praseodymium:** together with neodymium in permanent magnets

🔵 Non-critical material: **61.5%**
🔴 Critical material: **38.5%**

Solar photovoltaic

🔵 **Al** **Aluminium:** in panel frames and inverters or in alloys for construction and support

🔴 **B** **Boron:** as dopant (p-type) in crystal lattice of the silicon-based wafers

🔵 **Cd** **Cadmium:** in thin-film cadmium telluride (CdTe) photovoltaic technology

🔵 **Cu** **Copper:** highly used for wires, cables, inverters, also in CIGS technology

🔴 **Ga** **Gallium:** as dopant in semiconductors or in CIGS technology

🔴 **In** **Indium:** as indium-tin-oxide (ITO) conductive layer or in CIGS technology

🔵 **Fe** **Iron:** in steel alloys for different parts and in fixing systems of PV installations

🔵 **Pb** **Lead:** in alloys with tin (Sn) as solder for electric circuits and interconnectors

🔵 **Mo** **Molybdenum:** as back contact for CIGS or in stainless steel frames

🔵 **Ni** **Nickel:** in electroplating or in stainless steel frames, fasteners and connectors

🔵 **Se** **Selenium:** in thin-film copper indium gallium selenide (CIGS) solar cell

🔴 **Si** **Silicon:** as semiconductor materials in crystalline or amorphous solar cells

🔵 **Ag** **Silver:** as conductive paste on front and back side of the crystalline solar cells

🔵 **Te** **Tellurium:** in thin-film cadmium telluride (CdTe) photovoltaic technology

🔵 **Sn** **Tin:** in combination with lead for soldering or with indium in conductive layers (ITO)

🔵 **Zn** **Zinc:** as transparent conductive oxide in the front contact of solar cells

🔵 Non-critical material: **75%**
🔴 Critical material: **25 %**

Energy storage (batteries)

🔵 **Al** **Aluminium:** for battery packaging or as current collector foil (cathode)

🔴 **Co** **Cobalt:** as lithium-cobalt oxide in LiB's cathode or additive in Ni-MH electrodes

🔵 **Cu** **Copper:** as current collector foil at anode side, in wires and other conductive parts

🔴 **C** **Graphite:** high-grade purity in anode electrode in lithium-ion battery (LiB)

🔵 **Pb** **Lead:** as oxide in the negative electrode of the advanced lead-acid battery

🔵 **Li** **Lithium:** as lithium-cobalt oxide (cathode) and as salt (electrolyte) in Li-ion battery

🔵 **Mn** **Manganese:** as electrolytic manganese dioxide for cathode and steel production

🔵 **Ni** **Nickel:** as hydroxide or intermetallic compounds in LIB and Ni-MH electrodes

🔵 Non-critical material: **75%**
🔴 Critical material: **25%**

Source: JRC analysis.

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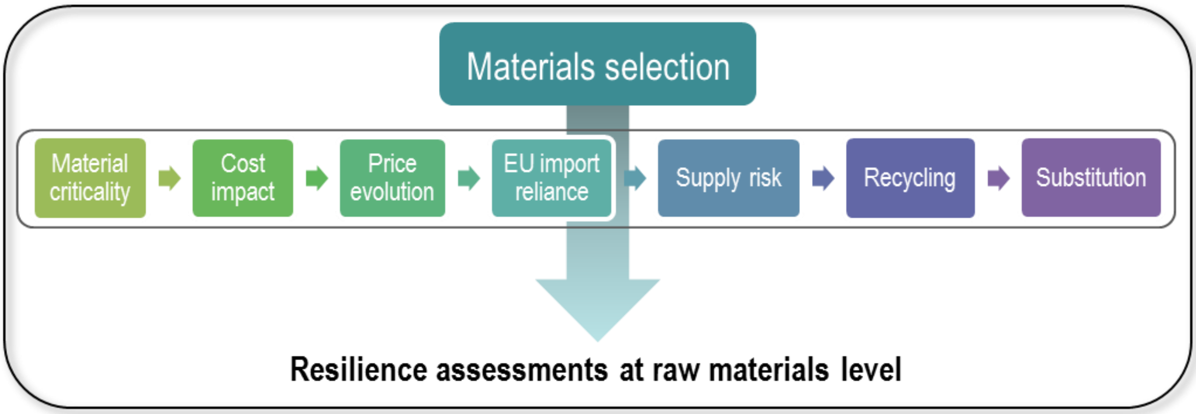
[1] NB: (i) Boron is obtained from borate minerals. Borate is identified as critical in the 2017 CRM list. (ii) Silicon is intended to be silicon metal: silicon used in solar PV is in the form of polysilicon. Silicon metal is the primary feedstock for almost all polysilicon used in solar PV. Silicon metal is identified as critical in the 2017 CRM list.

3.2. Assessment of raw materials

Several parameters, mainly concerning the sustainable supply of raw materials, are used to assess semi-quantitatively the EU's resilience to raw materials supply for the mass deployment of wind, solar PV and battery technologies (Figure 4). In addition, recycling and substitution potential were taken into consideration for the assessment.

Figure 4. Parameters used to assess the EU's resilience at raw materials level.



Source: JRC representation.

A short explanation is given below for each of the parameters used.

3.2.1. Criticality of materials

The criticality of the selected materials is in accordance with the latest European Commission study on CRMs (European Commission, 2017a). The materials in red circles were assessed as critical for the EU economy, thus having both high supply risk and high economic importance. The role of the selected materials in the different technologies is also described in Figure 3.

Overall, 40 % of the materials required for wind, solar PV and batteries are critical according to the new 2017 CRMs list. Lithium and silver were also identified as materials for which supply shortages can be expected for the large-scale deployment of batteries and solar PV (Blagoeva et al., 2016). Thus, 44 % of the materials listed in Figure 3 are potentially problematic materials for these three technologies.

Assessment: all critical materials according to the CRM 2017 list required in a given technology were assigned a value equal to 0. Conversely, non-critical materials were assigned a value equal to 1. The average of all assigned values — a numerical between 0 and 1 — was taken as a measure of "Material criticality" parameter — see Figure 4.

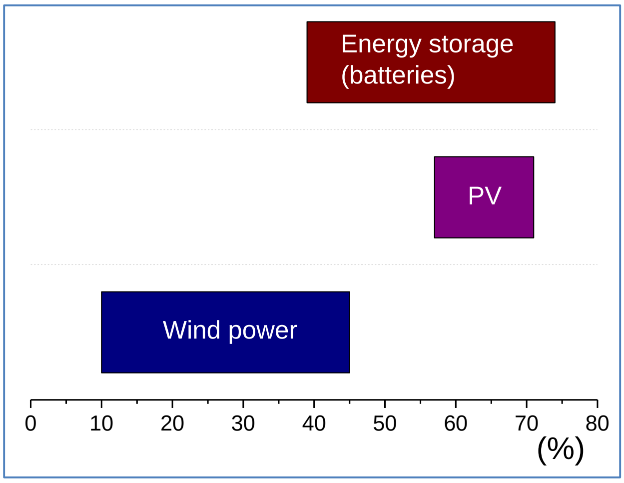
Box 2. 40 % of the materials used in wind turbines and around 25 % of the materials used in PV panels and batteries are evaluated as critical for the EU economy based on the 2017 CRMs list.

3.2.2. Impact of materials on the cost of technology

The price of materials is a substantial part of the final cost of the three technologies. Therefore, an increase in the price of materials may adversely affect the production costs and profit margins of technology manufacturers.

Batteries rely on the most intensive use of materials per unit output, leading to a substantial part of the cost of batteries — up to 74 % (Figure 5). This means that any volatility in the price of materials can significantly affect the cost of batteries.

Figure 5. Impact of material prices (²) on the cost of wind turbines, solar PV panels and batteries



Source: JRC representation, with data from: Berger, 2011; CCS, 2012; CEMAC, 2015a; CEMAC, 2015b; DoE, 2015; EIA-ETSAP, 2017; Greentechmedia, 2012, 2017; IRENA, 2012 and WEC, 2016.

A relatively large impact of materials in the cost breakdown is also observed for solar panels, for example 57 % for thin film PV and 71 % for c-Si modules.

The least vulnerable technology in terms of the cost of materials is wind technology. Materials are responsible for 10-45 % of the cost of wind technology. This range takes into account different types of wind turbines, different capacities and different installation locations (onshore or offshore). The cost of offshore wind farms is less impacted with regard to materials. The future tendency, however, is to build larger turbines, employing bigger generators and blades. As blades become larger, the demand for materials increases exponentially, leading to a larger share of the final cost breakdown.

Assessment: the "Cost impact" parameter (Figure 4) was assessed as the complement (³) of the mean value of the impact of materials' prices on the cost of the relevant technology (Figure 5).

Box 3. Batteries are the most 'material cost-intensive' technology, and are therefore most vulnerable to price volatility, followed by solar and wind.

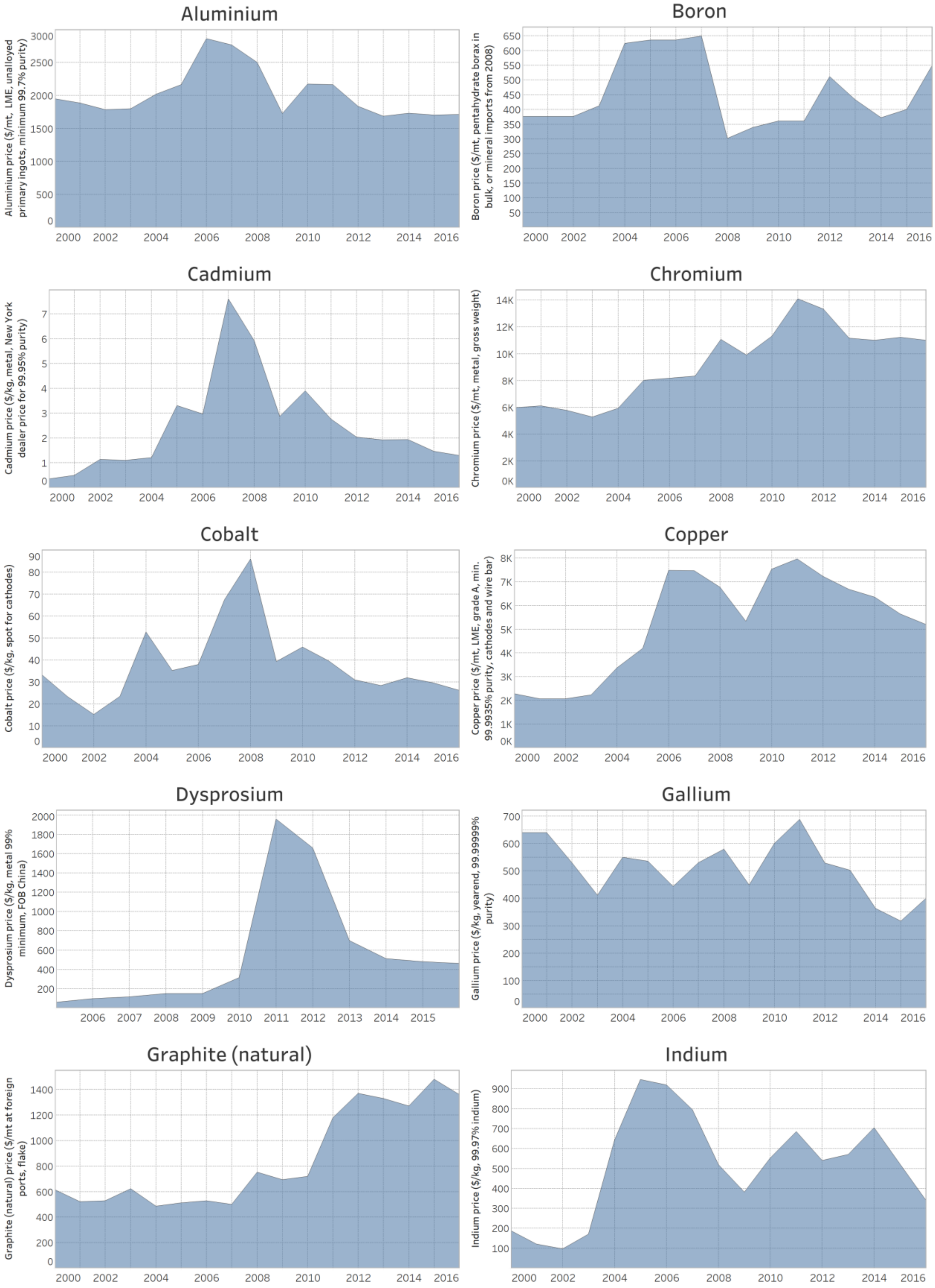
3.2.3. Changes in the price of materials

Increases in the price of raw materials can significantly influence the cost of technology, especially for more 'materials-intense' technologies, adversely affecting the profit margins of companies and therefore their competitiveness. Hence, price fluctuations are considered as a separate parameter in the following assessment. Changes in the price of the selected materials from 2000 to 2016 are shown in Figure 6.

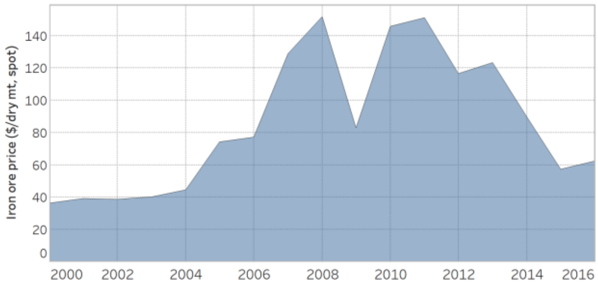
(²) In this figure 'material prices' refers to the costs associated with both raw materials and processed materials.

(³) Complement of a number is determined by subtracting that number from 1.

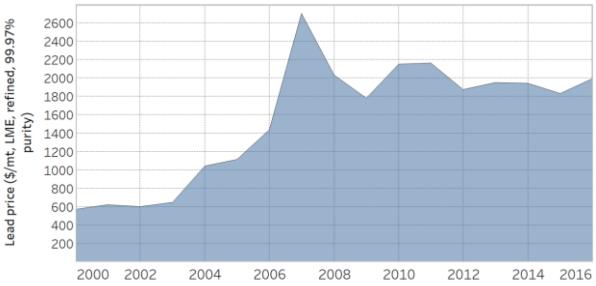
Figure 6. Raw materials prices from 2000 to 2016



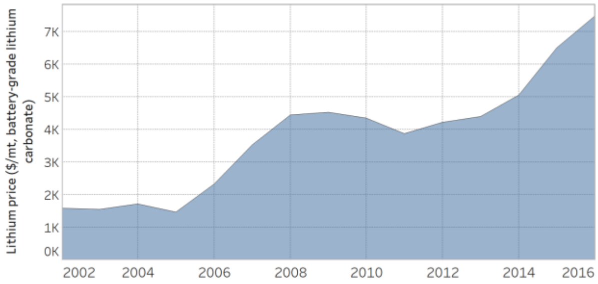
Iron ore



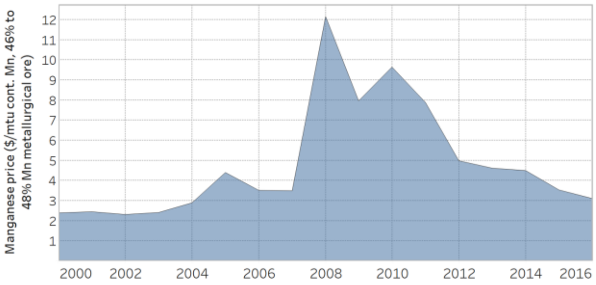
Lead



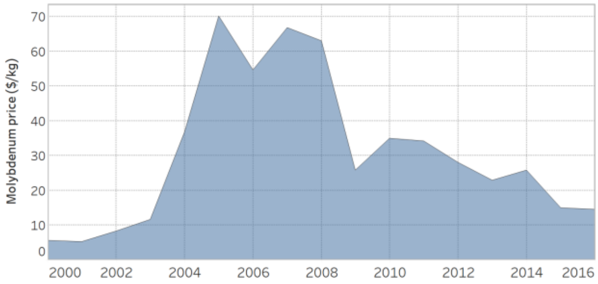
Lithium



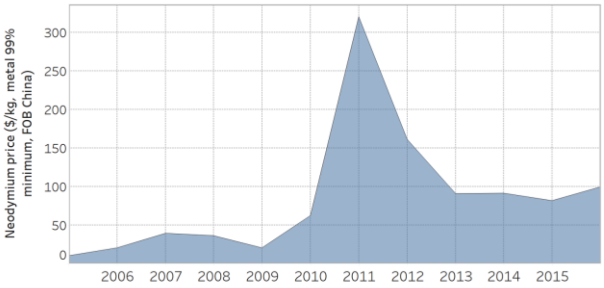
Manganese



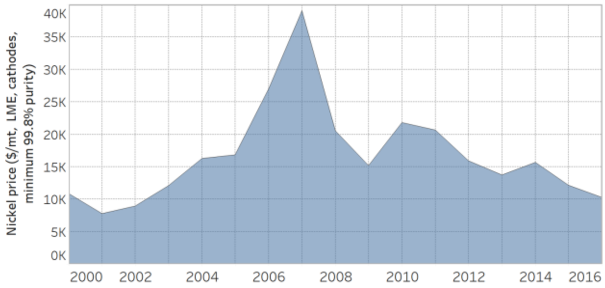
Molybdenum



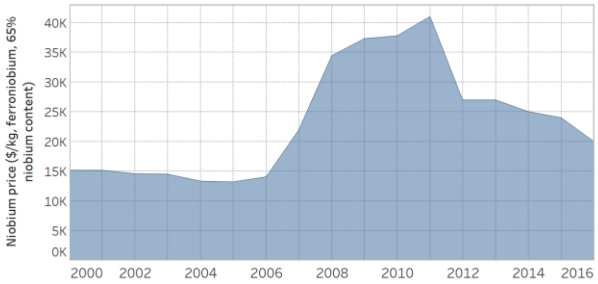
Neodymium



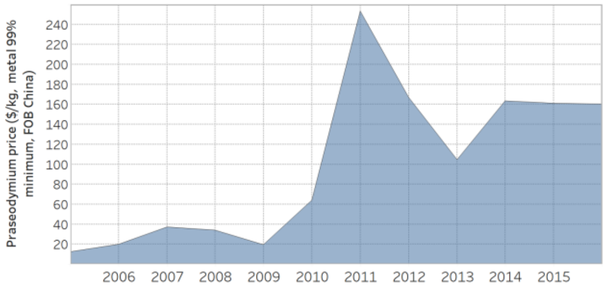
Nickel



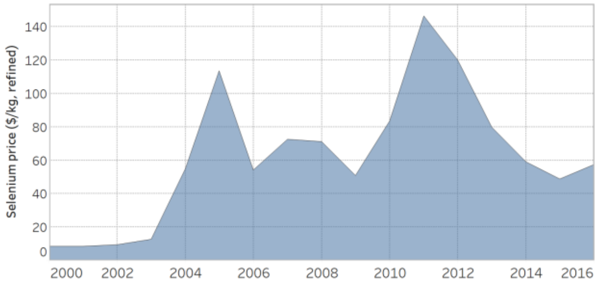
Niobium

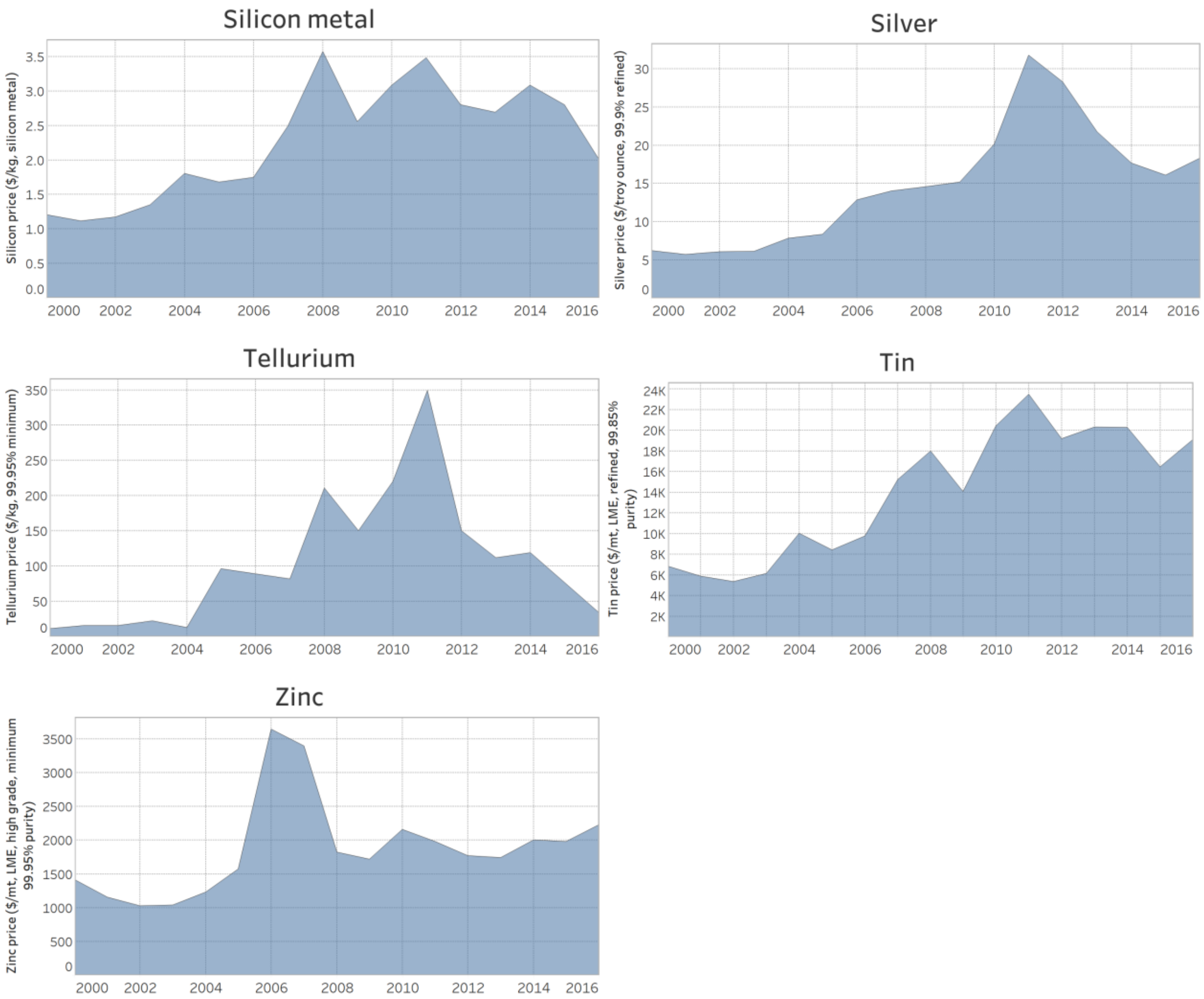


Praseodymium



Selenium



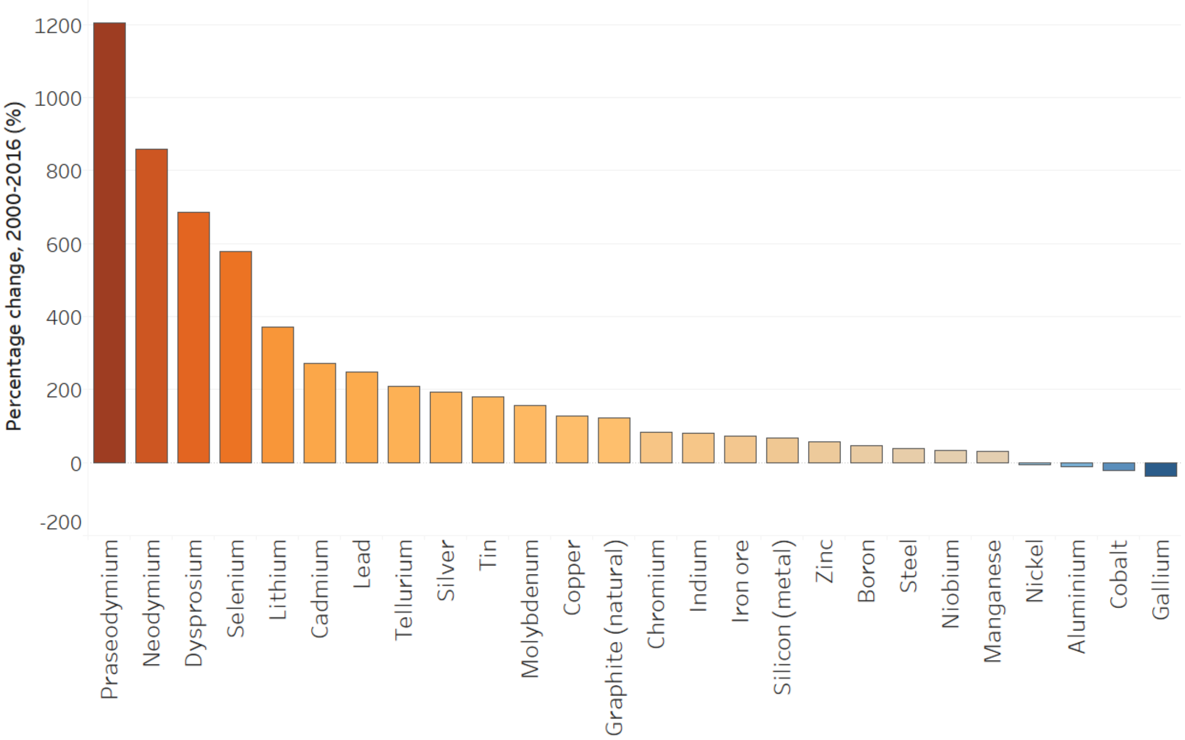


Source: JRC representation, with data from: Asian metal, 2017; Metalary, 2017; USGS, 2003, 2009, 2013 and 2017; World Bank, 2017a.

