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Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study

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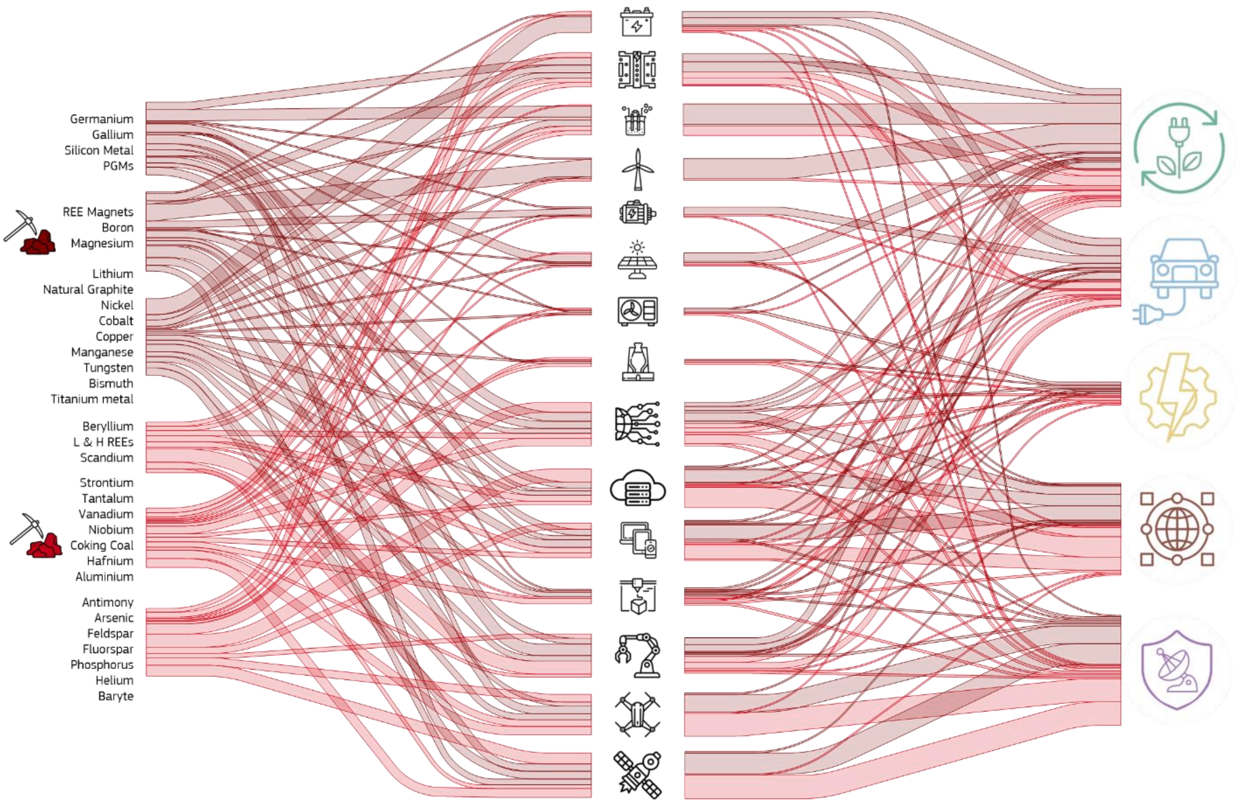

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Abstract

In order for the European Union to achieve the ambitious targets it has set for the energy and digital transitions and its defence and space agenda, it needs undisrupted access to critical raw materials and to many products which contain them. This foresight study presents a systematic and detailed analysis of the complete supply chains, from raw and processed materials to components, assemblies, super-assemblies and systems, for 15 key technologies across the five strategic sectors (renewable energy, electromobility, energy-intensive industry, digital, and aerospace/defence) responsible for the delivery of these targets.

The study assesses supply chain dependencies and forecasts materials demand until 2050 in the EU, other economic regions and the world. It also assesses the EU's materials needs and vulnerabilities now and in the future. As such, it provides a forward-looking basis to help identify strategic raw materials for key technologies and applications, to identify bottlenecks and to pinpoint the segments of supply chains which need strengthening and how. This study contributes scientific evidence to underpin the Critical Raw Materials Act, in tandem with which it is published.

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	Traction motors	Cynthia Latunussa
	Solar photovoltaics	Teodor Kuzov Giorgia Malano Samuel Carrara
	Heat pumps	Lorcan Lyons Anca Itul
	H2-DRI	Julian Somers Anca Itul
	Data transmission networks	Dominic Wittmer
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	Industry	Anca Itul
	ICT	Cynthia Latunussa Patricia Alves Dias Dominic Wittmer
	Aerospace and defence	Thibaut Maury Patricia Alves Dias

Executive summary

The energy transition is a materials transition. A clean energy system is much more minerals- and metals-intensive than a conventional fossil fuel energy system, and even with increased circularity, the implications for the extraction of raw materials, and for global competition to secure access to them, are enormous.

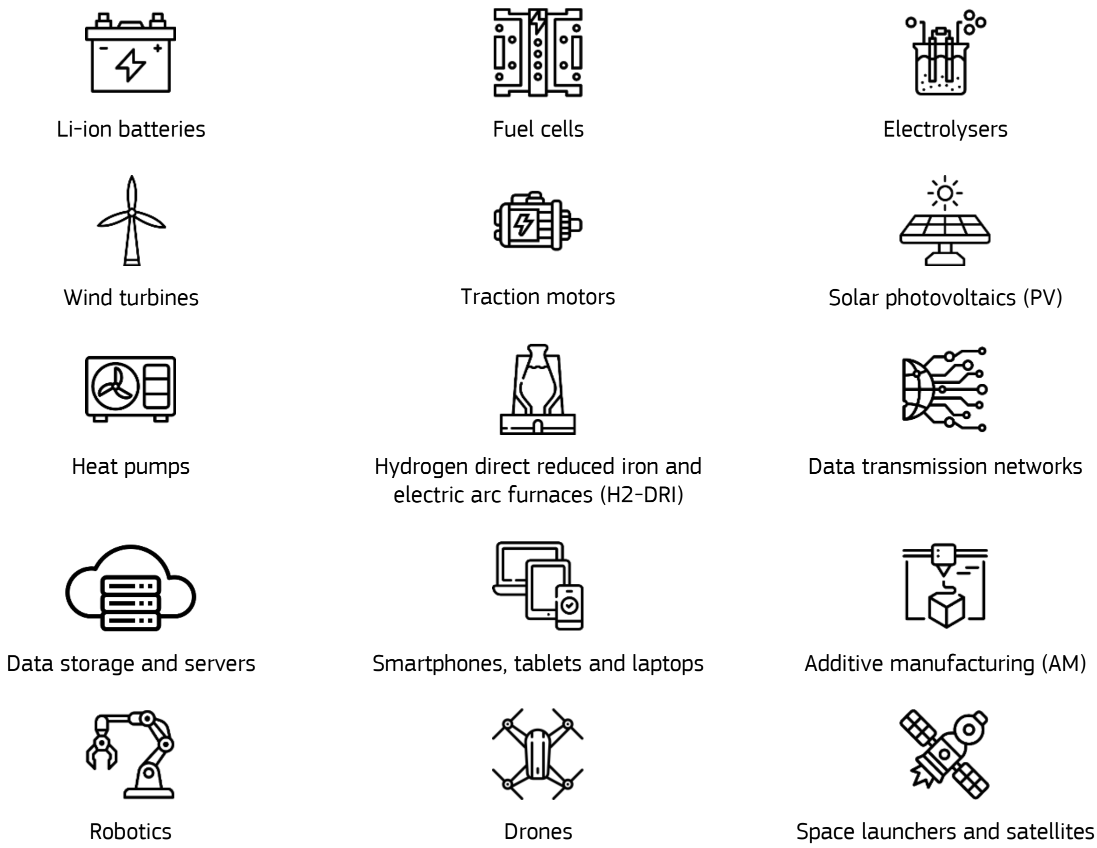
Russia's invasion of Ukraine in 2022 forced the EU to address its dependence on Russian oil and gas, and in doing so, to accelerate its targets for the energy transition, as set out in REPowerEU. This requires a massive increase in wind power and solar photovoltaic (PV) installation, batteries and hydrogen to store electricity and to power vehicles, and heat pumps for energy-efficient heating and cooling. All of these bring with them new demand for critical and strategic raw materials, many of which are also in demand for the technologies required to fulfil EU strategies for digitalisation and defence & aerospace.

The European Commission has therefore developed a proposal for a Critical Raw Materials Act, introducing the concept of strategic raw materials also on the basis of the demand projections contained in this analysis. Whereas a critical raw material is characterised by a high risk of supply disruption and its importance for the overall EU economy, a strategic raw material is additionally characterised by its importance for strategic areas such as renewable energy, digital, aerospace and defence technologies, its projected demand growth relative to current supply, and the difficulties of scaling up production.

Building on the 2020 foresight report (EC, 2020), this study explores the potential vulnerabilities and dependencies of fifteen technologies in five strategic sectors for the EU economy, namely: renewables, electric mobility (e-mobility), industry, information & communications technology (ICT), and aerospace & defence. The fifteen technologies are shown in Figure 1.

The report investigates the supply chain structure of technologies, identifying the relevant materials, components, and assemblies. It explores the potential bottlenecks along the different steps of the supply chain by assessing the relevant supply risk and future demand for the main raw materials needed in the selected technologies, based on policy-relevant scenarios or market trends.

Figure 1. Schematic representation of the fifteen technologies explored in this report



Source: JRC elaboration based on flaticon.com

Supply chain analysis

This study considers the 87 candidate raw materials assessed in the Criticality Assessment exercise 2023 (EC, 2023). Raw materials are divided into three categories: strategic, critical and non-critical. Table 13 in Annex 1 reports the full list of raw materials, while Table 1, below, shows the strategic and critical materials. In Table 1, the platinum-group metals (PGM) are grouped together; also, the rare-earth elements are clustered into three groups to emphasise those which are used in permanent magnets (such as neodymium and dysprosium), separating them from the remaining light and heavy rare-earth elements. These are indicated as REE (magnets), LREE (rest), and HREE (rest), respectively. Within each category, materials are reported in descending order of Supply Risk as calculated in EC, 2023.

The table shows the technologies in which the raw materials are utilised. The most widely used raw materials are aluminium (in all 15 technologies), copper, nickel, silicon metal (14), and manganese (13).

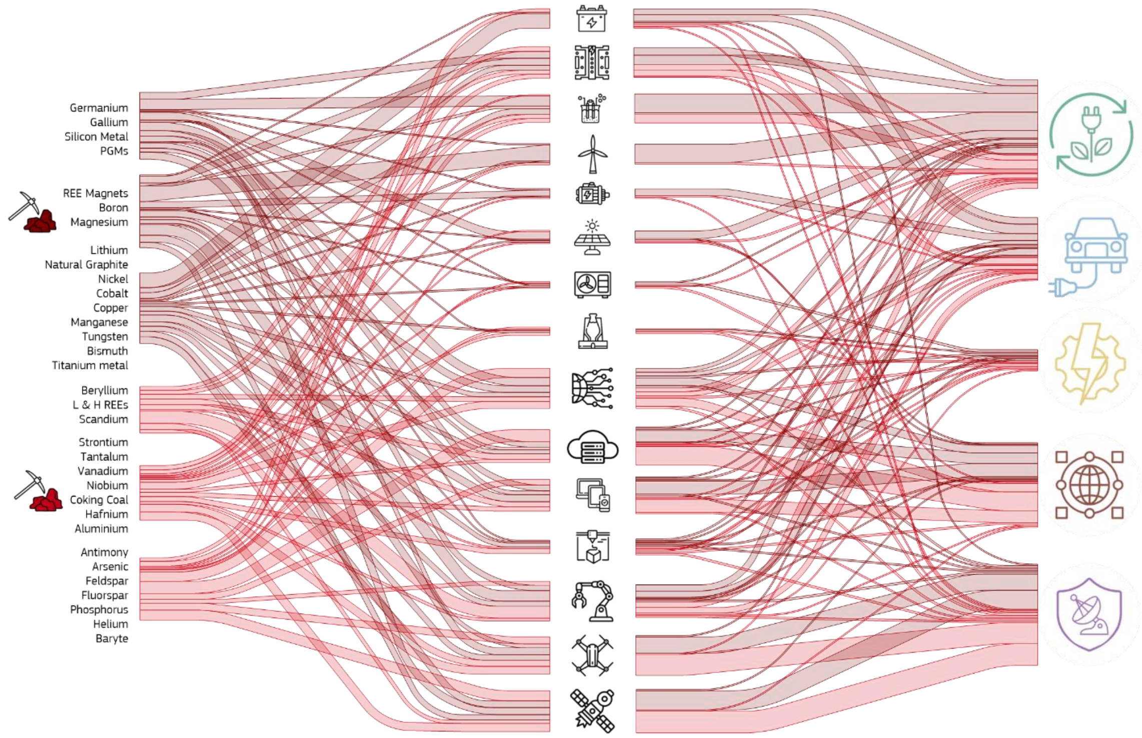
Table 1. Strategic and critical raw materials used in the technologies in scope.

Supply Risk	Raw material															
4.8	Gallium						●			●	●	●		●	●	●
4.1	Magnesium			●							●	●	●	●	●	●
4.0	REE (magnets)		●	●	●	●		●		●	●	●		●	●	●
3.8	Boron		●	●	●	●	●	●		●	●	●		●	●	●
2.7	PGM		●	●						●	●	●		●	●	●
1.9	Lithium	●								●		●		●	●	●
1.9	Bismuth									●	●	●				●
1.8	Germanium						●			●	●	●				●
1.8	Natural graphite	●	●	●					●	●		●		●	●	
1.7	Cobalt	●	●	●						●		●	●	●	●	●
1.6	Titanium metal											●	●	●	●	●
1.4	Silicon metal		●	●	●	●	●	●	●	●	●	●	●	●	●	●
1.2	Tungsten			●								●	●		●	●
1.2	Manganese	●	●	●	●			●	●	●	●	●	●	●	●	●
0.5	Nickel	●	●	●	●		●	●	●	●	●	●	●	●	●	●
0.1	Copper	●	●	●	●	●	●	●		●	●	●	●	●	●	●
5.3	HREE (rest)		●	●						●	●	●	●	●	●	●
4.4	Niobium			●	●					●			●		●	●
3.5	LREE (rest)		●	●						●		●		●	●	●
3.3	Phosphorus	●					●		●		●	●				●
2.6	Strontium		●	●						●		●				
2.4	Scandium			●							●		●			●
2.3	Vanadium		●	●					●	●			●	●	●	●
1.8	Antimony						●			●	●	●		●	●	●
1.8	Beryllium										●	●				●
1.6	Arsenic						●			●	●	●				●
1.5	Feldspar		●												●	
1.5	Hafnium										●		●		●	●
1.3	Baryte		●	●						●	●	●				●
1.3	Tantalum			●						●		●			●	●
1.2	Aluminium	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
1.2	Helium										●					●
1.1	Fluorspar	●					●	●		●		●		●	●	●
1.0	Phosphate rock									●						

Source: JRC analysis. Although it is a critical material, coking coal does not appear in the table as it is not used in any technology.

The Sankey diagram in Figure 2 shows the share of raw materials used across the fifteen technologies and five sectors considered in this report, focusing on the strategic and critical materials (non-critical materials are not shown). The renewable energy sector requires the biggest share of strategic raw materials.

Figure 2. Semi-quantitative representation of flows of raw materials to the fifteen technologies and five sectors



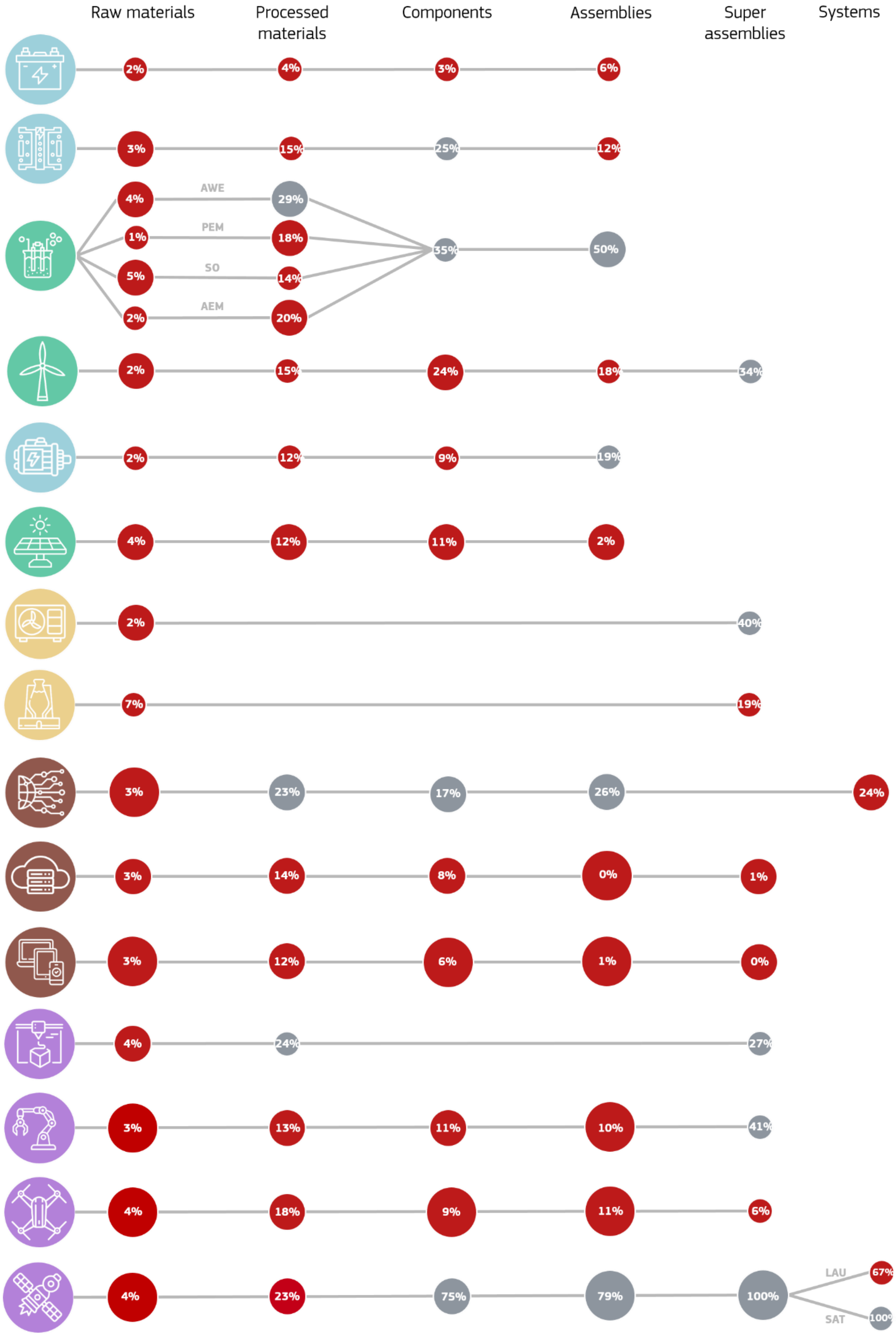
Source: JRC analysis (see Annex 3 for methodological details).

Figure 3 summarises the magnitude of the **supply risks for the EU identified along the supply chain steps** of the fifteen technologies analysed. Technologies feature four, five or six supply chain steps depending on their complexity. A missing bubble along the supply chain indicates that data were unavailable to develop a robust analysis for the corresponding step. For the same reasons of data availability, only a partial analysis, limited to raw materials and super-assemblies (i.e. the final technology step), has been conducted for heat pumps and hydrogen direct reduced iron (H2-DRI). Given their marked specificities, results are shown at a more disaggregated level for the raw and processed materials needed in the different types of electrolysers, as well as at systems level for space launchers and satellites.

The graph shows the steps characterised by vulnerability (red bubble) and those which are the least vulnerable (grey bubble). The bubbles also report the average EU share in global production for the relevant supply chain step. This share should not be intended as a direct indication of the colour of the bubble, although it is an important parameter in determining whether a supply chain step is critical or not.

Overall, **the EU shows significant vulnerability along the supply chains examined**: only 17 bubbles are grey out of a total of 70. Thus, 53 supply chain steps are considered to be critical. However, a general pattern can be identified in the graph. On the one hand, **the raw materials step is systematically critical for all technologies**. Here, the EU share in global production is never higher than 7%. On the other hand, **the EU's vulnerability tends to diminish along the supply chain**. In the last step of the chain (the final product, i.e. assemblies, super-assemblies, or systems), there are almost as many cases of non-vulnerability as there are of vulnerability. The EU is therefore reasonably strong in the manufacturing of the final technologies. The EU share in global production is, on average, 28% in these last steps (diminishing to 20% if we exclude space technologies, where the restricted nature of the market strengthens domestic production). Still, the criticality of the upstream steps highlights the challenges faced by the EU in order to guarantee an affordable and secure supply of the materials and components necessary to manufacture these technologies. Additionally, five technologies (i.e. batteries; solar PV; data storage and servers; smartphones, tablets and laptops; and drones) show vulnerability along the entire supply chain, thus highlighting the EU's dependency in the case of final products too.

Figure 3. Identified supply risks for the EU and EU share of global production volumes



Source: JRC analysis (AWE = alkaline water electrolysers, PEM = proton exchange membrane, SO = solid oxide, AEM = anion exchange membrane, LAU = space launchers, SAT = satellites; the bubble size is a proxy of the complexity of the supply chain step).

Demand forecast analysis

Meeting the EU's ambitious policy targets will drive an **unprecedented increase in materials demand** in the run up to 2030 and 2050. This report develops material demand scenarios, based on policy-relevant scenarios and market trends, with the aim of quantitatively assessing future material needs in each selected technology. In terms of geographical scope, the scenarios provide results for the EU, the US, China and the world. In terms of time horizon, demand is assessed in 2030 and 2050 (2030 only for ICT technologies), with 2020 as calibration year. Results are provided in absolute terms (tonnes per year) and in relative terms compared with the current global supply, in order to put demand in perspective (no future projections on supply are developed).

Figure 4 summarises the main results of the demand forecast analysis, showing the future patterns of the materials which are characterised by the highest growth relative to current global supply, alongside some additional strategic materials.

Given the enormous expected growth of **the e-mobility sector** in the coming decades, compared to its relatively low market share currently, this sector **includes the materials with the highest relative increase in demand**. The relevant technologies contributing to this sector are batteries, fuel cells and traction motors. Batteries are also considered under energy storage, which is also characterised by significant growth as it goes hand in hand with renewable technologies. Among the strategic materials, lithium, graphite, cobalt, nickel and manganese are the most relevant for batteries; the rare-earth elements, i.e. dysprosium, neodymium, praseodymium and terbium, are used in permanent magnets in traction motors; and platinum is used in fuel cells. Rare earths are also fundamental materials for the magnets used in wind turbines and ICT technologies; platinum also appears in electrolysers and ICT technologies.

Compared to 2020, lithium demand for batteries in the EU is expected to grow 12 times as large in 2030 and 21 times as large in 2050[1]. Globally, the increase with respect to 2020 is 18 times in 2030 and 90 times in 2050. A similar pattern is found for graphite (natural and synthetic). For platinum, the trend is analogous globally, while in the EU the growth for the latter is expected to be higher: 30 times in 2030 and 200 times in 2050 compared to 2020. By 2050, global lithium and graphite demand for batteries reaches 19 and 9 times the current global supply, respectively, while for platinum the impact is more moderate, with 2050 global demand in all technologies at 0.6 times the current global supply[2].

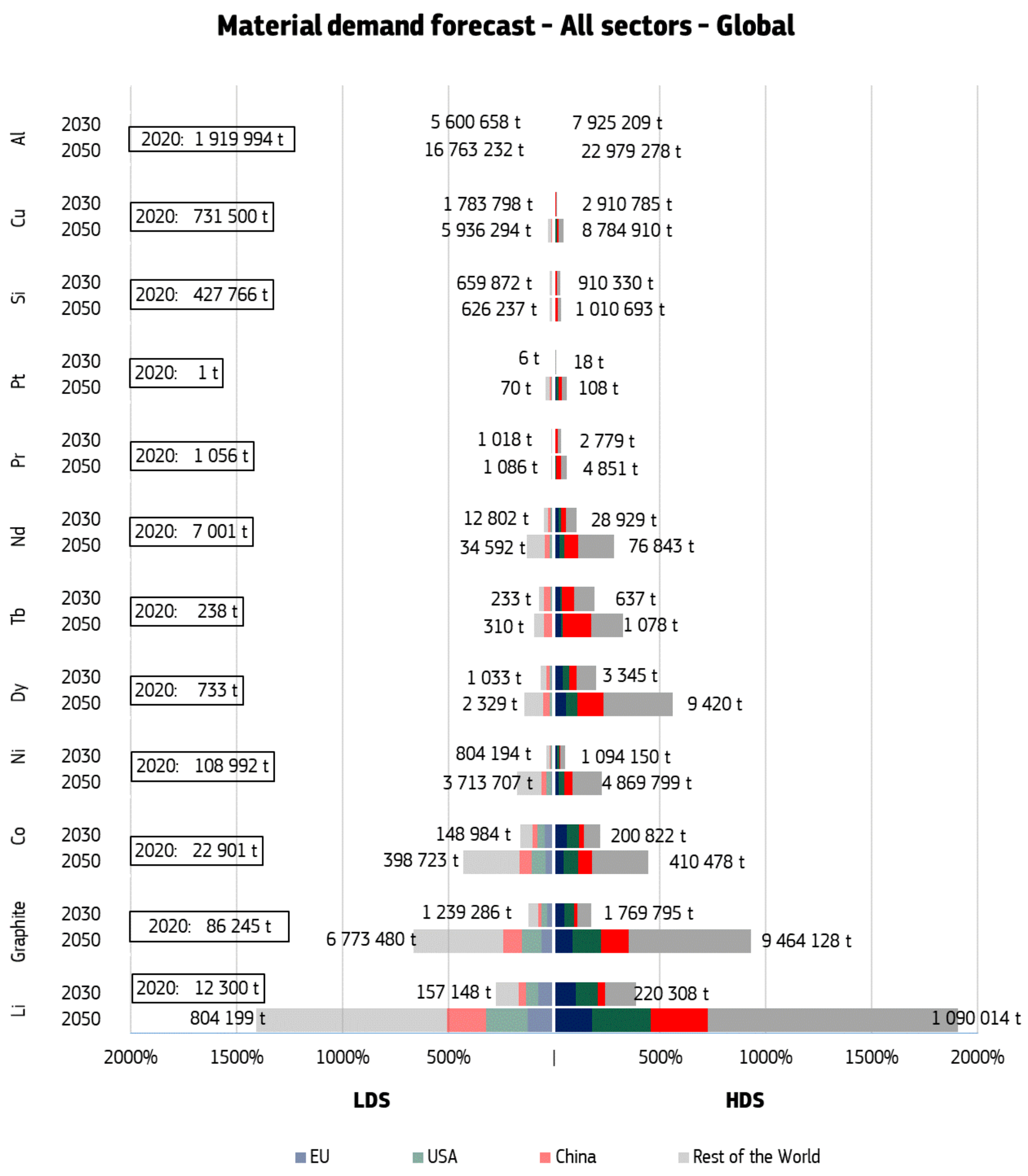
Neodymium and dysprosium (the most important light and heavy REEs, respectively, and crucial materials in permanent magnets) show a relative increase with respect to the current demand of 5-6 times by 2030 and 6-7 times by 2050 in the EU, and of 4-5 times by 2030 and 11-13 times by 2050 at global level. By 2050, global neodymium and dysprosium demand restricted to the technologies analysed in this report reaches around 3 and 5.5 times the current global supply, respectively. The relative growth of REE demand is more striking in the e-mobility sector, as this sector is still broadly at an early stage, while it is more moderate in wind turbines and ICT technologies, given the already high level of existing demand[3].

These estimates refer to the High Demand Scenario (HDS), which assumes rapid technology deployment and a combination of market shares and material intensities which result in a sharp increase of materials demand. Broadly speaking, in this scenario, future technology expansion is in line with the ambitious energy and climate change mitigation targets set by countries/regions (e.g. the REPowerEU targets for the EU in 2030), and it considers more robust digitalisation trends.

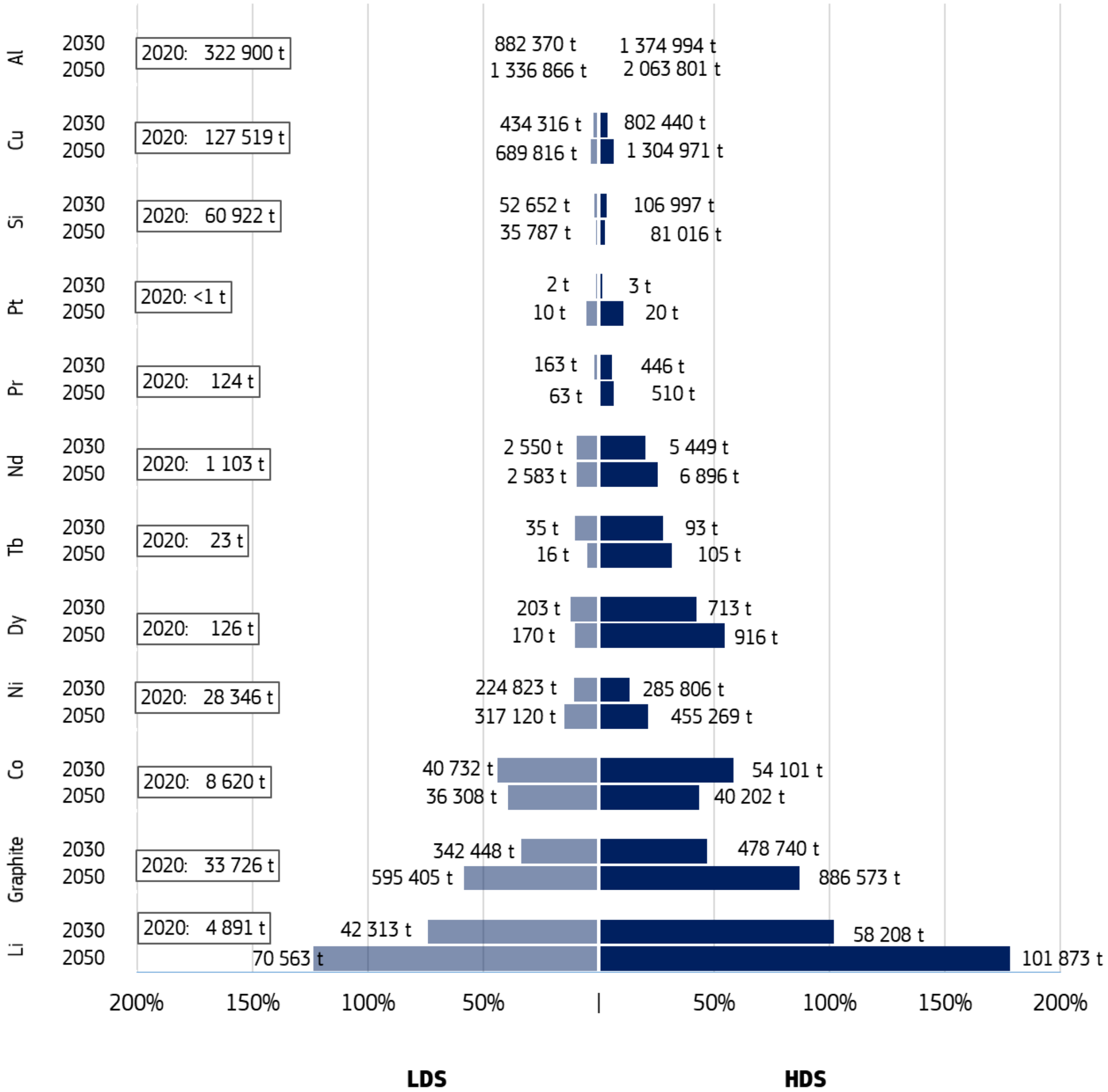
This work also considers a Low Demand Scenario (LDS), with slow technology deployment and combinations of market shares and material intensities. This results in a more moderate increase in materials demand than in the HDS (and in some cases even a decrease) but in general, the pattern of growth is clear in both. For instance, in this scenario, the 2050 global demand for lithium and graphite is around 14 and 7 times the current global supply, while it is around 1.5 times for dysprosium and neodymium.

[1] In this work, lithium also appears in smartphones, tablets and laptops, although in negligible quantities compared to batteries in both e-mobility (full and plug-in electric vehicles) and energy storage systems (ESS).
[2] The global supply value for graphite is referred to natural graphite.
[3] As already specified above, demand scenarios for the ICT technologies are developed only until 2030. Therefore, these technologies do not contribute to the 2050 figures.

Figure 4. Material demand forecast for all sectors: global (this page) and focus on the EU (next page)



Material demand forecast – All sectors – EU



Source: JRC analysis (Li = lithium, Co = cobalt, Ni = nickel, Dy = dysprosium, Tb = terbium, Pr = praseodymium, Pt = platinum, Si = silicon metal, Cu = copper, Al = aluminium).

Main findings and policy recommendations

The main findings and recommendations of this study can be structured along the following points:

- **Unprecedented increase in demand for strategic and critical materials.** In order to decarbonise the energy system, deliver the twin transition and ensure security and autonomy in strategic sectors, the EU depends heavily on many critical raw materials. Renewable energy technologies are far more materials-intensive than conventional ones. Demand for these materials is projected to increase multiple times to meet the targets of the twin transition. A similar increase is expected from the energy and economic transformation plans of other economies worldwide. Therefore, securing and increasing their supply becomes a strategic issue.
- **The EU is heavily dependent on third countries and in particular on China, at various stages of the value chain**. In all of the technologies analysed, there is a heavy dependence on imports from one country, namely China. These affect different stages of the value chains, ranging from raw materials only (e.g. electrolysers), to raw and processed materials along with components (e.g. wind turbines and magnets for electric motors) and even covering the complete value chain (e.g. solar PV). This dependence, combined with increased demand and global competition to secure access to the same pool of resources, significantly increases the risk of disruptions due to environmental and geopolitical reasons. In many cases, alternatives for diversifying supply from like-minded and reliable countries may not exist.
- The **time dimension** is very important: new developments in mining and processing require time to enter into operation, while recycling depends on the availability of sufficient end-of-life volumes, and this may not happen before 2030 for some technologies.
- Research into **substitution**, for example through advanced materials or alternative technologies, and innovations focusing on the more efficient use of materials are of paramount importance. These contribute to ensuring both strategic autonomy and leadership for the EU at global level.
- It is essential for the EU to closely **monitor** the supply chains of strategic and critical raw materials to provide good opportunities for risk mitigation and management.

1. Introduction

1.1. Policy context and objectives

Against the background of the climate crisis, which is driving an accelerating global race to dominate the production and development of clean technology, COVID-19 and Russia's invasion of Ukraine have caused turmoil in energy and industrial markets and supply chains, among the many other consequences of these events.

In response to the climate crisis and its commitments under the Paris Agreement, the EU adopted the European Green Deal (EC, 2019), as a comprehensive strategy for delivering the green transition, decarbonising the economy, and transforming it into a modern, resource-efficient and competitive system. It sets ambitious targets for the reduction of greenhouse gas (GHG) emissions by 55% compared to 1990 levels in 2030 (implemented in the "Fit for 55" package), and to net-zero by 2050. This transformation comes in tandem with increased digitalisation, which is necessary for maintaining an energy system based on intermittent sources and decreasing emissions from industry and transport. The Digital Strategy has established objectives and targets to achieve the digital transition (EC, 2022a).

In 2020, the COVID-19 pandemic highlighted the fragility of the equilibrium upon which global supply chains are based. Supply chains for chips, pharmaceutical ingredients, and raw materials such as magnesium were disrupted or put under severe stress.

Russia's invasion of Ukraine in 2022 forced the EU to assess its defence capabilities, which it has done with the Joint Communication on Defence Investment Gaps Analysis and Way Forward (EC, 2022b), and to improve them rapidly. It has also forced the EU to address its dependence on Russian oil and gas, as well as other materials. REPowerEU sets out new targets for deploying renewable energy technologies, massively electrifying transportation or shifting to hydrogen, and significantly increasing energy efficiency (EC, 2022c). This requires wind power and solar photovoltaic (PV) installation and batteries or hydrogen to store electricity and power vehicles, and heat pumps for energy-efficient heating and cooling.

The energy transition is a materials transition. A clean energy system is much more minerals- and metals-intensive than a conventional fossil fuel energy system – for example, an onshore wind farm requires nine times more mineral resources than a gas-fired power plant, and a typical electric car uses six times more material input than a conventional car. Unlike a system powered by fossil fuels consumed on use, the materials in the clean energy system remain and can be recovered and re-used at the end-of-life of the installations or devices.

Both UNEP's International Resource Panel (IRP, 2019) and the OECD (OECD, 2019) predict a significant increase in global demand for all resources, and the IEA's specific look at materials for the energy transition (IEA, 2021) projects a doubling to quadrupling of the demand for energy transition-relevant materials. The implications for the extraction of raw materials, even with increased circularity, are enormous. Therefore, a reduction of resource use in line with the sustainability principle is without doubt desirable, though not always achievable. A reduction or mitigation of demand can be achieved, for example, through technological innovation and increased materials efficiency, through market selection and policy incentives (benefitting solutions with lower material intensity), or even through behavioural changes, such as changing appliances and use-patterns resulting in electricity savings in the residential sector, or changes in mobility patterns in the transport sector (e.g. cycling, public transportation, car-pooling, car-sharing and walking).

Many of these assumptions have found their way into the analysis presented here, especially in the Low Demand Scenario (LDS), by carefully selecting the technology deployment scenario, market shares and material intensities for each one of the analysed technologies, or a reduction in annual sales (this is more closely described in Section 1.2). However, it is impossible to develop a modelling framework which consistently addresses these aspects across an extremely diverse portfolio of technologies, and a general horizontal assumption, e.g. a 10% demand reduction to take behavioural measures into account, would appear arbitrary and hardly justifiable.

The EU will not be completely self-reliant in its material needs, so it also needs to diversify its supply from around the world, with trusted partners that mutually benefit from this cooperation – so that the EU's supply of critical raw materials becomes indeed sustainable. In parallel, the EU needs to improve its framework for recycling and support innovation for materials efficiency and substitution. These are measures which the European Commission is proposing with its European Critical Raw Materials Act.

The European Commission has also introduced the concept of strategic raw materials in its proposal for a European Critical Raw Materials Act (EC, 2023a). Whereas a critical raw material is characterised by a high risk of supply disruptions and its importance for the overall EU economy, a strategic raw material is additionally characterised by its importance for strategic areas such as renewable energy, digital, aerospace and defence technologies, its projected demand growth and current supply, and the difficulties of scaling up production. Strategic raw materials have properties that make them very difficult to replace in the relevant technologies. For example, rare earth elements have special conductive, magnetic and fluorescent properties; lithium is an important component of rechargeable batteries because of its high electrode potential.

The production and trade of raw materials are global, and so will be the competition for them. The production of critical and strategic raw materials is, however, often highly concentrated in a few countries, on which the EU depends for supply. Every three years since 2011, the EU has published its list of critical raw materials, and with every reiteration the list has grown longer. The Raw Materials Initiative and the Action Plan on Critical Raw Materials have helped the EU in addressing the supply of raw materials, but the EU needs to do more to ensure its security of supply. The backbone of this list is a thorough assessment of the current global and EU supply and industrial application of more than 80 individual non-energy, non-agricultural raw materials, showing that production is increasingly dominated by a few countries.

This trend is not only visible for raw materials, but also for components and finished products, putting the EU in a precarious position in a world of shifting geopolitical balances. This report also investigates the concentration of production in the technologies that enable the green and digital transition and increased EU security. The EU is completely reliant on imports from China, for example, for its solar photovoltaic needs, a technology key to the success of REPowerEU. China accounts for 97% of the global output of advanced solar wafers, and there are indications that the Chinese government is considering a ban on exports of the technologies key to producing them (Bloomberg, 2023). Meanwhile, worldwide demand is projected to grow for silicon and silver. As Europe embarks on its own manufacturing of solar panels, we will be confronted with the challenge of securing these critical materials for ourselves.

It is therefore of paramount importance to forecast demand for raw materials, in this case until 2050. The forecast is based on the latest projections for the energy and industrial landscape in the EU and the global competition. It is equally important to assess the nature of demand and supply chains and identify vulnerabilities which might exacerbate an already urgent situation. In this way, policymakers and those in the business environment can anticipate issues rather than face crises, and they can prepare potential solutions.

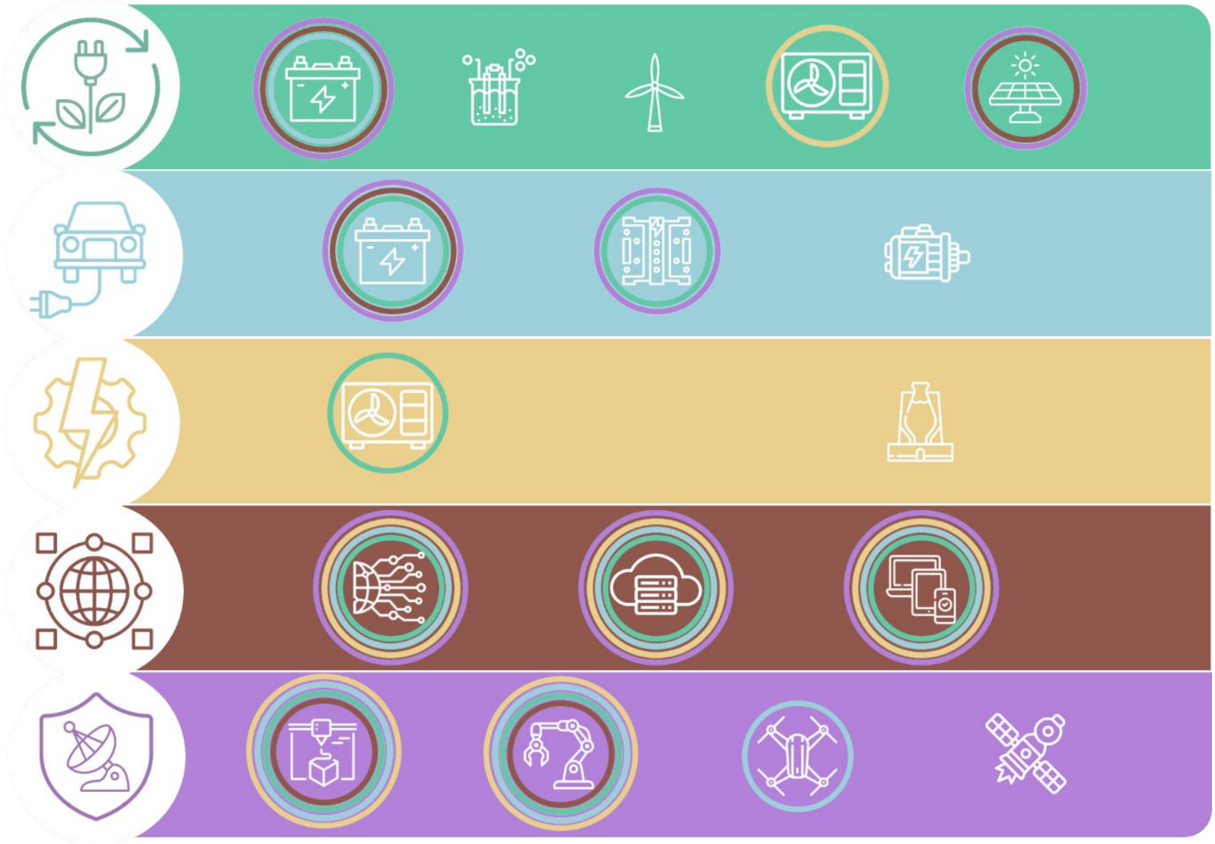
1.2. Methodology

This study, performed by the EC's JRC in partnership with DG GROW, explores the potential vulnerabilities and dependencies of fifteen technologies in five sectors which are strategic for the EU economy. These technologies are: Li-ion batteries; fuel cells (FCs); electrolysers; wind turbines; traction motors; solar PV; heat pumps; hydrogen direct reduced iron and electric arc furnaces (H2-DRI and EAF); data transmission networks; data storage and servers; smartphones, tablets and laptops; additive manufacturing; robotics; drones; and space launchers and satellites. These technologies fall within five strategic sectors of the EU economy: renewable energy, electric mobility (e-mobility), energy-intensive industry, information & communications technology (ICT), and aerospace & defence. Figure 5 schematically reports the allocation of the fifteen technologies to the five sectors, as well as their interlinkages. This study addresses batteries adopted both for electric vehicles and for electricity storage, and heat pumps for residential and industrial uses (which is why these two technologies appear in two sectors).

The report develops two main quantitative analyses: the supply chain analysis and the demand forecast analysis. The supply chain analysis investigates the supply chain structure of each technology, identifying the relevant materials, components and assemblies, and it explores the potential bottlenecks along the different steps of the supply chain. The demand forecast analysis, where data and models are available, assesses the future demand for the main materials needed in the selected technology, based on policy-relevant scenarios and market trends.

Sections 1.2.1 and 1.2.2 briefly describe the methodologies adopted to develop the supply chain analysis and the demand forecast analysis. The two analyses are developed for the fifteen technologies, with some limitations discussed in Section 1.3. The analysis of the five sectors builds on the information produced for the relevant technologies. More methodological details are presented in Annex 3.

Figure 5. Allocation of technologies to sectors and their interlinkages: renewable energy, e-mobility, energy-intensive industry, ICT, and aerospace & defence



Source: JRC analysis.

1.2.1. Methodology for the supply chain analysis

For each technology, the supply chain is divided into six potential steps: raw materials, processed materials, components, assemblies, super-assemblies and systems. Technologies can feature either four, five or six steps, making the final product(s) assemblies, super-assemblies, or systems, respectively. This differentiation is needed to capture the varying complexity of the technologies in scope. It is also needed as some technologies (e.g. batteries) are integrated into more complex technologies (e.g. drones). Table 2 shows the number of steps associated with each technology.

The analysis identifies the relevant elements in each step of the supply chain, i.e. the relevant raw materials, processed materials, components, assemblies, super-assemblies, and systems pertaining to each technology[4]. Provided there is data availability, a Supply Risk (SR) is calculated for each element according to the methodology developed for the 2017 Criticality Assessment, see EC, 2017. The Supply Risk for raw materials is directly sourced from the 2023 Criticality Assessment (EC, 2023b), while this study calculates the Supply Risk for the supply chain steps from processed materials onwards adopting a simplified methodology. Annex 3 describes in detail how the Supply Risk is calculated.

[4] Henceforth, the word "element" will identify a generic entry in any step of the supply chain, e.g. a raw material or a component depending on the supply chain step under consideration.

Table 2. Steps in the supply chain analysis for the different technologies.

Technology	Raw materials	Processed materials	Components	Assemblies	Super-assemblies	Systems
Li-ion batteries	●	●	●	●		
Fuel cells	●	●	●	●		
Electrolysers	●	●	●	●		
Wind turbines	●	●	●	●	●	
Traction motors	●	●	●	●		
Solar PV	●	●	●	●		
Heat pumps	●	–	–	–	●	
H2-DRI	●	–	–	–	●	
Data transmission networks	●	●	●	●	–	●
Data storage and servers	●	●	●	●	●	
Smartphones, tablets and laptops	●	●	●	●	●	
Additive manufacturing	●	●	–	–	●	
Robotics	●	●	●	●	●	
Drones	●	●	●	●	●	
Space launchers and satellites	●	●	●	●	●	●

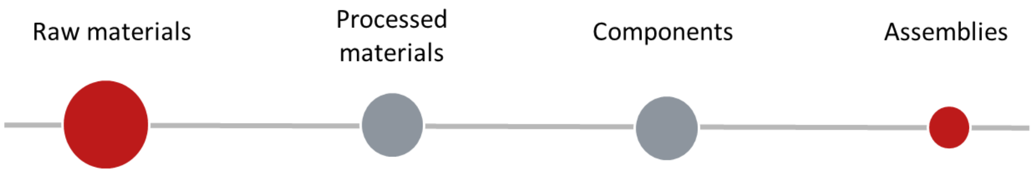
Source: JRC analysis. The dash indicates that no analysis has been carried out for the relevant step due to lack of data.

The Supply Risk can theoretically range from 0 to 20, but the highest value appearing in this work is around 6. Following the framework described in the Criticality Assessment (EC, 2023b), an element is defined critical if SR ≥ 1, while it is non-critical if SR < 1. Each technology section reports in detail the Supply Risk for the elements assessed in each supply chain step. These are reported in a bar chart. Critical elements are shown in red, while non-critical elements are shown in grey. Since this work aims to assess the supply risk at different steps of the supply chain in the fifteen technologies, economic aspects are not directly investigated. For the purposes of this work, we can reasonably assume SR ≥ 1 implies criticality, while SR < 1 implies a non-critical condition, then applying this framework to all supply chain steps.

The Critical Raw Materials Act also introduces strategic raw materials in addition to critical and non-critical raw materials. These raw materials considered indispensable for the twin green and digital transition and the security objectives of the EU. In our graphs, the strategic raw materials are identified with a darker red.

The Supply Risk associated with the different elements in one supply chain step are condensed into one single output summarising the risk level for the whole step. This highlights the steps which may represent a potential bottleneck along the supply chains. Figure 6 provides an illustrative example of such a representation.

Figure 6. Illustrative representation of the methodology to visualise the supply risk along the supply chain



Source: JRC analysis.

The colour shows whether the step should be considered as critical (red) or non-critical (grey). One step is considered critical if at least 30% of its elements are critical, or if at least 20% of its elements are critical and at least one of them shows SR ≥ 4, i.e. a very high level of criticality.

The size is a proxy of the complexity of the supply chain step. Bubbles can be small, medium, or large, depending on the number of elements appearing in the supply chain step, defined as follows (Table 3):

Table 3. Bubble sizes and corresponding number of elements in the supply chain steps.

Supply Risk	Raw materials	Processed materials	Components	Assemblies, super-assemblies, systems
	< 15	< 15	< 5	1
	15-39	15-39	5-14	2-4
	> 39	> 39	> 14	> 4

Source: JRC analysis.

Throughout the report, the graphs summarising the supply risk along the supply chain are accompanied by the country shares in global manufacturing. Within each stage, country shares are calculated carrying out an arithmetic average across all the elements assessed in that stage.

1.2.2. Methodology for the demand forecast analysis

The parameters needed for the raw materials demand forecast are the following:

- **Technology deployment**: this parameter describes the future evolution of the considered technology, available, for example, via fully-fledged scenarios (typically, for energy or mobility technologies) or via market growth rates; the annual capacity deployment or annual sales are the relevant variables to calculate the materials demand: complementary information on the product lifetime is necessary to derive these variables if only the overall installed capacity or stocks are available.

- **Sub-technology market shares**: each technology may have very different configurations or designs, which may be characterised by specific material requirements; in this case, estimates of the future technology mix are fundamental to develop raw material demand scenarios.

- **Material intensity and efficiency**: material intensity indicates the amount of material needed per unit of technology deployed (e.g. tonnes per megawatt in the case of power technologies, tonnes per vehicle in the case of e-mobility); future material intensity scenarios are also taken into consideration (material efficiency).

The modelling framework of the demand forecast analysis considers two scenarios:

- **High Demand Scenario (HDS)**
- **Low Demand Scenario (LDS)**

The HDS accounts for a rapid technology deployment and a combination of market shares and material intensities resulting in a rapid increase of materials demand, while the LDS considers slow technology deployment and combinations of market shares and material intensities resulting in a moderate increase or even a decrease in materials demand. For example: the projected rare earths demand for wind turbines in 2050 in the LDS is lower than the relevant 2030 and even 2020 demand; for smartphones, tablets and laptops, the LDS considers a significant reduction in the annual sales, indirectly modelling a reduction in the frequency with which consumers change their devices. The two scenarios are built combining relatively high and relatively low values for the three parameters listed above.

As discussed in Section 1.1, it is very difficult to create a comprehensive view of the Low and High Demand Scenarios for all the technologies under consideration. This is largely because we analyse a very diverse set of technologies. Specifically for energy and mobility technologies, this is also because we do not model an overarching energy or electricity or mobility demand sector, but we consider only a few specific technologies within these sectors. However, some common considerations may apply, notably for the energy technologies.

In the HDS, future technology expansion is in line with the ambitious energy and climate change mitigation targets set by countries/regions. In the EU, this means achieving the REPowerEU targets by 2030 and full decarbonisation by 2050. In the LDS, future technology expansion is much slower. For technologies which already have a consolidated market (i.e. wind power and solar PV), expansion broadly follows historical growth patterns, which are significantly lower than the levels required to reach the HDS targets. Technologies that are still characterised by limited penetration achieve significant growth even in the LDS (but again, much lower than in the HDS).

When applicable, market shares are differentiated to further consider different possible futures for relevant raw materials. For instance, wind turbine types featuring rare-earth permanent magnets are considered to maintain their current market shares in the LDS, and are characterised by strong expansion in the HDS.

Material efficiency also differs in the two scenarios. In the HDS, the material intensity is constant or slightly decreases over time, while in the LDS, the reduction is more pronounced.

The HDS and the LDS are designed to provide two illustrative patterns among the infinite possible scenarios, depicting a reasonably high and a reasonably low demand future. For instance, intermediate scenarios may be conceived by combining the high technology deployment of the HDS with the stronger material efficiency of the LDS, or the less optimistic assumptions on material efficiency of the HDS with the lower technology expansion of the LDS.

The demand forecast analysis develops scenarios not only for the EU, but also for the US, China, and the world. The base calibration year is 2020. Future demand is provided for 2030 and 2050 (only in 2030 for the ICT technologies). Demand is provided both in absolute terms (tonnage per year) and in relative terms compared with the current global supply (see Annex 4 for more details on this).

Additional details on the scenarios developed for the different technologies are reported in the relevant sections of Chapter 2 and in Annex 3.

1.3. Scope and limitations

This work has been developed by the European Commission, in a partnership between the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) and the Joint Research Centre (JRC). The methodology for the supply chain analysis is therefore tailored to highlight the vulnerabilities and dependencies of the EU. However, the demand forecast analysis also includes the US, China, and the world in order to put the EU's future material demand into global perspective and to compare it with the projected material demand of the other two main international actors, as the EU inevitably interacts and competes with others to supply resources and products on the global market.

The supply chain analysis focuses on the current situation, while the demand forecast analysis develops material demand scenarios with a horizon to 2050. The horizon is limited to 2030 for the ICT technologies, as the unpredictable technological development in this sector does not allow for sensible projections beyond the current decade. Forecast analysis of supply is not included.

The selection of the fifteen technologies analysed in this report is based on different criteria, such as i) the further expansion of relatively consolidated technologies in the context of the energy transition (e.g. wind and solar PV technologies) and the digital transition (e.g. data storage and servers), leading to a considerable increase in the relevant material demand, ii) the likely growth of emerging technologies (e.g. fuel cells, electrolysers, H2-DRI), and iii) their relevance in technologies strategic to EU security (e.g. space and drones).

The fifteen technologies are individually analysed in Chapter 2 in terms of (i) current supply bottlenecks along the value chain, (ii) future demand for raw materials, (iii) geopolitical dimension, and (iv) key observations and recommendations. The same structure is used in the sections of Chapter 3, which widens the scope to sectors. These sections condense the quantitative information developed for the technologies in Chapter 2, also including additional information on other relevant technologies not explicitly explored therein. Finally, the conclusions and recommendations for strengthening the supply chains, as well as for policy and future methodological developments, are included in Chapter 4.

This study faces some general limitations, as follows.

- The study focuses primarily on emerging technologies and on those sectors for which a significant growth is expected in the future. Although the study covers a considerable number of technologies and sectors to provide a credible overview of EU industry, many others could not be taken into account, due to, for instance, a lack of data (e.g. lasers and nuclear energy). Enabling technologies, such as electric networks and controllers, were also excluded from the analysis.
- Due to limited information and data availability, the supply chain analysis for heat pumps and H2-DRI could only be carried out quantitatively for raw materials and super-assemblies (i.e. the final technology step), while the rest of the supply chain was explored qualitatively. Similarly, the full forecast analysis was not possible for six technologies (H2-DRI, data transmission networks, additive manufacturing, robotics, drones, space launchers and satellites): only market trends were reported for these.
- The production shares of the different countries are a key element in the Supply Risk assessment of the relevant materials and components along the supply chain of each technology. This assessment is based on market research reports and publicly available information. Unfortunately, data are not available for all the elements identified as relevant in a supply chain. Therefore, the supply chain analysis is based on the restricted portfolio of elements for which data are available (the full set of elements is reported in the annex for possible future developments of this work).
- Normally, company headquarters are used instead of production locations. However, this distinction may not always be clear or relevant. Also, if only the company names were available without any additional information on the actual market shares, the so-called "headquarters method" was applied, of counting the relevant companies and distributing the shares among countries based on the headquarters location.
- Although the study is put in the global perspective following the COVID-19 pandemic and Russia's invasion of Ukraine, some data used in the analysis may refer to the years before 2020, therefore the picture is no longer fully representative in some cases.
- The demand forecast analysis is developed considering two deterministic scenarios of low and high material demand: a more complete analysis should consider a wider range of possible futures and its integration with a stochastic approach; also, given the high number of technologies assessed, the scenarios may not necessarily provide fully consistent storylines across technologies, despite our efforts to use the same sources when possible.
- The demand forecast analysis produced future scenarios for material demand, while no projections are produced for supply. As described in the previous section, future demand is compared with the current supply. Although this is a sensible measure to put the demand levels in perspective, this clearly does not take into consideration that future supply will likely increase to try to follow demand.

2. Raw materials and supply chains in strategic technologies

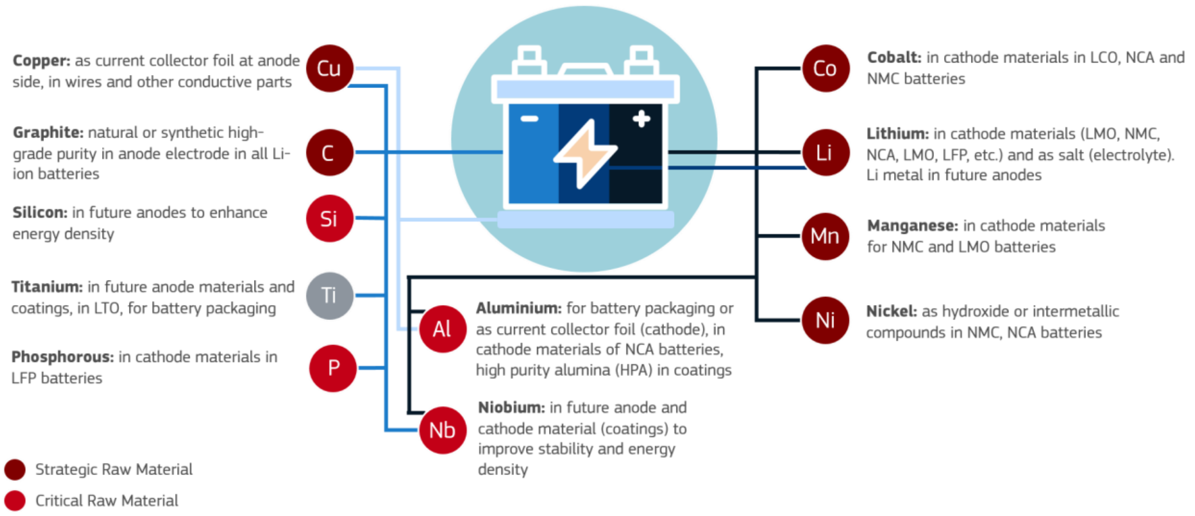
2.1. Li-ion batteries

2.1.1. Introduction

Li-ion batteries (LIBs) are strategically important to the attainment of a more sustainable and decarbonised Europe (EC, 2019). Forward-looking studies have already identified challenges from a supply perspective (EC, 2020; DERA, 2021), and various EU initiatives underline the high policy and industrial interest in this technology (JRC, 2020). LIBs are increasingly used in strategic sectors such as mobility, energy storage systems and portable devices, and this trend is expected to increase further in the next decade (BatteriesEurope, 2021a). Their performance is continuously improving, and LIBs are rapidly replacing other types of rechargeable batteries like nickel metal hydride (NiMH) and lead-acid (PbA) batteries in various applications (EC, 2020; JRC, 2019; JRC, 2020; JRC, 2022a) while their use is extended in new applications, e.g. e-bikes (EC, 2020; JRC, 2021a). LIBs are expected to dominate the global and the EU battery market for the next two decades even though novel battery types are expected to arise (e.g. sodium batteries).

The main components of a LIB are the cathode, anode, electrolyte and separator. Cathodes and anodes are made of different materials that characterise the battery's performance. Several chemistries are already commercialised, and other chemistries are currently under development (pilot and lab projects) (BatteriesEurope, 2021a, 2021b). The most important raw materials considered in this study are reported in Figure 7. Table 16 in Annex 2 provides further details.

Figure 7. Selection of raw materials used in Li-ion batteries and their function



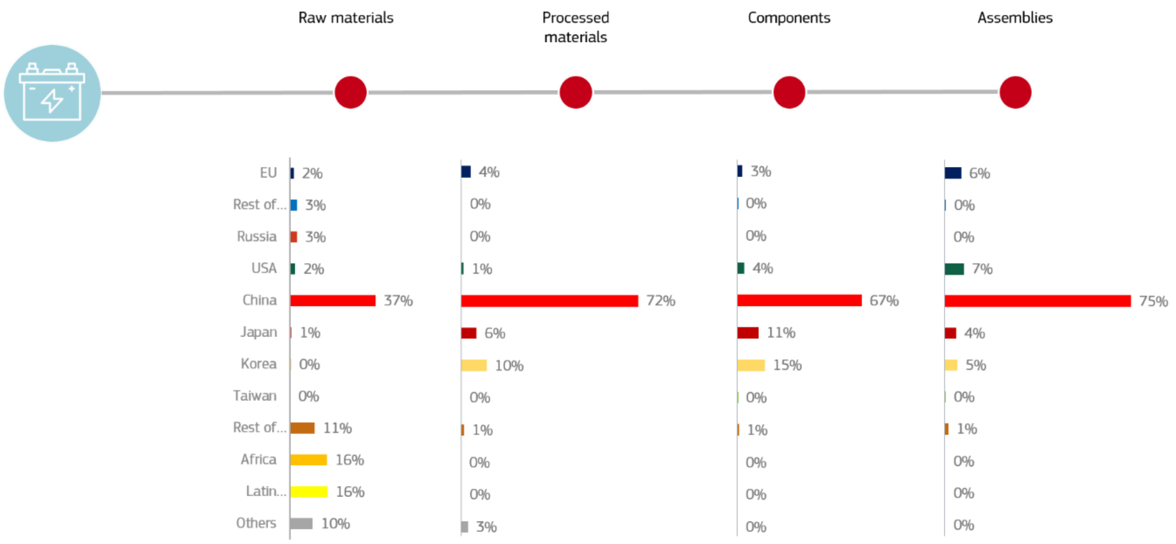
Source: JRC analysis.

R&D&I investment is needed urgently to decrease EU dependency on third countries. Several initiatives have been promoted in the EU to develop a "competitive, innovative and sustainable battery value chain", among which is the recent Batteries Regulation proposal (COM(2020) 798). Key challenges and actions are mapped by bodies such as Batteries Europe, and several projects have been founded (e.g. the Important Project of Common European Interest – IPCEI).

2.1.2. Current supply chain bottlenecks

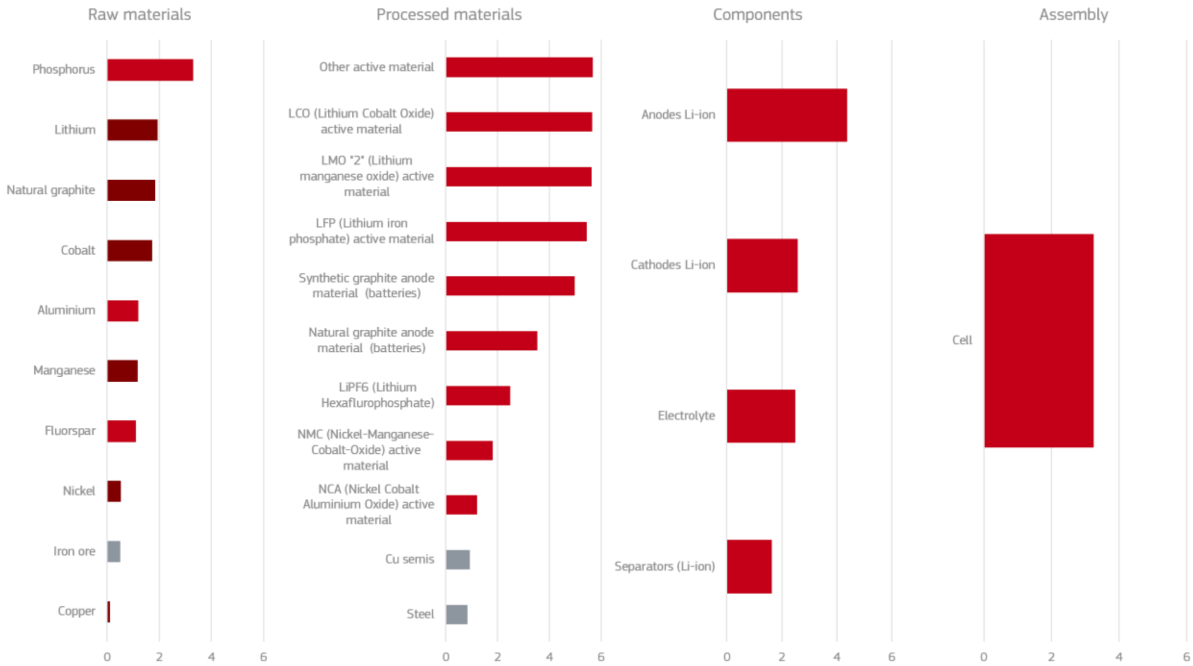
Among the most used materials embedded in LIBs, cobalt, lithium and natural graphite are classified as critical raw materials. The list of CRMs also comprises fluorspar, niobium, phosphorous and silicon metal which are currently employed in lower amounts but are expected to be further used in the future. Key producers of the LIBs supply chain are graphically represented in Figure 8. The detailed Supply Risk values are reported in Figure 9.

Figure 8. An overview of supply risks, bottlenecks, and key players along the supply chain of Li-ion batteries



Source: JRC analysis.

Figure 9. Detailed Supply Risk of all elements in the Li-ion battery supply chain



Source: JRC analysis.

The EU is dependent on third countries for the supply of raw materials for the manufacture of LIBs, and represents a very low share of global production (Figure 8). What is most striking is that supply is highly concentrated in China, which dominated global capacity in 2020: it accounted for 60% of refined cobalt, 93% of graphite active materials (from natural and synthetic graphite), 69% of refined lithium, 79% of battery-grade manganese (electrolytic and high-purity sulphate) and 63% of nickel sulphate production capacity (JRC, 2022b). The most significant bottlenecks in the EU supply chain are identified for lithium and graphite, as in 2021 there was no capacity to refine lithium or graphite for batteries. The EU's position is stronger for refined cobalt (8% of the global capacity in 2020) and battery-grade nickel (10% of the worldwide capacity in 2021) (JRC, 2022b) As regards lithium, the EU mainly imports raw materials from Chile, Australia and Argentina, but European mines and refineries currently under development are expected to provide more input to the LIBs value chain by 2030 (JRC, 2022b).

Similarly, there are dependencies and bottlenecks downstream in the supply chain for processed materials, components and assemblies, as supply is controlled by an oligopoly in Asia. Chinese companies hold a dominant position with massive supply shares, and companies from Korea and Japan have considerable shares, especially in components (anodes and cathodes). EU and US companies have very low shares in global supply chains for processed materials and components, whereas capacities are more developed in the downstream stage of cell manufacturing (Figure 8).

Also due to their cost and to social aspects, the use of high-cobalt content LIBs is expected to decrease in favour of nickel-rich batteries or new chemistries. Lithium iron phosphate (LFP) batteries are currently mainly used in Asian countries. As LFP performance increases and the chemistry is more widely deployed, they will compete with fertiliser production for phosphates (Epstein, 2022).

The EU supplies about 9% of NMC (nickel-manganese-cobalt-oxide) and 14% of NCA (nickel cobalt aluminium oxide) active materials, but is fully dependent on anode and other cathode active materials (JRC analysis, based on BMI data).

2.1.3. Projected 2030 and 2050 material demand

Demand for LIBs will be driven by the automotive sector in the coming years. Demand for energy storage systems (ESS) storage will also increase, driven by the deployment of renewables.

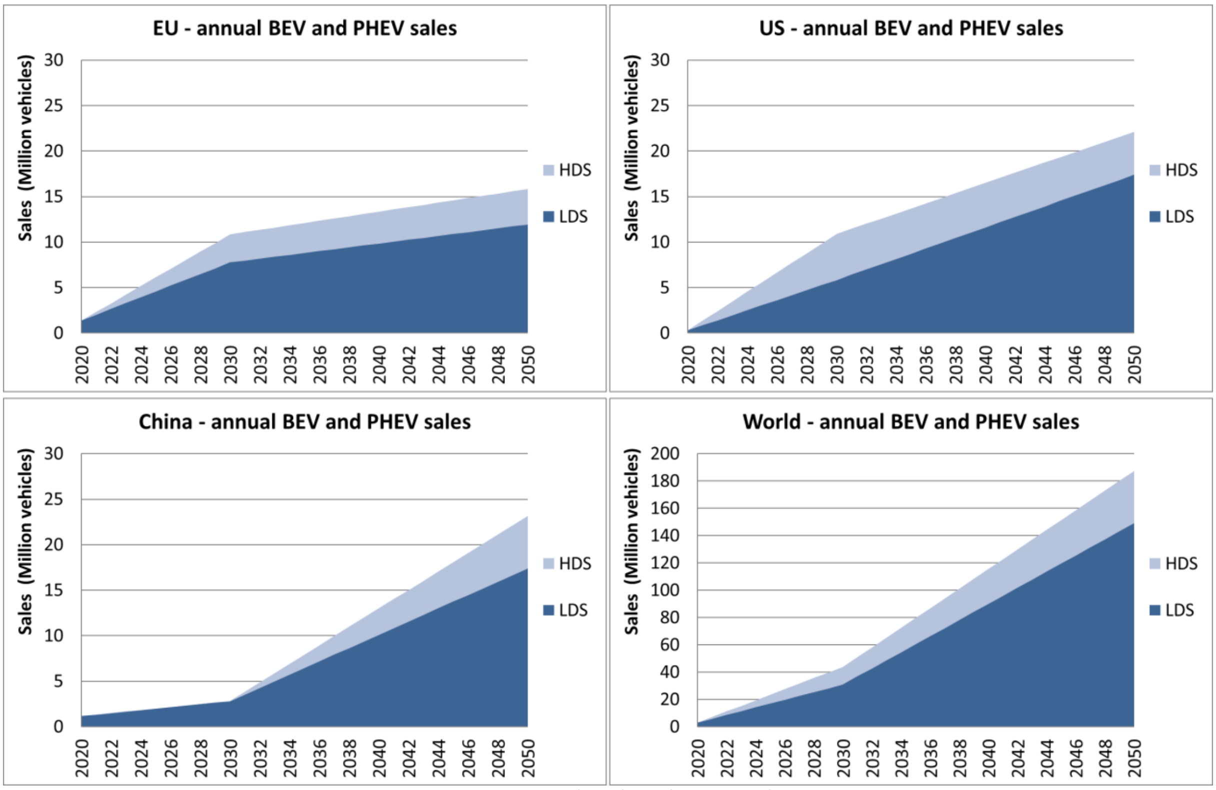
The future demand for traction battery materials is based on the number of electric vehicles (xEV) that will be placed on the market according to the GECO scenario. Although LIBs are also used in other applications related to mobility (i.e. light means of transport, medium and heavy trucks), only battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs) have been considered for the quantitative analysis. Figure 10 shows the sales of BEVs and PHEVs in four different regions in the world, according to the two different scenarios considered for the analysis, i.e. the LDS and the HDS.

The LDS assumes a slower penetration of xEVs compared to the HDS in the four global regions. The uptake of PHEVs will increase quite similarly in both scenarios, while in the HDS, the increase of BEVs will be higher. In addition, it is assumed that the resource efficiency of batteries will increase in time for both scenarios, although in the LDS scenario, the share of non-cobalt-based LIBs (e.g. LFP) will increase faster than in the HDS, as well as the content of cobalt in cobalt-based batteries will decrease in time, favouring the adoption of NMC811[5] and NMC9.5.5.

LIBs are already quite commonly used in ESS applications, and this technology is expected to further dominate the ESS market in the coming decades (JRC, 2018), despite the introduction of new types of batteries (e.g. vanadium redox batteries and sodium batteries). From 4 GW in 2015, the cumulative ESS capacity (both behind and in front of the meter) in Europe is expected to range between 55 GW and 86 GW in 2030[6], and between 211 GW and 373 GW in 2050 (Figure 11 and Figure 12). This is 20% and 16% of the global capacity in 2030 and 2050, respectively. The LDS and the HDS are based on the Stated Policies Scenario and the Announced Pledges Scenario from IEA (2022c), respectively. However, there are also other scenarios such as the Net Zero Scenario of the IEA, which projects 140 GW of added capacity in 2030 only (IEA, 2022b). For this analysis, in line with the e-mobility scenarios, the LDS here considers a faster penetration of low or non-cobalt-based batteries (e.g. NMC811 and/or LFP) than in the HDS scenario. The demand for materials for the two scenarios analysed is shown in Figure 13.

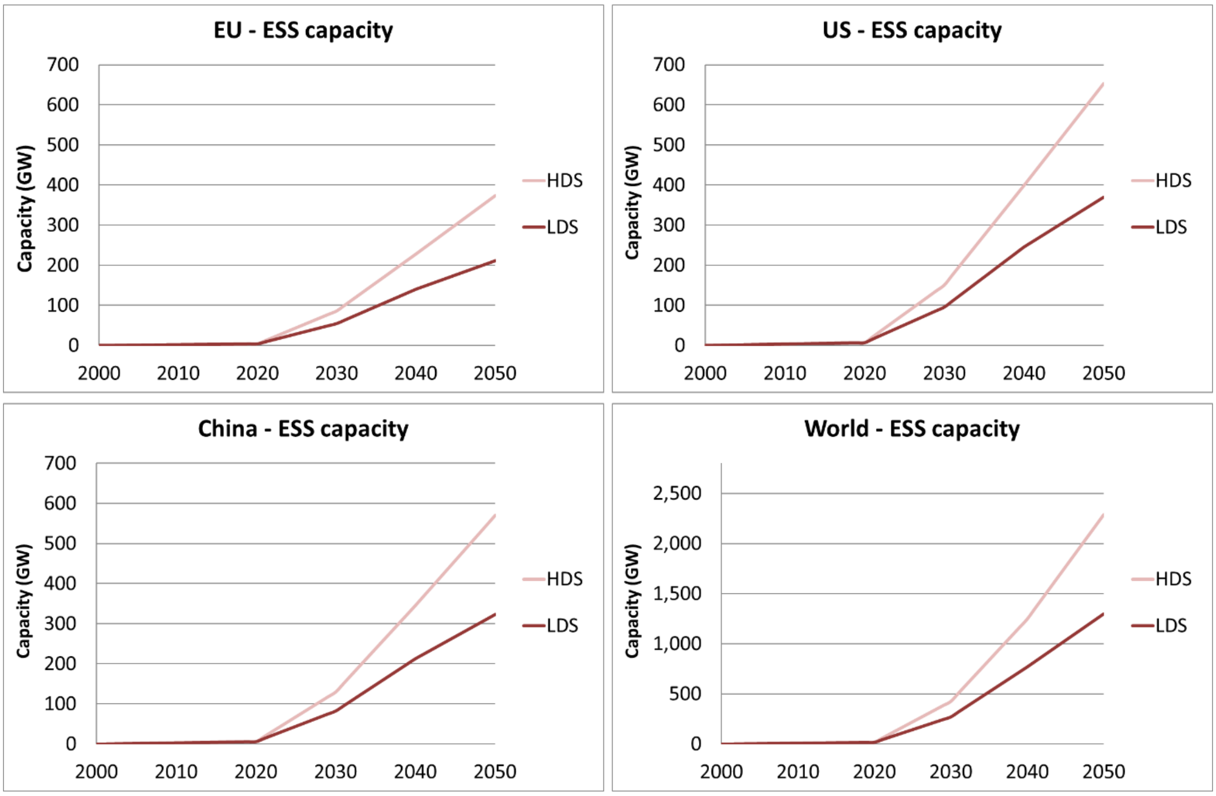
[5] NMC811 refers to nickel-rich layered oxide ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$)
[6] $CAGR_{2030\ vs\ 2020}$ = 30%-36%, $CAGR_{2050\ vs\ 2020}$ = 14%-16%

Figure 10. Annual sales of battery (BEVs) and plug-in (PHEVs) electric vehicles in the EU, US, China, and globally in the two explored scenarios



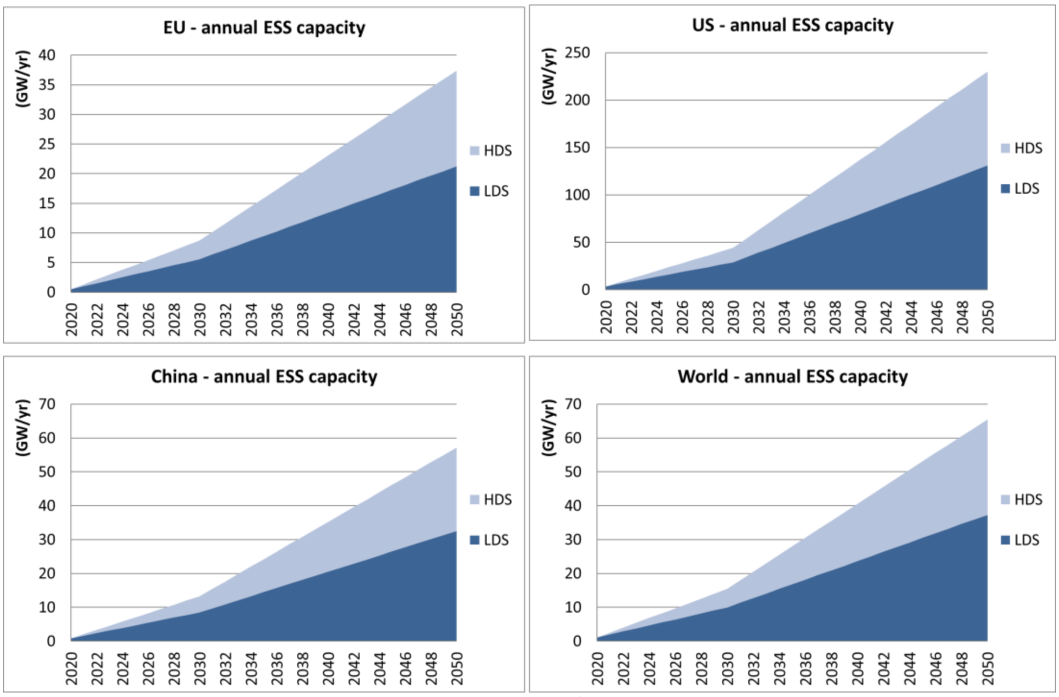
Source: JRC analysis based JRC, 2021b.

Figure 11. Battery Energy Storage System (ESS) capacity in the EU, US, China, and globally in the two explored scenarios



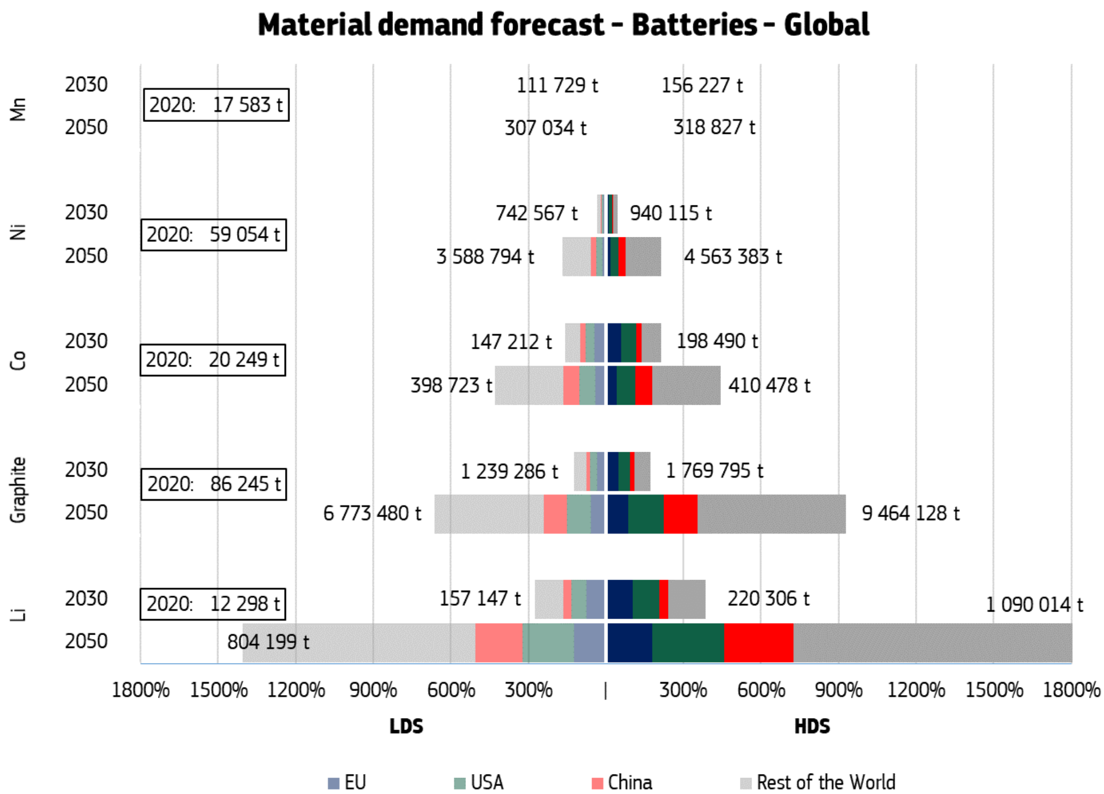
Source: JRC analysis based JRC, 2021b.

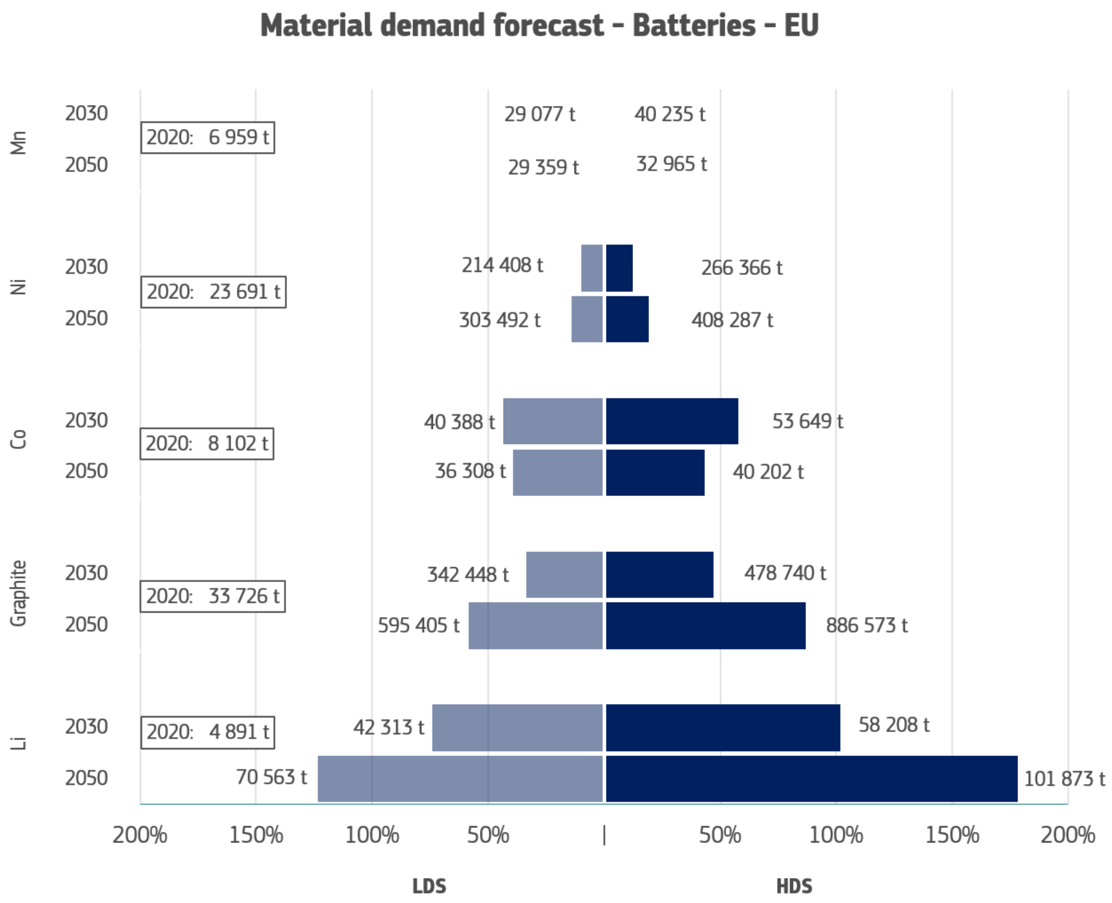
Figure 12. Battery Energy Storage System (ESS) annual deployed capacity in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis.