Materials are traded in a variety of forms, ores/refined grades and currencies, and under different contract periods. The price of materials varied dynamically between 2000 and 2016 following changes in supply and demand and in the economic and political situation worldwide. A particular cause for concern is the price of REEs, namely neodymium, praseodymium and dysprosium, which surged several times in 2011 due to export restrictions imposed by China as the monopoly supplier. Overall, prices rose from 2000 to 2016 for most materials needed for the considered technologies in this analysis (Figure 7).

The highest price increase was registered for the above mentioned REEs. The price of neodymium and praseodymium increased considerably in the first half of 2017 (by 21 % for neodymium oxide and 34 % for neodymium-praseodymium alloys). These materials are used in the production of permanent magnets, which are used in manufacturing PMSG-based wind turbines and in high-efficiency permanent magnet synchronous-traction motors used in EVs. The price of neodymium and praseodymium increased by 8 % and 6 % respectively in the second quarter of 2017 compared to the first quarter. The price of dysprosium fell by 2 % over the same period as a consequence of a reduction in specific consumption in non-temperature-dependent magnet applications. According to Roskill, the prices for neodymium and praseodymium are forecast to grow strongly over the next 3-4 years as demand for neodymium iron boron (NdFeB) magnets takes off (Roskill, 2017).

Figure 7. Changes in the price of materials between 2000 and 2016



Source: JRC representation, with values from Figure 6.

The price of lithium carbonate and cobalt, used in the cathode of a battery, almost doubled in the first semester 2017 as result of the increasing popularity and rising sales of EVs. Moreover, there are concerns among carmakers about securing the future supply of lithium and cobalt. It is expected that the growth in the production of cobalt would not be able to keep up with the growth in demand. A cobalt production deficit may be registered in 2021, followed by a significant shortage in the years after that (BNEF, 2017b).

The price of lead rose by 17 % in the first half of 2017, with the price of copper up by 14 %. Aluminium also registered a price increase of 13 % due to resurgent economic growth, particularly in China, and in increase in its use by carmakers.

According to the World Bank the price of metals increased by 10 % in the first quarter of 2017 and is projected to rise by 16 % by the end of 2017, driven by strong Chinese demand (World Bank, 2017b). The increase in the price of metals could be further boosted by increasing sales of global high-tech applications and EVs, declining mining mineral grades and possible production-cost inflation (Bloomberg, 2017a).

Assessment: for each technology, an average of the price increase rates (% change) in the period 2000-2016 for all relevant materials was determined. Subsequently, the three averages were normalised to the maximum; the complement of such values are then taken as the "Price evolution" parameter — see Figure 4.

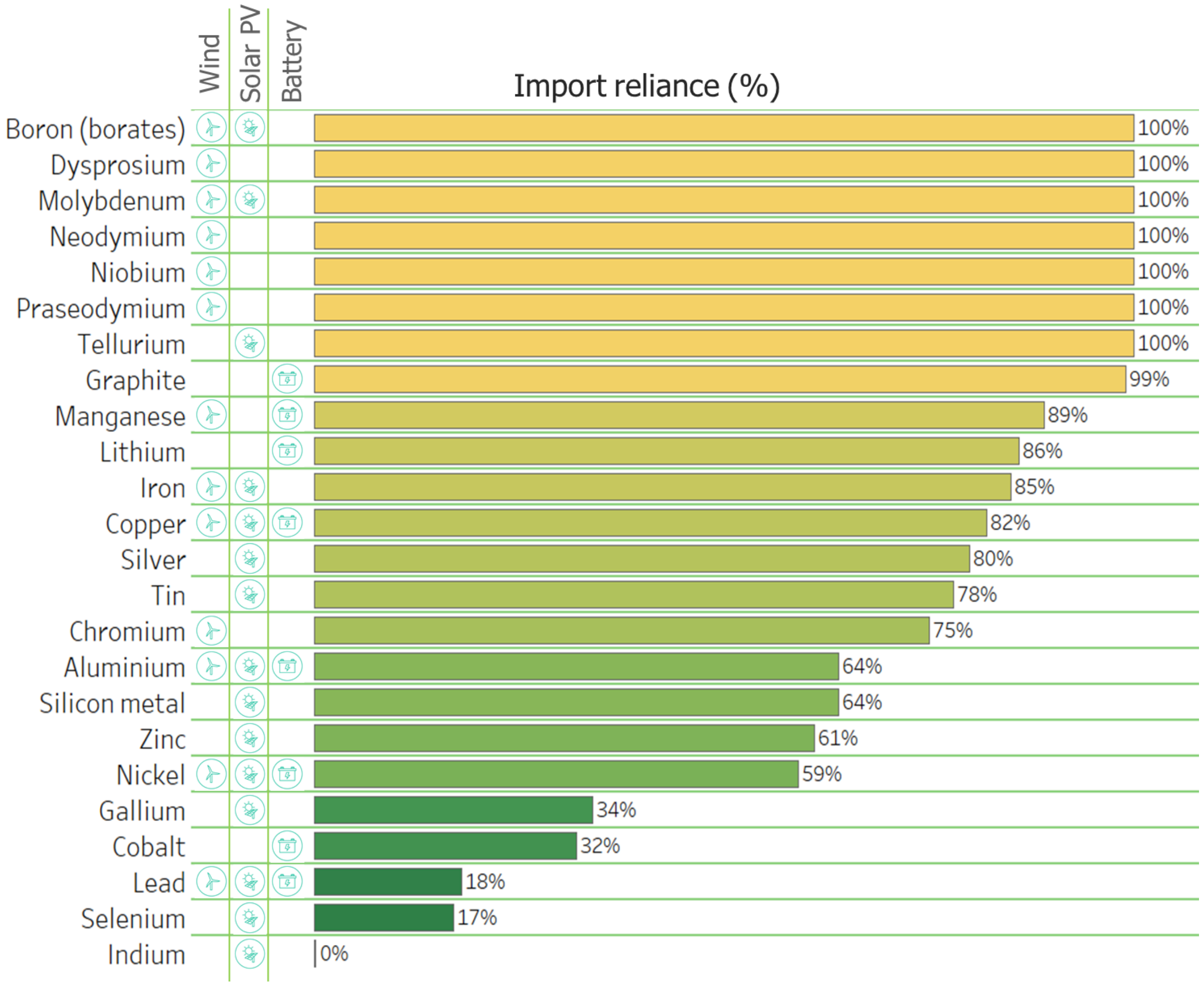
Box 4. The price of most of the materials required in wind turbines, solar PV panels and batteries has increased significantly between 2000 and 2016. The price of about half of the materials increased more than double and for several materials surged by a factor 9 to 13. The price of metals is projected to increase by 16 % in 2017, driven by resurgent economic growth, particularly in China.

3.2.4. EU import reliance

While raw materials are abundant in the Earth's crust, a potential deficit of mining and refining production could represent a bottleneck in the supply of materials for low-carbon energy technologies. The EU lacks extractive industry (mining activities) for many raw materials, therefore the refining and manufacturing industries rely on production and supply from mainly non-EU countries.

The EU largely depends on imports for materials that are important for the manufacture of wind turbine, PV and battery technologies (Figure 8). The EU's import dependency is 100 % for a group of seven materials, namely boron (borates), dysprosium, molybdenum, neodymium, niobium, praseodymium and tellurium. For 19 materials out of 24 the share of EU imports is above 50 %. Only indium shows an import dependency equal to zero.

Figure 8. Import dependency for the selected materials used in wind, PV and battery technologies (4)



Source: JRC representation, with data from European Commission, 2017a.

Assessment: For each technology, the average import reliance for all relevant materials was determined; subsequently its complement was used as "EU import reliance" parameter (see Figure 4).

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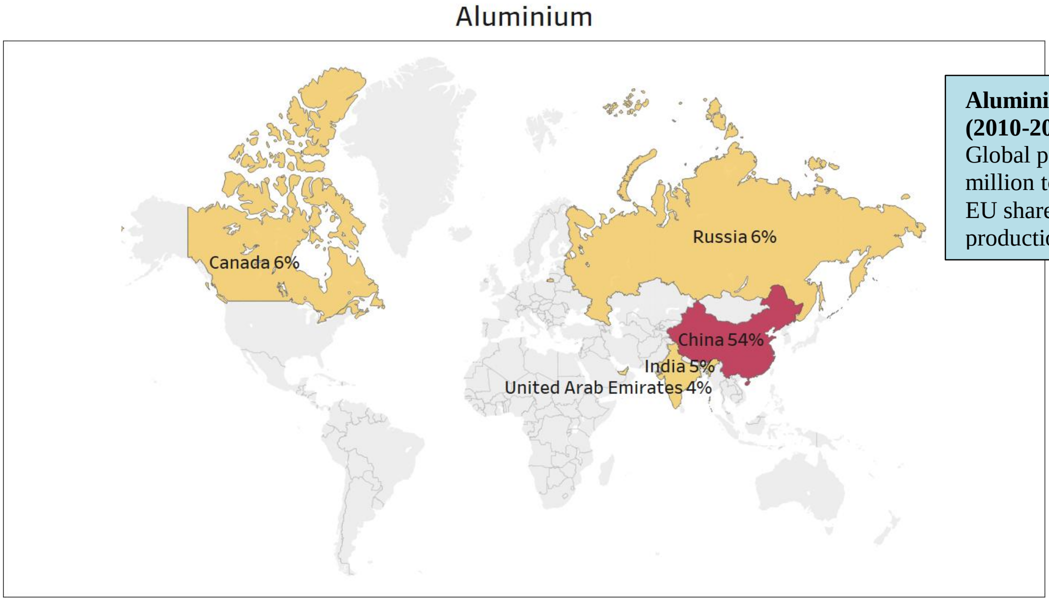
(4) NB: Cadmium is not included in this representation due to a lack of data. Data for iron ore were taken from the Raw Materials Scoreboard 2016 (European Commission, 2016a).

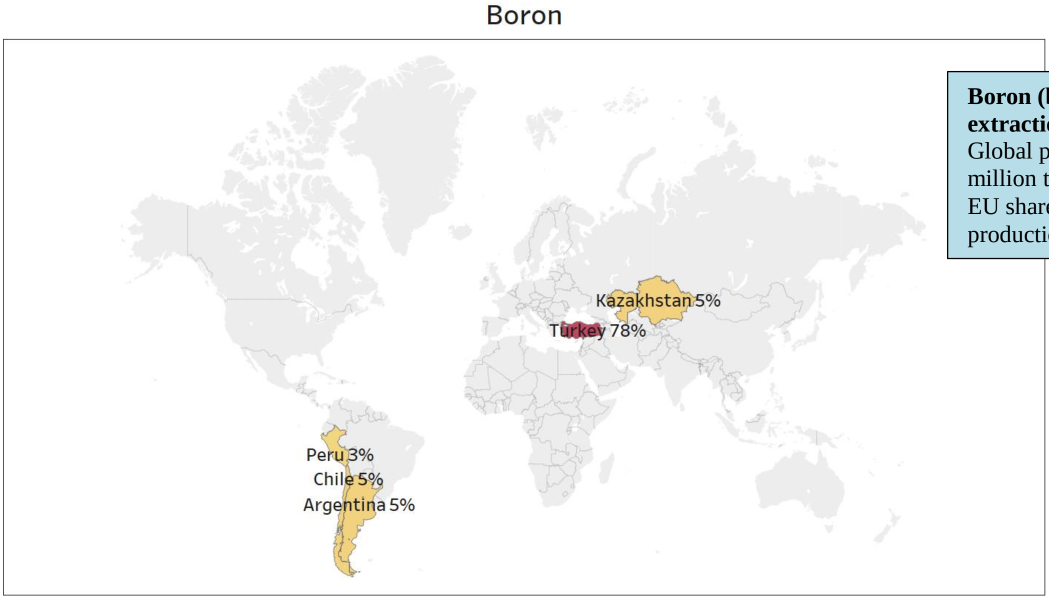
3.2.5. Major production countries

The geographical distribution of the major production countries of the selected materials is represented in Figure 9. Countries' share of global production, global material production (as an average value for the 2010-2014) and the EU's share of global production are displayed for each material.

Figure 9. Major production countries of the selected materials used wind turbines, solar PV panels and batteries in 2016 ([5])


Aluminium

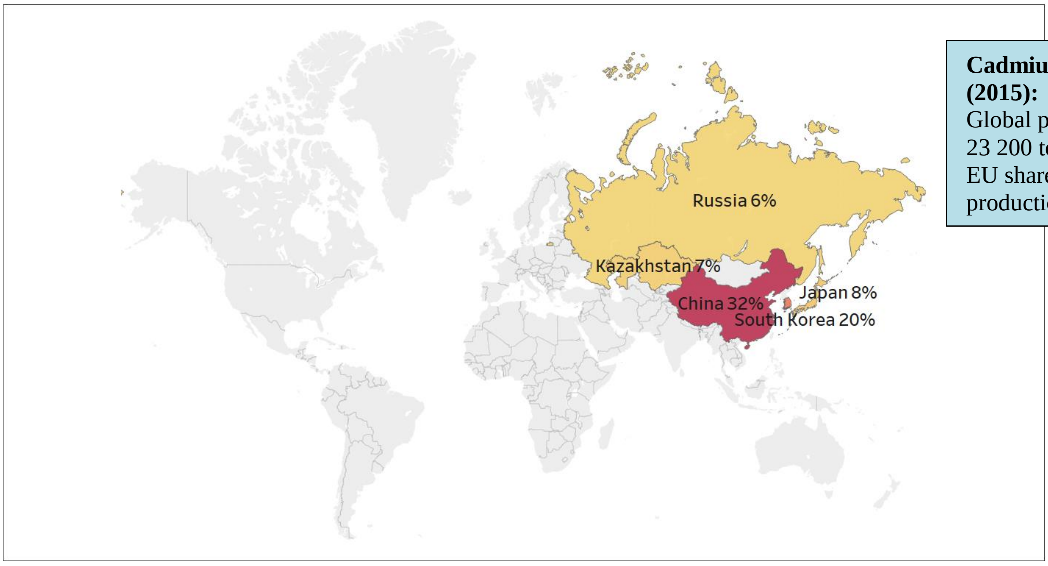
Aluminium refining (2010-2014):
Global production = 47 million tonnes
EU share of global production = 4.7 %


Boron

Boron (borates) extraction (2010-2014):
Global production = 1 million tonnes
EU share of global production = 0 %

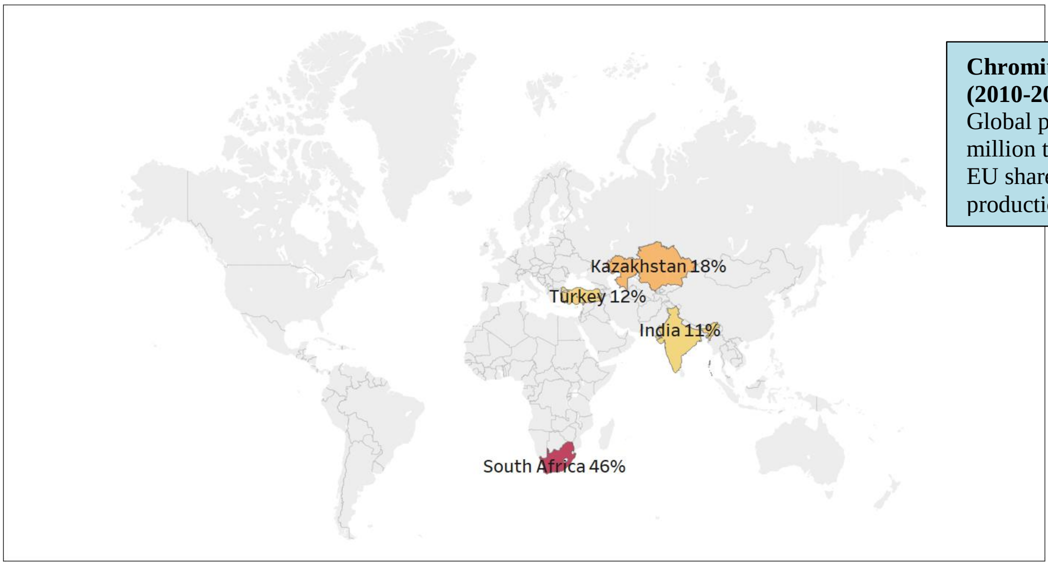
([5]) Global production represents the 2010-2014 average, except for iron ore, which refers to production in 2016.

Cadmium



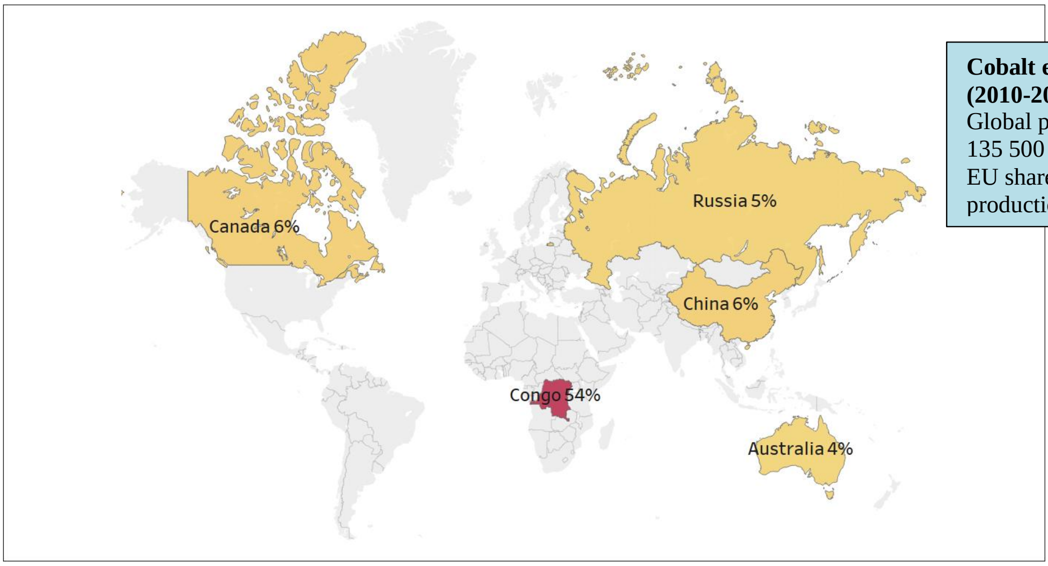
Cadmium refining (2015):
Global production = 23 200 tonnes
EU share of global production = 7 %

Chromium



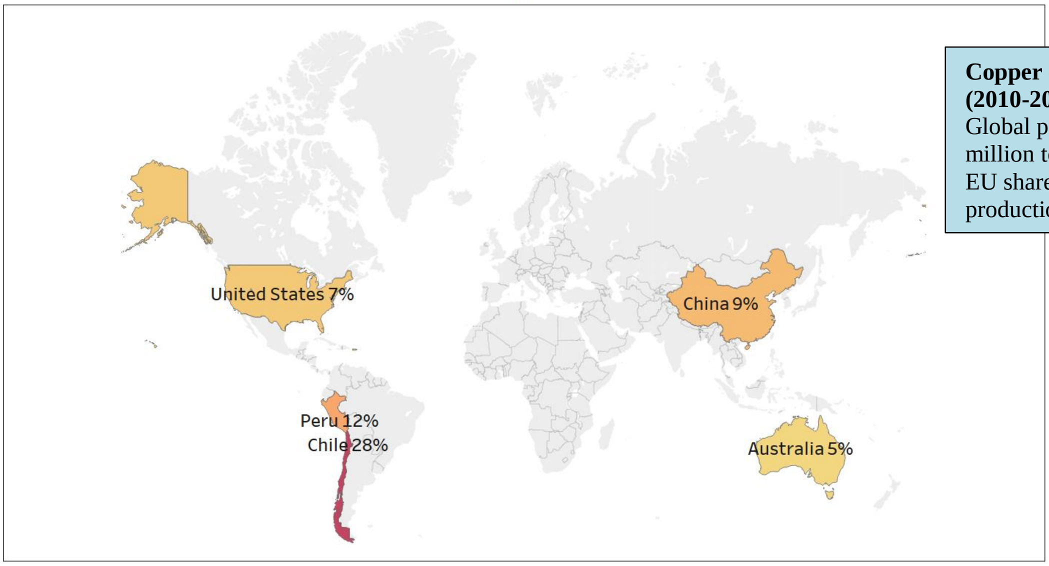
Chromium extraction (2010-2014):
Global production = 30 million tonnes
EU share of global production = 2.5 %

Cobalt



Cobalt extraction (2010-2014):
Global production = 135 500 tonnes
EU share of global production = 0.9 %

Copper



Copper extraction (2010-2014):
Global production = 17.1 million tonnes
EU share of global production = 4.7 %

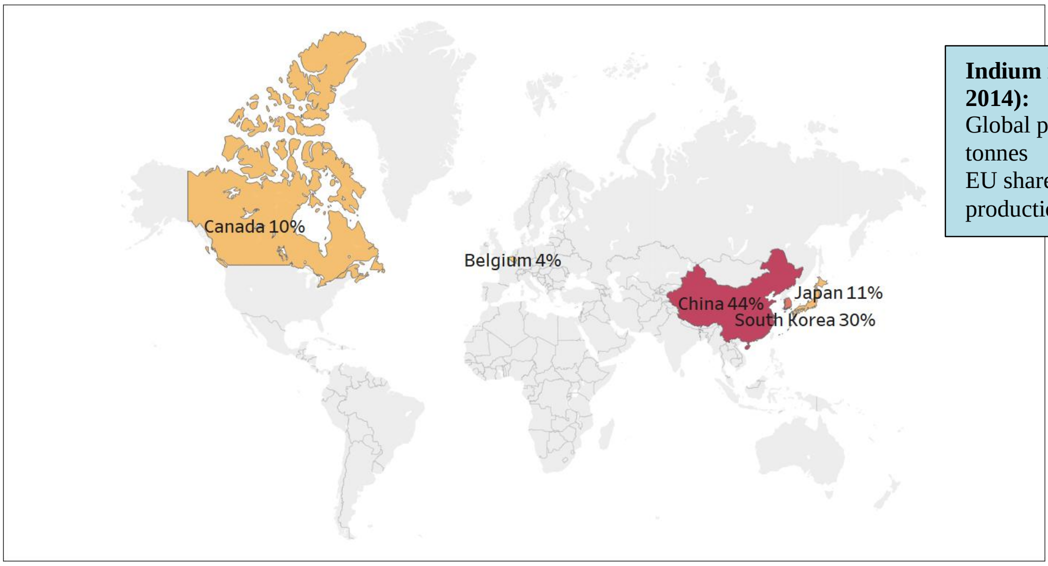
Gallium

Gallium refining capacities (2014):
Global capacity = 340 tonnes
EU share of global capacity = 8.8 %

Graphite (natural)

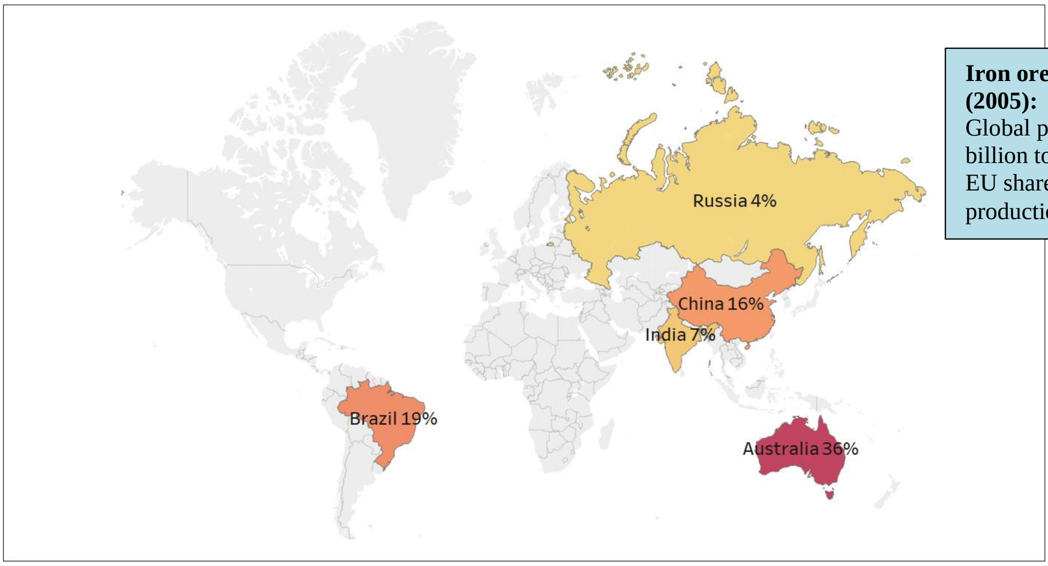
Graphite (natural) extraction (2010-2014):
Global production = 1.1 million tonnes
EU share of global production = 0.05 %

Indium



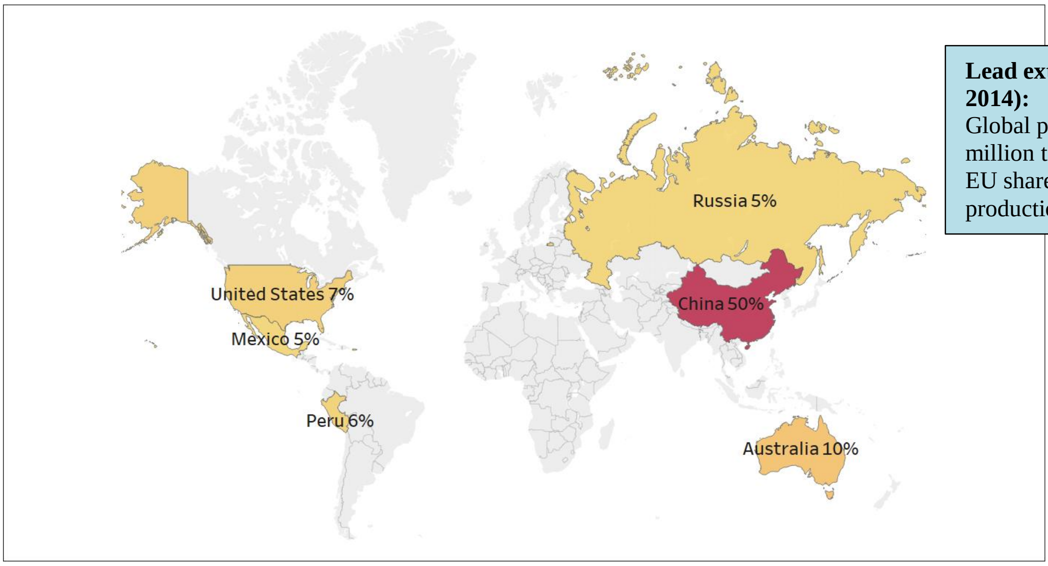
Indium refining (2010-2014):
Global production = 690 tonnes
EU share of global production = 6.9 %

Iron ore



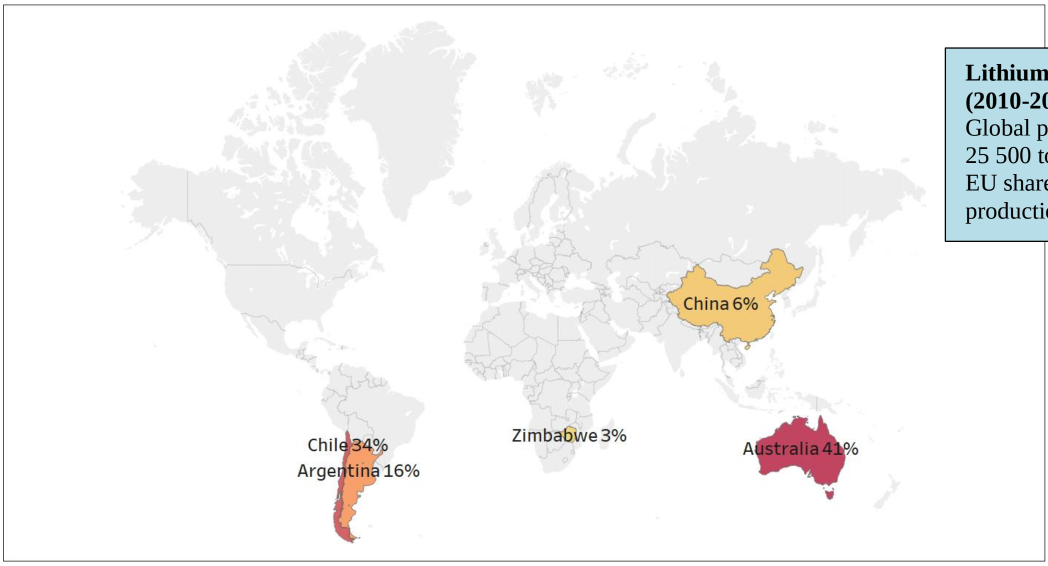
Iron ore extraction (2005):
Global production = 2 billion tonnes
EU share of global production = 6.9 %

Lead



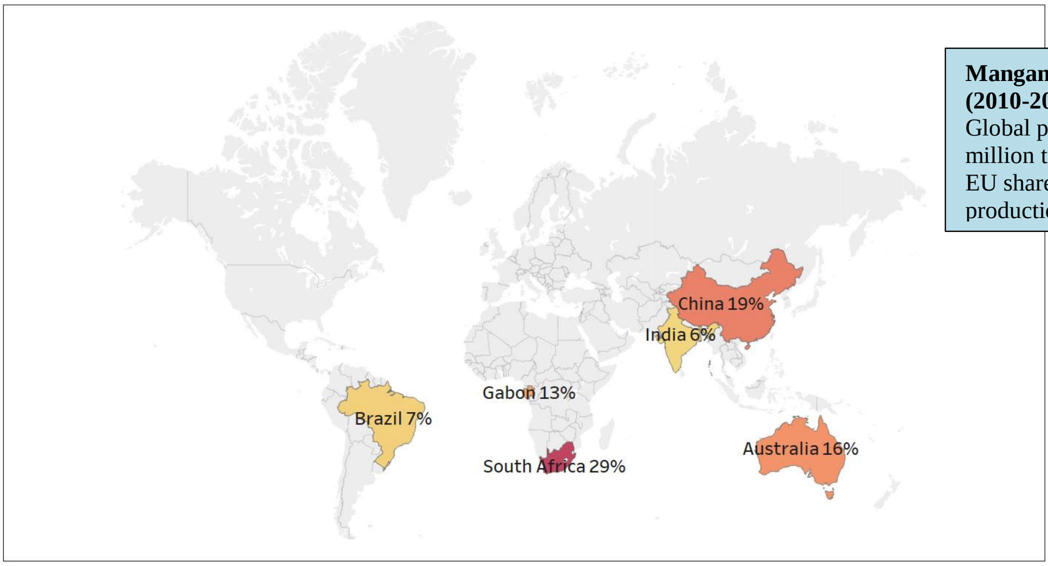
Lead extraction (2010-2014):
Global production = 5 million tonnes
EU share of global production = 4.3 %

Lithium



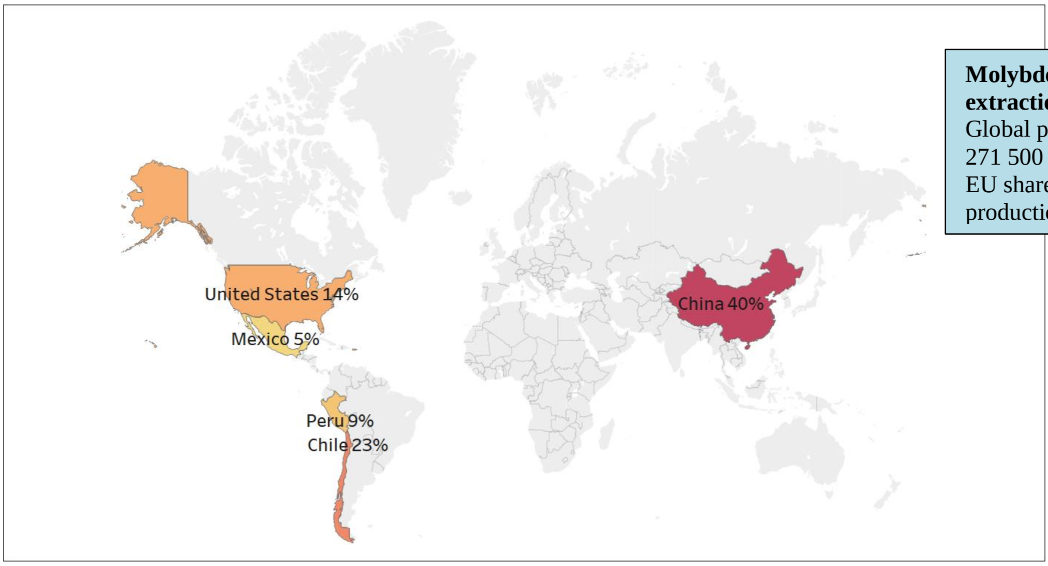
Lithium extraction (2010-2014):
Global production = 25 500 tonnes
EU share of global production = 1.4 %

Manganese



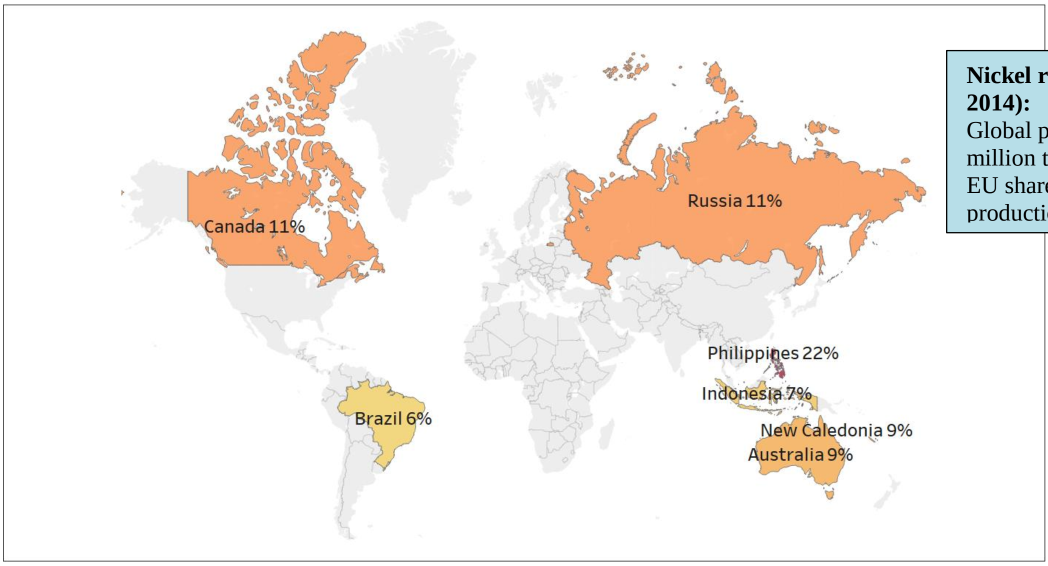
Manganese extraction (2010-2014):
Global production = 49.7 million tonnes
EU share of global production = 0.3 %

Molybdenum



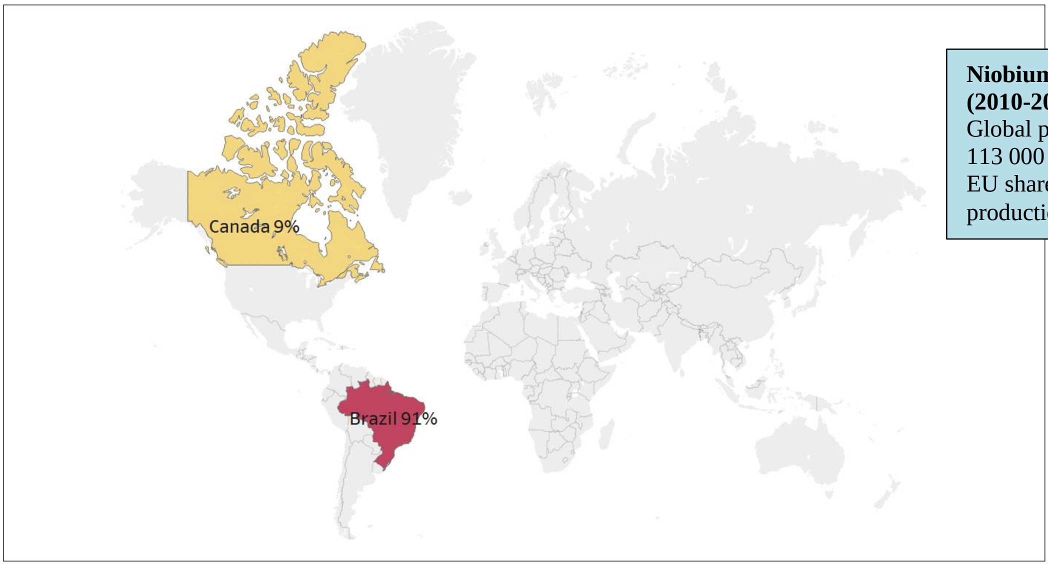
Molybdenum extraction (2010-2014):
Global production = 271 500 tonnes
EU share of global production = 0 %

Nickel



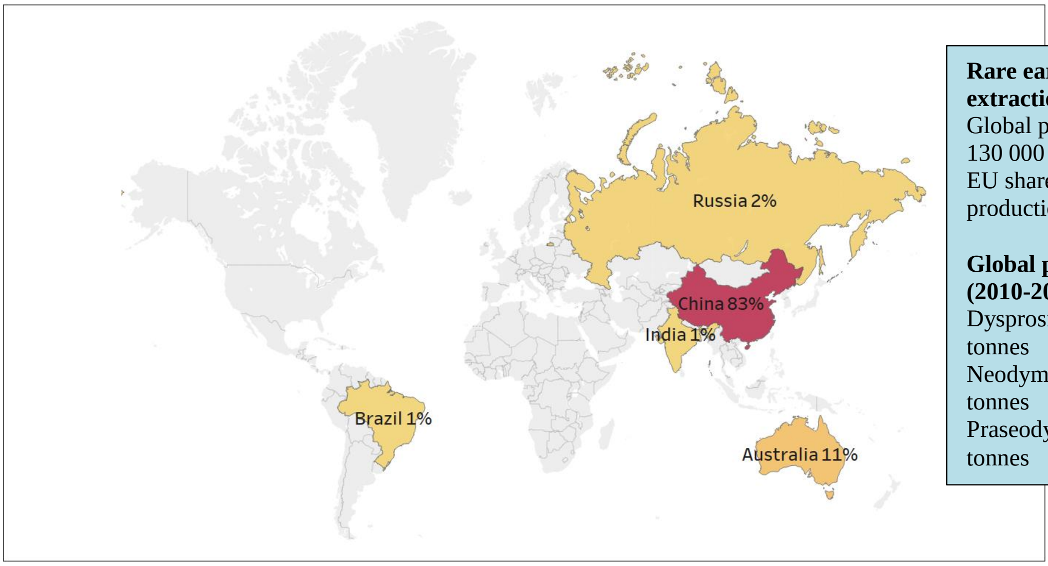
Nickel refining (2010-2014):
Global production = 1.75 million tonnes
EU share of global production = 6.6 %

Niobium



Niobium extraction (2010-2014):
Global production = 113 000 tonnes
EU share of global production = 0 %

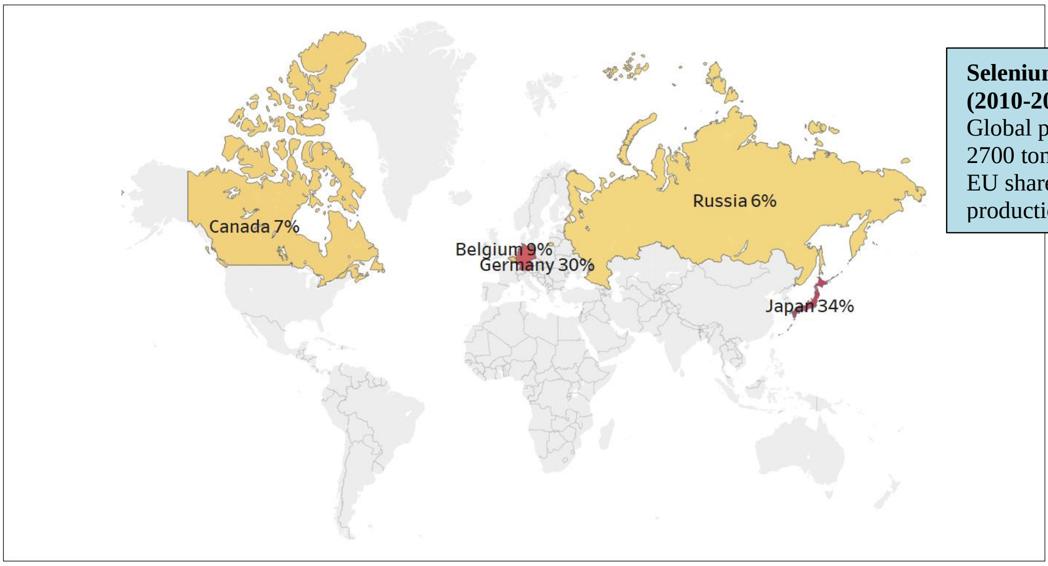
Rare earths



Rare earth oxide extraction (2015):
Global production = 130 000 tonnes
EU share of global production = 0 %

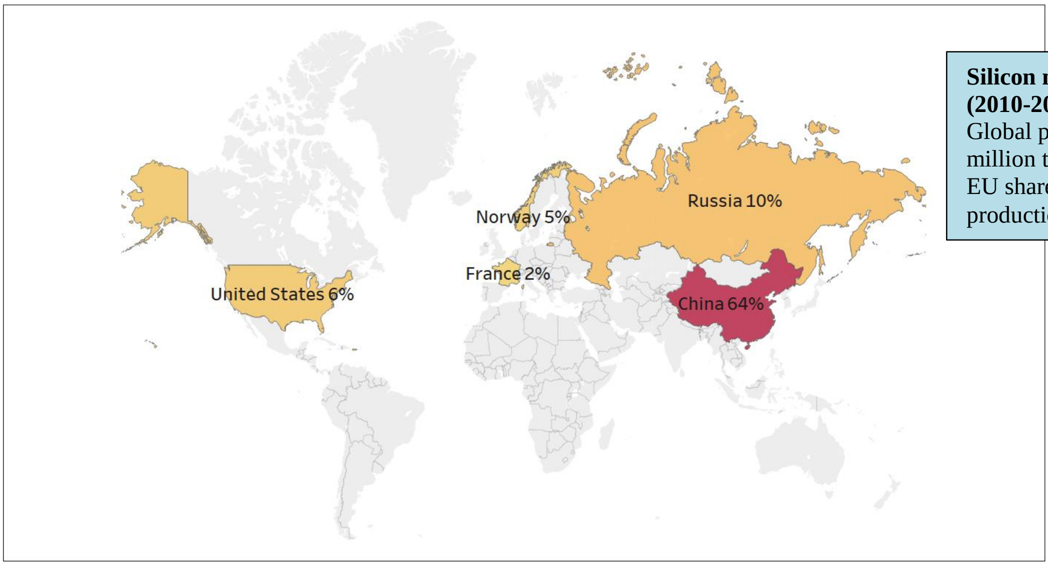
Global production (2010-2014):
Dysprosium = 1360 tonnes
Neodymium = 22 400 tonnes
Praseodymium = 6500 tonnes

Selenium



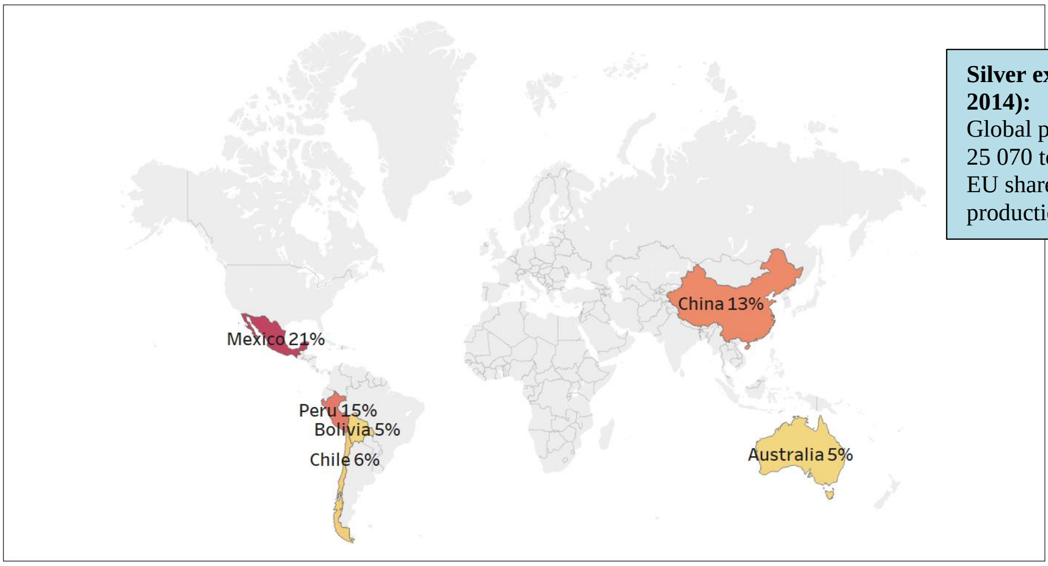
Selenium refining (2010-2014):
Global production = 2700 tonnes
EU share of global production = 42 %