Figure 13. Material demand forecast for Li-ion batteries: global (top) and focus on the EU (next page)





Source: JRC analysis (Li = lithium, Co = cobalt, Ni = nickel, Mn = manganese).

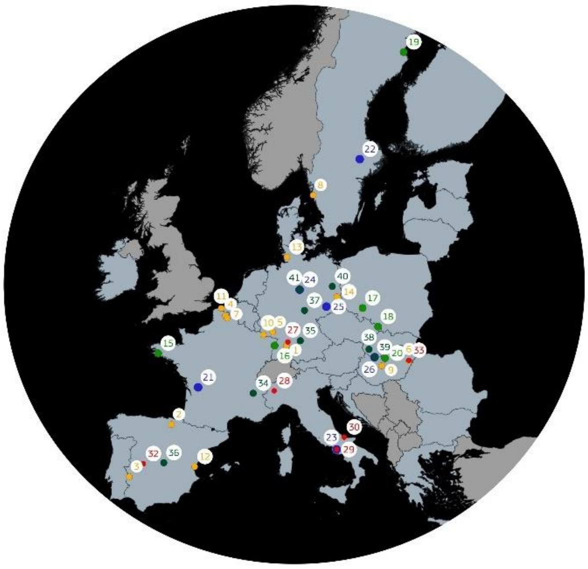
Compared to the current supply of materials, EU demand for aluminium, copper, iron and manganese in both 2030 and 2050 is lower than 3%, while for phosphorous and nickel it ranges between 10% and 30%. Major increases are observed for graphite (45% in 2030 and 85% in 2050) and lithium (100% and 170% in 2030 and 2050, respectively). In 2030, the cobalt demand for batteries will represent almost 60% of the current world supply, while it will decrease in 2050 to 40%, partly due to the shift towards more nickel-rich batteries. Lithium-manganese-oxide (LMO) batteries are widely used in other types of application, so the total demand for manganese for batteries is higher than the demand for e-mobility and ESS specifically.

2.1.4. Geopolitical dimension

The global market of LIBs is increasing and exceeded the most common lead-acid batteries in 2020 (JRC, 2022a). The EU has invested significant effort in developing a competitive and sustainable European batteries value chain (e.g. Battery Regulation proposal, IPCEI projects and funds), but still, Asia dominates the LIBs market, followed by the US. Asian companies are moving some of their production to the EU; among them, Korean companies in Hungary (Reuters, 2021; Benchmark Minerals, 2022; Hyun-bin, 2023). Poland is becoming the largest exporter of traction batteries in the EU due to LG Chem production (Fedyczkowska, 2021). European companies such as Northvolt, Saft and Varta are investing in battery production for both e-mobility and ESS applications, and Seri/FAAM produces and recycles both lead-acid (Pba) and LIB batteries. Several companies, including some start-ups, are currently developing ESS applications for residential and small business applications. In some cases, they join forces to do this, as with the partnership between Fluence and Northvolt (Northvolt, 2021; JRC, 2022a).

Forecasts reveal that the Chinese dominance across all segments of the LIB supply chain is expected to continue over 2030 but to a lesser extent, as supply globally will be diversified (e.g. for lithium). However, potential bottlenecks on the supply side will remain (JRC, 2022b). Regarding the EU, Australia and Canada are the two countries with the greatest potential to provide additional and low risk supply to the EU for almost all battery raw materials. In addition, Serbia is a likely source of lithium minerals for conversion to chemicals, and Norway is a reliable source of flake and, potentially in the future, of refined graphite. In the EU, most of the operating capacity for battery cells is currently located in Germany, Sweden, Poland, and Hungary, but new installations or the expansion of existing installations have been already announced or are under construction (Figure 14).

Figure 14. Name and localisation of planned EU battery cell manufacturing capacity in the EU



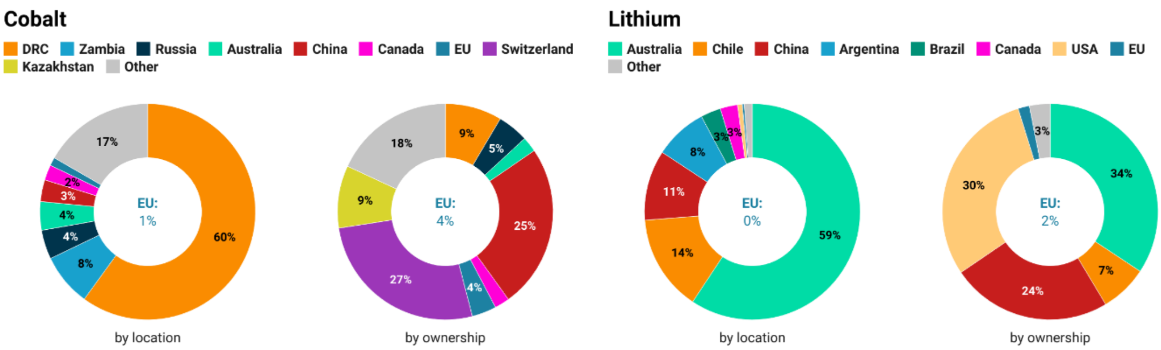
ID	Installation	Development status	Targeted Capacity (GWh)	Operating Capacity	Country
1	CellForce, Kirchentellinsfurt	Construction Planned	0.1 (2024)	-	Germany
2	BasqueVolt, Vitoria-Gasteiz	Construction Planned	2 (2025) and 10 (2027)	-	Spain
3	Phi4tech, Badajoz	Construction Planned	2 (2024) and 10 (2030)	-	Spain
4	ACC, Douvrin	Construction Planned	8 (2024) and 40 (2031)	-	France
5	ACC, Kaiserslautern	Construction Planned	13.4 (2025) and 40 (2031)	-	Germany
6	CATL, Debrecen	Construction Planned	60 (2026) and 100 (2027)	-	Hungary
7	Envision AESC/Renault, Douai	Construction Planned	9 (2024) and 24 (2029)	-	France
8	Northvolt/Volvo, Gothenburg	Construction Planned	16 (2026) and 32 (2031)	-	Sweden
9	SKI Plant 3, Iváncsa	Construction Planned	10 (2025) and 30 (2028)	-	Hungary
10	SVOLT, Linslerfeld	Construction Planned	6 (2025) and 24 (2028)	-	Germany
11	Verkor/Renault, Dunkerque	Construction Planned	16 (2025) and 50 (2030)	-	France
12	Volkswagen, Sagunto	Construction Planned	10 (2026) and 40 (2030)	-	Spain
13	Northvolt, Heide	Construction Planned	16 (2025) and 60 (2031)	-	Germany
14	SVOLT, Lauchhammer	Construction Planned	16 (2025)	-	Germany
15	Bolloré, Ergué-Gabéric	Expansion	1 (2022)	0.5	France
16	Leclanché, Willstätt	Expansion	4 (2025)	0.3	Germany
17	LGES, Kobierzyce	Expansion	67 (2023)	32	Poland
18	MES, Horní Suchá	Expansion	8.4 (2025) and 15 (2030)	1.2	Czechia
19	Northvolt Ett, Skellefteå	Expansion	43 (2023) and 60 (2027)	16	Sweden
20	Samsung SDI, Göd	Expansion	30 (2024)	20	Hungary
21	ACC pilot, Nersac	Operating	-	2	France
22	Northvolt Labs and R&D, Västerås	Operating	-	0.35	Sweden
23	FAAM Terevola 1, Caserta	Operating	-	0.33	Italy
24	Volkswagen Pilot, Salzgitter	Operating	-	NA	Germany
25	Blackstone Resources, Döbeln	Operating	-	0.5	Germany
26	SKI Plant 1, Komárom	Operating	-	7.5	Hungary
27	Daimler, Untertürkheim	Announced	NA	NA	Germany
28	Italvolt, Scarmagno	Announced	45 (2024)	-	Italy
29	FAAM Terevola 2, Caserta	Announced	7.5 (2027)	-	Italy
30	ACC, Termoli	Announced	12 (2026) and 40 (2031)	-	Italy
31	Volkswagen, TBC	Announced	10 (2028) and 20 (2031)	-	
32	Envision AESC, Navalmoral de la Mata	Announced	10 (2025) and 30 (2030)	-	Spain
33	EVE Energy, Debrecen	Announced	10 (2023) and 30 (2030)	-	Hungary
34	Verkor Innovation Centre, Grenoble	Under Construction	0.125 (2022)	-	France
35	Varta, Nördlingen	Under Construction	2 (2024)	-	Germany
36	Phi4tech pilot, Noblejas	Under Construction	0.3 (2022) and 2 (2023)	0.3	Spain
37	CATL, Erfurter Kreuz	Under Construction	24 (2023) and 80 (2030)	-	Germany
38	InoBat, Voderady	Under Construction	1 (2024) and 2 (2026)	-	Slovakia
39	SKI Plant 2, Komárom	Under Construction	9.8 (2022)	-	Hungary
40	Tesla Gigafactory 4, Grünheide	Under Construction	35 (2023) and 150 (2031)	-	Germany
41	Volkswagen, Salzgitter	Under Construction	20 (2025) and 40 (2027)	-	Germany

Source: JRC analysis (latest data update Sep 2022).

China currently dominates the refining of raw materials and the manufacturing of processed materials and components for batteries. While China has a clear advantage midstream and downstream, it faces supply shortages upstream in battery supply chains. For example, in 2020, China accounted for only 3% and 11% of global mine capacity for cobalt and lithium, respectively. Given the tight domestic mineral supply as feedstock for Chinese refineries, China has targeted investment in mining projects worldwide as part of its strategy to secure raw minerals. Chinese companies have acquired or are currently controlling substantial stakes in companies with mining rights in critical supply regions, e.g. the Democratic Republic of the Congo for cobalt, and South America and Australia for lithium. Finally, LFP manufacturers are speeding up their investment: Chuanjinnuo is planning to invest in 150 kt per year of LFP battery grade (Battery China CBEA, 2021).

In terms of battery cell manufacturing capacity, China is estimated to reach almost 5 000 GWh in 2030 (followed by the EU and US, with almost 1 000 GWh each).

Figure 15. Cobalt and lithium mine capacity by location and owner company headquarter in 2020



Source: JRC analysis (lastest supply data update: Sep. 21).

The US climate and tax bill of August 2022 (Congress.gov, 2022b), known as the Inflation Reduction Act (IRA), aims to catalyse investment in domestic manufacturing capacity and encourage the procurement of critical supplies domestically or from 'free-trade' deal partners. It is reported (Yue Li, 2022) that more than USD 13 billion of investment in battery raw material production and battery and xEV manufacturing in the US has been announced in less than three months since the IRA was signed.

Another piece of US legislation since late 2021 that catalyses investments in batteries – among other clean-energy technologies – is the Infrastructure Investment and Jobs Act (Congress.gov, 2022a) of November 2021, also known as the Bipartisan Infrastructure Law (BIL). BIL aims to support domestic manufacturers with critical raw materials and other necessary components to manufacture batteries. In total, IRA, BIL and the CHIPS & Science Act of August 2022 combined will invest more than USD 135 billion (The White House, 2022) to build the US xEV value chain, including critical minerals sourcing and processing and battery manufacturing.

In November 2022, Canada, though not a major player in the lithium value chain, invoked national and economic security to order the divestiture of three Chinese investments in Canadian mines engaged in critical minerals, including lithium, comprising two that operate in Argentina (Bouchard, 2022).

In June 2022, the establishment of the Minerals Security Partnership (MSP) (CRM Alliance) was announced. Partners of the MSP initiatives include Australia, Canada, Finland, France, Germany, Italy, Japan, the Republic of Korea, Sweden, the UK, the US, and the European Union, i.e. consumer-centric countries holding large geological deposits. The initiative aims to bolster the supply chains of CRMs, including those for clean energy and other technologies, by ensuring that they are produced, processed and recycled supporting the full potential of the partner countries in terms of their domestic capacity and geological endowments (US Department of Stateb). Details on how the partnerships will operate have not been published.

The Russian invasion of Ukraine and the subsequent economic sanctions exposed vulnerabilities to the security of supply and caused uncertainty in the markets for several raw materials (OECD, 2022). Russia produced about 20% of the world's Class I nickel (IEA, 2022a) and exported 37 700 tonnes of class 1 nickel to China, 52 800 to Europe and almost 5 000 to the US in 2021 (Statista, 2022). Nickel prices have been strongly influenced, and on 8 March 2022, concerns over potential sanctions on Russian nickel exports sparked an unprecedented price rise, forcing the London Metal Exchange (LME) to cancel all of the day's transactions and suspend trading. Regardless, manufacturers are wary of doing business with Russian companies due to logistical challenges.

Indonesia imposed a full ban on the export of nickel ore in January 2020, and domestic processing requirements for nickel ore have obliged companies to process or refine the raw materials in Indonesia prior to export. Indonesia was the world's biggest exporter of nickel ore before it banned exports. Following the EU's challenge, the World Trade Organisation (WTO) ruled in November 2022 that Indonesia's export ban and domestic processing requirement on nickel ore violates WTO rules (EC, 2022). Indonesia appealed the WTO report in December 2022 (WTO, 2022).

2.1.5. Key observations and recommendations

- **Diversify supply**. Although China will remain dominant in the supply of raw and processed materials for batteries, diversifying supply by establishing secure trade agreements with other countries (e.g. Australia) can reduce the EU supply risk for almost all of the key raw materials for Li-ion batteries.
- **Strengthen refining capacity and accelerate the development of production capacity for battery components**. The EU's reliance on imports of primary supply feedstock (concentrates and intermediates) for conversion in its refineries is expected to continue in the coming years, especially for cobalt and nickel (JRC, 2022b). However, the expansion of refining capacity for key raw materials (lithium, nickel, cobalt, graphite and manganese) is feasible and will reduce supply risks for downstream manufacturers considerably. Moreover, proper measures are needed to implement the operating capacity in the EU for the production of anodes and cathodes to support the EU's self-sufficiency in e-mobility and energy storage.
- **Accelerate the development of a sustainable European Li-ion battery value-chain**. The development of a system attracting innovative companies to the LIB value-chain, including mining and exploration, manufacturing, use and end-of-life management (including re-use) can, directly and indirectly, decrease the supply risk related to the key LIBs raw materials as well as components and assemblies. The recirculation of components, for example, reduces the need for new virgin materials.

- **Invest in R&D&I**. To create a competitive LIB industry in the EU, innovation is required throughout the value chain, with new business models and IT tools. Skills already available should be further developed and exploited, ongoing and new research projects nurtured, expertise attracted and partnerships forged and reinforced.
- **Enhance circularity and data availability along the whole Li-ion battery value chain**. Demand for primary materials for batteries can be decreased, as well as the criticality of raw materials supply, through ecodesign (i.e. reuse, remanufacturing, second use and recycling), which has the potential to maximise the value of raw materials. This requires an in-depth knowledge of material flows, from extraction to end of life, to develop a long-term, sustainable and competitive EU Li-ion battery value chain.
- **Foster international cooperation**. Cooperation among business stakeholders can be prioritised on both R&D&I and investment, especially involving countries close to the EU in terms of values and standards. Examples of such cooperation already underway should be further encouraged.

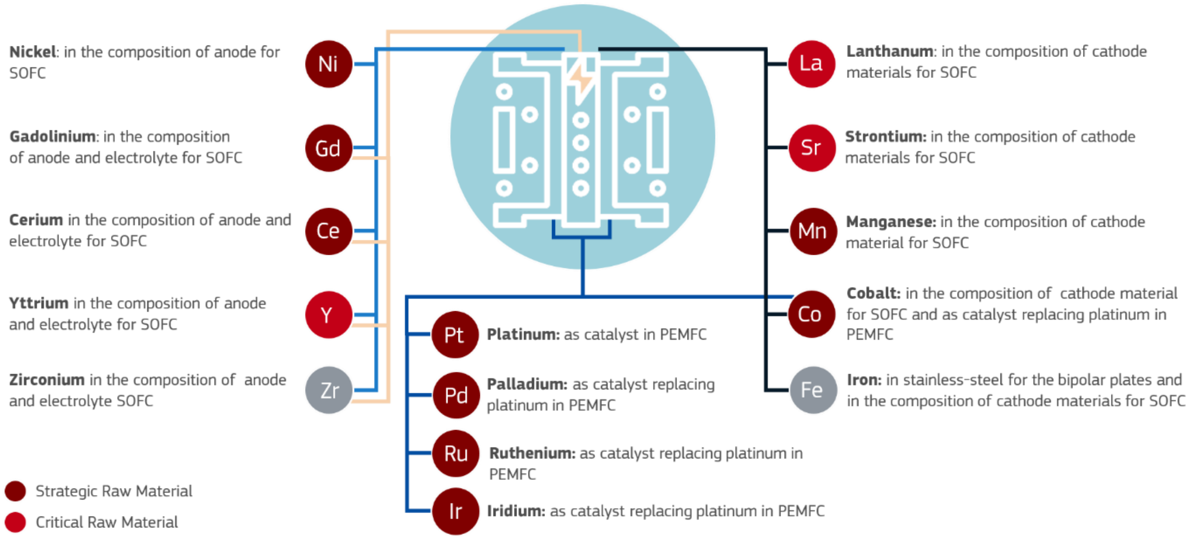
2.2. Fuel cells

2.2.1. Introduction

Fuel cells (FCs) are electrochemical devices that directly convert the chemical energy of the reactants, e.g. hydrogen and air, into electricity and heat (Alaswad et al., 2022). FCs are used for three main areas: transport applications (75%), stationary power generation (24%) and portable applications (<1%) (E4tech, 2020). FCs produce only water, no atmospheric pollutants such as nitrogen oxides (NOx), sulphur oxides (SOx), or particulate matter, and near-zero greenhouse emissions if working with renewable clean resources (FFFs and Hydrogen Joint Undertaking, 2017). Compared with combustion engines, FCs have no moving parts (except for pumps or compressors in some FC plant subsystems), which allows for stealthy, vibration-free and noiseless operation. Compared with batteries, FCs provide nearly instantaneous recharge capability, higher power densities and the electrodes are not consumed as they do not take part in the reaction. However, the reactants need to be fed continuously from external stores (Alaswad et al., 2022).

Figure 16 gives an overview of the most important raw materials used in the composition of FC components.

Figure 16. Selection of raw materials used in fuel cells and their function



Source: JRC analysis.

Proton exchange membrane FCs (PEMFC) and solid oxide FCs (SOFC) were selected for this study, because these technologies dominate the market, both in number and in capacity. Individual FCs are connected to achieve higher voltage and power in assemblies called stacks. The most important components of FCs are the membrane electrode assembly (MEA) and the bipolar plates. The MEA comprises an electrolyte, two gas diffusion layers (GDLs) which act as anode and cathode, and the catalyst. Other components include cell interconnects and cell sealants. The choice of materials for each component depends on the FC operating temperatures.

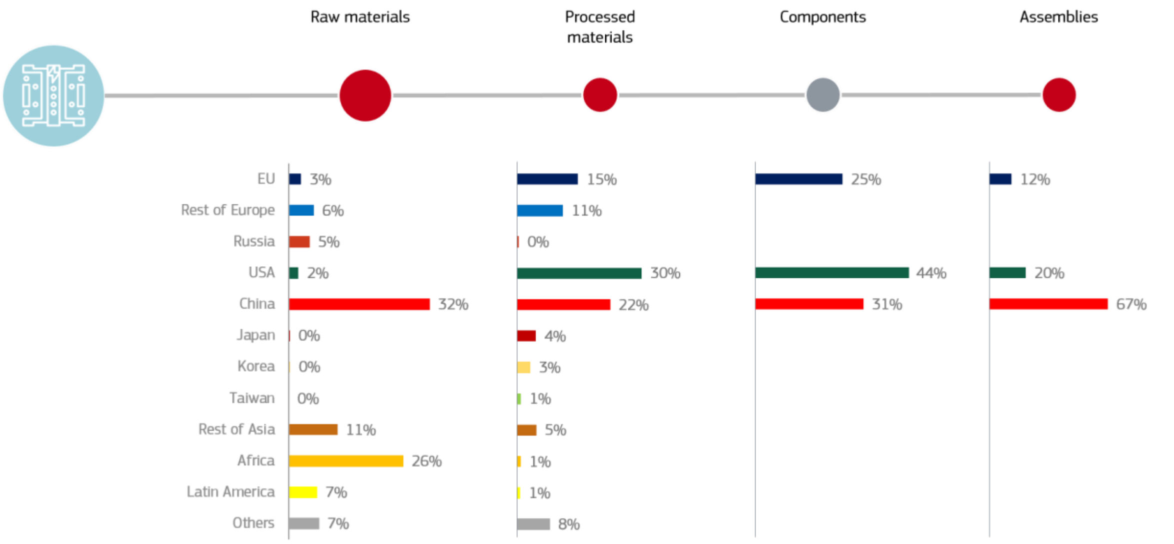
For the PEMFCs, which operate at low temperatures, the most important processed materials are carbon paper/cloth-based or other carbonaceous materials including carbon nanotubes and graphene nanosheets treated with polytetrafluoroethylene (PTFE) for the GDL and platinum or platinum alloys for the catalyst. The electrolyte is a membrane made of perfluorosulfonic acid (PFSA) polymers such as Nafion and the bipolar plates are non-porous graphite, coated or non-coated metals and polymer-carbon or polymer-metal composites. In comparison, SOFC operates at significantly higher temperatures (500-1000 ^{0}C) and requires different processed materials. Nickel-yttria-stabilised zirconia (Ni/YSZ) cermet or nickel-gadolinium doped ceria (Ni-GDC) are used as anode materials, while strontium-doped lanthanum manganite (LSM) or strontium-doped lanthanum cobaltite ferrite (LSCF) are used as cathode materials. The electrolyte is YSZ or GDC (Mendonça et al., 2021; Mahapatra et al., 2014). High temperature stainless steel is used for the bipolar plates. Consequently, the most important raw materials used in FCs are platinum and platinum group metals (PGM), graphite, yttrium, zirconium, cerium, gadolinium, lanthanum, cobalt, manganese, iron ore and nickel. The materials and components related to the hydrogen production and storage are not considered here.

Cost continues to be a large barrier to the adoption of FC vehicles, competing with internal combustion engines. Under high-volume production, the catalyst, which is commonly platinum, accounts for approximately 40% of the cost of a FC stack (Aminudin et al., 2023). Hence, the technological development focuses on two different avenues. The first is developing platinum electrodes with low platinum content through an enhancement of the platinum utilisation by increasing its active sites, thinning the active layer thickness and introducing smaller, nanometer-sized, platinum particles. Alternatively, the platinum can be totally or partially substituted with other metals. One option is palladium, since it has very similar properties, and is about three times cheaper and fifty times more abundant than platinum. Additionally, due to environmental concerns with the production of Nafion®, efforts are made to replace current membranes with non-fluorinated alternatives, typically consisting of a poly-aromatic backbone (Mardle et al., 2022).

2.2.2. Current supply chain bottlenecks

The highest risk in the supply chain for FCs is the raw material step. The EU produces less than 3% of the raw materials, 18% of the processed materials and 25% of the components used in the manufacturing of FCs. In terms of system assemblies, Europe's FC manufacturing remains low in comparison with other regions, with only 12% of the global production share. Figure 17 provides an overview of all the supply chain steps and their associated risks, as well as the key players for each.

Figure 17. An overview of supply risks, bottlenecks, and key players along the supply chain of fuel cells



Note: In the case of components, the graph represents combined categories for Europe (EU27 together with Rest of Europe), North America (USA + Canada), and Asia (China, Japan, Korea, Taiwan, and Rest of Asia) presented at the level of the main source.

Source: JRC analysis.

Eighteen of the 24 **raw materials** required for the production of both PEMFC and SOFC are deemed critical for the EU economy according to the 2022 CRM list. The EU is almost entirely dependent on foreign sources. China is the world's leading producer of several CRMs, producing 100% of the total output for cerium and yttrium, more than 85% of the total output for lanthanum and gadolinium and 65% of natural graphite. Cobalt world production is largely sourced from the Democratic Republic of the Congo (63%) and processed in China (63%), while PGM metals come from South Africa, all countries with low environmental standards and poor social governance. In particular, platinum mining is mainly concentrated in South Africa (71%), followed by Russia (12%) and Zimbabwe (8%). This fact, combined with competing demand from automotive catalytic convertors, chemicals production, medical services and electronic appliances, keeps its price high. This situation is not likely to change in the future.

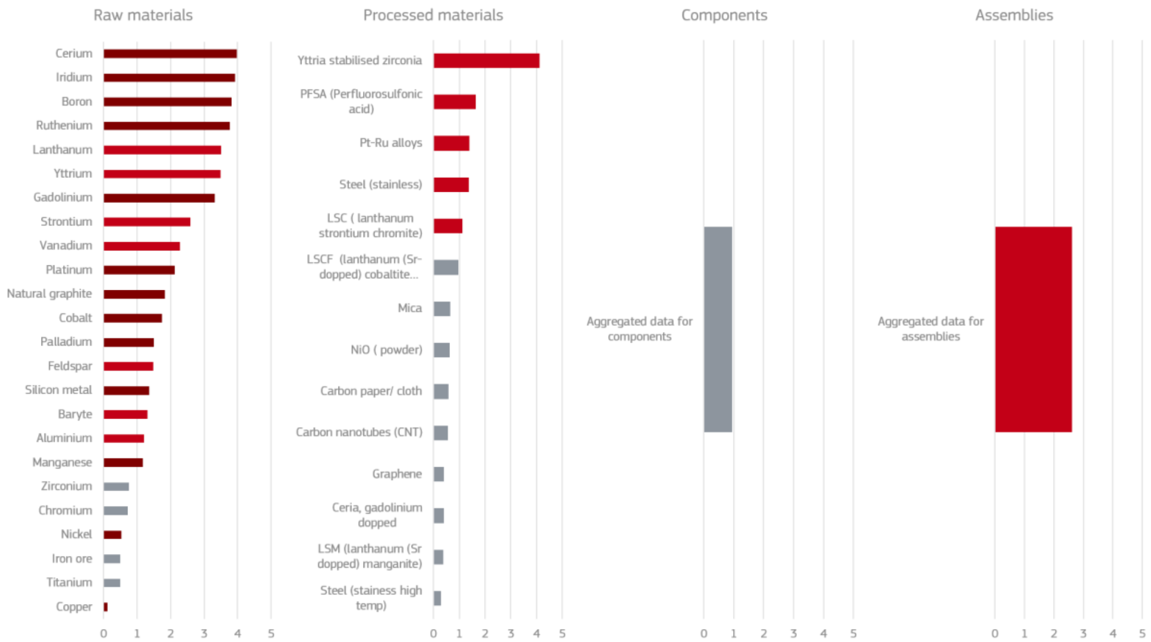
In the **processed materials** step, 19 materials have been identified as relevant to the production of PEMFC and SOFC. Among these are PFSA, YSZ, GDC, Ni/YSZ, Ni-GDC, LSM, LSCF, high and low temperature stainless steel, carbon paper/cloth, carbon nanotubes, graphene and sealant materials such as mica and barium silicate glass. The headquarter method has been applied to all elements, except for stainless steel and mica, where production volumes were identified. Overall, Asian companies supply 36% of the processed materials, the US 23% and Europe 18%, respectively. YSZ shows the highest supply risk among the processed materials. China dominates its production, with 85% of the global share, the rest being produced in the US (8.5%) and the EU (3.7%).

At the **components** step, the data for suppliers were assessed cumulatively. The rapid pace of growth and the number of acquisitions, emerging companies and joint ventures in numerous countries cause the data to change frequently. The largest manufacturers and suppliers of FC components are North America (44%) and Asia (31%) (JRC, 2019). The EU ranks third with 25%. At the component level, most companies only produce one component in the supply chain and there is little vertical integration for both PEMFC and SOFC supply chains. By exception, the MEAs may be manufactured by those who produce the membrane or catalyst materials. Europe has Johnson Matthey, which is one of the top two producers of PEM MEAs in the world. However, most demand is in transport applications, which is Asia-based. Similarly, Chinese suppliers for MEA SOFC dominate the market because of access to raw materials and low labour costs (E4tech, 2019).

Asia is not only leading the **stack** deployment of FCs (67% of total units), but is also home to nearly 85% of FC system megawatts manufactured in 2020 (Fuel Cells and Hydrogen Observatory, 2021). A large part this is due to Toyota's and Hyundai's FC passenger car manufacturing. Outside Asia, notable FC manufacturing activity is found in the US with a focus on stationary FCs and material handling applications. In Europe, FC system manufacturing remains low (12%) in comparison with other regions and the activity is spread across a pool of companies active in different FC technologies and applications, often driven by demonstration projects or early commercialisation. Several globally leading FC technology suppliers such as Bosch (DE), Ceres (UK), Elcogen (EE) and many more have headquarters in Europe and participate in market growth elsewhere. Ceres (UK) is licensing technology to global OEM partners in Japan, China in South Korea, Elcogen (EE) to Japan OEM partners.

Figure 18 provides the full detail on the Supply Risks of all elements along the supply chain.

Figure 18. Detailed Supply Risk of all elements in the fuel cell supply chain

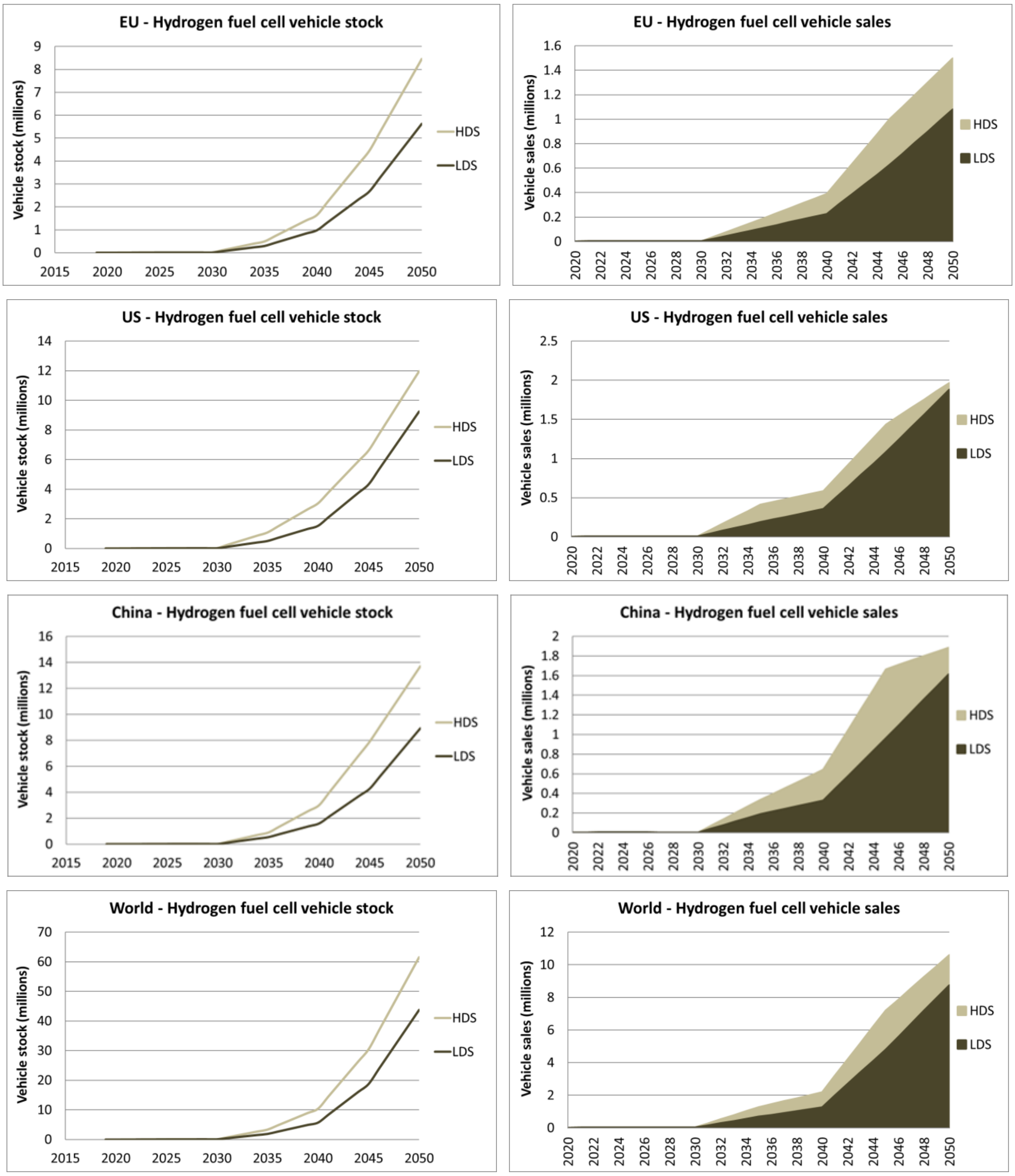


Source: JRC analysis.

2.2.3. Projected 2030 and 2050 material demand

PEMFCs lead both in terms of units and MW deployed capacity, driven by an ever-larger number of applications in the transportation sector. In the coming decades, the FCs will experience the strongest growth in the passenger car market. Based on the predicted size of the fleet of vehicles, it is possible to derive the material demand. The current analysis focuses on platinum, the indispensable raw material for the catalyst layer for PEMFC. Detailed information regarding the scenarios and the methodology applied are given in Annex 3. Figure 19 shows the estimated numbers of FC vehicles for the EU, US, China and globally for the two scenarios considered.

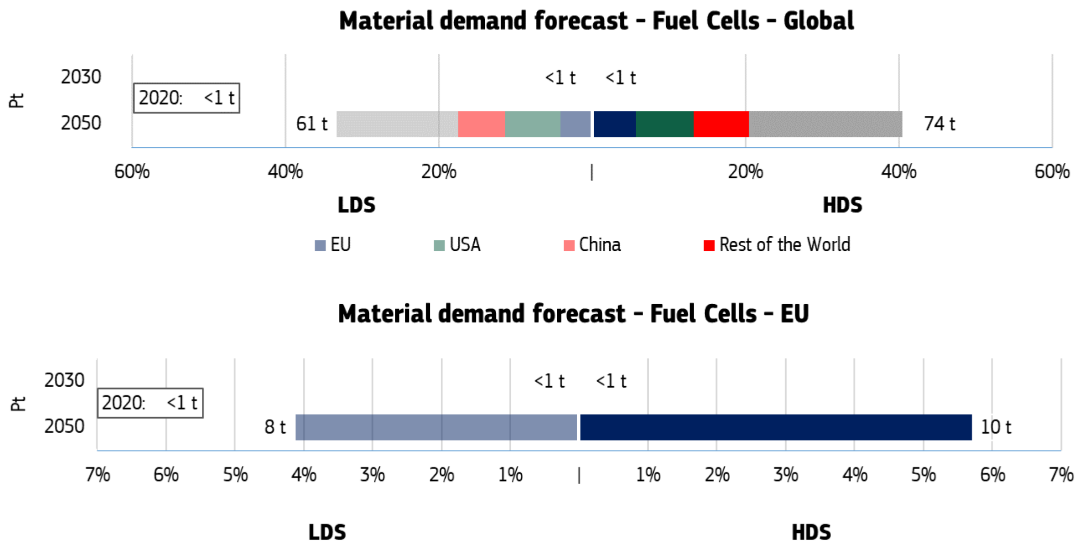
Figure 19. Fleet and annual sales of fuel cell vehicles in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis.

For the LDS, in the EU, the estimated number of FC vehicles is projected to increase slowly until 2030 and following a step increase, to reach a little more than 1 million units by 2050. The HDS anticipates a similar evolution for the FC vehicle fleet, projecting 1.5 million units by 2050. Worldwide, 10.5 million FC vehicles are estimated to be deployed by 2050. Consequently, in the EU, the estimated demand for platinum for FC vehicles for the LDS is estimated to increase to 7.5 tonnes in 2050. For the HDS in 2050, the demand is projected to reach 10.5 tonnes. The 2050 estimates represent 23% (LDS) to 32% (HDS) of the 2020 globally supplied platinum. In China and the US, the 2050 demand is expected to be slightly higher than in the EU in both scenarios considered. At global level, the increase in platinum consumption in FC vehicles is foreseen to increase to 61 tonnes (LDS) or 74 tonnes (HDS) in 2050 (Figure 20). The global 2050 projections for FC vehicles represent 33% to 40% of the 2020 globally refined platinum. Despite the targets set to decarbonise the transportation sector, through switching to hydrogen-fuelled FC cars, the demand for platinum will remain high. This is because the current amount of platinum used in a FC vehicle (Toyota, 2020) is around 3.5 times higher than that contained in the catalytic converters of conventional internal combustion vehicles.

Figure 20. Material demand forecast for fuel cells: global (top) and focus on the EU (bottom)



Source: JRC analysis (Pt = platinum).

2.2.4. Geopolitical dimension

In terms of FCEV deployment, Korea, the United States, China, Japan and Germany cover 95% of the market stocks. In 2020, Korea took the lead in the manufacture and deployment of FCEVs, surpassing the United States and China, to reach more than 10 000 vehicles (IEA, 2021). This segment is expected to further expand, driven by supportive government policy (E4tech 2021) such as the ambitious public procurement measures for FC electric vehicles (Hydrogen Council, 2022).

In China, FCEVs are almost exclusively buses and trucks, representing 94% of global FC buses and 99% of FC trucks, respectively. In Japan, Toyota provides 33% of global FC stocks. Honda discontinued production of its Clarity FC, with the remaining stock available for lease through 2022.

Europe's FC car numbers are growing, but slowly. BMW is testing its iHydrogen NEXT concept car, while Audi will no longer include FCs in its future product portfolio. In France, start-up Hopium presented the first prototype of its Māchina, a high-end FC sedan. The vehicle will be commercially available after 2025. Danish FC start-up, Blue World Technologies (BWT), continues to expand its factory in Aalborg, aiming for an annual capacity of 500 MW by the end of 2023. In the UK, Jaguar Land Rover has teamed up with R&D partners to develop a new FC prototype vehicle.

Bosch is planning to produce the stationary fuel-cell systems at its manufacturing sites in Bamberg, Wernau, and Homburg, as well as its development sites in Stuttgart-Feuerbach and Renningen – and will invest hundreds of millions of euros by 2024. This clearly positions Bosch as a systems supplier for stationary FCs with its own value creation in the cell and stack segment (Bosch, 2020).

2.2.5. Key observations and recommendations

Of the 24 raw materials used in PEM and SO fuel cells, 18 are flagged as critical for the EU economy. China is the major supplier of the relevant CRMs, supplying more than 32%, followed by a series of countries in Africa (27%) and the rest of Asia (11%). Russia supplies 5% of CRMs, while the EU produces less than 3%. This poses significant supply risks due to political instability in the countries where the resources are located. Asian companies are market leaders in the remaining steps of the supply chain, while Europe does not enjoy a clear advantage at any step. The maximum share estimated for the EU is 25% for the components and 18% for the processed materials.

Several measures can be considered for improving the EU's position in materials supply chains for fuel cells:

- **Improve manufacturing opportunities in the EU.** An increase in EU fuel cell manufacturing capacity requires a growth in the capacity to supply processed materials and subcomponents. Investment in clean technology manufacturing needs to be driven by more net-zero incentives. Policies may need to evolve rapidly to support EU manufacturing capacity along the full value chain. This could include the creation of demand visibility and regulatory certainty by adopting legally binding measures across end-use sectors such as transportation.

- **Recycling, reuse and substitution.** Enhancing the recycling of PGMs can reduce supply risks at the refining stage. R&D efforts are needed to improve the efficiency of recycling technology and the cost of recycling, creating a substantial economic driver for the expansion of recycling activities. Alternatively, platinum could be substituted partially or totally with other metals such as metal oxides, nitrides, carbide or chalcogenides. However, these options demonstrate poor stability and low activity, making them difficult to substitute for platinum on an industrial scale.

- **Promote R&D, skills and competences.** The most relevant R&D actions should target the development of low- or zero-PGM catalysts (including bioinspired catalysts), reducing the use of critical raw materials, and the safe and sustainable use of all processed material, including the development of PFAS-free ionomers and membranes (Clean Hydrogen Joint Undertaking, 2022). Researching the potential for REE mining and refining in Europe would offer alternative supply options in case of severe disruptions. Simultaneously, significant investment in human capital should be made. To meet the demand for skilled workers along the value chain for fuel cells, the EU should invest in education and training programmes that provide the workforce with the necessary skills and knowledge. On the one hand, this could include tailored retraining and skill-raising programmes for the existing workforce to develop practical, hands-on experience. On the other hand, academia should be encouraged to play a more active role in teaching with the focus on a science, technology, engineering, and mathematics (STEM) curriculum.

- **Foster international collaboration and standardisation activities. Partnerships** along the value chain – for example between electrolyser suppliers and project developers and between component manufacturers and fuel cell stack manufacturers – can be used to jointly develop products and synchronise scale-up (Hydrogen Council, 2022). The lack of standards is a major institutional barrier to deploying hydrogen technologies. Efforts should be put into accelerating the introduction of technical standards for fuel cell manufacturing, use and recycling as well as equal emission standards for hydrogen traded internationally.

2.3. Electrolysers

2.3.1. Introduction

Hydrogen will play a key role in the world's transition to a sustainable energy future. Green hydrogen is a priority area in the European Green Deal and RePowerEU initiative for achieving a clean and circular economy and can contribute to the decarbonisation of many sectors (Hydrogen Council, 2021), (World Bank, 2022). Water electrolysis is a key process for the production of green hydrogen, also allowing for the better integration of renewable energy sources in the EU energy system. In 2021, water electrolysis accounted for only around 0.1% of global hydrogen production (IEA, 2022a) due to the limited availability of renewable electricity, as well as the high cost of electrolyser systems and low durability compared to other available technologies. As hydrogen can be produced at lower cost by steam reforming, **water electrolysis technology** has been slow to advance. Globally, the total hydrogen production is about 500 billion Nm^3/year, mostly obtained by the steam methane reforming process.

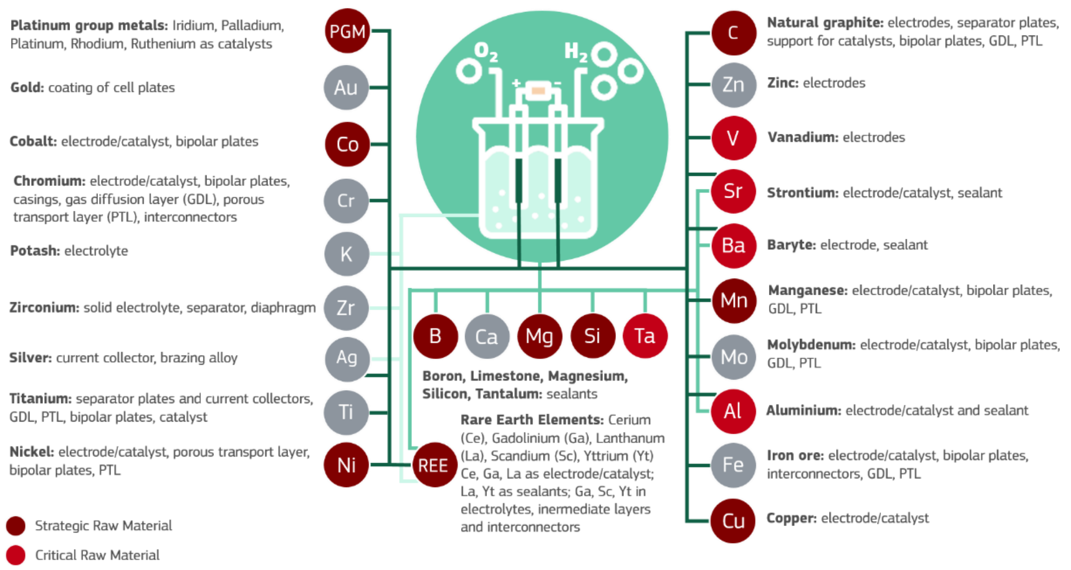
Four electrolyser types are considered in this assessment:

- Low temperature electrolysers: alkaline water electrolysers (AWE), proton exchange membrane (PEM) electrolysers, also known as polymer electrolyte membrane electrolysers, and anion exchange membrane (AEM) electrolyser, and
- High temperature electrolysers: solid oxide (SO) electrolysers.

While the technology readiness level of the alkaline and PEM electrolyser technologies is market uptake, the SO electrolysers are still at demonstration phase and AEM electrolysers are poised between large prototyping and demonstration. Alkaline electrolysers have specific advantages over PEM, such as lower energy consumption, higher lifetime, lower maintenance, lower water purification requirements and a lower reliance on critical raw materials than PEM and SO electrolysers. PEM electrolysers, in turn, have specific advantages over alkaline, such as better flexibility for variable loads, lower minimal load, smaller stack size, higher purity of hydrogen gas (useful only in some applications) and higher output pressure. Although the performance of AEM electrolysis is still lower than that which can be achieved with conventional technologies, this system combines the advantages of both PEM and alkaline technologies, allowing the scalable production of low-cost hydrogen from renewable sources (Collins, 2021) (Patel, 2021). SO electrolysers have some issues related to the lack of stability and degradation, which have to be solved before going to commercialisation on a large scale. Though still in the research phase, SO electrolyser technology can become economically competitive in future.

The main materials used in the four types of electrolysers are shown in Figure 21.

Figure 21. Selection of raw materials used in electrolysers and their function

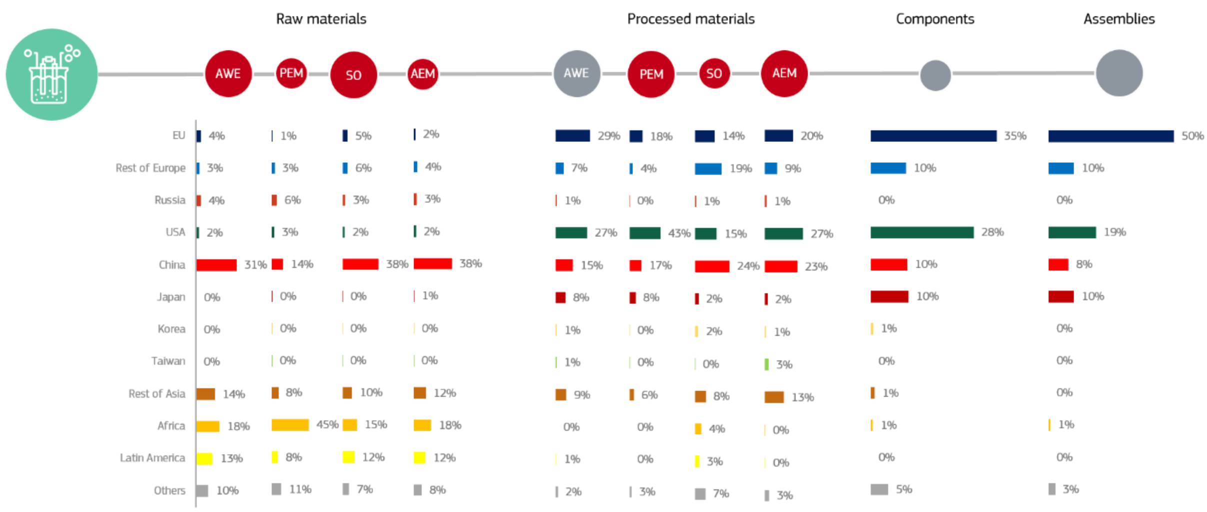


Source: JRC analysis.

2.3.2. Current supply chain bottlenecks

Four supply chain steps are considered in this analysis, namely: 1) raw materials; 2) processed materials; 3) components for electrolyser stacks; and 4) electrolyser stacks (assemblies). An overview of the key suppliers and potential bottlenecks in the supply chain of electrolysers, marked by red circles, is shown in Figure 22.

Figure 22. An overview of supply risks, bottlenecks, and key players along the supply chain of electrolysers



Source: JRC analysis.

The full list of raw materials considered in this assessment for the four electrolyser technologies is presented in Table 18 reported in Annex 2[7]. Nickel, manganese, chromium and iron are common materials for all electrolysers. Aluminium, cobalt, copper, lanthanum, molybdenum, natural graphite and zirconium are used in three of the technologies. Of course, there are key materials for a particular technology, such as platinum group metals (mainly iridium and platinum), titanium for PEM electrolysers, as well as yttrium and other REEs for SO electrolysers.

Potential materials have also been indentified which can be used in a certain technology to improve, for example, the performance and/or durability of electrolysers, but are not essential for the technology today (in the sense that the technology can exist also without them). There is vast ongoing research, in particular on less developed technologies such as SO and AEM electrolysers, but also on more established technologies such as alkaline and PEM. Thus, "potential materials" are also those currently researched for electrolyser applications. The future usage of these "potential materials" also needs to be monitored during the development and deployment stages of electrolyser technologies, even if they are not assessed here.

Potential materials for alkaline technology, used in some advanced alkaline electrolysers, are platinum, palladium, iridium, ruthenium, gold and titanium. Cobalt, tungsten, tantalum, tin, niobium, antimony and silicon have been identified as potential materials for PEM electrolysers[8]. Samarium, neodymium, ytterbium, praseodymium, europium, ruthenium, bismuth, barium, platinum, palladium, indium, vanadium, gallium,

[7] Various sources were used to make the inventory of raw materials, processed materials and components: (Bareiß et al., 2019), (Bernt et al., 2018), (Bessarabov et al., 2018), (Campagna Zignani et al., 2022), (Carmo et al., 2013), (Colli et al., 2019), (David et al., 2019), (Elder et al, 2015), (Fuel Cell and Hydrogen Joint Undertaking, 2020), (Grigoriev, 2020), (Henkensmeier et al., 2021), (Hu et al., 2021), (Hydrogen Electrolyzer, 2021), (Immanuel et al., 2020), (IRENA, 2020), (Kiemel et al., 2021), (Kumar et al., 2019), (Lim et al., 2017), (Lunderberg, S., 2019), (Mendoza et al., 2019), (Miller et al., 2020), (Nechache et al., 2021), (Pandiyan et al., 2019), (Patyk et al., 2013), (Pavel et al., 2014), (Rashid et al., 2015), (Shirvanian et al., 2020), (Sosa-Fernández et al., 2020), (Vincent et al., 2021), (Yodwong et al., 2020), (Zhang et al., 2022), (Zhao et al., 2020), (Lotrič, A. et al., 2021).

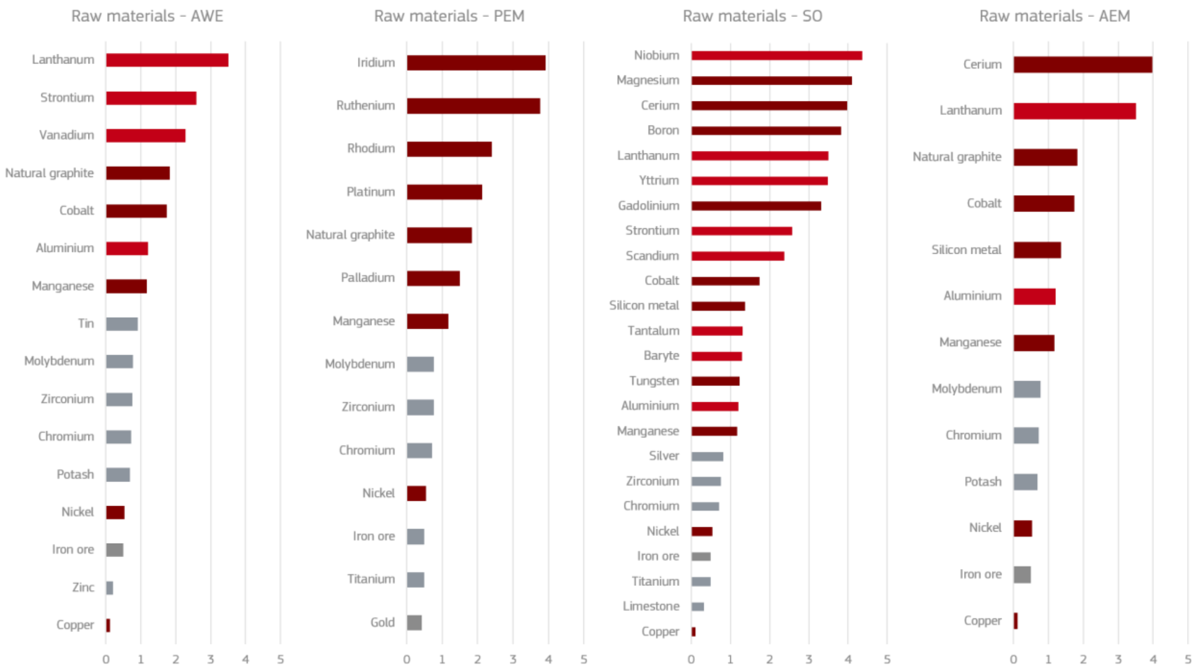
[8] Significant research efforts are focused on reducing noble metal content by mixing transition metal oxides such as Ti, Sn, Ta, Nb, Sb, Pb and Mn oxides with IrO2 and/or RuO2. The solutions are not yet market-ready and it is still under debate whether a full replacement of iridium is possible. A more feasible option is a strong reduction.

titanium, molybdenum, scandium and silicon are acknowledged as potential materials for SO electrolysers.[9] Ruthenium, iridium, platinum, palladium and titanium are identified as potential materials for AEM electrolysers.

Common materials used in balance of plant (BoP) components such as pumps, sensors, heat exchanger, gaskets, etc. are plastics, metals (such as copper, aluminium, gold, silver, nickel, lead, and iron), rubbers, polymers (e.g. Teflon), fiberglass and semiconductors. Most of these materials are also used in the stack assembly. The current assessment is therefore limited to electrolysers stack, also due to the fact that CRMs are mainly used in the stack itself rather than in the BoP. Common coating and varnishes are excluded since they are not considered fundamental for the analysis.

The Supply Risks for selected key raw materials and processed materials are shown in Figure 23 and Figure 24, respectively, while the Supply Risks for electrolyser components and stacks are shown in Figure 25.

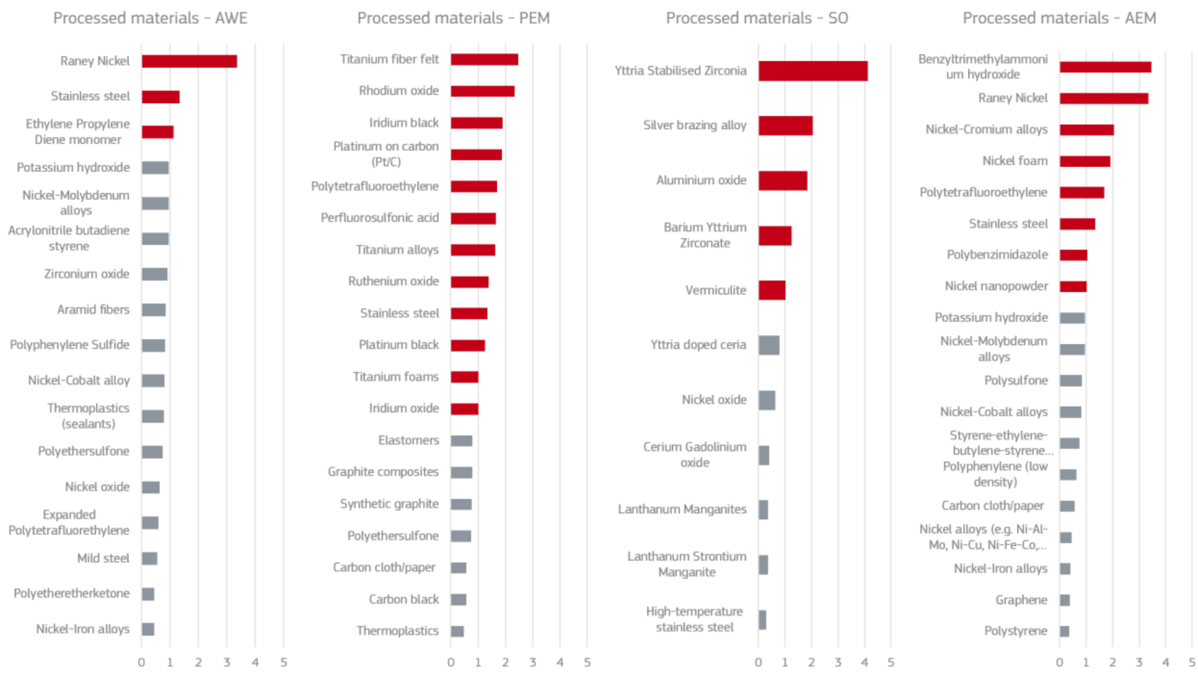
Figure 23. Detailed Supply Risk of selected raw materials in the electrolysers supply chain



Source: JRC analysis.

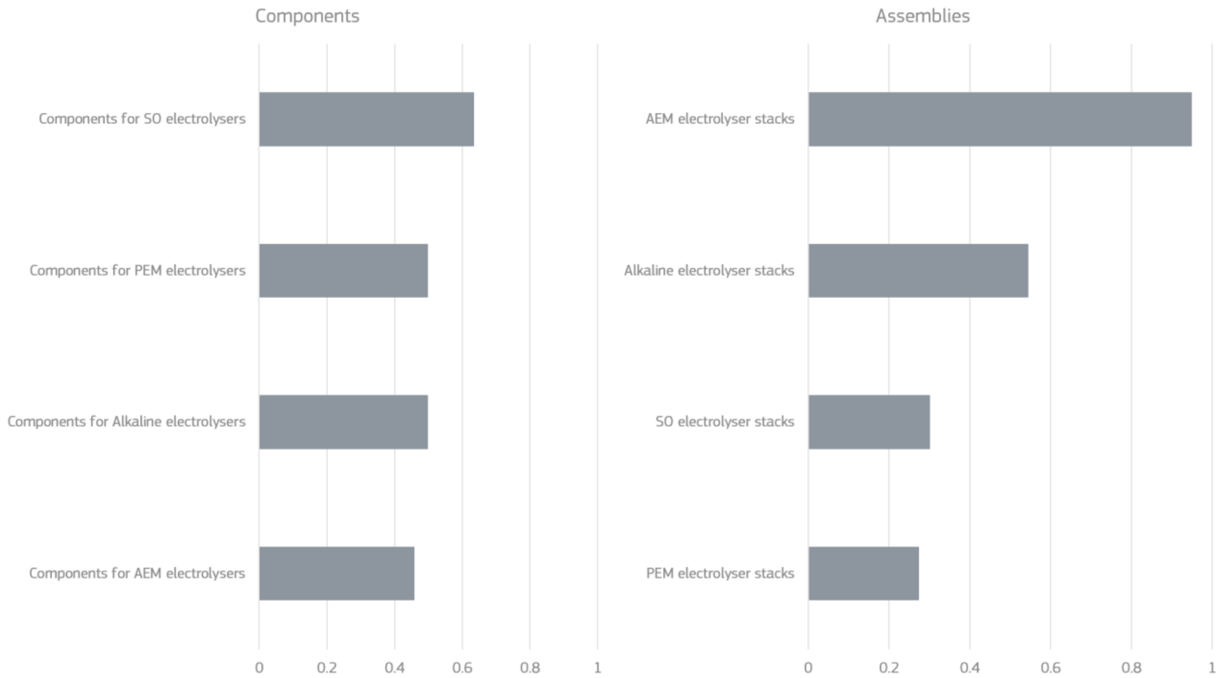
[9] The potential raw materials for SO electrolysers were selected based on list of processed materials being investigated for future use in this technology, such as yttrium-doped barium cerate zirconate, scandia-stabilised zirconia and cerium-doped scandia-stabilised zirconia, strontium-magnesium doped lanthanum gallate, lanthanum strontium ferrite , samarium strontium cobaltite, lanthanum strontium gadolinium magnesium oxide, lanthanum strontium gallium magnesium oxide, lanthanum strontium chromium manganite, bismuth copper vanadium oxide, refined zirconia powder, refined ceria powder, samarium doped ceria, lanthanum gallate, refined bismuth oxide powder, barium strontium cobalt ferrite, lanthanum chromite / yttrium chromite, lanthanum strontium titanate, yttrium doped barium cerate zirconate, porous platinum, porous iron, barium cerate, barium zirconate, lanthanum nickel oxide, lanthanum niobium oxide, lanthanum cobaltite, lanthanum strontium chromite, praseodinium nickel oxide, and lanthanum praseodinium nickel oxide.

Figure 24. Detailed Supply Risk of selected processed materials in the electrolysers supply chain



Source: JRC analysis.

Figure 25. Detailed Supply Risk of components and stacks in the electrolysers supply chain



Source: JRC analysis.

Raw materials

In terms of raw materials, the EU is lagging behind, producing between 1% and 5% of the required materials. Key suppliers of raw materials are China, South Africa and Australia.

Processed materials

The EU is also well positioned in terms of the production of processed materials, being one of the three main suppliers. Other key suppliers of processed materials are the US, China, India, Japan and Norway. The most critical technology in relation to processed materials is PEM, followed by AEM and SO. Processed materials with the highest supply risks and their main suppliers are: RanyeNi (India), titanium fiber felt (China), rhodium oxide (China), iridium black (US), carbon supported Pt (Pt/C) (US), yttria stabilised zirconia (China), silver brazing alloys (India), benzyltrimethylammonium hydroxide (China), nickel-chromium alloys (China), and nickel foam (China).

The EU is fully dependent on the supply of titanium fiber felt, carbon-supported Pt, barium yttrium zirconate, silver brazing alloys, lanthanum (strontium) manganites, polybenzimidazole, nickel foam, benzyltrimethylammonium hydroxide and Ni-Cr alloys.

Components

The EU is also the major supplier of components for all three technologies except AEM electrolysers, where it is the second major supplier. Besides the EU, the US, Japan and China are other key suppliers of components for electrolysers.

Assemblies

The EU is leading the manufacturing of stacks for all four technologies. Other key suppliers are China and Japan for alkaline electrolysers, Japan and the US for PEM and SO technologies, and the US for AEM stacks.

2.3.3. Projected 2030 and 2050 material demand

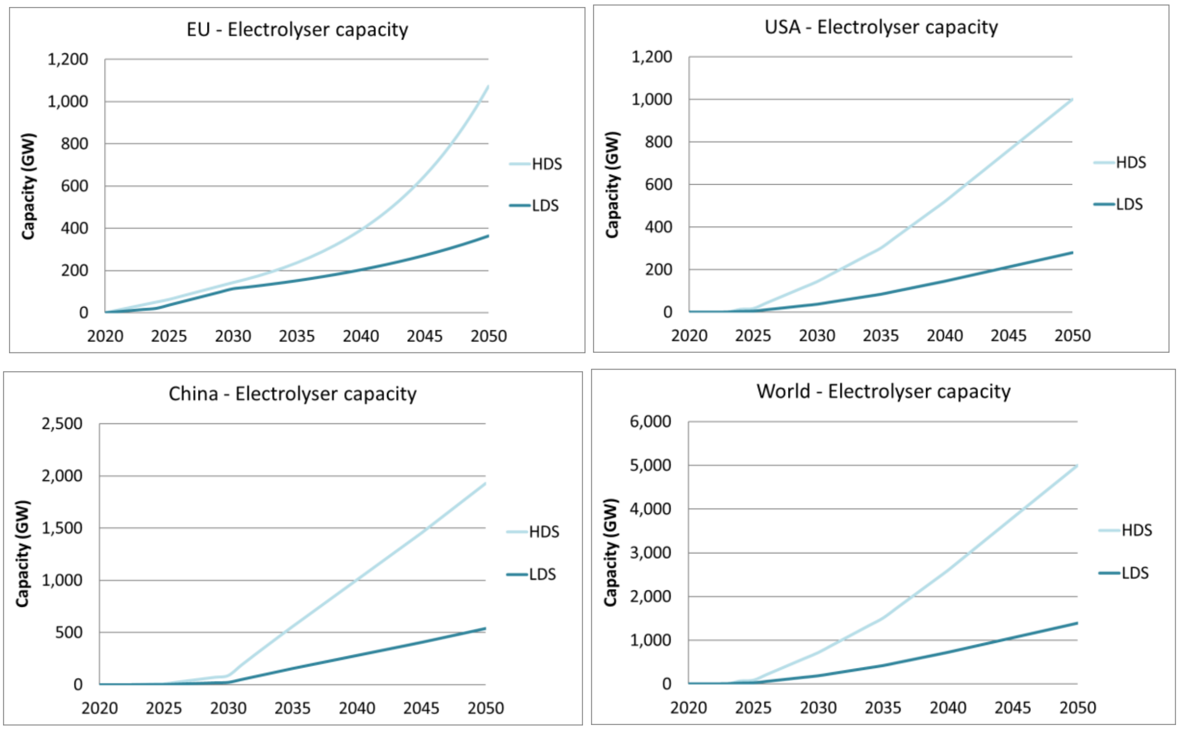
The future annual demand of materials for electrolysers depends on several factors, such as installed capacity, electrolyser efficiency and lifetime, market shares of the different electrolyser technologies, as well as materials loading evolution until 2050.

Installed capacity

The installed capacity in the EU, the US, China, and globally are taken from official sources. For EU capacity, additional analysis is performed. Various asumptions were also made to estimate the evolution of market shares for these countries until 2050. Details regarding the sources, data, and assumptions used can be found in the methodological Annex 3 (Section 2.3 Electrolysers).

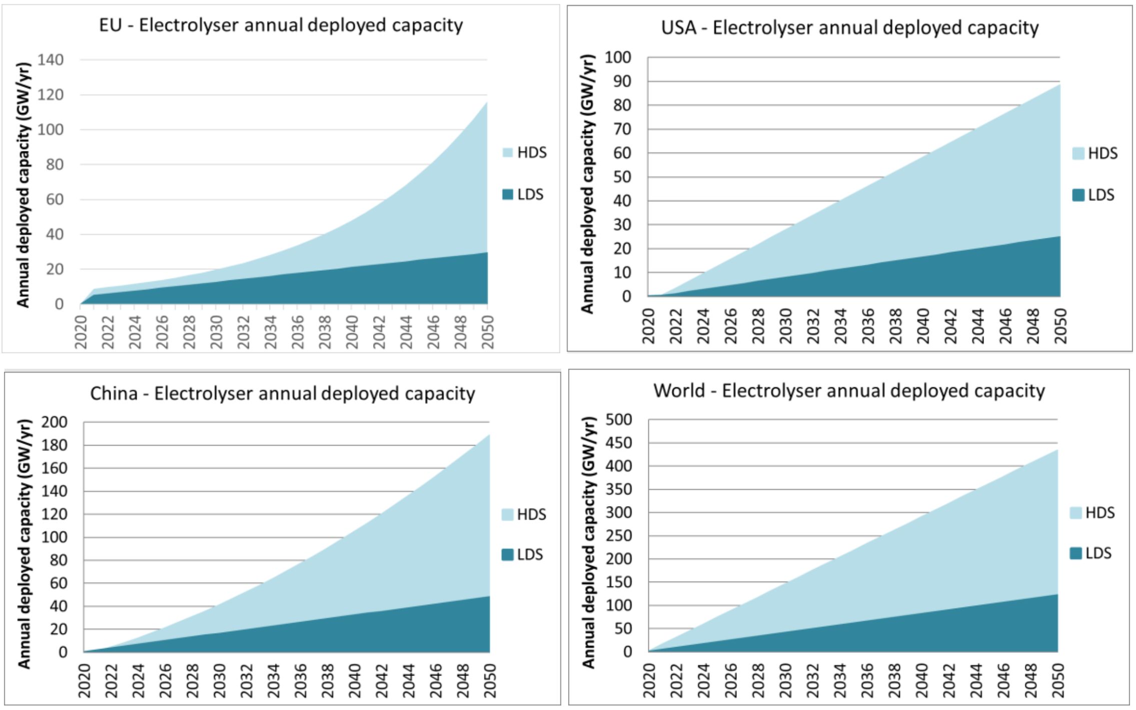
The evolution of the cumulative electrolyser deployment capacity in the EU, US, China and globally until 2050 is presented in Figure 26, while the annual deployment capacity is given in Figure 27.

Figure 26. Electrolyser capacity in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis

Figure 27. Electrolyser annual deployed capacity in the EU, US, China and globally in the two explored scenarios

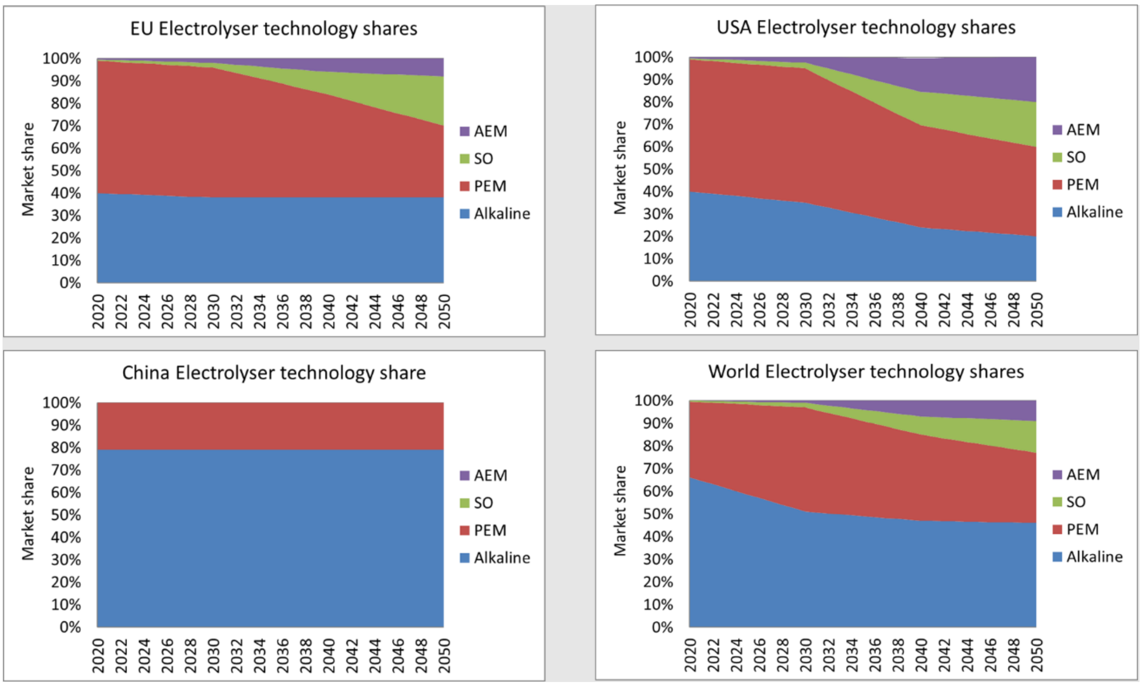


Source: JRC analysis.

Market shares evolution until 2050

The market shares for different electrolyser technologies assumed here for the EU, US, China and globally are shown in Figure 28.

Figure 28. Current and forecast shares for alkaline, PEM, SO and AEM electrolyser technologies until 2050



Source: JRC analysis. The same technology shares are assumed for high and low demand scenarios.

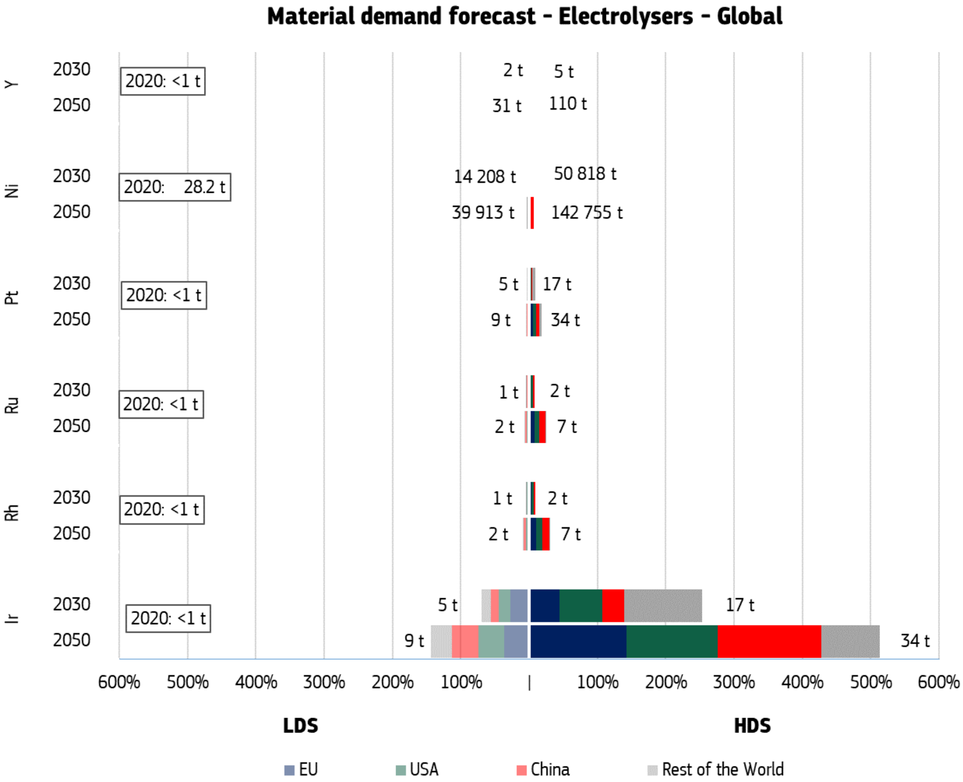
Materials demand

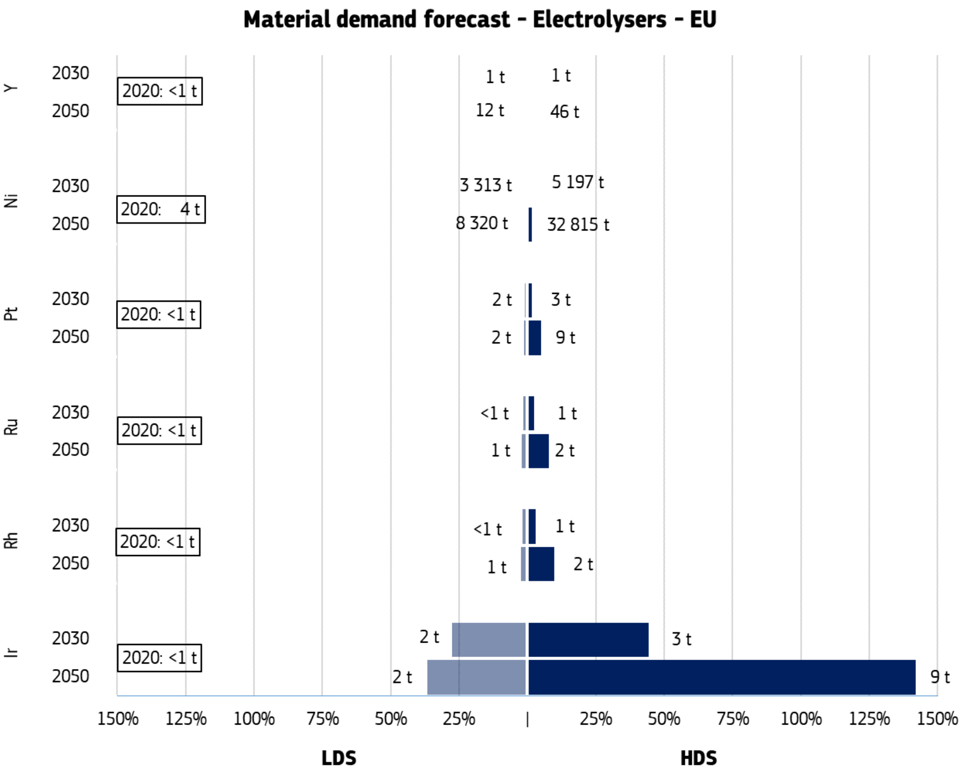
The annual demand is presented in Figure 29 for selected materials used in electrolysers in the EU, US, China, and globally in 2030 and 2050, in the low and high deployment scenario, as a fraction of the current global supply.

Iridium can become a critical material for the deployment of electrolysers in the EU: its demand would exceed the current global supply by 2050. It should be noted, however, that the demand could be relaxed if further reduction in the catalysts loading is achieved from 2030 onwards, compared to the SRIA 2030 targets for PGMs. In addition, primary materials demand can be further reduced by recycling and re-use practices: according to a recent study (World Bank, 2022), around 40% of demand can be satisfied by such practices from 2030 onwards.

No supply shortages are foreseen for the other materials reported in Annex 4.

Figure 29 Material demand forecast for electrolysers: global (top) and focus on the EU (bottom)





Source: JRC analysis (Ir = iridium, Rh = rhodium, Ru = ruthenium, Pt = platinum, Ni = nickel, Y = yttrium).

2.3.4. Geopolitical dimension

Targets for the global deployment of hydrogen production technologies are growing rapidly. The sum of all national targets for the deployment of electrolysis capacity has reached 145-190 GW in 2022, more than double the 74 GW of 2021. However, uncertain demand, unclear regulatory frameworks, the lack of infrastructure and non-existent operational experience present a high risk for first large scale development projects. Governments can support project developers by adopting policies that help them to mitigate risk and leverage private investment. Several governments have begun to implement such policies:

- **European Union**: The European Commission approved funding of EUR 5.4 billion to support its first hydrogen-related Important Project of Common European Interest (IPCEI), with a focus on hydrogen technologies (July 2022). Three more IPCEIs dealing with industrial applications, hydrogen infrastructure and mobility are expected in late 2022 and early 2023. In 2021, Germany launched the H2Global initiative, which uses a mechanism compensating the difference between supply prices (production and transport) and demand prices with grant funding from the German government (Baker McKenzie, 2022), (Kyllmann, 2022). France, the Netherlands (TNO, 2020), (TNO, 2021a), (TNO, 2021b), Spain, Portugal, Italy, Poland, Finland, Hungary and the Czech Republic have also recently adopted hydrogen-focused national hydrogen strategies (KPMG, 2023), (Wappler et al., 2022).
- **United States**: The Bipartisan Infrastructure Law adopted by the US Congress in 2021 assures grants for the creation of hydrogen hubs as well as incentives to foster infrastructure and electrolysis manufacturing. In addition, a USD 504 million loan guarantee has been made by the US DOE Loan Program Office for a large-scale hydrogen storage project. Several tax credits and grant funding have also been made available in support of hydrogen technologies by the Inflation Reduction Act (August 2022).
- **China** aims to become a global leader in hydrogen, seen there as a frontier technology. China's Medium and Long-term Plan for Hydrogen Energy Industry Development (2021-2035) was issued in March 2022. China has the confidence to rapidly expand its green hydrogen industry within the next decade and local policy and industry developments are already moving far beyond the national strategy and its conservative targets, building momentum for the green hydrogen industry. Compared to the EU and German strategies, which prioritise green hydrogen, China's strategy is colour-agnostic for now, with plans for green hydrogen to overtake grey and blue hydrogen only after 2030 (Brown et al., 2022). State-owned enterprises and public-funded R&D centres are rushing to develop hydrogen technologies, with the expectation of a massive ramping up of the industry. The country already accounts for a third of global electrolyser manufacturing capacity and will become more competitive as it scales up production.
- **Other countries** such as Japan, South Korea, Australia, New Zealand, Canada, Chile, the UK, Norway, Ukraine, Brazil, Russia, Colombia and Morroco have also developed hydrogen strategies (Wappler et al., 2022).

All these countries are EU competitors in terms of the relevant materials when it comes to the scaling up of electrolyser production. Considering that only a small percentage of the raw materials is extracted internally in the EU, the preservation of innovation and knowhow will be critical for the EU in order to keep its current leadership in electrolyser technology. This applies across the board, from materials processing and advanced material development to closing the loop with various circular strategies.

It should be mentioned though, that the EU's future green hydrogen demand could be met partially by imports. According to Aurora Energy Research, "renewable hydrogen imports into the EU from Australia, Chile, and Morocco would be economically attractive in 2030, supporting the bloc's goal of sourcing half of its hydrogen consumption from imports by 2030" (Aurora Energy Research, 2023).

2.3.5. Key observations and recommendations

Electrolysers are crucial technology for green hydrogen production using electricity from renewable energy sources. It is a new technology, projected to grow rapidly worldwide in the coming years. In 2022, the global installed electrolyser capacity was around 1.4 GW and is expected to grow to 134-240 GW by 2030 if all the projects currently in the pipeline are realised. However, to align with the Net Zero Emissions by 2050 Scenario, electrolysis capacity of above 700 GW would be needed by 2030, which requires a significant acceleration in the growth of manufacturing capacity, which is currently at just under 8 GW per year.

The most critical step in the supply chain is raw materials, followed by processed materials. Around 40 raw materials and 60 processed materials are required in alkaline, PEM, SO and AEM electrolyser production. The EU produces between 1% and 4% of the raw materials required, and key suppliers are China, South Africa and Australia. The EU produces between 14% and 29% of the processed materials required. Other key suppliers of processed materials are China, USA, India, Japan and Norway.

At present, most electrolysers in the EU are of the alkaline and proton exchange membrane (PEM) types. China and Australia are the major suppliers of raw materials for alkaline electrolysers, and China and South Africa for PEM. Currently, more than half of the manufacturers of large-scale electrolysers are located in the EU, predominantly in Germany and France, but also in Denmark, Italy and Spain.

Solid Oxide (SO) technology is expected to gain more prominence beyond 2030. Anion exchange membrane (AEM) electrolysers are a recent and still developing technology, combining the advantages of both PEM and alkaline technologies, allowing the scalable production of low-cost hydrogen from renewable sources.

Although the EU is at the forefront of electrolyser production, China in particular seems to be moving much faster in reducing costs and increasing shipments, but also in realising bigger project installations (Murtaugh et al., 2022). The lower production costs and more established supply chain have also enticed foreign brands to build factories and set up joint ventures in China to produce electrolysers (Creamer, 2021). Therefore, actions should be taken to preserve Europe leadership in electrolyser manufacturing and innovation.

For green hydrogen production, electrolysers will need to use electricity from renewable energy sources such as wind, solar power, hydropower and other renewable sources. This will require the installation of greater numbers of solar panels and wind turbines. It also introduces additional pressure on the availability of the materials required for these technologies, as well as other limitations, such as high land usage and water requirements.

The following actions to strengthen the electrolysers value chain are proposed:

- **Supply diversification**. In the short term, diversification of supply (securing long-term contracts with other smaller suppliers) can mitigate disruptions from major suppliers of key materials for electrolysers like China, Russia and South Africa. Alongside the diversification of external supply, the EU should explore its potential to build **internal EU capacities** for mining, refining and processing critical raw materials to produce the advanced materials needed for electrolysers. **Tailings reprocessing** has been also reported as a potential source for the extraction of PGMs and other critical materials (Avina et al., 2018).

- **Boosting recycling, re-use, repair, substitution, materials efficiency and circular design**. The recycling potential of electrolysers will only be realised after 2030, having a more tangible effect towards 2040 (World Bank, 2022). Recycling infrastructure for the collection, dismantling and processing of the relevant products, components and materials needs to be put in place in good time. R&D should be supported to develop innovative recycling methods offering high yield rates and high-quality secondary materials. The fast uptake of electric vehicles in Europe is accelerating the phase-out of conventional vehicles (with internal combustion engine) to cut CO_2 emissions by 2035. The platinum used in auto catalysts could therefore be an interesting source of secondary raw materials for electrolyser manufacturing as early as 2030. Indeed, closed-loop recycling of spent autocatalysts to recover materials such as platinum is a well-established practice, and these flows could be channelled into the electrolyser industry. To be able to confirm the secondary raw materials potential, the EU will need to develop recycling infrastructure for platinum and iridium catalysts, develop and maintain data on secondary raw materials relevant for electrolysers, and check material stocks and flows as well as competition between sectors.

  In the short to medium term, **substitution** has the potential to reduce demand for these key materials, and is already being addressed in research projects supported by the Clean Hydrogen Partnership. In general, for electrolysers, new, low-cost, high-performing and durable materials are required. The research focus is on thinner membranes (electrolytes) in particular, along with more active and durable catalysts and fewer critical raw materials. For PGMs used in electrolysers, future supply shortages can be avoided by the reduction of PGMs catalyst loading in PEM electrolysis cells with PGM-free compounds. Besides substitution, reducing the **materials intensity** for certain materials such as iridium, platinum and other platinum group metals could help prevent supply shortages in future.