Silicon



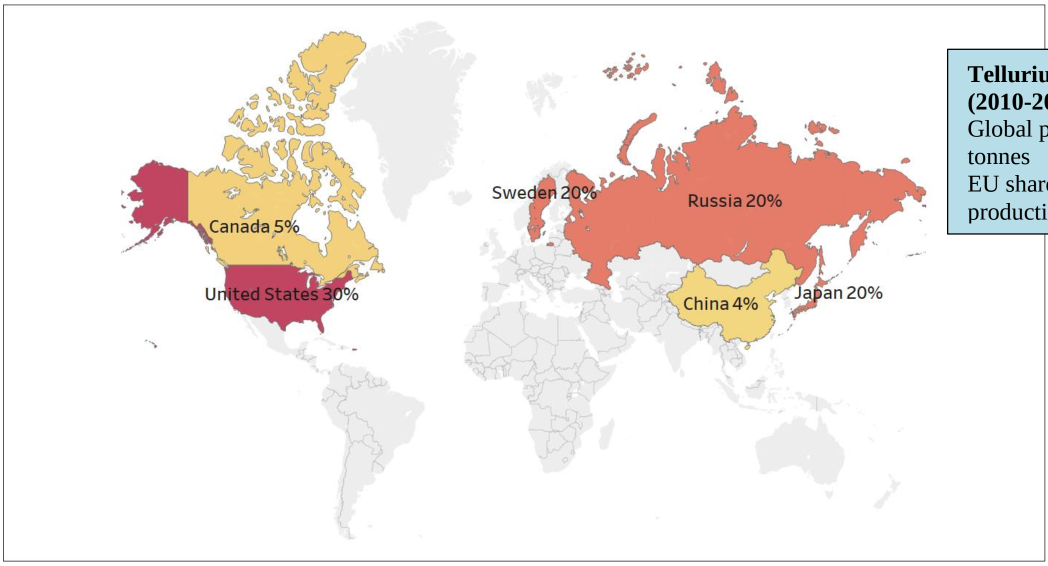
Silicon metal refining (2010-2014):
Global production = 2.29 million tonnes
EU share of global production = 8.5 %

Silver



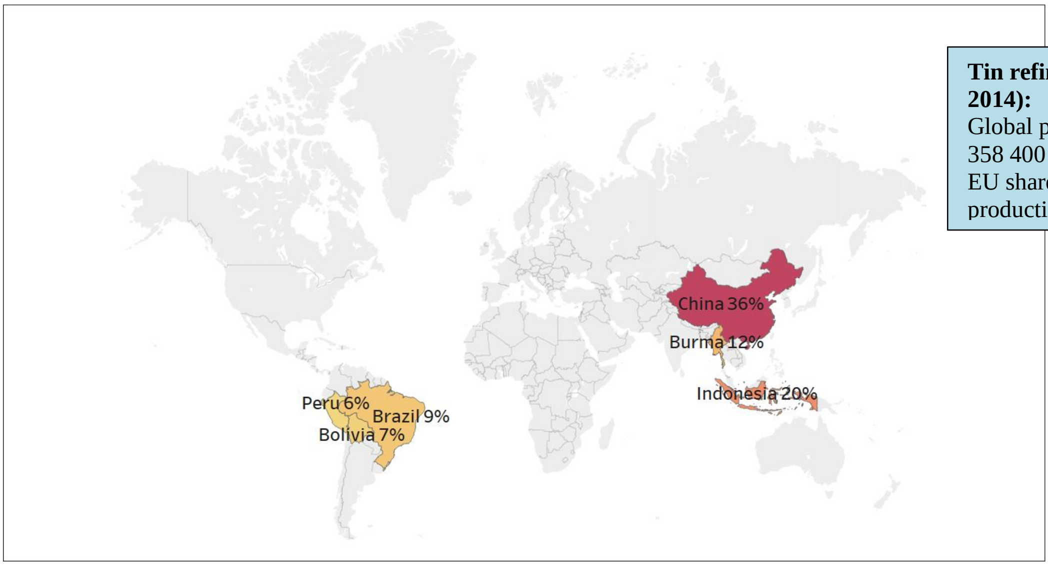
Silver extraction (2010-2014):
Global production = 25 070 tonnes
EU share of global production = 6.9 %

Tellurium



Tellurium refining (2010-2014):
Global production = 142 tonnes
EU share of global production = 8.5 %

Tin



Tin refining (2010-2014):
Global production = 358 400 tonnes
EU share of global production = 3.2 %

Zinc

Zinc extraction (2010-2014):
Global production = 13.1 million tonnes
EU share of global production = 5.7 %

Source: JRC representation, with data from European Commission, 2017a; Statista, 2017a; USGS, 2017.

Most of the materials selected for this study are mainly produced outside the EU, and in some cases the production is concentrated in one country. For example, more than 90 % of niobium is currently produced in Brazil, 83 % of REEs are produced in China and 78 % of boron is produced in Turkey. China is the main producer of 10 of the 23 materials listed in Figure 9, while the EU is the main producer of only one material — selenium. The EU has no production at all for four materials (i.e. boron, molybdenum, niobium and REEs). For the other three materials (i.e. cobalt, natural graphite and manganese) the EU's share of global production is below 1 %.

Special attention should be given to REEs due to the high concentration of supply — the quasi-monopoly of China — and the lack of substitutes without compromising performance. The supply chain for REEs consists of mining, separation, refining, alloying and manufacturing (devices and component parts). Pursuing its techno-industrial development strategy, China has become the worldwide leader in all these steps. In this respect, in June 2017 it was announced that a Chinese-led consortium had purchased the US Mountain Pass rare earths mine and processing facility previously operated by Molycorp (Mining, 2017a). Between 1965 and 1985 the Mountain Pass mine was the principal worldwide supplier of REEs.

The lack of mining, refining, alloying and manufacturing capacity that could extract and process REEs is a major issue for the EU. China is ramping up its production of wind turbines, EVs and bikes, consumer electronics and other items, and will therefore require more and more REEs from its own domestic production to cope with the increasing demand. Environmental standards are also becoming more stringent in China, which may affect both the production volume and cost of REEs.

Assessment: The supply risk for all relevant materials as assessed in the 2017 CRM list (European Commission, 2017a) is used to account for the security and concentration of supply. For each technology, the average value of the supply risks for all relevant materials is normalised to the maximum supply risk to obtain a numerical value between 0 and 1. The complement is then used as "Supply risk" parameter (Figure 4).

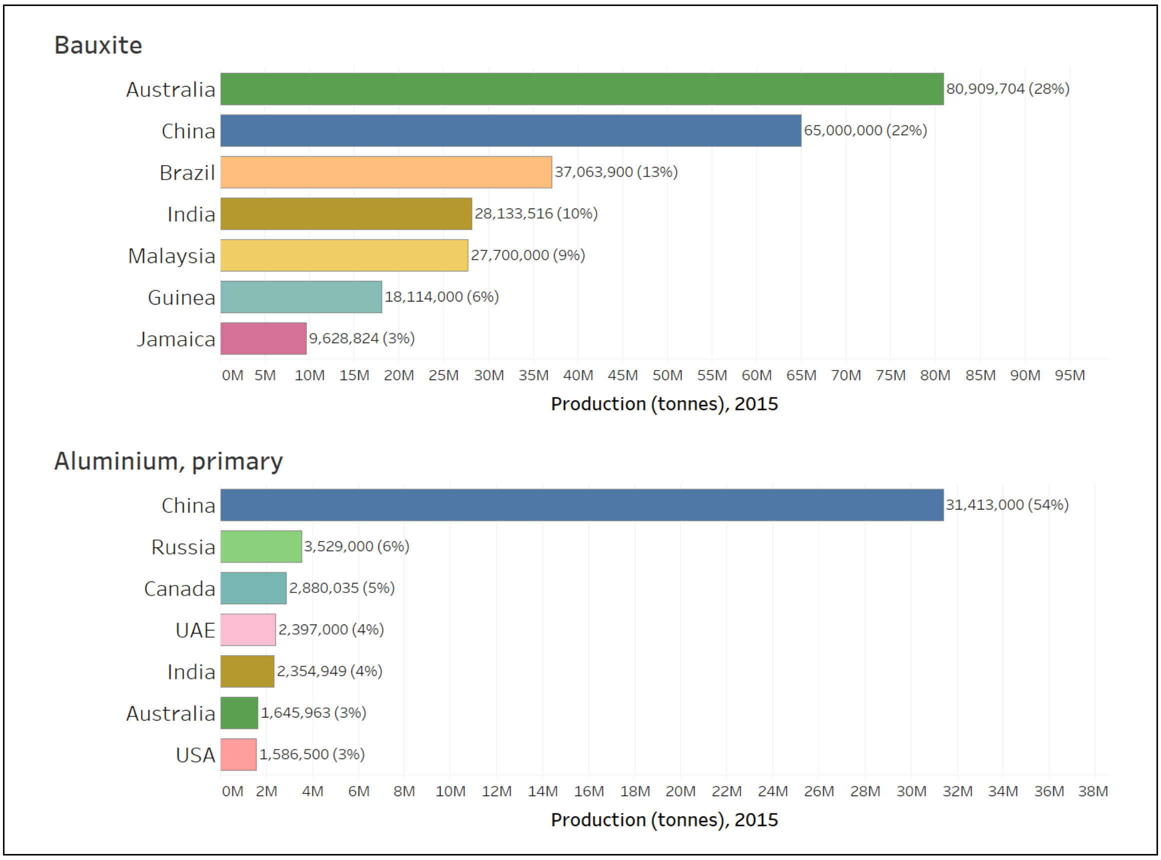
Box 5. There is no or little EU sourcing of raw materials required for wind turbines, solar PV panels and batteries. China is the largest global supplier for about half of them.

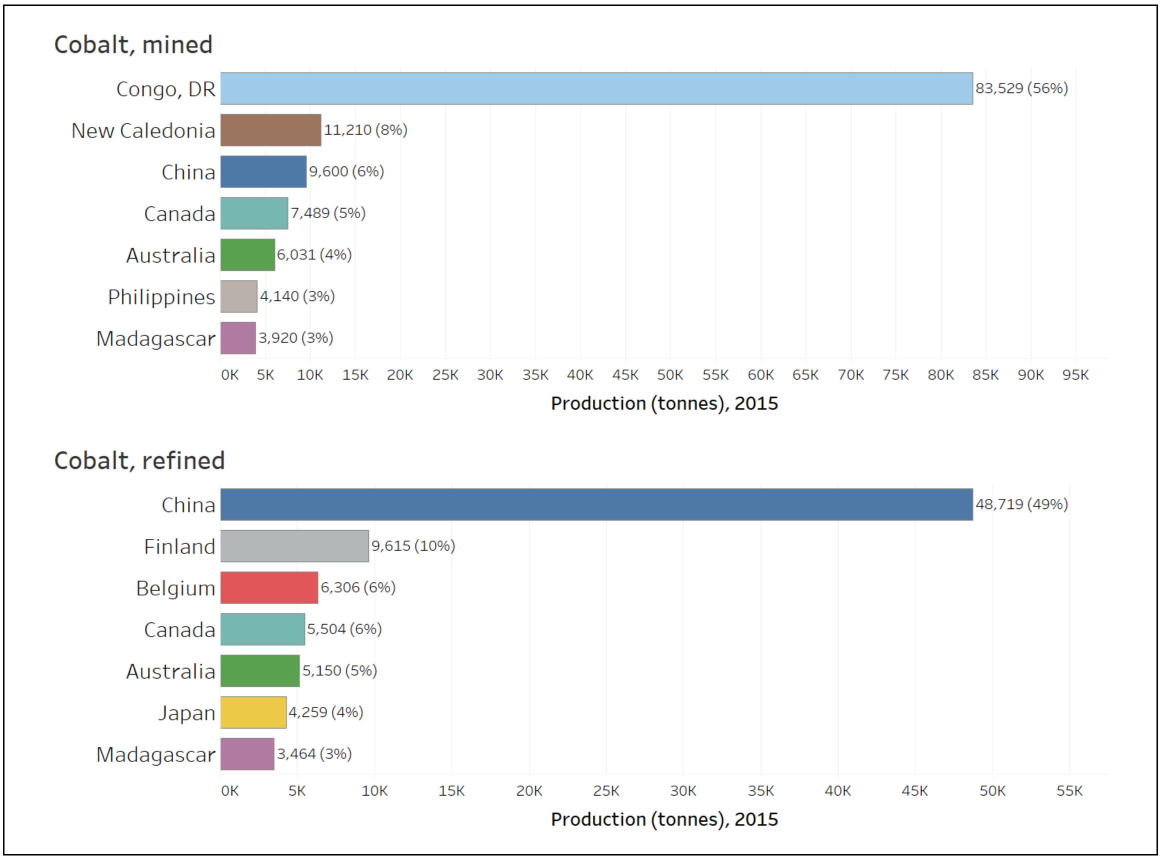
3.2.6. Mining versus refining

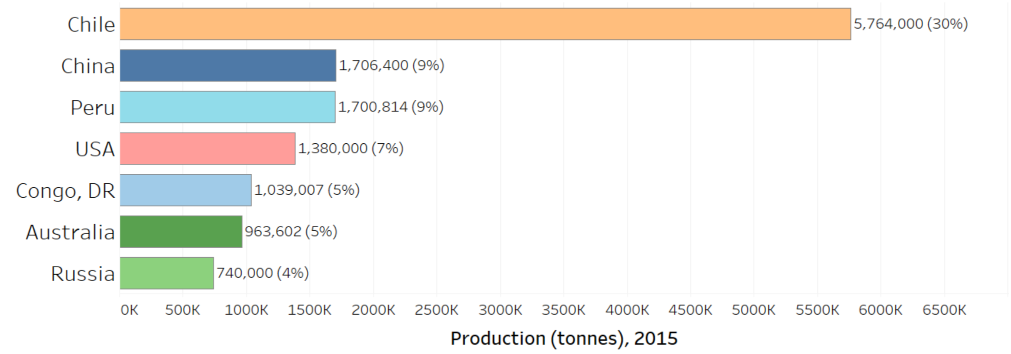
Some materials needed for renewable energy generation (wind power and solar PV) and its storage applications (batteries) are often not extracted and refined in the same country. This is particularly true for aluminium, cobalt and copper. While in 2015 Australia was the main producer of bauxite, the Democratic Republic of the Congo the main producer of mined cobalt and Chile the main producer of mined copper, China was the largest producer of refined metals for all these three materials. For other materials, such as iron, lead, nickel, thin and zinc, China is the main producer of both mined and refined materials.

The major producing countries of some of the refined materials, in addition to mining countries, are shown in (Figure 10) for comparison.

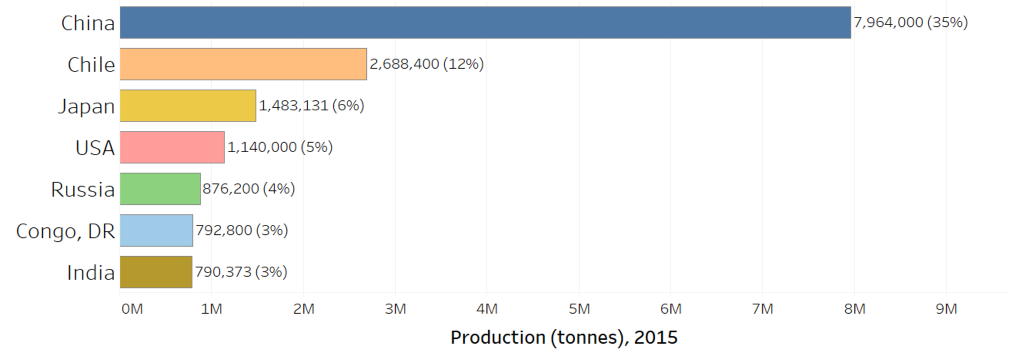
Figure 10. Major producing countries of some mined and refined metals