It is vital to develop **circular electrolyser designs** to allow for the easy replacement of parts during service, the **re-use** and **repair** of some components, and easy dismantling for recycling. All of these can contribute to reduce the demand for primary materials.

Extended Producer Responsibility schemes via the **take-back business model** can be considered, where electrolyser manufacturers will have the responsability to take the equipment back for repair, re-use or recycling. This may help to reduce general waste streams, make more efficient use of materials and encourage manufacturers to adopt more “circular” design.

- **Boosting R&D and innovation in the EU**. Electrolysis-related research projects supported by the Clean Hydrogen Partnership are already being asked to form a better understanding of lifecycle performances and the materials efficiency of the technologies they develop. Increasing electrolyser performance and durability, and therefore lifetime, can help to reduce the use of critical materials in this technology significantly (TNO, 2021a&b).
- Last but not least, the current **knowhow** for manufacturing electrolysers/components should be preserved within the EU. While China currently produces the cheapest electrolysers in the world, Europe leads on innovative technologies which are better suited to producing green hydrogen, seen by many as a ‘silver bullet’ for decarbonisation.

2.4. Wind turbines

2.4.1. Introduction

Wind power is one of the most efficient and consolidated technologies in the renewables portfolio. As such, it plays, and is projected to play, an increasingly important role in the decarbonisation of the power sector. The actual expansion of this technology depends on its techno-economic performance as well as on the effectiveness of the regulatory frameworks and relevant energy policies.

Wind turbines convert the kinetic energy of wind into mechanical energy (rotational movement of the rotor), which is then converted into electricity in the generator. In the absence of a material fuel, the cost per kilowatt-hour chiefly depends on the capital expenditure (CAPEX). Thus, the stability of material supply and the evolution of material prices are crucial factors for this technology.

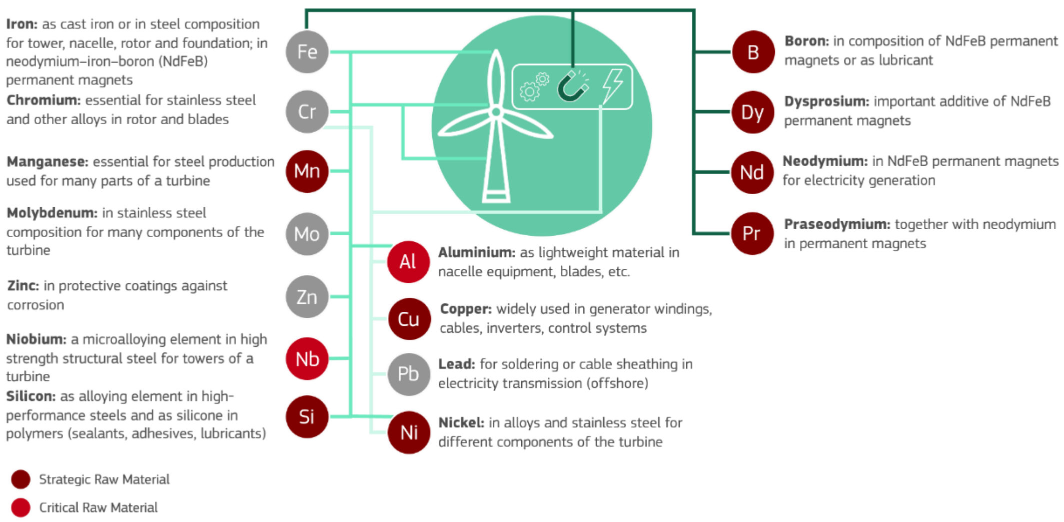
Generators are the component which most differentiates wind turbines. The sub-technology configurations considered in this work are defined based on the different generator types: i) DD-EESG (direct-drive electrically excited synchronous generator); ii) DD-PMSG (direct-drive permanent magnet synchronous generator); iii) GB-PMSG (gearbox permanent magnet synchronous generator); iv) GB-DFIG (gearbox double-fed induction generator); and v) GB-SCIG (gearbox squirrel cage induction generator). Direct-drive turbines can be based on permanent magnet generators or can incorporate an electrically excited generator. Eliminating the gearbox, direct-drive permanent magnets enable a reduction in size, hence a reduction in the turbine's weight, which is a key element especially in offshore applications. A promising technology for future direct-drive turbines, still at an early stage, is represented by high-temperature superconductors (HTS).

Wind turbines' electric generators (especially offshore technologies) rely extensively on rare-earth permanent magnets to deliver their high efficiency and performance levels. These rare-earth elements (REE) are dysprosium (Dy), neodymium (Nd), praseodymium (Pr), and terbium (Tb). In 2020, generators containing rare-earth permanent magnets were adopted in nearly all offshore wind turbines in the EU and in approximately 72% of the offshore wind turbines deployed worldwide. The share of onshore turbines installed in 2020 that use permanent magnets was around 13% in the EU and 22% globally (JRC, 2022).

Blades are another fundamental component of wind turbines. Blades should be designed and manufactured to combine the optimisation of the energy output (proportional to their length) and the need to withstand variable wind speeds and contain weights. Therefore, materials must combine high strength-to-weight ratio with high stiffness and fatigue. Thanks to its high stiffness and low density, balsa wood is a key material used in wind turbine blades (spar caps, blade cores). A set of other composite materials including glass fibre, carbon fibre or polymers, and plastics can also be used.

Figure 30 shows the main raw materials and components appearing a wind turbine.

Figure 30. Selection of raw materials used in wind turbines and their function

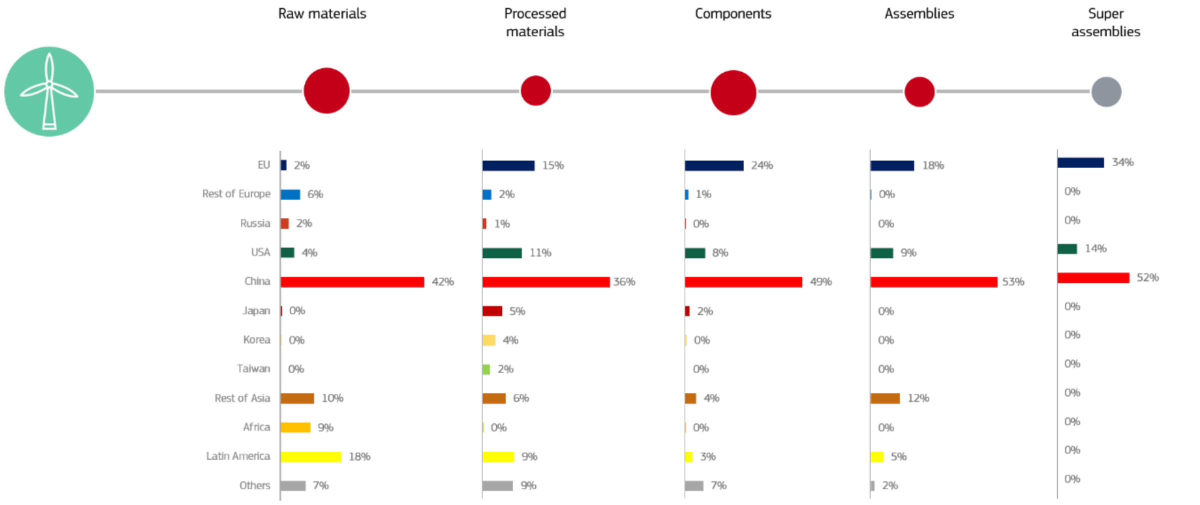


Source: JRC analysis.

2.4.2. Current supply chain bottlenecks

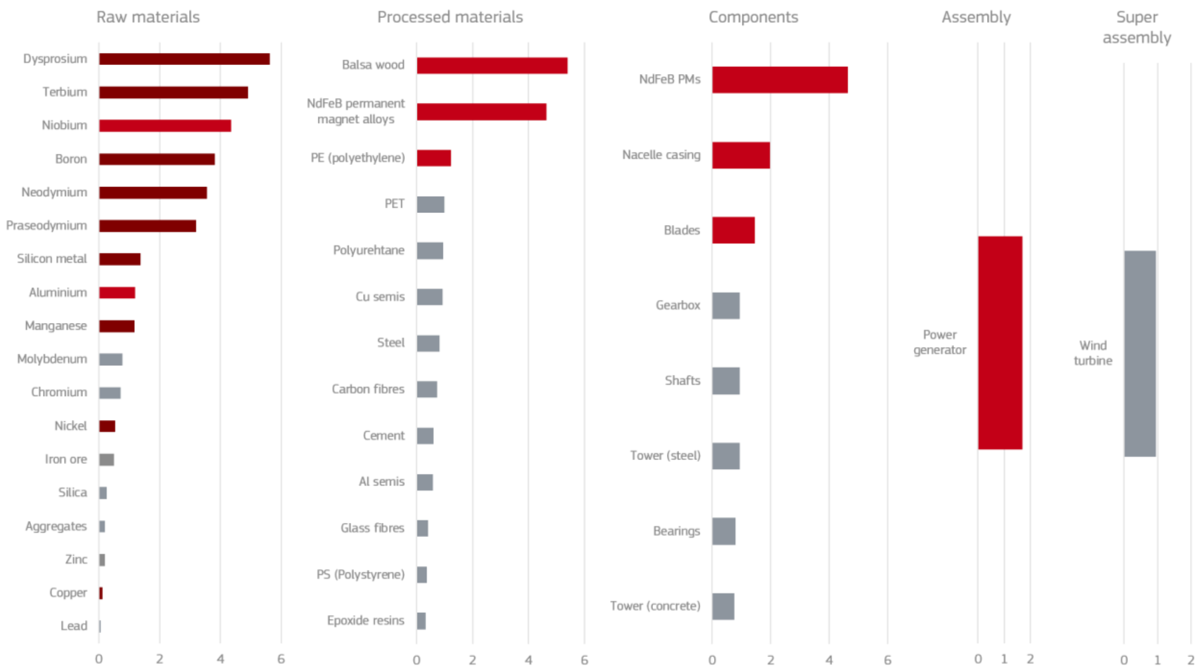
The wind turbine supply chain features five steps: raw materials, processed materials, components, assemblies, and super-assembly. Table 20 in Annex 2 summarises the elements for each step of the supply chain, Figure 31 summarises the main bottlenecks and key players in the different steps of the supply chain, while Figure 32 reports their supply risks.

Figure 31. An overview of supply risks, bottlenecks, and key players along the supply chain of wind turbines



Source: JRC analysis.

Figure 32. Detailed Supply Risk of all elements in the wind turbine supply chain



Source: JRC analysis.

The highest supply risk and most critical bottlenecks are to be found in the REE and permanent magnets supply chain. The REE market is highly concentrated and controlled by China across the whole permanent magnet value chain, from extraction and metal refinement (raw materials stage), alloying (processed materials stage), and magnet manufacturing (components stage).

Other raw materials with a high Supply Risk are niobium (used for steel alloys in turbine towers) and boron (also used for permanent magnets). The latter is also a strategic material. Additional strategic materials relevant in the supply chain of wind turbines are aluminium, copper, manganese, nickel, and silicon metal. The EU production share in raw materials is only 2%, while China leads with 43%.

Balsa wood[10] is almost exclusively (more than 90%) produced in Ecuador, resulting in the highest Supply Risk among processed materials and the second highest along the whole supply chain just behind dysprosium. This is leading countries to study counter-measures to relieve this almost total dependency. China is developing domestic balsa production, aiming at satisfying 10% of its demand after 2024 (BNEF, 2022). Also, blade manufacturers are currently replacing balsa wood with recycled polyethylene terephthalate (rPET) or hybrid designs, which ensures a competitive alternative. Biocomposite materials might be another alternative to balsa wood in the near future (e.g. biocomposite innovations based on hemp hurd cellulose claiming a comparable density to balsa and better compressive strength) (JRC, 2022).

Most elements are non-critical in the processed materials and components stages. However, mainly due to the high criticality of the REE supply chain (raw materials, alloys, and magnets) and balsa wood, the EU shows weaknesses along the entire supply chain, except for the final stage related to the wind turbine manufacturing. In this field the EU is self-sufficient, although it has recently lost its global leadership, now taken over by China: since our previous 2020 foresight report (EC, 2020), the EU share in global production has decreased from 58% to 34%, while the Chinese share has increased from 23% to 52%.

2.4.3. Projected 2030 and 2050 material demand

In 2020, global wind power capacity was 732 GW (698 GW onshore wind and 34 GW offshore wind). Among the regions under consideration, China had the highest onshore capacity (273 GW), while the EU hosted the largest offshore capacity (14 GW). The US showed a barely detectable offshore wind capacity (30 MW). China deployed most of the global capacity added in 2020, i.e. 69 GW out of 105 GW for onshore wind and 3 GW out of 6 GW for offshore wind (the latter value being slightly higher than the 2.5 GW deployed by the EU).

The two forecast scenarios consider quite diverse futures. In the LDS, growing trends mostly follow the historical patterns; in the HDS, wind power expansion is in line with ambitious climate change mitigation targets. More specifically, for the EU, the LDS is taken from the official EU Reference scenario (EC, 2021), while the HDS is built considering the targets defined by REPowerEU for 2030 (EC, 2022) and by the Climate Target Plan for 2050 – MIX scenario (EC, 2020b). These also align with the targets specifically defined for offshore wind in the EU Offshore Strategy (EC, 2020c). In the HDS, the wind capacity installed is 1.5 and 2.5 times higher than in the LDS in 2030 and 2050, respectively. Instead, JRC-GECO scenarios are adopted for the regions outside the EU. In particular, the "Current Policies" scenario is adopted as LDS, while the "1.5°C-Differentiated" scenario is adopted as HDS (JRC, 2021). For the global scenarios, GECO values for the EU have been overridden by the EU values adopted in this work.

In the LDS, global wind capacity reaches 1 400 GW in 2030 (1 300 GW of onshore wind and 100 GW of offshore wind) and 4 050 GW in 2050 (3 700 GW of onshore wind and 350 GW of offshore wind). In terms of annual deployment, this broadly means maintaining comparable levels to today. In the HDS, global wind capacity reaches 2 500 GW in 2030 (2 300 GW of onshore wind and 200 GW of offshore wind) and 8 400 GW in 2050 (7 600 GW of onshore wind and 800 GW of offshore wind). In order to meet these targets, annual deployment must considerably accelerate in the next decades. For instance, globally it will be necessary to rise from a current deployment rate of about 100 GW/yr of onshore wind to 200 GW/yr in 2030 and 500 GW/yr in 2050, and proportionally in the individual regions.

Figure 33 shows the wind power capacity from 2020 to 2050 in the EU, US, China, and globally according to the two considered scenarios, sorting between onshore and offshore wind. Figure 34 reports the capacities that must be deployed annually to reach such levels, also including capacity retirement[11].

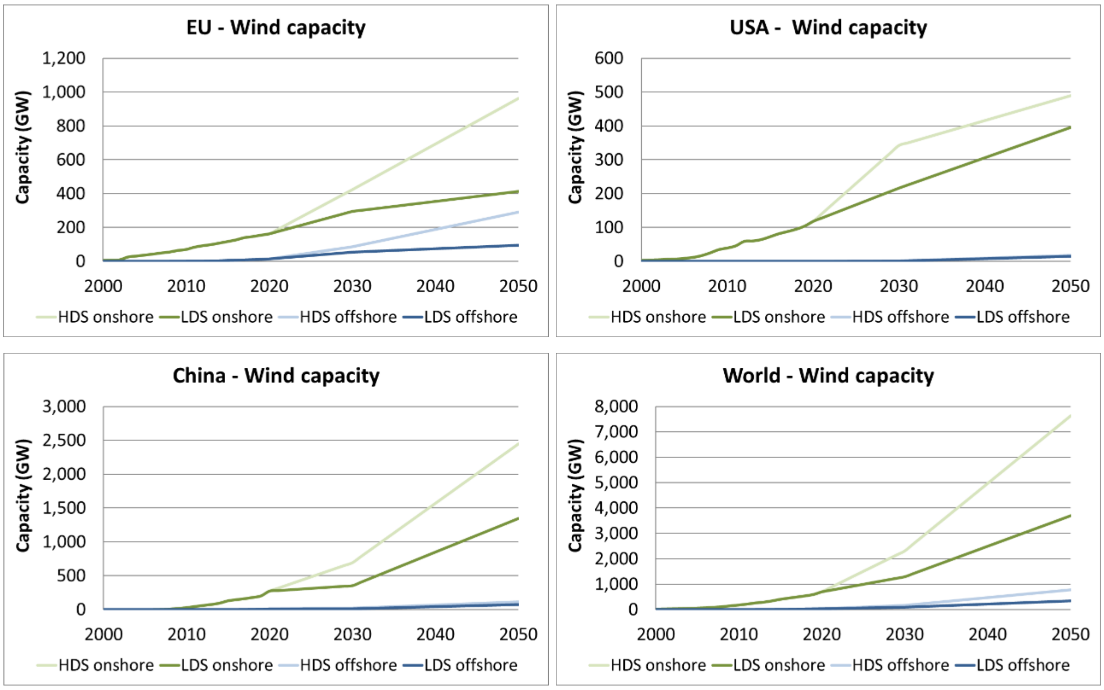
Scenarios for the market shares are defined based on the penetration of permanent magnet generators. For onshore wind, the penetration of PM generators remains constant at the current level in the LDS, while it grows considerably in the HDS to the detriment of the double-fed induction generators currently dominating the

[10] Balsa wood does not appear in the list of the candidate materials of the 2023 Criticality Assessment. Therefore, for consistency reasons, it has been considered as a processed material in this work.

[11] In the LDS, the Chinese pattern until 2030 is strongly influenced by the massive capacity deployed in 2020.

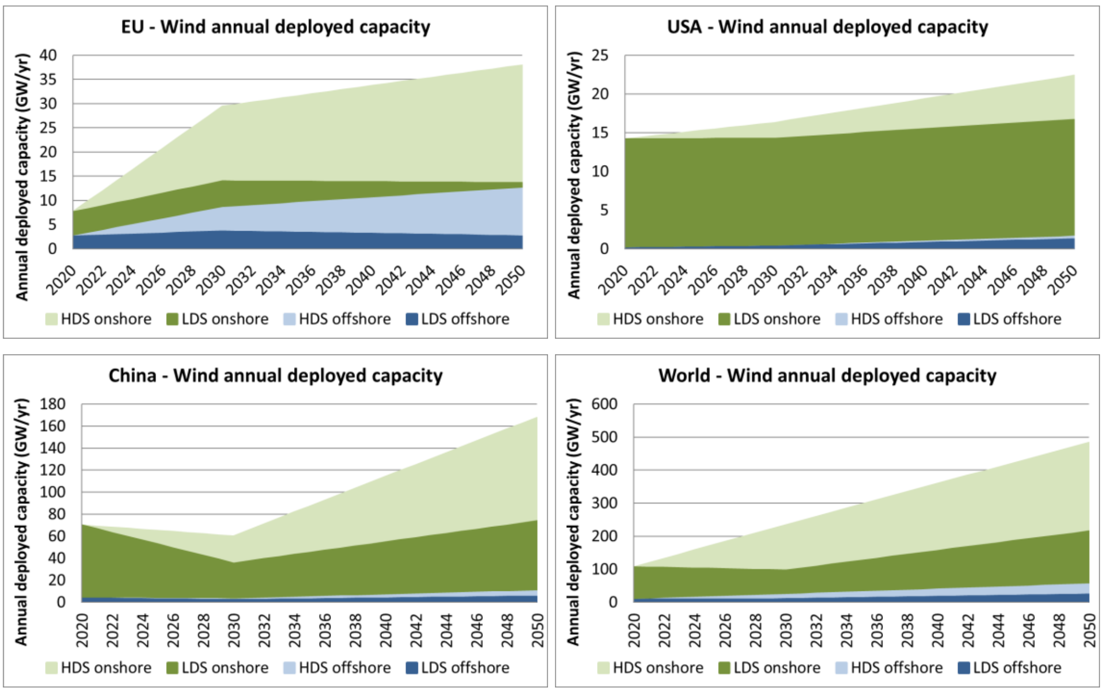
market (JRC, 2022). For offshore wind, the PM generators' market share decreases to around 50% in 2050 in the LDS (with a corresponding expansion of double-fed and squirrel cage induction generators), while it progressively grows until gaining full market dominance in the HDS.

Figure 33. Onshore and offshore wind capacity in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis.

Figure 34. Onshore and offshore wind annual deployed capacity in the EU, US, China, and globally in the two explored scenarios



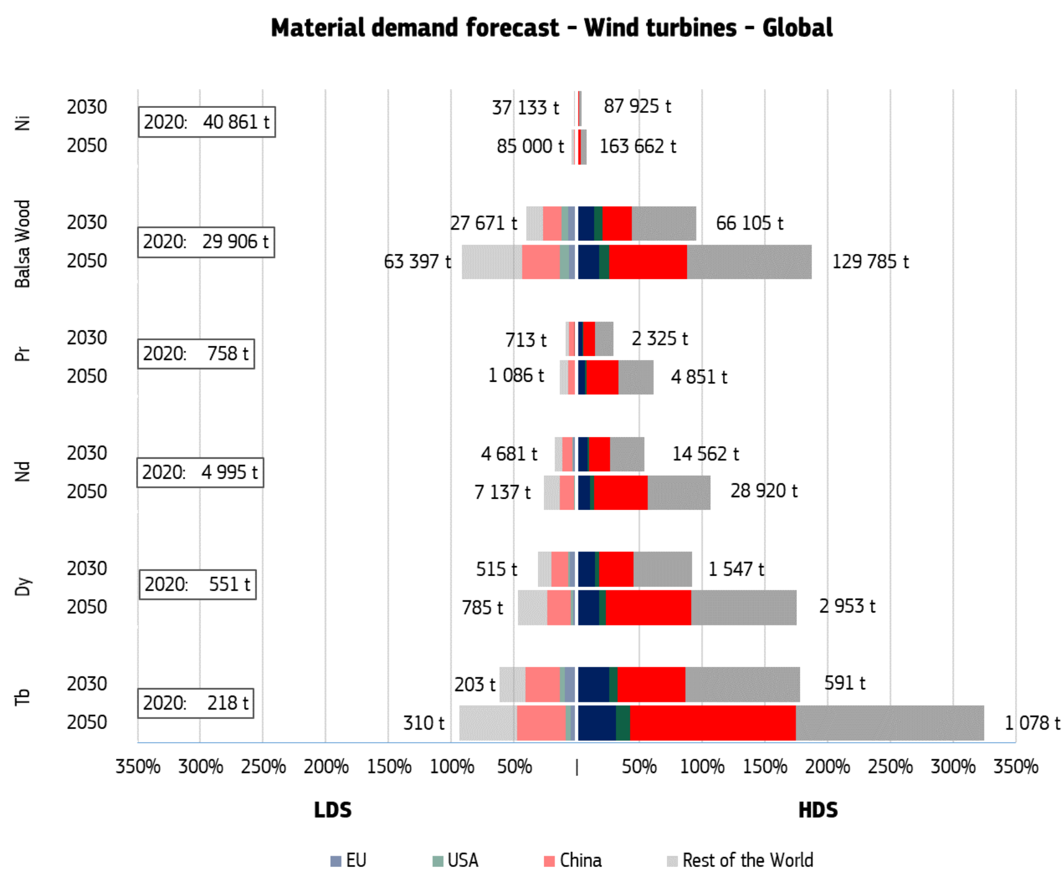
Source: JRC analysis.

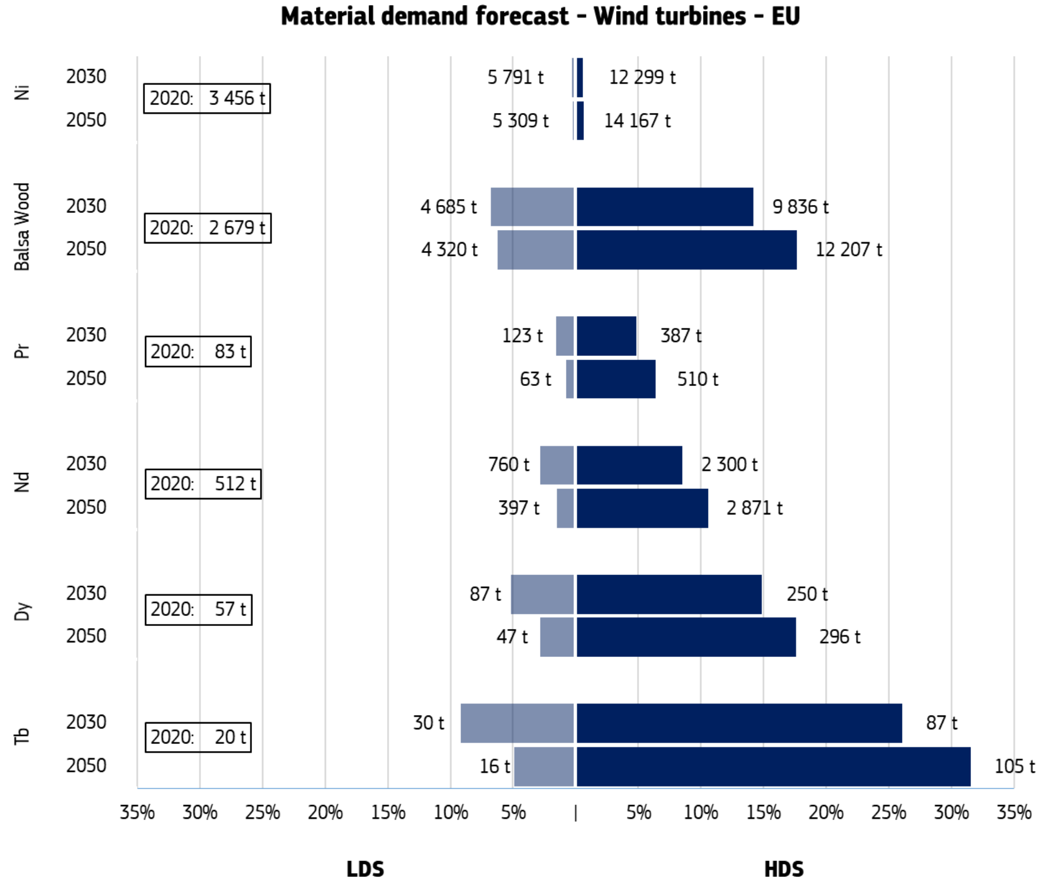
Two different rationales are applied to define scenarios for material intensity. The material intensity either remains constant (LDS) or slightly decreases until 2050 (HDS) for the general materials, i.e. concrete, steel, plastic, glass/carbon composites, balsa wood, aluminium, chromium, copper, iron, manganese, molybdenum, nickel, and zinc. For the specific materials, essentially used in permanent magnets (i.e. boron, dysprosium, neodymium, praseodymium, and terbium), no reduction is considered until 2030, while a 2% yearly reduction is considered afterwards. In general, the material intensity values replicate what reported in JRC, 2020.

Figure 35 shows the annual material demand for REEs in 2030 and 2050 compared with 2020. In the EU, REE demand will increase 4.5 times until 2030 and 5-6 times until 2050 (showing the effect of material efficiency). In the LDS, material demand grows slowly until 2030 and then decreases below 2020 values in 2050 (demand in 2030 and 2050 is 1.5 and 0.8 times the 2020 demand, respectively). A similar pattern is visible in the US and the world, although with lower values. In China, the demand evolution is highly influenced by the massive capacity deployment in 2020, showing a growing trend in relative terms only in 2050 in the HDS. Comparing the demand in absolute terms across regions, China clearly outpaces the EU and the US. In general, the EU share in global demand is around one tenth.

For neodymium, by 2050 the global demand in the HDS for wind turbines alone will reach a level comparable to the current global supply. For dysprosium, this will be almost twice the current global supply, and even three times for terbium, given its relatively lower usage in other technologies. For praseodymium, demand will be around half of the current global supply. For balsa wood, having a slower decrease in material intensity than REEs, global demand will be around twice the current global demand. Among the other strategic materials, nickel shows the highest demand relatively to the current global supply, although at much lower levels.

Figure 35. Material demand forecast for wind turbines: global (this page) and focus on the EU (next page)





Source: JRC analysis (Tb = terbium, Dy = dysprosium, Nd = neodymium, Pr = praseodymium, Ni = nickel).

2.4.4. Geopolitical dimension

China's dominance of the REE supply chain creates a huge dependency, as well as a security threat (the manufacturing of fighter jets, for example, depends on the supply of magnets from China). Over the last decade, China progressively relaxed its monopolistic position in the early stages of the supply chain, while it consolidated its dominant position in the later stages. Specifically, in 2010 China accounted for 97% of the global share in REE mining and concentration, and 75% in magnet manufacturing (Eggert et al., 2016), while recent data reveal a share of 63% for mining and 93% for magnet manufacturing (European Raw Materials Alliance, ERMA, 2021). The reasons are environmental (mining has a high environmental impact), economic (later stages of the supply chain carry more value added), and mainly strategic (stronger position due to the dominance of the entire supply chain).

In this respect, a risk is related to the **intended exploitation of Chinese dominance of supply chains**. For example, China could affect European competitiveness by flooding the magnets market with lower-priced products. Or they could impose low production quotas, trade restrictions, and even cut down exports, causing a shortage of materials and components fundamental to the twin green and digital transition in the EU. The example of China's controlled action in 2010-2011, reducing REE export quotas to less than half and resulting in a tenfold surge of prices, can serve as a lesson learned.

2.4.5. Key observations and recommendations

In 2019, about 130 000 tonnes of rare-earth permanent magnets (NdFeB) were produced worldwide, which corresponds to a market volume of EUR 6.5 billion. Today, there is a production capacity of only 1 000 tonnes left in Europe, while 16 000 tonnes of magnets are imported from China each year. There are only eight known manufacturers of permanent magnets in Europe, two of which are ultimately owned by American companies. The remaining six are European-owned (with minority shares held by a Chinese company in one case), with a stable ownership and operational profile. Vacuumschmelze, Germany, which produces NdFeB and SmCo magnets, together with its Finnish subsidiary Neorem, is the only major high-performance "sintered" magnet producer in Europe. Manufacturing capacity for sintered magnets also exists at Magneti Ljubljana, Slovenia, and Magnetfabrik Schramberg, Germany. The only operating magnet recycler in the EU is Kolektor, Slovenia, collaborating with Magneti.

There is a price difference of about 20-30% for a magnet produced in Europe compared to its equivalent produced in China, depending on the application. As noted by ERMA, "*the key question is rather what the real costs are to have access to a sustainably produced magnet, that is, financially, environmentally, socially, and in terms of supply risks*" (ERMA, 2021).

In the medium term, risk mitigation strategies which should be considered to reduce dependencies include:

- **Diversification of materials supply** through international partnerships in ongoing and future exploitation projects globally. Apart from China, rare earth reserves are also found in Australia, Malaysia, Canada, Africa, Japan, the United States, and Europe. The undisrupted supply of raw materials is a prerequisite for developing a sustainable manufacturing sector and for attracting investment in the permanent magnets value chain. Fostering EU green alliances is a way to strengthen partnerships and secure supply chains to make the EU wind industry more resilient.
- **Development of domestic supply.** Diversification of materials supply potentially includes the EU itself. The recent announcements about the discovery of REE ore deposits in Sweden and Finland can pave the way for the potential development of domestic mining in Member States, which requires dedicated investment. Among the various technical, policy, and economic aspects, the acceptance of mines by local communities is a crucial factor. Engagement with affected citizens is necessary, along with awareness-raising on the importance of extraction (Boissenin et al., 2022).
- **Improving mining, refining and manufacturing opportunities in the EU**. Domestic REE mining and refining, and permanent magnet manufacturing facilities, are important assets in the wind industry's value chain. Norway, Sweden and Finland hold REE reserves, and mining investment proposals have been submitted to the Raw Materials Investment Platform. The European Raw Materials Alliance (ERMA) has identified 14 investment cases, with projects covering the complete value chain (mining, rare-earth metallurgy, magnet making, separation and recycling) and spread all across Europe, with a total investment volume of EUR 1.7 billion. If these projects are realised, 20% of Europe's rare-earth magnet needs until 2030 could be sourced from inside the EU, while significant expertise and know-how will also be retained. However, this would not be enough to cover all of the EU's needs.
- **Enhancing the circularity of the value chain**. The recycling of REE materials and magnets is currently very low (with an end-of-life recycling input rate below 1%). This is due to limited availability of economically viable recycling processes and a lack of separate magnet collection. The available secondary source is also still limited, due to the average lifetime of wind turbines (30 years) and the relatively recent deployment of the permanent magnet wind turbine technologies. Additional challenges for the recycling of permanent magnets from wind turbines arise from their relatively big size (magnets for wind turbines typically weigh from 150 kg to 1 tonne or even more, compared to 1-2 kg in e-vehicle motors). Although the REEs generated from recycling are not expected to completely cover primary demand in the near future (2030), it is important to start strengthening recycling projects and infrastructure as soon as possible and to make the investment necessary to cover a significant demand share after 2030. The required decommissioning of windfarms at the end of operation in most Member States should facilitate collection and selective dismantling. Standardisation is being initiated at EU level to ensure efficient material reuse and the recycling of the critical raw materials contained in wind turbines.
- **Substitution and alternative solutions**: Currently, there is no competitive alternative solution to high-performance NdFeB magnets. Substitution is therefore a medium to long-term option. Various alternatives are currently being considered and tested with varying degrees of success. There is ongoing R&I work, notably in the production, recovery, efficiency and substitution of permanent magnets, with several H2020 projects addressing this area, including SecREEts, REFREEPERMAG and PASSENGER. Other relevant EU-funded projects dealing with alternative technologies, using fewer REEs and innovative technologies for recovery and reuse, include ECOSwing and SUSMAGPRO. However, further R&D work is hugely needed. More specifically:

- Material substitution for REEs magnets: while alternative magnets have been developed, such as plastic ferrites, other (ceramic) ferrites, and alloys added to paramagnets (AlNiCo or Ce-Co doped alloys), their performance is inferior to REE-based permanent magnets and thus further R&D is needed for viable alternatives.

- Component substitution: Not all types of generators use permanent magnets. Possible long-term alternatives are multi-polar synchronous generators such as those used by Enercon (annular generator), or squirrel cage induction generators. Vestas onshore models have been moving away from PMSGs since 2011 and have also announced the reduction of light rare earth element content from their most recent EnVentus turbines, while eliminating the use of heavy rare earth elements in this specific model (Vestas, 2021) (JRC, 2022). In the future, alternatives may also include superconductor-based generators, although operation drawbacks still exist.

- Increase in REE materials efficiency, by reducing the amount of REE necessary to produce NdFeB magnets. Here an option is to use hybrid drive generators, which utilise a smaller permanent magnet compared to standard systems. This could lead to savings of up to two thirds of neodymium, praseodymium and dysprosium per turbine.

- Exploring alternative and non-conventional sources of REEs such as from mining waste, as by-product extraction from phosphates, bauxite, iron ore, nuclear fuels, coal & coal waste products, and from nodules found on the sea floor. This is a realistic solution as it is already being rolled out at industrial scale (LKAB BOLIDEN REEMAP case).

EU competitors exploring rare earth-free generators include General Electric, which is developing a high-efficiency, ultra-light low temperature superconducting generator, and UK-based Greenspur, with designs of ferrite-based direct-drive permanent magnet generators, which use an axial flux architecture as compared to conventional radial designs.

2.5. Traction motors

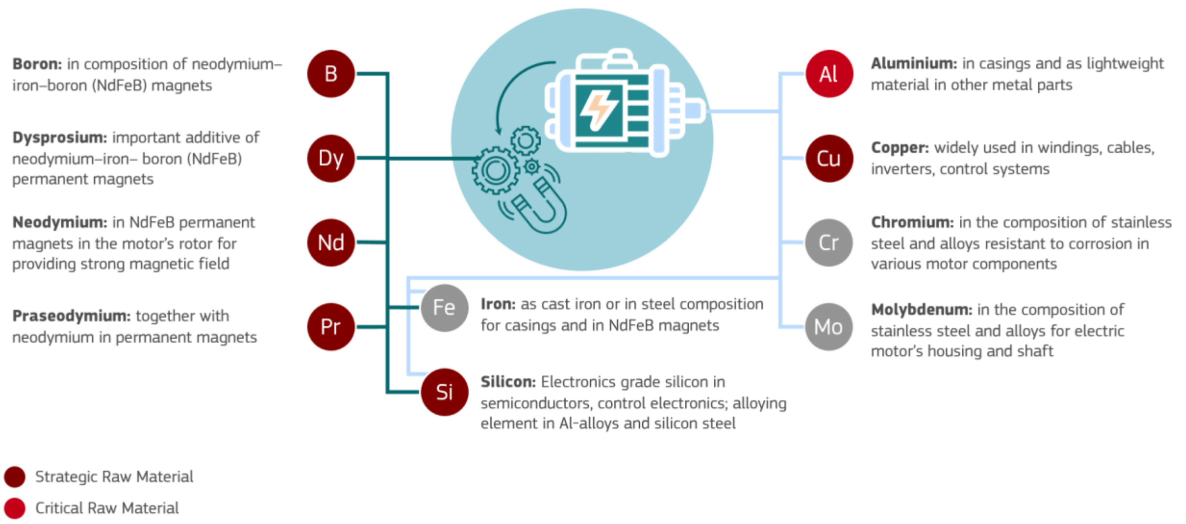
2.5.1. Introduction

Electric motors are used in a large range of applications from small electronic products and e-bikes to the large motors in electric drivetrains in vehicles and heavy transport (EC, 2020). Electric motors provide propulsion and regenerative braking and can be used as generators in certain hybrids. This assessment covers traction motors used in electric vehicles (EVs), as in battery electric vehicles (BEVs) and plugin hybrid electric vehicles (PHEVs). EVs are two to four times more efficient than conventional internal combustion engine models. EVs can also reduce reliance on oil-based fuels and, if running on low-carbon power, can deliver significant reductions in greenhouse gas emissions (IEA, 2021). In 2021, there were about 5.5 million electric cars on European roads, and 17% of the cars sold in the EU were electric (IEA, 2022). BEV registrations accounted for 54% of electric car registrations, continuing to exceed those of PHEVs in 2020.

A traction motor is an assembly of stator, rotor, bearings, housing and shields. It requires high performances such as high torque densities, while being lightweight, with high efficiency for e-mobility purposes (EC, 2020). The most important raw materials in traction motors are REEs such as neodymium, praseodymium and dysprosium. These materials are used to make NdFeB magnets alloys in the rotor. As manufacturers have to cope with space restrictions due to the need to integrate two drive trains into the car (the electric engine and the combustion engine), permanent magnets are the preferred technology for hybrid cars for their compact size and high performance (Pavel et al., 2017).

Figure 36 shows the main raw materials and components relevant to traction motors.

Figure 36. Selection of raw materials used in traction motors and their function



Source: JRC analysis.

There are different kinds of motor used in passenger cars, such as the AC induction motor or the asynchronous motor (ACIM), wound rotor synchronous motor (WRSM), permanent magnet assisted reluctance motor (PMAR) and AC permanent magnet synchronous motor (PMSM). ACIM and WRSM use more copper since the rotor is based on copper instead of permanent magnets. Both PMSM and PMAR use permanent magnets on the rotor. The dominant type of motor reported in 2020 is still PMSM, with a 55% share, followed by PMAR, ACIM, and WRSM with 22%, 17%, 6% respectively (Edmondson et al., 2022). There are variations in the content of magnet and copper between motor types and manufacturer.

Research efforts continue into the substitution of materials in EV, but with no breakthroughs as yet, the most dominant types of motor used in EVs in the EU remain unchanged. Automakers are generally converging on PM motors because of the high-power density advantage, efficiency (greater range) and currently acceptable magnet prices. However, permanent magnets are very susceptible to price volatility. The first half of 2021 saw a significant jump in price, leading to uncertainty in this market. The consistent cost of neodymium over the years after a large peak in 2011 has motivated manufacturers to continue adopting PM motors and fewer non-PM motors. The trend in traction motors is towards cost reduction by substituting expensive rare earths with copper in wound rotor and induction motors. Further efforts have been made to replace copper with aluminium, a lighter and cheaper material. However, aluminium is less electrically conductive, thus requiring a greater volume of metal (Edmondson et al., 2022).

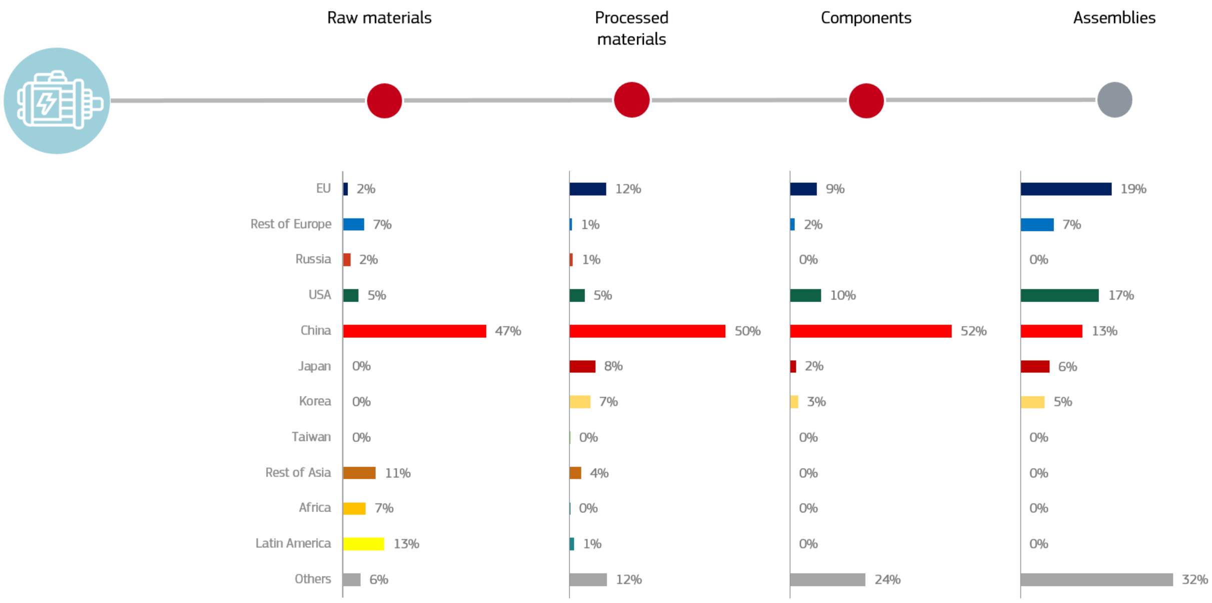
Typically, there are two different scenarios in the supply of motors for EV manufacturers: in-house development by vehicle manufacturers (OEMs[12]) themselves (for example, Japanese, American and European traditional car manufacturers) or motor development by suppliers and manufacturers (Altair, 2019), or a combination of the two. In 2022, only a few vehicle manufacturers fully made their own components.

2.5.2. Current supply chain bottlenecks

The traction motor supply chain features four steps: raw materials, processed materials, components, and assemblies. The new methodology in this assessment defines traction motors as assemblies instead of components. The list of the elements for each step of the supply chain is presented in Table 21 in Annex 2. Figure 37 summarises their bottlenecks, and Figure 38 pictures the supply risk by elements.

The highest risk in the supply chain of traction motors is at the raw materials stage. Traction motors contain significant quantities of strategic raw materials such as boron, dysprosium, neodymium and praseodymium, copper and aluminium. Some of these raw materials are characterised by very high supply concentration (boron in Türkiye and REEs in China) as well as concerns related to environmental and social performances along the supply chain (EC, 2020). The extraction of REE is known to be notoriously polluting. Many countries have REE mines but don't have the processing facility. The supply risk value for dysprosium, boron, neodymium and praseodymium are the highest of all the materials evaluated in the 2023 CRM list. In addition, wind energy and other motors compete for these materials (EC, 2020).

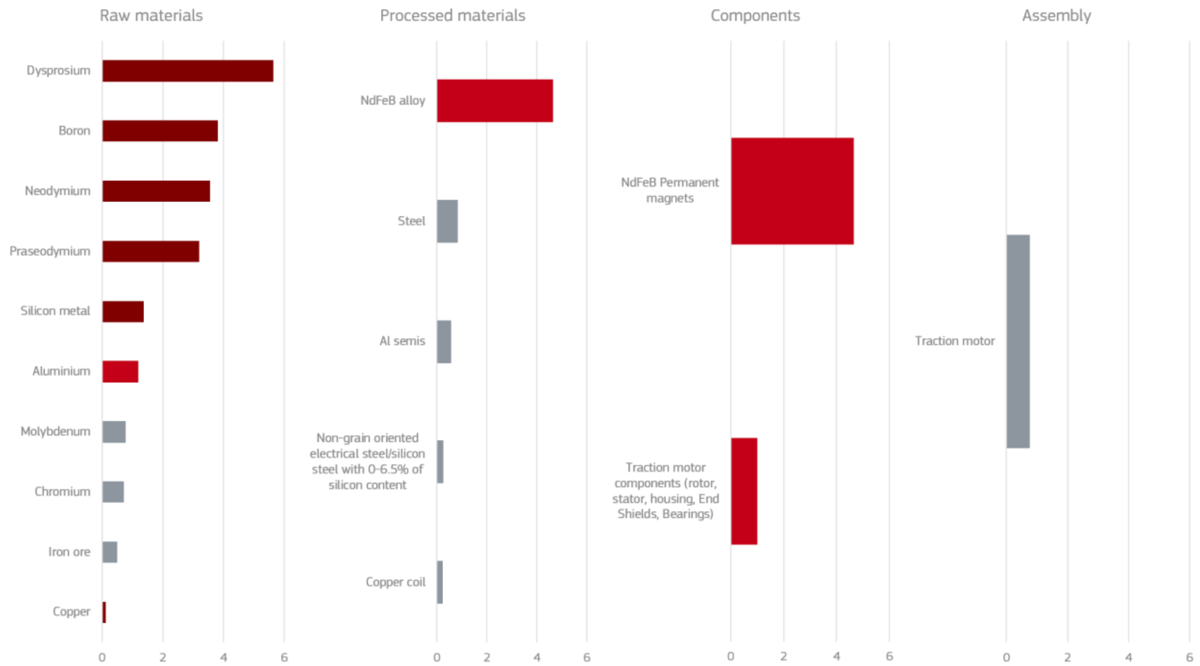
Figure 37. An overview of supply risks, bottlenecks, and key players along the supply chain of traction motors



Source: JRC analysis.

[12] Original Equipment Manufacturers.

Figure 38. Detailed Supply Risk of all elements in the traction motors supply chain



Source: JRC analysis.

In terms of processed materials, the NdFeB alloy used to produce permanent magnets has the highest supply concentration, with 90% of global processing capacity located in China. The stator of a traction motor uses non-grain oriented electrical steel (NOES). There are different grades for this type of electrical steel. Of the over 11 million tonnes of NOES produced in 2020, xEV-grade NOES accounted for a total of 456 000 tonnes (IHS Markit, 2021). Electrical steel production is rather well distributed globally, in particular in Asia (88% in China, Japan, and South Korea), the US and the EU. The other processed materials such as copper semis, steel, and aluminium semis, have a low supply risk.

The components of traction motors assessed in this study are permanent magnets, stator, housing, end shields, bearings and rotors. The supply concentration of traction motor components is not high as OEMs claim to manufacture their components in-house at different percentages (Bellon and White, 2022). Permanent magnets are an exception. Most of the production of NdFeB magnet and powders tends to be located close to the processing sites since the transportation of magnet powders is challenging (Smith et al., 2022). China dominates the production of NdFeB magnets with an 85-90% share, the rest being produced in Japan (10%) and in the EU and US. A few European producers are found at different stages of the REE value chain, including alloy makers and magnet manufacturers in the EU that operate mainly from imported processed materials (EC, 2020).

Traction motors are the final output of assembly activities in this supply chain analysis and only cover those used in BEVs and PHEVs. The share of traction motors production by company and country was estimated and identified for each vehicle manufacturer. The EU share was approximately 20%, dominated by German car producers. In general, the manufacturing capacity of traction motors for EVs is not highly concentrated.

In China, the world's biggest market for EVs (50% share), BYD and many other OEMs are able to manufacture traction motors in-house. An analysis suggests that this situation has been possible because of the presence of the local, well-established aluminium diecast manufacturing industry, and China's hold on cobalt mining in the Democratic Republic of the Congo (Mobility Foresight, 2022). Many OEMs in Europe that were largely dependent on imports from Asia, are at the final stage of planning to set up motor manufacturing in-house[13] (Mobility Foresight, 2022).

[13] As reported, to-date for example VW's MEB platform is based on in house manufactured motors at European and Chinese factories.

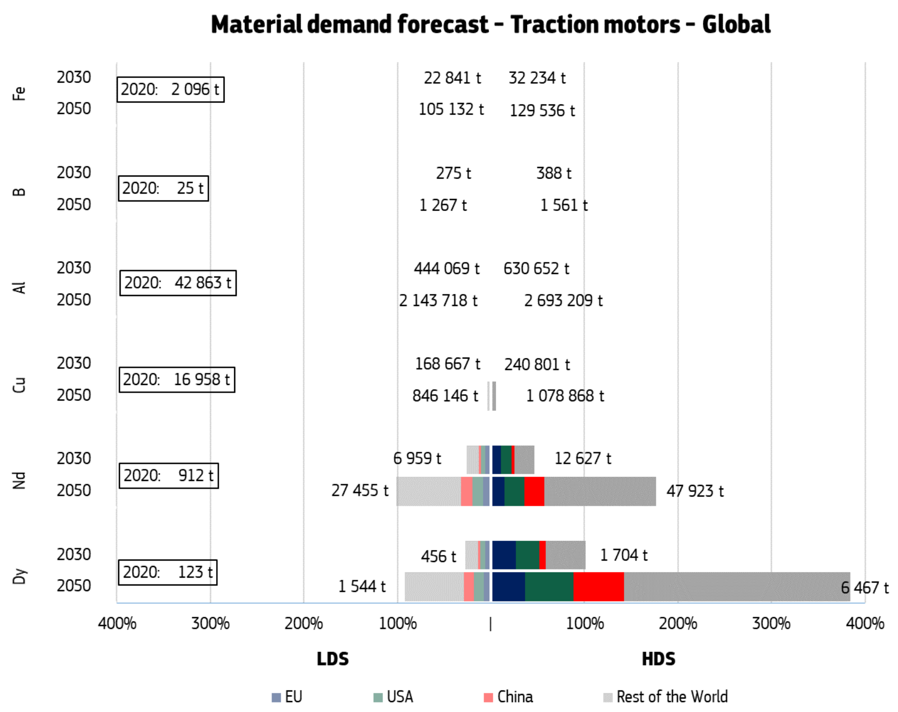
2.5.3. Projected 2030 and 2050 material demand

The raw materials demand forecast is an estimation based on the number of electric vehicles put on the market in the future and the raw materials content per vehicle[14], in line with the scenario of battery technology in e-mobility. This scenario only refers to e-mobility through electric vehicles, which cover BEVs and PHEVs. E-bikes account for a high share of the application of electric motors but are out of the scope of this assessment. Permanent Magnet (PM) motors are predicted to remain dominant and thus drive demand for the rare earth elements used in the magnets (The White House, 2021a). Given OEM announcements, the use of critical rare earths such as dysprosium and praseodymium is expected to be significantly reduced per vehicle due to the mining difficulty, price volatility and overall cost in comparison with other materials. An overall increase is expected in long-term demand (Edmondson et. al., 2022).

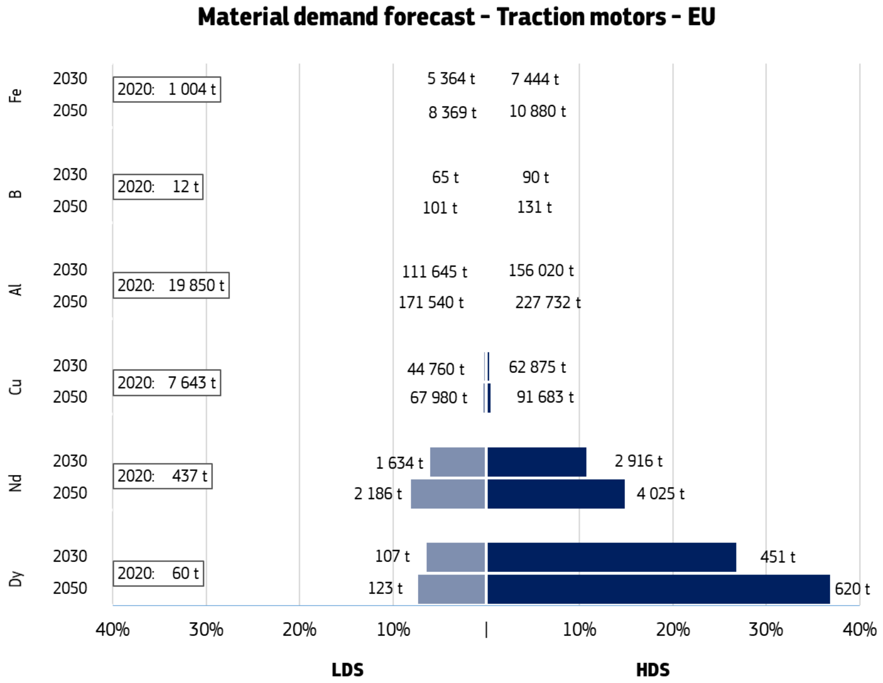
The assumptions used in the material demand forecasts for traction motor are the following:

- All PHEVs use PM motors, while 77% of BEVs are based on PM motors, and the remaining 23% are based on induction motors.
- High Demand Scenario: by 2030, demand for both neodymium and dysprosium will be 10% less than in 2020 and by 2050 it will be 15%. Low Demand Scenario: by 2030, demand for neodymium will reduce by 30%, and by 2050 by **40%, while for dysprosium the reduction will be 66% by 2030 and 75% by 2050, following the same assumption as the 2020 report** (EC, 2020). Both scenarios assume that the same functionality is kept. The assumptions concerning the reduction of materials in electric motors consider material efficiency improvement, dematerialisation through motor design and possible PM component substitution (EC, 2020).
- The quantity of **boron and iron in the magnet, and of copper and aluminium, remains the same, with no reduction by 2030 or 2050**.

Figure 39. Material demand forecast for traction motors: global (this page) and focus on the EU (next page)



[14] The material content used for this forecast is based on the study by Tilman et. al., 2020. The REE composition in the permanent magnet refers to the publication by Andre and Ljunggren, 2022.



Source: JRC analysis (Dy = dysprosium, Nd = neodymium, Cu = copper, Al = aluminium, B = boron, Fe = iron ore)

The Forecast shown in shows that compared to 2020, the EU demand for dysprosium and neodymium will grow by approximately 7 times by 2030 and 9-10 times by 2050. At global level, the demand for dysprosium and neodymium is expected to grow 14 times by 2030 and 53 times by 2050 with respect to 2020 levels. According to the high demand scenario, the annual demand for dysprosium and neodymium for traction motors in the rest of the world would be double or triple the 2020 level of supply. Regarding aluminium, boron, copper, and iron, despite a similarly high growth in global demand by 2050, the supply is less problematic than for REEs.

2.5.4. Geopolitical dimension

Sales of electric cars reached another record high in 2021 despite the COVID-19 pandemic and supply chain challenges. China and Europe accounted for more than 85% of global electric car sales in 2021, followed by the United States (10%), where they more than doubled from 2020 to reach 630 000 units (IEA, 2022). The success of EVs is being driven by policy support and the response of automakers to demand. China, the EU, and the United States have adopted key policies and measures that support the deployment of electric vehicles and zero emission vehicles (ZEVs) for light-duty and heavy-duty use (IEA, 2022). The growth of EV sales in China has been supported by government efforts to accelerate decarbonisation in the new Five-Year Plan (2021-2025) (IEA, 2022). In the EU, sales have been driven by tightening CO_2 emission standards, subsidies and tax benefits (IEA, 2022). Meanwhile, in 2021, several major automakers[15] announced plans to accelerate the transition to a fully electric future by developing new product lines as well as converting existing manufacturing capacity (IEA, 2022). Finally, five times more new EV models were available in 2021 than in 2015, increasing the attractiveness for consumers. In the United States, the increased production of Tesla models and the availability of next generation electric models by automakers have encouraged these sales (IEA, 2022).

The major players both upstream and downstream of electric vehicles, such as China, Europe, the United States, and Japan, have announced their strategies to secure their rare earths/magnets and electric vehicles supply chains.

Before the 1990s, the Chinese government encouraged the development of the upstream rare earths sector. China has established itself in the past two decades as the country with the highest processing capacity of rare

[15] These companies are among others, Toyota, Volkswagen, Ford, Volvo, Geely, BMW, Mercedes, General Motors, Stellantis, Hyundai, Kia, Dongfeng and BYD (International Energy Agency, 2022).

earths and at the same time a major consumer of them in manufacturing. Currently, the production of rare earths in China is held by a small number of state-owned companies, which may serve to further increase pricing power (Smith et al., 2022). Since 1 December 2020, under the Export Control Law, China has been closely monitoring its domestic needs and strategically securing access to rare earth sources worldwide, including deposits in California, Madagascar, and Greenland (Gauß et al, 2021). In addition to Chinese competitiveness in the NdFeB magnet sector, China also produces equipment to manufacture magnets that is about one third to one half the cost of western equipment (Smith et al., 2022). Since the early 2000s, China has shifted focus to downstream activities, with more concerns about environmental impacts and industrial reorganisation (Shen et. al., 2020). Downstream, China progressively decreased subsidies for purchasing EVs after tripling its sales figures in 2021 compared to 2020. China recently announced its ambition to develop sufficient charging infrastructure to meet the needs of 20 million new energy vehicles (NEVs, which include BEVs, PHEVs and fuel cell electric vehicles) by 2025. The 20% NEV by 2025 target was established in the Development Plan for the NEV Industry (2021-2035) (IEA, 2022).

The United States has set a new target to make half of all new vehicles sold in the country in 2030 zero-emissions vehicles, including battery electric, plug-in hybrid electric and fuel cell electric vehicles (The White House, 2021b). While China dominates each of the major stages in the supply chain, the United States currently has limited domestic production capacity for the sintered neodymium magnets used in wind turbines and electric vehicles (Smith et al., 2022). The importance of critical raw materials, including rare earths, has been recognised by the United States. Under the Biden administration, the United States has announced plans to expand domestic rare earth processing. The US Federal Government has launched initiatives to incentivise critical mineral development from secondary and unconventional sources, for example from coal ash[16] and other mine waste, reducing the need for new mining (The White House, 2022). In 2021, the government has also announced an investment project to separate and process heavy rare earth elements in Mountain Pass[17] (California), which is expected to produce enough magnets to power 500 000 EV motors annually (Sloustcher, 2021), (The White House, 2022).

Japan is the second largest magnet manufacturer after China. Japan has dominated expertise in magnet production, as demonstrated by their US and foreign patent applications (Smith et al., 2022). Patents have provided a significant barrier to entry for new magnet producers. For example, Japanese company Hitachi holds patents that cover the standard techniques for producing sintered magnets, making it difficult for new magnet producers without a Hitachi license. The patents owned by Japanese companies have helped to keep Chinese magnet producers from flooding the Japanese domestic markets (Smith et al., 2022). Japan imports approximately 60% of its requirements for rare earths from China (ANRE, 2020). In 2020, Japan announced its strategies in securing a stable supply of rare earths, such as supply diversification, securing emergency reserves domestically, and promoting international cooperation for the enhancement of supply chains in mine development, smelting, and product manufacturing (ANRE, 2020).

Although not considered critical, there have been some disputes regarding electrical steel in the United States. Electrical steel is considered a critical material for its role in modernising electrical grid infrastructure and transitioning the country to clean energy. An investigation by the US Commerce Department completed in October 2020 stated that the country's reliance on imports is a potential threat to national security. The US government applied import tariffs (Erickson, 2022).

Intellectual property/patenting related to electrical steel technology has also been a source of conflict. For example, in October 2021, Nippon Steel sued Toyota and Baoshan Iron and Steel (Baosteel), a subsidiary of the state-run China Baowu Steel Group, which is the largest steelmaker in the world. Nippon Steel claims the steel supplied by Baowu to Toyota for its hybrid motor cores violates its patents on composition, thickness, crystal grain diameter, and magnetic properties (Vititori et. al., 2021).

2.5.5. Key observations and recommendations

Globally, demand for electric motors will continue to grow as governments move towards phasing out petrol and diesel cars. The permanent magnet-based electric motor will continue to be the preferred technology due to its size and high performance. The supply risk related to the REE in permanent magnets will remain the most

[16] Funded by the Bipartisan Infrastructure Law (BIL)

[17] In autumn 2021, MP Materials announced the construction of a rare earth metal, alloy and magnet manufacturing facility in Texas and a long-term supply agreement with General Motors to power the motors (Sloustcher, M., 2021)

important issue for traction motors. Several key recommendations were already presented in the previous Foresight Study of 2020 (EC, 2020), and more detailed in the chapter on wind turbines:

- **The diversification of REE supply**, for example through strategic trade partnerships with resource-rich countries (Gauß et al., 2021).
- **Improving manufacturing opportunities of REEs and permanent magnets in the EU.** Developing capacity in the processing of REEs and manufacturing of PMs are important, as these stages might influence later stages of the value chain, including motor design.
- **Promoting recycling and reuse** of electric motors to make sure that end-of-life products containing rare earths stay in Europe. This can be achieved by introducing and implementing regulations and standards that facilitate the reprocessing and recycling of products (Gauß et al., 2021). Currently the majority of these 'scrap' flows are exported to Asia (EC, 2020). The Joint Research Centre is currently investigating further requirements on e-drive motor removal prior to shredding in order to establish prerequisites for permanent magnet recycling. These measures will contribute to the establishment of recycling infrastructure and the promotion of secondary market materials in the EU (JRC, 2023).
- **Defining standards and certification schemes** for more sustainable rare earth magnets and motors, for example through ecodesign requirements that set higher levels of reuse, remanufacturing and recycling, and the increased use of recycled content in new products (EC, 2020).
- **Promoting R&D investment** to incentivise efforts to better understand rare earths extraction, processing, recycling, and materials design. Innovation in materials and processing must be combined with innovation in optimising rotor geometries of traction motors to increase motor efficiency (Gauß et al., 2021).

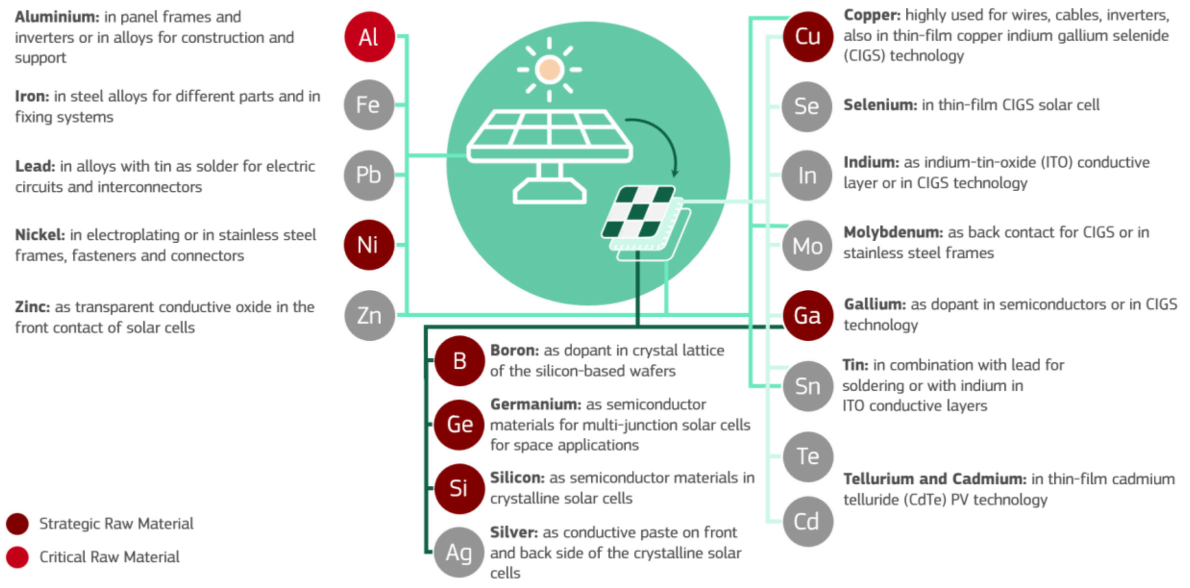
2.6. Solar photovoltaics

2.6.1. Introduction

Solar energy converted to electricity by photovoltaic (PV) technology is anticipated to play a major role in the transformation of the world's power markets. The cost of PV energy has decreased over time thanks to technological advancement, economies of scale, and manufacturing expertise, which has significantly increased global deployment. This technology will also play a crucial role to meet 2050 climate and energy targets and to phase out fossil fuels.

The REPowerEU Plan means a further increase in demand for silicon-based solar modules and the critical raw materials needed to produce them, compared to the Fit-for-55 path for solar technologies. The overall net capacity is expected to reach 592 GW by 2030[18] (EC, 2022). A selection of the most common raw materials used in solar PV technology and their functionality can be found in Figure 40.

Figure 40. Selection of raw materials used in solar PV and their function



Source: JRC analysis.

The analysis here is focused on commercial PV technologies that are already available and have the potential to remain relevant in the solar PV industry. These include wafer-based crystalline silicon (c-Si) (either mono-crystalline or multi-crystalline silicon), as well as thin films made of copper indium gallium (di)selenide (CIGS) or cadmium telluride (CdTe). According to Fraunhofer ISI and the IEA, c-Si solar modules account for around 95% of the world's installed PV capacity, with thin film modules making up the remainder. Because CdTe and CIGS can be placed on flexible substrates, they are appropriate for unconventional or building-integrated PV applications.

Amorphous silicon cells are used in some small-scale and low-power applications (Jean et al., 2015) and are currently being phased out. They are not considered here. A vast array of new PV technologies with high potential is currently being developed, e.g. organic tandem cells (cheaper production, semi-transparent but with low efficiency), inorganic tandem III-V multi-junction cells (typically adopted for space or military applications due to their high prices), hybrid devices at the nanoscale level, perovskite cells and multilayer and tandem silicon-perovskite and silicon-CdTe hybrids (these technologies can raise the efficiency to more than 30% and with mass manufacturing could achieve competitive production costs).

[18] In this section, all capacity values are in AC (alternating current) unless indicated otherwise.

According to the latest Clean Energy Technology Observatory (CETO) report, the average PV module efficiency increased from 9% in 1980 to 14.7% in 2010 and 20.9% in 2021 (JRC, 2022a, p3). Currently, c-Si photovoltaic modules are maintaining efficiency of 24% (and over), perovskites have 17.9% average module efficiency and 25.7% record cell efficiency, while "multi-junction technology, silicon-based tandems with III-V top material (32.65% module efficiency) together with perovskite-silicon tandem devices (31.25% module efficiency) are the two most promising and efficient technologies" (JRC, 2022a).

These new concepts show high potential for significant increases in efficiency and/or reductions in cost through improvements in device architecture and material functionality. In the coming years, especially after 2030, greater market shares are anticipated for some of these more advanced cell designs. However, every application is specific and tailored to address a specific issue, in other words there is currently no perfect all-round technological solar solution but a multitude of high-potential technologies with their pros and cons and respective suitability. This makes it increasingly difficult to make a reliable prediction for the longer-term (i.e. 2050 horizon) solar PV technology landscape, since it is one of the fastest developing fields in terms of increased efficiency and price reductions.

There are a number of R&I initiatives and tools at EU level that develop R&I projects to increase the efficiency, reduce the costs, enhance lifetime, and make major advances in manufacturing and installation. The Strategic Energy Technology Plan Implementation Working Group on Solar Photovoltaics (EC, 2017) and the European technology and innovation platform (ETIP) PV play a key role in this sector. The latter's Strategic Research and Innovation Agenda provides a roadmap to facilitate future European PV R&I advancements in: (i) efficiency of established technologies (crystalline silicon and thin films) and new concepts; (ii) reduction of the cost of key technologies; (iii) further enhancement of lifetime, quality and sustainability and hence improving environmental performance; (iv) enabling mass realisation of "(near) Zero Energy Buildings" (NZEB) by Building-Integrated PV (BIPV) through the establishment of structural collaborative innovation efforts between the PV sector and key sectors from the building industry; and (v) large scale manufacturing and installation (ETIP PV, 2022).

Manufacturing of PV systems requires various materials such as silicon metal, silver (used as paste to collect and transmit electrons, and create an electric current), silica (for high transmittance and resistant glass in PV modules), aluminium (for making the frames around the solar modules), copper (as conductor material in cabling, earthing, inverter, transformers and PV cell ribbons), indium, gallium, selenium, cadmium and tellurium (used in thin film cells). Germanium is used in tiny quantities, and for this reason, dependence on it is marginal for modules used in the energy market. Therefore, this material is not considered in the forecast for industrial solar PV energy applications. However, due to its qualities and performance, the material is key in solar applications for the space industry.

2.6.2. Current supply chain bottlenecks

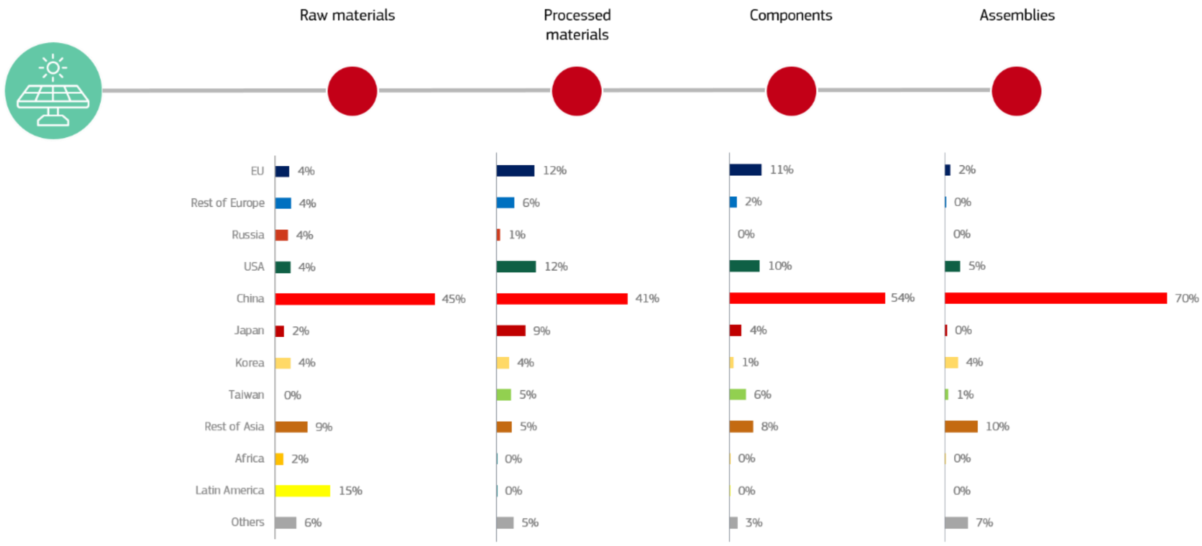
The same businesses usually make solar cells and modules. Manufacturers strive to make PV modules as efficient as possible while also cutting prices and material use. The potential to improve efficiency in upcoming commercial technologies is shown by the increased efficiency reached by PV cells in the lab. Due to the PV industry's anticipated high growth rates and market dynamics, manufacturers were required to investigate the reduction of silicon and other materials in the production process. Through the use of creative designs and material applications, this led to the development of new generation solar PV modules with lower material consumption and greater efficiency. Table 22 in Annex 2 lists the factors taken into account for each stage of the present analysis of the solar PV supply chain.

The rapid deployment of renewable energy in the EU and worldwide will put some pressure on the supply of certain relevant raw materials used in PV systems. Some of them have a high Supply Risk and are defined as CRMs for the EU, such as silicon metal, gallium and borates. Other raw materials such as silver, aluminium, as well as some of the elements crucial for the thin film technologies such as copper, indium, selenium, cadmium, and tellurium have a lower Supply Risk.

As hardly any PV cells are manufactured in the EU today, the increased demand for raw materials is reflected in the demand for the final products (i.e. the PV modules). If, however, the EU embarks on the largescale manufacturing of PV modules, it will be faced with the need to secure the necessary materials.

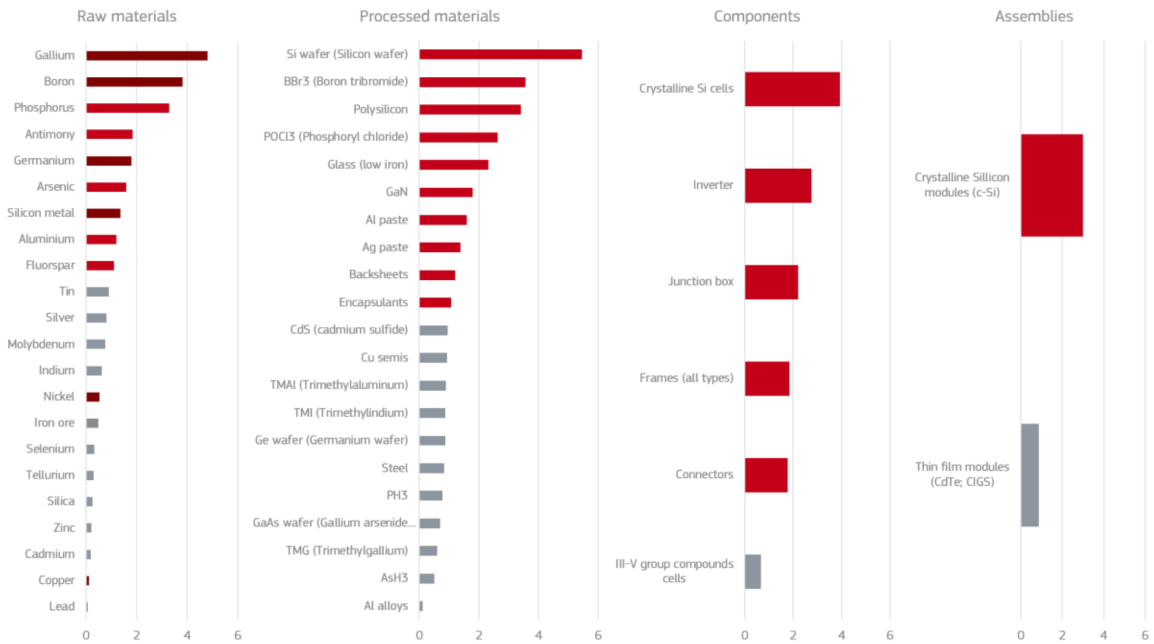
There is a significant supply risk along the whole supply chain, which is dominated by China. The resulting supply risk of the supply chain steps and key countries and regions are presented in Figure 41, while the detailed Supply Risks of the elements appearing in the supply chain are presented in Figure 42. The EU supplies 4% of the raw materials used in PV systems. Among all the materials, silicon metal is the most used material in photovoltaic cells. Many countries contribute to the supply of raw materials, but since China is the dominant player especially for silicon, this step has a significant supply risk.

Figure 41. An overview of supply risks, bottlenecks, and key players along the supply chain of solar PV[19]



Source: JRC analysis.

Figure 42. Detailed Supply Risk of selected elements in the Solar PV supply chain



Source: JRC analysis.

The risk factor for the processed materials required for thin films and c-Si differs significantly. Some producers of thin films are situated outside of China, resulting in a lower supply risk. China is the main producer of c-Si, and together with the technology's market share, this results in a high supply risk.

Another weak point in the PV technology supply chain is at the component level, where China also dominates the supply market. China's solar manufacturing capacity expanded significantly in the years after the 2008

[19] Note: For calculating the values for assemblies, an additional factor was added based on the 95% c-Si market share.

economic crisis, when the Chinese government implemented a solar PV feed-in tariff in 2011. The largest ten manufacturers by capacity for each part of c-Si cells supply chain represent over 90% of the total nameplate capacity production from polysilicon to wafer and more than 50% for cells and modules (BloombergNEF, 2022). In 2021, the list of top ten companies in terms of c-Si cells production include seven from China, one from Canada (Canadian Solar), one from the US (First Solar), and one from South Korea (Hanwha Q Cells) (Blackridge Research, 2022).[20] Most manufacturing plants of c-Si cells are in China, but also in Canada, South Korea, Taiwan, Malaysia, Singapore, Vietnam, India and the US.

According to the IEA, the EU manufacturing capacity for c-Si cells accounted for only 0.6% of the overall global production in 2021, particularly in Germany, with a few small manufacturers in Italy as well (IEA, 2022a). A slightly higher proportion of solar modules based on both silicon and thin-film is registered in the EU, although the main production is usually located in Asia. Germany, Italy and France have some small manufacturing capacities.

After China, Germany is one of the largest polysilicon manufacturers, with Wacker Chemie the leading company. However, this key material is then exported for further processing to China, which has a monopoly on the ingot- and wafer-making processes, which are the steps prior to the solar cell manufacturing process (see Figure 46). Although the EU is home to many solar module manufacturers, most of them import solar cells from Asia. The EU's trade deficit for modules, cells and components went from over EUR 6 billion in 2020 to over EUR 9 billion in 2021, with China supplying over 75% of EU imports (JRC, 2022b).

According to the European Climate-Neutral industry Competitiveness Scoreboard (CIndECS), Germany, the US, Japan, China and South Korea host almost 70% of identified innovators, while the EU as a total hosts 23% of innovators in the PV field. In particular, Germany is fourth behind the US, Japan and China among the world's leading countries in terms of innovation (JRC, 2022b).

In terms of other PV system components, the most significant are the inverters which convert the variable direct current output of a solar module into the alternating current used in the grid. After a three year period of having a considerable share in the inverter market, the two largest EU players in this segment – SMA (Germany) and Power Electronics (Spain) – have grown less than other companies from China and have therefore not maintained their competitiveness in 2021. The European companies reduced their market share from 14% in 2018 to 11% in 2021. In addition, the EU is dependent also on imports for the chips needed for the production of inverters. Thus, even though the market potential for this technology in Europe is very high, the global market is concentrated, with the top 10 producers representing over 85% of the volumes and EU manufacturers lagging behind the Chinese leaders.

The EU as a total, and each individual Member State, exhibited a negative relative trade balance between 2019 and 2021. The EU's extra-EU imports increased by 14% between 2015 and 2021, while for the same period, its exports decreased by 6% (JRC, 2022a).

2.6.3. Projected 2030 and 2050 material demand

Figure 43 shows the total solar PV capacities installed from 2000 to 2020 and projections until 2050 in the EU, US, China, and globally according to the two considered scenarios.

The solar PV capacity worldwide in 2020 was 710 GW. Among the considered regions, China was the one with the highest net installed capacity of 254 GW, while the EU came in second with 136 GW, followed by the US with 74 GW.

Both scenarios foresee an expansion of this technology, although at a different pace. In the LDS, the growing trajectory broadly follows the latest years' trend, while the HDS considers a stronger expansion to meet the ambitious energy and/or climate change mitigation targets. More specifically, for the EU, the LDS is taken from the official EU Reference scenario (EC, 2021), while the HDS is built considering the targets defined by REPowerEU for 2030 (EC, 2022) and by the Climate Target Plan for 2050 – MIX scenario (EC, 2020). Instead, data from the International Energy Agency's World Energy Outlook are adopted for the regions outside the EU. In particular, the "Stated Policies Scenario" scenario is adopted as LDS, while the "Announced Pledges Scenario"

[20] Note: In some cases, such as Canadian Solar, almost all of the manufacturing capacity of a company is located in China even though the producer is not Chinese and its share does not contribute to the Chinese production share.

scenario is adopted as HDS (IEA, 2022b). Similar to wind turbines, IEA values for the EU have been substituted by the EU values adopted in this work.

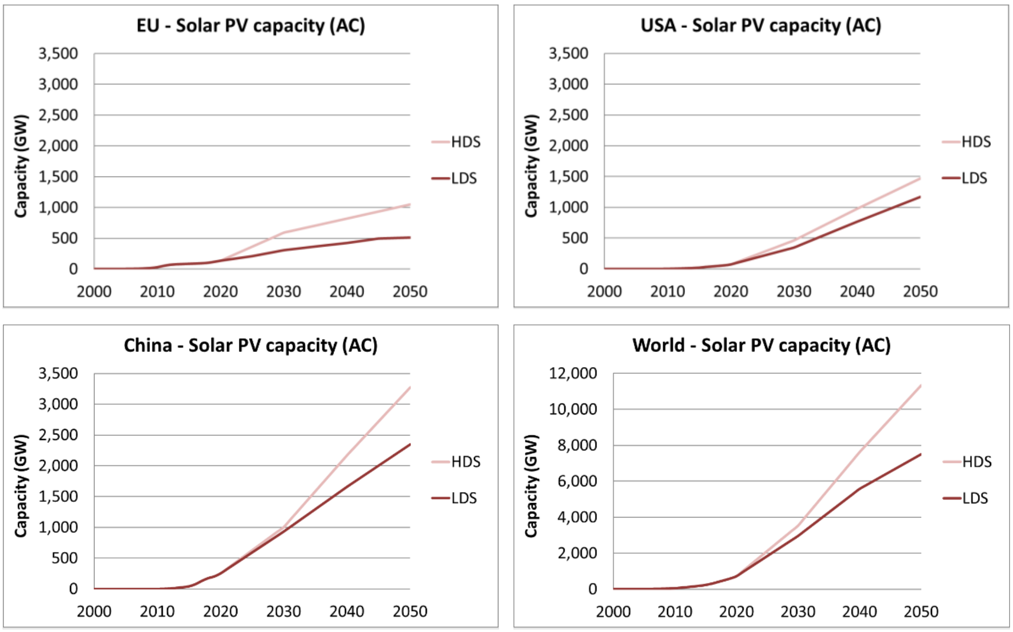
In 2030, the world is expected to reach 2 950 GW and 3 520 GW of installed capacity in the LDS and HDS, respectively; in 2050, 7 500 GW and 11 340 GW, respectively. The main share of this growth is expected to come from China, reaching 935 GW (in 2030) and 2 350 GW (in 2050) for the LDS, and 1 000 GW (in 2030) and 3 270 GW (in 2050) for the HDS.

When it comes to the EU, the two scenarios estimate quite different futures. The LDS reports 307 GW in 2030, while for 2050 the scenario anticipates around 514 GW. In the HDS, capacity reaches 592 GW in 2030 (the REPowerEU capacity target) and 1050 GW in 2050. In the US, the LDS projects 350 GW in 2030 and 1 170 GW in 2050, while the HDS projects 465 GW by 2030 and 1 470 GW by 2050, respectively.

In order to cope with these targets (notably the HDS capacity), annual deployment must considerably accelerate in the coming decades. Figure 44 reports the annual installations needed to reach these levels of the two scenarios. This would require considerable investment and an increase in production capacities along the whole supply chain globally as well as domestically in the EU. Globally, in the LDS the annual deployed capacity accelerates from the current 157 GW/yr to to 300 GW/yr and 470 GW/yr in 2030 and 2050, respectively, while in the HDS these would go up to 420 GW/yr in 2030 and 760 GW/yr in 2050, respectively. In the EU, the LDS implies a substantial constancy around 25 GW/yr over the considered period, while in the HDS the deployment effort should increase to 50 GW/yr in 2030 and 60 GW/yr in 2050, respectively.

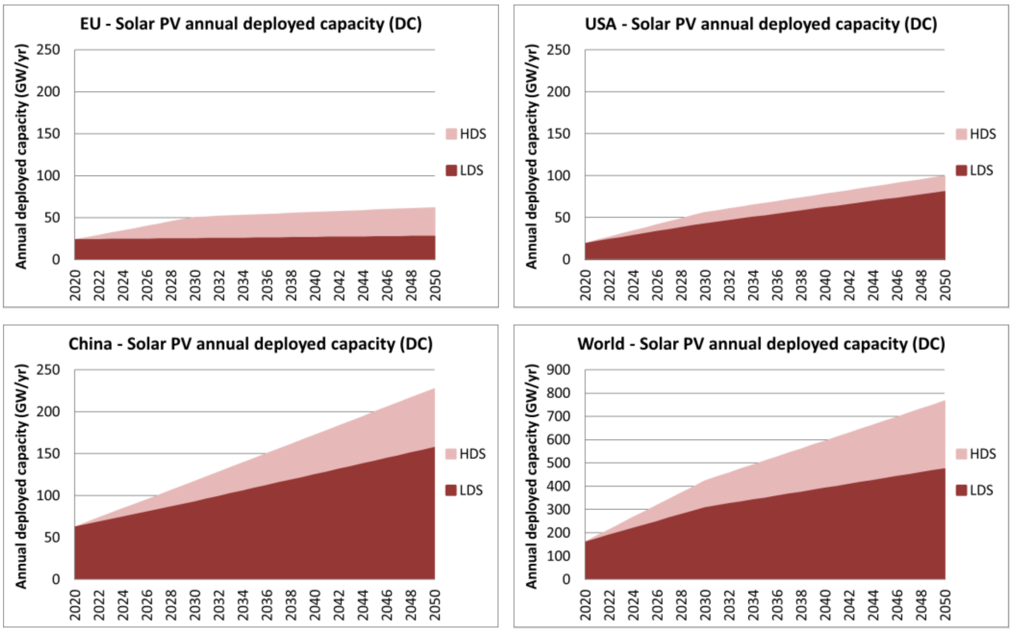
Unlike the capacities reported above, which are expressed in AC (alternating current), data on the annual capacity deployment show in Figure 44 are reported in DC (direct current). This is necessary because solar PV panels generate current in DC form, which is then converted in AC through an inverter before entering the electric grid. While the AC capacities are relevant for the energy balance in the grid, the material requirements depend solely on the installed capacity in terms of DC. In this work, we assumed a DC-to-AC ratio (also known as ILR, Inverter Loading Ratio) equal to 1.25, which means that the annual deployed capacities in AC which would derive from the installed capacities reported above are increased by 25% (Kougias et al., 2021).

Figure 43. Solar PV capacity in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis.

Figure 44. Solar PV annual deployed capacity in the EU, US, China, and globally in the two explored scenarios



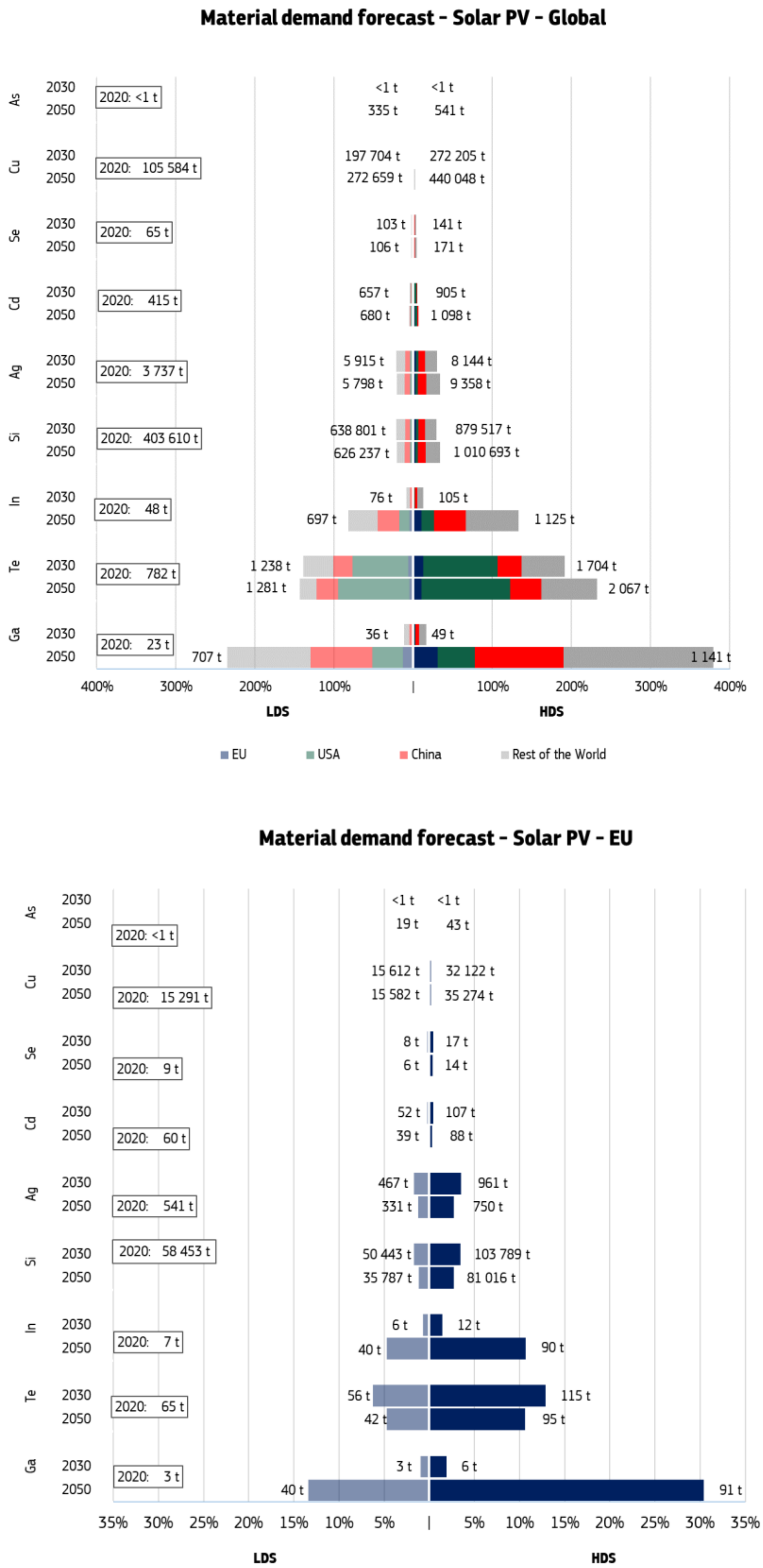
Source: JRC analysis.

Scenarios for the market shares are mainly based on the current technologies that are expected to maintain considerable share of the market in the coming decades. Specifically, c-Si remains the dominant solar PV technology. In addition, from the few assessed technologies, after 2030 the model foresees growth in new modules (notably, GaAs), whereas the other thin-film options already present in the market (i.e. CdTe and CIGS) are projected to remain relatively stable in terms of market share.

Assumptions for the material intensity are the same for the two scenarios. The material intensity slightly decreases over time for the general materials (i.e. concrete, steel, plastic, aluminium, copper, iron, molybdenum, nickel, and zinc), reaching 90% of the current value in 2050. For the specific materials used in c-Si and thin film modules, a 2% yearly reduction is considered.

Figure 45 shows the projected annual material demand for silicon and silver in 2030 and 2050 compared with 2020, followed by the projections for some selected materials needed for the thin-film modules. In the EU, silicon demand is projected to increase around 1.8 times until 2030 and up to 1.4 times until 2050 in the HDS (showing the effect of material efficiency and the emergence of alternative solar PV solutions).

Figure 45. Material demand forecast for solar PV: global (top) and focus on the EU (bottom)



Source: JRC analysis (Ga = gallium, Te = tellurium, In = indium, Si = silicon metal, Ag = silver, Cd = cadmium, Se = selenium, Cu = copper, As = arsenic)

2.6.4. Geopolitical dimension

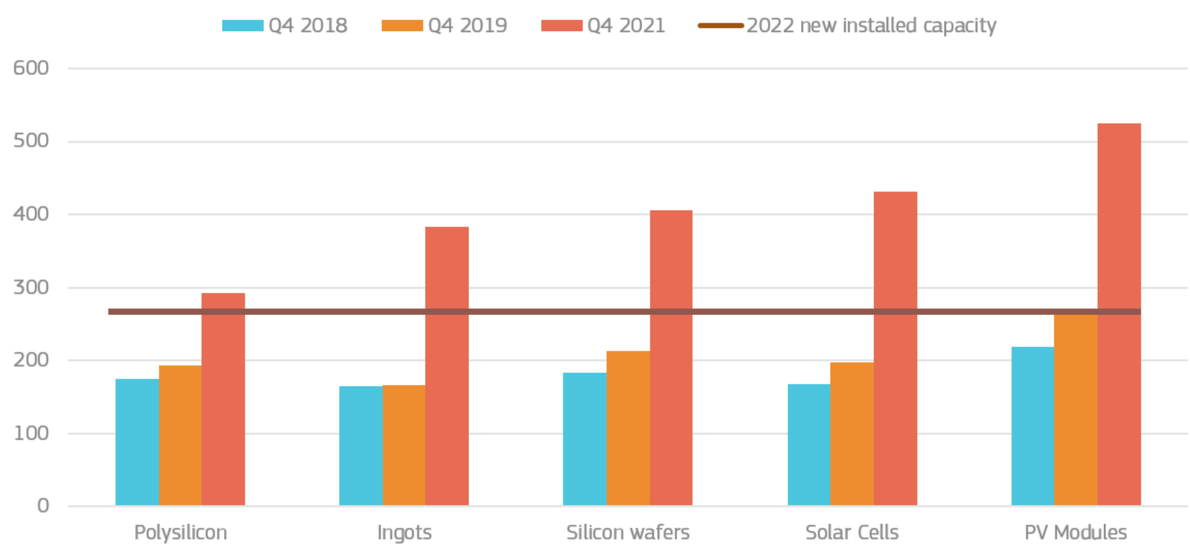
The EU's main trading partner and supplier is, and will remain for the foreseeable future, China. This **dependence on one main supplier country is a major bottleneck and could hamper planned deployment of the technology**, as seen in the COVID-19 crisis following the closure of a number of Chinese production facilities. A few companies in the EU are still able to produce small quantities of high purity gallium, germanium, boron and indium, but their number has been decreasing over the last decade.

The EU is a net importer of silicon embedded in the final products, as domestic production cannot satisfy demand. The processing of silicon is energy- and carbon-intensive, making it particularly difficult for the EU to compete in terms of global production. 68% of refined silver metal comes from domestic production within the EU; mainly from Germany, Italy, France and Belgium. Switzerland, the US and the UK provide most of the imports (20%).

There were some challenges with silicon supply in the past due to a lack of development of new purifying facilities. Today, solar module **manufacturers are still concerned about potential polysilicon shortages and price instability**. In fact, after a spike in 2017, the price of polysilicon was going down until mid-2020. This was followed by soaring prices for two years until the end of 2022 and a consequent decrease at the beginning of 2023 (Denning, 2023). In 2021, the prices more than quadrupled for a year as surging demand for new solar power outpaced production capacity and caused developers to delay projects (Bloomberg, 2021). This was largely caused by the COVID-19 crisis and the closure of some factories in Asia. However, according to Bloomberg projections, since then, "production capacity has increased by almost a half and, importantly, if all new projects announced or under construction materialise, it would expand by a further 164%" (Denning, 2023). The new capacities were partly responsible for triggering the big reduction in the price of the material but also highlight China's fundamental dominance of the solar sector. The country "accounts for 80% of current polysilicon capacity and virtually all of the projects under construction or planned" (Denning, 2023).

Thus, following political stimuli (i.e. the US Inflation Reduction Act) that ease the downstream issues of the supply chain, there are announcements for the planning of solar modules factories in the US and potentially in Europe (e.g. the EU Solar Strategy). However, for the foreseeable future, they will continue to depend largely on polysilicon from China. According to Bloomberg, this dependence is largely due to the unit capital expenditure requirements for polysilicon production in Europe and the US being more than 3.5 times those of China, which makes it very difficult to build competing supply chains (Denning, 2023).

Figure 46. Global year-end silicon PV supply chain manufacturing capacity versus 2022 global new installation (in GW/year)



Source: JRC analysis based on BloombergNEF, 2022 and Enkhardt, 2022.

In 2022, the solar PV industry produced more than 300 GW of modules, which is an "incredible 45% year-on-year increase compared to 2021" (Colville, 2022). While the actual 2022 global PV capacity installation figure hit more than 260 GW (see Figure 46), the expected new build capacity in 2023 would grow to 316 GW worldwide and 48 GW in Europe according to Bloomberg (Enkhardt, 2022). **China remains the clear leader when it comes to manufacturing abilities for the main solar PV technology.** In 2022, the country produced 90% of polysilicon, 99% of wafers, 91% of c-Si cells and 85% of all c-Si modules (Colville, 2022).

After several European manufacturers announced their intention to increase their production capacities, the landscape of large-scale production in the EU is beginning to change. In Germany, Italy and France there are plans for strengthening the position in the global market for heterojunction technology (HJT) modules with several new manufacturing capacities being announced in the coming years. Some of the largest announced capacities also include the construction of a 5 GW production of monocrystalline silicon wafers for PERC cells in Seville by the Spanish start-up Greenland, in collaboration with Fraunhofer Institute (ISE) and Bosch. The details of the already-announced production facilities are presented in Table 4.

Table 4. Solar PV production facilities announced in the coming years.

Company	**Plant location**	**Actual plant capacity**	**Manufacturing plans**	**PV Technology**
Meyer Burger	Freiberg (Germany) Thalheim (Germany)	400MW	1400 MW (cell) (2022) 1000 MW (module) (2022) 5000 MW (long-term objective)	HJT Heterojunction
Greenland Giga Factory	Sevilla (Spain)	-	5000 MW (module) (2023)	PERC
Enel Green Power	Catane (Italy)	200 MW	3000 MW (cell & module) (2024)	HJT Heterojunction
REC Solar	Hambach (France)	-	2000 MW (module) (first stage) 4000 MW (module) (2025)	HJT Heterojunction
Solarge B.V.	Eindhoven (Netherlands)	-	300 MW (module) (2022)	PERC
Kioto Energy	St. Veit/Glan (Austria)	150 MW	450 MW (module) (2022) 750 MW (module) (2023)	Mono c-Si Mono c-Si bifacial
Saule technologies	Wroclaw (Poland)	Pilot production line	100 MW (module) (-)	Perovskites
Oxford PV	Brandenburg an der Havel (Germany)	Pilot production line	200 MW (cells and modules) (-)	Perovkite-c-Si

Source: adapted from JRC, 2022a.

2.6.5. Key observations and recommendations

The REPowerEU Plan foresees an overall net capacity by 2030 of almost 600 GW. Given the current trend of installing 1.25 to 1.3 times the AC capacity in DC, this would bring the total nominal PV capacity in the EU to approximately 740-770 GWp. Compared to previous years, this would require a significant annual market volume increase annually by 2030, which can be achieved if the current market trends are maintained.

However, the ramp-up of the annual market in the EU requires a focus on material efficiency as well as risk-hedging to avoid disruption of the international supply chain. To achieve this, it is necessary to establish and strengthen a European value chain capable of supplying between a quarter and a third of the annual European market. This is currently possible for the production of polysilicon, backsheets, contact materials, inverters, and the equilibrium of system components. However, new production capacities are needed for solar glass, wafers and cells (JRC, 2022a).

New advancements in photovoltaics will be critical in the coming years, both to meet the EU's climate targets and to encourage the emergence of competitive new European industrial players and clusters producing higher value products capable of relocating an increased share of the PV supply chain in Europe. To this end, strengthening European R&I efforts and increasing manufacturing capacities for key steps in the supply chain will be key.

Finally, a number of strategies can be implemented to mitigate risks along the supply chain:

- **Diversification of materials supply** by strengthening existing supply partnerships and forging new partnerships can ensure an undisrupted supply of materials. The price of polysilicon is growing due to market conditions and dominant suppliers, but the EU could further expand its own manufacturing capacity. A proportion of the EU's silver and glass needs could be covered by an increase in internal production and imports from trusted partners. Canada could supply almost all of the EU's electronics and PV import needs for germanium as well as a range of other CRMs. Ukraine has a number of CRMs that could play a crucial role in the closer cooperation and integration with EU energy markets.
- **Recycling and reuse** of solar modules is in its early days as the average lifespan for this technology is 30 years and the volume of end-of-life products is therefore still low. The recycling methods for solar PV exist, but the technologies for high-value materials recovery need to be improved. Developing these technologies and constructing dedicated PV module recycling plants could enable the recovery of a larger amount of materials, reducing the demand for primary materials and thus lessening the EU's reliance on imports. The European Waste from Electrical and Electronic Equipment Directive makes solar PV producers in the EU market legally responsible for end-of-life management.
- **More efficient use** of the main materials, such as silicon, silver and glass, thanks to recent progress in design and production techniques.
- **R&I efforts need to be strengthened** in the areas of increased efficiency and substitution strategies, by implementing new technologies such as **perovskite solar cells**, including perovskite/silicon tandem solar cells.
- **EU manufacturing capacity should be expanded** to create a strong domestic production value chain, especially for silicon ingot, wafer and cell segments, and to take advantage of rapid innovation in manufacturing techniques for increasingly sustainable PV products.
- **Policy measures** such as the new EU Solar Energy Strategy, the European Solar Rooftops Initiative, the European Solar PV Industry Alliance, and simplified permitting procedures, will help create new business opportunities for developing European PV supply chains. In addition, in 2023, the Commission will propose two mandatory internal market instruments – an Ecodesign Regulation and the Energy Labelling Regulation – concerning solar PV modules and inverters sold in the EU.

2.7. Heat pumps

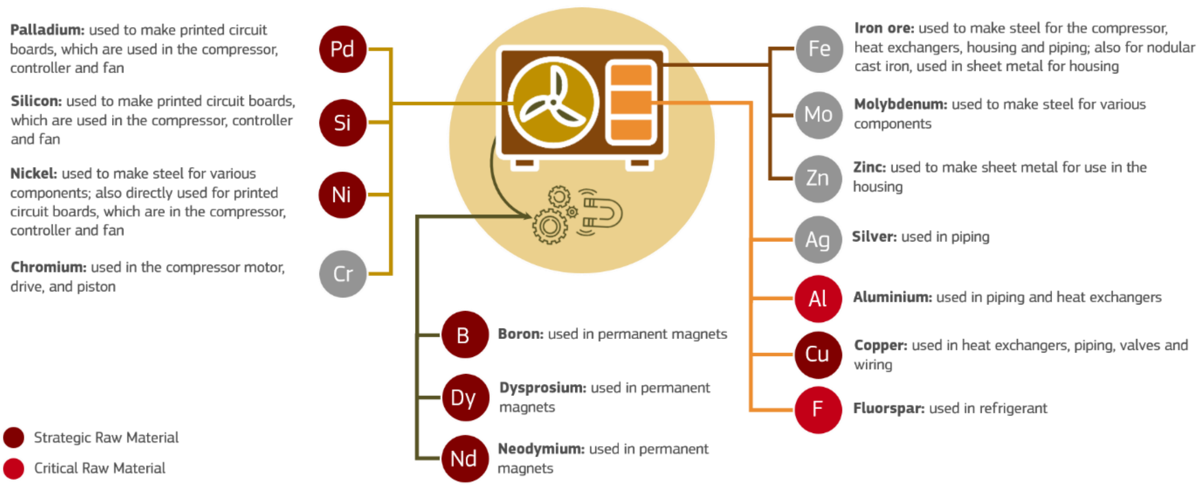
2.7.1. Introduction

A heat pump is a device that transfers heat from a lower temperature source, e.g. ambient air, to a higher temperature demand, e.g. a building, using a refrigeration cycle. In buildings, heat pumps are used for heating, hot water, and in some cases also for cooling. They can be deployed in individual dwellings, multi-dwelling buildings and district heating and cooling (DHC) networks. For a more detailed description of heat pumps in buildings, see JRC, 2022. Heat pumps can also be used for industrial applications, depending on the temperature (see Section 3.3).

Heat pumps are important because they are much more energy efficient than boilers; enable the greater use of renewable energy sources, ambient energy and waste heat; and can increase the flexibility of the entire energy system. Their use is promoted by a range of policies at EU and Member State levels, notably the REPowerEU Communication.

Heat pump systems can be classified by ambient heat source (air, ground or water) and whether they distribute heat using a) warm air (including via fan coils or air ducts) or b) hot water piped to radiators or underfloor heating (hydronic heat pumps). By far the most common types of heat pump use electricity and the refrigeration cycle to concentrate and move heat.

Figure 47. Selection of raw materials used in heat pumps and their function



Source: JRC analysis.

A heat pump system is generally comprised of a) a heat source system, which could be an air fan in the case of an air-source heat pump or a heat collector for ground- or water-source heat pumps, b) a heat pump unit containing two heat exchangers (evaporator and condenser), a compressor, an expansion valve and a controller c) a heat distribution (and in some cases storage) system.

The fan or heat collector sources low-temperature heat from the environment, which is then extracted by the evaporator using a refrigerant. The gaseous refrigerant is then compressed, raising its temperature, and this higher temperature heat is transferred via the condenser to air or water in the heat distribution system to provide space heating or hot water.

Heat pumps are manufactured from similar raw materials to the boilers they replace, and hydronic heat pump systems have comparable plumbing systems to boilers as well. Many components are also not specific to heat pumps, and sourcing is closely linked to related sectors such as boiler, air conditioning, and refrigeration manufacturing.

Compressors and housing (casing) are made from reinforced steel. Heat exchangers are made from low-alloyed steel (for a plate heat exchanger), copper or aluminium. Piping can be made of steel, copper or aluminium depending on the refrigerant used, and welded using silver. Electrical cables and expansion valves use copper. Pipework is insulated with an elastomer (ethylene, propylene or vinyl-chloride monomers) and cables are insulated with polyvinylchloride (PVC). Direct current (DC) inverters, DC pumps and DC fans all rely on printed circuit boards (PCBs) and semiconductors.

Refrigerants for compression heat pumps can be synthetically produced fluorinated gases (F-gases) or naturally occurring refrigerants such as ammonia, water, methanol, carbon dioxide or propane. A shift to natural refrigerants where possible is under way, as a result of industry implementing the F-Gas Regulation.

Large heat pumps (for industrial and DHC applications) are made from similar materials to smaller ones. However, materials may be used in different combinations and proportions depending on the temperature and refrigerant used.

Heat pumps can have another technology acting as a back-up in case of failure, to meet peaks, or to take advantage of variable energy prices. The most common back-up technology is an electric heater.

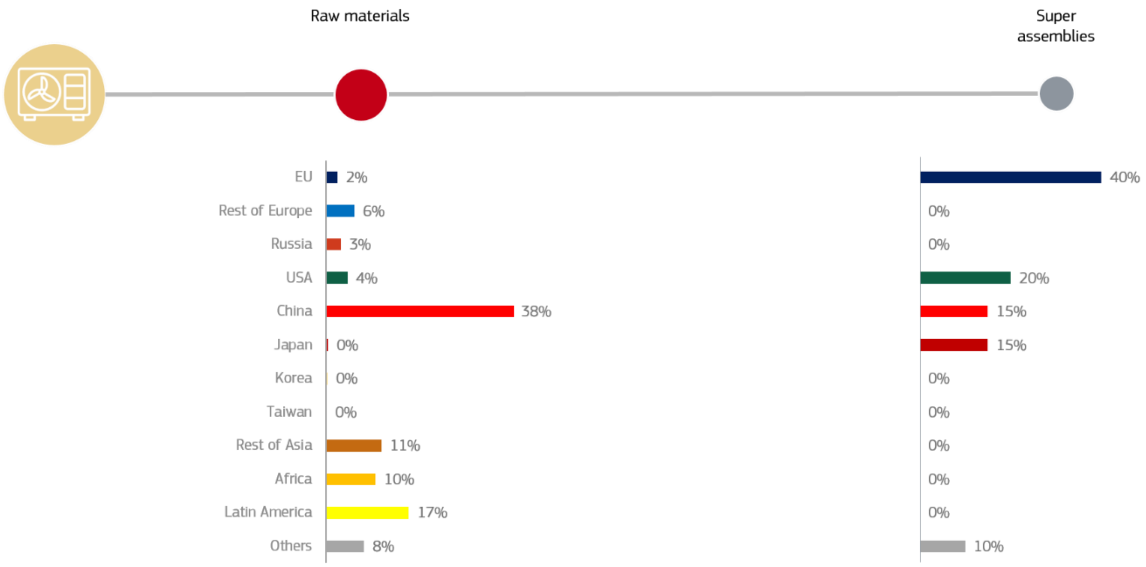
A so-called hybrid system is a heat pump combined with another technology, such as a gas boiler or solar thermal system, as a supplementary heater. Smart controls are used to operate and optimise such systems.

Finally, heat pumps can also be integrated with rooftop PV, thermal storage and smart controls. Such systems can take into account solar production to maximise self-consumption and respond to grid load signals for demand-side flexibility. Flexibility can also be provided through large heat pumps in DHC networks.

2.7.2. Current supply chain bottlenecks

Heat pumps do not have specific materials vulnerabilities but are vulnerable to volatility in metals prices and the supply of semiconductors (see discussion elsewhere in this report). More widespread integration of smart controls may exacerbate the latter vulnerability but is important in order to enable flexibility that increases comfort and contributes to energy system flexibility.

Figure 48. An overview of supply risks, bottlenecks, and key players along the supply chain of heat pumps



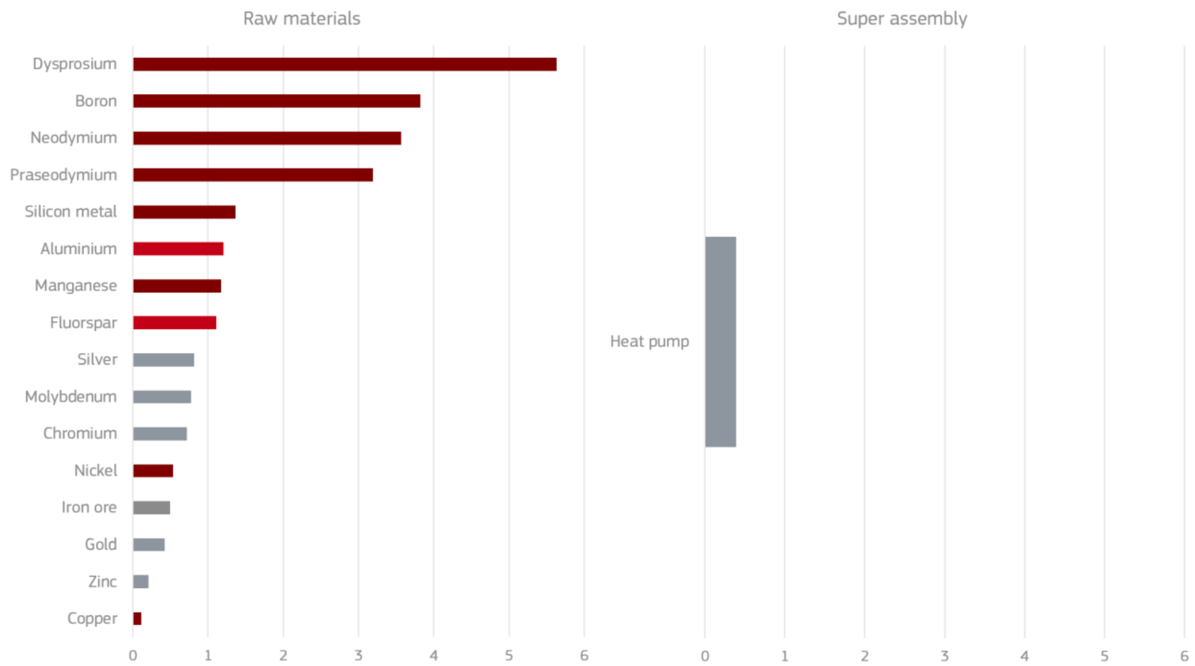
Source: JRC analysis.

Permanent magnets are a potential risk because there are few short-term solutions to a disruption to imports from China (also discussed elsewhere in this report).

In the longer term, recycling and substitution can be effective strategies. For example, to address volatility in the supply of semiconductors, manufacturers could revert to simpler designs, such as alternating current fans.

Bottlenecks not related to materials include the lack of trained installers and the availability of finance – both for households (for the up-front cost of purchasing the heat pump) and manufacturers (for the expansion and conversion of production lines). These issues are related to broader economic issues of labour shortages and rising interest rates in Europe. Supply has also been constrained by COVID-19 and by the very rapid rate at which demand is increasing, leading to lags in delivery. Sales for 21 European countries were up 34% in 2021 according to data from the European Heat Pump Association (EHPA).

Figure 49. Detailed Supply Risk of selected elements in the heat pumps supply chain



Source: JRC analysis.

2.7.3. Projected 2030 and 2050 material demand

The outlook for heat pumps sales is unequivocally strong, but the precise magnitude of that sales growth over long periods such as the 2030 or 2050 horizons remains highly uncertain. Figure 50 presents indicative high- and low demand scenarios (HDS and LDS) for heat pumps sales in the EU, the United States, China, and the world.

For the EU, the LDS is based on an initial growth rate of 8%, as seen in Europe in 2020 according to the EHPA. That data covers heat pumps used mainly for space heating and hot water. The HDS is based on an initial growth rate of 19%, as seen in 2019. In both cases, a declining growth rate is projected from 2030 onwards, as the market becomes progressively saturated and the lowest hanging fruit are picked.

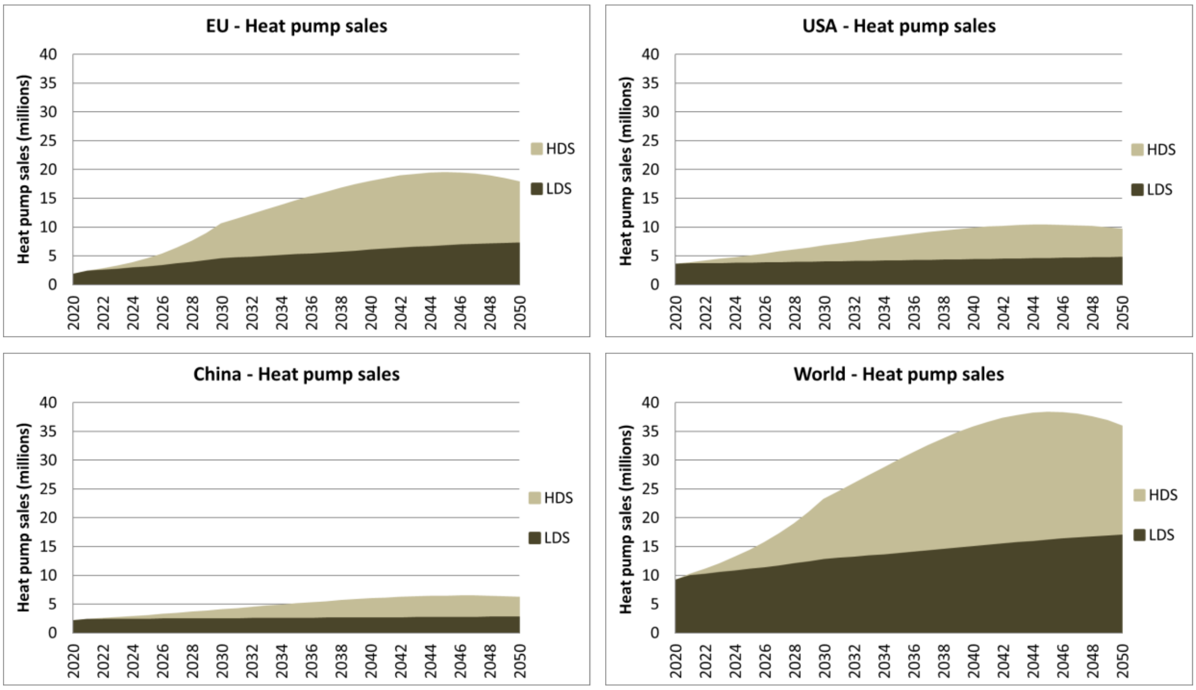
For the United States, both the LDS and HDS take as their starting point a 13% average annual growth rate seen for unitary air-source heat pumps over the period 2000-2020. Although largely comparable for the purposes of these charts, that data might also include a small share of heat pumps used mainly for space cooling, and exclude a small share of ground-source heat pumps. Lower growth rates are projected for the US market as it is assumed to be closer to saturation already. However, the recently announced Inflation Reduction Act might change this picture in an upward direction.

For China, both the LDS and HDS take as their starting point an initial growth rate of 12.6%, as seen in 2021 for air-water heat pumps. The growth rate is projected to decline due to saturation over the outlook period, albeit slightly slower than in the United States.

The projection for sales at world level above is the sum of the EU, the United States, China and the rest of the world – assumed at a quantity of 2 million in 2020, increasing slightly each year to 2050. For comparison, an International Energy Agency projection of 600 million heat pumps worldwide in 2050 under a Net-Zero scenario would fall roughly halfway between the LDS and HDS presented here. IRENA on the other hand projects just 290 million heat pumps in 2050 in a 1.5 scenario but from a much lower base (53 million in 2019), likely due to differences in which heat pump types are included.

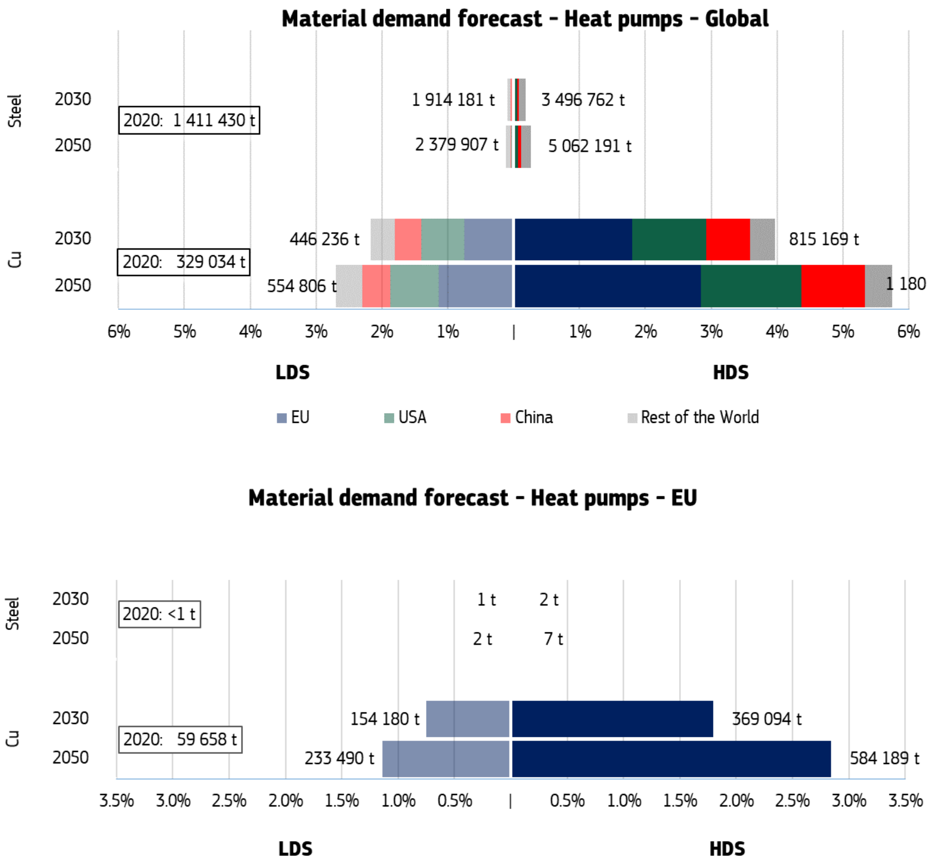
The projections above result in the outlook for materials demand for steel and copper shown in .

Figure 50. Heat pump sales in the EU, US, China and globally in the two explored scenarios



Source: JRC analysis.

Figure 51. Material demand forecast for heat pumps: global (top) and focus on the EU (bottom)



Source: JRC analysis (Cu = copper).

2.7.4. Geopolitical dimension

The geopolitical aspects of semiconductors and permanent magnets are discussed elsewhere in this report. Heat pumps do not need the most advanced chips so perhaps may be less severely affected. Regarding assembled heat pumps, most heat pumps sold in the EU are manufactured in the EU. Nevertheless, the EU trade balance turned negative in 2020 and imports from China in particular rose dramatically in 2021. It remains to be seen whether this was a temporary effect of the pandemic or the acceleration of a longer term trend.

The much larger air conditioning sector may target the EU heat pumps market, starting with air-air heat pumps but not limited to those. Meanwhile, many EU manufacturers of (notably air-water) heat pumps also manufacture other heating systems including boilers. It remains to be seen how quickly they are willing or able to convert their product development and production lines to heat pumps. It should also be noted that several competitor parent groups have EU subsidiaries carrying out manufacturing in Europe.

Technologically, the EU is a leader in heat pumps, in particular in ground-source and large heat pumps, and in the use of natural refrigerants. F-Gas refrigerant supply is dominated by China, so the more widely available natural refrigerants represent an opportunity to reduce that dependence. See JRC, 2022 for more detail.

2.7.5. Key observations and recommendations

Heat pumps are made of similar materials in type and quantity to the boilers they often replace, with the notable addition of a refrigerant. Heat pumps do not have specific vulnerabilities in terms of materials, but are vulnerable to volatility in metal prices and in the supply of semiconductors and permanent magnets (though perhaps to a lesser degree than for other technologies). Recycling and substitution will become important strategies as the market scales up, which it is doing very rapidly.

Bottlenecks are related to the need to rapidly expand production to meet demand, and the shortage of installers (related to the broader shortage of technical workers in Europe). Segments of the market might be targeted in the short term by air conditioner manufacturers from outside the EU. In the longer term and at the higher end of the market, the EU is a technology leader and might stand to take advantage of a shift towards more efficient heat pumps and heat pumps using natural refrigerants. Much may also depend on how business models and policies develop, and on developments at the installation stage of the value chain.

The following policy recommendations are proposed to strengthen the heat pump supply chain:

- **Statistics at national and Eurostat levels** should be improved to track and monitorthis fast-moving market.
- **Public investment in heat pump research and innovation** is currently at very low levels relative to other technologies and an urgent increase is required. Although heat pumps are a mature technology, further investment is needed in areas such as reduction of up-front costs, increased efficiency and plug-and-play business models.
- **The prioritisation of heat pumps in work on standardisation and interoperability** would increase their attractiveness to households, ensure a level playing field, and maximise system benefits from flexibility.
- While heat pumps are promoted as a key technology, it is important to **continue to maintain high ambition across related energy policy areas including renovation and district heating**.

2.8. Hydrogen direct reduced iron and electric arc furnaces

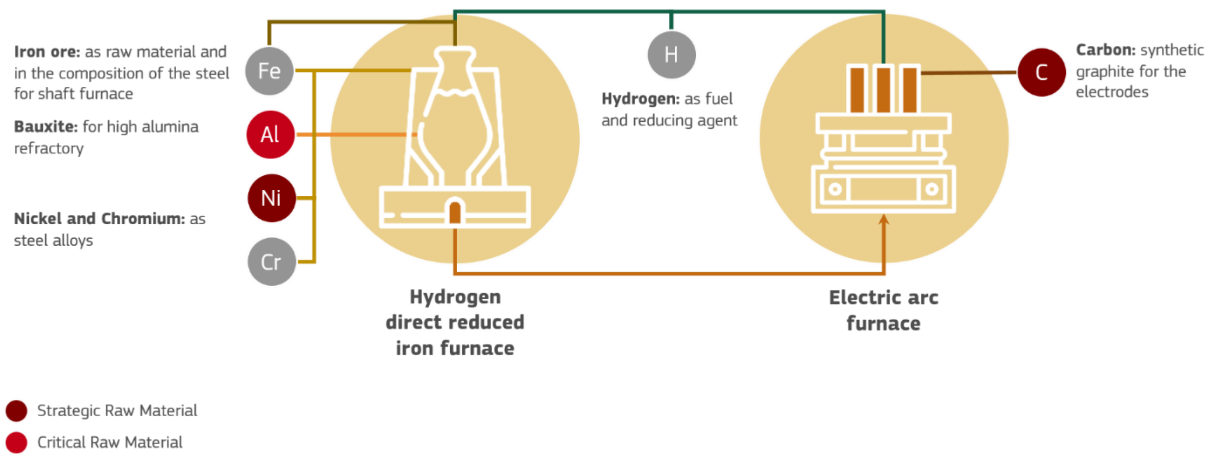
2.8.1. Introduction

The steel industry is an important sector of the EU economy, providing a key material for many other strategic technologies and industries. At the same time, the steel industry is a major CO_2 emitter, responsible for some 5% of all EU CO_2 emissions. If the EU's climate targets are to be met, a process transformation is mandatory.

Conventionally, there are two distinct steel manufacturing routes: the primary route and the secondary route. The **primary route** makes new steel from mined iron ore, while the **secondary route** uses mainly steel scrap to make recycled steel. The first stage of the primary route is the **ironmaking**, where iron ore is reduced to iron. This is taking place in a blast furnace (BF) using coke (refined metallurgical coal). The iron is then refined into steel in a basic oxygen furnace (BOF) by reducing its carbon content, removing impurities and adding alloying elements. This is referred to as **steelmaking**. The integrated BF-BOF route is extremely CO_2 and energy-intensive. In the EU, around 60% of crude steel is made via the primary route, with the remaining 40% made from recycled scrap metal in the secondary route. The scrap is melted in an electric arc furnace (EAF) by means of an electrical arc passing between graphite electrodes and the charged material, at temperatures of over 1 500 °C. The main energy input to this process is electricity, so secondary steel has a much lower direct CO_2 intensity than primary steel from the BF-BOF route. Currently, a high share of steel is already recycled in the EU. Maximising the share of secondary steel production is desirable, not least from an emissions point of view, but is limited due to the quality of steel scrap (mainly copper contamination).

Alternatively, iron ore can be reduced to iron by direct reduction (DR). In this process, iron ore is directly reduced to iron in its solid state at high temperatures (around 900°C, below the melting point of iron) in a reduction shaft furnace using a gas mixture of hydrogen and carbon monoxide obtained from reformed natural gas, syngas or coal gasification. The resulting direct reduced iron (DRI) is then melted into steel in an EAF with oxygen and lime to make steel. This DRI-EAF steelmaking route is already commercially deployed across the world and accounts for around 5% of global steel. The DRI-EAF process is primarily used in countries with abundant and cheap access to natural gas or coal, primarily in India and the Middle East, as well as Russia, Mexico and the United States. There is one existing DRI plant in the EU, located in Germany, which has been running since the 1970s. Hydrogen direct reduced iron (H2-DRI) builds on the existing DRI technology, but uses hydrogen gas feed to reduce the iron ore. If a low-CO_2 hydrogen source is used, this process can be close to CO_2-free. Figure 52 gives an overview of the most important raw materials used in H2-DRI and EAF.

Figure 52. Selection of raw materials used in H_2-DRI ironmaking and EAF steelmaking and their function



Source: JRC analysis.

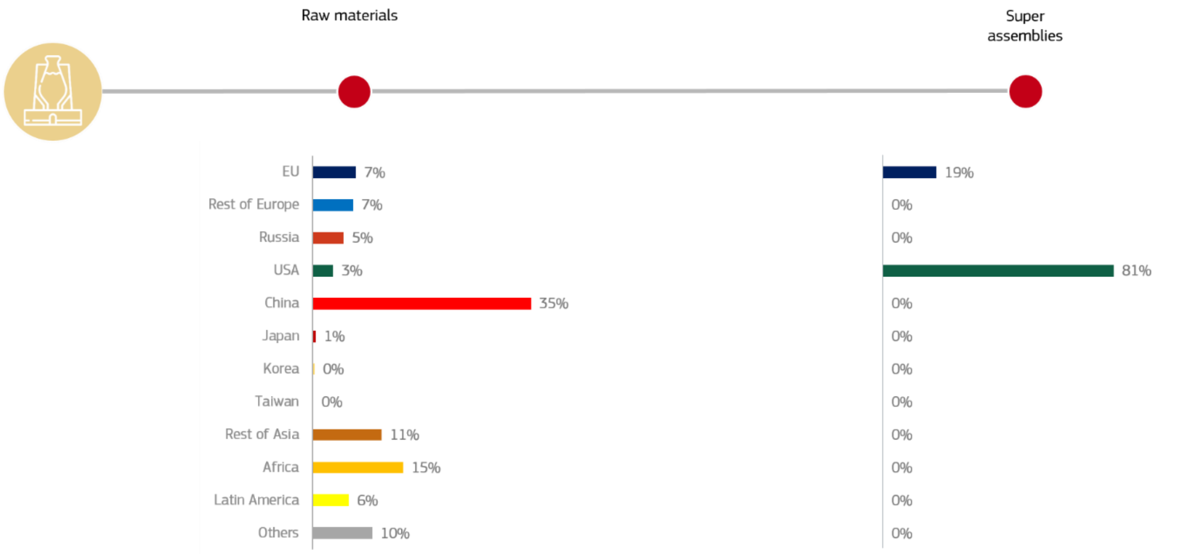
Currently, different types of technologies for DR processes are deployed across the world (shaft furnace, fluidized bed, rotary kiln) (Cavaliere, 2022). The most common one is the DRI shaft furnace technology, where the reduction of iron ore to sponge iron takes place in the presence of gaseous reductants in a shaft. Two different shaft furnace processes that are currently commercialised: the Midrex process, owned by the Midrex company, and the Energiron technology jointly owned by Tenova and Danieli.

Midrex has the dominating market share, accounting for around 80% of global DRI production in 2021 (Midrex, 2021). At the heart of both processes is a reduction shaft or reactor, several meters in diameter and over one hundred meters high, in which reducing gases flow in counter-current to iron ore pellets at around 900°C. In the Midrex process, natural gas (CH_4) is reformed in an external reformer to carbon monoxide and hydrogen on a nickel catalyst. In the Energiron process, the reforming of natural gas occurs in-situ within the shaft furnace, thus eliminating the need for an external reformer. Due to the in-situ reforming, the Energiron process claims that it can use hydrogen as the main reductant without any major modifications to the existing process scheme (Energiron). Besides the shaft furnace, the process gas heater is an important additional component, both for the Midrex and the Energiron process. Both processes are complex industrial plants with many additional installations and auxiliary facilities. To save energy and decrease capital cost, in 2007 German company MME implemented several special features to the Midrex process. The result was a new patented technology for DRI production called Pered. Currently, its market share is below 2% (Midrex, 2021).

2.8.2. Current supply chain bottlenecks

The key **assembly** at the heart of the DRI plant is the shaft furnace, where the iron ore reduction takes place. Other important **assemblies** include the process gas heating and the top gas recovery systems. As with any industrial process that circulates gases and heat, standard **components** such as compressors, pumps, fans and pipes are also part of the system. The **processed materials** used in the plant are materials that are commonly used in various industrial metallurgical or chemical plants. The direct reduction shaft furnace vessel is made of carbon steel and lined with high alumina refractory material. Heat and corrosion resistant nickel-chromium steel alloys are used for the cast pipes that are exposed to high temperatures. Other **raw materials** include iron ore and phosphorus, vanadium, silicon, chromium, manganese for steel and steel alloys, bauxite and natural graphite for the refractory lining. High grade iron ore (DRI-grade) is required as pellet raw material. The supply of DRI-grade pellets is limited. Ukraine, Brasil and Canada are the main suppliers of high-grade iron ore. There could be a potential lack of supply of DRI-grade pellets to satisfy future increasing demand (Doyle et al., 2021). This would require additional investment in iron ore beneficiating plants, the development of new high-grade ore mines or the development of technologies using lower DRI-quality ore. Six of the 14 raw materials required in DRI plants are deemed critical for the EU economy according to the 2022 CRM list (Figure 53).

Figure 53. An overview of supply risks, bottlenecks, and key producers along the supply chain of the H2-DRI ironmaking supply chain



Source: JRC analysis.

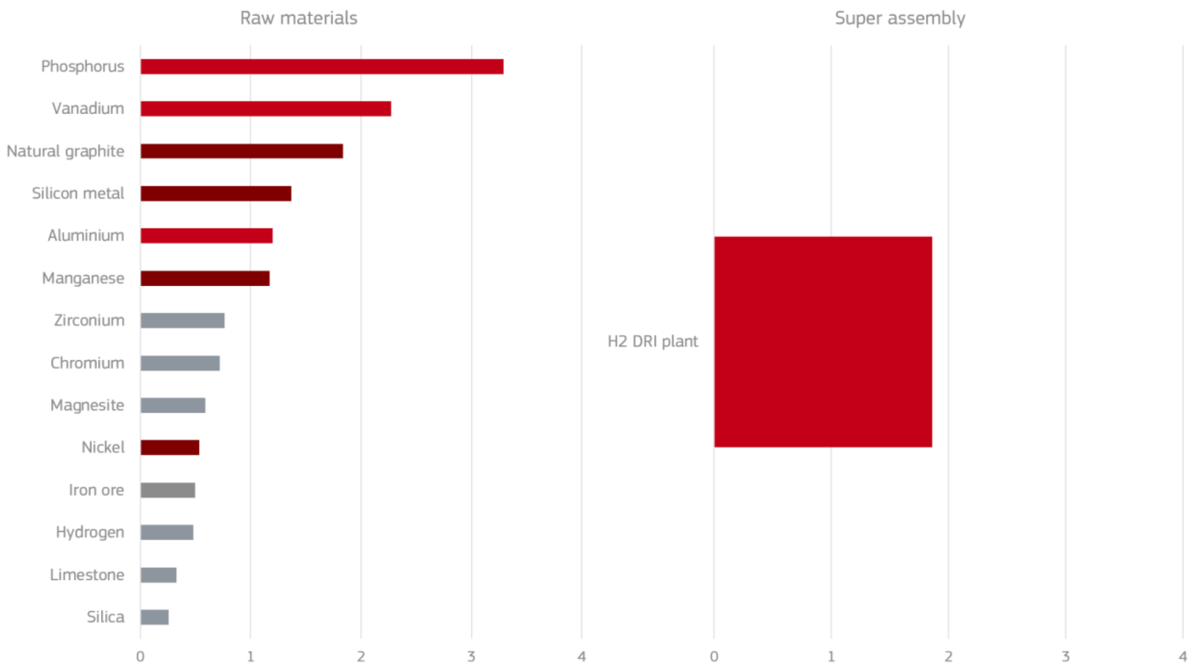
No critical supply chain bottlenecks were identified in the materials and components supply chain of DRI plants. However, in the raw material step, there are some materials which show a high supply risk. These are phosphorus (79% processed in China) and vanadium (62% sourced from China and 11% sourced from South Africa) used as steel alloys and natural graphite (65% sourced from China). Moreover, the DRI technology ownership is restricted to two companies: Midrex and Tenova/Danieli. Midex Technologies is a US-based company, which is itself owned by Kobe Steel, one of Japan's leading steelmakers. The other DRI technology, HYL Energiron, is jointly owned by Tenova and Danieli, two Italian companies. Midrex currently has the largest market share in globally installed DRI facilities, however several European steelmakers have contracted Tenoval/Danieli with respect to pilot 100% hydrogen-based DRI pilot plants.

If the primary steel capacity of the EU is to switch from the BF-BOF to the DRI route, it is likely that a number of EAFs will also need to be built. EAFs are extremely widespread and commercially mature, with around 150 plants in the EU alone. Graphite electrodes are an important part of the EAF value chain and a potentially critical component during the operation of the EAF. Graphite electrodes are used as electricity conductors inside the EAF to create the electric arc that melts the raw materials. They are consumed throughout the steelmaking process, at a rate of 1.5 kg to 3 kg per tonne of steel (JRC, 2017). Thus, the demand for graphite electrodes is directly correlated to the amount of EAF steel being produced. Long-term growth demand of EAF steelmaking (via secondary route steelmaking as well as new natural gas and hydrogen DRI-EAF) will result in an increased demand for graphite electrodes. Graphite electrodes are made of synthetic graphite, which is produced from the refining of petroleum coke, needle coke and pitch coke. Synthetic graphite is a key material for lithium-ion battery anodes.

China has the largest global graphite electrode making capacity, followed by Japan, India and the US (BloombergNEF, 2021b). Several of the major global graphite electrode manufacturers (notably Tokai Carbon and Showa Denko of Japan, Graphite India Limited and GrafTech of the US) have subsidiary companies and production sites in the EU. EU and global (excluding China) graphite electrode production is very consolidated, and according to the EU steel association Eurofer, the number of producers servicing the global demand for graphite electrodes is less than ten (EC, 2020). The drive towards decarbonising the steel industry, not just in the EU but globally and especially in China, could increase the demand for graphite electrodes in the future and could lead to a possible graphite electrode shortage in the future (Fastmarkets, 2021).

One of the prerequisites for the deployment of hydrogen-based DRI will also be the availability of large amounts of renewable hydrogen and the deployment of renewable energy solutions. In this regard, there is a clear **synergy between this steelmaking technology and other technologies** assessed in this report, notably **electrolysers, wind power and solar PV.**

Figure 54. Detailed Supply Risk of selected elements in the H2-DRI ironmaking supply chain



Source: JRC analysis.

2.8.3. 2030 and 2050 technology prospects

Although natural gas-based DRI is a common and widespread manufacturing process, **there are currently no commercial DRI plants operating with a 100% hydrogen feed.** The most advanced project developing the use of 100% renewable hydrogen-based DRI is the Hybrit partnership between the steelmaker SSAB, the iron ore miner LKAB and the utility Vattenfall in Sweden, which produced the first batch of fossil-free steel from its pilot plant in 2021 (SSAB, 2021a). Pilot and demonstration plants using 100% hydrogen have been announced in the EU for both types of shaft furnace technologies, including:

- a Midrex demonstration plant at ArcelorMittal's Hamburg site (Arcelor Mittal, 2019)
- The DRI installation in Gijón at ArcelorMittal Sestao (Arcelor Mittal, 2021a)
- the DRI demonstration plant being built by Energiron for the HYBRIT project in Gällivare, Sweden (SSAB, 2020), with demonstration plant operations to begin in 2026 (Olsson et al., 2020). For the same project, a DRI small-scale pilot for trilas was inaugurated in 2021 in Lulea.
- the Memorandum of Understanding (MoU) between German steelmaker Salzgitter and Italian plant builder Tenova to use the Energiron technology as part of the SALCOS project (Salzgitter, 2022)
- Energiron DRI plants used for the transition of Tata Steel Netherlands IJmuiden steel mill from the current BF to green-hydrogen based steel (Steel Orbis, 2022)
- H2 Green Steel will build the world's first facility for DRI running on 100% green hydrogen, based on Midrex's technology in Boden, Sweden (H2 Green Steel, 2022)

Since the DRI process is an entirely different technology to the current BF route prevalent in Europe, new direct reduction furnaces will have to be built if this technology is deployed. The largest direct reduction plants currently being built have capacities of up to about 2.5 Mt of DRI per year (Midrex, 2020). As a rough indication, to replace all 80 Mt of pig iron produced in the EU in 2019 (World Steel Association, 2020), assuming an 80% capacity utilisation rate of the steelmaking plant, would require around 40-50 new direct reduction reactors of 2-2.5 Mt of capacity to be built by 2050.

The European Commission did not release disaggregated data showing the trajectory of industry in its published scenarios. However, several recent external scenarios modelling the decarbonisation of EU industry by 2050 have been published. The deployment of DR plants depends on the future steel demand outlook, the development of other decarbonisation technologies, as well as the share of secondary to primary steel production. For instance, Material Economics modelled three 2050 decarbonisation pathways that focus on different solutions: New processes (H2-DRI), material efficiency and circularity, and carbon capture technologies (Material Economics, 2019). In the New Processes pathway, total steel production remains at 181 Mt in 2050 (EU27+UK) with H2-DRI amounting to 63 Mt of steel production, while in the circular economy pathway steel production stands at 139 Mt in 2050 (EU27+UK), of which 97 Mt are via the secondary route and only 27 Mt are H2-DRI. In all scenarios, the deployment of H2-DRI technologies only starts post-2030. The Sustainable Development Scenario by the IEA sees a more modest deployment of H2-DRI, with around 10 commercial-scale plants (15 Mt of crude steel output) replacing existing BFs by 2050 (IEA, 2020). Other reports discussing global net-zero pathways for the steel industry (BloombergNEF (2021a) see new natural gas based DRI plants being built by 2030, while from 2030 onwards the majority of new-build primary steel capacity is H2-DRI.

From our partial review of the supply chain, no material bottlenecks have been identified. However, a separate aspect of the supply chain can be highlighted. Since there are currently only two providers of direct reduction shaft technology, if the global demand of new DRI plants were to increase dramatically, there could possibly be a lack of sufficient skilled people to execute and build the new plants.

Another component of DRI-based steelmaking that has been highlighted is the need for DRI-grade iron ore pellets. Since the reduction of iron ore in the DRI shaft happens below iron's melting point, no slag metallurgy (removal of impurities) occurs in the DRI plant. This is why shaft furnace DRI processes use iron ore pellets as feedstock that typically have higher grade (higher iron content, lower gangue levels) than BF pellets. The supply of DRI-grade pellets is limited and there could be a potential lack of supply of DRI-grade pellets to satisfy future demand (Doyle et al., 2021). S&P Global estimates that DR-grade iron ore pellet demand could increase more than fivefold in the next three decades (S&P Global, 2022). This will require additional investments into iron ore beneficiating plants, the development of new high-grade ore mines or development of technologies for DRI based on lower-quality ore. It is worth pointing out that there are also other DR technologies using fluidised-bed technologies that are being developed that can use iron ore fines directly, bypassing the need for DRI-grade pellets. In Austria, Primetals/Voestalpine is piloting the Hyfor technology, based on the Finex fluidised-bed/smelting-reduction process (Mitsubishi Heavy Industries, 2021). The Circored fluidised bed technology developed by Finnish company Metso Outotec can also operate on 100% hydrogen-based and avoids the need for iron ore pellets. It has already been demonstrated at industrial-scale through a demonstration plant built in 1999 in Trinidad (Metso Outotec, 2021).

The construction of new EAFs is linked to two separate drivers: their deployment as a complimentary technology to direct reduction plants (the DRI-EAF steelmaking route), and the deployment of standalone EAFs as the share of the secondary steelmaking increases. Regarding their use with DRI plants, several EU steelmakers are exploring an alternative route to DRI-EAF steelmaking by combining the DRI plant with the existing BOF at their integrated steelmaking sites. This option allows the use of lower-grade iron ore pellets (Lüngen, H. B., 2021). To do so, the DRI from the direct reduction plant first needs to be smelted in a submerged arc furnace (SAF) before being made to steel in a BOF. Both ArcelorMittal at its site in Dunkirk (ArcelorMittal, 2021b) and Thyssenkrupp at its Duisburg plant (Thyssenkrupp, 2020) have announced plans to integrate a hydrogen-based DRI plant with a smelting furnace to produce low CO_2 steel. SAFs use a different type of electrodes than those used in EAFs (so called Söderberg electrodes), which are consumed at a much lesser rate than graphite electrodes. The DRI-SAF-BOF route addresses both the iron ore pellet and the graphite electrodes supply chain issues of the DRI-EAF route.

Scenarios modelling the decarbonisation of the steel sector also see an increase in the use of EAF to process recycled steel scrap into steel. Material Economics model up to 108 Mt a year (EU27+UK) being made by recirculated steel in the New Processes scenario (Material Economics, 2019). The IEA also shows a slight increase in the share of steel coming from the recycling route in its Sustainable Development Scenario, accounting close to 60% of steel production in the EU (compared to 41% in 2019) (IEA, 2020). At a global level, several decarbonisation scenarios model a vast increase in secondary steelmaking. For example, the BloombergNEF Net Zero scenario assumes an increase in secondary manufacturing from 27% of global production today to a maximum 45% of total steel manufactured in 2050, or 1.2 billion tonnes in absolute terms, from 428 million today (BloombergNEF, 2021c). This long-term growth in EAF steelmaking will lead to an increasing demand for graphite electrodes, from 1 million tonnes a year in 2020 to 5.7 million tonnes by 2050 (BloombergNEF, 2021b).

2.8.4. Geopolitical considerations

There is a recent momentum shift among major global steelmakers to decarbonise steel production. Over the last year, the five biggest steelmakers (by 2019 steel production volume) have announced that they aim to achieve carbon neutrality by 2050, with various intermediary targets by 2030. Together, those five steelmakers namely ArcelorMittal (EU), Baowu (China), Nippon Steel (Japan), HBIS Group (China), POSCO (South Korea) accounted for 18% (334 Mt) of global crude steel production in 2019.

Several market analysts have noted that China's EAF steelmaking capacity is expected to continue growing in the foreseeable future. The Chinese government is currently encouraging steel plant capacity swap, so as to replace older integrated steelmaking plants with new EAFs (S&P Global, 2022).

Tenova will supply The ENERGIRON® technology for a plant with a capacity of 1M ton/year, making it the **largest hydrogen-based DRI facility in China.** The plant will be installed at **Baosteel Zhanjiang Iron & Steel Co., Ltd**, located in the Zhanjiang Economic and Technological Zone, Guangdong Province, China (Energiron, 2022). This follows the first Energiron DR plant installed at the HBIS facilities in the Hebei province, producing 0.6 Mton per year of quality DRI starting from the end of 2021 (Danieli, 2020).

By 2025, China aims for EAFs to account for over 15% of its total crude steel production, compared to 10% in 2020 (Reuters, 2022). Due to this shift from BOF to EAF steelmaking, Chinese companies have also increased their graphite electrode manufacturing, with 380 000 tonnes of graphite electrode capacity under construction (half of their current operating capacity) (BloombergNEF, 2021b).

Japan is the second biggest synthetic graphite producer after China, but the majority of their production is destined for their internal market. The US is the third biggest graphite electrode producer, however due to the high share of EAF steelmaking, which accounts for around 70% of crude steel production, it is also reliant on imports to cover its demand (Damm, S., 2021).

2.8.5. Key observations and recommendations

Hydrogen DRI is likely to become an important technology to make low-carbon steel, both in the EU and around the world. In a high demand estimate, where all of the current primary capacity is replaced with hydrogen DRI plants, around 40-50 new reactors would need to be built. As these technologies need materials and components that are common to the industrial sector, **no significant bottlenecks have been identified** in the construction of these plants. However, the major potential bottleneck for the roll-out of this technology remains the availability of large amounts of renewable and low-emissions hydrogen as well as the supply of DR-grade iron ore (depending on the ramp up of the DRI-SAF-BOF route or the DRI-EAF route). If all current primary production of steel in the EU (about 90 Mt) were to be replaced by a 100% H2-DRI route, this would annualy require 5.5 Mt of hydrogen. Some EU steelmakers are developing an alternative route to DRI-EAF by integrating the DRI plants with the existing BOF. However, globally, the general trend is to deploy more EAF, which could lead to increased graphite electrode demand.

Several measures can be considered for improving the EU position in the materials supply chain for direct reduced iron and electric arc furnaces:

- **Diversify materials supply for graphite electrodes**. EAF steelmaking is expected to increase around the world, both in combination with DRI plants and for secondary steelmaking from scrap. The demand for graphite electrodes has been highlighted as a possible supply chain bottleneck. Contrary to the overall DRI or EAF plant, which only needs to be built once, graphite electrodes are consumed during the steelmaking process. Furthermore, graphite electrodes are made of synthetic graphite, which is a key material for anodes in lithium-ion batteries. The growing market for lithium-ion batteries could represent an additional competing demand for synthetic graphite.
- **Support manufacturing of graphite electrodes and synthetic graphite in the EU**. China has the largest global graphite electrode making capacity, followed by Japan, India and the US. China also dominates the synthetic graphite market which is crucial to the manufacture of graphite electrodes. Efforts should be put into supporting the EU manufacturing of graphite electrodes and synthetic graphite. New processing plants are currently being built in Sweden (Leading Edge Materials), Finland, Norway (Vianode), Germany (SGL Carbon) and other parts of the EU, which will provide state-of-the-art processing and manufacturing facilities.
- **Develop skills and competences (for hydrogen DRI)**. Since there are only two companies providing the DRI shaft-furnace technology worldwide, if the demand for these plants were to increase simultaneously around the world, the availability of skilled personnel could slow down its deployment. Developing skills and competences in advance could help prevent a possible bottleneck, should the demand increase suddenly.
- **Promote R&D** in the use of lower grade iron ore pellets in DRI production and the identification of alternatives to the DRI-EAF route, such as the DRI-SAF-BOF route, to avoid problems with the supply of high-grade iron ore pellets, whose supply is limited (Doyle et al., 2021).

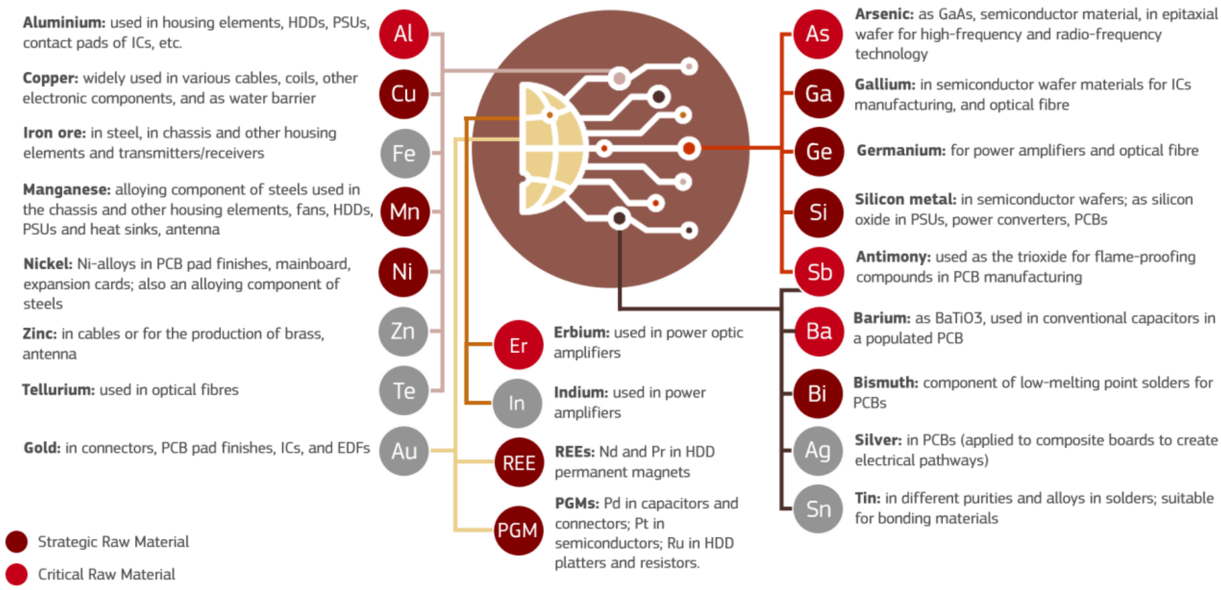
2.9. Data transmission networks

2.9.1. Introduction

The megatrend of digitalisation will have massive consequences on the amount of digital data processed and transmitted in many types of activities (commercial, domestic, mobility, IoT, etc.). These data are shared between stakeholders, often across borders and between continents, with high demands on short-term data availability. Consequently, data transmission speed and reliability are of utmost importance for the instrumentality of these activities and thus have direct and indirect impact on European businesses and societies, fostering growth, jobs, and competitiveness (EC, 2015). Business and military activities require, in addition, the securing of data transmission against espionage, cyber-attacks, hacking etc. Data transmission networks (DTN) basically enable modern telecommunication by connecting individuals, institutions, and systems with each other on a global scale.

Figure 55 shows a selection of raw materials with functional use in data transmission networks technology.

Figure 55. Selection of raw materials used in data transmission networks and their function



Source: JRC analysis.

Grid-bound nets and wireless transmission nets are often considered to be separate technologies due to their different, complementary technical solutions. As this study relates to the functionality of data transmission in general, it addresses grid-bound nets (including submarine and terrestrial cable systems) and wireless transmission networks jointly as parts of DTN technology.

Various types of data transmission network with functional similarities exist, but generally differ regarding their set-up and physical form. Most networks are connected with each other, forming the global data transmission network. The DTN technology can be split into three main systems. While the *data transmission and IP core network* facilitate the transmission of data over long distances, the *fixed broadband (BB) access network*, and the *mobile/wireless/cellular access network* provide to the end users tethered or wireless access to the global network, respectively. The *data transmission and IP core network* includes *submarine optical cable systems*, which connect continents and countries across seas and oceans. An additional separate network system not yet covered by the three above-mentioned systems are the *enterprise networks*. Due to the technical similarities with other fixed equipment, these are not considered separately in this study. While specific communication systems like the European Train Control System (ETCS) are related to the DTN technology, these are excluded from this assessment due to their high degree of hardware specialisation.

In wireless transmission, the transfer of information does not take place via a physical linear medium but via waves propagating in the atmosphere or in space (typically radio waves). Such communication can take place at a very wide range of distances, ranging from a few meters (domestic Wi-Fi systems, Bluetooth, infrared) to millions of kilometres (space communication). Wireless communication systems are schematically based on transmitters and receivers. Receivers/transmitters can be embedded in portable end devices (see Section 2.11 on smartphones, tablets and laptops).

Submarine and terrestrial cable systems are the backbone of the intercontinental internet today, and thus it is not possible to imagine worldwide communication without these. Submarine cable systems are set up by optical fibre cables and branching units, while the signals require repeaters, or fibre-optical amplifiers. These elements are secured against submarine environments (e.g., marine fauna, submarine landslides and water chemistry). The transit of data signals between the submarine ("wet plant products") and the terrestrial cable systems ("terrestrial plant products") requires cable landing points, which comprise various specific units and equipment for, amongst others, system surveillance, monitoring, and protection ("dry plant products"). Underground cable systems and above-ground wires are used to transport the signals ashore. The grid-bound net, increasingly dominated by optical fibre at the expense of copper wires, is complemented by radio link systems (base transceiver stations) to the local communal terminal block or broadcast antenna. The "last mile" supporting the end user (tethered internet connection, mobile web-enabled devices) is covered by local data cables or wireless transmission, depending on the physical and economic geography.

The overall network equipment hardware (service providers, operators) market has an annual market value of over USD 90 billion, possibly up to USD 100 billion. This value considers mainly the main equipment hardware and not infrastructure, support systems and civil works or deployment. Submarine optical cable systems and enterprise networks hardware can also be included in the category *data transmission and IP core networks*.

The estimated market values of data transmission network systems are shown in Table 5.

Table 5. Estimated market value (revenue in 2020) by data transmission network system.

System	Market value (billion US$)	Comments
Mobile / Wireless / Cellular access networks	45-50	
Fixed broadband (BB) access networks	15-20	
Data transmission and IP core networks	30-35	"routers" and "optical and microwave transmission" each amount to about half of the system
Submarine optical cable systems	10-15	market value includes deployment and support, treated as part of data transmission in this study
Enterprise networks	30-40	market value may include "overhead"

Source: Compilation based on (Weissberger, 2021; Grand View Research, 2022; Boujelbene, 2021; Communications Today, 2021).

The development of DTN is closely linked to trends in electronic equipment, in particular in data storage and servers (Section 2.10) and in end use devices (Section 2.11), both in terms of data demand and technology. Since DTNs are highly complex and varied, this study prioritises the assemblies and components of highest relevance to the DTN technology[21].

Data transmission networks are considered partly dependent on satellites technology, for example radionavigation-satellite services (RNSS). For many years, geosynchronous equatorial orbit (GEO) and medium Earth orbit (MEO) satellites provide internet access to remote areas, like small islands that are not connected to the global network infrastructure via submarine cables (Miller, 2022). While the number of active satellites has grown steadily in recent decades, there was a boost in the propagation of satellites. Within two years (2021-2022), the number of active satellites doubled (Statista, 2023), especially due to the commissioning of

[21] The high number of elements in the supply chain required to select lements that could be analysed within the scope of this study. For details see Annex 2, Table 26.

commercial satellites[22]. There are no indications however that satellite data transmission will be able to replace submarine data transmission short-term (Mauldin, 2019). Given the discrepancy in prices, satellite data transmission is commonly considered overpriced, and the average lifetime of low Earth orbit (LEO) satellites is still short (Wood, 2021).

The deployment of undersea cables is increasingly fuelled by modern Unmanned Surface Vehicles (USV), a specific form of drones (see Section 2.14 on drones).

There is significant overlap with other ICT technologies, in particular data storage and servers, as servers also play a crucial role for data transmission. REEs have a prominent role, given their particular characteristics which are used for example in HDD permanent magnets (dysprosium, neodymium and praseodymium), but also for optical fibre, along with terbium with its magnetoactive properties in numerous optical crystals. Terbium competes with other doping materials like cerium due to their differing absorption patterns. In broadband optical networks and CATV applications, erbium-doped fibre amplifiers (EDFAs) are used and have thus become the preferred choice for long-distance optical fibre communication. Germanium is used for its low optical dispersion and therefore very low chromatic dispersion in its transmission spectrum (Sinoptix, 2022). Gallium is a relevant raw material in power amplifiers.

Steel (iron, chromium, manganese, nickel etc.) and aluminium are used for housing elements, or chassis, to protect the technical installations. They are thus not essential for the technology as such, but crucial for the infrastructure accommodating the technology. Copper, however, is the preferred metal, along with aluminium, as a water barrier in submarine cables, but it is also used as ordinary conductor in connectors and cables within and outside DTN assemblies. For wireless transmission, zinc and manganese are important materials in antenna, while iron is used in transmitters/receivers.

2.9.2. Current supply chain bottlenecks

The global Internet is by far the largest data transmission network globally, and its size and access diversity imply a substantial and complicated network hardware. The many supply chain elements, which are relevant for the production and maintenance of the DTN technology, mean that the DTN supply chain is complex, and there are numerous potential supply chain bottlenecks.

In general, the DTN supply chain elements cover two types of equipment:

- functional equipment, primarily various types of electronics required for the data transmission itself.
- non-functional equipment for containing and sheltering the functional equipment against unauthorised access, weathering, physical shocks etc., such as housing, containers and antenna towers.

Given the focus of the study on functional equipment, non-functional equipment has not been considered for the sake of simplification.

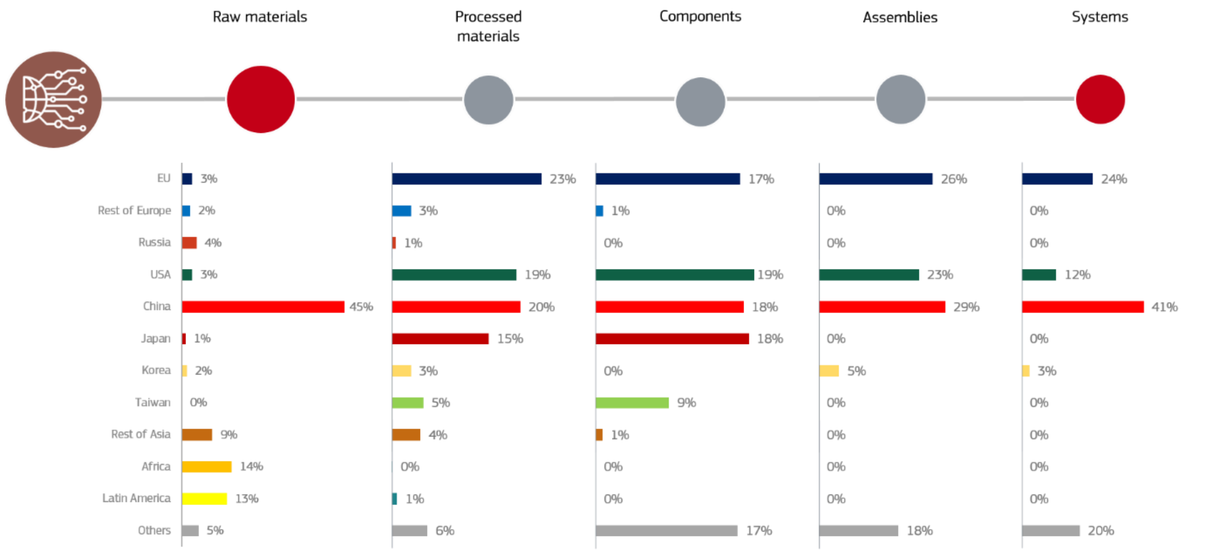
The data transmission networks supply chain features six steps: raw materials, processed materials, components, assemblies, super-assemblies, and systems. Table 26 in Annex 2 lists the elements along the six stages of the supply chain.

Figure 56 reports the supply risks along the DTN technology stages[23] and reveals potential bottlenecks along the supply chain. Overall, there is a significant market concentration for the analysed supply chain stages from processed materials to systems: The cumulative market share of the four countries with the highest market shares is between 72% (components) and 80% (systems).

[22] Several enterprises intensified the activities on LEO satellite broadband ventures, namely Starlink, OneWeb, China Satellite Network Group, Project Kuiper, Telesat Lightspeed, Lynk Global, and a Boeing venture (Leins, T., 2021)

[23] The super-assembly stage is omitted as there has not been sufficient data available assessing the supply risk of this stage.

Figure 56. An overview of supply risks, bottlenecks, and key players along the supply chain of data transmission networks



Source: JRC analysis[24].

The detailed Supply Risks of the elements appearing in the supply chain are presented in Figure 57.

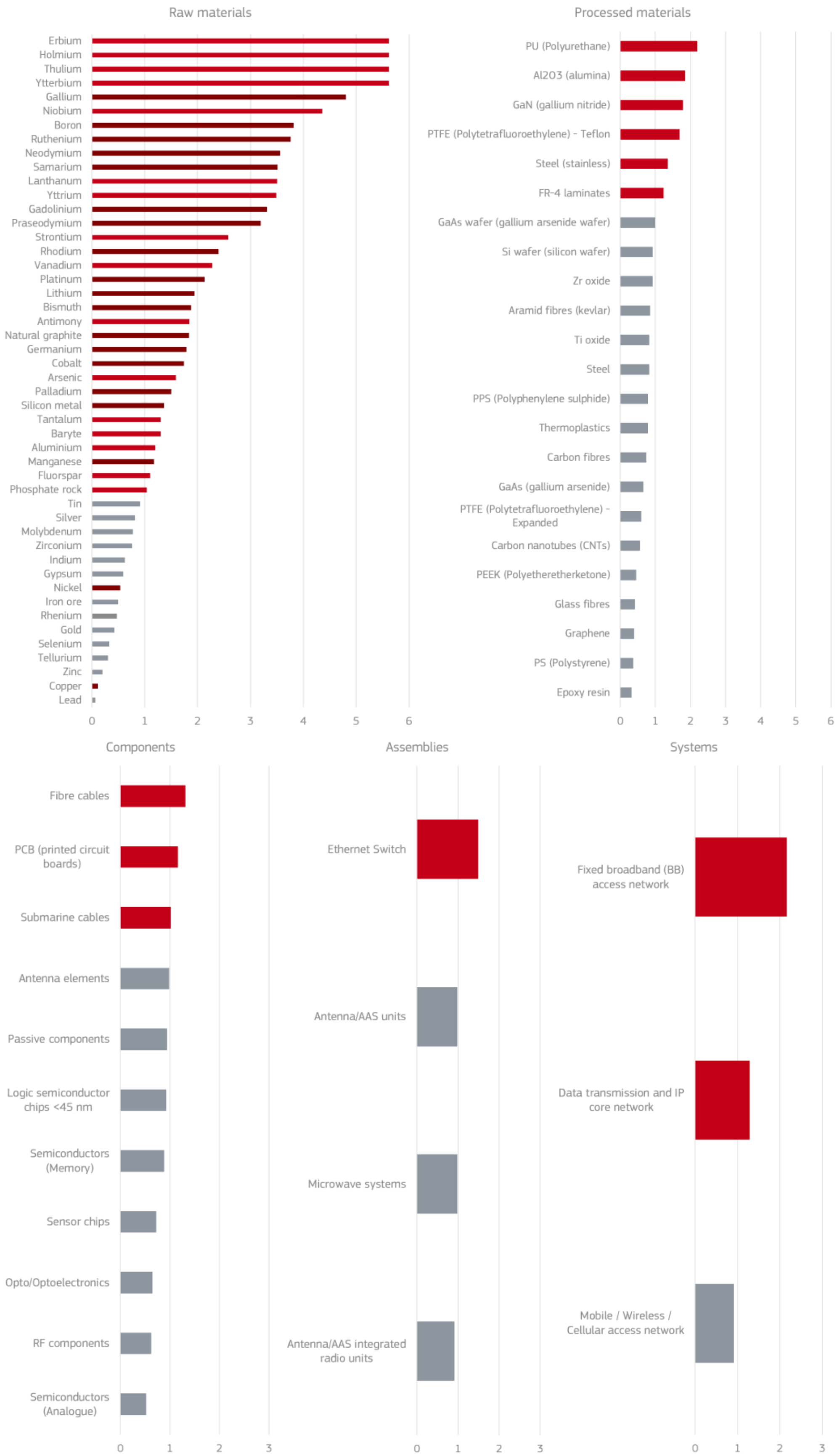
In total, 48 raw materials are relevant to data transmission networks. The EU does not show any domestic supply for ten out of these 48 raw materials and thus is fully dependent on imports. China is by far the most important supplier of raw materials for data transmission networks (45%), followed by Africa (14%), Latin America (9%), and Rest of Asia[25] (9%). All other countries and regions, respectively, show a supply share ≤5%, including Rest of Europe, USA, and Russia. The domestic EU supply of raw materials is just 3%. 33 of the 48 raw materials are flagged as critical to the EU economy, namely erbium, holmium, thulium, ytterbium, gallium, germanium, niobium, boron, ruthenium, neodymium, samarium, lanthanum, yttrium, gadolinium, praseodymium, bismuth, strontium, rhodium, vanadium, lithium, antimony, natural graphite, cobalt, palladium, arsenic, platinum, silicon metal, tantalum, baryte, aluminium, manganese, fluorspar, and phosphate rock. China is the only supplier of several REEs (Tm, Y, Yb, Ho), and also the very dominant supplier of samarium (85%), silicon metal (76%), gallium, germanium, lanthanum and neodymium. Brazil dominates the niobium supply (92%), while South Africa is the key supplier of rhodium (81%), and ruthenium (94%).

Dopant materials of the fibre-optic cables are among the raw materials with the highest supply risks, namely germanium, borate, or REEs used for doping fibre cables (Tb, Dy, Yb, Tm, Pr, Er), thus competing with the use of REE (Dy, Nd, Pr) and boron in HDD permanent magnets. Erbium-doped fibre amplifiers (EDFAs) are the preferred choice for long-distance silica-based optical fibre communication. EDFA are used for optical amplification, which is based on the process of stimulated emission of erbium ions in a silica matrix (Thyagarajan, 2006). Other critical materials in the submarine cable production are aluminium and copper, which are amongst others used as water barrier. Further critical raw materials with high supply risks are bismuth, gallium, and niobium, which are used in general electronic components like digital signal processors, transcoders and control electronics.

Regarding processed materials, polyurethane (PU) is a critical processed material used both as water barrier in submarine cables, and at microwave circuits. Alumina ($Al2O3$) with certain purity is used as dopant in the optical fibre core production. Gallium nitride is a further processed material showing high supply risk. It is required for various electronic components, like digital signal processors, transcoders, or control electronics, and in particular for the wafer production, which requires likewise silicon ingots (silicon metal) of very high purity if used as base carrier material.

[24] The super-assembly stage is not covered by the graphs due to a lack of data at this supply chain step.
[25] "Rest of Asia" refers to any Asian countries beside China, Japan, Korea, and Taiwan.

Figure 57. Detailed Supply Risk of selected elements in the data transmission networks supply chain



Source: JRC analysis.

Among the components, fibre cables show the highest supply risk due to the dominance of China (43%), as well as Japan (23%) and US (16%). Similarly, submarine cable production shows a high market concentration, led by the EU (Italy and France together with more than 60% production share) and China (28%). The third component considered critical is printed circuit boards (PCB), due to the large production capacity in China and Taiwan, which together account for almost 65% of the market, while the EU is a comparably minor producer with 4% of the global market. It should be mentioned that for a significant range of components, the data available was not sufficient to assess the supply risk, thus the assessment should be completed in future analyses.

The only assembly element identified as critical is that of network switches (multiport network bridge). Ethernet switches are the most common form of network switches. The US is the dominant producer, with almost two-thirds (64%) of the global production, followed by China (10%).

2.9.3. 2030 technology prospects

With "big data" becoming a mainstream trend in many societal and business areas, the demand for data transmission capacity has grown steadily and is expected to remain strong. Business activities depend more than ever on fast data transmission. A key driver of this capacity demand is the persisting industrial change, which is fuelled by joining data-driven technologies (artificial intelligence, advanced robotics, etc.) that can be subsumed by the term Industry 4.0, i.e. the Fourth Industrial Revolution. A further prominent driver is the Internet of things (IoT), i.e. the ubiquitous interaction of digital devices. Moreover, governmental and leisure activities need data transmission capacities for various applications. Accordingly, high-speed data transmission infrastructure is needed by businesses, and more general by modern societies, to handle the ever-increasing volume of data transferred over long distances. The IT industry serves these demands not only by accelerated deployment of land-based and submarine cables, but also the fast-paced rollout of 5G, the upcoming technology standard for broadband cellular networks.

As the development of global data transmission networks has so far not been analysed in detail, an independent forecasting approach was developed within the scope of this study to estimate future annual sales. The basis of this approach was an existing model estimating global production for the Information and Communication Technology (ICT) and the Entertainment & Media (E&M) sectors (Malmodin and Lunén, 2018; Malmodin, 2022a). While the DTN technology enabled the fast expansion of data transfer volumes over the years, the model results for the material demand were rather stable over the last decade (Malmodin, 2022b). Based on this information, the material demand for 2020 as an approximation was equated with the demand for 2015. The material demand value for 2020 was then used as base value for forecasting the demand for the period until 2050[26]. This study advanced the results further by estimating the spatial resolution for major world regions.