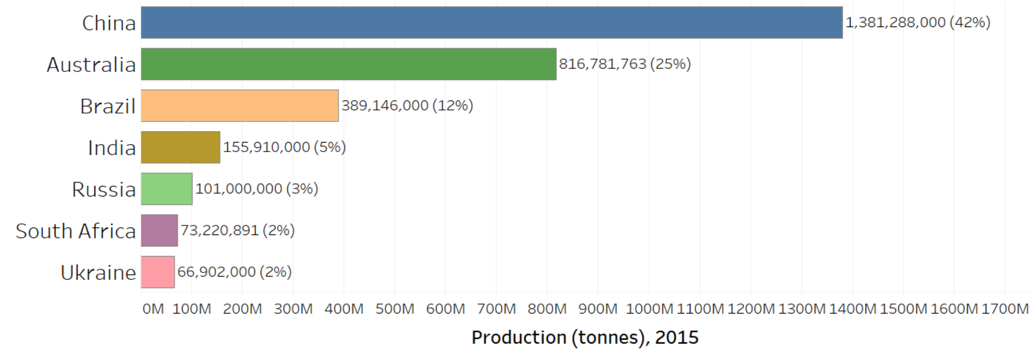




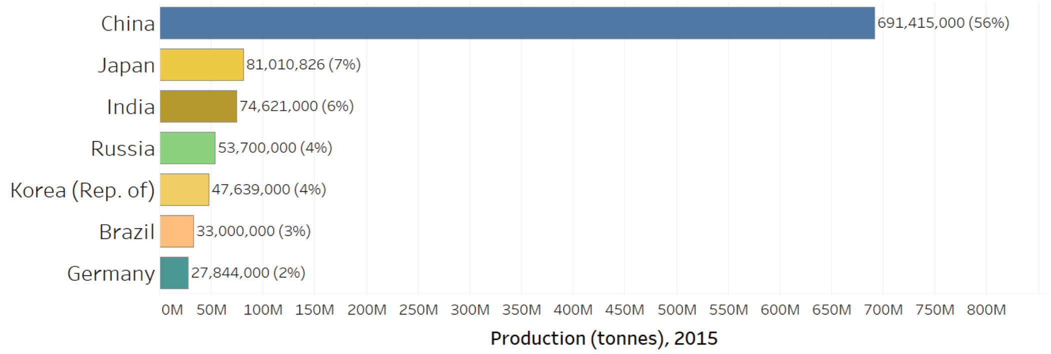
Copper, mined



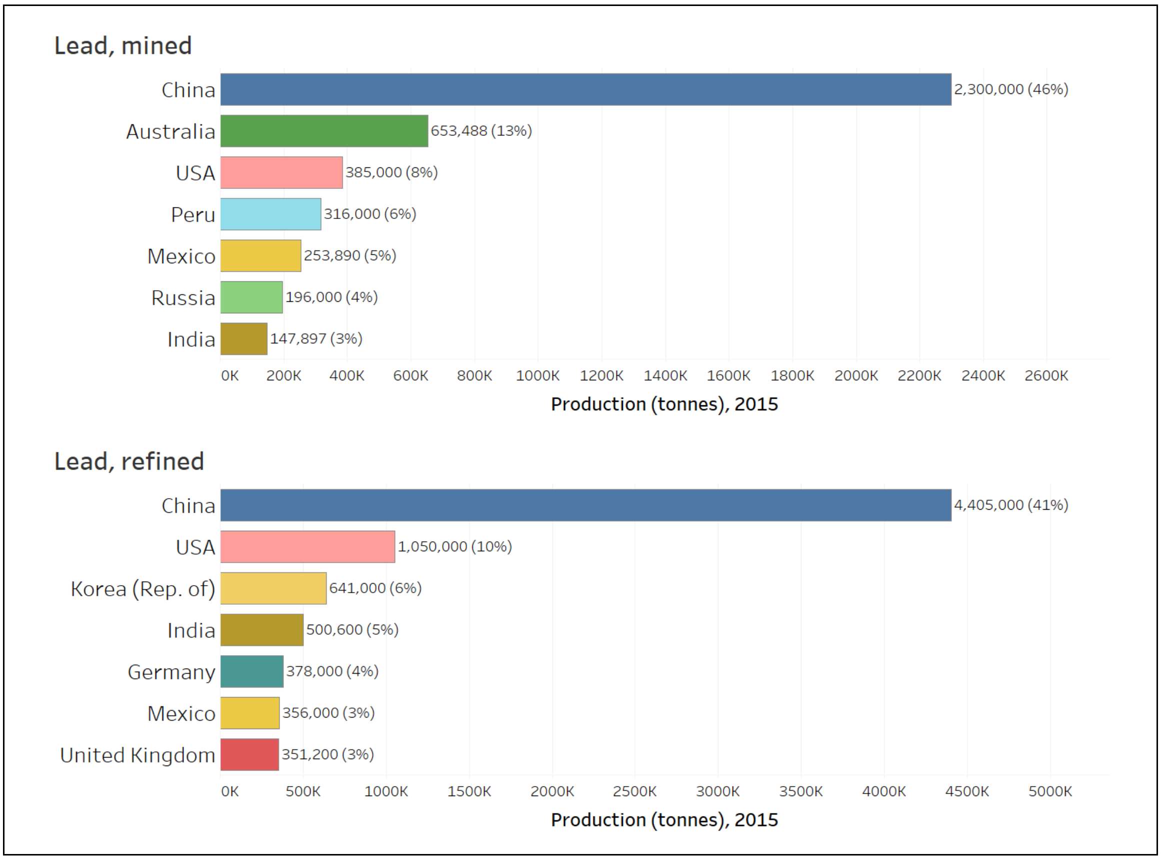
Copper, refined

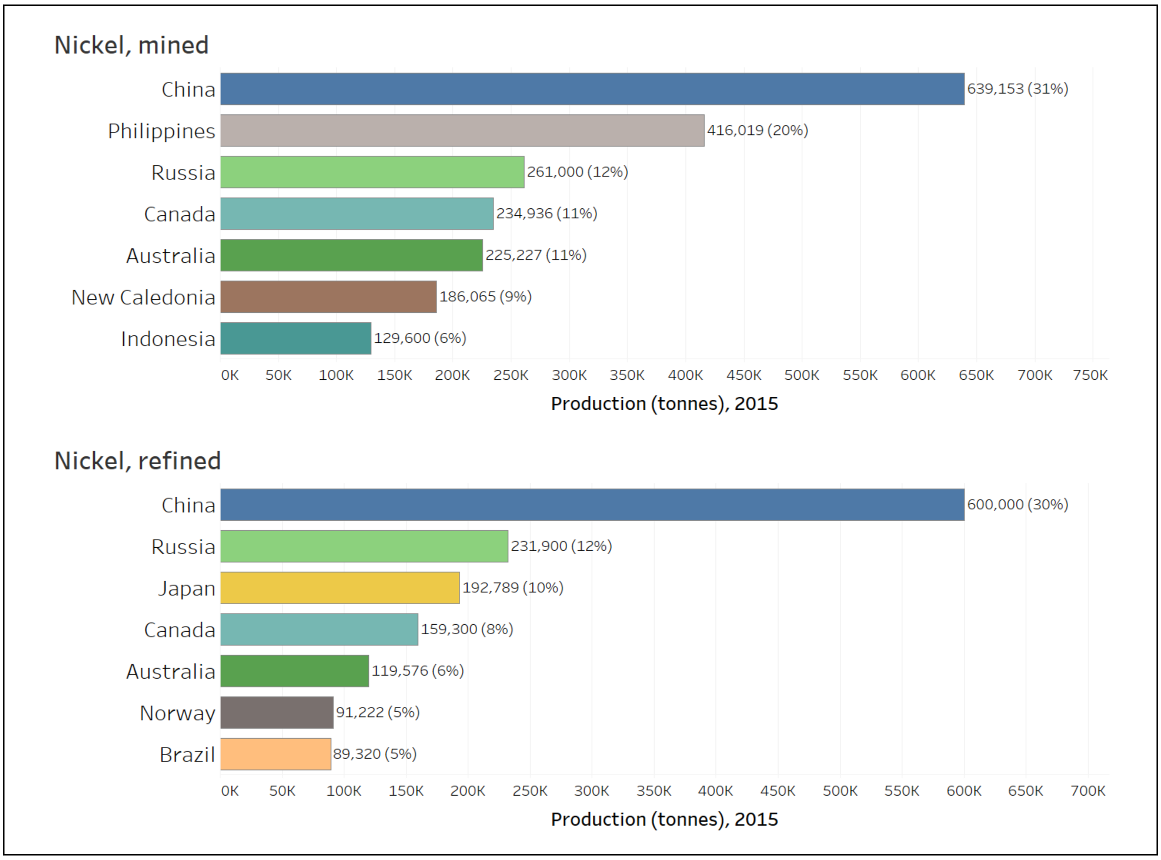


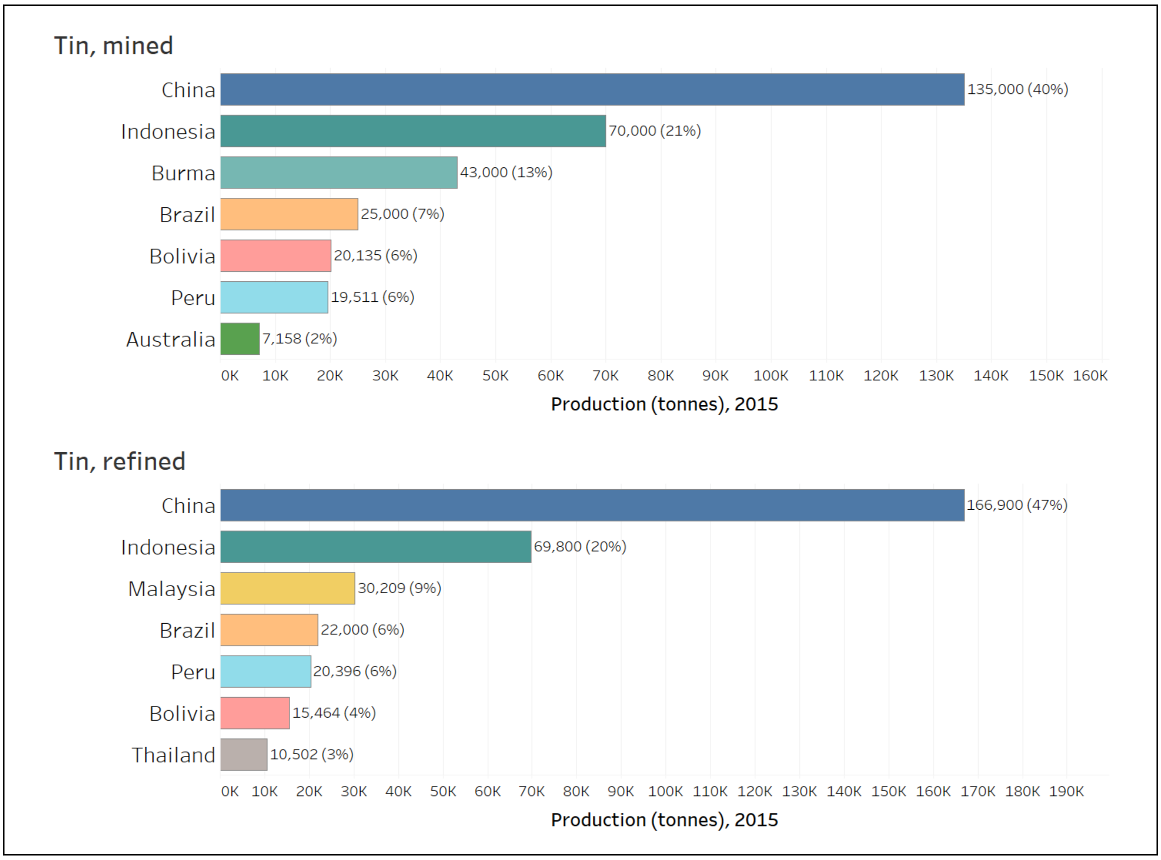
Iron ore, mined

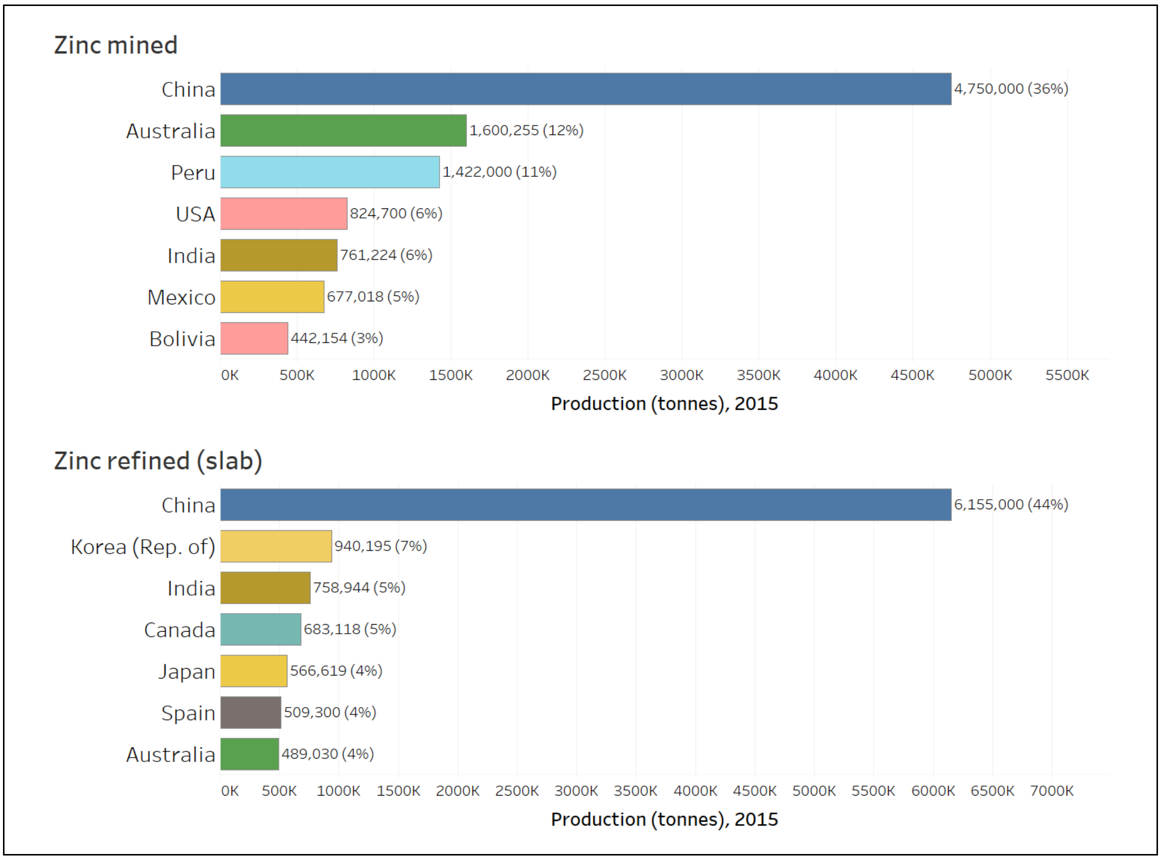


Iron pig, smelter


Lead, mined
China
2,300,000 (46%)
Australia
653,488 (13%)
USA
385,000 (8%)
Peru
316,000 (6%)
Mexico
253,890 (5%)
Russia
196,000 (4%)
India
147,897 (3%)
0K
200K
400K
600K
800K
1000K
1200K
1400K
1600K
1800K
2000K
2200K
2400K
2600K
Production (tonnes), 2015
Lead, refined
China
4,405,000 (41%)
USA
1,050,000 (10%)
Korea (Rep. of)
641,000 (6%)
India
500,600 (5%)
Germany
378,000 (4%)
Mexico
356,000 (3%)
United Kingdom
351,200 (3%)
0K
500K
1000K
1500K
2000K
2500K
3000K
3500K
4000K
4500K
5000K
Production (tonnes), 2015


Nickel, mined
China
639,153 (31%)
Philippines
416,019 (20%)
Russia
261,000 (12%)
Canada
234,936 (11%)
Australia
225,227 (11%)
New Caledonia
186,065 (9%)
Indonesia
129,600 (6%)
0K
50K
100K
150K
200K
250K
300K
350K
400K
450K
500K
550K
600K
650K
700K
750K
Production (tonnes), 2015
Nickel, refined
China
600,000 (30%)
Russia
231,900 (12%)
Japan
192,789 (10%)
Canada
159,300 (8%)
Australia
119,576 (6%)
Norway
91,222 (5%)
Brazil
89,320 (5%)
0K
50K
100K
150K
200K
250K
300K
350K
400K
450K
500K
550K
600K
650K
700K
Production (tonnes), 2015





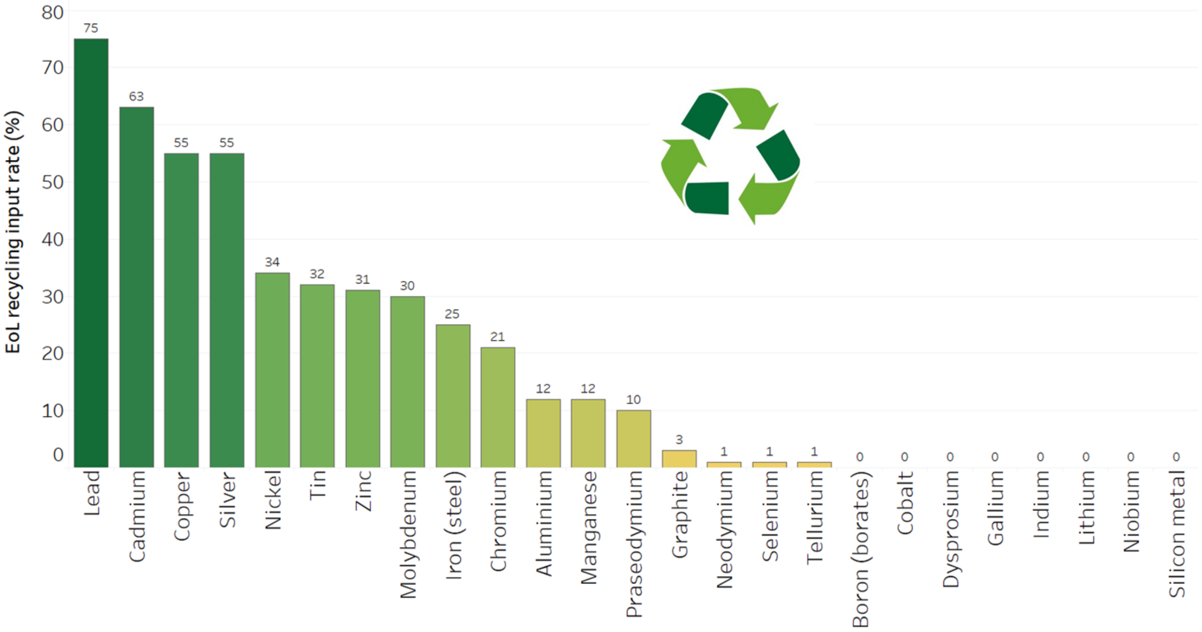
Source: JRC representation, with data from BGS, 2017.

3.2.7. Recycling

Recycling can help to improve the availability of materials by generation of so-called secondary materials, thus increasing security of supply. In addition it can bring down the costs of raw materials, thus securing long-term business and improving the competitiveness of EU technology manufacturers. Moreover, it has been proved that recycling can often reduce the environmental impact of mining for primary materials.

The EoL-IRRs of the materials used in wind, solar PV and battery technologies are shown in Figure 11. In this analysis the end-of-life input recycling rate (EoL-IRR) is used as a measure of the recycling potential of a given material. It represents the share of the recycled (secondary) material flow of the total material production. For example, EoL-IRR = 30 % means that 30 % of the total production material consists of recycled material from end-of-life products and 70 % is primary mined material.

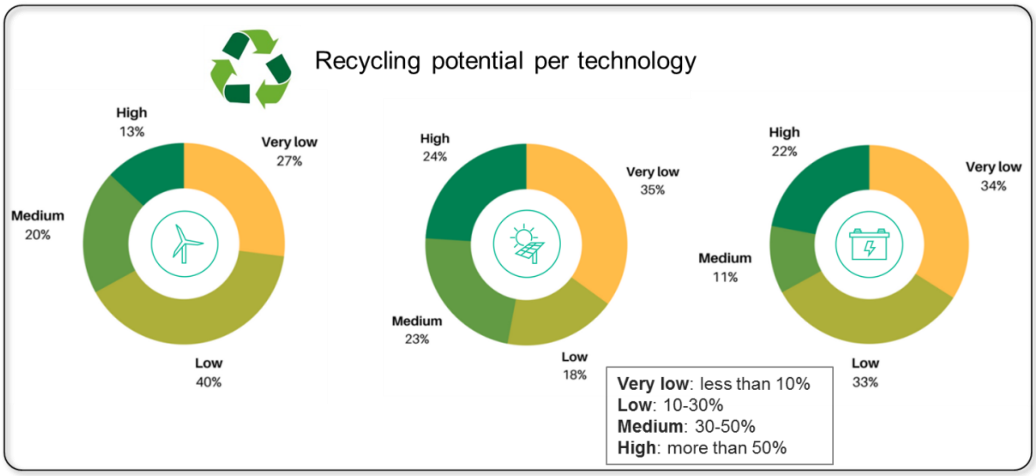
Figure 11. EoL-IRR of materials used in wind, solar PV and batteries



Source: JRC representation, with data from European Commission, 2016a, 2017; ISSF, 2017; UNEP, 2011.

Today around one third of the materials used in wind turbines, solar PV panels and batteries have an EoL-IRR lower than 10 %. The fraction of materials exhibiting a very high recycling potential (EoL-IRR > 50 %) is relatively small, varying between 13 % in wind and 24 % in solar PV technology (see Figure 12).

Figure 12. Recycling potential expressed as an EoL-IRR of materials for wind turbines, solar PV panels and batteries



Source: JRC representation, with data from European Commission, 2017a.

Assessment: The "Recycling" parameter in Figure 4 corresponds to the recycling rate (EoL-IRR) evaluated for each technology as the average of the EoL-IRR of all relevant materials as determined in the 2017 CRM list (European Commission, 2017a).

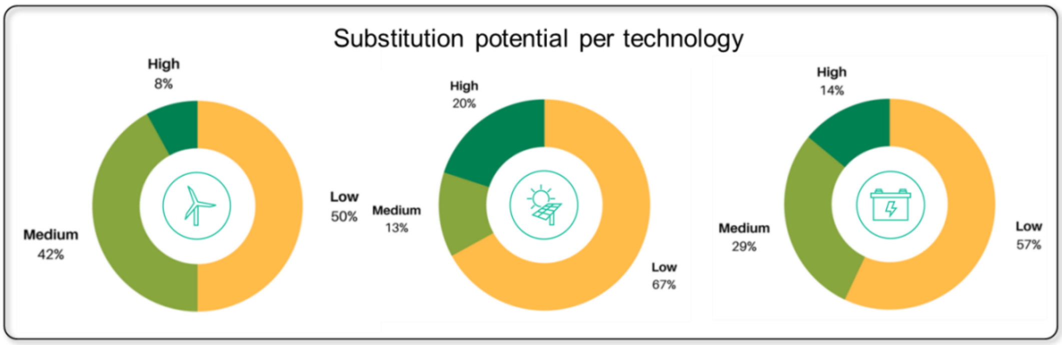
Box 6. Currently, the recycling potential expressed as an overall EoL-IRR of the materials used in wind turbines, solar PV panels and batteries (Li-ion) is fairly low.

3.2.8. Substitution

Substitution is considered a sustainable strategy to moderate the demand for some critical materials and thus reduce the supply pressure and EU import dependency on these materials. Moreover, it can be also an innovative way to create diversification in the supply of materials with benefits for the EU's competitiveness concerning materials.

Around 50 % of the materials required in wind turbines are barely substitutable (they have a low substitution potential). This percentage increases to 57 % for batteries and 67 % for solar PV panels (Figure 13). In general, the substitution potential of materials for the three technologies is low (Figure 14).

Figure 13. Substitution potential (6) of materials for wind, solar PV and battery technologies



Source: JRC representation, with data from European Commission, 2017a.

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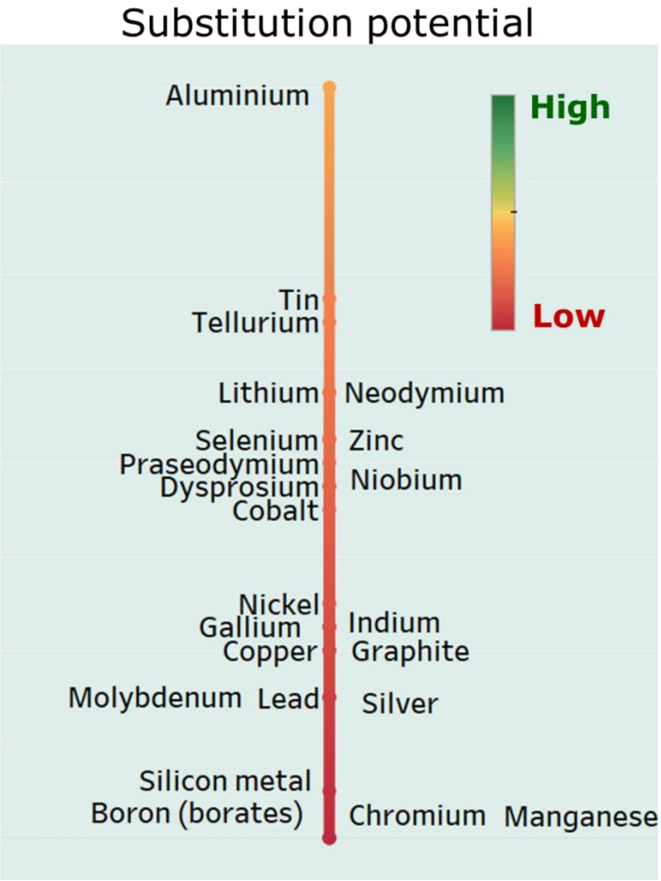
(6) Substitution potential refers to the substitution of a material used for different end-use applications as estimated in the 2017 CRMs list (European Commission, 2017a).

Figure 14. Substitution potential of the materials used in wind turbines, solar PV panels and batteries



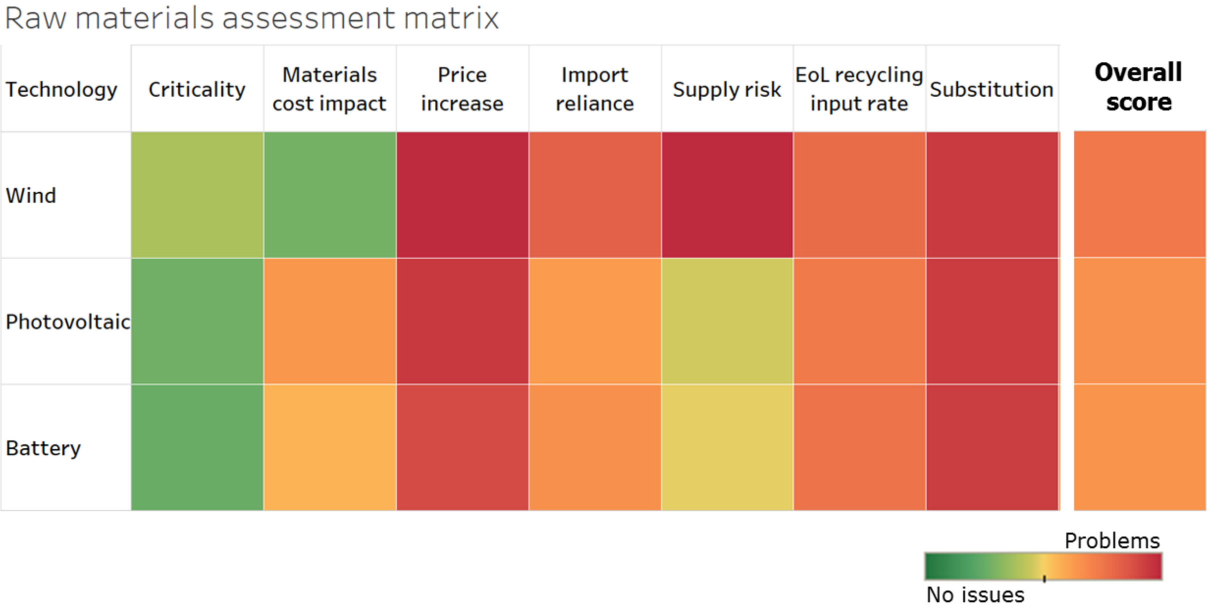
Source: JRC representation, with data from European Commission, 2017a.

Assessment: For each technology, the corresponding substitution index is calculated as the average of the substitution indexes of all relevant materials as determined in the 2017 CRM list (European Commission, 2017a). According to the EC methodology, the substitution index can be as high as 1 if a material is not substitutable at all. To account for the reverse logic in our study, the "Substitution" parameter in Figure 4 is the complement of the substitution index for each technology.

Box 7. The overall substitution potential of materials used in wind turbines, solar PV panels and batteries is generally low, especially for solar PV.

Finally, a traffic lights assessment matrix for the raw materials required in wind turbines using permanent magnets, solar PV panels and battery technologies is shown in Figure 15 following the methodological approach proposed in this work.

Figure 15. Assessment matrix for raw materials needed in wind turbines, solar PV panels and battery technologies



Raw materials assessment matrix

Technology	Criticality	Materials cost impact	Price increase	Import reliance	Supply risk	EoL recycling input rate	Substitution	**Overall score**
Wind	🟩	🟩	🟥	🟥	🟥	🟧	🟥	🟧
Photovoltaic	🟩	🟧	🟥	🟧	🟨	🟧	🟥	🟧
Battery	🟩	🟧	🟥	🟧	🟨	🟧	🟥	🟧

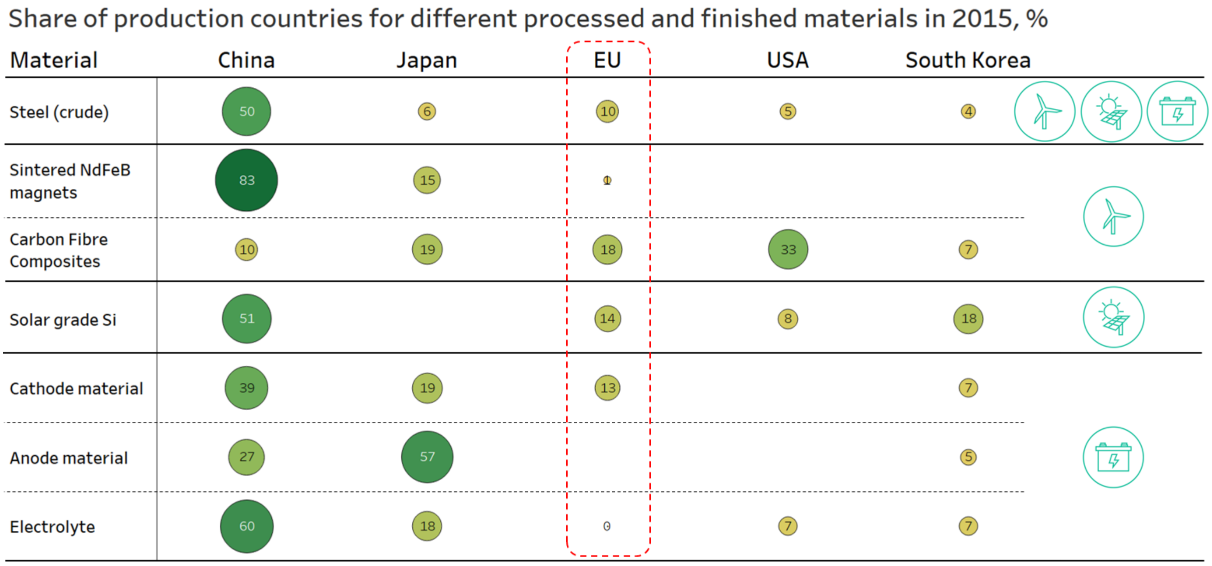
Source: JRC analysis.