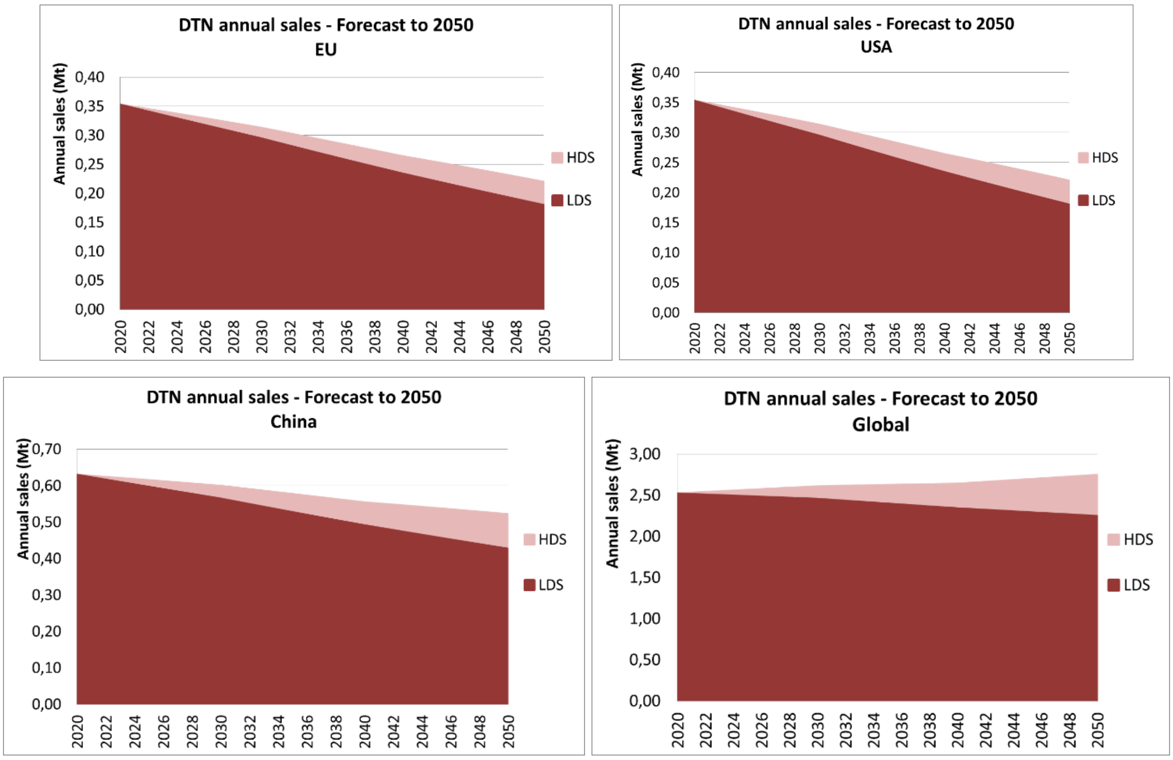
Figure 58 visualises the market forecast (tonnage) at the global scale, and for the EU, US, and China, respectively. The market forecast subsumes the demand for a comprehensive list of materials[27] without differentiating these items in the results.

The global material demand shows a rather stable development, where miniaturisation effects were counterbalanced by the growth of data transmission capacity. At the geographical level, China and in particular the EU and the US, show significant downturns because the market share of the rest-of-world (RoW) increases at the expense of the market shares of China, EU, and US, respectively.

[26] The basis for these advancements were founded estimates.

[27] The listing of raw materials comprises main materials (e.g. iron/steel), main non-ferrous metals (aluminium, chromium, copper, etc.), and specialty metals.

Figure 58. Annual sales of data transmission network in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis.

2.9.4. Geopolitical dimension

Sites, cities, or regions can become temporarily isolated from the world wide web, due to natural disasters for example, and also due to conflicts. In many cases, a lack of telecommunication hinders modern life, which today requires significant data flows both directly (end users) and indirectly (e.g., infrastructure needs). Data transmission networks provide technical solutions for cross-border information-sharing and ultimately provide the tools to control domestic or foreign information transfer, which may affect the sovereignty of governments, individuals, and enterprises from various sectors including those managing critical infrastructure (industry, energy, transportation, aerospace and defence, finance and healthcare). Thus, well-functioning data transmission networks are crucial for an agile economy and administration. Further, to a certain extent the functioning of society as a whole depends on the availability of data transmission, as with electricity.

Regarding hardware, submarine cables are the backbone of long-distance data transmission. At a global scale, there are around 490 submarine cable systems in service[28]. Submarine cables vary in length, from hundreds to several thousands of kilometres. They concentrate the data flow between countries and continents, through a limited number of lines, and are thus more vulnerablethan the mobile or wireless network system. Submarine cables form an essential part of intercontinental and other long-distance data transmission facilities. A recent proof of the relevance and extreme vulnerability of European submarine infrastructure is the incident of the Nord Stream attack in the Baltic Sea (Irish, 2022), which equally applies to submarine data transmission infrastructure. Seabed security is therefore becoming a part of national resilience strategies and a key priority for countries around the world. The control of data transmission networks (hardware, software), or parts thereof, thus implies the control of domestic or foreign data transmission, and ultimately affects the related data sovereignty.

Until the mid 2010s, the submarine cable market showed a slow growth in the deployment of new cable systems. Submarine cables were commonly financed, or owned, by international consortia of telecom providers and other, often private companies (often an enhanced number of owners) which rented the cables to companies. Since 2016, a new phase has started with both a massive rise in submarine cable deployment and

[28] The Submarine Cable Map 2022 shows 486 cable systems and 1306 landings.

a significant shift of ownership towards big tech companies, i.e., large-scale cloud service providers and media service companies that from then on appeared as major investors in new submarine cables. For example, Facebook (Meta) and Microsoft owned together with Telxius Telecom the transatlantic Marea cable system (Kim, 2022). Similarly, Google started to build submarine cables on its own[61]. This dynamic can mean an increased risk of market concentration, which is of particular relevance as big tech is concentrated in a single country, namely the US. Dependencies exist at the level of distinct submarine cable connections, and there is a threat of upcoming oligopolies in the data submarine cable market.

2.9.5. Key observations and recommendations

Reliable and fast data transmission is increasingly important to the functioning of societies and economies and requires specialised hardware and software facilities. Hardware ownership, in particular ownership of submarine cables, has recently started to become concentrated in fewer hands, and this process may speed up in the coming years.

- **Securing the supply chain and production capacity required**. Certain critical raw materials are essential for the production of components and assemblies, including REEs like erbium, which is a key ingredient of fibre amplifiers in submarine cable systems. These CRMs need to be safeguarded through measures outlined for many of the technologies in this report, such as raw material partnerships, domestic EU mining, and production and increased material efficiency.
- **Increase the resilience of data transmission by deploying additional cable system capacity for fully controlled data transmission.** The rising concentration of submarine cable ownership can pose a risk for a stable, unhampered and free data transmission at a global level, including Europe[29]. Controlling or owning a submarine cable network would increase the resilience of the functioning of unhindered data transmission by DTN. Therefore, the EU needs possible means of controlling or owning a submarine cable network to increase the resilience of data transmission. Beyond issues of production of components or assemblies required for the DTN system, there is an additional potential bottleneck in the deployment and installation of the submarine data transmission cables, as these require the usage of highly specialised cable-laying barges. The potential impact of reduced installation capacity on secure data transmission merits further investigation.

[29] This risk is higher in geographically remote areas than in areas like Europe that have several submarine cable connections, often in parallel, with a certain redundancy of Europe-US and Europe-Asia cable systems. Nevertheless, the actual risk that data transmission can be hindered, or controlled, between countries using targeted technical measures should be further explored. Nevertheless, a sound technical risk analysis is required to assess this potential bottleneck profoundly.

2.10. Data storage and servers

2.10.1. Introduction

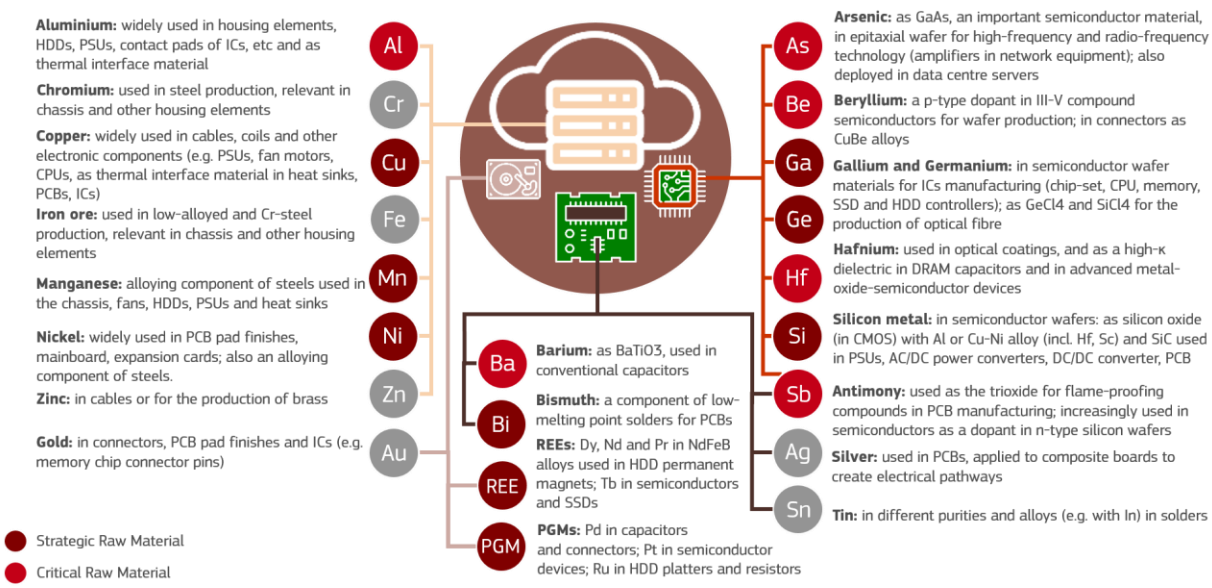
Data servers, storage and network equipment consist of computer systems and associated components, mostly operated interconnectedly and typically housed in data centres.

Today, the world has around 8 000 data centres. The US (33%), the UK (5.7%), Germany (5.5%), China (5.2%), Canada (3.3%) and the Netherlands (3.4%), had the majority of data centre infrastructure in 2021 (Daigle, 2021). The EU constituted a share of around 17%.

Data centres for digital information management have witnessed unprecedented growth in technologies and services over the years. Trends such as Cloud Computing, Internet of Things (IoT), Industry 4.0 and Big Data are driving this growth at a very fast pace, leading to a multiplication of data generated and increasing computing requirements. These are also central to the EU's competitiveness as data is often considered a catalyst for economic growth and innovation across all economic sectors (EC, 2015).

Data servers and storage equipment require a variety of raw and processed materials in their construction (Figure 59).

Figure 59. Selection of raw materials used in data storage and servers, and their function.



Source: JRC analysis.

Structural materials such as aluminium but also chromium, manganese and nickel, relevant alloying components of steels, are widely used in the chassis and other elements (e.g. fans, hard disk drives, power supply units). Nickel-alloys are commonly used in PCB (printed circuit board) pad finishes, mainboard and expansion cards. Aluminium and copper are important thermal interface materials in heat sinks, while copper is additionally used in cables, coils and for cladding double-sided and multilayer PCB boards. $BaTiO_3$ is employed in conventional capacitors in a populated PCB. Bismuth and tin, used in different purities and alloys (e.g. with indium), are components of low-melting point solders, where also silver-based inks and films are applied to create electrical pathways. Antimony is mainly used as the trioxide for flame-proofing compounds in PCB manufacturing where glass fibre/epoxy laminates (FR-4) is the structural substrate.

Silicon metal is the prevalent material for semiconductor wafers. It is consumed as silicon oxide (CMOS) with aluminium or copper-nickel alloy (incl. hafnium, scandium) and SiC (silicon carbide). Other key materials required to produce semiconductors, include arsenic, in epitaxial wafer for high-frequency and radio-frequency technology, beryllium, a p-type dopant in III-V compound semiconductors, hafnium, used in advanced metal-oxide-semiconductor devices, antimony as a dopant in n-type silicon wafers, scandium nitride (ScN) as a binary III-V indirect bandgap semiconductor, gallium and germanium. Germanium is also used as $GeCl_4$ and $SiCl_4$ for the production of optical fibre.

Dysprosium, neodymium and praseodymium are components of NdFeB alloys used in HDD permanent magnets while terbium is additionally used in semiconductors and SSDs (solid state drives).

A variety of PGMs are used for different applications: palladium in capacitor manufacturing and connectors; platinum in semiconductor devices; high purity ruthenium powder in the magnetic layers of HDD platters and resistors. Gold is used in connectors, PCB pad finishes and ICs (integrated circuits) (e.g. memory chip connector pins). CuBe alloys are well known for their superior stress relaxation resistance and fatigue strength and are used in connectors. Hafnium (IV) oxide is used in optical coatings, and as a high-κ dielectric in DRAM capacitors.

Disk platters are either based on aluminium alloys or glass and the cables for power supply and communication rely on copper or glass fibre.

Thermal interface materials (TIM) are used in almost all components of a data centre including the server boards, switches, and power supplies. Ceramic-filled silicones are the most prevalent (IDTechEx, 2020).

The server, storage and network equipment are considered super-assemblies for the purposes of the current assessment. A server can be differentiated according to design, application purpose/performance, number of processors or price (Montevecchi et al., 2020). Some essential performance indicators for servers are related to assemblies such as the Central Processing Unit (CPU) architecture, model and number of CPUs/Cores/Threads; number of Random Access Memory (RAM) and type; External controller based (ECB) disk storage size and type; Graphic Card(s), Graphics Processing Unit (GPU) model and number. A server is additionally composed of a power supply unit (PSU), connectors and expansion cards. It consists of multiple components which can be traded separately and independently and include active and passive electronic components[30] sitting on a PCB surface, cooling elements consisting of CPU heat sinks and fans, I/O control and network connectors.

A data storage product on the other hand is composed of an integrated storage controller, connected to the storage devices, either using HDD or SSD technologies, as well as a power supply unit and embedded network elements. The main components include housing elements, a disk platter, spindle and voice coil motors, read and write heads, active and passive electronic components including semiconductor devices, cooling elements and connectors.

Enterprise SSDs are used in combination with HDDs for data storage in data centres. As SSDs score better than HDDs in many performance indicators, the latter are gradually disappearing and being replaced by SSDs. Another core replacement reason next to performance is the decreasing price of SSDs. Nevertheless, HDDs still have a strong edge in terms of cost and capacity, with the development of hard drive technology advancing on several fronts to push the limits of high-capacity enterprise HDDs that use energy-assisted recording technologies (Sliwa, 2020). In a data centre HDDs provide high capacity at lower cost for “cold” data, whereas SSDs will be used for “warm” data which needs to be accessed more rapidly and more frequently (Yole Développement, 2022). This trend is also increasing the proportion of 3.5-inch HDDs and increasing requirements for heads and media.

Adapting to meet the needs of miniaturisation, better thermal management, increased speed, and performance has imposed slight changes in the material composition of servers and data storage products over time. In particular, the semiconductor industry for processors and memory is achieving and implementing further improvements with each technology generation (EC, 2015). The continuously growing demand for bandwidth and higher frequencies has led to an increasingly larger introduction of photonic technologies and related materials such as gallium, germanium, and indium in III-V semiconductor components. While GaAs will likely remain the mainstream technology for sub 6 GHz instead of CMOS, it is challenged by GaN technology in many RF power applications (Statista, 2022). Devices based on AlScN are considered to be the next generation of power electronics (Fraunhofer IAF, 2019).

The PCB industry is already thinking beyond the basic FR4-type PCB concept to new 3D printed solutions that could be a paradigm change for the electronics industry over the next decade (Gardiner, 2014; ITRI, 2015). Although TIM technologies are not likely to change significantly, the trend towards higher performance TIM will continue as devices utilise more dense arrangements of integrated circuits (ICs).

In general, there has been an increasing move to green materials and chemicals, driven not only by consumer demand, but by regulations such as EU REACH (EC, 2006). Phosphorus flame retardants (PFRs) are often

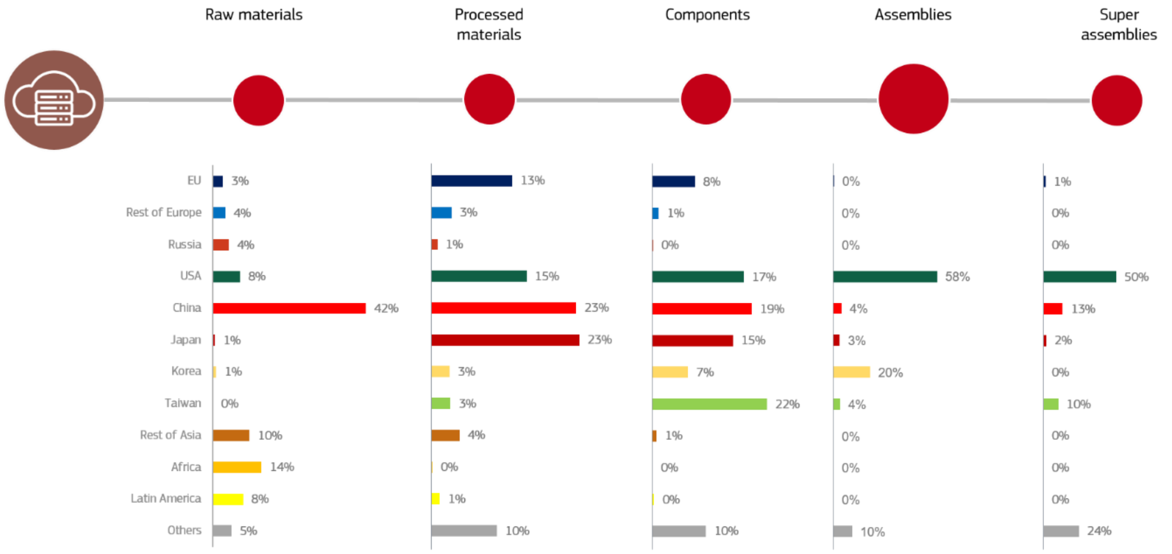
[30] Active electronic components include semiconductors - memory and logic chips. Passive electronic components include resistors, capacitors, and inductors.

proposed as alternatives to brominated flame retardants (BFRs), which in 2008 were used in approximately 90% of FR-4 PCBs (EPA, 2015). The RoHS Directive[31] pushed the phase-out of lead and has increased bismuth's use in electronics as a component of low-melting point solders. Soldering technology is rapidly diversifying to adapt and in niche high-end markets will become just one of several available joining technologies in the future (ITRI, 2015).

2.10.2. Current supply chain bottlenecks

While the EU holds a reasonable share in processed materials and components to produce data server and storage equipment (13% and 8%, respectively), its production share is only marginal at the assembly and super-assembly levels (<1%) (Figure 60). Assemblies and super-assemblies are dominated by US suppliers, accounting for 58% and 50% of global production at each stage, respectively. The markets for components are also consolidated in Taiwan (22%), China (19%), the US (17%), and Japan (15%) The raw materials consumed in servers and storage equipment are mainly produced in China (42%). China enjoys a quasi-monopolistic position in the production of the most critical raw materials (rare earths, gallium, germanium and magnesium) and is also an important player in the markets for aluminium, antimony, bismuth, indium, phosphorus and silicon metal accounting for at least half of the global production.

Figure 60. An overview of supply risks, bottlenecks, and key players along the supply chain of data storage and servers



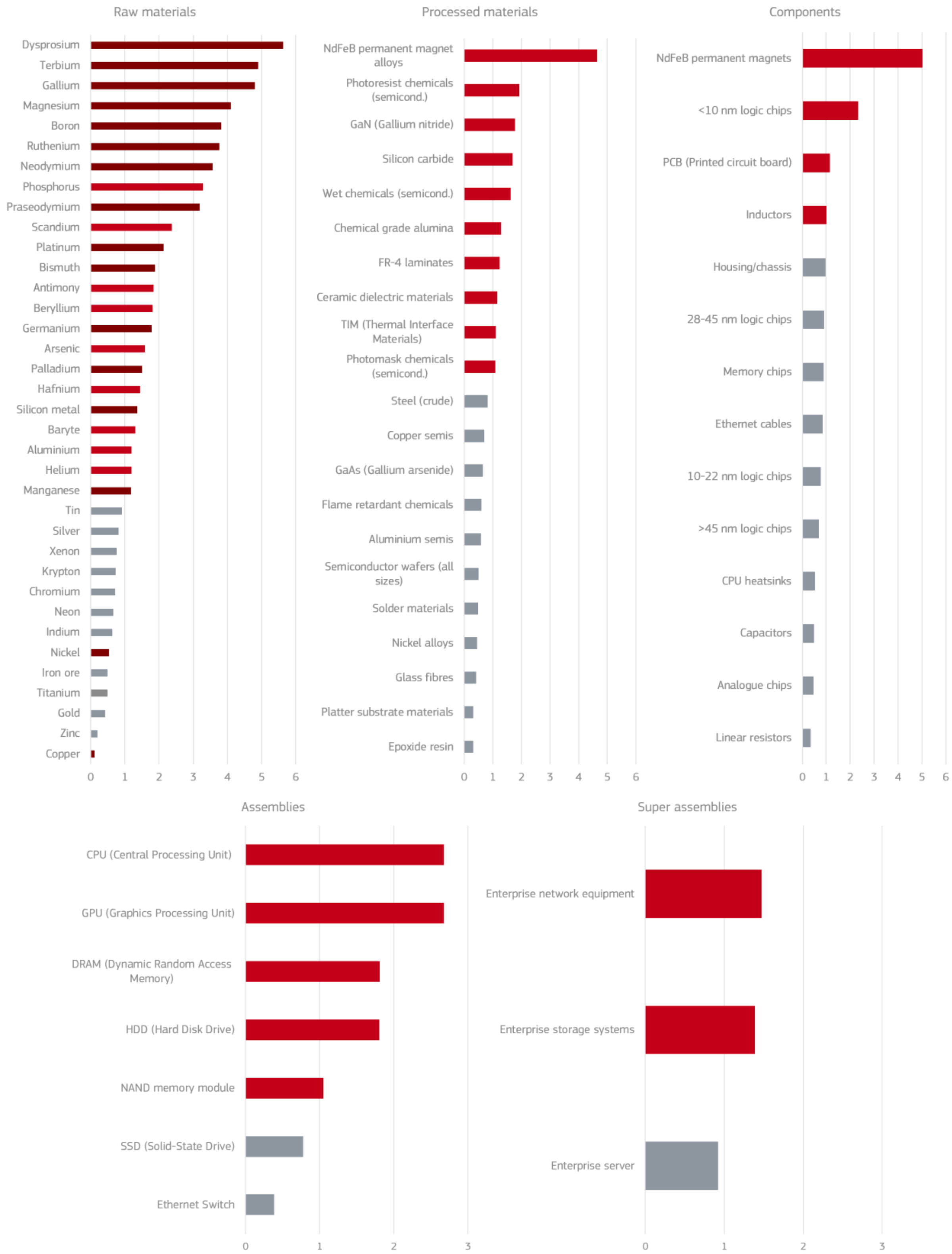
Source: JRC analysis.

In detail, there are supply risks at various stages and levels across the servers and storage value chain. With respect to raw materials, the supply of rare earths, especially the HREEs (dysprosium and terbium), remains one of the most critical, in that all the global production originates from China. Russia is the most significant world supplier of palladium metal in unwrought or in powder form (40%), however the UK, together with the US, Germany, Switzerland, and Canada are the most significant exporters of semi-manufactured forms. Likewise, the EU is an important global supplier of refined ruthenium metal, even though it depends entirely on third countries for the supply of ruthenium originating from primary sources (South Africa is the largest producer representing 94% of the world´s production). Germanium, on the other hand, is mainly produced in China, with a 90% share of global production, followed by Russia (5%). While it is estimated that around 30% of global germanium supply originates from recycling (mostly from new scrap generated during the manufacture of fibre-optic cables and infrared optics), the supply of germanium is further constrained by its by-product nature.

[31] The RoHS 3 (EU 2015/863) Directive restricts the use of lead above 0.1 %. There used to be an exception for lead in solders which included servers and storage (Exemption 7(b) of Annex III of the RoHS Directive) which however ran out in 2016 and was not renewed. (https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en.

Like germanium, gallium and indium are also recovered as by-products, which adds new challenges and uncertainties to supply. The detailed Supply Risks are reported in Figure 61.

Figure 61. Supply bottlenecks along the value chain of data servers and storage.



Source: JRC analysis.

Among the key processed materials, the risk of difficulties in supply is heightened for NdFeB alloys, gallium nitride, SiC, chemical grade alumina, FR-4 laminates, ceramic dielectric materials and thermal interface materials. As with permanent magnets, further down in the supply chain, NdFeB specialised alloys are produced in China to the extent of 90%, which results in a high supply risk and unfavourable import conditions. Gallium nitride production also features a high supply risk; with 85% of the world market, Japan is the world's largest producer. In 2020, China was the top exporter of SiC worldwide (52%), though the EU also accounts for an important share of the market (19%). This is comparable with the non-metallurgical grade alumina market, with 46% originating from China followed by the EU with 19%. China and Taiwan are major contributors to the global output of FR-4 laminates, with companies located in the EU accounting for about 7% of this market. Japan is the largest supplier of electronic ceramic powder materials, occupying about 65% of the global market and the US is the dominant region in the global thermal interface materials market (62% share). To this list must also be added the chemicals used in semiconductors manufacturing, the production of which is mainly concentrated in Japan.

The aluminium semis industry is much less concentrated than other segments, however, in 2018, it is estimated that China had a total share of approximately 50% of the global production of semi-finished aluminium products (USITC, 2017). That same year, the EU accounted for about 7% of the global semis production, being largely reliant on Chinese imports of FRP (flat-rolled aluminium products) and extrusions (27% and 37% respectively).

With respect to components, one third of the elements assessed are exposed to supply risks. China, for example, enjoys a monopoly position in the market for permanent magnets, controlling 94% of the global production. Semiconductor chips, on the other hand, have varying levels of vulnerability, depending on the specific product. Taiwan has 40% of the world's logic chip production capacity and leads, with 92% of the market, in the most advanced nodes at 10 nm or below that are required to manufacture CPUs and GPUs chips for data centre servers (SIA/BCG, 2021). The EU, on the other hand, has a significant competitive advantage in analogue products, accounting for 22% of the global market. Overall, the EU production of semiconductors has declined over the last 20 years: from a peak of 22% in 1998 to 13% in 2010 and down to more than 9% in 2017 (Decision, 2020). In 2019, the market for semiconductors destined for servers, data centres, and storage was valued at EUR 57 billion, about 15% of all uses.

Supply risks concerning PCBs, on the other hand, result from the large production capacity available in China and Taiwan, which collectively account for nearly 65% of the market. While the European landscape is said to be highly competitive, owing to the presence of multiple players, the EU is a minor producer comparably, with 4% of the global market.

Japan is the largest contributor to the passive electronic components market. Discrete inductors are perceived to be the segment with the most severe constraints, given the little diversified production.

At assembly level, CPU and GPU modules are highly critical elements in terms of supply risk considerations, as production is located almost entirely in the US. US-headquartered firms collectively account for more than a 90% share of these advanced semiconductor devices, although manufacturing of these products is largely done in Asia (SIA/BCG, 2021). As far as HDDs are concerned, significant market changes have occurred in recent years. To date there are only three HDD manufacturers left (Seagate, Western Digital and Toshiba), the rest being merged or acquired by all the main players. The HDD market is also currently highly concentrated in the US. DRAM storage drives are a business with hundreds of players, targeting a multitude of applications, most of which are based in Korea (72%) and the US (21%). Server computers for data centres are the most important systems in terms of DRAM use. NAND memory modules are also mostly manufactured by Korean companies, with 44% of the global market. Samsung is the key vendor for both DRAM and NAND, accounting for about 43% and 33% of the global production, respectively.

Lower supply risks concerning SSD storage drives and switches on the other hand, result from a more diversified supply, with shipments proceeding from Korea, the US, Japan, Taiwan, Hong-Kong and China. Nevertheless, it should be noted once more that some large companies hold considerable shares of the markets: Samsung is the largest manufacturer of SSD with around 30% of the global market; Cisco ranked first among vendors in the third quarter of 2020, occupying a share of about half of the global Ethernet switch market.

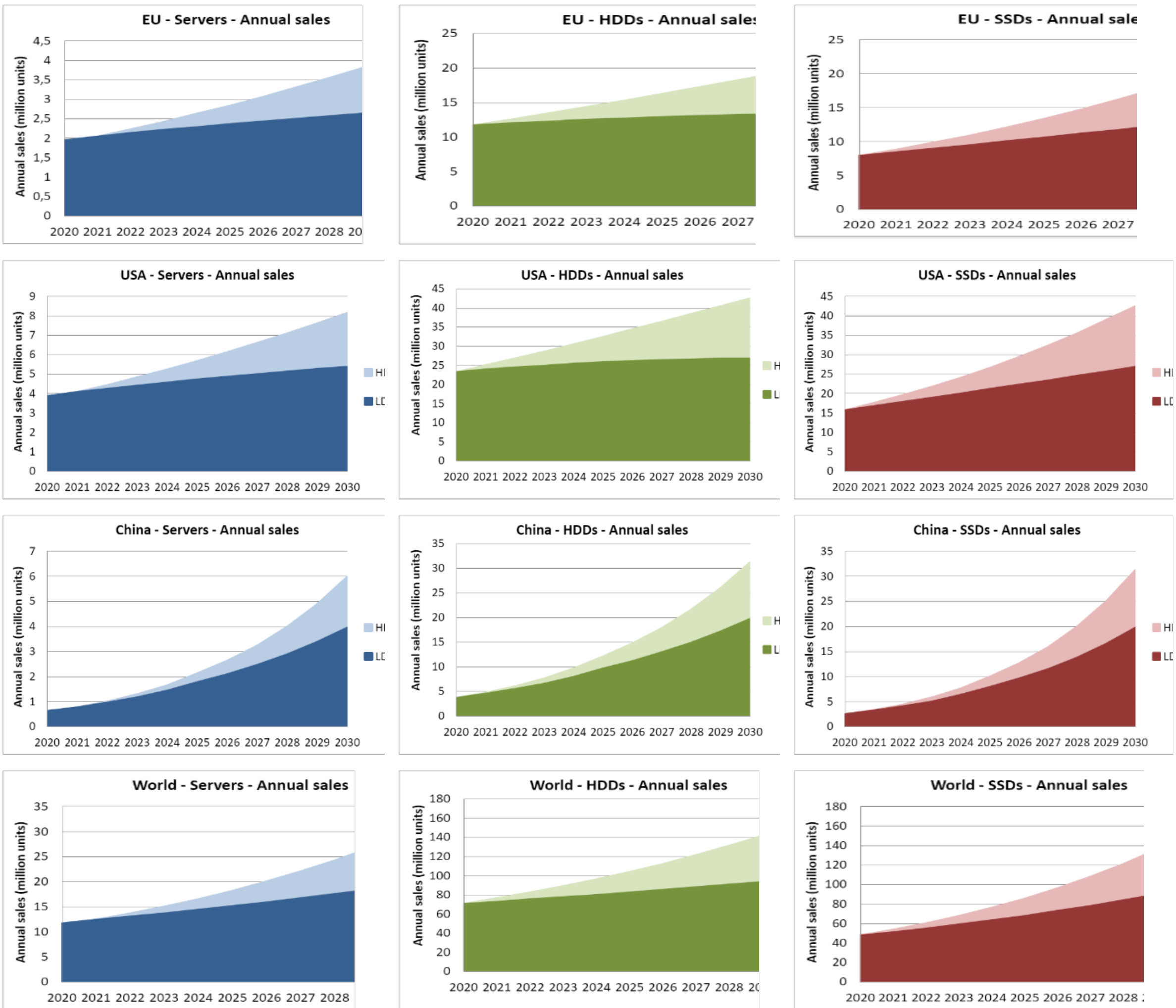
Enterprise storage systems and network equipment markets appear to be highly concentrated, with a few large players. In 2019, Cisco had a 56% share of the global enterprise network market and Dell Technologies was the largest external enterprise storage systems supplier in 2020, accounting for 29% of worldwide revenue. The server supply, on the other hand, is faced with less critical market conditions. It is consolidated in the US, Taiwan and China, which compete strongly for the leading position. Original design manufacturers (ODM) account for more than 85% of the server and storage sales to the top server cloud providers.

Across the value chain, the EU has relative strengths in relation to hafnium, copper alloys and semis, nickel alloys, epoxide resins, flame retardant chemicals, GaAs, glass fibres, thin-film ceramics, platter substrate materials, specialised aluminas, solder paste, silicon carbide, ethernet cables, CPU heat sinks, analogue and 10-22 nm logic semiconductors. For each of these, the EU accounts for over 10% of the global production.

2.10.3. Projected 2030 material demand

The demand for servers and storage equipment is already substantial. In 2020, around 12 million servers and 118 million storage units, allocated among HDD and SSD drives, were sold to the global data centre market. The quantities of enterprise and near-line HDDs amounted to 70 million units and those of enterprise SSDs to 47 million units[32] (Figure 62).

Figure 62. Annual sales of data servers and storage equipment in the EU, US, China and globally in the two explored scenarios.



Source: JRC analysis.

[32] It is assumed that only around 14.3% of all SSDs are Enterprise SSDs, the rest being Client SSDs used in desktops, laptops, etc. (Rounded estimations based on Yole Développement, 2021).

Various projections suggest that the future increase in demand could be significant, given high expectations concerning the sector development amidst continued digitisation of all aspects of modern life.

For example, MIC (Market Intelligence & Consulting Institute) anticipates the global server shipment volume to grow by a compound annual growth rate (CAGR) of 4.06% (in 2021-2025, reaching 15.7 million units in 2025 (MIC, 2021). Based on MIC's findings, edge servers and high-performance computing servers are two key factors to drive next round of growth for the server market. This estimate is in line with the global data centre market growth proposed by P&S Intelligence of 5.1% CAGR between 2021-2030 (P&S Intelligence, 2022). IDC's more optimistic expectations, on the other hand, forecast that the server market will grow at a CAGR of 10.2% in 2021-2026, despite persisting market challenges and concerns about the macroeconomic and geopolitical environment (incl. remnants of impact from the pandemic, historically high inflation, supply chain disruption and geopolitical conflict) (IDC, 2022).

Taking these projections collectively into account, it is estimated that in the LDS, 19.3 million servers will be sold in 2030, increasing from 12 million units shipped in 2020. This volume is projected to be around 29 million in the HDS. For the lower estimate, this would represent an increase of 5% while for the upper estimate it is 10%.

As far as HDDs are concerned, it is estimated that around 27% of all HDD shipments are near-line and enterprise drives used for second tier storage in enterprise and especially data centre (cloud) applications. These products alone are estimated to witness 3.2% CAGR in a low demand scenario, growing to 96 million units in 2030, up from 70 million units in 2020. This volume can approach 153 million units in a high demand scenario[33]. Here the outlook is less clear, however it is assumed that enterprise HDDs will remain the dominant storage technology in data centres until 2030, by which point SSDs will constitute 50% of the market. This is in line with an overall decline in HDD shipments for all other applications such as desktops and laptops, where SSDs have already outnumbered HDDs.

A continued growth trend is also expected for enterprise SSDs. Through the forecast period, worldwide unit shipments are expected to increase at a CAGR of 7.8% in the LDS and at a CAGR of 12.4% in the HDS. The lower estimate, anticipating 96.1 million units in 2030 is in line with IDC's 5-year demand projections.

Whilst the US data centre market is the largest contributor to the deployment of server and storage products, China will likely contribute to most of the growth over the forecast period (Figure 62). The data centre market in China is projected to grow at a CAGR of 23.72% during 2020-2025 (Technavio, 2022) as the region focuses on continuing the digital transformation, catching up with the rest of the world. However, the US's investment in research and development leading to the establishment of next-generation centres, together with the fact that it is home to multiple infrastructure providers, will facilitate the more rapid expansion of the sector, as the US will still account for the largest share of the market in 2030.

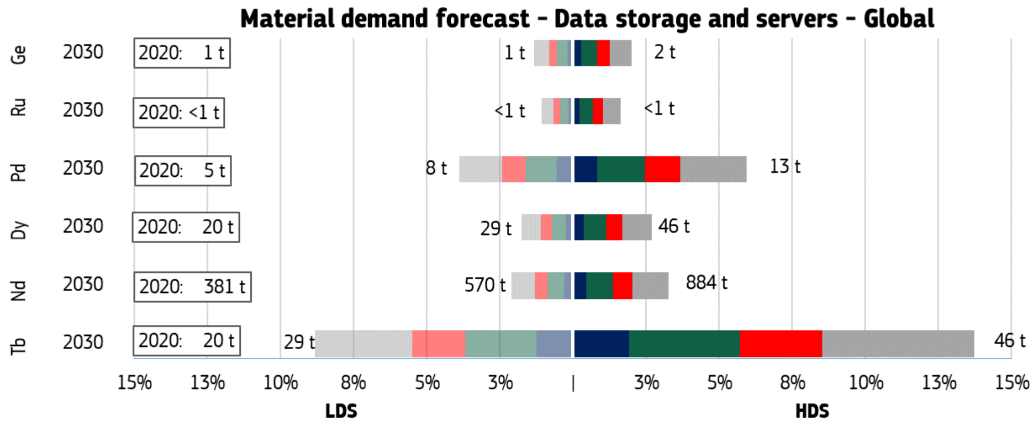
Yet, the relative impact of these changes in the demand for raw materials may not be significant, given very low usage rates. Figure 63 shows the raw materials for which consumption in data servers and storage is at least 1% of the current global supply. This is constituted by critical raw materials only, with the rare earths showing the highest demands in comparison to what is available on the market.

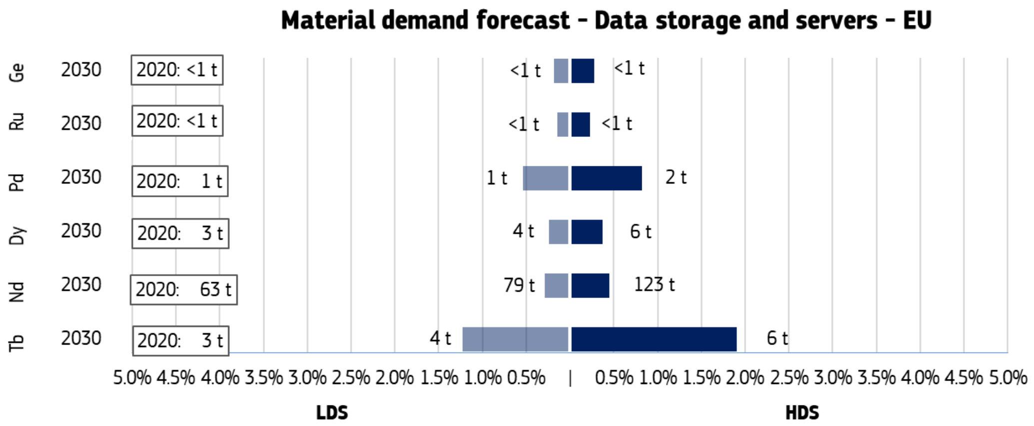
In 2020, almost 1.5% of neodymium and dysprosium consumption worldwide is used in data servers and storage. Terbium on the other hand was consumed to the extent of 20 tonnes, cumulatively in magnets and semiconductors. Its consumption in data servers and storage today could represent a fraction of 6% of the global annual demand. These trends leading to less available supplies, are especially troubling in a context of increased demand for such materials in renewable and low carbon energy technologies, also projected to grow exponentially as the world electrifies itself away from fossil fuels. If on the positive side, the demand for terbium in the lighting industry (which until just recently represented 68% of terbium applications) is likely to fall even further in the future due to changes in the lighting market structure (EC, 2020), that of dysprosium used exclusively in magnets will hardly be alleviated.

In 2030, demand is expected to increase by (on average) 1.6 times in the LDS and by 2.5 times in the HDS.

[33] Methodological note: Collectively, HDD's and SSD's deployed in data centres, are expected to increase at the same rates proposed for servers in the LDS and HDS scenarios. The individual volumes of HDD´s and SSD´s in each scenario were calculated annually in proportion to an assumed steady decrease of HDD´s in data centres from 59% in 2020 to 50% in 2030, matched by a commensurate increase in SSD´s, from 41% to 50%.

Figure 63. Material demand forecast for data storage and servers: global (top) and focus on the EU (bottom)





Source: JRC analysis (Tb = terbium, Nd = neodymium, Dy = dysprosium, Pd = palladium, Ru = ruthenium, Ge = germanium).

Reuse of data server and storage components are key aspects likely to have an impact in the data centre market as many of the major hardware manufacturers have already implemented end-of-life policies. Based on various sources, the European Commission (2015) estimates an average reuse rate of 50% for servers and 25% for storage systems, which should lead to a decrease in the manufacturing of new equipment.

2.10.4. Geopolitical dimension

Demand for data centres differs by country, reflecting a variety of market forces and policies (Daigle, 2021). Whether it be driven by financial services as in the UK, or by a significant manufacturing and industrial capacity as in Germany, it is consensual that the demand for ICT processing and storage resources will grow in the coming years as a consequence of digitalisation of information and data across a variety of sectors, the up-surging demand of IoT devices, and Industry 4.0 adoption. Such growth, to which also the expansion of edge data centres should contribute beyond 2030, will continue to be characterised by a shift to much greater shares of cloud-based services and hyperscale data centres (IEA, 2022). It will also lead to strong innovations in the server and storage market landscape, aimed at enhancing performance, speed, and memory.

Government initiatives contributing to the strong uptick in investments in this industry are numerous across the globe. The UK government, for example, announced proposals to boost competition in the digital sector. Malaysia announced investments in infrastructure, for faster and wider internet connectivity, under a 10-year plan aimed at developing the country's digital economy. India plans to enhance the contribution of the digital economy to 20% of the GDP in the next five years (P&S Intelligence, 2022). In the EU, some 100 new data centre projects are due to be introduced over the next four years, with most located in the new so-called Tier 2 markets (Carvill, 2022).

China's plans to develop its digital economy are far advanced. Whilst Chinese data centres represent today only 5% of the global fleet the region was said to house 10% of all hyperscale facilities worldwide during the fourth quarter of 2020, next to the US with a 40% share of the market (Statista, 2020). In June 2022, China's East-to-West Computing Resource Transfer project was fully operational (Chen, 2022) and plans were approved to build eight national computing hubs across the country, as well as ten national data centre clusters (China Daily, 2022).

Furthermore, Chinese suppliers are already key players across the supply chain of data servers and storage[34]. China is known to have the world's largest capacity for the production of electronic components and equipment, with a huge domestic market that allows economies of scale to be realised. In its plan "Made in China 2025", introduced in 2015, China announced its willingness to not only maintain and develop its position of electronics manufacturing strength, but also to take the lead at every step of the global electronics value chain (Decision, 2020).

In the broad data servers and storage supply chain, the geographic concentration of the leading global suppliers or their ownership is present at various points and stages, which could affect the sector's ability to continue delivering. Recent disruptions in the semiconductors supply chain have been fuelled by additional uncertainties in demand triggered by the COVID-19 pandemic. The global chip shortage in 2021, originally concentrated in the automotive industry, was brought about by changing consumer habits driving new surges in demand for electronic devices, together with challenges in chip capacity allocation (Statista, 2022).

Various studies show that production of certain components relevant to data servers and storage, face increased challenges to achieve greater market diversification, given the massive economies of scale required to compete, the large investments in capital equipment and a very thin profit margin for producers (Paumanok, 2020). Barriers to entry are said to be relevant for example in thick film chip resistors, the production of which is almost non-existent in the US and Europe, with China and Japan being the largest producers.

In China, the presence of many upstream manufacturing companies, as well as the development of raw materials production, are all collectively contributing to growth, raising further the concentration, intensification and verticalisation of production. The rare earths, which are found to be amongst the most critical raw materials, have, for several years, been produced almost exclusively in China or by Chinese companies operating across the Chinese border into Myanmar (Adamas Intelligence, 2022). China also leads the extraction of other ten raw materials required for data servers and storage. Because the large percentage of variable costs in the production of certain electronic components is related to raw materials, the implications of the traditionally high volatility of raw materials prices are substantial. For example, in recent years, thick film chip resistors production has been severely impacted by the increase in the price of ruthenium (Paumanok, 2020).

Additional threats to this technology lie in the fact that the same raw materials, components and assemblies are central to many other technologies. They are used across a range of applications including aerospace and defence systems (with emphasis on satellite demand), core telecommunications networks, automotive and consumer electronics, which are expected to witness significant growth in the future. However, a broadening scope of applications is also a driver of changes in the data servers and storage segment. For example, the increasing electronic content in vehicles can provide opportunities for innovations in processes and technology (Technavio, 2022). The increasing budgets for R&D of innovative satellite-based products, propelling the growth of the aerospace industry in Europe, can provide opportunities for manufacturers (AMR, 2021).

2.10.5. Key observations and recommendations

Data centres and related IT infrastructure, including data server and storage equipment, are key resources for essential sectors and services, including government, energy, transportation, healthcare and finance.

While the EU holds a reasonable share of processed materials and components for the production of data server and storage equipment (13% and 10%, respectively), its production share is only marginal at the assembly and super-assembly levels (<1%). Assemblies and super-assemblies are dominated by US suppliers, accounting for 58% and 50% of global production at each stage, respectively. The markets for components are also headquartered in the US (27%) and Taiwan (21%).

[34] To an extent, this dominance was not clearly demonstrated as supply risks in this study have been often measured in terms of company headquarters location as a proxy for where the technology is produced.

In addition to a geographic concentration, it is noted that some large companies hold considerable shares of the markets. This is also linked to the development of verticalised production models[35].

Most raw materials are used in these essential applications in very small quantities, below 1% of current global consumption, which does not in principle pose an unacceptable risk. However, demand for the rare earths can call on a significant proportion of what is available on the global market – around 1.5% in the case of neodymium and dysprosium and up to 6% in the case of terbium. This is a pressure point for a technology still very much reliant on high-capacity HDDs, especially as the rare earths are also required for other critical technologies which are far more resource-intensive and where exponential growth is expected (e.g. wind power and EV traction motors).

The following risk mitigation strategies could be considered.

- **Develop new advanced manufacturing capacity domestically.** Enhancing the resilience of the supply chain for EU data servers and storage means building and maintaining some advanced manufacturing capacity domestically, especially at the assembly and super-assembly levels. This should aim to address the most sensitive needs in critical applications, covering at least the expected domestic consumption.
- **Support the competitiveness and resilience of EU producers against risks of market distortion.** Given significant entry barriers for European manufacturers, on markets characterised by substantial economies of scale, there is a need for effective investment and incentives to create a level playing field with global competitors and contribute to their competitiveness against alternative available locations in Asia. For example, according to the OECD (2019), building up semiconductor capacities and facilities in certain areas may prove challenging if met with little support in the form of below-market debt and equity and R&D investment incentives.
- **Upgrade the capabilities of the domestic industry**. The introduction of new capacity ready for mass production in the EU could effectively be achieved by drawing on and consolidating pre-existing advanced manufacturing infrastructure. In this study, EU leadership has been identified with regard to a number of relevant elements such as copper semis, epoxide resins, flame retardant chemicals, GaAs, glass fibres, silicon carbide, analogue and 10-22 nm logic semiconductors, amongst others. These are all produced in the EU and constitute at least 10% of global supply.
- **Invest strategically in the rare earths value chain.** At the raw materials level, notably concerning rare earths, EU policies should further encourage strategic investment to develop leadership in the circular economy, as endorsed for example by the European Raw Materials Alliance (ERMA) (Gauß et al. 2021).
- **Encourage the substitution of highly critical raw materials**. There are success stories in the substitution of critical raw materials in the data servers and storage supply chain. For example, ceramic capacitor producers, especially those with high levels of palladium in their electrodes, have transferred production to Ni-based electrode systems, hedging against changes in the cost of Pd and reducing their exposure to the PGMs supply chain (Paumanok, 2020). As far as permanent magnets are concerned, research and development activities have concentrated in recent years on reducing dysprosium and terbium usage. Further progress to reduce and completely eliminate their current consumption would seem at least possible (e.g. Gauß et al. 2021).
- **Further encourage R&D activity**. While barriers may be present at all stages, they tend to become less relevant with regard to innovation. The EU can thus reaffirm its position within and across the global supply chain by ensuring a contribution to technology development with research and intellectual property, as well as strong protection for IP rights, in a sector manifestly characterised by ongoing technological progress (SIA/BCG, 2021). Priority areas for upstream research include materials processing, reduction of REE content, use of process waste and of recycled material to offer cost-effective and reliable products (e.g. Gauß et al. 2021). The EU

[35] E.g. Samsung is the key vendor for both DRAM and NAND and is also a major manufacturer of HDD and SSD, semiconductor materials and devices, and passive electronic components; Toshiba produces thin-film ceramic substrates, semiconductor materials, and storage devices; HiSilicon and parent company Huawei produces semiconductor wafers and devices, servers, storage devices, ethernet switches, providing an important global share of cloud IT infrastructure.

should also build on ongoing initiatives and improve cooperation amongst stakeholders. The Open Compute Project (OCP) Community includes hyperscale data centre operators and industry players, joined by telecom, colocation providers and enterprise IT users, working with vendors to develop and commercialize open innovations that, when embedded in product are deployed from the cloud to the edge (OCP, 2023).

- **Address labour supply constraints and focus on building skills**. Access to high-skilled talent is also deemed critical for certain R&D-intensive supply chain elements such as semiconductors. A survey carried out in 2020 suggests that talent risk is seen by 30% of respondents as one of the leading issues facing the semiconductor industry, alongside a return to territorialism/nationalism and supply chain disruption (Statista, 2022). The survey also pointed to other areas of improvement which include standards and regulations in new end markets like IoT, autonomous vehicles, 5G and artificial intelligence.

- **Promote reuse practices.** Finally, improved functioning of the supply chain can also be achieved through incentives to encourage the reuse of data servers and storage equipment, moving past the ingrained belief that physical destruction is necessary (Financial Times, 2022). Greater awareness from customers about the efficacy and reliability of practices on drive reuse, disseminated for example by large operators in the data centre market, could help foster the uptake of second-hand drives.

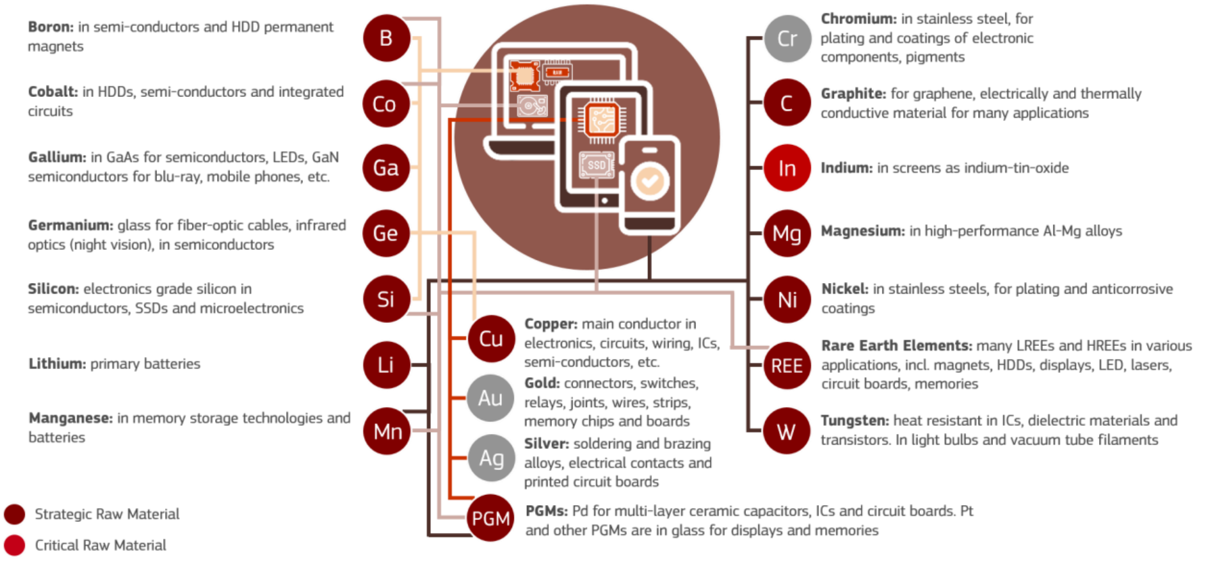
2.11. Smartphones, tablets and laptops

2.11.1. Introduction

As the most common ICT[36] devices, smartphones, tablets and laptops[37] affect people's everyday lives in many ways, whether in the workplace, in education, at home or on the move (Eurostat, 2016). Recently, these electronic devices were mentioned among the products in the most sensitive ecosystems where the EU can be considered highly dependent on imports from third countries (EC, 2021c). In 2017 the value added by ICT services and manufacturing sectors represented 3.7% and 0.3%, respectively, of GDP in Europe (JRC, 2020).

The COVID-19 pandemic accelerated the use of digital technologies for working, learning, entertaining, socialising, purchases and access to everything from health services to culture (EC, 2021a). On 9 March 2021[38], the European Commission presented a vision and avenues for Europe's digital transformation by 2030 which will drive an increasing demand for ICT devices and services.

Figure 64. Selection of raw materials used in smartphones, tablets and laptops and their function



Source: JRC analysis.

Smartphones, tablets and laptops are complex technologies that use a large number of raw materials in various parts. Smartphones, tablets, and laptops are equipped with numerous chips with specialised tasks. Logic chips are used for processing tasks for example, the central processing unit (CPU), also known as the "brains of a computer") and the graphics processing unit (GPU), a specialised processor which renders images, animations and video for output to a display (EC, 2017). Most personal computers have at least one component which provides a means of permanently storing data using memory chips, for example random access memory (RAM) (EC, 2017). Other parts such as audio devices and radio transmission utilise analogue chips. Electronic grade silicon metal, boron, germanium, gallium, indium, cobalt, graphite and lithium, are among the raw materials used in semiconductors chips. In addition, some noble gases such as krypton, neon, and xenon are used in the

[36] Information and communication technology, abbreviated as ICT, covers all technical means used to handle information and aid communication. This includes both computer and network hardware, as well as their software (Eurostat, 2016).

[37] A smartphone is a hand-held electronic device designed for mobile communication, internet connection and other uses (e.g. multimedia, gaming). It can be used for long-range communication over a cellular network of specialized base stations known as cell sites (EC, 2021b). A tablet can be defined as a 'type of computer lacking a physical keyboard, relying solely on touchscreen input, having solely a wireless network connection (e.g. Wi-Fi, 3G), and primarily powered from an internal battery. A laptop/notebook computer is a computer designed specifically for portability and intended to be operated for extended periods of time either with or without a direct connection to a main power supply (Tecchio, P., et. al., 2018).

[38] European Commission Press Release on 9 March 2021: Europe's Digital Decade: Commission sets the course towards a digitally empowered Europe by 2030. The EU's ambition is to be digitally sovereign in an open and interconnected world, and to pursue digital policies that empower people and businesses to seize a human centred, sustainable and more prosperous digital future (European Commission, 2021d).

manufacturing of semiconductor chips. Smartphones, tablets and laptops are powered by battery cells made of nickel, cobalt, aluminium, manganese and lithium. The permanent magnet, a component made from rare earth elements, is used in audio devices, displays and vibrating alarms. Copper is used in connectors, printed circuit boards and wiring. PGMs are used in capacitors and indium as indium-tin-oxide is used in screens.

The innovation of the hardware (components chips, screens, etc.) and software (Operating Systems, etc.) in smartphones, tablets, and laptops technology runs in parallel (EC, 2020b). There are several trends in the technology designs of smartphones, tablets and laptops in terms of hardware. **Increasingly powerful chips will be developed.** In the past 60 years**,** the progress in the semiconductor field has followed Moore's law, which predicts a duplication of the number of transistors in an integrated circuit (IC) every two years and conversely a reduction of the transistor size (EC, 2021b). Innovation leads to thinner and more powerful chips consuming less energy (EC, 2021b). The Intel processor, for example, has gone from 10 μm technology node[39] in 1972 to 7 nm in 2021. To date, some high-end smartphones use chips with 5 nm technology nodes. **Storage solutions have witnessed a shift from HDD to SSD.** The miniaturisation trend applies also to the memory chips, including those used for memory storage. In addition, other technological advances have occurred in memory storage. Historically, HDD (hard disk drive) technology has always been used in the computing segment. Compared to HDD, SSD (solid-state drive) technology has high read and write performance, shock resistance (no moving components) and low power consumption (no motors unlike HDDs) and is smaller lighter and silent compared to HDD. SSD technology is expensive but extensive use of flash memories in tablets and smartphones has helped reduce prices by increasing quantities (EC, 2020b). Thus, SSD technology is very efficient and has been commercialised for many years. Lastly, the **increasing market share of OLED screens.** OLED (Organic Light-Emitting Diode) production capacity for smartphones has increased from 5.4% in 2016 to 31.9% in 2022 (Statista, 2017). The demand for OLED display comes from high-end smartphones (EC, 2020b). The reason for its increasingly popularity is that OLEDs have a very fast response time, can be used for curved and flexible screens, and provide good view angles and an always-on display mode (EC, 2021b).

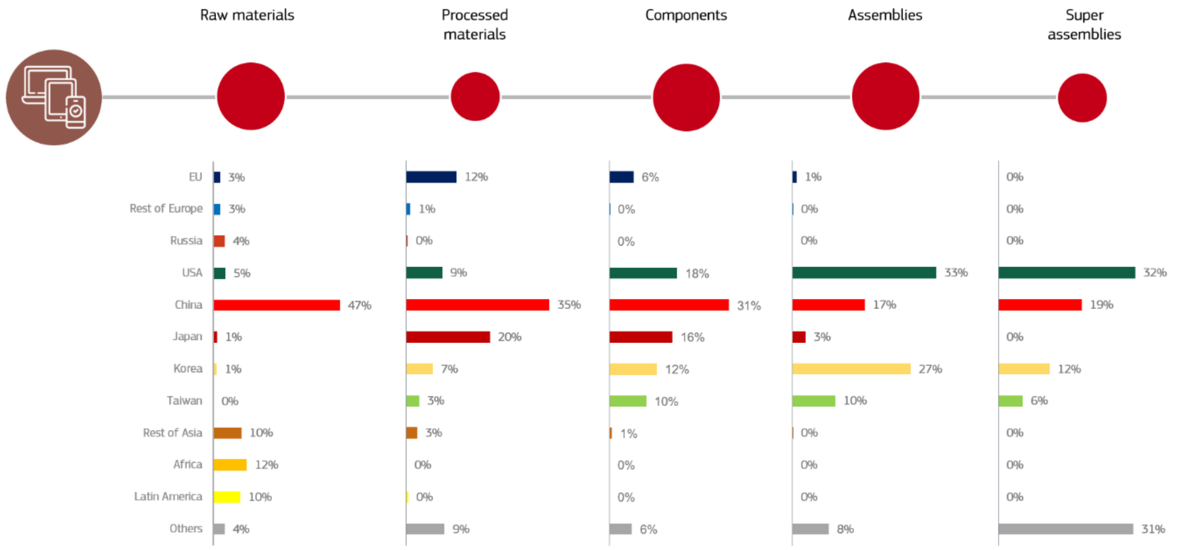
2.11.2. Current supply chain bottlenecks

Smartphones, tablets and laptops are composed of more than 300 parts with a complex global supply chain network. Table 28 in Annex 2 presents the elements identified at each stage of these technologies from raw materials to super-assembly (non-exhaustive). Smartphones can be assembled in China, use semiconductors designed in the United States but made in Taiwan, using raw materials and chemicals from Japan and machines made in Europe. Any disruption at any stage in the supply chain could impact the whole supply chain, not only to the EU but also globally. In these complex technologies, although the raw materials stage is found to be critical for the EU, it is only a part of the potential challenge facing the supply chain, as the manufacturing of components, assemblies and final product take place mostly in Asia (EESC, 2019).

Figure 65 shows the overview of supply risk at all stages and Figure 66 by elements.

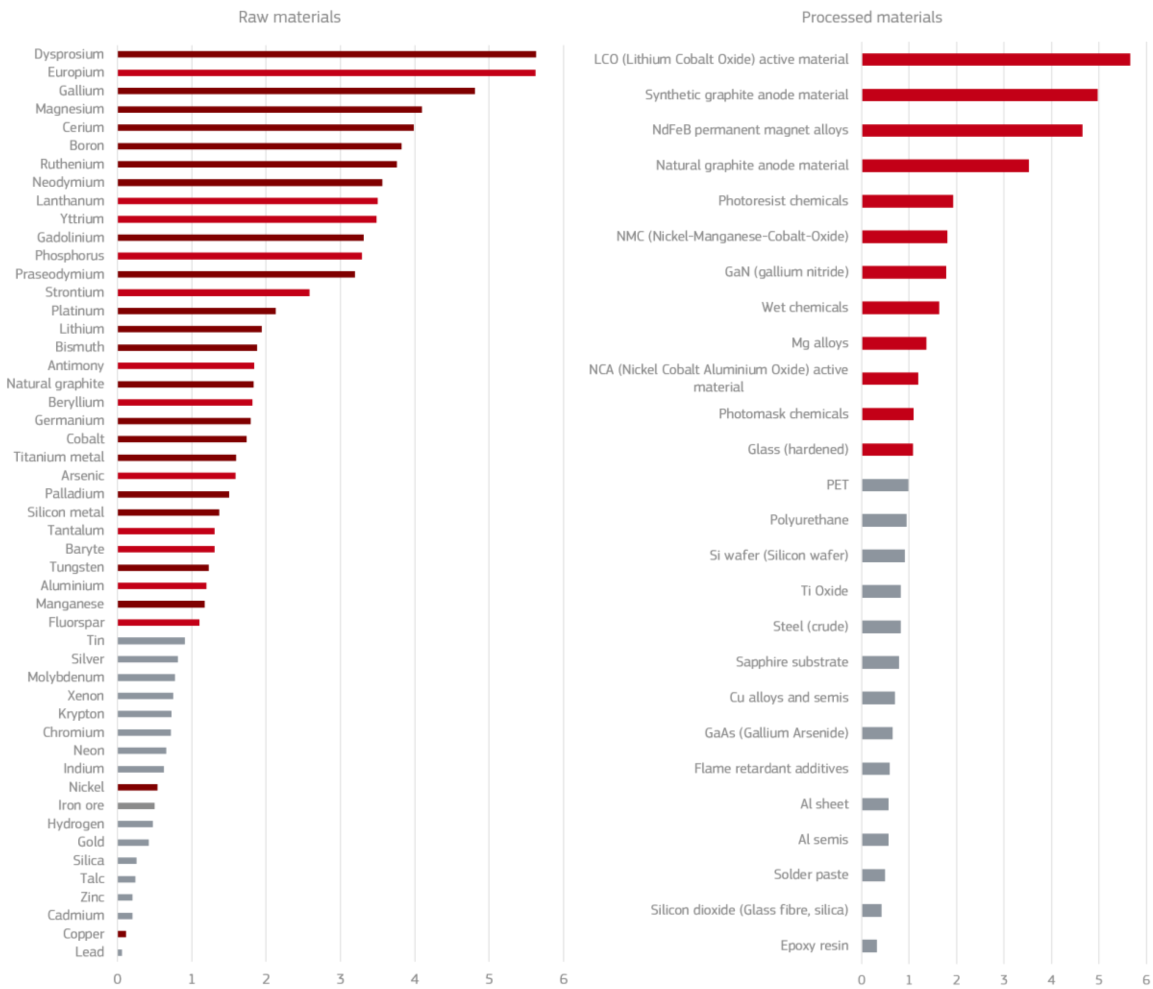
[39] In terms of semiconductor device, what is considered as a product at this level is a semiconductor die in a package that has gone through assembly, packaging, and testing (back-end manufacturing)

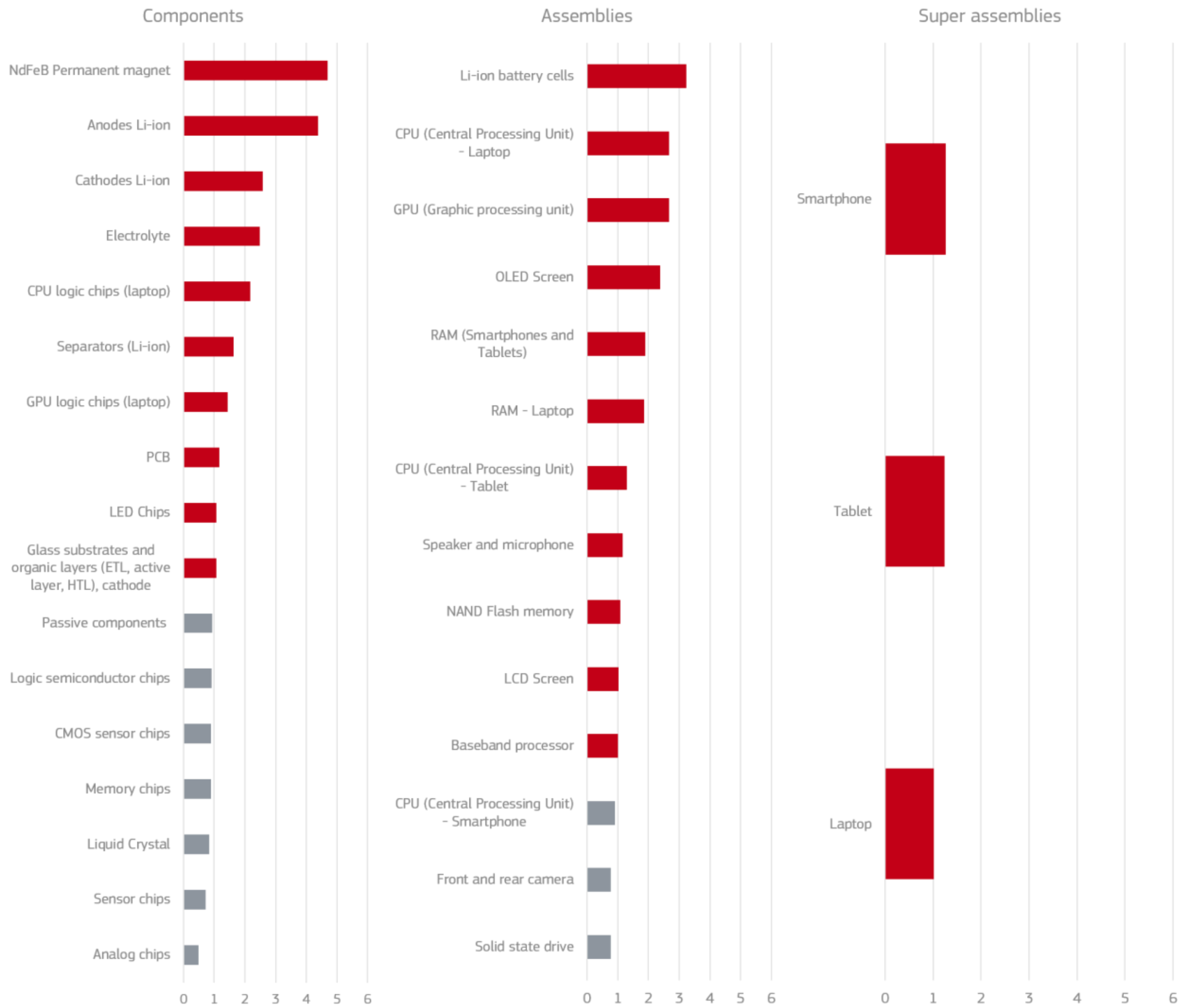
Figure 65. An overview of supply risks, bottlenecks, and key players along the supply chain of smartphones, tablets and laptops



Source: JRC analysis.

Figure 66. Detailed Supply Risk of selected elements in the smartphones, tablets and laptops supply chain





Source: JRC analysis.

China has the biggest share of most of the raw materials in digital technologies by 47% of share, followed by Africa as continent (12%). The EU share is approximately 3%. The higher supply risk for raw materials is associated with the manufacturing of the semiconductor, magnet and battery. Electronic-grade silicon metal (higher than nine nines purity, 99.9999999%) and boron (5N), high-purity germanium and gallium (6N-7N) are among the critical raw materials used in semiconductors. The production of these raw materials is currently dominated by China, except for boron in Türkiye. For silicon metal, despite the abundance of silicon, the production of high purity silicon is capital- and energy-intensive. In the case of permanent magnets, the production and processing of rare earths into permanent magnets are dominated by China.

The average supply risk for the processed materials considered at this stage is high. The elements with highest potential supply risk at this stage are permanent magnet alloys for speakers and vibrating alerts, synthetic and natural graphite and lithium cobalt oxide active material for the battery, photoresist, photomask and wet chemicals, gallium nitride for the manufacturing of semiconductors, and hardened glass for screens.

All the active materials of Li-ion battery cells and permanent magnet alloys (NdFeB) are produced predominantly in China. Japan's position is strong in the manufacturing of semiconductor materials and chemicals, such as silicon wafer (57%), gallium nitride (85%), photomask chemicals (53%), wet chemicals (60%), and photoresist chemicals (90%). Therefore, the photolithography chemicals have a high supply risk as its supply is mostly manufactured by Japanese companies. In screen technology, the hardened glass has a high supply risk with Taiwan, China, Japan, and South Korea as the main players in the market.

The EU has an important share in the production some of the lower-risk processed materials such as PCB-epoxide resin (32% of share), silicon dioxide used in glass fibre (44%), copper semis and alloys (12%), and gallium arsenide used in radio-frequency semiconductors (29%), and silicon wafer (14%).

The average supply risk at components stage is high. In particular, the elements with a high supply risk are laptop CPU chips, lithium-ion battery cell components (anode, cathode, and electrolyte), permanent magnets (used in speakers, fans, vibration alert), PCB board, LED chips, Screen components (glass substrates, organic layers, active layers), Li-ion battery separators, and GPU logic chips for laptops.

Smartphones, tablets and laptops use semiconductor chips with a node size of less than 45 nm. The main producers of consumer laptop CPUs, AMD and Intel, both United States-based companies, have been using 14 nm technology and are currently moving towards 10 nm and below. In mobile phone technology, between 2015 and 2016, the 28 nm process began to be used in mobile phone application processors and basebands at scale. Nowadays the market has matured and is expected to have a long lifespan on these products due to its good balance between cost and performance (He, H., 2020).

In general, Taiwan is a leader in the fabrication capacity of logic semiconductors used in processors with a 47% share, followed by the United States with 27%. China is ahead of other regions in the production of Li-ion battery cell components (more than 50%), PCB (40%), and permanent magnets (90%). South Korea holds 46% of memory semiconductor fabrication capacity, while Japan supplies passive components (47%), discrete and analogue semiconductor technology (27%) and CMOS camera sensors (46%). The United States has the major share (39%) of sensor chips fabrication. Europe is mainly present in analogue semiconductor fabrication capacity. In terms of analogue chips, Europe holds 24% of the global capacity.

The components with low supply risk are memory semiconductors, liquid crystals used in screens, passive components, CMOS chips used in cameras, other logic semiconductors chips<45 nm (used in CPUs of smartphones and tablets), discrete, analogue, and other semiconductor (DAO) chips such as sensors, and other integrated circuits necessary for connectivity, screens, speakers and more.

The average supply risk at assembly stage is high. The individual elements with a high supply risk are CPU, GPU, RAM, NAND Flash memory, baseband processor, LCD and OLED screen for smartphones, lithium-ion battery cell, speaker, and microphone. The United States is a leader in the design of CPUs and GPUs (100%)[40] for laptops, and CPUs for tablets (54%). South Korea is the principal manufacturer of memory storage RAM and NAND, each with a 75% and 45% share, and LCD and OLED screen technology with a 33% and 84% market share. European semiconductor producers account for only 2% of the global production of semiconductors dedicated to PC & data processing (EC, 2020b). The manufacturing of battery cells and packs for mobile ICT devices is geographically concentrated in East Asia (See the chapter on battery for more detailed information). The major companies in the smartphone battery market in terms of revenue share in 2020 are Amperex Technology (China), LG Energy and Samsung SDI (South Korean), each with 42%, 26% and 15% shares. The EU depends on imports of battery cells, which exposes the industry to supply uncertainties and potentially high costs (EC, 2020a). China is a large player in the production of audio devices (38%). Cameras and SSDs have a low supply risk with supply spread in several countries, mostly in east Asia.

The supply risk at super-assembly stage is found to be high. Based on the headquarters of the major brands in the market, South Korea, China, and the United States are the main players in smartphones, tablets and laptops technology. In general, the EU is not a major player in the computing industry (EC, 2020b). In recent years only 2-3% of all mobile phones sold in the EU have been manufactured in the EU (EC, 2021b). Over the past 30 years, the ICT industrial base has evolved from being vertically integrated to being highly outsourced, with most major brand companies outsourcing nearly every step of and input into the manufacturing process (US Department of Commerce and US Department of Homeland Security, 2022). The EU relies greatly on the import of these technologies due to the small domestic manufacturing capacity of the final products. The only PC manufacturer in the EU is the German company Wortmann AG. This company still produces desktop PC, laptops and tablets (EC, 2020b).

Beyond raw materials availability, the semiconductor value chain involves a high amount of capital in R&D and specialised equipment. Despite the limited capacity to produce smartphones, tablets and laptops, the EU stands as a world leader in terms of semiconductor equipment production, for example, lithography and wafer handling technology (EC, 2020b). In 2021 the EU had 20% of the total semiconductor manufacturing equipment market (a 92% share for optical exposure equipment, 74% microlithography and mask-making equipment, and 50% of other equipment for wafer manufacturing) (TechInsights, 2022).

[40] Some companies design and manufacture their own chips in-house while others do not have their own fabrication capacities (fabless).

As other major industrial countries such as the United States, South Korea, Japan and China invested greatly in the semiconductors sector (see geopolitical dimension), the EU adopted the European Chips Act in 2022. This Act aims to double the market share in semiconductors from 10% to at least 20% by 2030, for example through a support for foundries and facilities which will design and produce semiconductor components for the European market. The amount of investment for this sector was EUR 43 billion (European Parliament Think Tank, 2022).

Regarding raw materials, the EU has been putting effort into regulating waste management and secondary raw materials recovery, for example with the introduction of Software updates directive[41], WEEE directive and the RoHS directive[42]. The aim of these directives is to guarantee lifetime extension of electronic products which will contribute to the efficient use of resources and the retrieval of secondary raw materials through re-use, recycling and other forms of recovery. In 2016, in the context of the Ecodesign Working Plan, the Commission announced a separate strand of work on ICT products (including smartphones, tablets and laptops) in order to determine the best policy approach for improving their energy efficiency and wider circular economy aspects. The future output of this Ecodesign project will be policy recommendations on the inclusion of Ecodesign criteria to improve the material and energy efficiency of the products (EC, 2023b). Thus, the quantity of raw materials recovered at the end-of-life of the product is expected to increase.

Moreover, the circular economy action plan for secondary raw materials includes a number of actions such as introducing requirements for recycled content in products, ensuring the smooth expansion of the recycling sector in the EU, developing further EU-wide end-of-waste criteria for certain waste streams, standardisation, and assessing the feasibility of establishing a market observatory for key secondary materials.

2.11.3. Projected 2030 material demand

The demand for tablets and laptops showed an increase during the pandemic in 2020 and 2021. Due to the need for telework during this period, the demand for digital infrastructure increased substantially (de Vet, J.M.D.E., et. al., 2021).

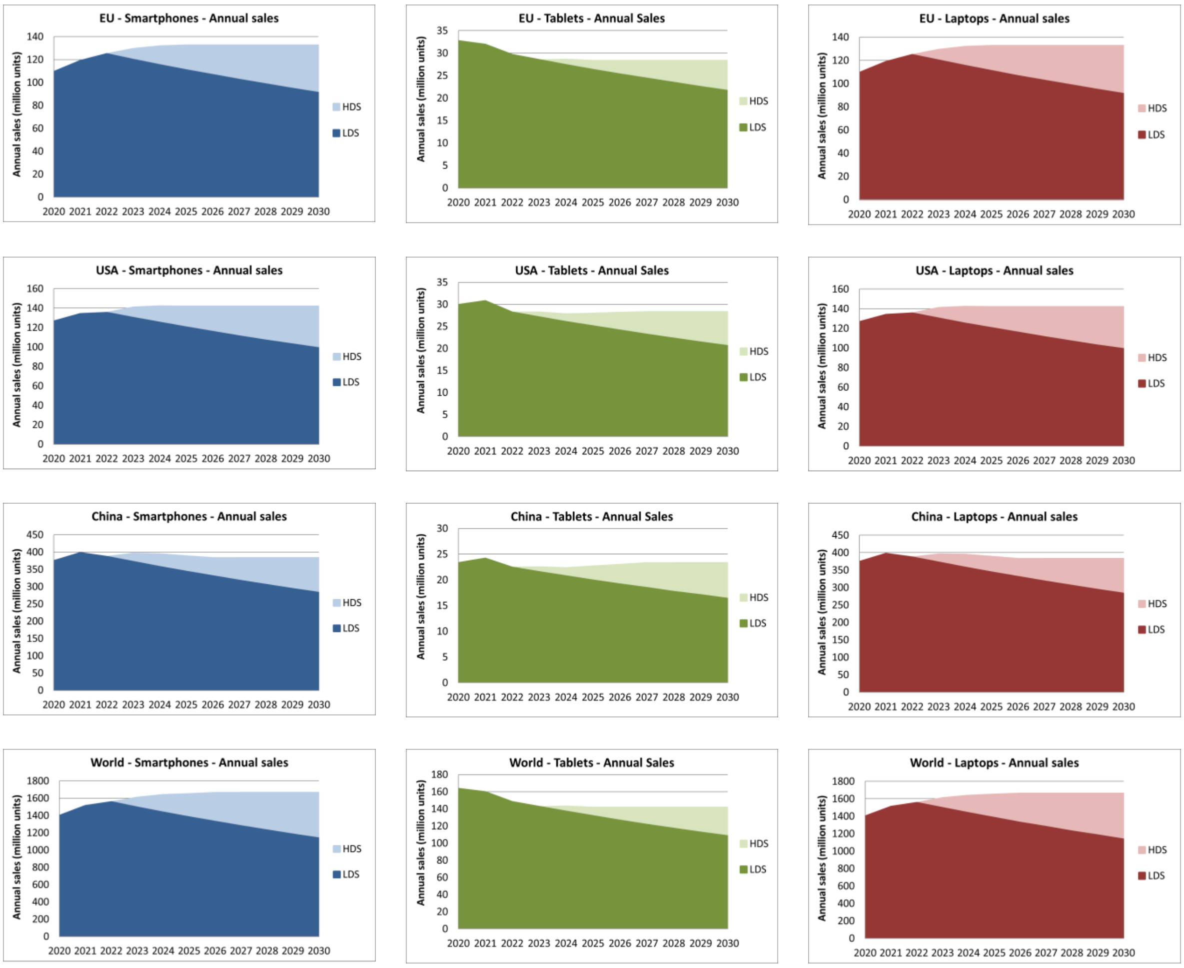
The future demand scenarios for the EU, United States, China, and the Rest of the World is presented in Figure 67.

The scenario of high demand is based on market sales forecasts at saturation level. The low demand scenario assumes that the implementation of ecodesign and energy labels, expected to extend the product lifetime, would be in place from 2023 to 2030. This scenario would lead to declining sales figures. In both scenarios, the materials usage is assumed to remain constant. In the high demand scenario, the yearly material demand would increase by 1.1 times and in the low demand scenario by 0.8 times compared to material demand in 2020.

[41] Software updates Directive (EU) 2019/771. This directive concerns contracts for the sale of goods covers among other aspects information requirements for security updates and guarantees.

[42] The EU introduced the WEEE Directive and the RoHS Directive in 2012, With this directive batteries, printed circuit boards, liquid crystal displays have to be removed from separately collected mobile phones, smartphones and tablets (EC, 2021b)

Figure 67. Technology deployment for smartphones, tablets and laptops

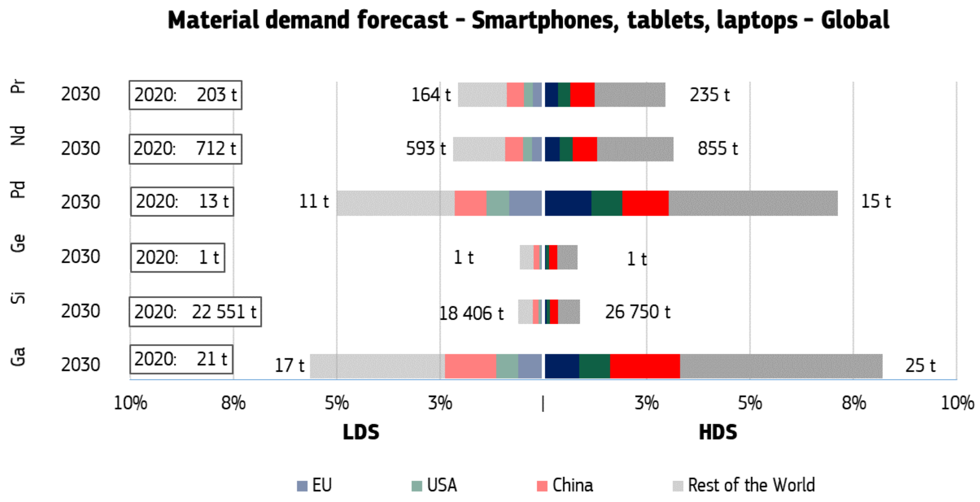


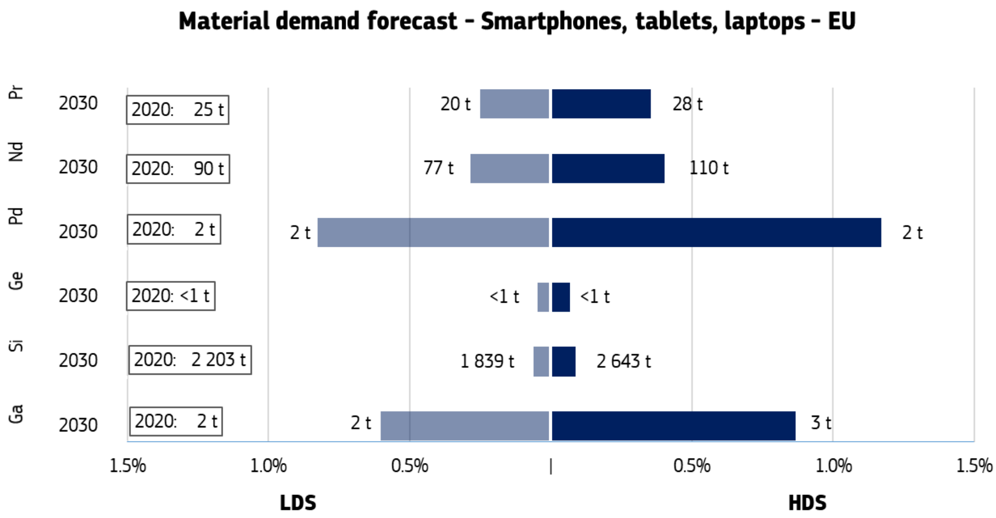
Source: JRC analysis.

Figure 68 reflects the material demand forecast for some raw materials, namely silicon metal, gallium, germanium (used in semiconductors), neodymium and praseodymium (REEs), and palladium (used in electronic components). The material content used in these figures were based on scientific publications[43]. Given the short cycle of smartphones, tablets and laptops and the variability of products from each OEM, the material consumption figures may not represent accurately the material consumption used in the technologies in this assessment. Nevertheless, smartphones and personal computing represented 46% of the market for semiconductor applications in 2020 (ASML, 2022).

[43] The material content of smartphones, tablets, and laptops were estimated and elaborated based on the data from Bookhagen, B., et. al. (2020), PROSUM project and publication by Wagner M.A., et. Al. 2021, and Preparatory study on the Review of Regulation 617/2013 (Lot 3) – Computers and Computer Servers (draft report) Task 4 report Technologies (EC, 2017)

Figure 68. Material demand forecast for smartphones, tablets and laptops: global (top) and focus on the EU (bottom)





Source: JRC analysis (Ga = gallium, Nd = neodymium, Si = silicon metal, Ge = germanium, Pd = palladium, Pr = praseodymium).

2.11.4. Geopolitical dimension

Semiconductors are at the very heart of the geopolitical scene, with tensions rising between the US, China and Taiwan (JRC, 2022). In September 2020, the US government sanctioned China's largest chipmaker, Semiconductor Manufacturing International Corporation (SMIC), citing military end-use in China. Two months later, China released its fourteenth five-year plan, advocating autonomy in semiconductor production as a way to achieve technological self-reliance (also based on foreign investments). In 2021, the US Army War College suggested that the Taiwan Semiconductor Manufacturing Company (TSMC), the most important chipmaker in the world and China's most important supplier, could have been the main reason behind the pursued Chinese reunification with Taiwan (JRC, 2022). The United States has also been lobbying the Dutch government to stop the photolithography equipment company ASML from selling its machines to China. To date, ASML has been unable to ship its most advanced extreme ultraviolet lithography systems to China as it cannot obtain an export license from the Dutch government (Bloomberg, 2022), (Khan, S.M., 2020).

The government of **China** has been supporting the development of its electronics industry, subsidising the construction and equipment of PCB manufacturing plants. China also supported the growth of its LCD industry by providing government subsidies and reduced taxes to domestic display manufacturers (US Department of Commerce and US Department of Homeland Security, 2022). Semiconductors were highlighted as a key area of the Made in China 2025 plan, a government initiative that aims to boost the production of higher value products. China aims to produce 40% of the semiconductors it uses by 2020 and 70% by 2025 (Kharpal, A., 2019). Currently, only 16% of the semiconductors used in China are produced in the country, and only half of those are made by Chinese firms, according to a report by the Center for Strategic and International Studies (CSIS, 2019). In other words, the country is still reliant on foreign technology, largely American (from the same source as above). In addition to massive investment in semiconductor sector, the government supports semiconductor production in China by offering a range of incentives, grants, cheap utility rates, low-interest loans, tax breaks, and free or discounted land (JRC, 2022). In China, semiconductor investment is mainly driven by The National Integrated Circuit Industry Investment Fund. In 2020, investment in China's semiconductor companies reached EUR 32.8 billion[44] (JRC, 2022). In 2019 the fund raised another EUR 29.9 billion in a new funding round from the Chinese Ministry of Finance, state-owned enterprises, and local governments. Furthermore, hundreds of local funds have been created to support the industry with more than EUR 43.9 billion of funding. In December 2022 Reuters (Zhu, J.,2022) reported investments of CNY 1 trillion (approximately EUR 133.7 billion) over a five-year period to support domestic chip production in response to the US sanctions. Chinese companies also receive tax breaks for investing in assembly, packaging and R&D of chips (Gooding, M., 2022).

To date, the **United States** applies multiple types of export controls on China. The US has been tightening semiconductor export controls with stricter licensing policies (including for deemed exports for Chinese nationals). These controls cover various types of semiconductor manufacturing equipment (SME), chips, materials, software, and technical data to all Chinese entities (public and private)[45]. Export license decisions are made on a case-by-case basis, historically resulting mostly in approvals (Khan, S.M., 2020). The US has also imposed stricter controls on major Chinese entities like Huawei and expanded military end-use and end-user controls to cover a wider range of Chinese end-uses and end-users, such as SMIC (Khan, S.M., 2020).

In June 2021, US Customs and Border Protection issued a 'withhold release order' targeting a major supplier of metallurgical silicon powder over allegations that it used forced labour. The US also blacklisted some Chinese major manufacturers of monocrystalline silicon and polysilicon used in solar panel production said to have been involved in human rights violations in Xinjiang.

The global value chain of semiconductors is at the centre of the ambitious national investment plans of the United States (JRC, 2022). In 2021, with the Fabs Act, the US established an investment tax credit to incentivise domestic semiconductors manufacturing. In August 2022, President Joe Biden signed the CHIPS and Science bill, proposed in 2021, into law, authorising EUR 48.6 billion[46] in subsidies for semiconductor production and boosting funding for research (Johnson, L., 2022) (Shepardson, D., Mason, J., 2022).

As the world leader in semiconductor foundries and integrated circuits, the success of the **Taiwanese semiconductor industry** can clearly be linked to government policy and the prioritising of capital in the development of the industrial and academic foundations on which prosperity depends (Chang et al., 2021). This effort has continued to date, via the Invest Taiwan initiative. In this initiative, Taiwan grants tax credits, help securing land, water and electricity and the coordination of investment in the semiconductor sector.

Japan, the market leader in semiconductor materials, experienced geopolitical tensions with South Korea in 2019. This situation resulted in Japan imposing export controls on semiconductor materials to Korea, impacting approximately EUR 6.5 billion[47] in semiconductors per month (BCG, 2021). Incidents and natural disasters in Japan have also impacted the global supply of semiconductor materials and products. Japan has announced

[44] Conversion from USD to EUR was done by referring to Bloomberg's exchange rate (https://www.bloomberg.com/quote/USDEUR:CUR) at 0.9351 Euro/dollar dated on 13/02/2023.

[45] Among SME, these controls cover some types of lithography, deposition, ion implanting, testing, and wafer handling tools. Excluded: etching, process control, assembly, and wafer manufacturing tools. The high-end semiconductors controls cover field-programmable gate arrays (FPGAs), partly cover central processing units (CPUs), and do not cover graphics processing units (GPUs); it remains unclear whether they cover application-specific integrated circuits (ASICs) customized for artificial intelligence. Among materials, these controls cover certain types of masks, resists, consumable gases, wafers, and materials that become wafers and chips. Among software, these controls cover software used with or to help produce SME, but not electronic design automation (EDA) software used to design chips. Technical data associated with the above technologies is also controlled. These controls also require US employers to apply for "deemed export licenses" for Chinese nationals who would access controlled technical data or source code in the United States during their employment. (Khan, S.M., 2020)

[46] Converted from USD 52 billion

[47] Converted from USD 7 billion

investment plans worth EUR 6.35 billion[48] to attract advanced chip manufacturers, including Taiwan's TSMC, to build production facilities (European Parliament Think Tank, 2022).

South Korea has approved up to EUR 60.8 billion[49] in support for semiconductor supply chain by 2030 with the ambition to attract more than EUR 420.8 billion[50] in investment from the private chips sector. The support also includes tax incentives and relaxed regulation (JRC, 2022).

The Russian war on Ukraine has raised concerns regarding the supply of rare gases for semiconductor production, especially neon. Both Russia and Ukraine are significant sources of rare gases with Ukraine as a leading global supplier of purified neon gas (EC, 2022c).

2.11.5. Key observations and recommendations

The outsourcing strategy that became popular in the 1990s has moved most of the manufacturing capacity of electronic components and assemblies from areas such as Europe and the United States to Asia. Thus, the supply chain of ICT products has become global, with interdependencies between countries with capacity in different aspects of the manufacturing chain. In the advanced semiconductor technologies used in ICT products, the EU suffers a major risk of supply due to limited manufacturing capacity. The EU also faces supply risks at the stages of raw materials, processed materials, and components, as they are mostly produced elsewhere. Moreover, past events have shown that geopolitical tension, industrial accidents, and natural disasters may influence the supply risk of certain materials or components. However, aiming for the vertical integration of the manufacturing of smartphones, tablets and laptops is highly challenging, if not impossible, for all players, as various competences and manufacturing capacity have stabilised at a competitive price. The EU must also compete with other major industrial countries who have invested heavily in the semiconductors sector.

- **The promotion of more balanced interdependencies will improve Europe's position, leverage and supply security in the global semiconductor value chain** (European Parliament Think Tank, 2022). Europe is home to world-leading semiconductor organisations producing specialised semiconductor manufacturing equipment and semiconductor processed materials.
- **The improvement of manufacturing opportunities in the EU is already in motion**. The European Chips Act states as one of its goals the building and reinforcing of capacity to innovate in the design, manufacturing and packaging of advanced chips[51]. Through the Act, the EU aims to play a leading role in the design and manufacture of the next generation of microchips, down to nodes of two nanometers and below.
- **Addressing skills shortages, attracting talent and supporting the emergence of a skilled workforce are crucial to the development of the sector.** Demand for talent in the electronics sector has been increasing in the last 20 years. The microelectronics industry in Europe was directly responsible for 455 000 high-skilled jobs in 2018 (EC, 2022b). Yet, retaining highly skilled talent remains one of the sector's main challenges (EC, 2022b).
- **Promoting foreign investment cooperation with overseas partners** could bring in the expertise and capital needed at a scale which will make it possible to expand and upgrade European semiconductor manufacturing (European Parliament Think Tank, 2022).
- **Promoting recycling, reuse and substitution** through careful product design, ensuring more efficient use of materials and energy, and easy disassembly of components and materials identification. In 2022, the EU proposed the first draft of ecodesign requirements regulations for smartphones and tablets. These regulations aim to ensure that mobile phones and tablets are designed to be energy efficient and durable, and easy to repair, upgrade, maintain, reuse and recycle (EC, 2023a).

[48] Converted from USD 6.8 billion
[49] Converted from USD 65 billion
[50] Converted from USD 450 billion
[51] As presented by DG CNECT at the informative session with stakeholders in March 2022(DG CNECT, 2022)

2.12. Additive manufacturing (3D printing)

2.12.1. Introduction

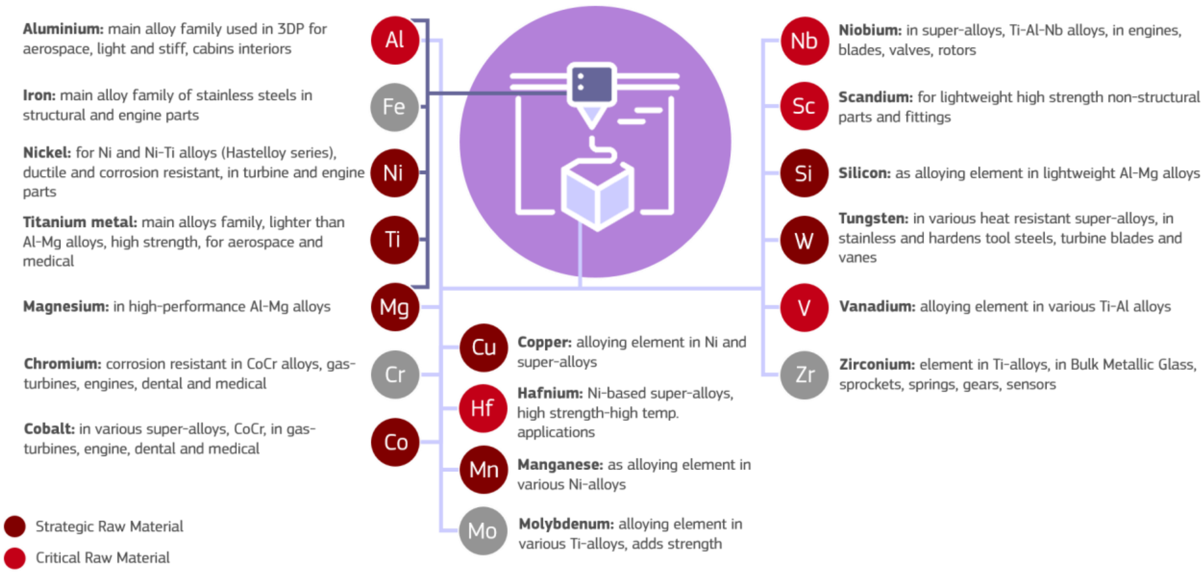
Additive manufacturing (3D printing) is a technology that turns digital 3D models into physical objects by building them up in layers. This technology enables small quantities of customised goods to be produced at relatively low costs (EPMA, 2021). Additive manufacturing offers key cost advantages for the production of low volumes of geometrically complex and materially simple objects and provides unprecedented design freedom for customisation and prototyping. The technology also offers valuable opportunities to strengthen resilience in value chains, especially in manufacturing sectors where spare part inventories can be costly (Andrenelli and López González, 2021). The automotive and aerospace sectors originally led its technological development. These sectors use AM for the creation of models and prototypes, for short-run production and for non-critical parts (Wohlers Terry et al., 2021).

The benefits of AM methods over conventional manufacturing methods are that no tooling is required, small production batches can be kept economical, designs can be adapted fast, products can be optimised for functionality, custom product manufacturing is feasible, with complex geometries, simpler supply chains are possible, with shorter lead times and lower inventories, and material waste can be reduced by as much as 90% (Vafadar et. al., 2021).

The trend in AM applications is shifting from prototyping to functional part manufacturing in various verticals. Particularly relevant sectors include automotive, aerospace and health, consumer goods, electronics, energy, industrial equipment and tooling, and construction, with varying degrees of maturity realised across these sectors (EC, 2021a). In particular, the area of metal AM, the focus of this assessment, experienced growth from 2017 to 2018, following the considerable (80%) increase in systems sold between 2016 and 2017 and high growth rates for 3D printers (EC, 2021a).

The AM system is composed of a printer and the metal AM material. The metals used in AM systems are primarily in powder, wire, filament, sheet, and tape form. Metal powder, for example, plays a very important role in the AM processes. The quality of metal powder used will have a major influence not only on the properties of the product, but also the build-to-build consistency, the reproducibility between AM machines, the production of defect-free components and the manufacturing defects on surfaces (EPMA, 2015).

Figure 69. Selection of raw materials used in additive manufacturing (3D printing) and their function



Source: JRC analysis.

The most common alloy families used in AM are powders of aluminium-magnesium, titanium, nickel, stainless steel and special alloys. These alloy families use specific quantities of additional alloying elements providing various material properties, such as cobalt, hafnium, niobium, magnesium, scandium, titanium, vanadium, tungsten and zirconium. Various titanium alloys are used for high-strength and lightweight applications (EC, 2020a). Steel, nickel-based alloys, and titanium products made up more than 68% of the available metals for AM in 2020 (Wohlers et al., 2021).

The metal AM processes are classified based on the feedstock format (wire/filament/sheet/powder/liquid) and thermal source (Vafadar, A., et.al, 2021). The most commonly used AM processes are material extrusion (ME), Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Material Jetting (MJ), and Binder Jetting (BJ)[52]. Powder bed fusion is the leading technology used for metal-based AM, with a market share of approximately 85% (Küpper et al., 2019).

AM still faces several challenges that condition its deployment and impact. The most significant barriers are a lack of standards, interoperability and certifications for machines, materials, products and processes (Eurofound, 2017). The cost of the raw materials and the requirement for post-processing in the form of smoothing and sanding or assembling can still be high (Ceulemans, J. et. al., 2020). The AM processes are generally suitable for unitary or small series and are not suited to mass production (EPMA, 2015). Regarding material choice, although many alloys are available, non-weldable metals cannot be processed by additive manufacturing and difficult-to-weld alloys require specific approaches (EPMA, 2015). The quality of parts, especially metal parts, is also an important aspect in AM as they may have some residual internal porosities (EPMA, 2015).

Many AM machine manufacturers are working in faster hardware (SAM, 2019), increasing the level of automation and freedom in design (Michelsen and Collan, 2020), hybrid machines, advanced monitoring solutions or simplification of material handling and recycling as well as integration with subsequent post processing steps (SAM, 2019). New materials and process improvements will enable new AM applications (Langefeld et. al., 2019). For example, APWORKS, together with Airbus, has developed Scalmalloy, a high-strength aluminium alloy for aerospace applications (APWorks, 2020).

2.12.2. Current supply chain bottlenecks

The key stakeholders in the value chain of additive manufacturing are the producers of machinery and equipment, AM material suppliers, service providers, and facility centres[53]. In the case of AM metal powder, its production involves several stages. The first stage involves the mining and extraction of ore to form a pure or alloyed metal product (ingot, billet and wire) appropriate for powder production; the second stage is the production of the powder, and the final stage is classification and validation[54] (EPMA, 2021). The supply chain of ore and metal extraction is well established and supplies a vast range of pure metals and specific alloys to global markets (EPMA, 2021). AM powders can be acquired either directly from the AM machine provider, third party companies, or from an atomisation company (Dawes et al., 2015).

In this assessment, AM system features raw materials, processed materials, and super-assembly stage. The list of the elements assessed in AM systems can be found in Table 29 in Annex 2. The AM system supply chain bottleneck is presented in Figure 70 and the supply risk by elements is shown in Figure 71.

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[52] ME constructs 3D part by dispensing melted metallic filaments through a heated extrusion nozzle in a pre-determined path. PBF uses thermal energy such as electron and laser beams to melt and fuses area of a powder bed, layer by layer. Directed Energy Deposition creates 3D part by selectively adds materials (either in the form of wire or powder) using a combination of a nozzle and multi-axis robot to a substrate. MJ process creates a 3D layer by selectively spraying to the target location in droplets with the use of UV light to cure and solidify the liquid material. BJ process deposits a liquid-state binder agent through a print head onto the powder bed to bind the powder and form a layer. SL technique bonds layer by layer of sheets of material supplied from a feed roller. The recent development in the metal AM market is metal filled filaments which can be printed using FFF machines. Bound Powder Extrusion (BPE) is another recent ME development in the metal AM market. In this technology, the filament consists of a plastic binding agent and fine metal powder that is extruded through a nozzle. The desired part is printed layer by layer in a fashion nearly identical to conventional FFF printing; however, this process is followed by two additional post processing operations: washing and sintering, to produce a final high density fully metal part. (Vafadar et. al., 2021).

[53] Commonly, there are various types of collaborations between these stakeholders with the objective to either shorten the time to market, R&D purposes related to materials, processes, etc.

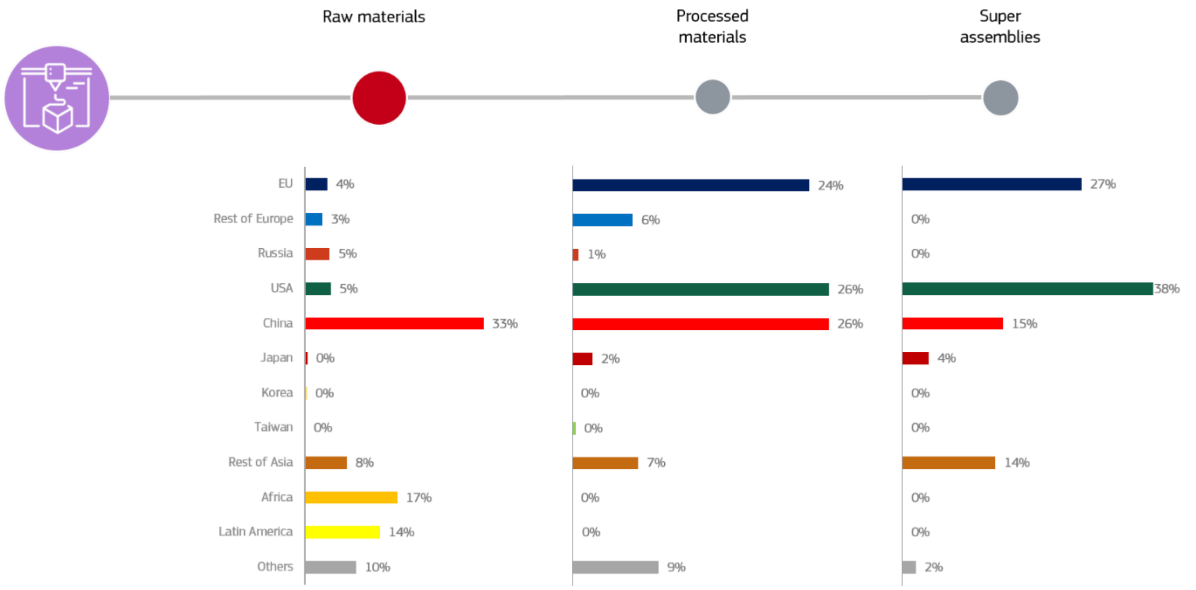
[54] AM requires more strict qualifications of material supply in terms of metal powders. This narrows the band of usable powder in an ordinary powder production, making the efficiency decrease in comparison to production of powders used in conventional methods such as Press & Sinter. Because of this, price per kilo of powder for the AM market is much higher than the price for the traditional PM market (EPMA, 2021).

Although there are EU AM powder providers (EPMA, 2022), the raw materials stage continues to pose the highest potential supply bottleneck in the sector for the EU. Most of the commercially used AM technologies are rigid in terms of input processing variables, making it difficult to customise powder compositions according to the end user needs (EC, 2020). The lack of availability of clean powders and transformation capabilities has been found as one of the barriers in the adaptation of AM in large scale (EC, 2016). The supply risk of AM materials for the EU is high for aluminium, cobalt, hafnium, magnesium, manganese, niobium, scandium, silicon metal, titanium metal, tungsten, vanadium, and low for chromium, iron ore, molybdenum and zirconium. In addition, copper and nickel are materials of concern because they are considered to be strategic materials. China is the major supplier of around 33% of the raw materials required in AM. The supply of AM-relevant CRMs from European countries is low (4% of share). In particular, there are significant risks for scandium and hafnium in super-alloys for space applications.

In the case of titanium, the EU does not produce primary titanium metal (sponge). Yet, some Member States produce titanium ingots from imported titanium sponge and/or scrap feedstock (EC, 2022). Regarding titanium ingot production, China (37%) and the US (28%) are the world's principal operators of melting capacity. The rest of the international capacity is located in Japan, Russia, Kazakhstan, Ukraine and the EU (about 5%) (EC, 2022).

In 2021, to curb domestic power consumption, the Chinese production of magnesium was halted, resulting in a supply shortfall, record prices and worldwide distortions in the supply chain in 2021 (European Aluminium, 2021). Environmental issues remain the main concern in China's domestic magnesium market given the country's determination to achieve carbon neutrality by 2060 and to cap CO_2 emissions before 2030 (Belda et al., 2022).

Figure 70. An overview of supply risks, bottlenecks, and key players along the supply chain of additive manufacturing (3D printing)

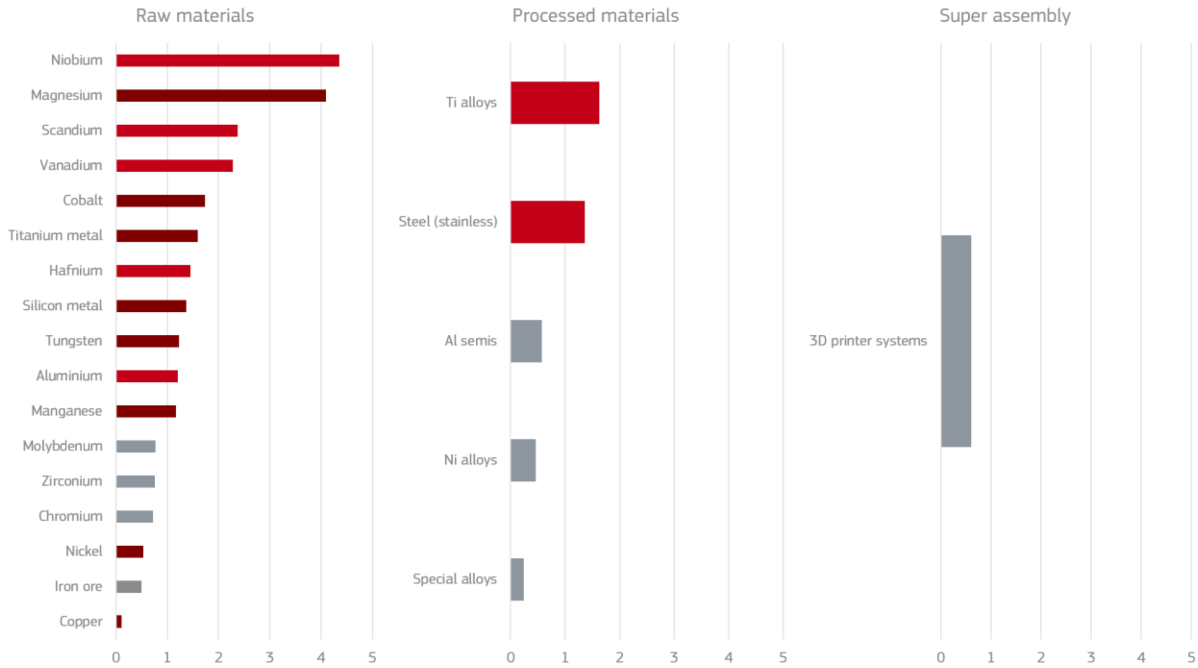


Source: JRC analysis.

At processed materials stage, the supply risk of most of the AM alloys and steel is low except for that of titanium alloys. The EU share of processed materials for AM is 24%, just third after the United States and China. The United States is dominant in the processing of titanium alloys with two third of the capacity, while the EU share is minor (2%). The EU has strong metallurgical capabilities to deliver processed materials, in particular for nickel alloys, stainless steels and special alloys. However, there is only a small number of metal powder suppliers globally. Any supply disruptions in one of these early material production stages are likely to have immediate and severe impacts on the availability of a wide range of components.

Finally, in AM system manufacturing, Europe[55] is well positioned with 27% of global sales in 2020, just second after the United States (38%). They are followed by China (15%), Israel (14%), Japan, (4%), and others (2%) (Wohlers Terry et al., 2021).

Figure 71. Detailed Supply Risk of selected elements in the data transmission networks supply chain



Source: JRC analysis.

Titanium and AM in the aerospace industry

One of the earliest adopters of AM technologies is the space industry, where the first proof of concept was launched 10 years ago. The use of additive layer manufacturing in the sector is today the norm for several demanding applications such antenna supports, wave guide or even engine-related pieces.

Indeed, the technology is well suited to the space industry, which combines low production rates with complex geometric design for the spacecraft pieces and mass-saving requirements (Vafadar et al., 2021). These advantages compensate for the fact that a 3D printed piece is often more expensive than using conventional manufacturing. Most of all, these technologies allow industrial stakeholders to increase their resource efficiency by avoiding the production of scrap. Since the EU is highly dependent on third country supply in terms of aerospace-grade metals, additive manufacturing could be a game changer in the field. For instance, current developments in the sector result in more than 90% savings in processed titanium mass. It is particularly relevant from a strategic autonomy point of view because the EU does not have domestic extraction of titanium, the most important raw material in the aerospace sector. The sources of supply for titanium sponge suitable for critical aircraft equipment are limited. After the closure of the US plant, the only qualified producers of aviation-grade titanium sponge are in Japan, Russia and Kazakhstan. In 2020, sponge production capacity of an aeronautical quality accounted for about 40% of global titanium sponge production (EC, 2022). The qualified melting capacity for aerospace alloys accounts for 54% of the total processing capacity, with approximately 100 kt/year of solid products output (EC, 2022).

[55] Not exclusively limited to EU-27.

2.12.3. 2030 and 2050 technology prospects

Currently, due to the data limitation, it has not been possible to project the market growth of AM technology other than in terms of monetary value. The market size of AM is predicted to grow six times as large by 2030 compared to 2020, according to Wohler's Associates (Wohlers Terry et al., 2021). There is not enough information on the quantity of materials used in AM, but some estimations are available. The demand for titanium for AM in medicine and dental applications was expected to grow from more than 150 000 kg of titanium in 2016 to almost 1.1 kt by 2022 (Gasman, 2015). The use of titanium alloys in AM for automotive and aerospace industries may increase from around 29 kt in 2010 to 48 kt in 2050, according to one study (Nyamekye et. al., 2023). For aluminium, BCG estimated that the share of specialised aluminium alloys in the AM materials market would increase dramatically, representing up to three-quarters of the market by 2027. However, BCG predicted that the share of standard aluminium alloys would decline from around 90% in 2017 to between 25% and 30% in 2027 (Küpper et. al., 2019).

2.12.4. Geopolitical dimension

Investment in the AM sector is widespread among industrialised countries. Europe[56] and the US have a strong lead in AM innovation, reflected in the number of patent applications in the sector: as many as 47% (Europe) and 35% (US) of all AM inventions for which a patent application was filed with the EPO (European Patent Office) since 2010. In the EU, during the years 2015 to 2018, AM patent applications grew at an average annual rate of 36%, which is more than ten times faster than the average yearly growth of patent applications to the EPO in the same period (3.5%). New industrial applications of AM technologies account for the largest share of patent applications in AM so far (50%). Other patent applications are related to machines and processes (38%), innovation in materials (26%), and digital technologies (11%) (Ceulemans et. al., 2020). In the area of metal 3D printing, Europe has been in a competitively advantageous position, however this is set to change with United States companies increasing their presence in the metal 3D printing market, also through the acquisition of European players (EC, 2021a).

Outside of Europe, Japan is an important innovation centre for AM technologies (9%), while South Korea (1%) and China (<1%) made relatively modest contributions (Ceulemans et. al., 2020). The Asian 3D printing market is projected to experience considerable growth after lagging in 3D printing adoption relative to the Unites States and Europe in recent years (EC, 2021a).

Several countries have launched an additive manufacturing initiative, either by way of an association, a cluster or an industrial oriented platform (AM Motion, 2018).

In 2021, the Biden's Administration issued an Executive Order on America's Supply chain that highlighted, among others, the importance of additive manufacturing sector to US Supply chains (America Makes, 2022). Since 2012, the United States, with the founding of "America Makes", the nation's leading public-private partnership for additive manufacturing (AM) technology and education, has been working to accelerate the adoption of AM and the nation's global manufacturing competitiveness. In 2012, America Makes funded 22 research projects with EUR 12 million public investment and EUR 14 million industry cost share. It has also initiated a number of agency-directed research projects that have received over EUR 6.5 million in funding. In March 2014 it was announced that the federal government will increase the funding commitment to EUR 47 million (EC, 2014)[57]. America Makes' projects in additive manufacturing cover areas such as design, material, process, value chain, and a standardisation roadmap. When it comes to raw materials, the US aviation company Boeing halted purchases from Russia in early March 2022 at the outset of the war in Ukraine. Russia supplied one third of its titanium from Russia (Suga, M., 2022).

In **Russia**, the Association of the Industry of Additive Technologies (APOAT) was created in 2015 to coordinate the activities, protection of rights and representation of the common interests of its members. APOAT is a non-profit association, uniting persons interested in the development of the industry of additive technologies (AM Motion, 2018). Subsequently, in 2018 TVEL Fuel Company, a part of Russian state-owned nuclear firm Rosatom, established a special purpose subsidiary "Rusatom – Additive Technologies" (RusAT, JSC). RusAT integrates Rosatom's additive manufacturing operations in the nuclear industry focused on four areas: the production of a line of 3D printers and components; the development of metal powders and other materials for 3D printing;

[56] All the member states of the EU-27 together with Albania, North Macedonia, Iceland, Liechtenstein, Monaco, Norway, San Marino, Serbia, Switzerland, Türkiye and United Kingdom.

[57] The investment expressed in this paragraph was converted from USD to EUR

the creation of integrated software for additive systems; and the provision of services to support the use of 3D printing. RusAT opened its first Centre for Additive Technologies (CAT) at the site of the Moscow Polymetal Plant. The plant has 3D printers for producing metal powders, post-processing equipment and a product research lab to develop additive manufacturing technologies and demonstrate the possibilities of using additive technologies in industrial enterprises (Argus Media, 2020), (World Nuclear News, 2020). As part of the development of additive technologies, RusAT has developed six new national industry standards that were approved in December, including the design and quality of metal products, production based on selective laser alloying of metal powders, and laser alloying from a metal-powder composition of Ti-6Al-4V titanium alloy (EC, 2022).

The invasion of Ukraine by Russia changed the picture of the supply of titanium. During **the Russian war on Ukraine**, a coalition of 3D Printing companies have reportedly boycotted Russia (Molitch-Hou, M., 2022). It's not known to what extend this boycott has impacted the AM sector in Russia. The war has put titanium metal supply at risk and threatens access to titanium products used in the aerospace sector. About 45% of Russian export value of titanium products is destined for the EU. Imports from Russia and Ukraine equalled 17% of the EU's import value in 2020. In total, EU import flows from Russia and Ukraine corresponded to EUR 290 million in 2019 and EUR 195 million in 2020, of which more than 90% originated in Russia (EC, 2022). It is challenging to predict the medium-term impact of cutting ties with the Russian supply of aerospace mill products (EC, 2022).

In terms of raw materials, the global supply of titanium sponge may favour **Japan** due to the sanctions against Russia. In April 2022, the Japanese company Toho Titanium Co. reportedly increased its output of the aerospace-grade titanium as US aviation industry customers look for alternatives to Russian supply (Suga, M., 2022).

The Ministry of Economy, Trade and Industry (METI) of Japan invested over EUR 34 million to launch a new research association to develop metal AM technology, the Technology Research Association for Future Additive Manufacturing (TRAFAM) in 2014 (EC, 2014). The association's mission is twofold: to develop metal AM system technology and to develop binder jetting equipment for the rapid production of sand moulds (Kyogoku, H., et. al, 2019).

The **Chinese government revealed a national plan**, The Country's Additive Manufacturing Industry Promotion Plan 2015-2016, to ensure the growth and development of 3D printing technology business across international markets, exploit international level advanced 3D printing technology for the aerospace and other high-level industries, and to capture high market share in the global 3D printing services market. (Technavio, 2022). As a result of these actions, China has made considerable investment including providing support to promising companies, supporting standardisation efforts and bringing 3D printers into schools (EC, 2021a).

The Additive Manufacturing Industry Development Action Plan (2017-2020) is formulated as part of the strategic roadmap, Made in China 2025. The Chinese Ministry of Industry and Information Technology, in cooperation with eleven other agencies, released guidelines to strengthen and further develop the 3D printing sector in China. The Chinese government expects the 3D printing industry to keep up its annual growth rate of over 30% and its revenue to top approximately EUR 2.56 billion (CNY 20 billion) in 2020 (EC, 2020b). In February 2020, the Standardization Administration of China, together with six departments, issued the Action Plan for Leading Additive Manufacturing Standards (2020-2022), proposing that 'a new standard system for additive manufacturing based on China's national conditions and docking with the international market will be basically established by 2022' (E-Plus-3D, 2021).

A public-private collaboration model also runs in **India**. The Ministry of Electronics and Information Technology (MeitY) of India formulated the 'National Strategy on Additive Manufacturing'. The strategy aims to increase India's share in global AM to 5% in the next three years. Meity estimates that AM can add EUR 0.95 billion to India's GDP by that time (IBEF, 2022).

In **Israel**, the Advanced Additive Titanium Development Consortium (AATiD) was established in order to develop advanced technologies for the design and three-dimensional printing of optimised complex aero-structures made of titanium alloys, Ti-6Al-4V. The goal of AATiD is develop a methodology for parts selection which may be efficiently manufactured by ALM of titanium on appropriate equipment and to develop a methodology for the qualification of ALM titanium materials (AM Motion, 2018).

2.12.5. Key observations and recommendations

Raw materials supply can pose a high risk to the additive manufacturing sector in the EU. The EU is both a manufacturer of AM technologies and an active stakeholder in their application. Several strategies that can be employed to mitigate the possible supply disruption of AM materials include:

- **Supply diversification and trade agreements.** The US and EU have taken joint steps to re-establish historic transatlantic trade flows and address shared challenges in steel and aluminium (EC, 2021b). The EU has also been investing in the domestic supply of the relevant raw materials. In March 2022, EIT Raw Materials supported a joint venture in Finland between two Australian project development companies, Critical Metals Ltd and Neometals Ltd. This collaboration paves the way for a significant increase in the production of, among others, specialised steel applications in Europe (EIT Raw Materials, 2022). The ongoing war waged by Russia in Ukraine poses a supply risk for titanium which must be addressed (e.g. through the strategic partnership with Kazakhstan). Further attention should also be given to the strategic minor elements used in special alloys, such as scandium and niobium.

- **Promote R&D.** It is important for the EU to master the relation between processed materials (metal powder recipes) and the various AM technologies (EC, 2020a). In terms of innovation, AM is driven by technical progress, and therefore by patented inventions. Companies and inventors make use of the temporary exclusivity conferred by patent rights to market their innovations and, in doing so, to recoup their R&D investment (Ceulemans al., 2020).

- **Develop skills and competences.** The AM sector is growing so fast that the educational system can't keep up, and the lack of skilled workers poses a threat to the technology's adoption. AM-specific education and training will close this gap, fostering the technology's development and market uptake in Europe (SAM, 2021). Many existing facilities throughout Europe are already active in the field of 3D printing, such as Fraunhofer, TNO, UNIBO, VTT, Tecnalia and CEA. These will benefit from projects through learning, and better-connected networks, which will lead to technology spillovers for other companies.

- **Foster standardisation and certification**. The development of standards and an extensive certification system are crucial to the AM sector. The publication of internationally recognised credible standards is widely recognised as a key enabler to support the adoption of the technology across the widest possible range of industry sectors (EPMA, 2015). Globally, Europe is lagging behind in standardisation activities, for example in powder technology. EU funding represents a valuable instrument to plug this gap. The SASAM[9] project, for instance, delivered a roadmap for standardisation activities, coordinating a group of over 100 European and international AM industry stakeholders. It indicated the need and type of standards to be developed, specifying categories such as design, specific industrial needs, quality of manufactured parts, safety (regulations) and education (Geert and Renda, 2017).

- **Sustainability and safety.** In many industrial AM applications, the manual handling and loading of materials are still common practice. Two EU companies, Höganäs AB and Piab AB, have formed a partnership to exchange expertise with the goal of advancing automation in Additive Manufacturing, aiming to increase the sustainability and efficiency of the process. They are developing new solutions said to minimise metal powder waste while improving process efficiency and safety (EPMA, 2022).

- **Recycling and reuse, substitution**. Recycling offers Europe the potential to secure the resources it needs. In aluminium and steel, Europe already leads the way in recycling[58] (EC, 2021a). The potential for recycling 3DP components and powders not consumed in manufacturing should also be investigated (EC, 2020a). Specific sectors such as aerospace are working on recycling of titanium and other critical raw materials (EC, 2021). Challenges may arise from recycling of hybrid metal-composite materials (EC, 2021).

[58] The End-of-Life Recycling Input Rate of Aluminium in the EU is 69%; Source: EURIC, Metal Recycling Factsheet while for stainless steel is 56%.

2.13. Robotics

2.13.1. Introduction

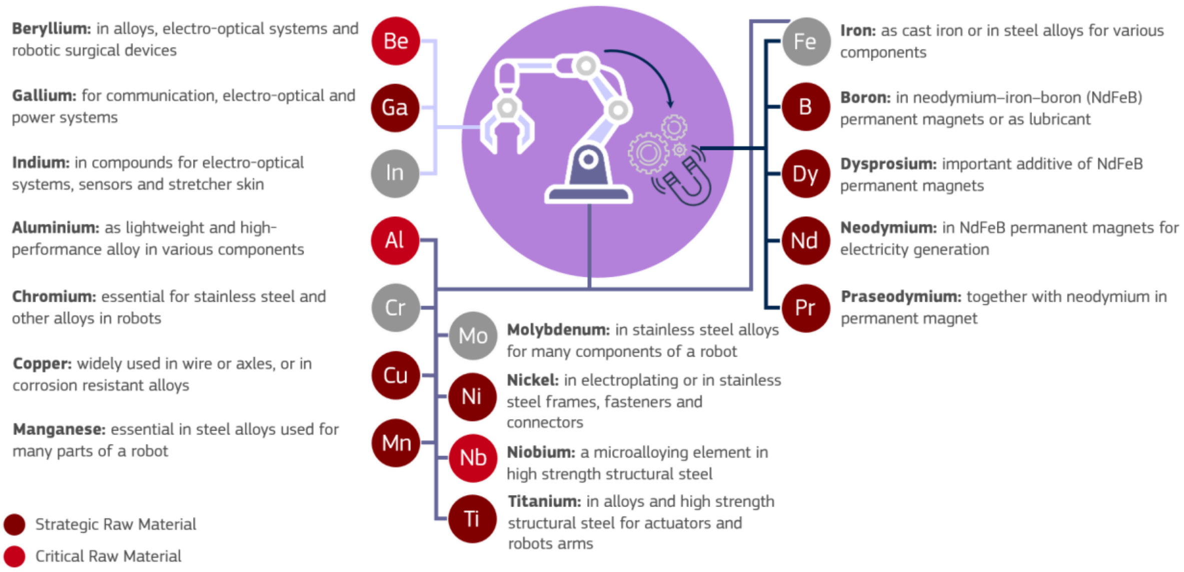
Robotics is an emerging technology with enormous potential for many applications in industry, agriculture, medicine, transportation, social services, defence, space exploration and undersea operations. Based on the function and field of application, the market for robots is categorised into two major segments, namely industrial robots (accounting for 80% of the current market) and service robots (20% of the current market, with almost half in logistics). It is expected that service robotics will displace industrial robotics in terms of sales and market value over the next two decades. Exoskeletons (or wearable robotics) are also of increasing importance, gaining market share in the future for both civil healthcare and defence applications.

Software-related challenges of robotics include the ability to perform more and more intelligent tasks by using complex software architectures. Continued developments in hardware design at both the system (robot) and the component level are necessary. The main components of mobile robots such as gears, actuators, power units, sensors, etc. require further miniaturisation next to a reduction in weight, especially for exoskeletons. Smaller, more powerful, high-speed and precision electronics pose another challenge for exoskeletons. Sensors are a very critical component of robots as they determine the accuracy of their activities.

Novel materials allow components to become smaller and lighter. For instance, the development of innovative materials (e.g., vanadium-based materials) could contribute to the creation of miniaturised, multifunctional motors and artificial muscles. The development of smaller and more efficient power sources (batteries with higher energy density, fuel cells for long-lasting operations, or other energy sources) and electric motors is specifically important for exoskeletons. Light metal alloys, such as titanium metal, magnesium and aluminium alloys, normally used in combination with composites (CFCs, kevlar, polymer–metal composites, etc.) are of particular interest for robotics due to their favourable strength-to-weight ratios. Other innovative materials such as metallic glass, printed liquid metals and liquid silicone rubber are seen as potential game changers in the field of soft robotics.

The raw materials used in robotics with a brief explanation of their function are shown in Figure 72.

Figure 72. Selection of raw materials used in robotics and their function



Source: JRC analysis.

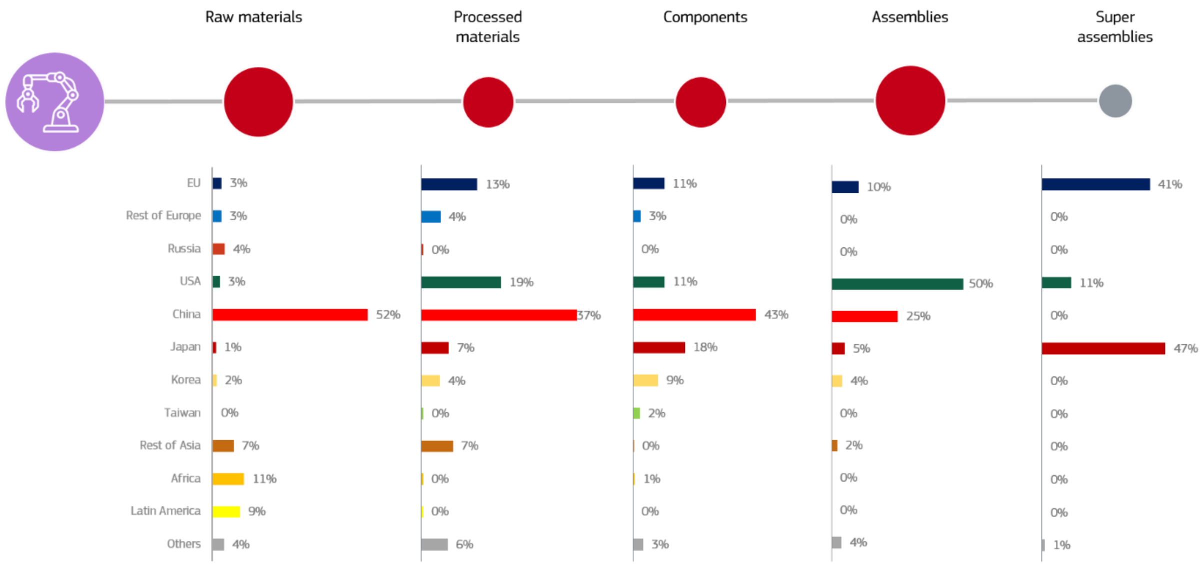
New materials and advances in making electronic skin for interactive robots are under development. Flexible (stretchable) electronics are realised via the synthesis of novel materials such as composites of soft materials with conductive fillers or via smart structural engineering and designs such as serpentine-like structures for interconnects or wires. One of the main challenges facing electronic skin development is the ability of the material to withstand mechanical strain and maintain sensing ability or electronic properties, including the fragility of sensors, the recovery time of sensors, repeatability, overcoming mechanical strain and long-term stability. More efficient robot designs require multifunctional materials, integrating processes such as sensing, movement, energy harvesting and energy storage. Such materials can change over time to adapt or heal. Recyclability and self-healing properties are therefore critical in the future design of new electronic skins.

2.13.2. Current supply chain bottlenecks

The robotics supply chain features five steps: raw materials, processed materials, components, assemblies, and super-assemblies. Table 30 in Annex 2 lists the elements along the five stages of the supply chain.

Figure 73 reports the supply risks along the robotics technology stages and reveals the potential bottlenecks along the supply chain. It further provides an overview of the key supply countries averaged per supply chain stage.

Figure 73. An overview of supply risks, bottlenecks, and key players along the supply chain of robotics



Source: JRC analysis.

The risk to the supply of raw materials and assemblies is potentially high, and there is a medium risk in relation to the supply of processed materials and components. In total, 45 raw materials are considered relevant to robotics. China is by far the major supplier of raw materials for robotics (52%), followed by Africa (11%), Latin America (8%) and Rest of Asia[85] (7%). The EU produces domestically only a minor share (3%) of the raw materials needed. 30 of the 45 raw materials are flagged as critical to the EU economy (see figure 74). Almost a quarter of the materials for robotics are supplied by numerous smaller countries, providing significant opportunities for supply diversification.

The EU is the third largest producer of the processed materials (13% production share), following China (37%) and the US (19%). There are possibilities to diversify the supply of processed materials. However, it should be noted that the EU is fully dependent on the supply of several processed materials used in robotics such as specific aluminium alloys, for which India and the US are key suppliers. With regard to batteries, the EU is fully dependent on the supply of several processed materials for Li-ion batteries (lithium iron phosphate active material, lithium cobalt oxide active material, and lithium manganese oxide active material), for which China is the dominant supplier. Moreover, potential bottlenecks could also occur in the supply of natural graphite anode material required in robotics, along with lanthanum strontium chromite.

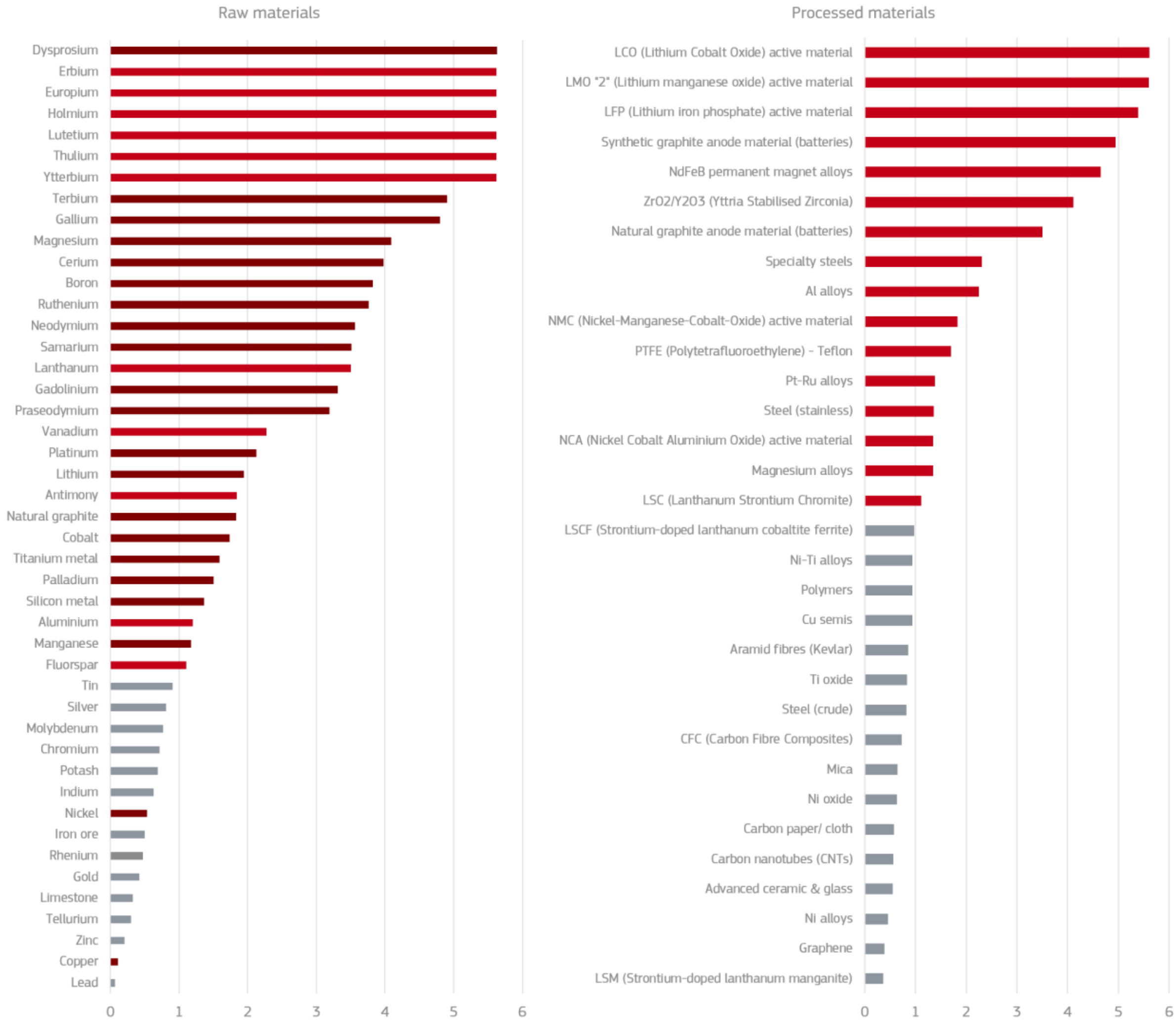
The largest manufacturer and supplier of components is China, followed by Taiwan, Japan, South Korea, and US. The EU, with a rather small production share of 9%, is vulnerable in relation to the supply of components. The EU is particularly dependent on the supply of seven key components, namely NdFeB permanent magnets, semiconductors (logic <10nm), gears, and Li-ion batteries (anodes, cathodes, electrolyte, separators). Japan (85%) remains the key supplier of gears, China for NdFeB permanent magnets. China is also a major supplier of Li-ion batteries components.

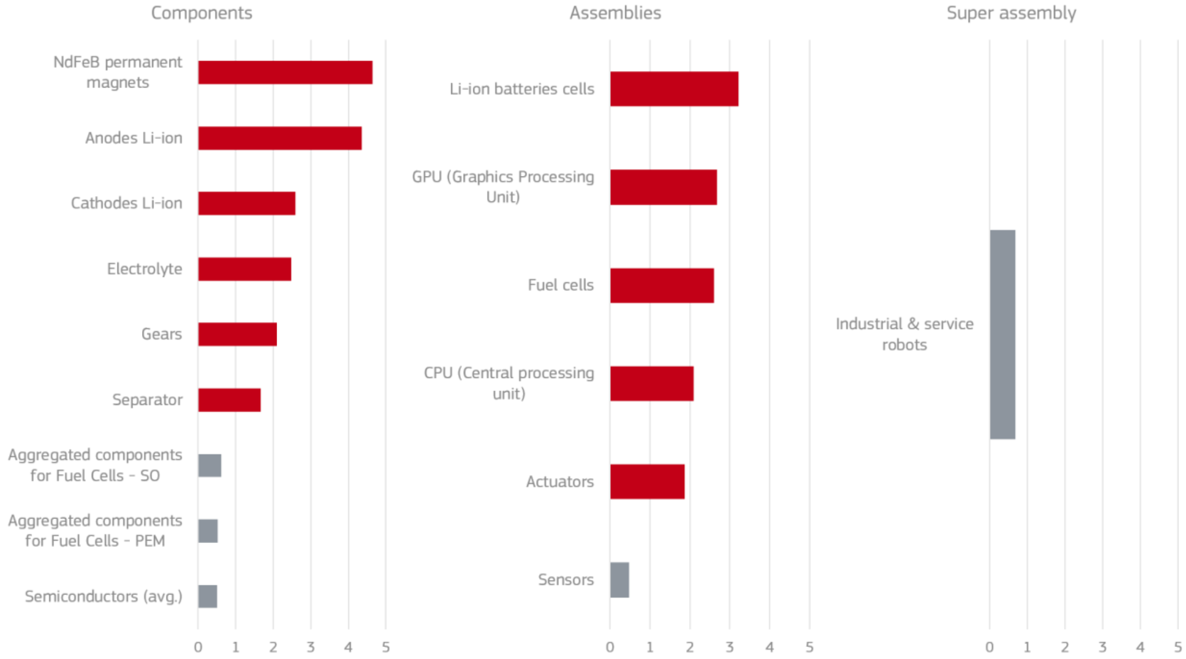
At the assembly level, five out of the six assemblies are considered having a critical supply risk. China is the dominant supplier of both Li-ion batteries cells and fuel cells. The US is the major supplier of actuators, CPUs and GPUs. Other key suppliers are Japan (sensors), Israel (actuators), South Korea (CPUs, sensors). The EU is the second largest supplier of fuel cells (20%), and – together with Israel – of actuators (11%), and – together with US, of sensors (23%).

While the ultimate stage of the robotics supply chain, i.e., the supply of industrial and service robots, is highly concentrated, the EU holds a strongly position in the global supply. Asia, mainly represented by Japan, leads the industrial and service robotics market followed by the EU (both >40%), while the US shows a market share of 11%.

The Detailed Supply Risk of selected materials along the supply chain is represented in Figure 74.

Figure 74. Detailed Supply Risk of selected elements in the robotics supply chain





Source: JRC analysis.

The lack of raw materials and assemblies, but also the lack of a sufficiently skilled work force in the EU and the increasing competition from China (through the acquisition of leading European robotics companies by Chinese companies) are factors that may challenge in future the competitive position of the EU on the global market.

2.13.3. 2030 technology prospects

A compound annual growth rate (CAGR) of about 10% is projected in the coming years for the robotics market in general, and a moderate growth of <8% CAGR is expected in the industrial robotics sector (Statista, 2016). The most rapidly growing robotic sectors will be consumer robotics (>20%) and commercial robotics (>13%). For specific service fields such as medical robots, a growth of >20% is anticipated. The global robotics market is expected to reach circa USD 126 million (more than 3 million units to be sold) by 2025 and USD 495 billion by 2040, accounting for more than 28 million units (The Business Research Company, 2018). Although the market for industrial robots is expected to experience slower growth in the automobile industry, the rising demand for automation in other manufacturing industries is creating a strong push for industrial robot manufacturers to diversify their portfolio further.

According to robotics industry representatives, there is huge potential for growth in the service robots' market, in contrast with to the more mature industrial robotics industry, which has more competitors, less profit differentiation and tighter profit margins.

The large-scale uptake of robotics will depend to a certain extent on the further development of new advanced materials. Moreover, it will depend also on the overall economic development, as advanced automation requires significant investments. It is difficult, if not impossible, to quantify future raw materials demand, as there are too many variables that could affect commercialisation, such as new sectors adopting robots, the evolution of design and advanced materials.

2.13.4. Geopolitical dimension

Without doubt, the field of robotics and the artificial intelligence accompanying it play an important role in addressing global and regional challenges of various sectors and the society. It is argued that the “industrialisation of intelligence”, including artificial intelligence, turns the foundations of political and social organisation upside down (Alexandre and Miailhe, 2017). Robotics has a direct and indirect impact on various areas of society. For example, industrial robots directly influence the efficiency of industrial production and indirectly influence patterns of international trade.

There is a massive potential effect on demand for human manpower, as robotics has the potential to rationalise jobs that are currently performed by humans. There is controversy whether, and to what degree, jobs will be lost in the third sector, depending on the sector and the current level of automation. This development might, on the other hand, be balanced by new jobs or even lead to a net increase. A study by McKinsey Global Institute projected that automation will replace circa 800 million jobs by 2030 (Mc Kinsey Global Institute, 2017). As the vulnerability of the employment market is strongly linked to certain sectors and skill levels (Yantong, Z. et al., 2022), certain regions are potentially more exposed to changes in unemployment rates, average wages and future labour skills. Such massive changes in job markets have the potential to influence national politics by means of voter reactions (Prakash, A., 2018).

The development of robotics, as well as drones, will continue to have a huge impact on the defence sector. Several countries, including the United States and China, are driving forces in exploring the potential of robotics in the defence sector. Analysts detect new forms of proxy war supported by robotics, including for example swarm wars (miniaturised drone swarming), changes in military strategies, and combat operations by means of autonomous robots (Shaw, I. G., 2017). In future, artificial intelligence may become more relevant not only to protect infrastructure, but also robotics and drones.

In more general terms, robotics and artificial intelligence are considered to be possible game changers regarding the fundamental role of people and demography for a state to enable and scale up domestic production, wealth, and military power. As a consequence of digitalisation, states free themselves from the constraints of demography and geography, which play reduced roles in limiting their power (Dear, K., 2021).

2.13.5. Key observations and recommendations

Robotics is an emerging technology offering enormous potential for many applications. Its technological challenges lie in both software and hardware, with further research and innovation needed in materials engineering, design, electronics and software. China is the major supplier of CRMs, with more than 40%, followed by South Africa (10%) and Russia (9%). At the level of raw materials, it is important to secure access and diversify the supply of those materials used in robotics for which the EU has no or very low domestic production, such as chromium, cobalt, molybdenum, natural graphite, nickel, magnesium, vanadium, copper, tin, antimony and bismuth.

It is difficult to predict the growth rate and materials demand in robotics due to the variety of sectors involved. The highest growth is expected in the service sectors, such as logistics robots, but a lower growth rate of between 10% and >20% is forecast for other branches of the industrial and service robotics market. Growth projections for exoskeletons, also used across various sectors, are even more optimistic, forecasting a CAGR of up to 40-50% in the next few years.

The main policy recommendations are:

- **Diversifying materials supply**. China is the major supplier of more than one third of the raw materials required in robotics. Other suppliers are South Africa (7%) and Russia (6%). Many small suppliers have a market share of less than 6%, offering significant opportunities for supply diversification.
- **Improving manufacturing opportunities in the EU**. Further diversification through strengthening and investing in the local components manufacturing industry would be beneficial.
- **Recycling and reuse, substitution**. The ecodesign of robotic products, including exoskeletons (or wearable robotics) should be incentivised to ensure the more efficient use of materials and energy as well as the easy disassembly of components and materials identification, and their reuse or recycling.
- **Promoting R&D, developing skills and competences**. Development of advanced, light and high-strength structural and functional materials is the main research line for robotics. Promising materials appear to be magnesium, aluminium, titanium alloys, special steels and composites (fibre reinforced), including combined polymer–metal composites. Research funding in terms of size, weight, technology, software, materials and applications is expected to significantly influence the European robotics market. Great emphasis should be put on SMEs to promote growth in the civil and defence robotics market. With regards to robotic components, it is necessary to further develop smaller, more powerful, high-speed and precision electronics including the cyber physical security of electronics systems (such as controllers). This last aspect is a key issue as robotics systems are developing increasing levels of autonomy, artificial intelligence and software

integration. R&D investment is therefore required in methods to protect robotic systems and critical infrastructure against cyber supply chain attacks. In the field of exoskeletons, research opportunities are focussed on software to coordinate exoskeleton movements, vital sign- and stress-monitoring technologies, visual augmentation systems/operators, and automated remote sensors for increasing situation awareness, reducing surveillance, and improving communications connectivity.

- **Ensuring a sufficient high-skilled work force to attract and maintain technical expertise**. Robotics companies already perceive the lack of a skilled workforce as a big potential bottleneck for the future development of this sector in the EU. High-level maths software engineers and those with robotics PhDs are in high demand, and the main competition for them is expected to come from China and India. Business and academia should be encouraged to identify skills gaps and skills shortages for the robotics sector. Tailored retraining and up-skilling programmes can be an important follow-up, which the European Commission can support. It is also up to stakeholders (industry, academia, etc.) to take advantage of relevant EU funding, such as Erasmus and European Structural and Investment Funds.

2.14. Drones

2.14.1. Introduction

Unmanned aerial vehicles (UAVs) are recoverable or expendable aircraft without a human operator on board. The term drone is a technical, more comprehensive term comprising any type of unmanned vehicle (UV), including the less prevalent ones like unmanned ground vehicles. This study, however, follows the common parlance and considers drones as synonymous with UAVs.

Starting in the 1970s, the civil applications of drones gained ground, and dominate the market regarding the number of units, with over a million units sold by 2015 in various fields of application such as agriculture and the provision of data for science, logistics and commerce. However, the market size in terms of value is still dominated by military applications, followed by commercial and hobby applications (Statista, 2019).

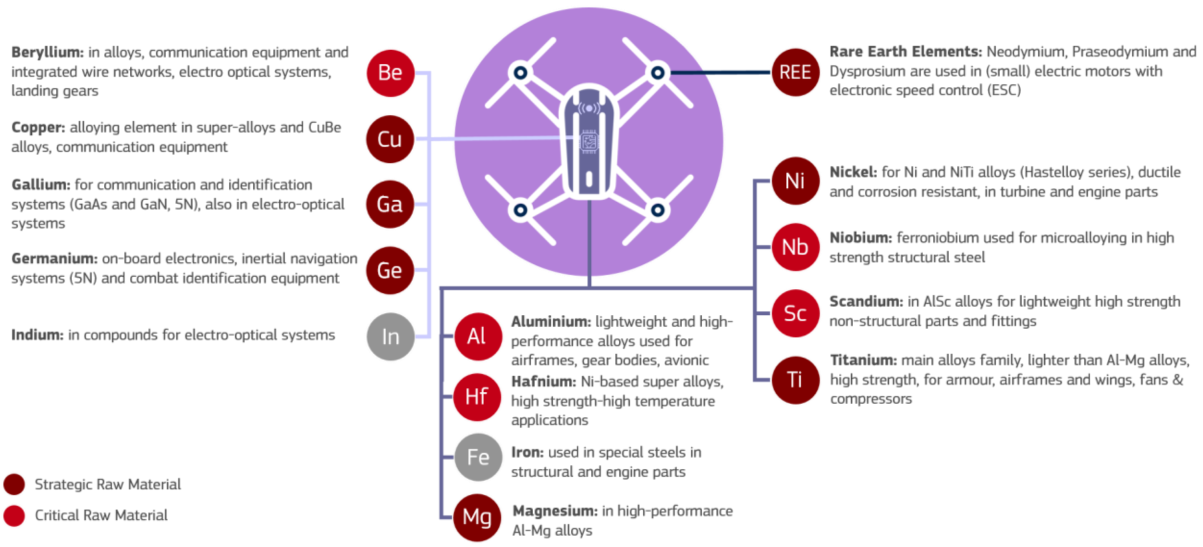
Civil and commercial applications of drones comprise remote sensing for aerial monitoring and investigation for agriculture, infrastructure inspection, border monitoring and surveillance, research and development, and other data collection processes, along with the transport of goods, for example parcels in the logistics sector (JRC, 2019, EPRS, 2019).

In contrast with civil and commercial applications, the defence market is today dominated by large UAVs, and this is expected to remain the case for the next two decades. The dimensions, technologies and materials used in larger UAVs are similar to those in manned aircrafts. C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance), cyber security, and embedded computing are key applications with promising emerging markets.

To realise these applications, like any modern aircraft, drones are composed of numerous components, often up to several hundred individual parts. As drones can basically be considered a special type of robot, the composition and components are similar to the ones described for robotics (chapter 0). Correspondingly, typical drones assemblies are actuators, power units and conductors, controllers, electronics, wheels, axles, supporting structures, sensors, etc., including specific assemblies necessary for vehicle lift, like wings or rotors, and components for aerial navigation, like altimeters, or navigation systems. Their main assemblies are the airframe, propulsion systems, actuators, avionics, connectors, surveillance systems, and in case of defence applications in addition weapon systems.

Figure 75 provides an overview of selected relevant raw materials used in drones production.

Figure 75. Selection of raw materials used in drones and their function



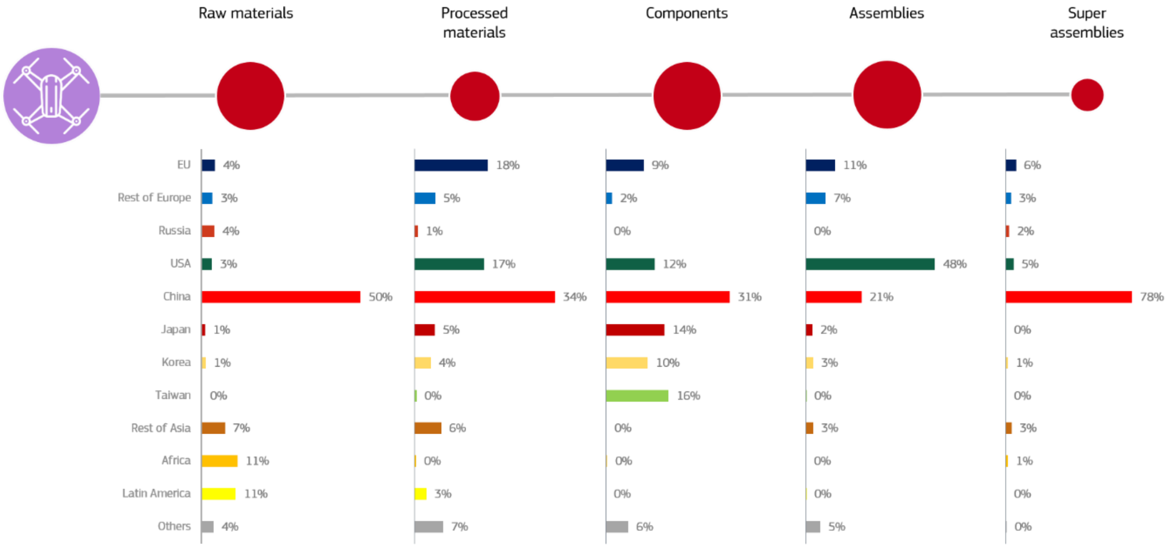
Source: JRC analysis.

2.14.2. Current supply chain bottlenecks

The drones supply chain features five steps: raw materials, processed materials, components, assemblies, and super-assemblies. Table 31 in Annex 2 lists the elements along the five stages of the supply chain.

Figure 76 reports the supply risks along the robotics technology stages and reveals the potential bottlenecks along the supply chain. It further provides an overview of the key supply countries averaged per supply chain stage.

Figure 76. An overview of supply risks, bottlenecks, and key players along the supply chain of drones



Source: JRC analysis.

The risk to the supply of raw materials, components, and assemblies is potentially high, and there is a medium risk in relation to the supply of processed materials. Due to their complex composition with many components, a wide range of drone elements are relevant for drone production. In total, 50 raw materials are considered relevant to drones. 35 out of the 50 raw materials are flagged as critical to the EU economy (see Figure 77).

China is by far the most important supplier of raw materials (50%), followed by Africa (12%), Latin America (7%), and Rest of Asia[59] (8%). The domestic EU supply of raw materials is just 4%. China is the predominant supplier of most of the CRMs for UAVs, followed by South Africa and Russia. Raw materials of particular importance are REEs, magnesium, bismuth, and niobium, for which the dominant supplier is Brazil. Almost a quarter of the materials for drones are supplied by numerous smaller countries, providing significant opportunities for supply diversification.

35 processed materials are identified as relevant for drones[60]. The EU is the second largest producer of the processed materials (18% production share), following China (34%) and slightly in front of the US (17%). This is the highest share in global production along the supply chain stages of drones. Nevertheless, the EU is fully or to a high degree dependent on the supply of several processed materials used in drones, such as ferroniobium, Pt-Ru alloys, and several processed materials for Li-ion batteries, for which China is the dominant supplier. Moreover, potential bottlenecks could also occur in the supply of natural graphite anode material, along with lanthanum strontium chromite, strontium-doped lanthanum manganite, and strontium-doped lanthanum cobaltite ferrite. Further, the EU share in global production is low for processed materials like yttria stabilised zirconia, nickel-manganese-cobalt-oxide (NMC) active material, polytetrafluoroethylene (used for teflon), and nickel-manganese-cobalt-oxide (NMC) active material, as well as for certain specialty steels.

[59] "Rest of Asia" refers to any Asian countries beside China, Japan, Korea, and Taiwan.
[60] Compared to the previous edition of the foresight report, the analysis of the supply chain was thoroughly extended for processed materials, i.e. the number of processed materials considered relevant raised from 14 to 35.

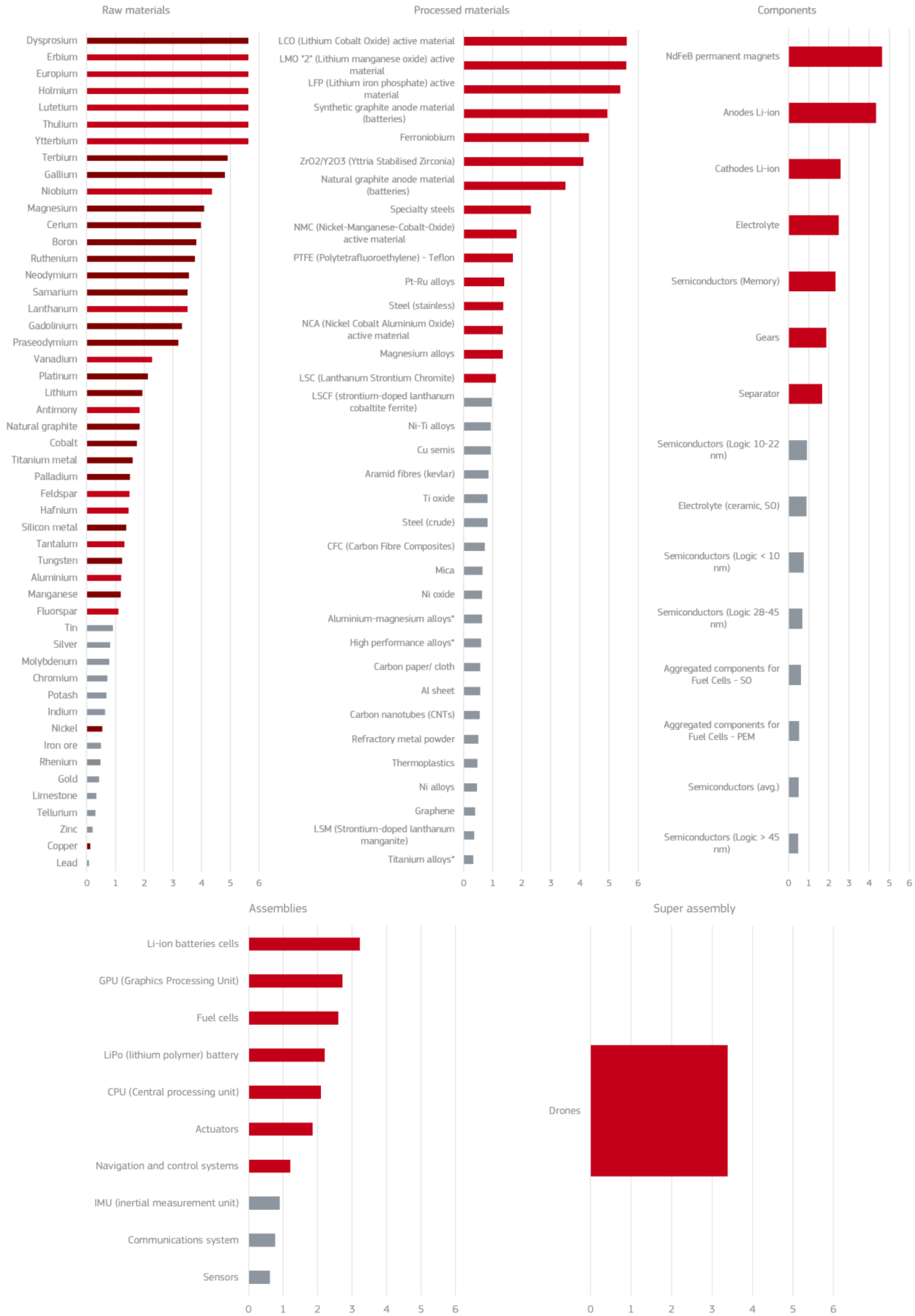
The supply of components for drones is dominated by Asian countries. The most important manufacturer and supplier is China (31%), followed by Taiwan (16%), Japan (14%), USA (12%), and South Korea (10%). The picture for the EU is very heterogeneous, depending on the specific types of components, but represents with 9% a rather small production share. The dependence on key components comprises NdFeB permanent magnets, semiconductors (logic <10nm), gears, and Li-ion batteries. Japan (85%) remains the key supplier of gears, and China for NdFeB permanent magnets.

At the assembly level, China is the dominant supplier of Li-ion batteries cells (75%) and fuel cells (66%). The US is the major supplier of actuators (CPUs and GPUs. Other key suppliers are Japan (gears, sensors), Israel (actuators), South Korea (CPUs, sensors). The EU is the second largest supplier of fuel cells (20%), and – together with Israel – of actuators (11%), and – together with US, of sensors (23%). The EU is fully dependent on foreign supply of LiPo batteries, and largely of Li-ion batteries cells.

As for the manufacturing of civil drones, China is the market leader, with a global market share around 75%. The EU is the second-largest supplier of civil drones, followed by the US and Israel.

The detailed Supply Risks of selected materials along the supply chain are represented in Figure 77.

Figure 77. Detailed Supply Risk of selected elements in the drones supply chain



Source: JRC analysis.

2.14.3. 2050 technology prospects

Small drones will dominate the civil and commercial subsectors until 2035. However, by 2050, larger civil drones can start to make an important impact on the market (more than 20%), because mobility applications will rise exponentially (reaching circa 20% of the total professional market). These types of UAV, for applications such as urban air mobility (aerial taxis), would require to be certified in the future. Large drones will stay behind in terms of unit numbers (15 000 versus 400 000).

Based on developments in the drones market for defence applications, it can be predicted that the impact of drones on surveillance will be significant. Autonomous and robotic systems are expected to make a significant change to military operations within the period until 2040, at both global and national scale.

2.14.4. Geopolitical dimension

The rapid growth of drone usage for commercial purposes accompanies the technological advances in the field of drones, and its spread across various sectors, including agriculture, surveillance and leisure. The potential of drones depends upon their integration into national airspace without reducing existing capacity for manned vehicles. The European Aviation Safety Agency (EASA), and the International Civil Aviation Organisation (ICAO) play important roles in the regulation of drones, mainly due to the ICAO Model UAS Regulations, which are supported by Advisory Circulars and Standards and Recommended Practices (SARPs) publications. National regulations compete in some places with regional or local rules. In general, it is a challenge to balance the extent of regulatory intervention with the options for using the drones for commercial and recreational purposes. The European Commission recognises the need for a coordinated European approach to reach the desired level of transport capacity and connectivity in the European Union (Clyde&Co, 2022).

The production capacity of UAVs has further advanced in the last decade, particularly for tactical and other military applications, globally and in the middle and near east in particular. The rise of Türkiye's military drone warfare capacities is worth noting; with innovative components, they have already proven their effectiveness in recent conflicts (Kasapoglu, 2022). In spite of the high risk related to the 'erosion of human rights, national security and ethical conduct in war and international law', the application of drones in conflicts is still insufficiently regulated.

2.14.5. Key observations and recommendations

China dominates the civil drones sector, and increasingly the share of professional drones, while the US and Israel dominate the military drones sector. The EU faces the serious risk of missing the opportunity to catch up with these global leaders on this key technology, which will be decisive for integrating comprehensive real-time geo-referenced intelligence into professional (civil) as well as military applications. The EU is highly dependent on external suppliers for raw materials and components as well as for the final product. China is the predominant supplier of raw materials. Downstream, the market is increasingly competitive, with the US strongly dominating certain components (e.g., IMU, GPU and microprocessors) and drones with advanced capabilities in the defence sector. China is shown to be the major supplier of CRMs for drones, delivering more than 40% of CRMs.

The main policy recommendations are:

- **Diversifying materials supply**. More than 50% of the raw materials for drones are supplied by a wide range of smaller supplier countries, providing promising opportunities for supply diversification.
- **Promoting R&D, developing skills and competences**. The Materials for Dual-Use report (JRC, 2019) recommends the intensification of R&D efforts in selected key strategic components and assemblies, and in certain larger military unmanned aerial vehicles, to reduce the EU's dependence on imports, as well as the streamlining of military procurement in the EU to boost efficiency and dynamism. Software design skills also need to be supported and strategic alliance(s) should be considered.
- **Fostering international collaboration and standardisation activities**. Advancements in EU regulation and standardisation are necessary.

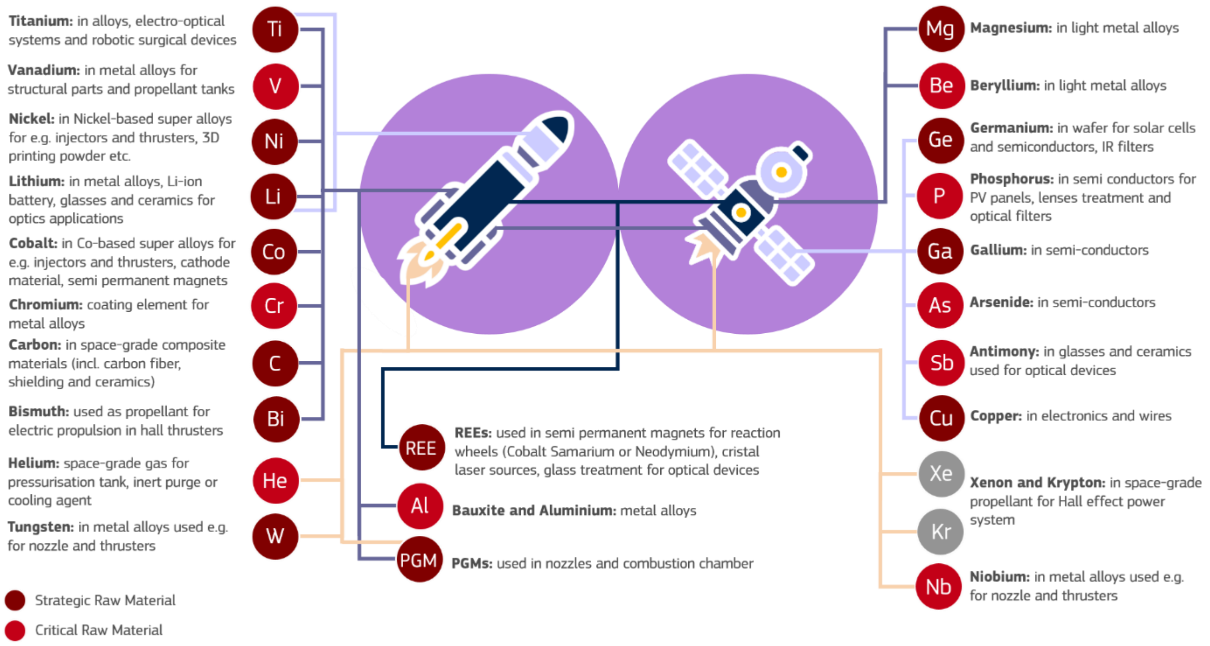
2.15. Space launchers and satellites

2.15.1. Introduction

The space sector, although small in size, is today a **key enabler** to help Europe's industry to achieve the twin transitions towards climate neutrality and digital leadership. Satellites orbiting Earth are used in many areas and disciplines, including space science, Earth observation, meteorology, climate research, telecommunication, navigation and human space exploration. The main economic added value of the space sector is not in the data or imagery transmitted through spacecraft, but rather in the potential downstream applications and new markets enabled by the tremendous quantity of data generated. Since launchers are required to put satellites in orbit, the two technical systems can be merged into an overarching technological category under the name **"space systems"**. Space launchers and satellites are both very complex systems integrating hundreds of parts and components which require a wide variety of raw and processed materials in their construction (Figure 78).

The space industry designs, develops and manufactures spacecraft and launchers, along with the associated ground systems for satellite control and operations. The sector is organised around **large system integrators (LSIs)[61] specialised in bringing together components and subsystems** into a whole and ensuring that those subsystems function together once in the launch pad. These parts and components can be developed internally or by subsidiary/joint-venture companies while others are directly imported from third countries. The European space sector is rather concentrated, with four industrial groups (Airbus, Thales, Safran and Leonardo) directly responsible for more than half of total industry employment. Smaller, but sizeable, space players such as GMV, RUAG and OHB provide additional employment and capabilities to the European space industry (ASD-Eurospace, 2022). Despite being distributed across all European Space Agency member states[62] the main industrial sites, according to ASD, are located in France, Germany, Italy and to a lesser extent the UK (as full member of the ESA), Spain and Belgium.

Figure 78. Selection of raw materials used in space launchers and satellites, and their function



Source: *JRC analysis.*

One important element to consider when assessing supply chain bottlenecks is that space activities are carried out by only a **few space-faring nations with geopolitical interests**, often with a mix of governmental

[61] These enterprises have at least one ongoing prime contract worth over EUR 200 million that involves space-related infrastructures launchers or satellites (mainly ArianeGroup and Avio for launchers, Airbus DS, Thales Alenia Space, OHB for satellites).

[62] See European Space Agency (ESA) industrial policy and geographical distribution (known as *geographic return rules*): https://www.esa.int/About_Us/Business_with_ESA/How_to_do/Industrial_policy_and_geographical_distribution

policies and private space ventures. Therefore, the space industry and specifically launch activities and satellites manufacturing for the institutional domestic market segment (including both civil and military applications) can be considered at least partly **a captive market.** Data compiled over the period 2017-2019 by PWC (2020) suggests that the two third of European launch contracts were issued following open market rules, whereas all other geographical areas **majoritarily apply restricted/captive markets rules**: 73% of the launch contracts for Japan, 77% for the US, 79% for Russia, 87% for India and more than 99% for China. According to ASD, the share of sales to European public entities, including both launch services and spacecraft manufacturing, was around twice the share of commercial sales in 2021, with EUR 5 500 million as opposed to around EUR 3 000 million respectively (a trend observed over the last four years with around 65% of industry sales from European public institutions).[35] Nonetheless, the space sector is a positive contributor to the European trade balance with an average net surplus of EUR 1.5 billion per year in the past decade.

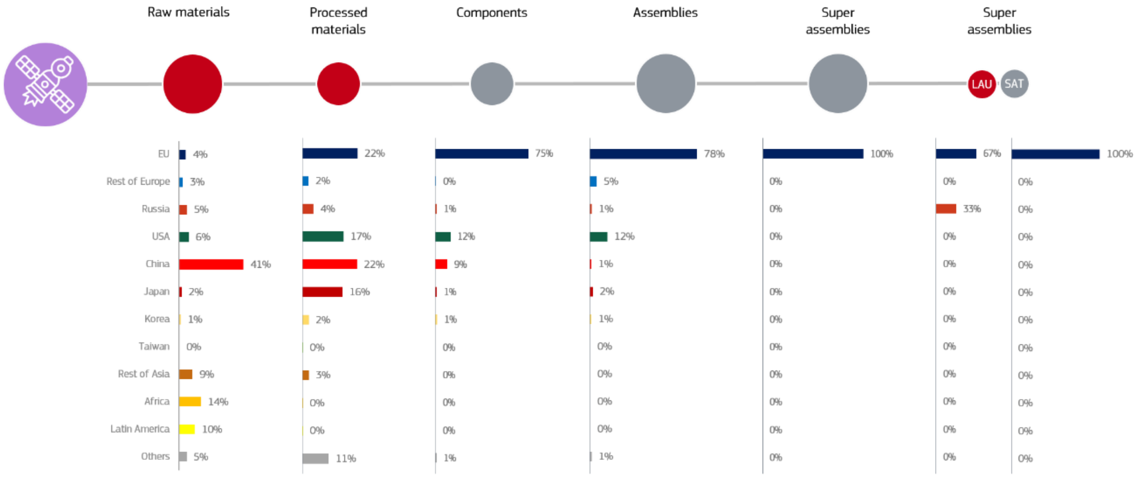
Both the COVID crisis and Russia's invasion of Ukraine negatively impacted the European space sector during recent years and continue to threaten the security of supply for materials and components.

As with most industrial value chains, **European space systems rely on (critical) raw materials**, which are among the first building blocks of the industrial value chain. Figure 78 provides a first mapping of the direct use of strategic and critical (raw) materials. Most **space-grade materials and qualified components are highly specific** and require advanced manufacturing capabilities and technologies. The sector is only a minor customer in terms of volume compared to other large-scale industries. This position may increase the **vulnerability** of the sector also because the **substitution** of materials is not straightforward due to the stringent and time-consuming testing and qualification steps. Conversely, when considering **cross-sectorial competition** against more conventional sectors, one advantage of the sector stems from its high **"willingness to pay"** premiums to supply specific materials and components. The **stockpiling** of strategic materials/components is feasible for the space industry, which has not adopted the structure of the "just-in-time" manufacturing of sectors such as automotive and electronics.