As can be seen, oranges and reds prevail in the assessment matrix, which denotes that potential issues linked to raw materials can be expected for all three technologies. Based on the above assessment, wind turbines employing rare earth-based permanent magnets appear to be the most vulnerable technology due to the very high supply risk associated with REEs, high EU import reliance, negligible recycling and the lack of substitutes.

4. Selection and assessment of processed materials

The EU’s dependency at the downstream stages in the supply chain may also be a strong limiting factor affecting the EU’s resilience on materials supply and further the competitiveness of the EU renewable energy industry. Besides raw materials, several processed/finished materials are required in these three technologies. The processed materials selected for evaluation in terms of global suppliers are as follows: steel for all technologies, permanent magnets for wind turbine generators, composite materials for turbine blades and solar grade silicon for crystalline silicon PV, along with cathode and anode materials and electrolytes for batteries. The share of the main suppliers of these materials is visualised in Figure 16. This study addresses only those processed and finished materials for which supply issues can be expected. Steel is included because of its relevance to all three technologies and recent developments associated with the restructuring of the global steel industry.

Figure 16. Estimated share of key producing countries in 2015 for several processed and finished materials used in wind turbines, solar PV panels and batteries



Source: JRC assessment based on information from various sources presented in Blagoeva et al., 2016.

Details for each processed material can be found in the following subsections.

4.1. Steel

Steel is an important processed material used in all three technologies for different parts and equipment as follows.

- **Wind turbines**, in the key components of the turbine: tower, nacelle and rotor.
- **Solar PV**, in racks or frames for attaching the modules in both ground- and roof-mounted PV systems.
- **Batteries**, in different parts, e.g. tabs, end plates, terminal assemblies, container, etc.

Since a wind turbine is largely made of steel, the wind power sector needs far more steel per megawatt than solar PV and batteries. Is has been estimated that the global demand for steel in 2015 for the global installed capacity of both wind and solar power was 10.1 million tonnes (BNEF, 2015). This amount represented less than 1 % of global steel production in the same year, which was 1 621 million tonnes. China accounts for about half of global production and the EU for 10.2 % (see Figure 16).

Even though no issues are expected in the supply of steel for low-carbon technologies in particular, the EU's competitiveness in steel production is currently affected by Chinese overcapacity registered in recent years, which led to a collapse in prices. A process of transformation, restructuring and innovation, along with policy measures, is needed to promote a level playing field to ensure that the European steel companies are not put at a disadvantage in relation to steelmakers from other regions or competing materials. While process control, innovation and automation lead in general to an increase in the productivity and competitiveness of a certain industry, the number of jobs within the sector may be affected. This is the case for Voestalpine AG, a new rolling steel mill that opened in 2017 in Austria and is able to make about 500 000 tonnes of steel wire a year with only 14 employees (Bloomberg, 2017b). To produce the same product volume in a facility built in the 1960s as many as 1 000 employees were needed. Overall, in the past 20 years the number of worker-hours needed to make a tonne of steel has decreased by 64 % (from 700 to 250) as a consequence of improving productivity. Following the steel crisis between 2008 and 2015, the European steel industry lost almost 84 000 jobs (about 20 %), and the number of jobs is predicted to decrease by a further 20 % over the coming decade (Bloomberg, 2017b).

Steel is an infinitely recyclable material and it also has a limited environmental impact, thus it plays a key role in the circular economy model.

4.2. Permanent magnets

Permanent magnet generators for wind turbines are being used more and more, especially in offshore applications, as this type of generator provides self-protection against overloads and easy maintenance. The expected high growth rate of wind power is likely to drive the global permanent magnet market, including for high-energy-density NdFeB magnets. This segment is estimated to grow at a compound annual growth rate of over 10 % by 2024 (Global Market Insights, 2017).

Although Japan is the world leader in innovation for permanent magnets and holds most of the patents for NdFeB manufacture through Hitachi Metals Ltd, most NdFeB magnet production is based in China. The manufacturing capacity of the United States for all types of magnets is also rapidly declining and starting to move to China (Freedonia, 2015; Humphries, 2013; Hurst, 2010; Morrison and Tang, 2012).

With China controlling the majority of rare earth metal mines, a large number of manufacturers of NdFeB magnets are now located in that country. In 2014 China produced 69 000 tonnes of NdFeB magnets, or about 83 % of global production, and it has the capacity to produce almost double that amount (Roskill, 2015). Japan is the second-largest country in terms of production share.

Faster-growing markets for permanent magnets are expected in developing areas. Due to their superior performance, demand for NdFeB magnets is likely also to increase in the automotive sector for electric traction motors. For example, for its new Model 3 RWD Long Range carline, Tesla is considering to switch from the rare earth-free asynchronous reluctance (induction) motors (currently used in the Model 3 RWD standard and the Model X AWD vehicles) to a three-phase permanent magnet motor to increase efficiency of the electric powertrain.

4.3. Carbon fibre composite

Carbon fibre composite (CFC) has already proved to be an enabling technology for structural parts of wind turbine blades. It allows production of a thinner blade profile and can lead to weight savings of at least 20 % compared to an all-glass blade. Offshore wind systems especially would benefit from the characteristics of carbon fibres.

Vestas and Gamesa were the first companies to use CFC in their turbine design. Although the cost of CFC is 10 to 20 times as much as E-glass, these companies reported that the whole system cost is less than a system with an all glass-fibre blade, since carbon fibre-based blades require less-robust turbine and tower components.

Supply concerns, the high price of carbon fibre and processing challenges for blades are some of the factors that the manufacturers need to evaluate before they make the transition to a new CFC-based blade technology.

In 2015 the wind turbine market was the third-largest segment in terms of carbon fibre consumption, after the aerospace and defence, and automotive sectors, requiring 14 500 tonnes of CFC, or 13 % of global demand (Kühnel and Kraus, 2016). The key suppliers in the global carbon fibre market are Cytec Solvay (Belgium), Hexcel (United States), SGL (Germany), Teijin (Japan) and Toray (Japan).

The EU is an important player in CFC production, with a capacity of about 18 % in 2015 (Figure 16). However, the total EU demand for CFC was estimated to be much higher (35 % of the global demand) (Kühnel and Kraus, 2016).

It is estimated that the global demand for CFC in wind turbines will increase at a compound annual growth rate of 10-12 % (2015-2022), as larger turbines with ever-longer rotor blades will depend on a higher proportion of carbon fibre for the supporting structures to guarantee stability and acceptable weight.

4.4. Solar-grade silicon

Solar grade silicon, called also polycrystalline silicon, is the principal feedstock in the crystalline silicon-based PV industry for the production of conventional solar cells. Crystalline silicon PV technology represents around 96 % of the solar PV market in Europe. High-purity polysilicon is also used in the electronics industry.

China is the major supplier of solar-grade silicon, with 51 % of the global market share, followed by South Korea (18 % market share). The major Chinese suppliers are GCL-Poly Energy Holdings Limited and TBEA Silicon Co. Ltd. The European company Wacker Chemie AG (Germany) supplied about 14 % of global polysilicon production in 2015 (Jäger-Waldau, 2016).

4.5. Cathode, anode and electrolyte materials (Li-ion batteries)

In 2015, 88 % of the world’s total LIB manufacturing capacity for all end-use applications was located in Japan, South Korea and, increasingly, China. These countries also produced the vast majority of battery-cell components such as cathodes (85 % of global capacity), anodes (97 %), separators (84 %) and electrolytes (64 %) (Gerpisa 2017).

4.5.1. Cathode materials

Several metals in oxide form are used in Li-ion battery as cathodes: lithium cobalt oxide, lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminium oxide, lithium manganese oxide and lithium iron phosphate. Since the quality of the cathode material impacts the overall performance of the cell, the major battery-cell manufacturers, such as Panasonic (Japan), LG Chem (South Korea) and BYD (China), have chosen to develop their own in-house cathode material production capacity (Hocking et. al., 2016). The total market demand for cathode materials was approximately 140 000 tonnes in 2015, with a quarter of it used in the automotive sector (Pillot, 2015a). The production of cathode active materials is dominated by Asia, with China manufacturing around 39 % (by weight) of the total amount produced in 2015, Japan around 19 % and South Korea around 7 %. The EU suppliers — Umicore (BE) and Johnson Matthey (UK) — together produced about 13 % (by weight) of the total amount of cathode materials in 2015 (Pillot, 2016).

The highest growth rate is expected for lithium nickel manganese cobalt oxide chemistry (almost five times), followed by lithium nickel cobalt aluminium oxide and lithium manganese oxide (around three times) by 2025. EU suppliers have the opportunity to increase their supply of lithium nickel manganese cobalt oxide. The production of lithium nickel cobalt aluminium oxide, currently dominated by Japan, may also represent an opportunity for existing/new EU manufacturers.

4.5.2. Anode materials

The vast majority of Li-ion batteries use graphite powder for their anodes. Graphite materials are either synthetically produced (synthetic graphite) or mined from the ground (natural graphite), then heavily processed before being baked onto a copper foil to serve as anodes.

The total market for anode materials for all Li-ion battery applications exceeded 76 000 tonnes in 2015, with 40 % required by the automotive sector. This is expected to grow to more than 250 000 tonnes by 2025. Historically, the production of anode active materials has been dominated by Japan and China (Element Energy Limited, 2012). In 2015 Japan supplied 57 % of anode active materials, China 27 % and South Korea 5 %.

The main global players are Hitachi Chemicals (Japan), BTR Energy (China) and Nippon Carbon (Japan), together supplying more than 60 % of anode active materials. Other producers include Mitsubishi Chemical (Japan), LS Mtron Carbonics (South Korea), ShanshanTech (China) and Tokai Carbon (Japan). EU-based companies such as SGL, Imerys, and Heraeus, along with other non-EU firms such as 3M, DuPont, Dow, Dow Corning, Envia (United States) and ShinEtsu (Japan), have also shown an interest in anode active materials manufacturing, but do not yet play a significant role in the global supply.

4.5.3. Electrolytes

The global market for electrolytes for all Li-ion battery applications was slightly over 62 000 tonnes in 2015, with a 33 % market share required by the automotive sector. Market growth to more than 235 000 tonnes is expected by 2025, with the share required by the automotive sector increasing to around 50 % (Pillot, 2015b).

Similar to cathode and anode active materials, the production of electrolytes for Li-ion batteries is dominated by Asian suppliers, with China producing close to 60 % (by weight) of the total market, Japan 18 % and South Korea 7 %. The EU-based electrolyte producer — BASF (Germany) — supplied around 200 tonnes of electrolyte, or about 0.4 % of the total market volume, in 2014, but decreased its supply significantly in 2015. Nevertheless, there may be opportunities in formulating and producing advanced new electrolytes, for example for high-voltage Li-ion cells.

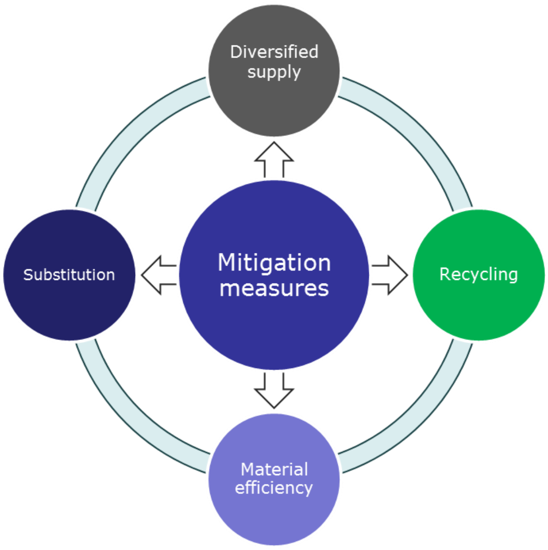
Assessment: The EU Resilience with regards to processed materials required in wind turbines, solar PV panels and Li-ion batteries is addressed via concentration of supply and the EU share of the global market for each specific material. Details on this evaluation can be found in the JRC report (Blagoeva, 2016).

Box 8. Wind technology using permanent magnets appears to be the most vulnerable technology in terms of the supply of processed/finished materials, followed by batteries and solar PV.

5. Mitigation measures

There are several ways to improve the EU's resilience to potential issues linked to materials supply, as summarised in Figure 17.

Figure 17. Mitigation measures to improve the EU's resilience in relation to materials supply



Source: JRC representation.

- **Recycling**: recovering materials from end-of-life products and production scrap and reusing them, thus reducing waste and environmental harm.
- **Substitution**: replacing some problematic materials with other materials which are more abundant and possibly less expensive.
- **Material efficiency**: using less material to produce the same output. In particular, this may be important for minor metals, such as REEs which are expensive and supplied by only one country — China. A typical example is the reduction of the amount of dysprosium in permanent magnets for non-high-temperature applications, such as wind turbines. Another example is the reduction of the cobalt content in batteries as the battery design becomes more efficient. Cobalt is mostly mined in the Democratic Republic of the Congo (conflict area) and refined in China.
- **Diversified supply**: extending the number of 'secured' suppliers to the EU via trade agreements and blocking export restrictions (European Commission, 2013). Diversified supply also includes extending the existing mining capacity in the EU and opening new mines.

The abovementioned measures were analysed in depth in a recent JRC report in the context of the future deployment of wind, PV and EV (including battery) technologies (Blagoeva et al., 2016). Substitution appears to play an important role in the long term (after 2030), whereas 'recycling is found to be the most effective mitigation measure to deal with potential materials supply shortages in the 2030 timeframe'. Recycling and substitution are also seen as a business opportunity for many EU companies, with benefits for economic growth and new jobs.

Box 9. By 2030 recycling can be a viable mitigation measure to deal with potential material supply shortages for wind turbines, solar PV and battery technologies.

6. Technological developments

Since recycling was found to be a feasible mitigation measure to secure some secondary materials flows and also to reduce the expected waste in the considered timeframe, recycling aspects for the technologies concerned (wind turbines, solar PV and batteries) are further analysed and elaborated upon below.

Substitution as a mitigation measure has great potential in the longer term — after 2030. Therefore, future opportunities for substitution in these three technologies are also briefly discussed below, although they are not taken into account in the final resilience assessment up to 2030.

6.1. Recycling of materials from wind turbines, solar panels and batteries

Recycling, or the possibility to recover certain material from its various end-use applications, has already been addressed in Section 3 at the level of raw materials. The three technologies under consideration — wind power, solar PV and batteries — are expected at the end of their lives to become the major secondary source of some specific materials, such as REE, lithium, cobalt, silicon, graphite, etc. Therefore, it is important to evaluate the recycling potential at the technology level as well.

The recycling of materials from renewable plants is challenging, since these technologies have been relatively recently installed, with a long lifetime and are dispersed throughout Europe. Only a few plants have reached the end of their lives, and the low amount of waste available is a limiting factor for the development of recycling processes at the industrial scale.

6.1.1. Recycling of wind turbines

Wind power is an emerging sector with high potential for closing the loop, in the context of a 100 % circular economy. The wind industry is relatively young, and thus practical experience in recycling materials from wind turbines is very limited. This is particularly true for offshore wind turbines, which is a fairly recent technology. **Most wind turbines have a design lifetime of 20-25 years or even longer.** However, the recycling of materials from wind turbines is rising up the agendas of policymakers, researchers and industry. Most of the materials used in wind power, such as steel, cast iron, aluminium and copper, are recyclable to a large extent. According to the literature (Pehlken et al., 2012), around 90 % of a wind turbine's mass, including the parts made of concrete, such as foundations, can be recycled. Most turbine components have a commercial value since they contain valuable materials such as steel, aluminium and copper. However, two components pose specific recycling challenges: **generators containing rare earth permanent magnets** and **blades**.

6.1.1.1. Generators containing rare earth element magnets

Only recently have industry and society started to pay more attention to the recycling of REEs due to rapid growth in demand, potential risks to future supplies, unstable prices and policies that mandate recycling of these critical elements (EPA, 2012). Currently the end-of-life recycling rate of REEs is less than 1 % (UNEP, 2011), and recycling of post-consumer permanent magnets is also very limited (European Parliament, 2015).

REEs such as neodymium, dysprosium and praseodymium, which are used in relatively large quantities in permanent magnet generators, can be extracted from decommissioned wind turbines. Some demonstration projects on recycling of REEs in permanent magnets show very high potential for recovery of these critical materials (Fraunhofer, 2015). However, the decommissioning of a sufficiently large number of wind turbines is expected to take place only after 2030. Hence, even though recycling permanent magnets and their constituent elements may provide great economic advantages offering an alternative source for this strategic alloy, at present there is no process at the industrial scale which allows for the recycling of REEs from end-of-life turbines (Gauß et al., 2015). The recycling of materials from electrical generators and motors is currently not officially regulated in the EU, although some Member States have announced their intention to add this to their national legislation (GOV.UK, 2017).

Some developments have been registered regarding recycling valuable materials from end-of-life hybrid and electric vehicles (H & EVs). The recycling of permanent magnets from H & EVs is expected to take place in the EU between 2023 and 2025. EREAN, a European network for the recycling of REEs from permanent magnets (EREAN, 2017), and another EU Horizon 2020 project, Demeter, recently published a new policy brief entitled 'Processing options and future possibilities for sustainable recycling of hybrid electric vehicles and internal combustion engine vehicles at vehicle recycling sites' (Demeter, 2017a). This policy brief addresses future challenges with respect to the recycling of EVs, including magnet electrical motors. The current EU directive (Directive 2000/53/EC) on the recycling of conventional internal combustion engine vehicles does not include the first wave of retired EVs.

Currently there is no collection, sorting and disassembly system for permanent magnets in Europe, meaning that no reliable feedstock supply is yet available. The recycling potential is also decreased due to the exporting of industrial machinery for materials reuse. However, the potential recycling of permanent magnets in the EU could be a profitable business. A recent study carried out by Öko-Institut revealed that the available annual feedstock of permanent magnets for recycling from different industrial applications (excluding H & EVs and wind turbines) in Germany will increase from 40 tonnes in 2015 to 100 tonnes in 2030 (Öko-Institut, 2015).

In short, the main emerging applications able to provide a tangible material feedstock to support recycling business at an economic scale in the EU would be EV traction motors and wind turbine generators. However, up to 2030, most wind turbines will still be in operation (assuming a 25-30-year lifetime). Therefore, the initial push for recycling companies in Europe is anticipated to come from the EV sector after 2023. At the same time, several projects dedicated to recycling permanent magnets have either been approved or are under way in China (Roskill, 2015). Thus it can be expected that China will strive to maintain its leadership position in supply of not only primary but also secondary REEs recovered from recycled magnets.

6.1.1.2. Blades

The recycling of blades could also be seen as a sustainable business, leading for instance to reduced amounts of waste originating from wind turbines and useful feedstock for the construction sector. Wind turbine blades have not been recycled until now since recycling has not been feasible either technologically or economically. However, over the last few years the potential for recycling blades has been explored in different R&D projects and in industry, and a number of solutions have been developed (EWEA, 2017). The EU's LIFE+ BRIO project, for example, is an initiative that aims to create a new sustainable system to manage and recycle wind turbine blades that are no longer in use (BRIO, 2016). The project demonstrated the potential to reuse the long fibres recovered from the composite to reinforce prefabricated concrete components, and use the remaining blade material with insulating properties in multilayer panels for construction purposes. In this respect the BRIO project proposes viable solutions to optimise procedures to dismantle wind farms by properly providing for the management of waste of this type. However, to support this business, legislative recommendations and guides to good practices within the European Union have to be drawn up to regulate these aspects. The benefit will be in terms of a cut in the management costs linked to dismantling and a reduction in the environmental impact of the service life cycle of wind farms.

6.1.2. Recycling of solar PV panels

Similarly to wind, solar PV is an emerging technology, with about 85 % of the global PV capacity having been installed in the last 5 years (Maydbray and Dross, 2016). The recycling of silicon, indium, gallium and other materials from PV modules, such as glass, aluminium, copper, silver, germanium and others, has a great deal of potential: more than 95 % of the total material mass is recyclable without additional cost or even at a profit. Solar PV modules manufactured with recycled materials need three times less energy than those made of newly produced silicon at equal capacity, thus making them more cost-effective (BINE, 2010).

Due to the long lifetime of PV modules — more than 25 years — significant recycling flows of solar modules are expected only after 2030. This still-young technology has generated little waste so far — only 1 % of the recycled panels are at end-of-life — which means the recycling PV panels is not yet economically viable. However, the potential is huge. A new study released by the International Renewable Energy Agency (IRENA) states that between 2 and 8 million tonnes of PV waste could be generated by 2030 depending on the failure scenario (IRENA, 2016). The figures will substantially increase by 2050, up to 60-75 million tonnes. The recyclable material in old solar modules will be worth USD 15 billion by the year 2050 assuming 4 500 GW of global installed PV capacity. This potential influx of material could produce 2 billion new panels. 'This brings about new business opportunities to "close the loop" for solar PV panels at the end of their lifetime. To seize these opportunities, however, preparations for the surge in end-of-life material should begin now' (IRENA, 2017). Industry should be prepared to recycle such quantities by setting standards. Moreover, if not properly disposed of, end-of-life PV panels can have negative environmental impacts, such as leaching of lead or cadmium and loss of valuable resources, for example aluminium, glass and rare metals such as indium, silver, gallium and germanium.

The EU is a pioneer in regulating PV waste: the EU waste electrical and electronic equipment (WEEE) directive requires that all solar PV panel suppliers finance the end-of-life collection and recycling costs. PV CYCLE (7) is an EU association, established in 2007, representing 85 % of the European PV market. The association is engaged in collecting and disposing of PV waste free of charge; the target is to collect 65 % of all dismantled PV modules. PV CYCLE is already recycling solar panels (mainly production scrap, panels damaged during delivery or installation or that failed before reaching end-of-life) from Spain, Germany, Italy, Belgium, Greece and the Czech Republic. No statistical data on PV collection and recycling is yet available for the EU.

While in the EU collecting and recycling solar panels is strictly regulated, these regulations do not yet exist in other advanced countries. In the United States there is no such regulation at federal level, except for the minority of panels that fail the toxicity characteristic leaching procedure test and thus are subject to the Resource Conservation and Recovery Act. Other rapidly growing solar PV panel markets such as China and India also currently lack specific PV panel waste regulations, though long-term policy goals have been established in these countries.