2.15.2. Current supply chain bottlenecks

Considering the significant variability of space missions (and thus embedded devices/instruments) and of the associated launcher vehicles to reach targeted orbits, '*generic*' elements of the value chains have been used for space systems. A more detailed definition of the launcher and satellite architectures according to their missions (e.g. communication, positioning and Earth observation) would be needed in the future to map the potential supply chain criticalities associated with components and assemblies. An overview of the supply risks addressed in this section are compiled in Figure 79. It should be noted that compared to the other technologies assessed, only EU manufacturing capabalities (and thus only EU supply) is considered. This can be explained by the partly captive and dual-use nature of the space market, still mainly funded by public subsidies or defence budgets.

Figure 79. An overview of supply risks, bottlenecks, and key players along the supply chain of space launchers and satellites.



Source: JRC analysis. Note: Due to the nature of the space technologies, only EU space manufacturing industry is included in the scope. Hence, only EU supply is addressed (and not the global one as it is the case for other technologies).

Critical raw materials and processed materials

A majority of the raw materials identified as strategic or critical are used directly or indirectly by the space industry. They are not concentrated in particular sub-systems or technologies but are dispersed across a myriad components used in the sector.

The most important concentration of critical raw materials in term of mass stems from the use of specific **metallic alloys**. The main desired properties are lightweight, high strength, high resistance to corrosion, oxidation and thermal shock, which are offered by **aluminium (obtained from bauxite), titanium metal, nickel and cobalt alloys**. Aluminium alloys used in the space sector are divided between aluminium-copper 2XXX series, aluminium-magnesium 5XXX series, aluminium-zinc 7XXX series and aluminium-lithium (or aluminium-cerium alloys (8XXX series). While not the main elements, **magnesium**, **scandium**, **silicon metal** and **chromium** often represent a non-negligible percentage in the composition.

A particular focus can be placed on Ti-6Al-4V, the most common **titanium alloy** used in aerospace and composed of around **90% of titanium, 6% of aluminium and 4% of vanadium.** Ti alloys are mainly used in launchers and satellites for cryogenic propellant tanks and some critical structural parts. While the EU is 100% reliant on **aerospace-grade titanium sponge** (primary metal stage) produced by only three countries worldwide – Japan (ca. 50%), Russia (ca. 35%) and Kazakhstan (ca. 15%) – several EU-based companies, joint ventures and non-EU subsidiaries produce titanium ingots and semi-finished products as well as titanium powders for additive manufacturing in Europe (JRC 2022). Stainless steel (obtained with **coking coal**), even if relatively heavy for space systems, is used in the composition of several launcher components. Lightweight alloys mainly manufactured with **high-purity magnesium** and **beryllium** are also used in the composition of structural elements for satellites. Finally, super alloys for spacecraft are mainly nickel or **cobalt**-based with substantial amount of **niobium** or **Tungsten**. Even if representing only a certain percentage in the total metallic alloys, the global supply of these CRM elements is very concentrated: 92% of niobium supply comes from Brazil, for example, and 91% of magnesium from China (JRC, 2019).

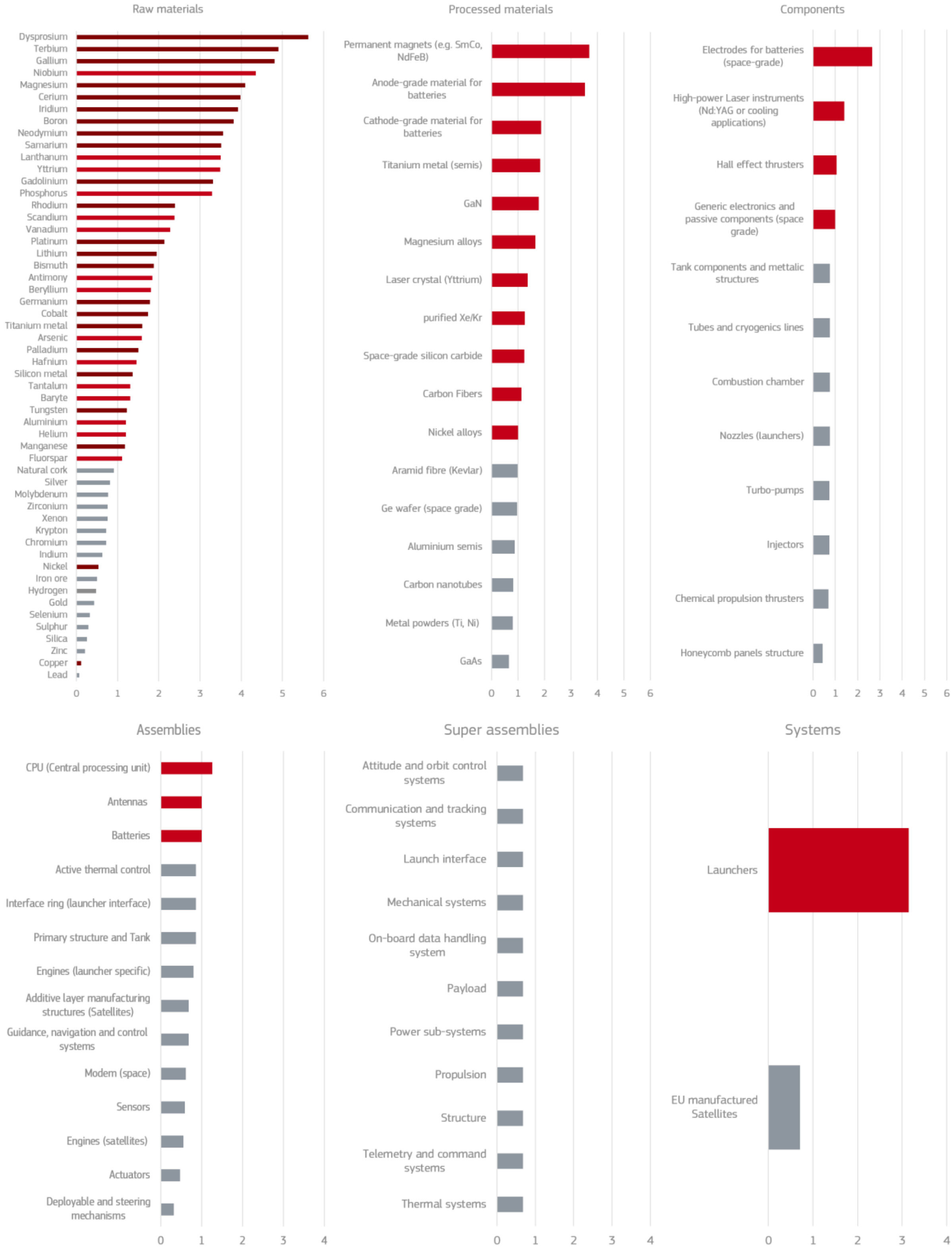
Advanced composites and ceramics materials are widely used in the space sector, mainly in the form of **carbon-fibre reinforced plastics** (CFRP) and their precursors, e.g. polyacrylonitrile (PAN), glass-fibre reinforced plastics used for structural pieces and **aramid fibres** (e.g. Kevlar) **and carbon nanotubes** for coating and shielding panels. Composite materials appear particularly critical because a **wider uptake of such materials and more particularly CFRP is expected in Europe** in the coming decade for space structural elements and cryogenic tanks (ESA, 2021). High performance carbon fibre materials are required in almost all space-relevant applications, appearing in components in launchers (typically high strength applications) and satellites (typically high stiffness applications). Regarding companies able to comply with space-grade requirements, around the two-third of those identified are Japanese-based (mainly Toray, Teijin, and Mitshubishi) (ECSS, 2011). According to Toray's own communication, its subsidy in France (Toray CFE) is the only producer of **high-modulus fibres** on the European continent thanks to a technology transfer from 2019 (Toray, 2020). US-based Hexcel company is also a strong player for aerospace-grade composite materials and associated precursors with production facilities in the US and Europe (mainly in France and Spain) where carbon fibres are produced. According to its corporate communication, EU-based company Solvay cooperates with other EU-based company SGL Carbon to produce intermediate modulus carbon fibres and supply Avio's company with advanced carbon fibres and composites (Solvay, 2020; 2021). For shielding applications, Aramid fibres are dominated by US (50%) and Japanese-based (25%) production, with no or limited production in Europe, while carbon nanotubes are also mainly produced in the US (43%) and to a lesser extent in Europe (19%) (JRC 2020) by firms including the Finnish company Canatu and the Arkema production plant in France. Finally, **space-grade ceramics** used for launchers nozzles, require **graphite** used in carbon-carbon materials (C-C) and also **silicon carbide (SiC)** the latter being the main advanced materials for manufacturing ceramic matrix composite components (CMCs). The production of **aerospace-grade SiC** is performed quite exclusively by NGS advanced fibers, a joint-venture owned by Nippon Carbon (50%), Safran (25%) *via* its subsidiary Safran Ceramics, and GE (25%), with only one production facility in Japan and a second opened in 2015 in the US (Selko, A., 2015). **Graphite** and **Tungsten**, or **Graphite** and **Chromium** also enter in the composition of Tungsten carbide and Chromium carbide respectively which are often used as coating elements for steel, aluminium or titanium alloys (Chanoine et al., 2019).

Semi-permanent magnets used in space systems contain **rare-earth elements such as samarium, neodymium** and **dysprosium.** For instance, the three-axis attitude control systems contain reaction wheels made of **samarium-cobalt magnet** (ESA, 2019a). China has been identified as the major supplier (80%) of REE magnets worldwide, while a few US-based and UK-based companies are also competing in manufacturing magnets (e.g neodymium iron **boron** - NdFeB) and magnetic assemblies for specific space applications.

Glass and ceramics for optical devices countain important amounts of critical and strategic materials. Optical instruments and remote sensors are needed for the Earth observation missions. For such purpose, **specific glasses** are manufactured with **phosphorus, lithium or borate** while **filters** for infrared applications are made with **germanium**. Mirror substrates based on rare earth elements thin film are also used to increase radiation resistance, e.g in **cerium-doped** glass used to cover PV solar cells. At least one German manufacturer, i.e. Zeiss has been identified to supply a large set of specific glass-ceramics to produce mirror substrates and optical lenses for which another German-based company called Schott is also a market leader with zerodur® glass ceramic series. Regarding laser crystal manufacturing, and more particularly Nd:YAG (neodymium-doped yttrium aluminum garnet), most of the industrial capacities are located in China (40%) and the US (35%) but at least three European companies (Baikowski, Crytur, Altechna) with facilities in Czechia, France and Lithuania are present in the market.

Noble gas and helium are widely used in space systems. High-purity grade **helium** (≥ 99.9%) is used as inert purge gas for hydrogen systems and a pressurising agent for ground and flight fluid systems or as a coolant for satellites' optical parts. Even if Europe demonstrates industrial capacities in the field with *Linde* and *AirLiquide* companies, the market of crude helium (extracted as a co-product of gas) is currently experiencing supply shortages, partly driven by mishap and planned outages but also the geopolitical context with a supply dominance of only three countries, Qatar, Russia and Algeria, representing 60% of global production (Cockerill 2022). **Xenon** is also widely used as a propellant in satellites' electric propulsion systems, space application representing the largest share (37%) of the global market in 2021. Since the xenon market is very volatile and demand is expected to increase drastically in the coming years, the space industry might experience a supply shortage (Herman & Unfried, 2015). To tackle this issue, substitution routes with **krypton** (which is collected in a ratio of about 10-to-1 compared with xenon) appears to be a promising option. However, despite important EU domestic production of crude and purified xenon/krypton, the supply of noble gas in Europe might remain at risk with most of the EU imports of noble gas in economic value currently coming from Russia (22%) and Ukraine (25%) (JRC, 2022b). Regarding alternative for Hall thruster propellant, several candidates have been identified, among others, **bismuth**, iodine, and more recently Argon (as announced for US Starlink 2nd generation).

Figure 80. Detailed Supply Risk of selected elements in the space launchers and satellites supply chain



Source: JRC analysis.

Components

Solar cells for PV systems represent 13% of the germanium demand worldwide. Multi-junction **solar cells** have become standard in space application with a typical **triple-junction solar cells** combining **germanium-substrate wafer** with **gallium indium phosphide** (GaInP) and **gallium arsenide** (GaAs) semiconductors. In Europe, **germanium substrates** qualified for space applications is manufactured by Umicore. The market is very competitive (ESA, 2018) with non-EU firms also well positioned, such as Canadian firm 5-n Plus and other US-based and Taiwanese companies, and significant investment is currently being made in the US for the next generation of cells. 5n-Plus recently acquired the European leader of **multi-junction solar cells** based on III-V compound semiconductors (5N Plus, 2021). Even if at least one other EU manufacturer of **space-specific** solar cells has been identified, this takeover might lead to a loss of EU strategic autonomy in the field while establishing the purchasing company as a supplier to both the European and US space programmes through Canada's membership status within the ESA. Outside Europe, substitution strategies have been implemented by SpaceX for its Starlink constellation, using **silicon-based solar cells** (supplied by Tawanese TSEC) which are traditionally used for terrestrial applications. This illustrates the tendency to use non-specific space-grade components for satellite production despite the potential lower reliability of such devices.

Electrical, Electronic and Electro-mechanical (EEE) components are the fundamental elements of any spacecraft, but a large number of EEE parts, including high-value components, are sourced from third countries. Overall, it was estimated in 2016 that on a typical ESA satellite programme, half of the EEE component procurement costs correspond to the procurement of components from the US. More recent figures suggest that 70-75% of component value for a typical ESA scientific mission goes to non-European suppliers (PwC, 2022, 2016). This dependency leads to major impacts in terms of both technological strategic autonomy and supply chain management. Regarding the last point, the supply of EEEs has been hit by severe disruptions and delays in the recent post-covid period. For instance, Thales reported bottlenecks in the EEE supply chain as the main cause for delays related to Telesat's Lightspeed constellation (ESPI, 2022). The recent trend of wider use of more affordable **commercial off-the-shelf (COTS) components** driven by the higher production volume of small satellites and constellations allows industry to diversify its supply possibilities but often lower the reliability and hamper the traceability when such elements are integrated into different electronic units and boxes of the satellite. With an increased use of COTS in the coming years, **testing facilities** to qualify such components could become a supply chain bottleneck, offering only limited capabilities in term of testing slots and thus threatening the reliability of European space missions. Recently, the French-based company TRAD, proposing such testing and analysis of radiation effects, was acquired by the US-based Heico Corporation via its subsidiary 3D plus. The US parent company also entered negotiation to purchase the European company Exxelia, one of the global leaders in the manufacturing of space-qualified passive components (e.g. capacitors, inductors, filters) (Heico, 2022).

Semiconductors used for space applications account for less than one percent of the global semiconductor market which could lead to increase sector's vulnerability (ASD-Eurospace, 2022b). However, the high willingness to pay for supplying semiconductors and the possibility of stockpiling prevent severe shortages. In addition, the size and associated numbers of transistors per chip is not the only property to consider when dealing with space systems, but its resistance to extreme conditions and radiations, reliability, and lower energy consumption are also important parameters to consider. In recent years, ESA identified **gallium nitride (GaN) semiconductors** as a key enabling technology for space, particularly for amplifying radio frequency signals and very high power-switching systems. UMS and OMMIC are the two European commercial sources for advanced **GaN,** and also GaAs, **MMICs** (Monolithic Microwave Integrated Circuit) and qualified semiconductor processes (ESA, 2022). However, GaN transistors used for such integrated circuits appear to be particularly critical, with no direct and independent supply capacity in Europe (Flaherty, 2022; EC, ESA, EDA, 2020). **Sensors** are also of prime importance and particularly for high-performance imaging based on infrared or visible range detectors. European capabilities in the field are concentrated at design level while activities focusing on production with large-scale **foundry** services appears very limited.

Thrusters and engine-related components are key technologies ensuring the propulsion of launch systems, and in-orbit positioning of payload. For Ariane launchers the components, such as injectors, valves, thrusters, combustion chamber, turbo-pumps and nozzles are produced locally in Europe. The situation differs for Vega and Vega C launchers which use the RD-843 single nozzle liquid propellant rocket engine manufactured by Yuzhmash in Ukraine, and for which potential stockpiling has been decided. For satellites, the situation depends greatly on the mission and the specificities of each payload. The new generations of commercial and scientific satellites are now equipped with **electric propulsion for which Europe demonstrates established capabilities** (Gonzalez del Amo and Di Cara, 2022). However, propulsion systems may face supply disruption mainly due to the significant market shares of Russian-based EDB Fakel company which manufactures propulsion units and electric thrusters and represented roughly 10% of the global space market before Ukraine's invasion (Sheetz, M. 2022), supplying e.g., the OneWeb constellation systems that should be replaced by US Astra thrusters (Foust, J. 2022a). Substitution with devices from other competitors seems feasible at EU level with Safran being well positioned (supplying Gallileo new generation's electric propulsion devices) or dynamic start-ups such as ThrustMe and Exotrail.

Metal structures for European space systems are produced locally, for instance titanium parts of propellants' tank are manufactured by MT Aerospace (an OHB subsidy) in Germany. Additive layer manufactured elements are produced also in Europe as detailed in Section 2.12.

Assemblies

Space systems require **lithium-ion batteries** for power storage and supply. Battery chemistry types for space systems need to be further investigated, also anticipating potential next generation solid-state batteries. According to Saft manufacturer's commercial website, materials for technologies used in Space are the following: nickel (Ni-Cd, $Ni-H_2$), primary lithium ($Li-SO_2$, $Li-SOCl_2$, and $Li-MnO_2$), and rechargeable lithium (Li-ion). The latter seems to be now the baseline for space systems, particularly LTO batteries with titanate-based anode (obtained by calcination of titanium oxides and lithium carbonates high-purity powders) but also NMC chemistry with an increased use of COTS devices.

Several other elements under the *Assemblies* categories appear critical in term of European strategic autonomy and enhancement of its industrial capabilities for the coming decades. For instance, **gyro units and inertial measurement units** covering different specifications and associated performance grades. A gap in the market for medium range gyroscopes has been identified with potential introduction of upgraded COTS components to fulfil the demand in the coming years (ESA, 2020). **Antennas** are also critical devices to allow high-speed signal transmissions. Large reflectors antennas technologies are largely dominated by the US, whereas Europe still need to gain in maturity before proposing similar technologies (EC, ESA, EDA, 2020). Finally, **Central Processus Units** (CPUs) are also largely **imported from US**, even if in this field space technology are conservative and tends to lag behind its faster-moving terrestrial equivalent (Krywko, J. 2019). Some European initiatives can be mentioned, mainly the development of LEON processors under ESA leadership which seek to ensure reliability and radiation hardening properties (CAES, 2022). In January 2023, the first EU space-qualified **programmable chips** known as field-programmable gate array (FPGA) has been presented by the company NanoXplore and is considered as a promising way to reduce EU technology dependences thanks to its flexibility which allow equipment manufacturers to programme it for a large diversity of tasks.

Super-assemblies and space systems (launchers and satellites)

Europe is a major space power regarding the **design and integration** of the large space systems mainly carried out by its prime contractors, Thales Alenia Space (Thales-Leonardo joint venture), Airbus DS, OHB, Avio and ArianeGroup (Airbus-Safran joint venture). Since final assembly of satellites' systems take place in Europe, no particular supply dependencies or bottlenecks have been identified in this domain, which encompasses among others: attitude and orbit control systems, communication and tracking systems, on-board data handling system, telemetry and command systems, power sub-systems, propulsion, structure, and thermal systems.

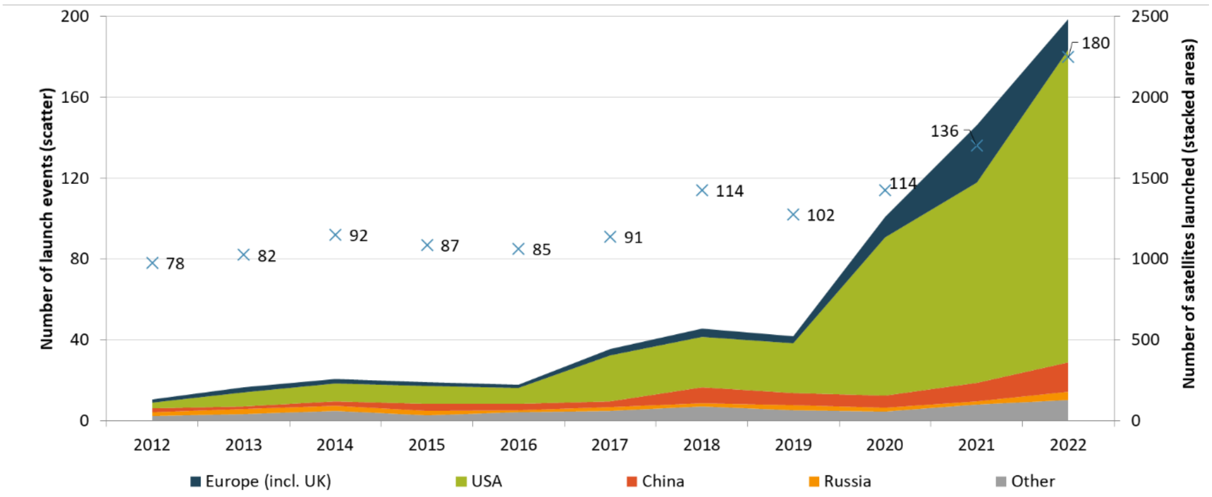
However, when looking at current **launching capabilities**, the situation can be considered as particularly **critical for Europe** which lost the access to the Russian-manufactured Soyuz launcher after the invasion of Ukraine in February 2022. Partly due to this disruption, the share of launches performed by EU commercial company Arianespace dropped dramatically, from 17 in 2021 (11% share of the total) to only 5 launches in 2022 (4% - see also Figure 82**Figure 82**). In the short term, the situation is even worse since the recent failure of the new Vega-C launcher on December 2022 and the delayed transition between Ariane 5 and Ariane 6, jeopardising **Europe's independent access to space** and its associated strategic autonomy (Hollinger, 2023). It is worth to mention that 'supply chain management' has been acknowledged as the source of the Vega C failure caused by composite carbon-carbon material over-erosion during the launch (ESA, 2023).

2.15.3. 2030 technology prospects (satellites only)

Estimating the future demand of space systems is not straightforward. It is, however, possible to track most of the launch events with the associated payload and mission. Hereafter some figures are proposed which are sourced from available datasets (see Figure 81). Very recently, a technological revolution started in the space sector with the launches of new megaconstellation systems starting in 2019 with OneWeb (more than 280 satellites deployed in 2021, and additional 116 in 2022) but, most of all, the SpaceX-owned Starlink constellation (more than 1 300 already deployed and active satellites). It is forecast that a range of 1 000 to 1 700 small satellites (<500 kg) will be annually launched until 2030 (Pardini and Anselmo, 2021; Euroconsult, 2021).

Even if the number of satellites launched dramatically increases, their limited size and mass allows them to be clustered to limit the number of launches. In the case of Starlink satellites (~260 kg), each launcher event put in orbit a batch of 60 satellites. This is the main reason why a more limited increase regarding the number of launch events is currently observed (+54% between 2010 and 2020). The space industry is nonetheless experiencing its highest launch rate since the beginning of the space era, with around 3 launch events per week worldwide.

Figure 81. Evolution of annual number of satellites launched per country (left axis) and annual of launch events (right axis) per year



Source: JRC based on Jonathan McDowell database (McDowell, J. 2023)

The increasing launch cadence is possible because the space industry is experiencing the progressive **'industrialisation'** of its space value chain. Significant increases in term of production volumes and associated demand for space grade materials and components are expected in the coming years mainly because of the **wider deployment of mega constellation systems**. Government and public institutions should continue to massively support the sector representing, in the coming years, an estimated 75%-share of the satellite manufacturing and launch markets value. Nonetheless, non-conventional players could also play a role regarding the diversification of the demand for space services, as for example agricultural firms, urbans planners as well as insurance and financial services.

Large economies of scale in satellite manufacturing and potential decrease in launch prices should boost the demand for new space infrastructures. **The vertical integration** of the production lines and reusability of booster stages already implemented in the US represent a major point in the space industry which is now developing **'mass production'** strategies. In Europe, a first mega-factory located in Belgium has been announced in June 2022, forecasting a production capacity of 500 satellites yearly starting in 2025 (Aerospacelab, 2022). The production and assembly of identical reduced-size spacecraft is made possible by the development of high-speed assembly lines for standardized satellite platforms also supported by 3D printing and digital engineering (Bernstein, L. 2022). A wider integration of commercial off-the-shelf (COTS) parts, particularly dealing with electronics and avionics (ESA, 2019b), should contribute to the increase of the production rate while at the same time fostering the risk of major supply disruptions as experienced today by more conventional sectors like automotive.

Table 6 gives a first overview of forecasts dealing with partly deployed or announced broadband mega constellation projects.

Table 6. List of planned constellations per company and country.[63]

Name	Company/Organisation	Country	Total number (planned)
Starlink *(partly deployed)*	**SpaceX**	**US**	**12 000**
OneWeb *(partly deployed)*	**OneWeb/Eutelsat**	**UK/FR**	**650**
IRIS^2	European Union	EU	170
Kuiper	Amazon	US	7 774
Hongyun	Xingyun (CASIC)	China	864
Hongyan	CASC	China	320
Yinhe	GlaxySpace	China	1000
Guangwang Cosntellation	GW	China	12 992
Hanwha	Hanwha systems	South Korea	2000
SpaceMobile	AST	US	243
Proliferated warfighter space architecture (PWSA)	SDA	US	150
Mangata networks	Mangata	US	791
Lightspeed	Telesat	Canada	1969
Kepler	Kepler	Canada	360
		Total	***(approx.) 40 000***

Source: data partly retrieved from Jonathan McDowell database (McDowell, 2023)

2.15.4. Geopolitical dimension

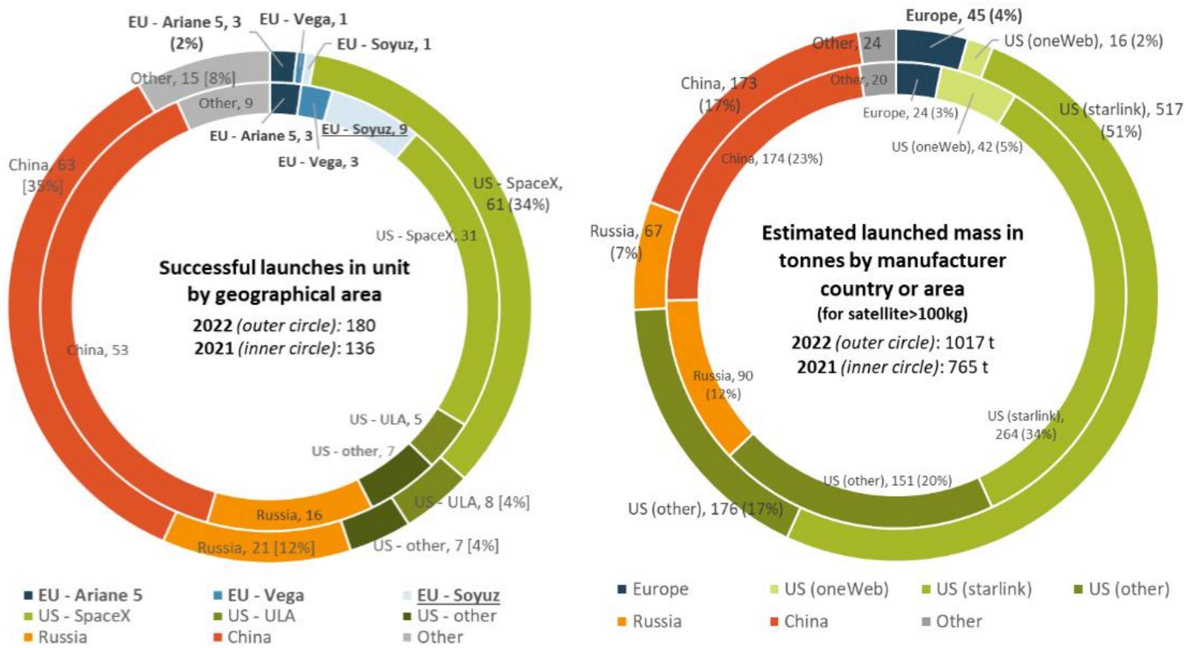
Space has always been used by nations to demonstrate their sovereignty, power and technological advance. From three space-launching countries (the USSR, US and France) and three additional countries owning satellites (Canada, United Kingdom and Italy) in 1966, more than 65 countries are today involved in space. However, **only a few of these states**, (mainly the US, China, Russia, Western Europe, Japan and India) have the **industrial and technical capacity** to manufacture their own satellites and launchers and operate the on-ground tracking, telemetry and control (TT&C) systems to monitor and guide their spacecraft.

Closely linked to the defence industry, the geopolitical/strategic dimension of the sector reinforces the risk of supply disruptions. The return of the **geopolitical dimension** in the space sector is illustrated by the growing ambitions of spacefaring nations on the commercial and export space markets, which is the case of the US, China and, to a lesser extent, Russia and India. The competitors of the EU in this field are at the same time the main suppliers of critical and strategic (raw) materials for space systems as highlighted in Section 2.15.2.

The two leading nations, the US and China, have ambitious plans and the capacity to implement them, with, in both cases, a powerful mixture of **governmental policies and private space ventures** (Denis et al., 2020). In addition, their internal market already represents a huge asset for commercial activities. Figure 82**Figure 82** compiles, for the years 2021 and 2022, the performance of each geographical area (Europe, the US, China, Russia) in terms of the number of successful launches and total mass of satellites manufactured and placed in orbit. **In 2022, US companies performed 42% of the 180 successful launches as opposed to 35% for China**. SpaceX dominates the commercial launch market with its Falcon 9 rocket, currently facing very limited competition from other US or European manufacturers (i.e. United Launch Alliance, Blue Origin and Arianespace). Consequently, there is an absence of market pressure which allows the company to maintain stable launch prices to the great benefit of its own Starlink constellation (Ralph, E. 2022). It should be noted that around half of the total mass placed in orbit in 2022 comes from new batches of Starlink satellites. Overall, the US space industry (including *OneWeb satellites*[64]) manufactured 70% in mass (i.e. more than 700 tonnes) of space systems in 2022. The other competitors are lagging behind with total launch masses of 173 tonnes, 67 tonnes and 45 tonnes for Chinese, Russian and European manufacturers respectively.

[63] In January 2023, only Starlink and OneWeb were deployed and functional. It is likely that not all the constellation projects will materialise.
[64] *OneWeb satellites* is a joint venture equally owned by OneWeb and Airbus Defence and Space with its main facilities in Florida

Figure 82. Number of successful launches in unit by geographical area (left) and estimated mass of satellites placed in orbit by manufacturing country (right) for the years 2021 and 2022.



Source: JRC based on Jonathan McDowell database (McDowell, J. 2023)

New collaborations in the field of space are being set up, such as new partnerships announced between the US, Japan and Taiwan (Schwartz et al. 2023), but also between China and emerging space nations such as Middle East countries (Jones, 2022). A **race for new mega-constellation systems**, and thus the development of mass-production industrial capacities, is likely to happen in the coming decade. The European Commission has put forward an ambitious plan for **the development of the IRIS² constellation** (Infrastructure for Resilience, Interconnectivity and Security by Satellite). This new space-based secure connectivity system will operate at multi-orbital level, with a more limited number of satellites65 compared to pre-existing mega-constellation systems (Starlink or OneWeb) or those planned, like Amazon's Kuiper or Chinese state-owned CASC projects. IRIS² should provide high-speed and secure enhanced **communication capacities** to governmental users as well as to business users, including additional applications such as border surveillance and crisis management (e.g. humanitarian aid).

2.15.5. Key observations and recommendations

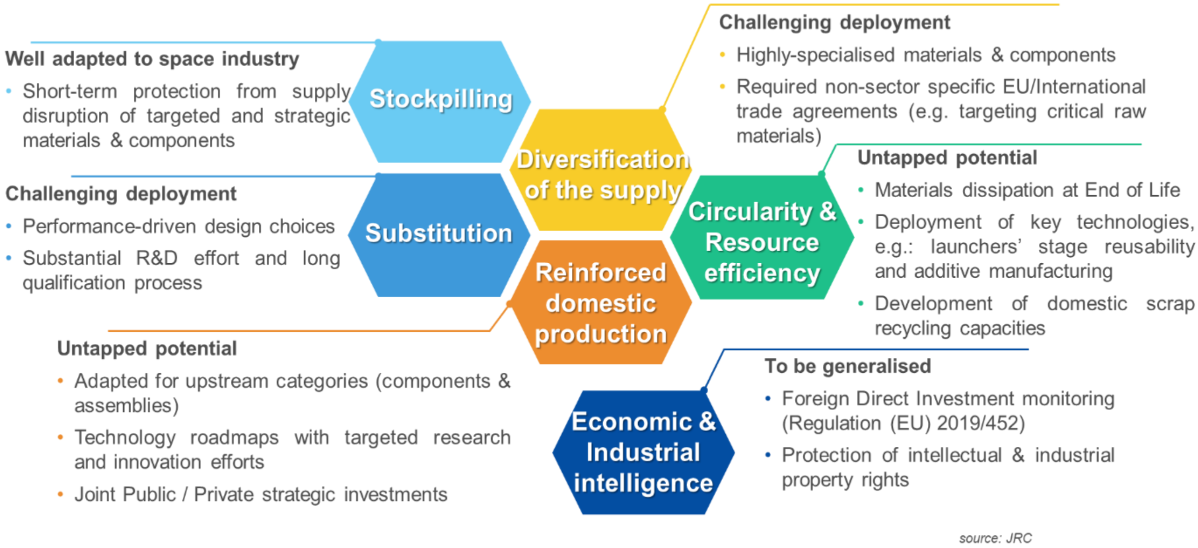
Monitoring supply chain bottlenecks is key to maintaining the strategic autonomy of the EU space sector and ensuring that it does not lag behind other space powers. **EU is a space power** with significant industrial capabilities and know-how, particularly regarding the assembly and integration of systems (i.e. the last stages of the value chain).

However, a high to very high **reliance** has been identified for critical raw materials in metal alloys or semis and also for electronics components. This dependence leaves **the space industry vulnerable** to supply shocks and **export controls**/restrictions from third countries, undermining EU competitiveness on global markets. The specificities of the sector with performance-driven components and "space-grade" materials **hampers the substitution potential** while its relatively small/niche size increases its vulnerability. In addition, the global **geopolitical context** and the proximity of the space sector to the defence industry reinforces the risk of potential supply disruptions, with possible **cross-sectorial competition** occurring to procure the same materials (titanium, tungsten, cobalt) or components (chips). The **industrialisation** of the sector with increased production rates and broader use of commercial off-the-shelf components, could also threaten the resilience of the the supply chains by going into competition with more conventional industries (automotives, renewables).

65 170 satellites scheduled between 2025-27 in low earth orbits according to EUSPA (2022)

The implementation of appropriate **mitigation measures** by the sector could help to anticipate and mitigate associated supply risks, as presented in Figure 83.

Figure 83. Mitigation measures to decrease supply risk and industrial dependencies of the EU space value chain.



Source: JRC own elaboration (Maury-Micolier et al. 2022). The figure presents qualitative assessments: "Well-adapted", "Challenging", "Untapped potential" or "To be generalised" for each of the mitigation measures.

- In the short-term, **stockpiling strategies** focusing on strategic components and processed materials appear to be well adapted to the space industry, which is characterised by a low production rate and **"willingness to pay"** premiums for accessing the more constrained materials or components (such as microchips).
- Conversely, the **diversification of the supply** is more challenging, as only a few global suppliers can provide "space-grade" materials and components with a space flight heritage[66]. This aspect has been highlighted with the Vega-C VV22 mission failure due to the over-erosion of a carbon-carbon composite supplied from Ukraine instead of an equivalent qualified material with flight heritage produced by Arianegroup (ESA, 2023). In addition, the restrictive/captive nature of the market and the European geographic return rules also limit diversification opportunities. However, commercial and geopolitical circumstances can force diversification, as has happened for titanium products (Barnier L., 2022), whose supply has shifted from Russia to Kazakhstan and Japan for aerospace-grade sponge, and to the US and the UK for wrought titanium products (JRC, 2022).
- **Substitution strategies** are not straightforward in this sector, with its long R&D phase and associated testing and space qualification procedures. Space-grade components could be substituted with widely available but less reliable commercial off-the-shelf **(COTS) products** for the automotive, aviation or renewables sectors (Foust, 2022b). However, on top of increasing **inter-sectorial competition** and therefore **rising prices**, this would make the space sector more vulnerable to the disarray and longer lead times which affected conventional supply chains after the pandemic. Regarding electrical, electronic and electro-mechanical (EEE) components, the disruption effects for the space sector are exacerbated by its limited demand share in comparison with other industries, complicating negotiations with suppliers (ESPI, 2022).
- The development of **recycling** routes in the sector is currently minor and limited to post-industrial waste streams. The uptake of recycled material in space systems is marginal. However, recycled germanium has been considered by the ESA for the solar cells of satellites (Kurstjens et al., 2018)

[66] Space flight heritage means the component has been flown in space during previous mission and demonstrate its reliability when operating in harsh environments

and titanium alloys obtained from post-industrial scrap may qualify for space application. Yet, the development of domestic scrap collection schemes and reprocessing of scrap, coupled with the wide deployment of additive manufacturing processes, could present an opportunity to **increase the sector's resource efficiency.** Indeed, some current processes suffer from very **low resource efficiency** and a low buy-to-fly ratio[67]. For instance, more than 90% of the titanium alloys used for cryogenic tanks is scrapped during manufacturing. Apart from the **reuse of the launchers' lower stages** (and potentially future upper stages), in which Europe is lagging behind the US[68], the recovery of materials at the end of the mission is not realistic in the short term due to the post-mission disposal practices based on atmospheric re-entry (i.e. demisability of the spacecraft materials for low orbits and re-orbiting into graveyard orbits for middle and geostationary orbits). The so-called 'design for containment' (Vidal Urriza et al. 2022) must mature substantially before the material loop can be closed for space systems.

- While the last stages of the value chain (i.e., sub-systems manufacturing and system integration) appear to be less at risk, the supply risks upstream are worth closer attention for some targeted components and advanced materials. The strategic and confidential nature of space systems manufacturing (which is widely based on dual-use technologies and components) complicate the screening of the operations and the associated disclosure of industrial process-related information. Nevertheless, **reinforced domestic production capacities** require the deployment of comprehensive **monitoring information systems** targeting the entire supply chain and aiming to identify potential gaps and criticalities. This should be completed with the design of **technology roadmaps** shared between research institutions and industrial stakeholders. Several European Commission initiatives address this objective, including the European Alliance of Space Launchers and the Observatory of critical technologies developed in the context of the Action plan on synergies between civil, defence and space industries (EC, 2021), and the establishment of a joint task force between the European Commission, European Space Agency and European Defence Agency to ensure European space sector non-dependencies (EC, ESA, EDA, 2020) in the coming years. The ESA proposal on EEE Space Component Sovereignty for Europe was granted at the Paris Ministerial in November 2022, to ensure a stable, predictable development and procurement approach for EEE parts over an initial five-year period, compensating for current volatility in the global microprocessor market (ESA, 2022b). The development of such initiatives allows the European sector to identify current technology gaps and anticipate future needs, securing EU strategic autonomy in the field. These initiatives should unlock **joint public/private investment** to increase the maturity of new technologies, enable their industrialisation and reinforce Europe's technological sovereignty.
- Finally, it is crucial for the space sector to focus on **foreign direct investment** in the field as well as developing **enhanced industrial property rights protection** to mitigate the risks associated with aggressive take-overs from third countries. The Regulation (EU) 2019/452 establishing a framework for the screening of foreign direct investments into the Union created a cooperation mechanism for Member States and the Commission to screen foreign investment. This framework is particularly relevant for the space & defence sectors, and also identifies raw materials as critical elements. In parallel, the recently adopted **Foreign Subsidies** regulation 2022/2560 (EU, 2022) and coming EU legislative acts should ensure a level playing field for industries to target unfair practices, counter aggressive take-overs, relocation incentives and foreign subsidies leading to market distortion.

[67] The *buy-to-fly* ratio is the weight ratio between the raw material used for a component and the weight of the component itself.

[68] Launchers' first stage reusability is systematically implemented by SpaceX since 2017, and to a lesser extent by BlueOrigin. In Europe, ArianeGroup-led consortium, funded by ESA, is working on Themis reusable stage demonstrator and Prometheus reusable engine demonstrator with an expected testing period from 2023 to 2025.

3. Raw materials and supply chains in strategic sectors

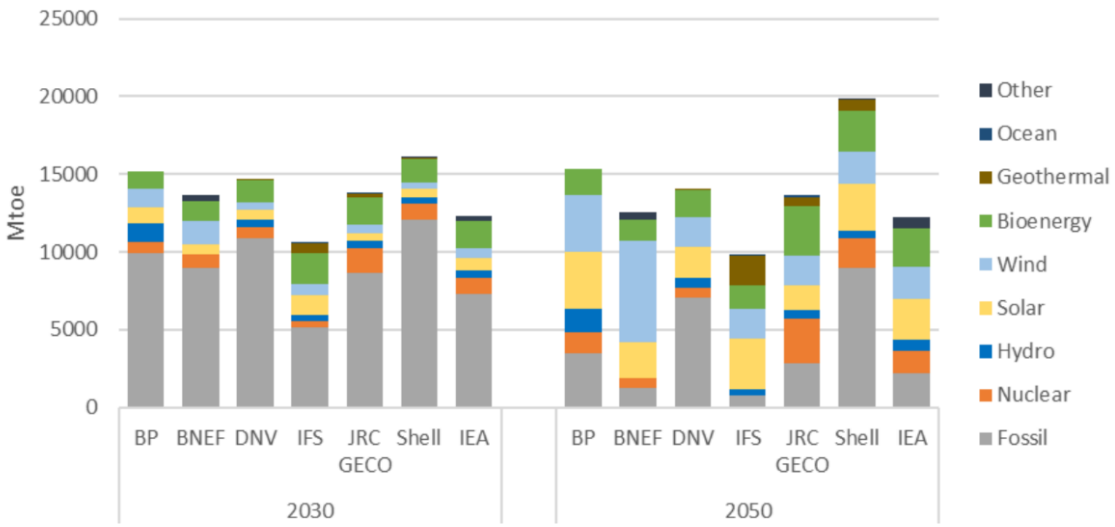
3.1. Renewable energy

3.1.1. Introduction

Renewable energy has a key role to play in the transition towards a low-carbon society and the achievement of independence from imported fossil fuels, both of which are top priorities for the EU. Faced with the challenge of reducing dependence on Russian fossil fuels, and the urgent need to speed up the energy transition, the EU adopted the REPowerEU Plan of Action in May 2022 (EC, 2022). The initiative sets ambitious targets and details specific actions for boosting the deployment of renewables, mainly wind power and solar photovoltaic (PV), hydrogen production, heat pumps for heating and cooling, and batteries for energy storage and the decarbonisation of the transport sector. The Plan also aims to preserve and strengthen the competitiveness of the European clean energy industry.

Solar PV, wind turbines, electrolysers, batteries, fuel cells and heat pumps (for residential applications) are all included in the analysis of this sector. Other technologies, such as bioenergy, hydroelectric, geothermal and ocean energy are also included in the renewable energy portfolio, but in a scoping exercise carried out early in this project, it was estimated that the impact and challenges of their growth on critical materials demand would be very low, and they were therefore excluded from further analysis. Whether the aim is the production of energy or hydrogen from renewable sources, or its storage, transport and integration in batteries, fuel cells or heat pumps, the sector is poised to grow at an increasing rate in the coming years. Wind and solar power, projected to become major energy sources globally and in the EU, will contribute most to this growth until 2050, as far as energy production is concerned (Figure 84).

Figure 84. Global primary energy consumption.



Source: Tarvydas et al., 2022

3.1.2. Relevant technologies

Figure 85 shows the main technologies involved in the renewable energy sector for generation and storage (i.e., batteries, electrolysers, wind turbines, heat pumps and solar PV). These technologies are also key contributors to other sectors. For instance, heat pumps contribute to energy-intensive industry sector through heating and cooling industrial processes using waste heat recovery. Solar PV contributes to the ICT, defence and energy-intensive industry sectors as an energy source, and batteries contribute to mobility, ICT and defence as the products manufactured in these sectors require uninterruptible power supplies.

Figure 85. Technologies involved in the renewable energy sector

Source: JRC analysis.

Wind energy deployment is expected to accelerate in the coming years due to the development of cost-competitive turbines and innovations in design aimed at increasing productivity, especially in offshore locations and areas with low wind conditions. This is reflected in the two alternative scenarios from GECO, both foreseeing favourable growth assumptions. The less optimistic forecast projects an increase in global wind power capacity from 732 GW in 2020 to 1 400 GW in 2030 and 4 050 GW in 2050. On the high side of the forecasting range, wind power capacity is projected to grow up to 2 500 GW and 8 400 GW in 2030 and 2050 respectively (Figure 33).

Solar PV will also see an exponential expansion in the years to come. As explained in 632.6.3, new technological developments will significantly increase their efficiency and reduce the cost through improvements in device architecture and material functionality. In the coming years, especially after 2030, greater market shares are anticipated for some of these more advanced cell designs. Assessed against macroeconomic criteria, the GECO scenario based on the least optimistic assumptions foresees an increase in registered global solar power from 710 GW in 2020 to 2 950 GW in 2030 and 7 500 GW in 2050. In the most optimistic scenario, solar power generating capacity is multiplied by 10 in 2030 and by 16 in 2050, in comparison with 2020 levels.

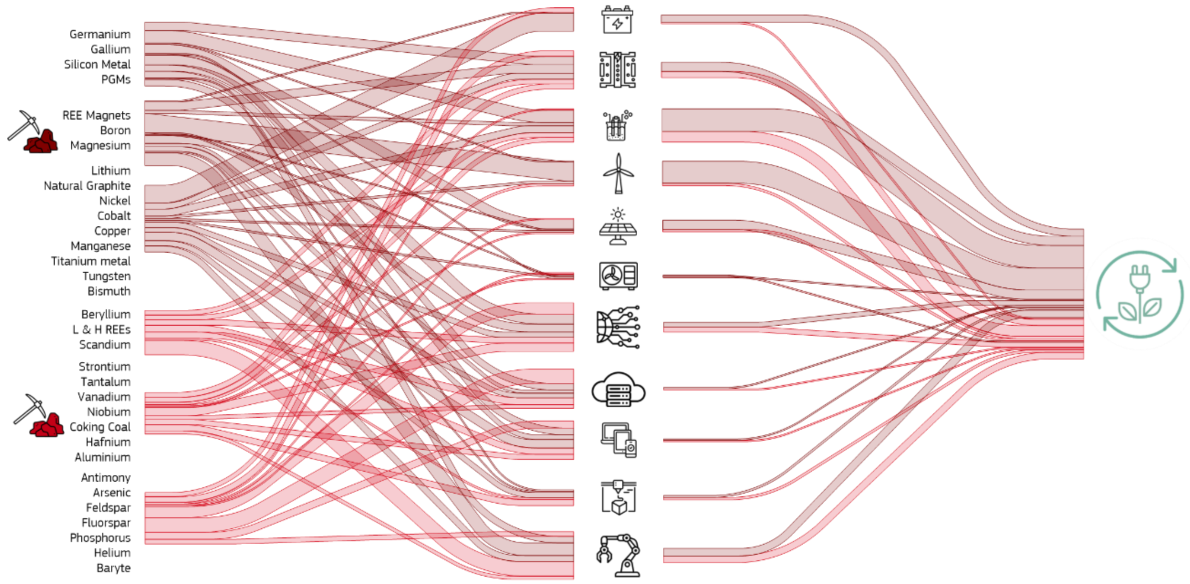
The intermittent nature of wind and solar energy requires thorough planning of storage capacity, which, together with resilient, reliable and affordable electricity grids, is a key factor for the success of the renewable energy sector. Interest in electrolysers has grown rapidly in recent years as a key technology for the production of hydrogen from renewable energy sources. The total installed capacity was expected to grow to over 1 GW by the end of 2022 (IEA, 2022).

Data transmission networks, robotics and 3D printing will also contribute to the acceleration of the renewable energy sector. Digitalisation has an impact along the entire renewable energy value chain, from generation to transport, distribution, supply and consumption. Robotics and 3D printing are expected to increase productivity and optimise the performance of various processes along the renewable energy value chain.

Projected sales of heat pumps, presented in , reach a peak in 2045, reaching 38 million in a high demand scenario in 2050, and 15 million in a low demand scenario. Regardless of the scenario, the trend increases over time.

As shown in Figure 86, wind turbines, electrolysers, solar PV and heat pumps are responsible for most of the material demand of the renewable energy sector. Wind energy accounts for the largest consumption of materials and especially those that are critical. Of all the sectors, renewable energy is the one that demand the most strategic and non-critical raw materials, and most of these materials are present in wind turbines, solar PV and electrolysers.

Figure 86. Semi-quantitative representation of flows of raw materials to the technologies of the renewable energy sector



Source: JRC analysis.

3.1.3. Current supply chain bottlenecks

As noted above, the sectoral analysis of renewable energy is based on the supply chain vulnerabilities and strengths of wind turbines, solar PV technologies, electrolysers and heat pumps.

Wind turbines require the largest share of heavy and light rare earth elements, which together with **boron** are indispensable for the manufacture of NdFeB permanent magnets. Neodymium is the key element, however dysprosium, praseodymium and terbium are also consumed to significant extents. **Aluminium**, **copper and steel** are the most relevant structural materials. **Aggregates** and **silica** are non-critical materials used in the highest proportions in the manufacture of wind turbines.

While most elements in the processed materials (eg PET, polyurethane, copper semis and steel and carbon fibres) and component stages (such as gearboxes, shafts, towers and bearings) do not face particularly high supply risks, the EU remains highly dependent on imports of processed materials such as permanent magnet alloys, balsa wood and polyethylene, and components such as NdFeB permanent magnets as well as blades. This creates an important vulnerability along the supply chain of wind turbines, which is only alleviated in its final stage of wind turbine assembly.

Solar PV technology requires a large share of strategic raw materials, including **silicon metal used in conventional PV systems**, and also **gallium** and **germanium** for thin film modules, which today account for some 5% of the PV capacity deployed. Other critical raw materials required in significant amounts include **antimony**, **arsenic**, **fluorspar** and **phosphorus**.

In comparison to wind turbines, solar PV relies on a higher proportion of raw materials, processed materials, components and assemblies imported from third countries China, for example, has a monopoly in the production of silicon ingots and wafers. As far as components are concerned, the EU accounted for only 0.6% of global crystalline silicon cell production in 2021, in Germany and to a lesser extent in Italy (IEA, 2022). The EU is also home to many solar module manufacturers, but most of these import solar cells from Asia.

<u>Batteries</u> utilise a large amount of strategic raw materials, especially **lithium**, **manganese**, **natural graphite** and **cobalt,** and of the critical raw material, **phosphorus**.

Battery cell assemblies are currently the weakest step in the value chain. Raw materials and components still need to be imported.

There are dependencies and bottlenecks downstream in the supply chain for processed materials, components and assemblies, as supply is controlled by an oligopoly in Asia, especially for components such as anodes and cathodes. Due to high costs, the use of high-cobalt-content LIBs is expected to decrease in favour of nickel-rich batteries or new chemistries.

Electrolysers require a significant share of strategic raw materials from the **PGM** group**,** specifically, **iridium**, **palladium**, **ruthenium** and **rhodium**, along with **silicon metal**, **titanium**, **aluminium**, **copper** and **magnesium**. A particularly large share of **scandium**, **strontium**, **yttrium** and **tungsten** is needed to produce electrolysers. Among the non-critical materials, sulphur has an important role in the manufacture of the electrolysers, and to a lesser extent, **zirconium**, **potash**, **limestone**, **gold** and **cadmium**.

Heat pumps require the strategic raw materials of **magnesium, boron, aluminium and copper** on the top of the materials already mentioned for the permanent magnets, **boron, dysprosium and neodymium.** The only relevant critical raw material is **fluorspar**. **Gold** and **zinc** are the key non-critical raw materials for this technology.

Nevertheless, no significant materials bottlenecks are identified, as most of the critical materials used in this technology are related to the microchips and IT controllers used for their operation.

In summary, **lithium** plays a crucial role in renewable energy technologies, followed by four **REEs** (neodymium, praseodymium, terbium and cerium), **borates**, **gallium, natural graphite** and **cobalt**. The critical raw materials most in demand are **feldspar**, **strontium**, **lanthanum** and **phosphorus**. Last but not least, **gypsum**, **selenium** and **silica** are the most required non-critical raw materials.

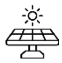
Supply chain bottlenecks: In all of the technologies analysed, key materials and components have been identified along the relevant value chains for which **the EU largely relies on supplies from third countries**. While in general, different technologies rely on different materials and components, there is always a **heavy dependence on imports from China**, in at least one stage of the value chain, whether that is extraction of the raw materials, refining, processing, component manufacturing or assembly.

Primary sourcing of critical raw materials from within the EU is in most cases very low, but EU **refining and processing capacity is currently very low**, **too**. This creates additional dependencies at multiple stages of the value chains. For example, the EU is completely reliant on imports from China along the whole value chain of rare-earth permanent magnets, while it has a strong manufacturing capacity for the final assembly of wind turbines. In other cases, such as solar PV, the reliance on imports spans the complete value chain, including the final PV panels. In the case of heat pumps, the rapid increase in the market share of Chinese manufacturing is of concern. For batteries, the value chain is being developed in the EU.

Table 7 displays a detailed breakdown of the different materials involved in the manufacturing of each technology. Figure 87 gives an overview of the different steps of the value chain for the main technologies involved in the renewable energy sector. Except for electrolysers, almost all steps (raw materials, processed materials, components and assemblies) are subject to a critical supply risk. For electrolysers, the critical step in the supply chain is access to raw materials. If the EU wants to maintain its leadership in this technology, it needs to address this vulnerability.

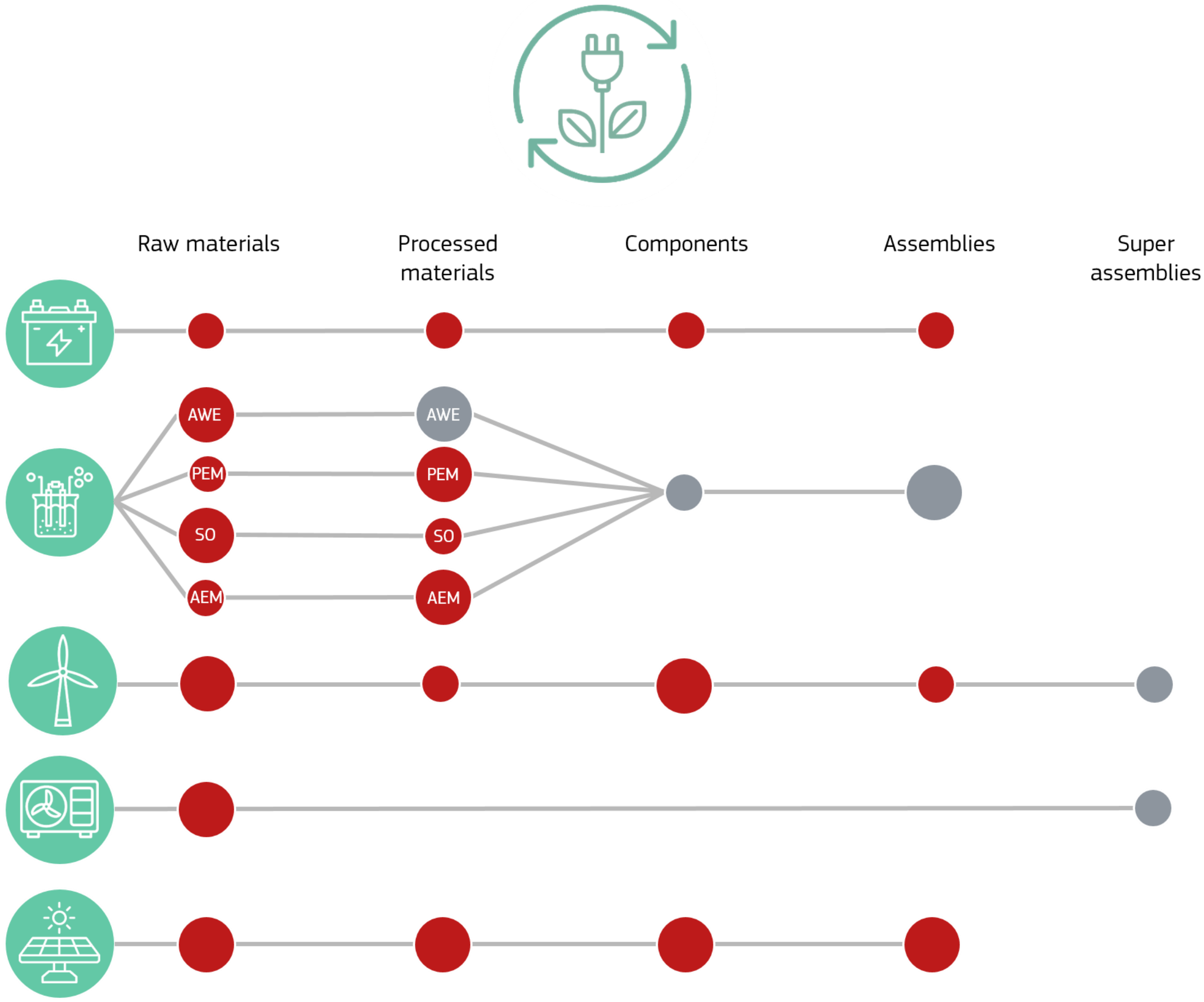
Table 7. Strategic, critical, and non-critical raw materials used in the renewable energy sector.

Supply Risk	Raw material					
4.8	Gallium				•	
4.1	Magnesium		•			
4.0	REE (magnets)		•	•		•
3.8	Boron		•	•	•	•
2.7	PGM		•			
1.9	Lithium	•				
1.8	Germanium				•	
1.8	Natural graphite	•	•			
1.7	Cobalt	•	•			
1.4	Silicon metal		•	•	•	•
1.2	Manganese	•	•	•		•
1.2	Tungsten		•			
0.5	Nickel	•	•	•	•	•

Supply Risk	Raw material					
0.1	Copper	•	•	•	•	•
5.3	HREE (rest)		•			
4.4	Niobium		•	•		
3.5	LREE (rest)		•			
3.3	Phosphorus	•			•	
2.6	Strontium		•			
2.4	Scandium		•			
2.3	Vanadium		•			
1.8	Antimony				•	
1.6	Arsenic				•	
1.3	Baryte		•			
1.3	Tantalum		•			
1.2	Aluminium	•	•	•	•	•
1.1	Fluorspar	•			•	•
0.9	Tin		•		•	
0.8	Molybdenum		•	•	•	•
0.8	Silver		•		•	•
0.8	Zirconium		•			
0.7	Chromium		•	•		•
0.7	Potash		•			
0.6	Indium				•	
0.5	Iron ore	•	•	•	•	•
0.5	Titanium		•			
0.4	Gold		•			•
0.3	Tellurium				•	
0.3	Limestone		•			
0.3	Selenium				•	
0.3	Silica			•	•	
0.2	Cadmium				•	
0.2	Zinc		•	•	•	•
0.2	Aggregates			•		
0.1	Lead			•	•	

Source: JRC analysis.

Figure 87. Overview of supply risks, bottlenecks, and supply patterns along the selected supply chains relevant to the renewable energy sector



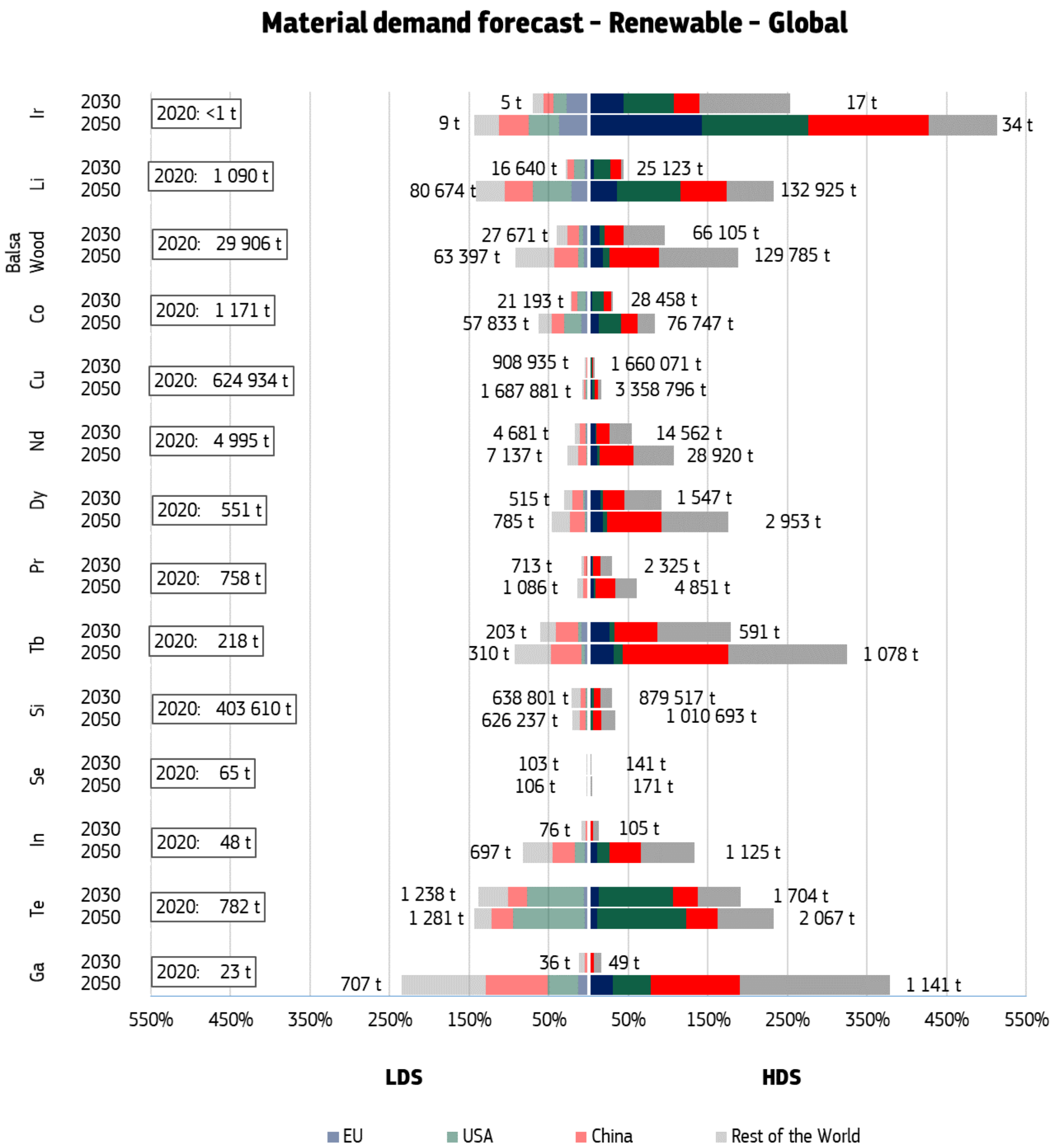
Source: JRC analysis.

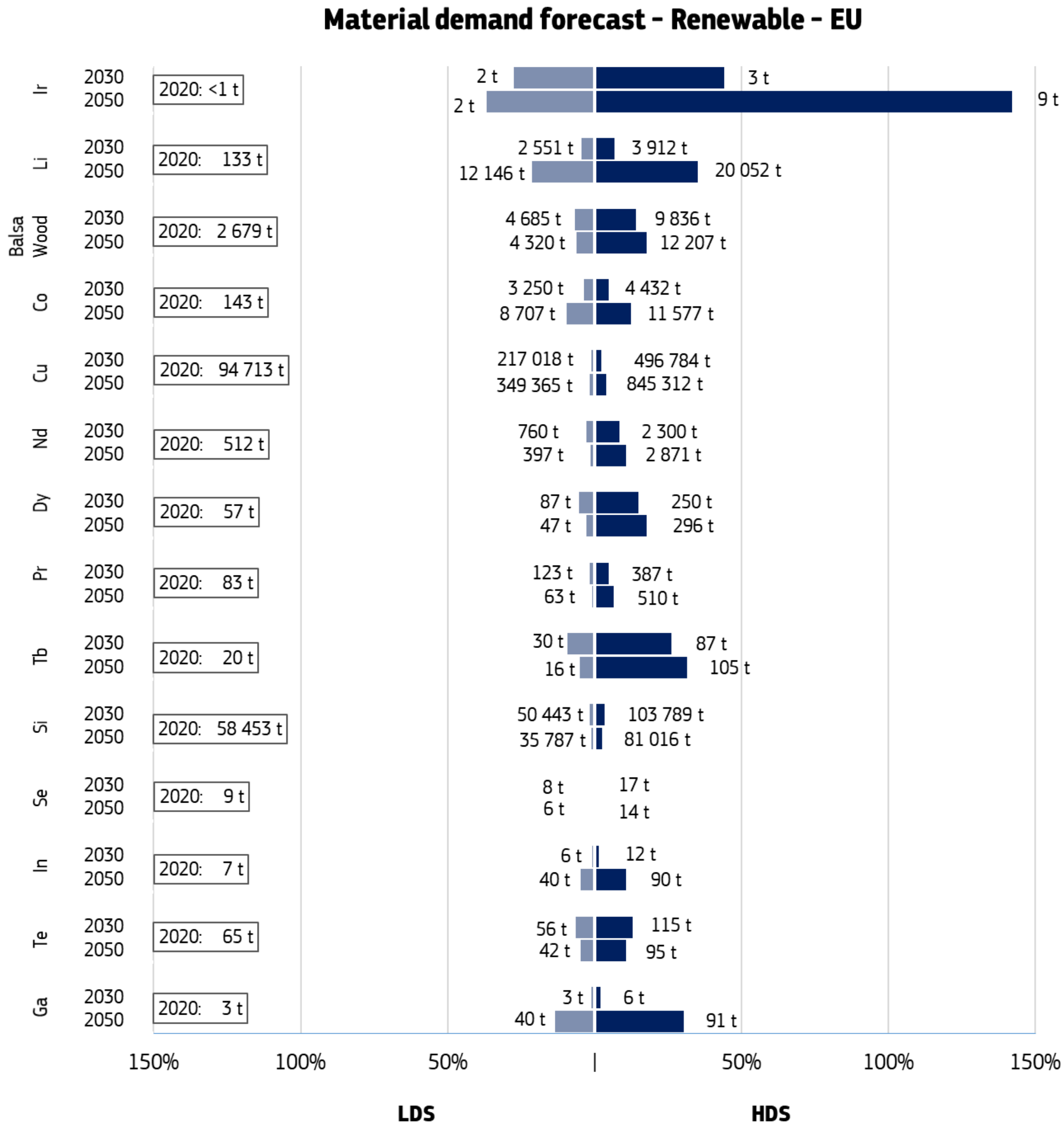
3.1.4. Projected 2030 and 2050 material demand

The renewable energy technologies described in Section 2 – in particular, wind turbines, electrolysers, solar PV, heat pumps and batteries – are aggregated in this section and analysed in the context of low and high demand scenarios.

Figure 88 illustrates the projected demand for the differnt raw materials intensively present in the renewable energy value chain. The bottom X-axis represents the forecast demand as a proportion of the current share of global supply. Even in the low demand scenario, global demand for terbium and gallium will surpass 100% of current supply in 2050. Lithium will be close to 100% in the LDS and over 150% in the HDS. 77% of the world's lithium supply is extracted in Australia and Chile, but 56% of it is processed in China and 32% is processed in Chile. Praseodymium, terbium, neodymium and dysprosium are extracted mainly in China and entirely processed in China. China also dominates the production of gallium. 73% of global boron reserves are concentrated in Türkiye. Other strategic, critical and non-critical raw materials with significance for the renewable energy value chain are palladium and iridium (platinum group metals), which are important for the catalysts in fuel cells and in digital applications. Iridium is particularly important, and 94% of it is processed in South Africa. In the low demand scenario, more than 100% of the current global supply is required by 2050, and in the high demand scenario, this figure shoots up past 500%.

Figure 88. Material demand forecast for the renewable energy sector: global (this page) and focus on the EU (next page)





Source: JRC analysis (Ga= gallium, Te = tellurium, In = indium, Li= lithium, Tb = terbium, Pr = praseodymium, Nd = neodymium, Dy = dysprosium, Cu= copper, Co= cobalt, Se= selenium, Ir= iridium).

The most used materials in c-Si panels, are silicon metal and silver. Crystalline silicon and thin-film technologies account for approximately 95% and 5% of the PV market share respectively according to Fraunhofer Institute for Solar Energy Systems, with most critical raw materials appearing in the thin-film technologies, i.e. CdTe or CIGS. 68% of refined silver metal is produced within the EU, mainly from Germany, Italy, France and Belgium. Switzerland, the US and the UK provide most of the imports (20%).

3.1.5. Geopolitical dimension

The analysis shows that the EU is **highly exposed to the risk of disruptions** related to the supply of selected materials and components.

The **US**'s Inflation Reduction Act (The White House, 2022), introduced in 2022, provides non-taxable entities participating in clean energy incentives with a direct payment option in lieu of tax credits. It will invest EUR 366 billion in energy security and climate change. 45% of renewable energy growth in the US can be attributed to state renewable portfolio standards (RPS) that require a percentage of electricity to be derived from renewable sources. The largest allocations are for renewable energy and grid energy storage with EUR 120 billion.

China's industrial policy has pushed forward clean energy technology innovation by supporting manufacturing capacity for strategic sectors, with low-cost capital, subsidies, strong incentives to produce technical components, lower prices and a large-scale policy push to boost exports. Strategies such as Made in China 2025 and China Standards 2035 illustrate how China is working on reducing its reliance on technology imports while maximising exports. This demonstrate China's ambition become a leader in the next generation of emerging technologies in renewable energy.

Furthermore, China can affect European competitiveness by flooding the magnets market with lower-priced products. It could also choose to impose low production quotas and trade restrictions or even limit exports, causing a shortage of the materials and components fundamental to the EU's twin transition. In this context, China supports rare earth companies to maintain their dominance in the international market and to prove itself as a reliable supplier.

China's State-owned Assets Supervision and Administration Commission of the State Council (SASAC) announced the establishment of the China Rare Earth Group in 2022, creating the world's largest producer of strategic rare earth elements and reinforcing the central government's direct control. China is the only country in the world with a fully integrated permanent magnets supply chain. In total, Chinese production accounts for approximately 60% of rare earth mining, 93% of rare earth processing and 94% of the NdFeB global markets (JRC, 2022).

No rare earth elements are currently being mined in **Europe**. However, rare earth deposits found in Sweden, Finland, Greece and Spain suggest that Europe could reduce its reliance on imports of these critical raw materials. The largest is the Per Geijer deposit in Sweden, with rare earth metal ore exceeding one million tonnes of oxides (LKAB, 2023). The old phosphate mine Sokli in Lapland has revealed a major deposit of REE. The Finnish Minerals Group cautiously estimates that Sokli could produce 10% of the REE needed in Europe for the production of permanent magnets. It also estimates that Sokli could produce 20% of the phosphate needed in Europe for fertilisers (Finnish Minerals Group, 2023). To diversify, EU industry and policymakers face the challenge of developing a domestic rare earth ecosystem - from extraction to midstream processing and further downstream manufacturing.

Russia's war in Ukraine triggered disruptions in the supply of critical raw materials to global markets. Russia has an important share of several raw materials including nickel, palladium, vanadium and boron (OECD, 2022). These are used in renewable energy technologies such as cathode materials for batteries, catalytic converters and redox flow batteries, respectively.

Türkiye holds a share of approximately 73% of the total global boron deposits at 803 million tonnes, and is the main exporter to Europe (Kar, Y. 2006). The country has been seeking to add value by processing more boron and producing semi-finished and finished products itself, instead of selling as raw material, as it has done until now.

Cobalt is currently crucial for batteries and energy storage, for which demand is rising as energy markets move away from oil and gas. The **Democratic Republic of the Congo** owns 63% of global reserves, and its poor governance makes it a problematic source in terms of security of supply and ethical trading (Manley, D. et al, 2022). Moreover, 70% of cobalt mines in the Democratic Republic of the Congo are owned by China and supply exclusively to Chinese refineries. Other mines could be a source of this metal as a by-product, but investment decisions are not usually led in terms of revenue from by-products.

In 2022, the Government of **India** announced an additional capital infusion to the Solar Energy Corporation of India (SECI) and to the Indian Renewable Energy Development Agency (IREDA). The installed power capacity in India is around 408.7 GW as of 30 November 2022. India plans to install 500 GW of renewable energy capacity by 2030.

Released in 2022, the **Canadian** Critical Minerals Strategy (Canadian Government, 2022) focused on sustainable development and the circular economy. Canada has been making advances in international engagement to secure its critical raw mineral supply chains, with agreements including the Canada-US Join Action Plan in 2020, The Canada-EU Strategic Partnership on Raw Materials in 2020 (to engage the EU and Canada in critical mineral and battery value chains), and the Canada-Japan Sectoral Working Group on Critical Minerals (to facilitate commercial engagement between Canadian and Japanese businesses).

Also in 2022, the **Australian** government released its Long-Term Emissions Reduction Plan to achieve net-zero emissions by 2050. The plan aims to achieve a net-zero economy through a technology-based approach, whilst protecting relevant industries, regions and jobs.

Alongside these strategies, various alliances have been sought across the world to strengthen supply chains. For example, the European Union and **Chile** have concluded a free trade agreement with a dedicated chapter on Energy and Raw Materials to liberalise trade relations and give EU companies greater access to key raw materials for the EU's green transition, such as lithium and copper.

This ever-growing activity demonstrates the growing interest of governments around the world in securing access to the raw materials required for the clean energy transition. The OECD has described the increasing use of local content requirements (LCR) in green industrial policies relating to solar PV and wind energy worldwide (OECD, 2015). These have played a growing role in renewable energy policy in the last 20 years and require firms to use a minimum level of domestically manufactured goods or domestically supplied services, having a direct effect on trade. Of the 20 LCRs that were active in 2015, 18 are still ongoing.

3.1.6. Key observations and recommendations

Establishing an energy system based on renewables requires a range of technologies which reaches beyond the production of renewable electricity alone. The deployment of these technologies, against an unstable geopolitical background, and in the grip of competing interests across the globe, could lead to the high demand scenario described in this report. The consequences of this scenario could be reflected, in the EU, in a REE demand increment of almost 5 and 6 times until 2030 and 2050 respectively, or a silicon demand increment of around 1.8 and 1.4 times until 2030 and 2050 respectively. While the bottlenecks and supply risk are critical in most steps of the value chain for the various technologies, these are especially high in the raw materials step.

The availability of critical raw materials can be compromised by a number of factors, including production concentration, economic, political and social constraints in expanding production capacities, and export restrictions. The risks can also be compounded by a lack of transparency in mineral supply chains and governance challenges in producing and processing countries.

Export restrictions are the most widespread trade policy measure applied in these sectors, as has been seen following the Russian invasion of Ukraine. They can have distorting effects on international markets by reducing global supply and raising prices, while creating uncertainty for importers (OECD, 2022).

The EU's reliance on China is present at each step of the renewable energy value chain. China dominates the production of rare earth elements and of gallium phosphorus, indium and silicon. And while they are present in smaller quantities, selenium and silica are also crucial for the energy transition. China is responsible for 71% of solar PV assemblies while the EU produces only 2%.

To mitigate China's dominance on key materials for the renewable sector, EU industry and policymakers could develop a domestic ecosystem for these – from extraction to midstream processing and further downstream manufacturing. This means diversifying supply and reducing dependency on rare earth elements, where possible by substitution.

Furthermore, local content requirements might pose a threat to the European wind turbines and solar PV supply chains as they hold the potential to distort trade and cause unintended effects on investment across value chains (reduced competition, reduced technology diffusion through trade (OECD, 2015)).

The supply chains for the technologies essential to the success of **REPowerEU** each involve a range of critical materials with their own weaknesses and criticalities, so the solutions cannot be one-size-fits-all. For wind turbine technology, securing the supply of rare-earth elements is crucial to establishing a manufacturing base for permanent magnets. Meanwhile, for solar PV, the lack of silicon should be addressed through domestic production and diversification as well as the investigation of new, more efficient systems.

In the case of battery technologies, there is also a lack of raw materials that could be covered by importing from low-risk countries and developing EU manufacturing capacity and circularity, paying special attention to supplies of lithium, nickel, cobalt, manganese and graphite. The EU has leadership in manufacturing capacity for electrolyser technologies, but there is a lack of material supply for PGMs that should be addressed through diversification and domestic production (for example through recycling). There are no projections of supply issues for materials for heat pumps, further than their use of permanent magnets and semiconductors. The systems of all the technologies addressed in this section require power electronics involving semiconductors.

They key observations and recommendations for this sector are as follows:

- **Diversification of material supply:** international partnerships should be established and strengthened. Alliances between countries are a way to strengthen these partnerships and secure supply chains to make the EU more resilient. Substitutions should be tested in the framework of R&D projects (JRC, commissioned by DG GROW, 2022).
- **International cooperation**: Synergies should be exploited between R&I strategies, financial support instruments and the innovation landscape at national, EU and international level. The Research, Innovation and Competitiveness chapters in the National Energy and Climate Plans should also be reinforced.
- **Development of a supply chain ecosystem for domestic supply**
    - Mining, separation and processing. Mining is a crucial aspect of the development of a domestic supply chain. There are already several known deposits in Europe from which REEs can be extracted. In particular, the newly discovered Swedish and Finnish reserves have the potential to become Europe's most important source of critical raw materials. Other reserves have also been identified in Spain, Greece and Greenland. However, the process of obtaining the permissions, performing sustainability assessments, developing the projects and producing the concentrate can take several years.

      Supportive policies are needed to encourage mining companies to make use of innovative technology including AI, automation and rapid material characterisation.

      Promoting a responsible mineral industry is of crucial importance, with policies to ensure transparency, an ethical business environment and engagement with local communities (for example, in addition to The Mine Waste Directive (2006/21/EC), sustainable mining and remediation management should account for mining using renewable energy sources to reduce environmental impacts (Haa, J., 2020)).

      Investment opportunities should be identified along the whole value chain, including promoting consultation processes with stakeholders in order to create buy-in and identifying bottlenecks such as regulations, permits and operating licenses.
    - Component and assembly manufacturing. Manufacturing capacity should be expanded for many components and assemblies, most important of which are permanent magnets in wind turbines, anodes and cathodes in batteries, and silicon wafer and cell segments in solar PV. In particular, for batteries, an expansion of the refining of key materials such as lithium, nickel, cobalt, graphite and manganese could reduce the supply risk for downstream manufacturers. Manufacturing should take advantage of rapid innovation in sustainable production techniques.

      The EU's competitiveness will rely strongly on its capacity to develop and manufacture the clean technologies that make the transition possible. The Net-zero Industry Act is set to address this by identifying goals for industrial capacity and providing a regulatory framework suited to quick deployment, simplified and fast-track permitting, the promotion of European strategic projects, and the development of standards to support the scale-up of technologies across the Single Market (EC, 2023).
    - Recycling. Products should be designed in order to optimise recycling at end of life, maximising the value of raw materials and keeping them inside the European economy. This will require new policies and strong commitment from the industrial sector. The EU is already implementing ecodesign measures for some technologies including electric motors. However, enhancing circularity will require the in-depth knowledge of material flows (eg. the traceability of components and assemblies to enable their classification according to qualities/grades).

      For wind turbines, 80-95% of the total mass of a wind turbine (including concrete and base metals) can be recycled. Appropriate collection, preparation and recycling processes for NdFeB permanent magnets will be necessary to capture the rare earth elements incorporated in this component. The recycling potential of NdFeB permanent magnets from wind turbines is particularly relevant: the average weight of permanent magnets in wind turbines is 600 kg per MW. Since solar modules became popular in recent decades, solar PV tends not to have reached end-of-life. For this reason, the volumes of recoverable raw materials and components are currently small. In fuel cells, recycling PGMs, could reduce supply risk at the refining stage.

- Substitution. Substitution must be considered a long-term option and not all materials can be substituted in all technologies. On average, an electric motor is equipped with 1.5 kg of permanent magnets. Although innovation is making good progress in terms of reducing the amount of rare earths needed for permanent magnets, wind turbines are still strongly dependent on rare earth permanent magnets while EVs are expected to profit from rare earth-free permanent magnets (JRC, commissioned by DG GROW, Draft 2022). Nd-Fe-B magnets are the only permanent magnets used by wind technology. In the automotive sector, both Nd-Fe-B and ferrite permanent magnets are widely used.

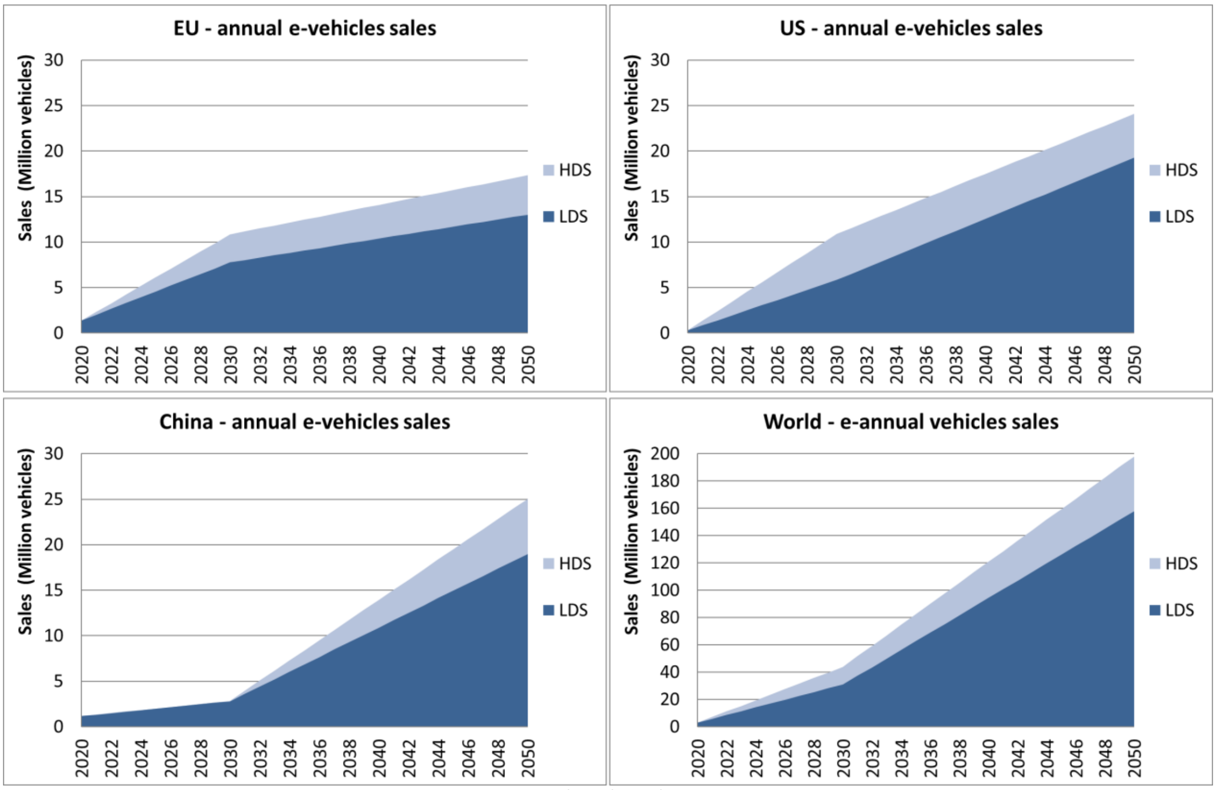
3.2. E-mobility

3.2.1. Introduction

The global penetration of e-vehicles is continuously increasing, supported by national policies and sustainability strategies. Although uncertainty is still high about the evolution of the e-mobility sector in national markets, and forecasts differ in the scientific literature, battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs) are expected to dominate the European electric vehicles (xEV) market, as trends suggest in other markets. The main drivers of such rapid penetration are the climate goals which aim to decarbonise the transport sector and make it more sustainable. Besides BEVs and PHEVs, new technologies are expected to be further adopted in the future (e.g. the fuel cell electric vehicles – FCEVs). New behavioural patterns should also be considered when forecasting the future EU and global fleet. For instance, the development of mobility-as-a-service (MaaS) and of connected, cooperative, and automated mobility (CCAM) can influence the definition of future mobility fleets (JRC, 2019a; EC, 2021). In all major markets, the transition towards xEVs increased rapidly in 2021 despite the COVID-19 pandemic. More competitive costs, regulatory measures encouring original equipment manufacturers (OEMs) to move towards EVs, national incentives for purchasing EVs, new xEV models and higher driving autonomy (Gorner and Paoli, 2021) are some of the factors which have encouraged increased xEV penetration.