What can be expected by 2050? According to IRENA's study, more than 40 % of PV waste will be accumulated in China, 20 % in the United States, 15 % in Japan, 15 % in India and only 9 % in the EU (only Germany has been taken into consideration in the analysis) (IRENA, 2016). Once again China comes up as potentially the biggest future producer of recycled (secondary) materials coming from decommissioned PV modules.

6.1.3. Recycling of batteries

Batteries are expensive and have a relatively short life span, therefore they offer good business opportunities for recyclers. Lead-acid remains the most suitable battery for recycling as 70 % of its weight contains reusable lead (Battery University, 2017). Currently, lead-based batteries are the only battery technology that operates in a closed recycling loop in EU, with 99 % being collected and recycled for the manufacture of new automotive batteries. This can be considered a good example of the circular economy already in action in the EU (ILA, 2016). Nickel-based batteries can also be recycled

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(7) http://www.pvcycle.org/

easily. Iron and nickel are retrieved and used again in stainless steel production. There are no particular issues associated with recycling lead-acid or nickel-based batteries, thus this study focuses on recycling for the emerging technology of Li-ion battery.

The recycling of materials from Li-ion batteries is technologically possible but economically unpractical. Often it is cheaper to mine and process a raw material than to retrieve it from recycling, and this is the case for the materials in Li-ion batteries. At present, Li-ion battery recycling is mainly limited to portable batteries from consumer electronics. Only 5 % of the Li-ion batteries sold in 2010 were collected and recycled in the EU (Gies, 2015).

The estimated weight composition of a Li-ion battery is 5-20 % cobalt, 5-10 % nickel, 5-7 % lithium, 15 % organic chemicals, 7 % plastics and 12-21 % graphite, with the remaining weight being copper, aluminium and steel (Dunn et al., 2012; Gaines and Nelson, 2010; Shin et al., 2005). The materials that are commonly recycled from Li-ion batteries today are cobalt and iron. However, specific challenges related to the declining use of cobalt in some Li-ion battery types may make its recycling even less attractive, unless economical recovery is not also extended to the other materials (e.g. lithium and graphite) (CEC, 2015). Retrieving lithium from end-of-life batteries may never reach the break-even level. Moreover, if the purity of the recovered lithium is below 99.5 % then it is not suitable to be reused as a raw material in battery applications. Currently there is no form of large-scale recycling in place for graphite, which is the state-of-the-art anode material for most commercial Li-ion batteries. The main issue relates to the ageing process of the graphite electrode during operation, which affects the conductivity properties of the graphite. New processes are proposed by researchers to overcome this problem, which should be tested on a larger industrial scale (Morandi and Botte, 2016).

The cost of manufacturing Li-ion batteries is not related to the price of raw materials, as is the case with lead-acid and NiMH batteries. What makes Li-ion battery particularly expensive is the long processing and purification processes of the raw materials to reach battery grade. To overcome this issue, a specific recycling process, called 'direct recovery' is proposed by the US' company called OnTo Technology (8). Rather to recover basic elements throughout the traditional methods, this new process involves rejuvenating the cathode and re-using it again in a battery. The method seems to be a promising solution as it is cheaper, low-energy, low-emissions and generating limited waste.

Due to the recent adoption of EVs in the global and European markets, and taking into account the average lifetime of a battery, estimated to be approximately 10 years, EV batteries have not yet reached end-of-life insignificant numbers. Large-scale recycling is not expected before 2020 and will only be effectively realised after 2025. However, the future recycling potential of EV batteries is significant as these batteries may be easier to collect from customers if a dedicated system of return is established. The existing collection system for lead-based batteries is difficult to use due to inherent safety problems during storage (ILA, 2015).

The recycling of batteries in the EU, including collection and the treatment and recycling process, is regulated through the EU battery directive (Directive 2006/66/EC) (European Parliament and Council, 2006). Companies such as Umicore (Belgium) and Recupyl (France), which have developed their own recycling processes, have been active for several years in the battery-recycling sector. Japan has legislation for batteries that is similar to that of the EU (IRENA, 2015b). The Japan Portable Rechargeable Battery Recycle Center (JBRC), a non-profit organisation, provides used-battery collection boxes across the country. In the United States there is no federal law governing waste batteries, and each state may choose to implement its own policy and laws. China currently lacks appropriate policies and collection systems for batteries despite growing community concern about the impact of waste Li-ion batteries on the environment and public health. Adequate recycling infrastructure for batteries also needs to be developed

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(8) http://www.onto-technology.com/

in China (Zeng et al., 2015). From the data available today, China and Europe are almost equally positioned in terms of battery recycling capacity (different types of batteries are considered, including Li-ion) (Lebedeva et al., 2016). However, it can be expected that China will also strengthen its future leadership in this area, as there are many efforts to put in place appropriate policies and collection systems for battery recycling and building recycling infrastructure (CEF, 2011).

6.1.4. Semi-quantitative assessment of the recycling potential of materials from wind turbines, solar PV and batteries

The outcome of the above analysis is summarised in Table 1, taking into account the following four distinct elements.

- **Regulation:** whether or not a directive exists regulating recycling of the technology concerned; if 'no' = 0; if 'yes' = 1.
- **Research and innovation:** whether or not EU research projects are in place addressing the recycling issues of the technology concerned; if 'no' = 0; if 'yes' = 1.
- **Existing recycling capacity:** whether or not EU companies are already implementing recycling of the concerned technology; if 'no' = 0; if 'yes' = 1.
- **Recycling potential timeframe:** whether or not significant feedstocks for recycling can be expected by 2030 for the technology concerned; if 'no' = 0; if 'yes' = 1.

Table 1. Technological development assessment in relation to materials recycling from wind turbines, solar PV panels and batteries

Criteria	Applicability (yes/no)	Assessment score (0-1)	Remarks
Wind power technology			
Regulation	No	0	There is a lack of EU regulations for the recycling of wind turbines, and more specifically of permanent magnets-based generators and blades
Research and innovation	Yes	1	EU is engaged in R&I activities for the recycling of permanent magnets and blades
Existing recycling capacity	No	0	Industrial recycling capacity in the EU for permanent magnets and blades is currently lacking
Recycling potential by 2030	No	0	Positive contribution for secondary material flows from recycling of permanent magnets and blades from wind turbines can be expected after 2030
Final score wind tech.		**0.25**	

Criteria	Applicability (yes/no)	Assessment score (0-1)	Remarks
Solar PV			
Regulation	Yes	1	Directives on the recycling of PV modules are already in place
Research and innovation	Yes	1	R&I on the recycling of PV modules is ongoing
Existing recycling capacity	Yes	1	Industrial recycling of PV modules in the EU is already being done
Recycling potential by 2030	No	0	Substantial supply of secondary materials from PV modules is expected after 2030
Final score solar PV		**0.75**	
Batteries			
Regulation	Yes	1	Recycling of Li-ion batteries is regulated in the EU
Research and innovation	Yes	1	There are many R&I projects addressing the recycling of Li-ion batteries
Existing recycling capacity	Yes	1	Some industrial capacity for recycling of Li-ion batteries already exists in the EU
Recycling potential by 2030	Yes	1	A contribution from the recycling of Li-ion batteries can be expected before 2030
Final score batteries		**1**	

Source: JRC assessment.

Box 10. A significant contribution to the supply of secondary materials from wind turbines, solar PV panels and Li-ion batteries is expected only after 2025-2030, as these technologies are relatively young and have a long lifetime.

While the recycling of solar modules and Li-ion batteries is regulated in the EU and some recycling capacity already exists, the recycling of permanent magnets and blades still needs to be regulated. Collection, sorting and disassembly systems for permanent magnets and blades should be established to support future recycling in the EU.

6.2. Substitution at technology level: wind turbines, solar PV and batteries

As previously noted, 'substitution' per se is not used in the current evaluation due to the timeframe under consideration — 2030. Yet it is tangible mitigation measure with great potential as a game changer in the future and, therefore, merits some further elaboration.

Substitution should be addressed from different perspectives and levels, such as substitution at materials level (as discussed in Section 3.2) and substitution at technology level. For example, neodymium is a material with medium substitution potential in relation to all sectors in which it is used. However, no viable substitute materials for permanent magnets offering the same performance are currently commercially available. There are alternative technologies to permanent magnet-based turbines that are widely used, especially in onshore wind applications, however they do not offer the same level of performance. The EU plans to significantly increase the deployment of offshore wind turbines in the future. This will have a significant effect on the supply of materials such as REEs (neodymium, praseodymium and dysprosium) unless another highly efficient magnet technology is commercialised in the meantime. For instance, iron-nitride permanent magnets could in the future be a promising alternative to neodymium magnets due to their lower production costs, environmentally friendly manufacturing process, good compatibility with mass-production techniques, suitability for many high-tech applications — including electric traction motors, wind turbine generators and electronics — and, last but not least, ability to offer better performance than neodymium-based magnets (UMN, 2017). Currently this new magnet is in the demonstration phase, and progress should be seen on this technology in the future.

It is also possible to substitute silicon in solar PV, but in the longer term — at least 10-15 years from now. Perovskite solar cells are considered to be a future alternative to silicon technology, though again it is about substitution at technology (system) level rather than at materials level. For the time being, indium is not substitutable in thin-film solar cells without losing performance.

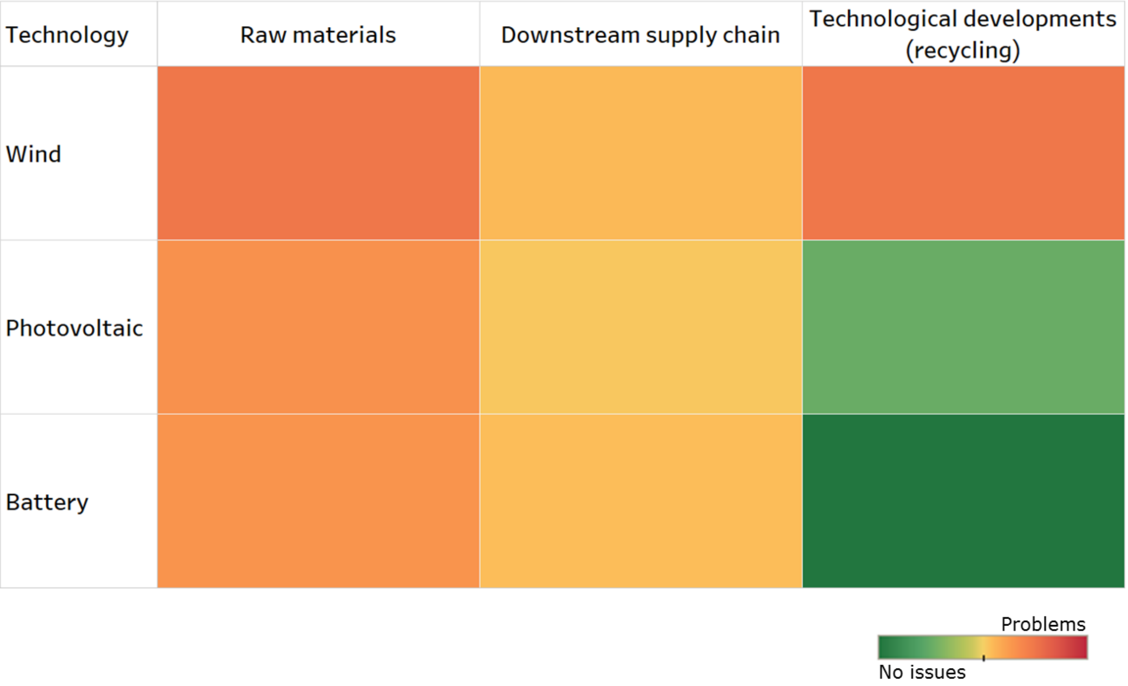
Concerning Li-ion batteries, a number of alternative chemistries, such as metal-air, lithium-sulphur, sodium-ion, magnesium-ion and flow batteries, are currently being explored. Hydrogen fuel cells and aluminium-ion and graphene-based batteries are also recognised as potential future alternatives to Li-ion. All these battery chemistries are at different development stages, and according to the experts they are 15-20 years away from commercialisation.

Box 11. Substitute materials and alternative technologies for wind turbines, PV solar and batteries do not exist today at industrial scale without compromising performance and costs. Technological breakthroughs can be expected only after 2030.

7. Overall assessment of the EU's resilience to materials supply issues for the mass deployment of wind, solar PV and batteries technologies

The EU's resilience to potential materials supply issues on the road to the mass deployment of wind, solar PV and batteries is evaluated though a semi-quantitative rating illustrated by a traffic light assessment matrix (Figure 18). Greens are associated with no particular issues, while reds indicate potential problems.

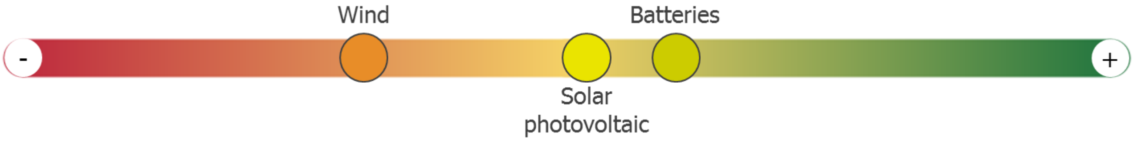
Figure 18. Assessment matrix of the EU's resilience linked to materials-related aspects for mass deployment of wind turbines, solar PV and batteries



Source: JRC analysis.

Permanent magnet-based wind turbines appear to be the most vulnerable technology in respect of raw materials. The reason is the EU's very strong dependency on REEs needed for permanent magnets in direct-drive wind turbines. REEs are expensive materials with very high supply risks and currently negligible recycling and substitution rates. Wind technology is also most susceptible in terms of the supply of processed/finished materials. In addition, and recycling progress made in the EU is somewhat lagging behind when compared to the other two technologies. All this this makes wind the most vulnerable technology with regard to materials (Figure 19).

Figure 19. The EU's overall resilience to materials supply for wind, PV and battery technologies



Source: JRC analysis.

This assessment is based on the assumption that direct-drive permanent magnet wind turbines will prevail due to their higher efficiency, such as their ability to produce more power output with slower wind speeds. The direct-drive configuration also eliminates the major cause of maintenance and repair of a wind turbine, which is the gearbox. Another reason to focus on this type of wind turbine is the EU's long-term plans to greatly increase offshore wind power, a sector in which turbine generators with permanent magnets are state-of-the-art technology.

The EU's resilience to materials supply issues in relation to the deployment of PV energy and batteries is higher than for wind power. Although the impact of materials on the cost of the technology is higher than for wind turbines, solar PV and batteries use materials most of which are not associated with high supply risk, and the EU's import reliance for these materials is somewhat lower. Europe holds a minor share of the market in the materials supply chain for all three technologies. However, the supply of materials needed for solar PV and batteries is somewhat less concentrated in comparison to materials used in efficient wind turbines.

Concerning the recycling of PV modules and Li-ion batteries, some recycling initiatives and types of infrastructure are available in the EU, while recycling of REEs from wind turbines and electric cars motors, particularly of neodymium, dysprosium and praseodymium, has yet to be regulated and commercially begun. Several initiatives have been taken in this regard (Demeter, 2017b; EREAN, 2017; European Parliament, 2015). Currently, China is actively involved in recycling permanent magnets and seems to be taking the lead in this sector, thus closing the loop from the mining of raw materials to the use and recovery of materials from end-of-life products.

A recent study highlighted the longer-term supply risk to the European wind and solar energy industry in terms of CRMs and the explicit role of China as a major supplier (Rabe et al., 2017). In this study some conclusions were drawn regarding the EU's future policy: the development of alternative substitute technologies which are less reliant on critical materials and the recycling of these materials are essential measures to secure the successful deployment of wind and solar energy in the EU.

Supporting and incentivising the recycling business in the EU is crucial in the context of a circular economy. It not only implies the generation of a secondary materials flow but will also contribute to preventing environmental issues caused by dumping waste batteries, PV modules and electrical motors/generators. Moreover, new jobs could be created in recycling companies. Innovative recycling processes need to combine environmental benefits and a secure supply of materials with a financial profit for the companies. Li-ion batteries are an emerging technology for the growing automotive and energy storage sectors. The availability of raw materials for this technology and the environmental effects associated with their extraction are often overlooked (McLellan, 2017). In addition, some materials are not currently produced in very economical conditions, such as in the case of lithium. But a reliable lithium supply is of vital importance for increasing the future production of cell batteries in the EU. Other materials such as cobalt and nickel are currently recycled from batteries. However, due to the low collection rate of batteries (around 9-10 % according to expert opinion), the total amount of secondary cobalt and nickel coming from these batteries is relatively low. The recycling of Li-ion batteries, solar panels and wind turbines is also highly relevant for the EU's circular economy (ECESP, 2017).

8. Opportunities to improve the competitiveness of the EU's wind, photovoltaic energy and battery industry through a sustainable materials supply

In general terms, the level of play of the EU's non-energy extractive industry (primary materials) and recycling industry (secondary materials) was evaluated in a recent study carried out for the European Commission (European Commission, 2015).

Several initiatives were suggested to support non-energy extractive industry, such as:

- improving knowledge of mineral endowment;
- addressing the cost of energy;
- focusing R&I on more-efficient extraction methods;
- simplifying the regulatory framework.

As for the recycling industry, the following actions are suggested:

- providing demand-side stimuli for the industry;
- addressing concerns associated with quality of recyclates;
- placing a stronger focus on the enforcement of existing legislation;
- establishing better accounting of the recycling industry within the EU Member States by collecting information and data on a regular basis.

Financial support mechanisms, fiscal incentives, reducing VAT and tax shelters for secondary materials can help to address the cost gap between primary virgin and secondary raw materials (SUEZ, 2016). For instance, China already has a VAT rate of 0 % on secondary raw materials to attract recycled material.

Furthermore, the analysis carried out in this study is used to anticipate and define some opportunities that could contribute to increasing the EU's competitiveness in wind, PV and battery technologies in relation to materials. China's leadership in producing many of the raw and processed materials needed in these technologies, as well as its increasing role in the whole supply chain, including recycling, may facilitate the country to strengthen its position as competitor in the future. Adequate measures should be taken in a timely manner in order to strengthen the EU's competitiveness in these three sectors in relation to an adequate and sustainable materials supply.

Four main opportunities have been identified and elaborated upon below for each of the three technologies.

Box 12. Opportunities to improve the competitiveness of the EU's renewables industry

1. Recycling and reuse following the circular economy model
2. Research and innovation
3. Diversifying the materials supply
4. Strengthening downstream manufacturing

8.1. Recycling and reuse following the circular economy model

8.1.1. Wind power technology

The Chinese and other big economies will continue to grow over the coming years, and China might struggle to keep its production in line with the rising global demand for REEs. There are indications that China's domestic demand for neodymium used in permanent magnets may exceed global production by 2025 (Mining, 2017b). Global companies located in China still have access to REEs at a significant price discount despite the recent WTO rulings. This in turn incentivises strategic downstream manufacturing companies, such as magnet producers, to move to China in order to be more competitive. In relation to recycling capacity, China is claiming also to be the future leader in permanent magnet recycling: several new projects have been approved or are under development in China that in total account for more than 37 000 tonnes of recycled magnet annual capacity (Roskill, 2015). By closing the production loop China has the opportunity to preserve its almost total monopoly on the supply of REEs.

As concluded in the report carried out by the European Rare Earth Competency Network (Erecon): ‘China has nurtured its REE industry over decades at a great expense, and will continue to try to capitalize on the opportunities this offers for developing high-tech industries. In the meantime, volatile prices and insecure rare earths access threaten to undermine European innovation and competitiveness and may slow the diffusion of priority technologies, such as electric vehicles and offshore wind’ (Erecon, 2015).

One feasible way to secure future EU access to the REEs needed for wind turbines, EV motors and other high-tech applications is to ensure a sustainable flow of secondary materials through recycling.

Adequate collection and recycling capacity should be established in the EU as soon as possible to deal with the increasing flows of used permanent magnets from industrial machinery. Additional feedstock will come from end-of-life EVs from 2025 onwards. The same companies could also recycle materials from decommissioned wind turbine generators. Due to the specificity of the recycling processes, proper regulation and the introduction of a mandatory labelling system indicating the type of permanent magnets will facilitate the recycling process and make it more effective. This can support the permanent magnet industry in the EU in the light of the growing market for EVs and wind turbines, which will contribute to increasing the demand for neodymium and praseodymium by almost 250 % over the next 10 years (Financial Times, 2017a). Tesla is also opting to use REE magnets in its Model 3 RWD Long Range vehicles instead of induction motors, to increase the performance of the electric powertrain (Industrial minerals, 2016).

It is worth noting that REEs generated from recycling will not meet the primary demand in a growing market. Expert estimates show that the contribution of recycling to the total supply could be up to 20 % due to imperfect end-of-life collection rates and recycling yields (recovery rate). Nonetheless, this may be sufficient, to a large extent, to secure the magnet-producing industries in EU in the short term, whilst in the long term primary mined sources could be developed (Erecon, 2015).

8.1.2. Solar photovoltaic technology

Silicon metal is currently not recovered from post-consumer waste. Most chemical applications, which account for 54 % of end uses, are dispersive and thus do not allow for a recovery/recycling process. Silicon metal is also not recovered from aluminium-silicon alloys, which represent 38 % of silicon metal applications.

In those industries that use metallurgical grade silicon some recycling streams exist for economic and environmental reasons. However, very little material is sold back to the market by metallurgical silicon users. The recycling of silicon wafers from the semiconductor industry is the subject of research and is not yet realised in marketable solutions.

There is some potential for recycling silicon metal from scrap in the PV industry. Most silicon scrap generated during crystal ingot and wafer production for electronic applications can be used in the PV industry due to the higher quality (purity) of the silicon metal (Woditsch and Koch, 2002). Yet this potential is rather limited; electronic applications account for only 2 % of silicon metal end uses.

Therefore, the tangible flow of recycled silicon metal for the PV industry is the industry itself. Including a recycling strategy in the manufacturing process for PV modules is important since it can ensure some secondary material flows for PV manufacturers and can also maximise their profits. Moreover, recycled silicon metal is less energy intensive than the primary form. The early adoption of recycling targets, unified for all Member States, may lead to higher recycling and recovery rates, as seen in Japan and Sweden (Auer, 2015). In addition, unification of the classification of waste streams from PV panels across Europe is highly desirable. Different definitions used across the EU have negative implications to collection and recycling financing as well as waste responsibilities, which pose challenges for producers.

8.1.3. Battery technology

The recycling of batteries is crucial to deal with raw materials supply issues in the future. One of the challenges making the business of recycling Li-ion batteries insufficiently developed at present and insecure for the future is the quantity of battery material needed to keep the rate of use of recycling facilities sufficiently high (Financial Times, 2017b). The risk is therefore to have an insufficiently large infrastructure in place and in time for the first big wave of spent Li-ion batteries coming from electric vehicles.

Although several companies in the EU are already recycling Li-ion batteries, mainly from consumer electronics, the EU recycling infrastructure targeting EVs and storage batteries has to be further strengthened. Certain companies have already begun to implement schemes for the recycling of used EV batteries. The expected growth in the demand for EVs in the coming decades is the long-term growth driver for companies such as Umicore, which in 2011 opened an industrial-scale recycling facility for end-of-life rechargeable batteries at its Hoboken plant (Belgium) (Umicore, 2017).

The concept of promoting the reuse of end-of-life EV batteries is spreading all over the globe, from the perspective of using resources more effectively and reducing the need for new products (batteries in this case) (EAARB, 2014). In specific cases, batteries that are no longer usable for their first application still have residual capacity that could be employed for other purposes (second use). A number of research initiatives and pilot projects have been developed to assess the reuse of batteries that are no longer suitable for EVs in energy-storage applications. Batteries2020 (9), the Energy Local Storage Advanced system (ELSA) (10), ABattReLife (11) and Netfficient (12) are examples of EU-funded projects aimed at finding the most suitable and sustainable second-use applications for EV batteries. Other research projects are being developed in collaboration with industry, including the following:

- In the Netherlands the project 2BCycled aims to determine the business case for a second life for discarded EV batteries, evaluating the economic potential of the local household system (ARN, 2014). As another example, 280 second-life batteries will provide 4 MW of power and 4 MW of storage capacity to the Amsterdam Arena (ArenA, 2016).
- BMW and Vattenfall have begun a research project looking at the secondary use of high-voltage EV batteries from MINI-E and BMW ActiveE vehicles for a multipurpose second-life application (trading, frequency regulation, etc.) (Bosch, 2016).
- Renault and Connected Energy are collaborating on the E-STOR energy storage product (Charged, 2016a).
- Nissan and Eaton have formed a partnership to introduce a unit home-energy storage system with second-life EV batteries (Charges, 2016b).

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(9) http://www.batteries2020.eu/

(10) http://www.elsa-h2020.eu/

(11) http://www.abattrelife.eu/

(12) http://netfficient-project.eu/

8.2. Research and innovation

Research and innovation, in close collaboration with industry, is one of the key opportunities for the EU to ensure the energy transition and deal with supply issues of raw and processed materials. Research and innovation is needed to improve material efficiency, increase recycling rates and find suitable substitutes. Innovation is a valuable asset also for the mining industry in Europe, addressing the challenge to mine deeper, recover more from the less available and less concentrated resources and use more effectively the mine tailings (considered waste) to recover materials. Resource efficiency, development of advanced recycling and mining technologies, and finding adequate alternative materials are research topics already addressed through various Horizon 2020 projects and the European Innovation Partnership on Raw Materials' Commitments (CRM-InnoNet, 2015; EASME, 2015; European Innovation Partnership, 2015, 2016). For instance, around EUR 14.5 million has been allocated for the period 2014-2015 for projects focusing on the recycling of raw materials from end-of-life products and buildings (European Parliament, 2015).

Investing in training and education programmes is also imperative for creating and maintaining the knowledge base and high professional skills in Europe.

8.2.1. Wind power technology

In 2013 the European Rare Earth (Magnet) Recycling Network (EREAN) was established with the objective of training young researchers in the science and technology of REEs, with an emphasis on the recycling of these elements from permanent magnets.

The development of innovative highly efficient recycling methods may alleviate the supply risk for some critical materials, especially REEs. Recycling technologies for REEs are still in the early stages of development and face inherent difficulties: many devices contain less than one gram of valuable REEs; the product design is unfriendly and not suitable for the easy separation of components, which makes the recycling process expensive. In addition, there is insufficient information of the REE content of different products. On top of this is the insufficient collection rate of end-of life products. All these inconveniences together can explain the current very low recycling rate of REEs — less than 1 %.

Finding alternative technologies can drastically change the long-term picture. New advanced technologies will come with new material requirements and new suppliers. For instance, if iron-nitride permanent magnet technology is proved and commercialised in the coming years this could significantly alleviate the EU's dependency on China for wind and EV materials since this new magnet relies on more abundant and cheaper materials.

The EU offers support for the development and demonstration of material-efficient solutions for equipment used in wind energy technologies (e.g. the Horizon 2020 project Neohire (13) on the use of REE, cobalt and gallium in permanent magnets).

As for the recycling of blades (another problematic component for recycling), at present there is not a large supply of composite waste for commercial recycling companies to be prosperous and to push for innovative recycling methods. The development of innovative techniques for blade recycling is highly desirable, and EU industry should be ready to adopt these processes within the next 10-15 years. It is also important to improve the design of next-generation wind turbine blades, which will make their disposal and recycling process easier and cheaper in future.

8.2.2. Solar photovoltaic technology

The development of innovative recycling methods for PV modules will allow the recovery of a larger amount of materials, reducing the demand for primary materials and thus lessening the EU's reliance on importing these materials.

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(13) http://neohire.eu

For example, the European research project ‘Full recovery end life photovoltaic’ (FRELP) (14) developed a pilot plant which allows the recovery of around 35 kg of metallurgical grade silicon from 1 000 kg of waste crystalline PV panels. The work also assessed the environmental performance of this innovative recycling process in comparison with the current treatment of PV waste in generic WEEE recycling plants (15). The results proved that the FRELP recycling plant has a slightly larger impact on the processing of PV waste compared to WEEE recycling plants, but it implies much higher benefits in terms of larger amounts of recycled materials (mainly silicon, precious and base metals, and glass).

8.2.3. Battery technology

Innovation in batteries can contribute overall to increasing the EU’s resilience through, for instance, establishment of new ‘European’ eco-friendly designs, allowing for reduced use of critical materials and obtaining high recovery rates through advanced recycling processes. This could also support the standardisation of Li-ion chemistries within the EU and will also give a push to the recycling industry in the EU.

Several examples can be given regarding innovation activities in batteries. Recupyl, a French company, which already collects and recycles batteries from EVs, has formed partnerships with the manufacturers of batteries and EVs in order to design eco-friendly batteries that can be recycled more easily and to develop high-yield processes to recycle next-generation batteries (Recupyl, 2017). Another French company, SNAM (Société Nouvelle d’Affinage des Métaux), which collects and recycles hybrid and EV batteries, is able to recycle up to 80 % of the battery weight (SNAM, 2015). A battery-recycling network has been developed by Toyota with certified companies such as SNAM and Citron (France), Accurec (Germany), Batrec (Switzerland) and Saft (Sweden) (Christidis et al., 2005). Colabats is an EU-funded project aimed at developing economically viable methods of NiMH and Li-ion battery recycling (C-Tech, 2017). The aim is to recover valuable materials including cobalt, lanthanum, cerium and other REEs.

8.3. Diversifying the materials supply

8.3.1. Wind power technology

In view of the current quasi-monopolistic supply of REEs from China, it is essential for Europe to diversify its supply via partnerships and participation in various ongoing and future exploration projects for REEs at a global scale. Several mines and processing facilities for REEs are now slowly ramping up their production after long delays. The United States did not produce REEs in 2016, but seven other countries aside from China did, namely Australia, Russia, India, Brazil, Thailand, Vietnam and Malaysia (Bradsher, 2011; Rare Earth Investing, 2017; Worstall, 2014).

High potential for REE mining also exists in Europe. The exploration projects in Sweden and Greenland, by Canadian and Australian companies, could potentially secure a large part of the European needs for REE in the coming decades according to experts (ERECON, 2015). It is claimed that with adequate funding and permits they could begin mining REE concentrates before 2020. A number of smaller projects are found in several other European countries, including Germany, Greece, Spain, France, Italy, Portugal, the United Kingdom and the western Balkan nations. These sites still require proper evaluation and therefore could potentially contribute to the domestic supply of REEs in the longer term.

Learning from the strategies of other countries that are heavily dependent on REE imports could also provide good examples to follow. For instance, China supplies more than 80 % of the REEs needed by the Japanese economy. Japan’s strategy to secure

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(14) https://frelp.info/

(15) Current treatment of waste PV panel is mainly based to the dismantling of aluminium frame and cables, and the further undifferentiated shredding of the panel.

access to REE is multifold: Japanese companies and the Japanese government are making joint venture agreements and partnerships around the world to secure supplies of REEs, particularly at the raw-material stage, and are investing in various exploration projects for potential mining in different countries. Research investment to increase material-use efficiency and finding substitutes for REEs in magnets and other critical applications is another mitigation measure. The Japanese government is also establishing a 'recycling-based society' with major efforts in urban mining (i.e. the recovery of materials from end-use applications, such as laptops and cell phones).

China is also striving to diversify sources and expand its capacity beyond its own territory. For example, the Mountain Pass rare earths mine and processing facility in the United States, previously operated by Molycorp, was recently purchased by the Chinese-led consortium MP Mine Operations LLC following Molycorp's bankruptcy in 2015. The REE market is rather dynamic and it is difficult to foresee what the supply balance will be by 2030. The available information on potential future mines points to reduced concentration of supply due to new players entering the market. However, the EU's dependency will remain high and it can be expected that the REE supply shortage will still negatively impact the EU's competitiveness in high-tech industry. It could also impede the progress of emerging clean technologies such as electric cars, fuel cells, PVs, windmills and efficient lighting (Ebner, 2014; Massari and Ruberti, 2013).

8.3.2. Solar photovoltaic technology

Crystalline silicon is currently the dominant global PV technology. Around 90 % of the market is based on this technology, and it will remain the leading technology in the EU at least until 2030. Meanwhile, thin-film PV technology is slowly gaining ground on the PV market. Other emerging PV technologies, such as those based on perovskite materials, dye-sensitised solar cells, organic compounds and quantum dots, look very promising and are subject of scientific interest, but their future looks insecure.

The main materials for solar PV technology for which potential supply bottlenecks can occur are silicon and silver. While silver can be substituted, for example by aluminium, no viable substitutes yet exist for silicon, and it is possible that none may be available in the short term. Silicon is used in wide range of applications and the prospects point to a constant increase in the demand for silicon in the future.

China is by far the largest supplier of raw silicon, accounting for around 65 % of world production in 2016 (Statista, 2017b). China is also investing in new raw silicon projects, while such projects are not expected to be started in Europe in the near future (16). New projects for opening new production facilities for silicon metal were also recently implemented in China. For example Xinjiang province increased its capacity by 1.8 million tonnes in 2016. It has been estimated that the total capacity of silicon production in China is about twice the current global demand (European Commission, 2017a).

China is also the main producer of silicon metal (the pure form of silicon required to produce polysilicon for PV modules). It produces more than 60 % of the worldwide supply. The next largest producers are Brazil and Norway, which account for 10 % and 7 % respectively. Silicon metal is identified as a critical material for the EU economy. According to the *Global silicon industry update* report (May, 2015), the global demand for silicon metal in 2015 slightly exceeded the global supply, which is an indication of supply bottlenecks.

The EU is a net importer of silicon metal as domestic production cannot satisfy domestic demand. The reliance of the EU on imports of silicon metal is estimated to be 64 %. Norway, Brazil and China are the main exporter countries to the EU, covering 73 % of total EU imports of silicon metal (Eurostat, 2016). It is challenging for Europe to be competitive in the global silicon metal market. The processing of silicon is an energy- and carbon-intensive process. The main energy source used by the major silicon-producing

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(16) Private communication with experts in the field.

countries such as China is coal, while most silicon metal plants in Europe have historically been located close to hydropower sources. Chinese producers also benefit from lower power tariffs, which explains the lower manufacturing cost of the silicon metal produced in China. In addition, silicon production in the EU is subject to the directive on the emissions trading scheme (Directive 2003/87/EC), which entails direct and indirect carbon costs.

The European manufacturing industry supplying solar grade silicon is represented by Wacker Chemie AG (Germany), which in 2015 provided around 14 % of total global production.

8.3.3. Battery technology

There are some concerns among Li-ion battery manufacturers that future production could be hindered by potential supply shortages of lithium, cobalt and natural graphite materials.

Lithium

Chile is the largest producer of lithium ore (44 %), followed by Australia (32 %) and Argentina (11 %). The three major suppliers of refined lithium compounds, such as lithium carbonates and lithium hydroxides (required in batteries), are Chile (36 %), Australia (31 %) and China (16 %). The reliance of the EU on imports of lithium compounds is estimated to be 86 %, of which the major part is imported from Chile (77 %), followed by the United States (10 %) and China (6 %) (European Commission, 2017a).

Only Argentina has export taxes on lithium products (OECD, 2016), and a free trade agreement is in place with Chile, the main supplier of lithium to the EU (European Commission, 2016b). Therefore, no particular supply issues should be expected for lithium in the short term. However, the lithium market is becoming very dynamic following the recent developments in the EV sector. It appears that this sector is evolving more rapidly than the forecast growth, and EV producers and battery manufacturers are rushing to ensure long-term supply contracts for lithium. In the context of planning future construction of mega-factories for Li-ion batteries, for example in Germany, the EU needs to take action to overcome a potential lithium supply shortage.

Cobalt

The battery industry is one of the major end uses of cobalt, requiring more than 40 % of the total demand. Although the Democratic Republic of the Congo is the main producer of mined cobalt, providing around 64 % of total mining production, most refined cobalt is supplied by China (42 %) (European Commission, 2017a). The EU relies greatly on imports of cobalt: more than 90 % of cobalt ores and concentrates are imported from Russia, followed by 7 % from the Democratic Republic of the Congo. The import of other forms of cobalt, such as cobalt hydroxides, originates mainly from the Democratic Republic of the Congo, which satisfies around 50 % of EU demand. The Democratic Republic of the Congo is also the main supplier of cobalt for China — the Chinese consumption of cobalt supplied by the Democratic Republic of the Congo has increased from 55 % to 70 % in just 5 years. The very high global competition for cobalt also means that there is a high risk of supply disruptions for the EU. Regarding export restrictions, China and the Democratic Republic of the Congo imposed export taxes of up to 25 % on cobalt ores and concentrates over the 2010-2014 period (OECD, 2016). Some EU free trade agreements are in place with minor suppliers such as South Africa and Turkey (European Commission, 2016c).

Graphite

China is the world’s leading supplier of natural graphite, with approximately 70 % of global production, followed by India (12 %) and Brazil (8 %). The EU is almost entirely dependent on imports of natural graphite. There is some marginal production in the EU, but this accounts for less than 1 % of the global output. The main suppliers of graphite to the EU are China (66 %), Brazil (13 %) and Norway (7 %) (European Commission, 2017a).

China has imposed export quotas on 12 commodities, including graphite and cobalt, both of which are critical materials for the EU economy (2017 CRM list). For several materials the export quotas were recently removed, and it is expected that they will be cancelled for all 12 materials between 2017 and 2018 (Roskill, 2016).

In summary, the current supply to the EU of materials essential for building Li-ion batteries is rather concentrated: 77 % of lithium is supplied from Chile, 90 % of cobalt ores and concentrates originated from Russia, 50 % of other cobalt compounds come from the Democratic Republic of the Congo and 66 % of the natural graphite is imported from China. Therefore, extending the list of potential supplier countries and ensuring long-term supply contracts is essential for EU industry to stay competitive in the dynamic Li-ion market. The possibility to extend EU domestic production should also be explored.

8.4. Strengthening downstream manufacturing

A sustainable supply of raw materials is necessary but not sufficient to ensure a competitive European renewables industry. The supply of raw materials is just the first step in the value chain, and therefore the whole supply chain should be strengthened, including downstream manufacturing.

Such a policy is also being adopted by China. The country is enhancing its competitiveness by closing the supply chain and prioritising its own downstream industry. In addition the Chinese policy includes attractive conditions for foreign investors, with guaranteed access to REEs and other materials as well as to the emerging Chinese market, which leads to the movement of foreign-owned facilities to China.

8.4.1. Wind power technology

Besides secure access to REEs, their processing and downstream manufacturing facilities are an important asset for the competitiveness of the renewables industry. Several steps are required to make the transition from raw materials to the production of permanent magnets, and China is keeping leadership in all these steps: mining, milling and concentrating ores (80-85 %), separation (80-85 %), refining (> 95 %), production of alloys and powders for magnets (> 95 %) and manufacturing (> 80 %) (DOE, 2015). Besides mining, the processing of REEs is a critical step due to its high environmental impact. Therefore, securing a sustainable supply of primary and secondary raw materials can also boost companies producing sintered neodymium-based magnets, which are now disappearing from Europe.

Monitoring innovation and new developments (e.g. iron-nitride permanent magnets) and being able to initiate production or timely secure contracts with producing countries are other opportunities for improving the sector’s competitiveness in the long term.

8.4.2. Solar photovoltaic technology

China now effectively controls the solar PV market. It owns two thirds of the world’s solar cell capacity and also purchases half of the world’s solar panels (The New York Times, 2017). China’s solar-power production capacity expanded more than tenfold from 2007 to 2012. Six of the top 10 solar-panel manufacturers are Chinese, including the top two, compared with none a decade ago. To bypass anti-dumping and anti-subsidy measures imposed by the EU and the United States on Chinese PV panels a few years ago, Chinese companies have invested in building factories in other countries, particularly Malaysia and Vietnam. Chinese plans for the solar industry in the next 6 years are even more ambitious. Beijing has pushed state-owned banks to provide at least USD 18 billion in low-interest loans to solar-panel manufacturers and encouraged local governments to subsidise them with cheap land.

Within this scenario, and considering that the EU has only minimal solar cell production (around 2 % of the global market in 2015), it is extremely challenging for the EU to compete with China. EU solar companies are going out of business due to unfair competition from China. According to the European PV community, solar manufacturers have being going bankrupt around Europe and many important players are considering withdrawing from the solar market. The EU solar industry needs urgent measures as stated in an open letter to European policy-makers (PV magazine, 2017).

Europe has capacity to produce solar grade silicon — Wacker Polysilicon AG (Germany, United States) is one of the world’s leading manufacturers of hyper-pure polysilicon for the semiconductor and PV industry. However, there is no sufficient manufacturing capacity of solar cells, which appears to be the weakest link of the solar PV value chain in the EU. Actions to support the European PV industry have been largely discussed and proposed in a dedicated JRC study (Ossenbrink at al., 2015).

8.4.3. Battery technology

In relation to Li-ion battery manufacturing, the EU’s reliance is very high for both raw materials and battery-related processed materials, such as cathodes, anodes and electrolytes. Li-ion battery manufacturing is concentrated in Asia — mainly China. China is also investing heavily in increasing its production capacity. A recent Bloomberg report indicates that by 2021 China could produce 120 MWh of battery capacity (enough to supply around 1.5 million Tesla Model S vehicles). This is over three times the cell capacity of the Tesla Gigafactory. This means that China is opting to keep its dominance in the Li-ion battery market in the decade to come.

Germany has also announced that it is to build a new gigafactory for Li-ion battery production in Frankfurt with a capacity of 34 GWh. Several proposals for further factories in Hungary, Poland and Sweden have been announced, though not all of them will produce Li-ion batteries (NextBigFuture, 2017). However, it is unlikely that the amount of batteries produced in the EU will be enough to satisfy the EV roll-out, a sector which is growing more rapidly than expected.

EU has little chance of competing with China when it comes to battery cost, availability of raw materials and manufacturing capacity. The EU can, however, compete on innovation aspects such as development of advanced materials, recycling and substitution, cell chemistry and manufacturing technologies that provide high performance, durability, sustainability and safety. The EU's battery industry should be supported via reducing the risk for investors, which could lead to further economies of scale. A number of actions to increase the competitiveness of the EU’s battery industry have been proposed in a recent JRC study (Lebedeva et al., 2016).

EU leaders are becoming more aware of the need to sustain the development of battery technology in Europe in support of European carmakers. Maroš Šefčovič, the European Commission Vice-President in charge of Energy Union, hosted in October 2017 a summit with the top executives from European chemicals groups, carmakers and battery manufacturers to promote cooperation in the sector, with up to EUR 2.2 billion of EU funding available to support the plan. Mr Sefcovic told Reuters that ‘Our ambition is to create real production [i.e. of Li-ion batteries] in the EU — a full value chain, including recycling’ (Reuters, 2017) and the *Financial Times* that ‘what we need is an Airbus for batteries. In the 1960s, we had a lot of smaller companies with cutting edge technologies but what they missed was the scale. We needed the Germans, the French and other Europeans to get together and to develop what today is a marvellous plane’ (Financial Times, 2017c).

Further collaboration with China under the EU-China Collaborative Research Arrangement (European Commission, 2017b) and Investment Agreement (European Commission, 2017c) (negotiations launched in 2013) is beneficial to support the building of a robust supply chain for a higher degree of EU resilience. An example of such collaboration is the Swedish graphite project Woxna. The Woxna production facility produces high-purity spherical graphite for Li-ion batteries. This facility can become an integral part of the EU supply chain for battery manufacturing. The project is being carried out in collaboration with a strategic Chinese technology partner with a well-established battery design (Mining Sea, 2016). Work is now underway to produce a larger quantity of high-purity spherical graphite that fulfils the commercial specifications.

9. Conclusions

Materials can have a significant impact on the competitiveness of the European clean-energy generation and storage manufacturing industry through several factors, among which the growing demand, security and concentration of supply, price volatility and materials cost intensity of the technologies. These factors, along with the EU's resilience to potential materials supply disruptions and possible mitigation actions, have been analysed for three key technologies, namely wind turbines, solar PV and batteries.

Between 25 % and 40 % of the materials used in wind turbines, solar PV and batteries are identified as being critical to the EU economy. The price of raw and processed materials can have a large impact on the cost of technology — up to 70 % for batteries and solar PV technologies and 45 % for wind technology. Therefore, the increase in the price of materials can negatively affect the competitiveness of the EU related industry dealing with generation of clean energy and storage. Most of the materials used in these three technologies registered an increase in price in the period between 2000 and 2016. The most prominent price rise — between 700 % and 1 200 % — was observed for REEs (neodymium, dysprosium and praseodymium), with a further increase expected over the next few years due to projected growth in demand for neodymium-based magnets. The price of lithium has also risen by almost 400 % in the last 10 years and is still growing steadily, almost doubling in the first half of 2017 due to recent developments in Li-ion batteries for the EV sector. The resurgent economic growth of some countries, mainly China, has stimulated demand for basic commodities like copper, aluminium and lead. Overall, an increase in metal prices of 16 % is expected by the end of 2017, driven by strong Chinese demand.

The EU is highly dependent on imports of raw and processed materials. The reliance of the EU on imports of raw materials is over 50 % for around 80 % of the materials required in wind turbines, solar PV modules and batteries. China is the global supplier of about half of the raw materials and is the major supplier of the refined materials considered in this study. China is also the leading supplier of all processed materials analysed in the study, with the exception of CFC for wind blades and anode materials for batteries, for which the United States and Japan are the leaders.

Overall, this study indicates that the wind power is the most vulnerable technology in relation to materials, followed by solar PV and batteries.

From the materials perspective, several opportunities to improve the competitiveness of the EU industry in the deployment of these technologies have been identified, namely: recycling and reuse; research and innovation, including maintaining knowledge and the high level of professional skills in the EU; diversified supply; and strong downstream manufacturing industry.

Hence, the main opportunities for the EU lie in investing in recycling, increasing manufacturing capacity along the materials supply chain, developing innovative mineral extraction, processing and refining techniques, recycling methods and finding alternative materials or technologies that do not require problematic materials. This should be sustained by adequate standardisation and regulation processes. Currently, recycling and substitution have little potential to increase the sustainability of materials supply. However, recycling could significantly improve the EU's resilience to potential materials supply bottlenecks and thus strengthen industry competitiveness in the medium term (2020-2025). Substitution could offer competitive advantages in the longer term (after 2030). Besides recycling and substitution, material efficiency and further diversification of supply could strengthen the competitiveness of European industries. Liaising with other countries such as China, Japan and the United States under various collaboration agreements, including innovation and research, establishing agreements with new suppliers, securing trade contracts with new partners for raw, refined and processed materials and increasing domestic production can support the competitiveness of EU industry within the 2030 time frame and beyond.

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List of abbreviations and definitions

CFC	carbon fibre composite
CRM	critical raw material
DD-PMSG	direct-drive turbine with permanent magnet synchronous generators
EoL-IRR	end-of-life input recycling rate
EV	electric vehicle
H&EV	hybrid and electric vehicle
Li-ion	lithium-ion
MW	megawatt (10^6 watts)
NdFeB	neodymium iron boron
NiMH	nickel metal hydride
PMSG	permanent magnet synchronous generator
PV	photovoltaic
REE	rare earth elements
WEEE	waste electrical and electronic equipment

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