The evolution of sales figures in different regions according to the GECO scenario is shown in Figure 89. Aligned with the IEA Announced Pledges scenario (IEA, 2023), global BEVs and PHEVs sales will exceed 40 million units in 2030. The Chinese and US markets are the EU's greatest competitors. The IEA 2022 Outlook (IEA, 2023) forecasts that China will sell more than 10 million BEVs annually by 2030, and the US between 3.6 and 6.1 million, lower than the BEVs forecast to be sold in Europe (between 4.6 and 7.7 million). The share of FCEVs will only start increasing globally from 2040.

Figure 89. Annual sales of electric vehicles (BEVs, PHEVs and FCEVs) in the EU, US, China, and globally in the two explored scenarios



Source: JRC analysis based on JRC, 2021.

3.2.2. Relevant technologies

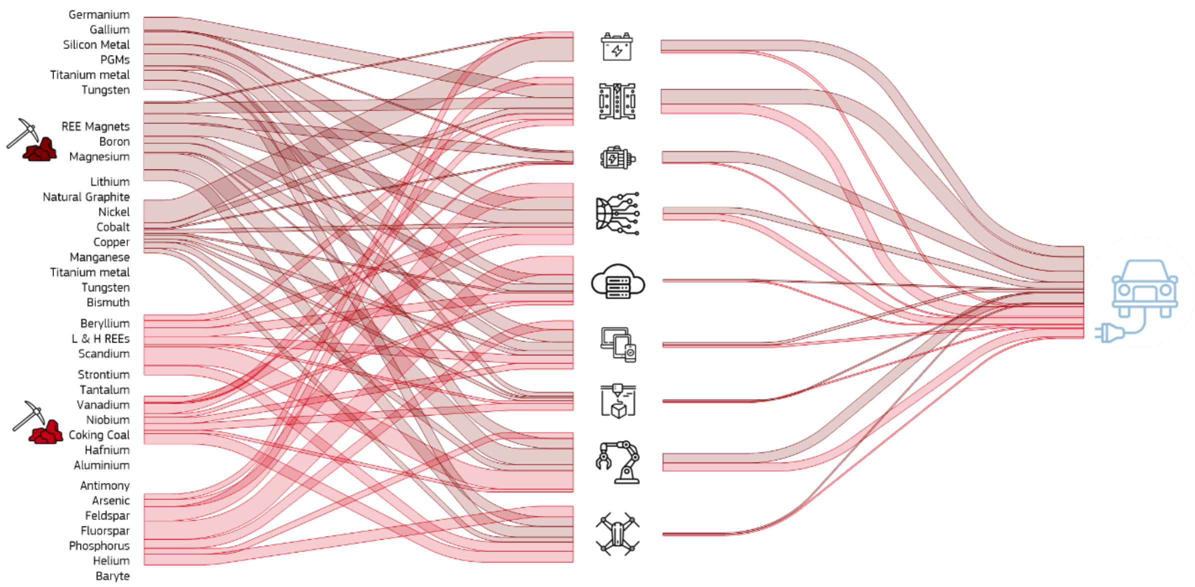
Figure 90. Technologies involved in the e-mobility sector

Source: JRC analysis.

Technological development is key to decarbonising the mobility sector. Key components for e-mobility are batteries, electric motors and fuel cells, and other enabling technologies are increasing in importance for the shift towards more sustainable and smarter mobility systems. For instance, electronics and data centres and related IT infrastructure will be further adopted in new vehicles to answer consumer expectations but also in relation to the deployment of connected, shared and autonomous vehicles. Europe is the leading region in automotive electronics production with 28% of the world global output in 2017. The (re)manufacturing industry is expected to further adopt robotics to automate production processes and to further adopt additive manufacturing and digital technologies for the maintenance and diagnosis of vehicles and components.

Figure 91 represents the proportions of critical and strategic materials in the technologies involved in the e-mobility sector.

Figure 91. Semi-quantitative representation of flows of raw materials to the technologies of the e-mobility sector



Source: JRC analysis.

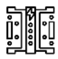
3.2.3. Current supply chain bottlenecks

Both critical and non-critical raw materials are used in the e-mobility sector and are expected to be used in the coming decades (EC, 2020) (Table 8). The most-used CRMs in terms of tonnage are those embedded in traction batteries, namely cobalt, lithium and natural graphite. Considering the intrinsic uncertainty of forecasting, and the adoption of non-traction Li-ion batteries (LIBs) in new vehicles (e.g. in place of lead-acid batteries) and traction batteries in e-buses and e-trucks, the demand for such materials could be even higher than that reported in Figure 93. It should also be noted that even though natural and synthetic graphite are characterised by conflicting benefits and competing costs, synthetic graphite currently holds the lion's share of the market. Finally, additives for coatings as well as new battery chemistries are under development, and are expected to be adopted in e-mobility (BatteriesNews, 2022; CIC energiGUNE, 2022; IEA, 2022), for instance more lithium iron phosphate (LFP) batteries.

Another bottleneck is represented by the supply of rare earth elements mainly used in magnets in traction motors and electronics in xEVs. Moreover, for almost all key and enabling technologies, the EU is dependent on third countries for processed materials, components and assemblies (mainly Chinese and US markets).

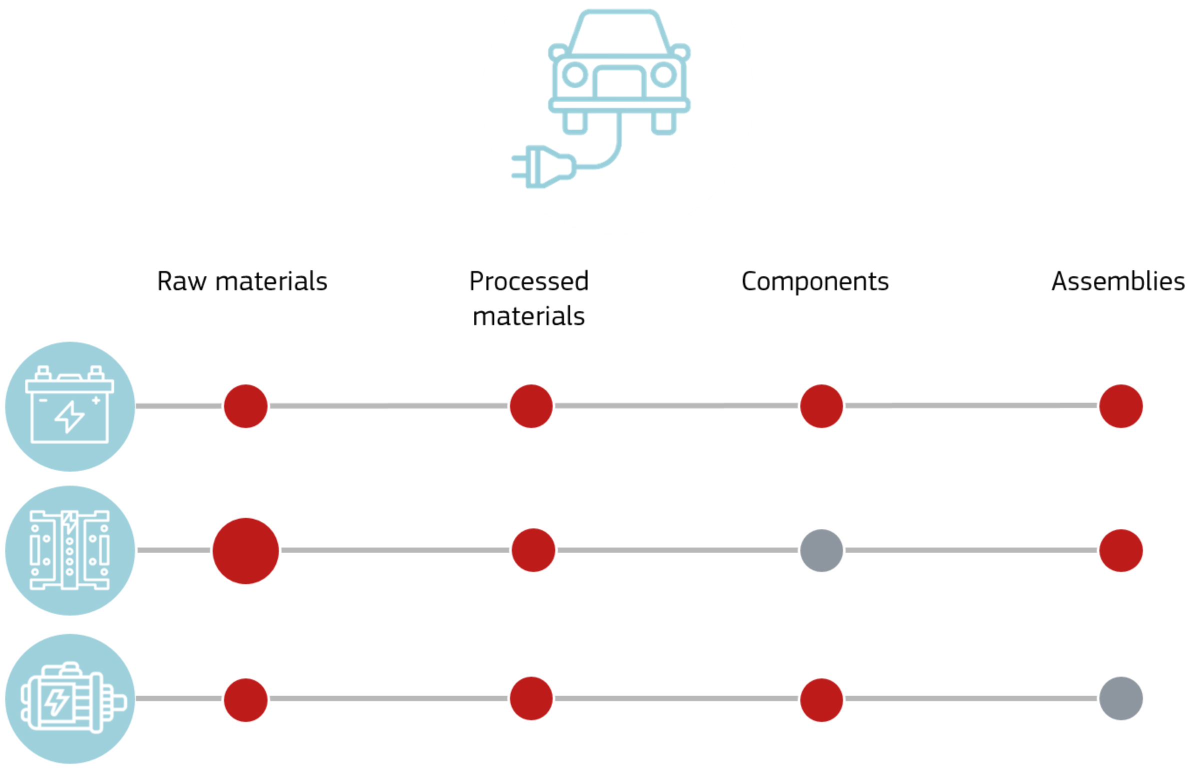
Figure 92 gives an overview of the different steps of the value chain for the main technologies involved in the renewable energy sector.

Table 8. Strategic, critical, and non-critical raw materials used in the e-mobility sector.

Supply Risk	Raw material			
4.0	REE (magnets)		•	•
3.8	Boron		•	•
2.7	PGM		•	
1.9	Lithium	•		
1.8	Natural graphite	•	•	
1.7	Cobalt	•	•	
1.4	Silicon metal		•	•
1.2	Manganese	•	•	
0.5	Nickel	•	•	
0.1	Copper	•	•	•
5.3	HREE (rest)		•	
3.5	LREE (rest)		•	
3.3	Phosphorus	•		
2.6	Strontium		•	
2.3	Vanadium		•	
1.5	Feldspar		•	
1.3	Baryte		•	
1.2	Aluminium	•	•	•
1.1	Fluorspar	•		
0.8	Molybdenum			•
0.8	Zirconium		•	
0.7	Chromium		•	•
0.5	Iron ore	•	•	•
0.5	Titanium		•	

Source: JRC analysis.

Figure 92. Overview of supply risks, bottlenecks, and supply patterns along the selected supply chains relevant to the e-mobility sector

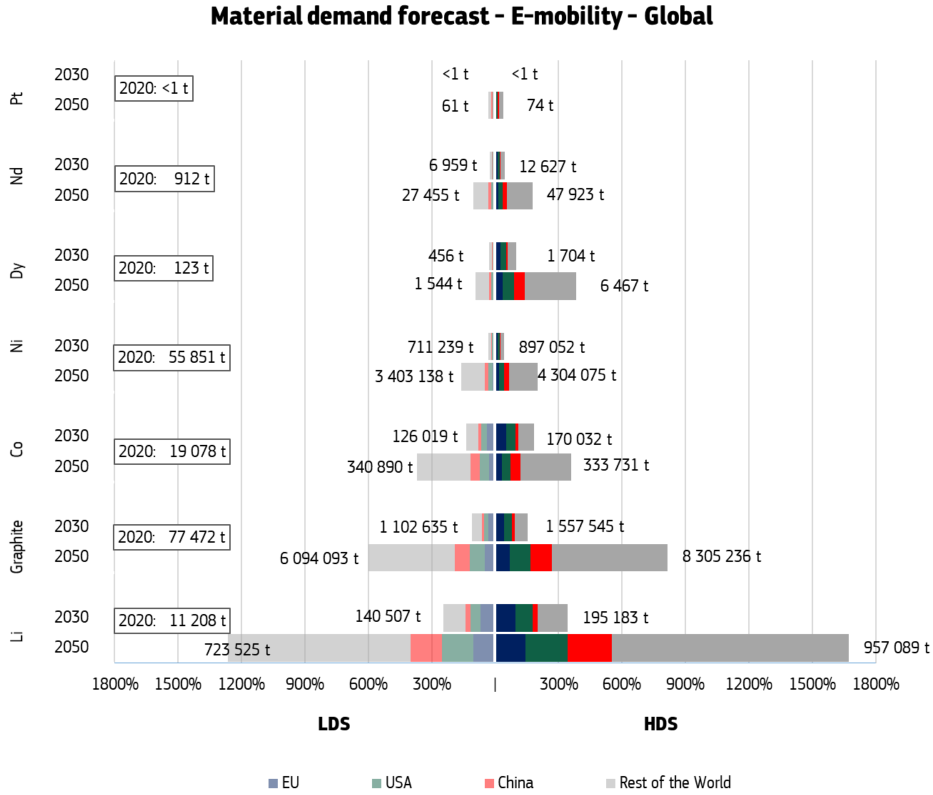


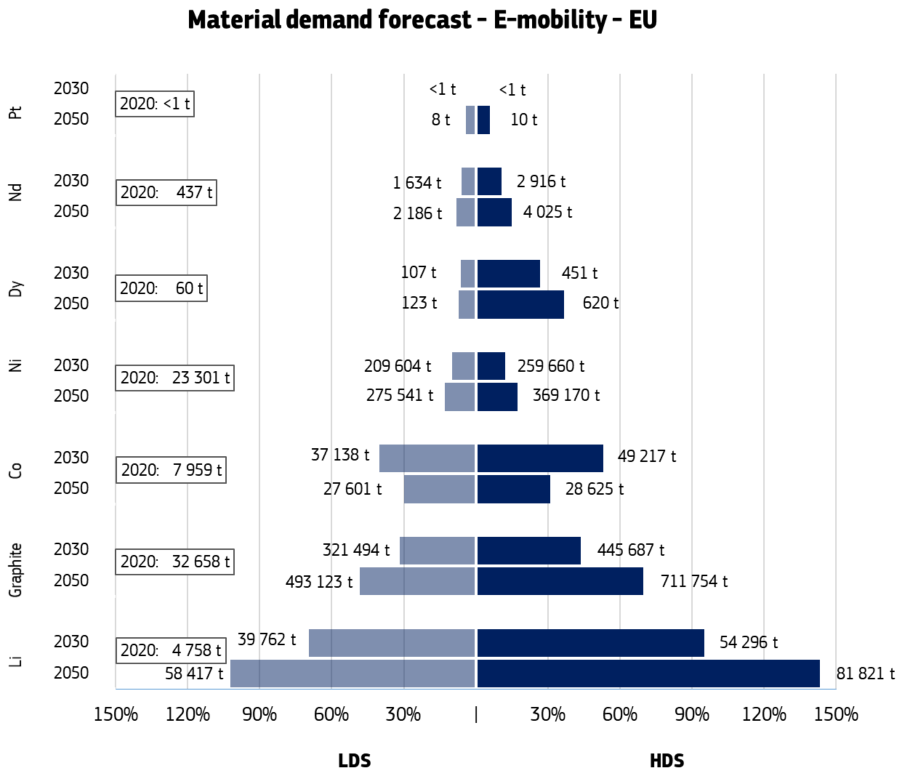
Source: JRC analysis.

3.2.4. Projected 2030 and 2050 material demand

Compared to the demand for materials for e-mobility in 2020, the most significant increases in terms of tonnage for the e-mobility sector are expected for platinum, phosphorus and iron; this is related to the the uptake of FCEVs from 2040 as well as the penetration of LFP batteries from 2030. However, this increase remains lower than 10% of the current global supply in 2030. On the other hand, although the increase in tonnage of other key materials for e-mobility is much lower, it is more significant relative to current global supply, as is the case for lithium, graphite, cobalt and dysprosium (Figure 93). Note that the reported value for graphite refers to all graphite, and further analysis should distinguish between natural and synthetic graphite.

Figure 93. Material demand forecast for the e-mobility sector: global (top) and focus on the EU (bottom)





Source: JRC analysis (Li = lithium, Dy = dysprosium, Nd = neodymium, Co = cobalt, Ni = nickel, Pt = platinum).

3.2.5. Geopolitical dimension

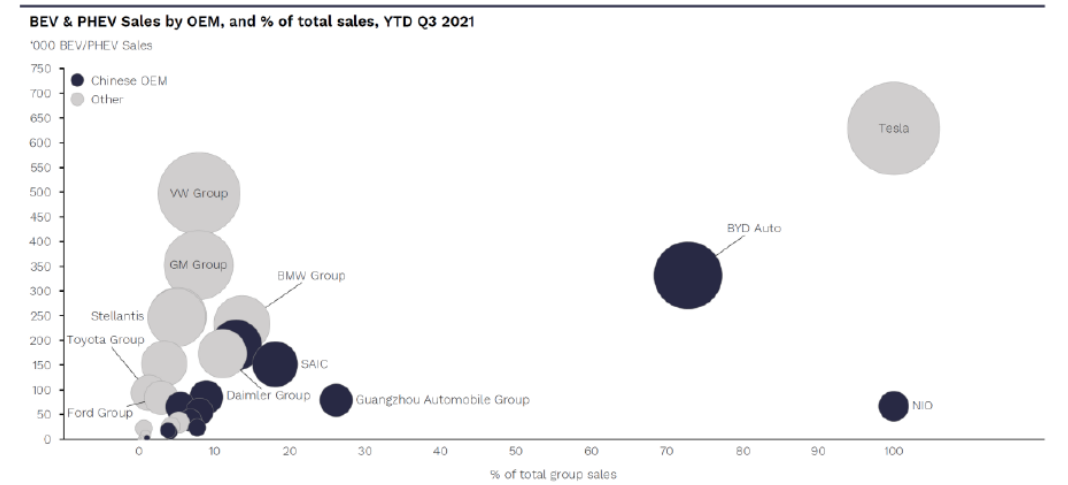
Despite the COVID-19 pandemic, new materials and technologies for the e-mobility sector are continuously developing to improve vehicles both in terms of performance and lifecycle environmental impacts in order to respect ambitious environmental targets. Governments worldwide are putting forward policies to accelerate the electrification of road transport and meet net-zero emissions targets. About one quarter of the global car market in 2021 was subject to a target of 100% BEV sales by 2035, or a ban on conventional vehicles, according to government announcements (IEA, 2022). Although still limited, FCEVs are expected to penetrate global markets. Currently, their application varies by location (in China they are currently mainly used, for example, for buses and trucks), but they are expected to be widely adopted in passenger mobility all over the world after 2030 (section 2.1, 2.2 and 2.5).

More than 52% of xEV production in 2021 was concentrated in six companies, including Tesla (US), VW (Germany) and BYD (China). Non-EU companies, especially Chinese ones, have been entering the EU market in recent years (Wilkinson, 2021; Rutishauser, 2023), and Tesla has had a cell giga-factory in the EU since 2022 (Grünheide (DE) plant) (Tesla, 2022).

Although Europe is the second producer of xEVs (with almost 20% of global xEV production), it is highly dependent on third countries for the key components, importing batteries and their components mainly from China (representing more than 75% of the global EV battery capacity in 2022), permanent magnets from China and Japan, and fuel cells from Korea (IEA, 2022; JRC, 2022). In this context, regional investment planned or announced in recent years supports the diversification of the components and car markets. In a recent study, CLEPA (2021) stated that about 80% of the xEV's added value is currently primarily related to batteries and secondly to electric motors, with Germany, Spain, and France the three main EU markets. It should also be noted that electronics and electrochemical suppliers will benefit from the shift from conventional vehicles to xEVs, since the demand for semiconductors and batteries components will increase (while demand decreases for mechatronic and mechanic suppliers) (CLEPA, 2021). The cost of electronics in vehicles has grown from about 20% of the total car cost in 2000 to 40% today, and is expected to reach 50% in 2030 (EP, 2021; Statista, 2022).

Mass production for e-mobility batteries has been announced by European companies, Northvolt, Saft and Varta, and VW plans to increase its battery capacity to 240 GWh in 2030 (JRC, 2022; IEA, 2022). BMW has also announced the creation of a battery assembly plant in Hungary (Benchmark Minerals, 2021). ERMA, in its "Rare Earth Magnets and Motors: A European Call for Action" (Gauß et al. 2021), underlines the need for the EU "to secure access to sustainably produced magnet rare earths at competitive costs from primary and recycled sources" to support and expand EU leadership in e-motors and design, also emphasising the need to improve circular strategies for e-motors.

Figure 94. Current position of the leading car producers on the global market



Source: RhoMotion, EV & Battery Quarterly Outlook Q4 2021, 2021 (JRC, 2022).

As regards the major xEV markets, China has announced its ambition to develop sufficient charging infrastructure to meet the needs of 20 million xEVs by 2025. Sales of xEVs in China achieved a market share of 16% in 2021 – more than tripling from 5% in 2020 – and subsidies have progressively decreased (IEA, 2022).

In the United States, the federal targets include 50% xEV sales by 2030 and half a million public chargers (IEA, 2022). The Inflation Reduction Act, besides incentives to increase the sourcing of key battery minerals locally or from partners with a free trade agreement, introduces economic measures to ease the switch towards xEV for consumers[69] (Congress.gov, 2022). Further investments have been programmed in 2020 to make the charging infrastructure more accessible (The White House, 2021), i.e. the National Electric Vehicle Infrastructure (NEVI) and the EVs4ALL programmes (The White House, 2022).

EU public investment in e-mobility has massively increased since 2019, also in relation to the COVID-19 stimulus package. At the time of writing, formal adoption is pending of the proposal in the Fit-for-55 package (COM(2021) 550) for a zero-emission mobility target for all new cars and vans registered as of 2035 (European Council, 2023)[70]. The proposal, in effect, mandates a ban on sales of conventional vehicles from 2035. To ensure that drivers are able to charge or fuel their vehicles in reliable networks across Europe, the revised Alternative Fuels Infrastructure Regulation (COM(2021) 559 final) will require Member States to expand charging capacity in line with zero-emission car sales.

Finally, Chile is leading the xEV market in Latin America and it recently announced the ambition of reaching 100% zero-emission light vehicles in 2030 and in public transport vehicles in 2035. African and Asian countries are promoting measures to support the electrification of mobility (e.g. Kenya is targeting a 5% annual import of xEVs by 2025 and Malaysia plans a full tax exemption for xEVs) (IEA, 2022), as well as the manufacturing of new vehicles (e.g. creating start-ups and adopting measures to incentivise domestic manufacturing) (ICCT, 2022).

3.2.6. Key observations and recommendations

The strategic importance of e-mobility is undeniable, and proper measures should focus on enhancing the whole e-mobility value chain. Beyond policy measures already in force, the development of a sustainable and competitive EU automotive sector requires further efforts on vehicles and their components, as well as on skills and societal aspects related to the mobility concept.

The key observations and recommendations for the e-mobility sector can summarised as follows:

- **Facilitate the development of a resilient e-mobility supply chain (including raw/processed materials and components)**.
    - Increasing the diversification of suppliers of raw and processed materials, as well as key e-mobility components (e.g. batteries, e-motors and electronics), will reinforce the autonomy of the e-mobility value chain.
    - Increasing the domestic supply of raw/processed materials, using both primary and secondary materials, together with the enhanced adoption of new circular (e.g. re-use) strategies in the automotive sector, can, directly and indirectly, increase material efficiency and significantly decrease the EU's dependency on raw materials and components from third countries.
    - Supporting the scale-up of domestic production of both components and vehicles should be done through proper economic and regulatory measures.
- **Strategically exploit existing expertise and partnerships along the whole e-vehicle value chain; adopt a holistic perspective.**
    - Support to new and innovative mobility solutions (including shared and collaborative mobility services, MaaS and public transport) can slow down demand for primary

[69] Qualifying xEVs will be eligible for a tax credit of up to USD 7 500 and USD 4 000 for new and used vehicles, respectively

[70] The Council adopted its general approach on the proposal in June 2022. An agreement with the European Parliament was reached in October 2022. The agreement will now (March 2023) have to be formally adopted by the two institutions

materials for e-mobility, especially in urban areas where societal trends are changing after the COVID-19 pandemic.

    - Expertise on end-of-life vehicles (ELV) management and treatment is well developed in the EU (automotive is one of the biggest remanufacturing sectors in Europe); ELV collection is reasonably mature; new targets for materials recycled content are under development. Exploitation of such knowledge and its integration in the design phase of vehicles will maximise the value of key materials and components in e-vehicles.

- **Reinforce international partnerships and investment in R&D&I.**
    - Efforts should be focused on fostering R&D&I projects involving more international partners, as well as advancing ongoing projects in the EU (e.g. promoting the scale-up phase of pilots). R&D&I should focus not only on next-generation technologies to ensure EU leadership in the e-mobility market (e.g. solid-state batteries and improved material efficiency), but also in systemic, sustainable solutions in the medium and longer terms (e.g. shared mobility, digital coupling and automation).
    - Digitalisation is becoming indispensable for the transition towards smart and sustainable e-mobility. Therefore, R&D&I should cover the whole lifecycle of e-vehicle components (mining, refining and manufacturing, the use phase and EoL steps), facilitating the collaboration of stakeholders across lifecycle stages and integrating a range of expertise, including green and digital skills, to create new added value and business models. This would, for example, include improved traceability and transparency along the whole value chain, metadata management and artificial intelligence for smarter mobility.

3.3. Energy-intensive industry

3.3.1. Introduction

The EU has set out a vision to achieve net-zero greenhouse gas emissions by mid-century as a contribution to achieving the Paris Agreement objectives of limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. Energy-intensive industries hold a central place in this vision. The iron and steel industry is a strategic sector to the EU economy, producing a material that is crucial to the most of the EU's industrial ecosystems. However, the iron and steel industry is also a major CO_2 emitter, responsible for aound 7% of global CO_2 emissions. Similarly, concrete is crucial for much-needed climate-resilient construction. The overall production of cement and concrete is estimated to account for around 5-8% of man-made CO_2 emissions. Decarbonisation of these manufacturing processes is essential if the climate targets are to be met.

3.3.2. Relevant technologies

The technologies discussed in this section are industrial heat pumps, hydrogen direct reduced iron, and carbon capture for cement manufacturing. These are all used in the decarbonisation processes of the energy-intensive industries (Figure 95).

Figure 95. Technologies involved in the energy-intensive industry sector

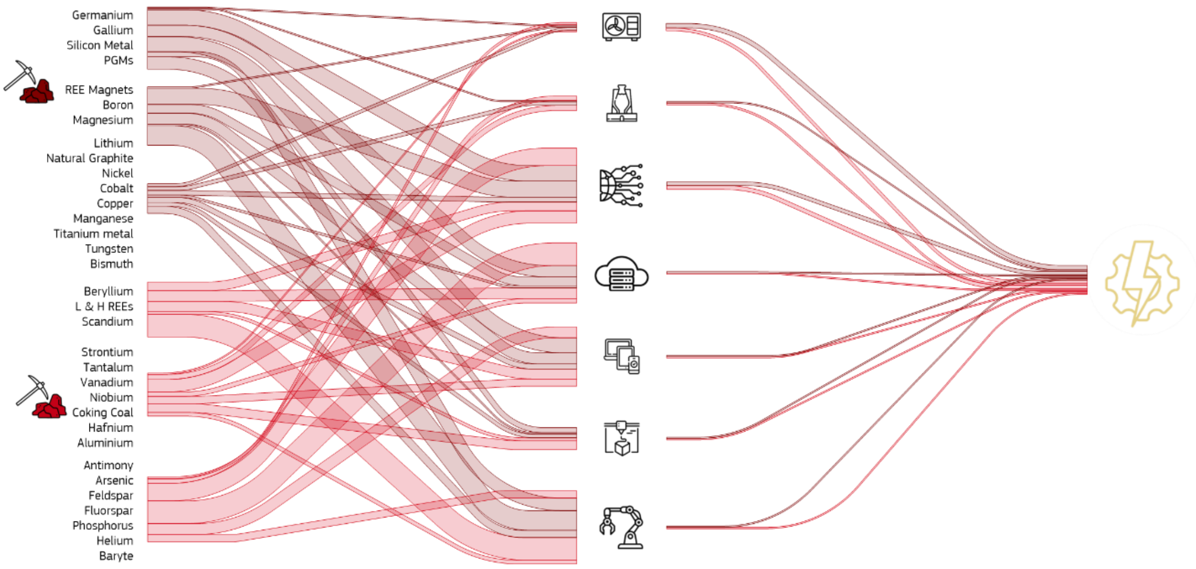
Source: JRC analysis.

Industrial heat pumps represent a technology that can decarbonise industrial process heat at temperatures above 70°C and below 180ºC. They can produce both heating and cooling for industrial processes using waste heat recovery as the heat supply source (BloombergNEF, 2021a). The application potential for industrial heat pumps spans multiple industries including food & tobacco, paper & pulp, chemicals, textiles and wood (in particular in drying processes), as well as in pasteurising, sterilising, evaporation and distillation (Arpagus et al., 2018). In addition, cement, chemicals and metals still have several low-temperature processes and waste heat streams which could support industrial heat pump integration (BloombergNEF, 2021a). The REPowerEU Plan encourages Member States to accelerate the deployment and integration of industrial (i.e. large-scale) heat pumps in a cost-effective way, for example by exploiting industrial heat. However, high temperature manufacturing processes above 500°C, such as those for steel and cement, are hard to decarbonise, because this quality of heat is only readily achievable via fuel combustion or electrification (BloombergNEF, 2022).

Hydrogen has great potential to provide a decarbonisation pathway for the steel industry, acting both as feedstock and fuel source (BloombergNEF, 2019a; 2019b). Hydrogen direct reduced iron (H2-DRI) builds on existing DRI technologies, which use natural gas in a DRI furnace instead of coal in blast furnaces to reduce iron ore to iron. H2-DRI replaces natural gas with hydrogen, eliminating carbon from this step (Material Economics, 2019). The swap to H2-DRI for the iron reduction requires the subsequent presence of an electric arc furnace (EAF) for steel manufacturing. Today, EAFs are used for steelmaking from recycled scrap. The further foreseen increased deployment of EAFs combined with H2-DRI also ensures the decarbonisation of the secondary manufacturing route (providing that EAFs are powered by clean energy). The remaining emissions stem from the EAF graphite electrodes which are consumed during the steelmaking process, corresponding to 2-5 kg CO_2 per tonne of steel (Material Economics, 2019).

Figure 96 shows the flow of raw materials to the technologies selected for the energy-intensive industry sector.

Figure 96. Semi-quantitative representation of flows of raw materials to the technologies of the energy-intensive industry sector



Source: JRC analysis.

The cement and concrete industries are CO_2-intensive. This is because 60% of cement manufacturing emissions are process emissions, inherently related to the decarbonation of limestone. The remaining 40% of CO_2 emissions comes from the fuels used to heat the kiln. Mitigating substantial amounts of CO_2 to reach global net-zero emissions by 2050 will be impossible without carbon capture (CC) and storage (IEA, 2021). CC involves capturing the CO_2 emissions from a cement kiln and safe disposal (storage) or use. Several different technological options are available at pilot and demonstration phase, but not sufficiently proven for such large-scale use (Scrivener et al., 2016). Construction of the first full-scale CC plant is expected to be complete by 2024 (BloombergNEF, 2020). The most promising CC technologies are amine scrubbing, calcium looping, membrane separation, direct capture via indirect heating and full and partial oxy-fuel combustion. Amine scrubbing is the most advanced in terms of the technology readiness level and can be retrofitted to existing cement plants (IEA, 2021). CO_2 can be selectively removed from the flue gas after being fed to an absorption column (scrubber) where an amine solvent selectively and reversibly absorbs the CO_2. The CO_2-rich solvent is then transferred to a desorber column and heated up (regenerated) to release the CO_2 (ECRA, 2007).

3.3.3. Current supply chain bottlenecks

No critical supply chain bottlenecks were identified in the materials and components supply chain for the contruction of DRI plants. However, DRI technology ownership is restricted to three companies. Midrex Technologies which owns the Midrex process, and Tenova and Danieli which jointly own the Energiron technology and Pered. Midrex has the dominating market share, accounting for around 80% of global DRI production in 2021 (Midrex, 2021).

An increase in EAF steel production will lead to increased demand for graphite electrodes and as a result for synthetic graphite, which is also a key material for lithium-ion battery anodes. China has the largest global graphite electrode production capacity, followed by Japan, India and the US (BloombergNEF, 2021b). The drive towards decarbonising the steel industry, not just in the EU, but globally and especially in China, could increase the demand for graphite electrodes in the future and could lead to a possible graphite electrode shortage (Fastmarkets, 2021).

DRI processes use iron ore pellets as feedstock that are typically of a higher grade (higher iron content, lower gangue levels) than BF pellets. Since the supply of DRI-grade pellets is limited, this could represent a potential bottleneck in the future (Doyle et al., 2021). S&P Global estimates that DR-grade iron ore pellet demand could increase more than fivefold in the next three decades (S&P Global, 2022).

Due to the continuous nature of the iron-making process and limited plant ramp up and down capabilities, the hydrogen supply would need to be fairly stable and available in the large amounts required. Alternatively, sufficient hydrogen storage could offer the necessary flexibility in terms of hydrogen supply. The chemical and petrochemical industry and the e-mobility sector will compete for the hydrogen supply, thus making it a scarce resource and a potential bottleneck.

Although full CCS value chains are yet to be implemented for the cement industry, a partial supply chain analysis identified MEA (monoethanolamine) and pumps and compressors as key components (US DoE, 2022).

MEA is the synthetic sorbent that absorbs the CO_2 from the flue gases. Its production requires ammonia and ethylene oxide, which subsequently uses nitrogen and hydrogen. MEA's primary use is for feedstock in the production of detergents, emulsifiers, polishes, pharmaceuticals, corrosion inhibitors and chemical intermediates. The agriculture industry dominates the global ammonia market, accounting for more than 80% of global ammonia demand (Material Economics, 2019), with top producing countries being China (48 Mt), Russia (12.5 Mt) and India (11 Mt). Currently, the MEA market is not large enough to accommodate CCS needs, raising concerns if the demand spikes suddenly.

Pumps and compressors are large machinery used across multiple industries. They require cast iron and stainless steel. The raw materials for cast iron, stainless steel and its constituent materials for alloys such as iron ore, chromium and nickel, do not face a high supply risk. However, other alloying elements such as phosphorus, vanadium and manganese show a high supply risk, with sourcing largely dependent on China (79% for phosphorus, 62% for vanadium and 51% for manganese). Additionally, there may be small concerns with the specific acid gas transport equipment for CO_2, based on its acidic nature. For both pumps and compressors, there is a large and diverse pool of suppliers in the global market. However, compressors need to be able to operate at higher temperatures.

As with the residential heat pumps, the main components in industrial heat pumps are the compressor, electronic controls, heat exchanger, evaporators, condensers, accumulator, housing, valves, fan motor and piping (US DoE, 2016). The main bottlenecks in the supply chain of industrial heat pumps are the permanent magnets and the semiconductors, which are sourced almost exclusively from China and Taiwan, respectively. Bottlenecks not related to materials include the lack of trained installers and the availability of manufacturers for the expansion and conversion of production lines. These issues are related to broader economic issues of labour shortages and rising interest rates in Europe

The technologies used in the decarbonisation processes of the energy-intensive industries require several raw materials ranging from critical and strategic to non-critical.

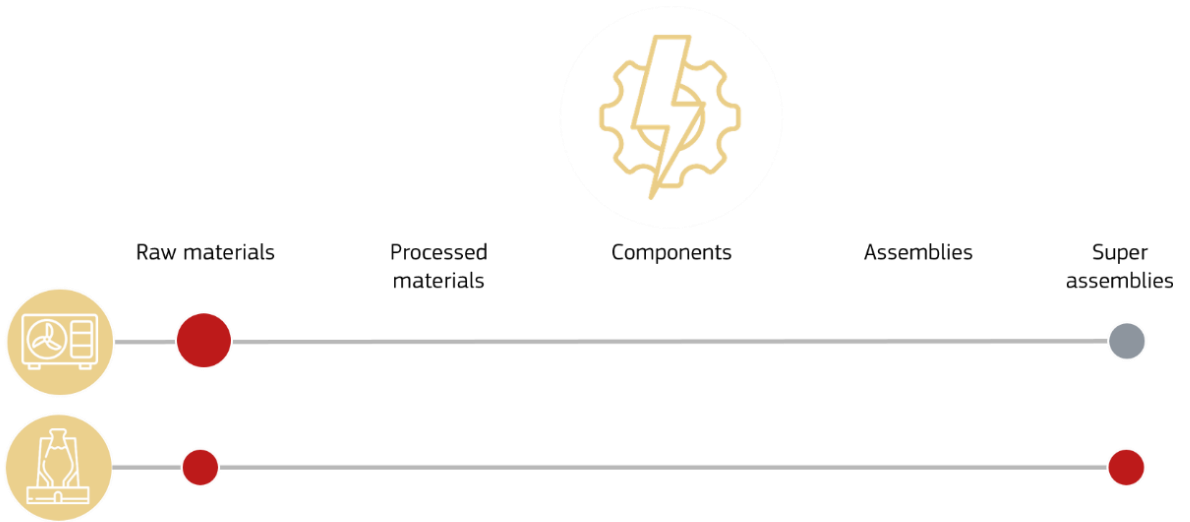
Table 9 gives an overview of the raw materials with the split among technologies. The potential supply bottlenecks of materials used in the technologies relevant to the energy-intensive industries sector are presented in Figure 97. We note that only a partial analysis was conducted for this sector.

Table 9. Strategic, critical, and non-critical raw materials used in the energy-intensive industry sector.

Supply Risk	Raw material		
4.0	REE (magnets)	•	
3.8	Boron	•	
1.8	Natural graphite		•
1.4	Silicon metal	•	•
1.2	Manganese	•	•
0.5	Nickel	•	•
0.1	Copper	•	
3.3	Phosphorus		•
2.3	Vanadium		•
1.2	Aluminium	•	•
1.1	Fluorspar	•	
0.8	Molybdenum	•	
0.8	Silver	•	
0.8	Zirconium		•
0.7	Chromium	•	•
0.6	Magnesite		•
0.5	Hydrogen		•
0.5	Iron ore	•	•
0.4	Gold	•	
0.3	Limestone		•
0.3	Silica		•
0.2	Zinc	•	

Source: JRC analysis.

Figure 97. Overview of supply risks, bottlenecks, and supply patterns along the selected supply chains relevant to the energy-intensive industry sector



Source: JRC analysis.

3.3.4. 2030 and 2050 technology prospects

All the technologies addressed in this chapter for the decarbonisation of energy-intensive industry sectors are in the early stages of their development. Pilot and demonstration plans have been announced for H2-DRI for the coming years, while a first full-scale project for carbon capture at a cement kiln is expected to complete construction by 2024. Similarly, industrial heat pumps are still rare in practice and require further development, demonstration and mass deployment. This is because demand is driven mainly by scattered industry sectors that aim to improve their thermal efficiency. Hence, it is difficult to predict future material demand for this sector.

Studies from various organisations estimate the total amount of global carbon capture across industries required by 2050 to be between 6 and 12 Gt (IPCC, 2019) and 7.6 Gt (IEA, 2021). Exceptionally, the Global Cement and Concrete Association (GCCA) published a Roadmap to net zero, setting the goal of 10 fully operational carbon capture cement plants around the world by 2030. Beyond that, up to 2050, the carbon capture contribution is projected to become significant, holding the highest share (35%) among various CO_2 emission reduction actions (GCCA, 2021). If we now consider the increase in cement consumption over the decades up to 2050, we can estimate its associated CO_2 emissions, on the basis of current production practices. In 2050, these emissions will amount to 3.8 Gt. By applying the 35% share, a carbon capture capacity of 1.33 Gt is obtained. This represents the estimated carbon capture capacity installed in the cement industry by 2050.

For H2-DRI plants, their future deployment depends on the future steel demand outlook, the development of other decarbonisation technologies, and the share of secondary to primary steel production. Material Economics modelled three 2050 decarbonisation pathways that focus on different solutions: new processes (H2-DRI), material efficiency and circularity, and carbon capture technologies. In the New Processes pathway, total steel production remains at 181 Mt in 2050 (EU27+UK) with H2-DRI amounting to 63 Mt of steel production, while in the circular economy pathway, steel production stands at 139 Mt in 2050 (EU27+UK), of which 97 Mt is via the secondary route and only 27 Mt is H2-DRI. In all scenarios, the deployment of H2-DRI technologies only starts post-2030. The Sustainable Development Scenario by the IEA sees a more modest deployment of H2-DRI, with around 10 commercial-scale plants (15 Mt of crude steel output) replacing existing BFs by 2050 (IEA, 2020). Other reports discussing global net-zero pathways for the steel industry (BloombergNEF, 2021a) see new natural gas-based DRI plants being built by 2030, while from 2030 onwards, the majority of new-build primary steel capacity is H2-DRI.

Scenarios modelling the decarbonisation of the steel sector also see an increase in the use of EAF to process recycled steel scrap into steel. Material Economics model up to 108 Mt a year (EU27+UK) being made by recirculated steel in the New Processes scenario (Material Economics, 2019). The IEA also shows a slight increase in the share of steel coming from the recycling route in its Sustainable Development Scenario, accounting for close to 60% of steel production in the EU (compared to 41% in 2019) (IEA, 2020). At a global level, several decarbonisation scenarios model a vast increase in secondary steelmaking. For example, the BloombergNEF Net Zero scenario assumes an increase in secondary manufacturing from 27% of global production today to a maximum 45% of total steel manufactured in 2050, or 1.2 billion tonnes in absolute terms, from 428 million today (BloombergNEF, 2021c). This long-term growth in EAF steelmaking will lead to increasing demand for graphite electrodes, from 1 million tonnes a year in 2020 to 5.7 million tonnes by 2050 (BloombergNEF, 2021b).

The German think tank Agora Energiewende predicts the widespread use of industrial heat pumps in the EU, which will be used to displace all fossil fuels from industrial heating below 500° C by 2035. This would mean bringing 8 GW of heat pumps into operation by 2030 and 12 GW by 2035 (Agora Industry, 2022).

3.3.5. Geopolitical dimension

There are few to no country-specific roadmaps for the deployment of decarbonisation technologies, and it is therefore difficult to assess the pathways of countries and regions. However, we note a few notable developments to present.

DRI is a common and widespread manufacturing process. In 2021, annual global direct reduced iron (DRI) production was 119.2 million tonnes (Mt), using coal and gas. The only European country, Germany, reportedly produced 0.5 Mt DRI in 2021 (Midrex, 2020). The first commercial-scale plant to use pure hydrogen as a reducing agent has been intermittently operating in Trinidad since 1999, preheating the iron ore fines with natural gas and reduced by hydrogen. It relies on a two-step reactor combination of circulating fluidised bed (CFB) and bubbling fluidised bed where the iron ore fines are first preheated with natural gas and then reduced by hydrogen (Nuber, 2006; Otto et al., 2017). Currently, no commercial DRI plants are operating with a 100% hydrogen feed, but the technology should be expected to be deployed for steelmaking worldwide.

A few pilot CC projects have turned into larger installations, and the technology is gathering momentum. Currently, there are still no large-scale clinker production lines in operation anywhere in the world that capture all of their process CO_2 emissions. The few that do capture some of their emissions are either running pilot projects or are doing so on a partial scale (Perilii, 2021).

Heidelberg Materials' Norcem plant in Brevik is part of Europe's first full-scale plant of CO_2 capture, transport and storage and the world's first CO_2-capture facility at a cement factory, scheduled to be fully operational in 2024 and set to capture around 400 000 t/yr of CO_2. The captured CO_2 will be liquefied, and temporarily stored at Brevik facilities, and then shipped to an onshore terminal, and from there transported and injected into a CO_2 storage site offshore in Norway under the North Sea, as part of the Norwegian government-backed Northern Lights project (Perilii, 2021).

A smaller scale CCU plant with a capacity of 50 kt CO_2 per year has been operational since 2018 in Anhui Conch's Baimashan plant in the city of Wuhu, in the Ahnui province, China. The pilot facility captures 3% of the total CO_2 emissions of the cement factory, which is sold to industrial customers. However, due to the limited local market for CO_2, the company has no plans to expand (Plaza et al., 2020).

In 2019, Dalmia Cement (Bharat) Limited announced it will build a large-scale facility of 500 000 tonnes per year carbon capture at its cement plant at Tamil Nadu, India. The facility will make use of Carbon Clean's CDRMax® technology, which combines the use of a proprietary solvent (amine promoted buffer salts, APBS) with novel heat integration. The partnership will explore possible uses for the CO_2 captured, including direct sales to other industries, or chemical manufacturing. No completion date or budget has been disclosed (Plaza et al., 2020).

Industrial heat pumps are in their infancy. IEA projects 500 MW/month of installed industrial heat pump capacity up to 2025, hence a significant development (unpublished IEA report Nov. 30). Technical solutions for the market segment for the temperature between 100°C to 200°C still have to be developed and further demonstrated. Currently, there is no large-scale industrial heat pump project in Europe, especially regarding high-temperature heat pumps (Defauw et al., 2022). The development of heat pumps for the process industry is driven by scattered national initiatives which are very much targeted towards local industry sectors (de Boer et al., 2020).

Almost half of the heat pumps installed have been in the food & tobacco industry (BloombergNEF, 2021a). Overall, Germany and Japan accounted for 42% of installations, while France, Canada, Austria and the Netherlands all represent around 10% each.

In collaboration with MAN Energy Solutions, BASF is developing the installation of the largest industrial heat pump of 120 MW in the high-temperature domain in the Ludwigshafen site (Defauw et al., 2022). Since 2021, Siemens has had a manufacturing factory in Duisburg, Germany. EHPA started a working group with the paper industry to push for the development of harmonised standard compressors for the paper industry (EHPA).

3.3.6. Key observations and recommendations

The industrial sector is in the early stages of its development, with pilot and demonstration plans announced (H2-DRI) and the first full-scale projects under construction (carbon capture in the cement industry). Despite commercial availability, industrial heat pump adoption remains low, and represents only a minor share of heat pumps currently sold. The sector is growing, and is building capacity.

Currently, there are no shortages in the supply chain. However, a rapid increase in deployment can hugely increase demand for the materials and components required. Bottlenecks not related to the materials include limited ownership for DRI technologies and the lack of trained installers for industrial heat pumps.

The EU is highly dependent on imports of several raw materials such as REEs and synthetic graphite. The demand for these materials face a high supply risk as well as a competing demand from the e-mobility and renewable sectors, with China dominating the REE market from raw materials extraction to permanent magnet production. The most critical are semiconductors, which are in short supply worldwide since late 2020 and are used in electronic controls by all other sectors, from e-mobility to space. Additionally, the upcoming ban on fluorine gas refrigerants puts the European industry in a critical position to deliver, due to the lack of available refrigerants in the high temperature range with low global warming potential.

3.4. Information, communication and digital technologies (ICT)

3.4.1. Introduction

Digital technologies have changed the way businesses operate, how people connect and exchange information, and how they interact with the public and private sectors (Negreiro and Madiega, 2019). ICT has also transformed production processes, eased the diffusion of new phenomena such as robotisation, automation and artificial intelligence, and paved the way for the international fragmentation of value chains.

3.4.2. Relevant technologies

Information and communication technology (ICT) is present in all areas of the economy and society. Devices such as smartphones, personal computers and tablets have seen a rapid rise in both technical performance and market penetration, drastically altering both our working lives and our everyday lives. Together with enterprise servers, storage systems, and data transmission networks, they are part of the technological revolution brought about by the internet and digitalisation (Figure 98).

Digital technologies and data hold tremendous potential to further accelerate clean energy transitions across the energy sector. In electricity systems, digital technologies can help integrate increasing shares of variable renewables, accommodate an overall rise in processing power, and improve the reliability of grids (IEA, 2022).

Figure 98. Technologies involved in the ICT sector

Source: JRC analysis.

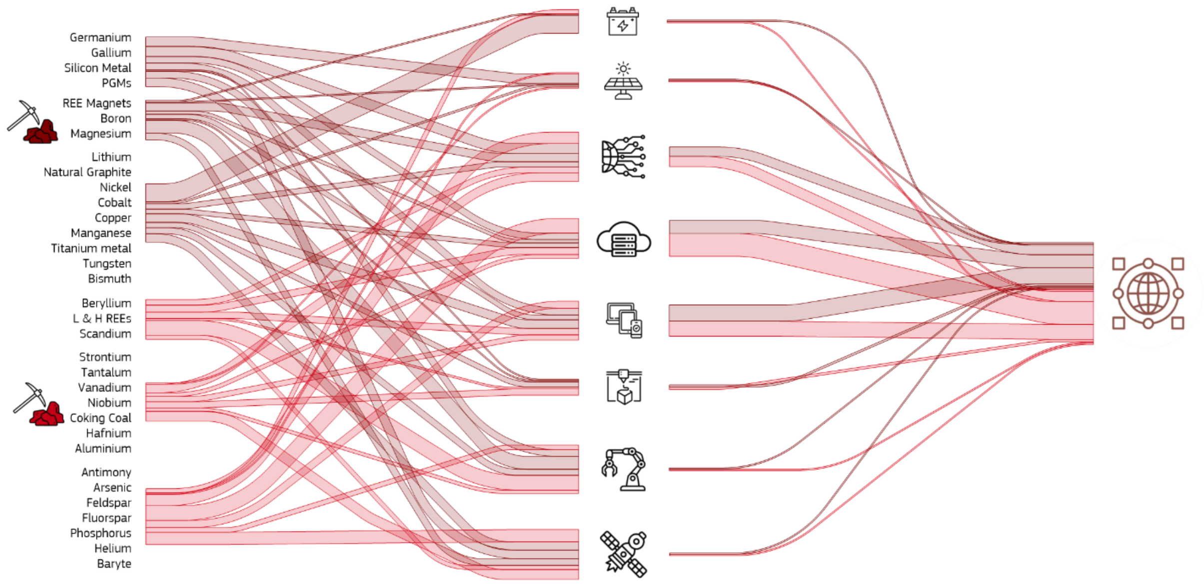
On the other hand, digital technologies also benefit from developments in other technological areas and from decarbonisation trends across industry. Reducing the carbon footprint of equipment in this supply chain entails a shift towards renewable energy for the manufacturing of semiconductors and printed circuit boards regarded as highly energy-intensive (EC, 2021b). Highly efficient automated manufacturing processes for digital devices and components are made possible thanks to the use of industrial robots. Lithium-ion (Li-ion) batteries, used in most of our modern-day smartphones, have enabled significant weight reduction, facilitated charging and improved autonomy. Innovations in the field of advanced electronics for space applications (e.g. satellites), that have been favoured by increasing research budgets aiming at promoting the growth of the aerospace industry in Europe (EC, 2023), can provide opportunities for manufacturers in the ICT value chain. Likewise, the competitive automotive sector in the EU is a driver of innovation in electronics with the potential for wider application.

In 2017, the EU had competitive advantages in various segments of the broader electronics market including automotive electronics (27% share of the global market), industrial electronics (20%), and aerospace and defence (22%) (EC, 2020).

Advanced electronics are central to all technologies in the ICT sphere, defining supply chains that are both complex and global in nature. These sophisticated supply chains, which rely on the supply of a vast array of critical, non-critical and strategic raw materials are also known to be vulnerable, making measures necessary to address security and resilience (Figure 99).

This assessment updates and expands upon the previous study with regard to digital technologies (EC, 2020). It aims to investigate, comprehensively, the supply chains of the smartphones, tablets, laptops, data server and storage equipment and data transmission network equipment found to be the most representative in the ICT sector[71].

Figure 99. Semi-quantitative representation of flows of raw materials to the technologies of the ICT sector



Source: JRC analysis.

3.4.3. Current supply chain bottlenecks

Smartphones, tablets, laptops, data servers, storage drives, and the functional part of data transmission networks feature multiple elements, ranging from materials to super-assemblies, with long and highly complex supply chains.

Across the value chains there are supply risks at all stages, from the poorly diversified production of certain critical raw materials such as rare earths, PGMs and noble gases to the EU's limited manufacturing capacity of highly strategic processed materials and components, such as advanced logic and memory semiconductor chips (Figure 100).

At raw materials level, the risk of difficulties in supply is heightened for silicon metal and gallium, indispensable for semiconductor wafers; germanium, borates, and REEs (dysprosium, neodymium, terbium, ytterbium, thulium, praseodymium, erbium) used as dopants in fibre-optic cables and HDD permanent magnets; bismuth and PGMs, used in general electronic components like digital signal processors, capacitors, transcoders, control electronics and solders; and helium for manufacturing semiconductor chips (Table 10).

The average supply risk at processed materials stage is also high across ICT technologies. Permanent magnet alloys are amongst the most vulnerable, with China unarguably leading the market, accounting for 94% of global production. In the production of semiconductor chips, gallium nitride and photoresist chemicals account for the highest supply risks, with most production concentrated in Japan.

Supply risks are high at components level in the supply chains of ICT devices. Technologies in this sector account for 71% of overall semiconductor chips demand (ASML, 2021). Chips used in smartphones, personal computing, servers, storage drives and wired & wireless infrastructure have varying levels of supply risk, depending on the specific type. Taiwan has 40% of the world's logic chip production capacity. On the other hand, the US leads in front-end activities that are most intensive in R&D, including chip design, which relies on highly advanced

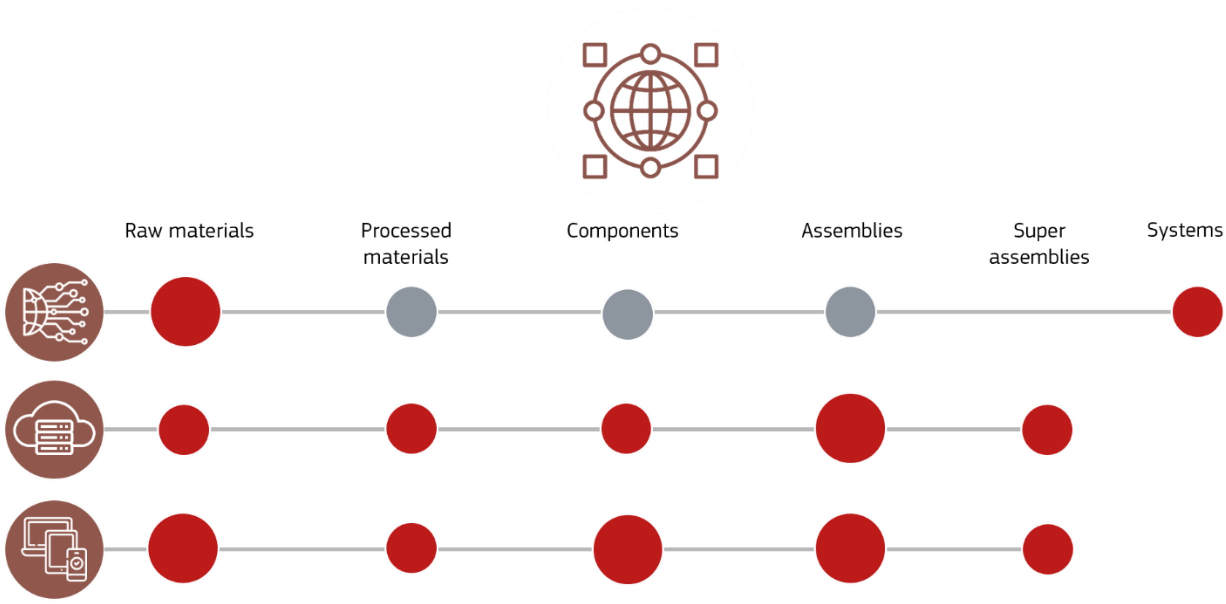
[71] Given its complexity, the assessment of data transmission networks is limited to functional equipment which is based on electronics. Smartphones, tablets and laptops are treated independently, with regard to the forecast analysis of devices and materials demand. As far as data servers and storage are concerned, the analysis concentrates separately on servers, enterprise and near-line hard disk drives and enterprise solid-state drives used in data centre applications.

electronic design automation (EDA). Firms specialising in components of battery cells and screens, audio devices and semiconductor back-end operations including assembly, packaging and testing, are concentrated primarily in East Asian countries. Permanent magnets are at high risk, with China dominating almost the entire supply chain of magnet production. For data transmission networks, the most vulnerable components are fibre cables and submarine cables.

Likewise, supply risks are high for most elements under consideration at assembly stage. One obvious challenge comes from semiconductor devices, namely CPU and GPU modules, as their production is located almost entirely in the United States. DRAM and NAND are also highly critical elements, with market shares dominated by companies headquartered in South-Korea. LCD and OLED screen technologies face high supply risks because of the dominant position held by east-Asian countries.

At the super-assembly stage, the production of enterprise storage systems, network equipment, smartphones, tablets and laptops appears to be highly concentrated, with a few large players. For all these devices, the EU relies greatly on imports from third countries, with limited domestic manufacturing capacities.

Figure 100. Overview of supply risks, bottlenecks, and supply patterns along the selected supply chains relevant to the ICT sector



Source: JRC analysis.

Table 10. Strategic, critical and non-critical raw materials used in the ICT sector.

Supply Risk	Raw material			
4.8	Gallium	•	•	•
4.1	Magnesium		•	•
4.0	REE (magnets)	•	•	•
3.8	Boron	•	•	•
2.7	PGM	•	•	•
1.9	Lithium	•		•
1.9	Bismuth	•	•	•
1.8	Germanium	•	•	•
1.8	Natural graphite	•		•
1.7	Cobalt	•		•
1.6	Titanium metal			•

Supply Risk	Raw material			
1.4	Silicon metal	•	•	•
1.2	Manganese	•	•	•
1.2	Tungsten			•
0.5	Nickel	•	•	•
0.1	Copper	•	•	•
5.3	HREE (rest)	•	•	•
4.4	Niobium	•		
3.5	LREE (rest)	•		•
3.3	Phosphorus		•	•
2.6	Strontium	•		•
2.4	Scandium		•	
2.3	Vanadium	•		
1.8	Antimony	•	•	•
1.8	Beryllium		•	•
1.6	Arsenic	•	•	•
1.5	Hafnium		•	
1.3	Baryte	•	•	•
1.3	Tantalum	•		•
1.2	Aluminium	•	•	•
1.2	Helium		•	
1.1	Fluorspar	•		•
1.0	Phosphate rock	•		
0.9	Tin	•	•	•
0.8	Silver	•	•	•
0.8	Molybdenum	•		•
0.8	Xenon		•	•
0.8	Zirconium	•		
0.7	Chromium		•	•
0.7	Krypton		•	•
0.7	Neon		•	•
0.6	Indium	•	•	•
0.6	Gypsum	•		
0.5	Iron ore	•	•	•
0.5	Hydrogen			•
0.5	Rhenium	•		
0.5	Titanium		•	
0.4	Gold	•	•	•
0.3	Tellurium	•		
0.3	Selenium	•		
0.3	Silica			•
0.2	Zinc	•	•	•
0.2	Cadmium			•

Supply Risk	Raw material			
0.2	Talc			•
0.1	Lead	•		•

Source: JRC analysis.

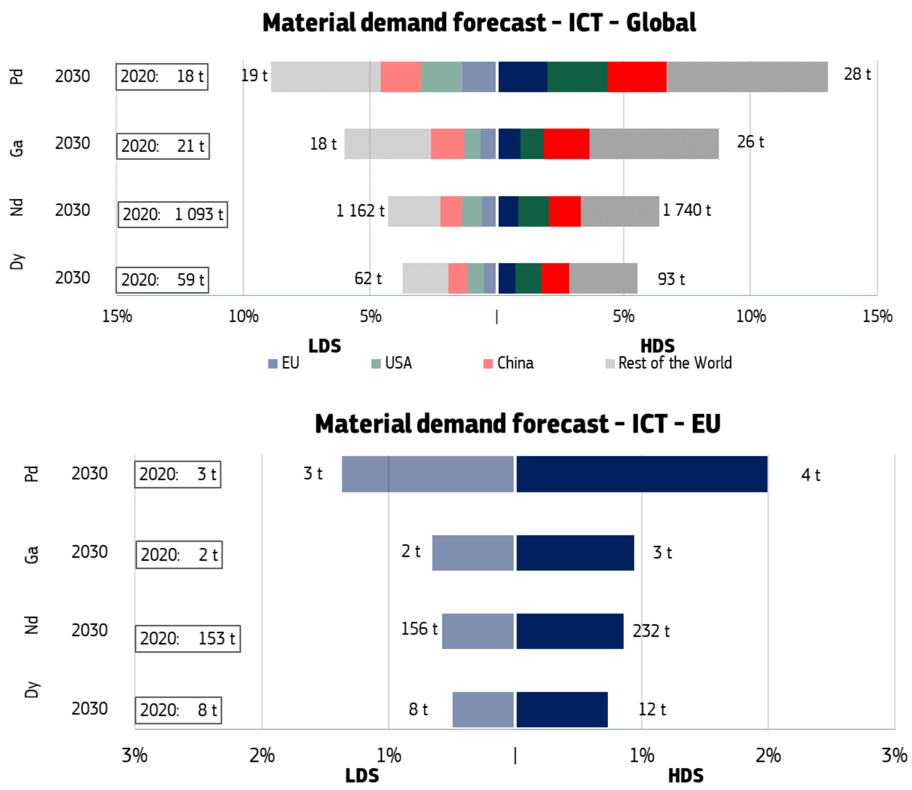
3.4.4. Projected 2030 material demand

The demand for data transmission capacity will continue to grow in line with the lasting global digital transformation megatrend that is spreading across countries and market sectors through the deployment of submarine and terrestrial cable systems. Significant changes are also expected in the annual deployment of servers and storage equipment as a consequence of the digitalisation of information and data, responding to trends such as cloud computing, the internet of things, industry 4.0 and big data, which will increase demand for ICT processing and storage resources. The demand for smartphones, tablets and laptops, for general communication and information access, is predicted to be constant until 2030 as the market reaches saturation point.

The demand in 2020 and forecast in 2030 for a selection of raw materials essential to the ICT sector are presented below (Figure 101). The aggregated totals reflect the contribution of smartphones, tablets and laptops and of data servers and storage to the overall demand in the ICT sector.

REEs, gallium and palladium are some of the most relevant raw materials in terms of demand, calling on a significant proportion of what is available on the global market. Dysprosium and neodymium, for example, used in HDD drives, vibration alarms, speakers, microphones, and cameras, are estimated to represent collectively around 7% of the current total supply. Gallium consumption is estimated to have amounted to 7% of the global supply in 2020, and that of palladium, to 8%. In 2030, in the HDS, palladium use can potentially increase to around 13% of today's available supply. Similar estimates have been made for dysprosium and neodymium, which taken collectively, can represent 12% of today's supply in 2030.

Figure 101. Material demand forecast for the ICT sector: global (top) and focus on the EU (bottom)



Source: JRC analysis (Nd = neodymium, Dy = dysprosium, Ga = gallium, Pd = palladium).

3.4.5. Geopolitical dimension

Data transmission networks provide technical solutions for cross-border information-sharing and ultimately provide the tools to control domestic or foreign information transfer, which may affect the sovereignty of governments, individuals, and enterprises in various sectors including those managing critical infrastructure (industry, energy, transportation, aerospace and defence, finance and healthcare). Submarine cables form an essential part of intercontinental and other long-distance data transmission facilities. A recent proof of the relevance and extreme vulnerability of European submarine infrastructure is the incident of the Nord Stream attack in the Baltic Sea (Irish, 2022), which equally applies to submarine data transmission infrastructure. Seabed security is therefore becoming a part of national resilience strategies and a key priority for countries around the world.

Until the mid-2010s, submarine cables were commonly owned by consortia of telecom providers and other, often private, companies. Since 2016, a new phase has started with both a massive rise in submarine cable deployment and a significant shift of ownership towards big tech companies. This dynamic can mean an increased risk of market concentration, which is of particular relevance as big tech is concentrated in a single country, namely the US.

In the case of data centres, government initiatives contributing to the strong uptick in investment in this industry are numerous across the globe. China's plans to develop its digital economy are also far advanced, which adds to the fact that the country has the world's largest capacity to produce electronic components and equipment, with a huge domestic market that allows economies of scale to be realised. China's ambition, enhanced by government support practices, sets the scene for potential disruptions in scenarios of trade or geopolitical conflict, especially in the case of manufacturing activities that are less easy to scale (e.g. semiconductor wafers).

Semiconductors are fundamental to all digital technologies and are illustrative of the international nature of the market and supply chains. The general consensus is that the increasing internationalisation and significant fragmentation of the semiconductor value chain began in the early 1980s, with the separation of chip fabrication and design segments. This led to the emergence of fabless firms, also in Europe (EC, 2020), many of which closed down after the 1990s, without being replaced. The lack of public investment to support the manufacture of advanced technologies, when compared with the US and Asia, has discouraged semiconductor industry development within the EU (EC, 2020). Today, the EU enjoys only a competitive advantage in analogue and 10-22 nm logic chips.

The COVID-19 pandemic triggered a global chip shortage in 2021, originally concentrated in the automotive industry but which spread to other sectors as well. Risks to the semiconductor supply chain and other manufacturing activities, featuring a high degree of geographic concentration, have also been linked to natural disasters, namely exposure to seismic activity. At present, competition for semiconductor leadership has intensified as the governments of highly industrialised countries such as China, Taiwan, the United States, Japan, South Korea and the EU commit substantial investments with a view to developing domestic capacities.

In China, the presence of many upstream manufacturing companies, as well as the development of raw materials production, collectively contribute to growth, deepening further the concentration, intensification and verticalisation of production. The exposure of the EU economy to geopolitical risks is high for many raw materials. Such risks derive from concerns regarding trade distortions (e.g. countries like China, which account for the majority of the world's production of rare earths, gallium, germanium, aluminum, antimony, bismuth, indium, lithium, magnesium, phosphorus and silicon metal), from major social, health, and environmental problems arising from unsustainable artisanal mining practices (such as in the Democratic Republic of the Congo, where most cobalt used in LCO batteries for powering smartphones, tablets and laptops is produced); from trade disputes in South Africa regarding PGM mines; or directly from Russia's invasion of Ukraine as in the case of noble gases.

3.4.6. Key observations and recommendations

The EU is a global player in ICT value chains but is highly exposed to rising and volatile raw material prices, inflation, geopolitical risks, and other risks related to inadequate manufacturing capacities unable to keep up with domestic demand.

While the EU holds a reasonable share of processed materials to produce data server and storage equipment (13%), smartphones, tablets and laptops (13%), its production share is only marginal at the assembly and super-assembly levels of both technologies (<1%). On the other hand, the EU demonstrates important capabilities across all downstream stages of data tramsission networks from processed materials to systems integration.

The supply of raw materials is a vulnerable stage in all three technologies, with China accounting for a large majority of production.

The following prevention and mitigation strategies could be considered to overcome potential bottlenecks across the supply chains of ICT technologies.

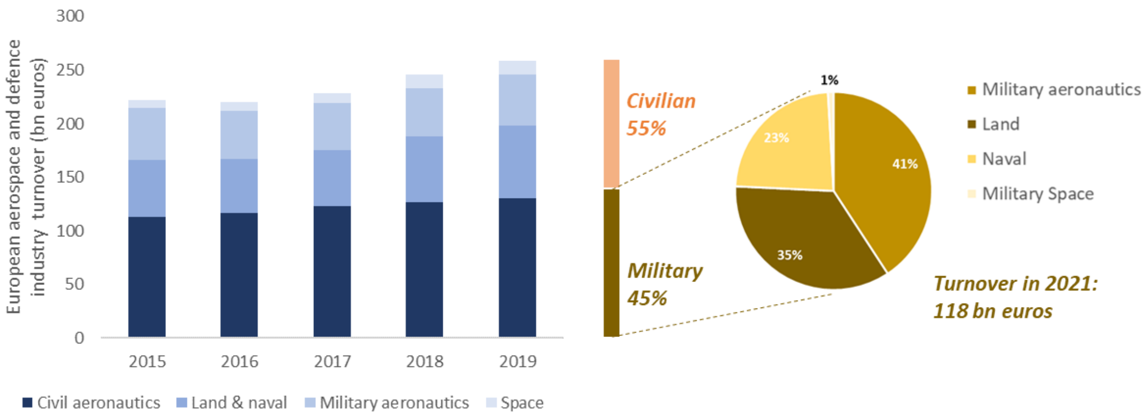
- **Safeguard the most strategic raw materials** e.g., by deploying partnerships and concluding trade agreements to diversify, incentivising domestic mining, and developing leadership in the circular economy, namely through recycling, re-use and refurbishing.
- **Draw on existing know-how and consolidate pre-existing advanced manufacturing infrastructure**. With a reasonable market share for many elements in ICT supply chains, in particular processed materials, together with a significant strength in the manufacturing of equipment for the various industries, like semiconductors (EC, 2020), there are opportunities for EU firms to acquire leadership in international markets and further consolidate production.
- **Support the competitiveness and resilience of EU producers against risks of market distortion.** Building capacity in the EU for the production of electronic components and assemblies, including semiconductor design, manufacturing and packaging, requires effective investment and financial instruments to create a level playing field with global competitors and eliminate barriers to entry. Exploring opportunities for establishing effective international cooperation intended to promote investments, bring in technical expertise and capital to European semiconductor manufacturing, would also lead to a balanced approach with the potential to yield effective results.
- **Address skills shortages**, attracting talent and supporting the emergence of a skilled workforce required for the sector's development (e.g. in semiconductors).
- **Increase the resilience of the ICT sector by deploying new and additional capacity for secure data transmission.** Controlling or owning a submarine cable network would increase the resilience of data transmission networks and ensure data sovereignty. Beyond issues of securing the supply of critical supply chain elements, e.g. by domestic production, there is an additional potential bottleneck in the deployment capacities of the submarine cables, as these require the usage of highly specialised cable-laying barges.
- **Comply with existing standards regarding the management of waste of electrical and electronic equipment (WEEE)**, promote re-use practices and incentivise research focused on increasing the collection and recycling rates of strategic raw materials. Today, the recycling of electronic materials is currently either technologically infeasible or not economically viable, despite high collection rates of IT and telecom equipment in certain EU Member States (EC, 2021). Most critical raw materials are lost in shredding residues or diluted into other recycled fractions. Losses are relatively higher for the rare earth elements, indium, gallium, magnesium and silicon, even in proper WEEE recycling channels. Re-use of end-use products on the other hand is already a reality and could be further encouraged across ICT technologies, leading to a decrease in the manufacturing volumes of new equipment. Today, the average reuse rate of servers is estimated at 50% and that of storage systems at 25%. Increasing awareness among customers about the efficacy and reliability of practices on drive reuse are key for the future uptake of second-hand drives.
- **Foster the substitution of highly critical raw materials**. There are examples of material substitution in the ICT sector to address high raw materials prices and to guarantee security of supply (e.g. nickel instead of palladium in ceramic capacitors). However, while some substitutes are able to fulfil the requirements (e.g. function, properties, manufacturing readiness and industrial and end-user uptake), the majority of substitutes are currently in the research and development stage, and market-ready solutions are scarce (Bouyer, 2019). Substitution and further miniaturisation can provide for sustainable solutions at least in the long term.

3.5. Aerospace and defence

3.5.1. Introduction

Civil and military aeronautics, military land and naval segments, and space, are all part of the large aerospace and defence sector. This sector has always been strategically important and remains at the forefront of technological development, playing a decisive role in terms of economic growth. In May 2021, the European Commission proposed an update of the 2020 New Industrial strategy (EC, 2021a). Among the 14 strategic industrial ecosystems identified, the aerospace and defence ecosystem is regarded as essential, representing around 2% in terms of EU value added and a turnover of around EUR 250 billion. Of this sum, EUR 125 billion is accounted for by aeronautics, EUR 12 billion by space and EUR 110 billion by defence (EC, 2021b) (Figure 102).

Figure 102. Turnover of the aerospace and defence industry in Europe by sector[72].



Sources: JRC elaboration using data from (ADS, 2022a).

The supply chains of the aerospace and defence sector are complex in nature and range from large system operators and integrators down to high-tech, specialised SMEs. In defence, and partly in space, EU Member States define the needs and act as the primary customers for a wide range of products. This industry supplies the EU with crucial capacities for open strategic autonomy. Border surveillance, secured diplomatic communication, law enforcement, fisheries control, climate variable monitoring, smart mobility and crisis management all depend on aerospace and defence technologies (EC, 2018).

Satellites and launchers are the key technologies in the space segment (described in Section 2.15). Passenger and cargo aircraft, including aero-engines and helicopters, represent the civil aeronautics segment. The military aeronautics sub-sector produces a spectrum of manned and unmanned aircraft systems, from combat aircraft and drones to transport aircraft and helicopters. The land defence sector encompasses a wide-ranging product portfolio spanning main battle tanks to families of armoured vehicles, artillery, guided ammunition, integrated systems and components for the battlefield, protection of soldiers and infrastructures. The naval sector in turn entails the full spectrum of vessels, including aircraft carriers and nuclear submarines (ASD, 2022a).

Defence

Russia's unprovoked aggression against Ukraine has significant implications for the European defence sector. This, together with general security challenges, is leading to increased military spending by EU Member States and the widespread recognition of the need to further strengthen the EU's defence capabilities and consolidate the European defence industry, often referred to as the European defence technological and industrial base

[72] Europe includes the UK, which is estimated to contribute around 15% of the aerospace and defence sector revenues, along with Turkey and Norway.

(EDTIB) (EC, 2022a). It has also underlined the need for intensified cooperation within the single market, to achieve an appropriate level of strategic autonomy (Gahler, 2022).

Across the globe, significant strides are being made towards strategic autonomy and self-reliance for defence procurement. Developing domestic capabilities has meant providing incentives to assist manufacturers in setting up capacities to produce strategic military systems and critical components. Strategic autonomy also implies sovereignty in the supply of manufacturing materials, which are used across the air, sea and land domains. The disruption of supply chains across global territories due to the COVID-19 pandemic has further emphasised the need for self-reliance (KPMG, 2020).

In the EU, the EDTIB is concentrated in France, Germany, Italy, Spain and Sweden, although smaller platform manufacturers, equipment suppliers and sub-suppliers, and niche producers also exist in other parts of Europe (ASD, 2022a). According to the ASD (Aerospace, Security and Defence Industries Association of Europe), the total number of SMEs doing business in defence is estimated at 2 000 to 2 500. In 2021, defence accounted for about 45% of the total revenues of the larger aerospace and defence sector (Figure 102).

Worldwide, the applications most likely to emerge as drivers of growth for the defence industry include intelligence, surveillance, target acquisition, and reconnaissance (ISTAR) technologies, as well as cybersecurity and the application of unmanned aerial vehicles (UAVs) (Statista, 2023a).

Civil aeronautics and space

Civil aeronautics is one of the most successful high-tech sectors in the EU, and the backbone of the European aerospace and defence ecosystem. European industry is world leading in the production of civil aircraft, including helicopters, aircraft engines, parts and components. It provides 405 000 jobs, generates EUR 130 billion in revenues and plays a leading role in exports, which in 2019 amounted to EUR 109 billion (EC, 2023a) (Figure 102).

Strong investment capacity is needed to continue the development of disruptive technologies, thus maintaining the competitiveness of the sector and developing safer and greener products. This economic investment should target not only the large aeronautical enterprises located in France, Germany and Spain but also their suppliers composed of dynamic small and medium-sized enterprises throughout the EU.

It is still unclear what the effects of the recent COVID-19 crisis will be in terms of aircraft fleet management. However, the fact that two of the largest European airlines (Lufthansa and Air France/KLM) are required as a condition of their financial support to take steps toward 'greening' their fleet should speed up the European fleet renewal rate with new-generation fuel-efficient aircraft (OECD 2021). This should increase the average annual retirements by 20-25% compared to the previous decade (Shay, 2022). The average aircraft is now younger than in the pre-pandemic years (Eurocontrol, 2022), reflecting the ongoing renewal trend and thus the expected stock increase of retired fleet waiting to be decommissioned and recycled.

3.5.2. Relevant technologies

The aerospace and defence sector deploys most of the technologies analysed in this report, with numerous interdependencies across, for example, ICT technologies, requiring careful coordination. Satellites and space launchers are key technologies for the aerospace sector (Figure 103).

In defence, many technologies have dual-use potential, namely, advanced batteries, fuel cells, robotics, unmanned vehicles (drones), space launchers and satellites, ICT technologies, photovoltaics and 3D printing. These technologies provide the systems and subsystems which are fitted into core defence platforms and general military equipment.

Drones, satellites, 3D printing and robotics applications are more tangible in the military sphere, given the fact that defence represents a significant part of these industries' turnover. The defence market is today dominated by large UAVs, and this is expected to remain the case for the next two decades. In 2020, military applications represented 54% of the global drone market (Statista, 2020a). Surveillance is the increasingly dominant use.

Figure 103. Technologies involved in the aerospace and defence sector

Source: JRC analysis.

Autonomous and robotic systems are expected to make a significant change in the nature of military operations within the 2021-2040 period, at both global and national scale. Defence applications already constitute 8% of the overall Exoskeletons market (EC, 2020).

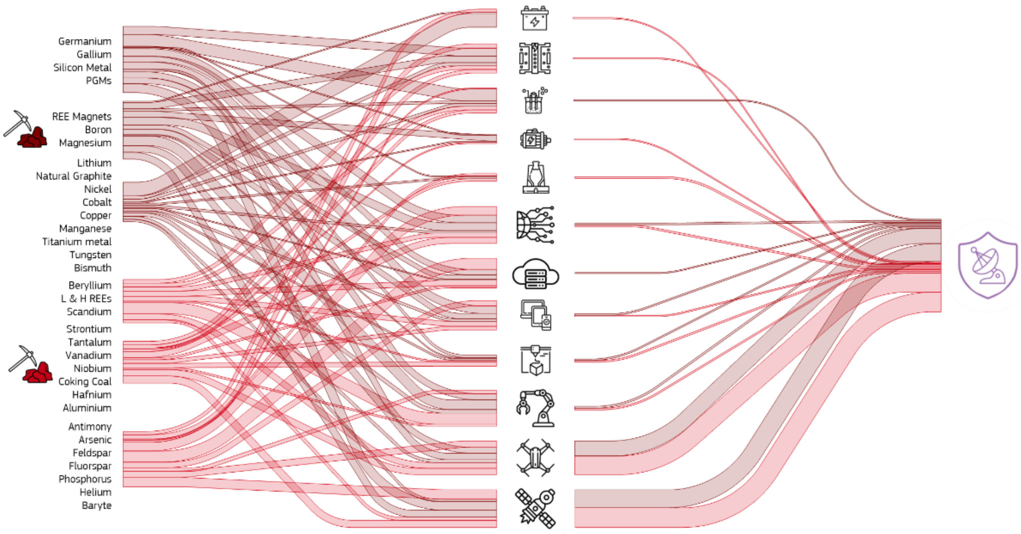
Military satellites include navigation, communications, and technology development missions, in addition to the intelligence-gathering activities. Worldwide, of the 2 666 satellites listed as active, only 339 have military uses (13%) (Statista, 2020b). In the US, 7% of the satellite fleet supports the military sector (UCS, 2022)

Technological integration of dual-use technologies in defence platforms has brought newer capabilities and improved operations with respect to response time, fuel efficiency, power handling capacity, and durability (Fortune Business Insights, 2021). 3D printing, for example, is rapidly maturing and in the case of defence, the benefits are numerous, from the production of lightweight and highly tailored parts to the development of special materials capable of withstanding demanding performance conditions (Clemens, 2022). Defence industries account today for around 5% of the 3D printing market (van der Zee et al. 2015) and this is expected to grow further in the future. 3D printing applications for commercial aeronautics and space sectors have been detailed in Sections 2.12 (additive manufacturing) and 2.15 (space launchers and satellites).

In the EU, the military aeronautic sector, producing a spectrum of manned and unmanned aircraft systems, from combat aircraft and drones to transport aircraft and helicopters, has benefited the most from developments in dual-use technologies and the EU's leading position in commercial aircraft manufacturing.

The proportion of critical, non critical and strategic raw materials in technologies relevant to the aerospace and defence sector are presented in Figure 104.

Figure 104. Semi-quantitative representation of flows of raw materials to the technologies of the aerospace and defence sector



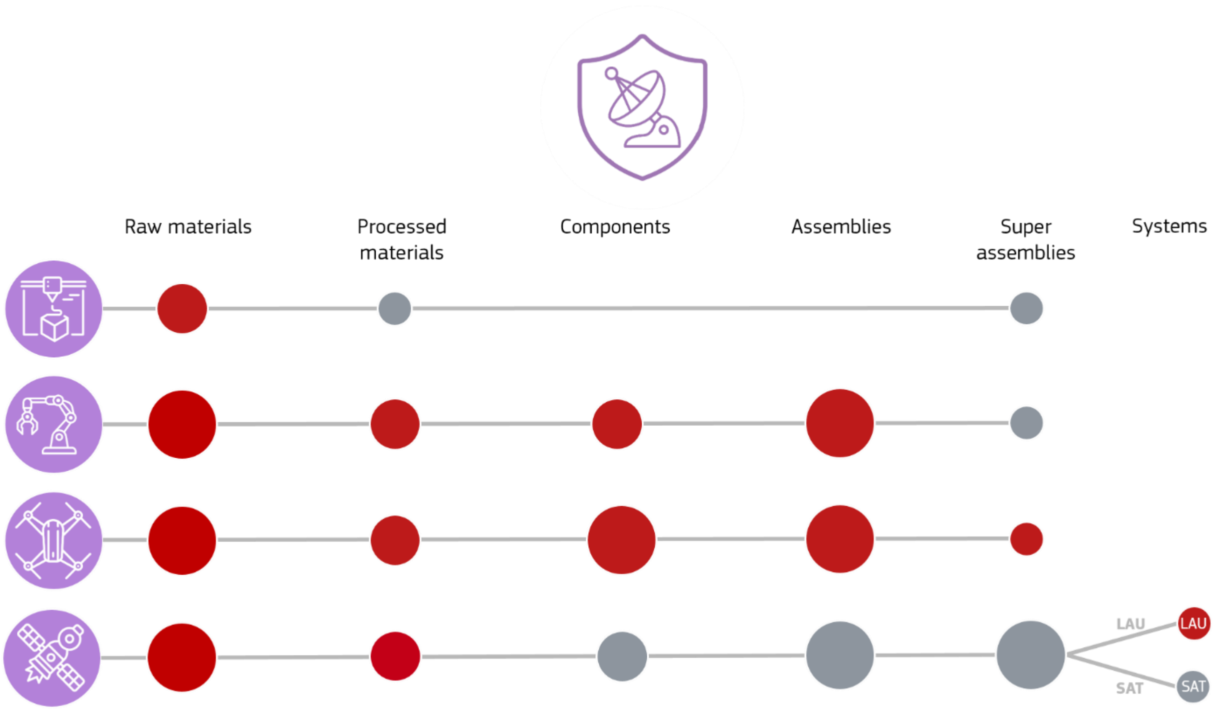
Source: JRC analysis.

3.5.3. Current supply chain bottlenecks

The various supply chains of dual-use technologies, space launchers and satellites all contribute to the performance of the aerospace and defence sector. Any disruptions of supply are likely to affect the development, production and maintenance of civilian and military platforms – aircraft, ground vehicles, ships and space systems – and the general competitiveness of the sector.

While these technologies are shaped by different market forces, and draw on very different supply chains, there are common challenges. The supply of raw materials and final assemblies are the most vulnerable stages in the supply chains of selected dual-use technologies. Drones and robotics are the greatest contributors to the level of risk (Figure 105). Raw materials production is also the first and most vulnerable stage of space lauchers and satellites, however in this case the EU demonstrates important capabilities in term of systems integration and final assemblies.

Figure 105. Overview of supply risks, bottlenecks, and supply patterns along the selected supply chains relevant to the aerospace and defence sector



Source: JRC analysis.

Critical and strategic materials

As with many other economic sectors, the aerospace and defence industry relies on the use of a wide range of raw and processed materials with unique properties that make them essential for the manufacture of components used in both civil and military applications (Table 11). Some applications need exceptional performance, tensile strength, or heat resistance, achieved at the expense of higher manufacturing or processing costs. As defence and space applications have very high purity requirements in general, the use of substitutes does not always guarantee the same performance. Hence, the potential supply risk of advanced materials is even higher compared to that of the constituent raw materials (e.g. minerals and metals). Due to stringent requirements, the uptake of secondary materials is also often challenging.

Steel, copper, aluminium, titanium, composites, and ceramics make up the primary categories of materials utilised in aerospace and defence production. They are essential structural materials used to manufacture the core platforms and structural elements of aircrafts and defence equipment, particularly armaments and the exterior bodies of tanks, land ships and armoured vehicles (KPMG, 2020). These materials are used in combination with nickel, vanadium, zinc, cobalt, antimony, molybdenum, boron, chromium, germanium, niobium, Tungsten, beryllium and lithium to form specialised alloys.

High-performance alloys that are used, for instance, in fuselages of combat aircraft, require niobium, vanadium, or molybdenum. Beryllium is used as a lightweight alloy in jet fighters, helicopters, and satellites as it is six times lighter and stronger than steel, and thus enables weight reduction and improved speed and manoeuvrability. Beryllium finds applications also in missile gyroscopes, gimbals and for inner stage joining of elements in missile systems. Tungsten is required to produce armour-piercing ammunition while tantalum and tantalum-Tungsten alloys are used for ballistic and other military applications also under powders for additive manufacturing and coatings. Cobalt super alloys are used in safety-critical parts. Copper-titanium alloys are used for non-sparking tools, and high-nitrogen steel is highly relevant for armour applications. Future aircraft alloys include aluminium-lithium (Al-Li), aluminium-scandium (Al-Sc) and aluminium-magnesium-lithium (Al-Mg-Li)[73].

Table 11. Strategic, critical, and non-critical raw materials used in the aerospace and defence sector, and their applications

Supply Risk	Raw material	Technologies				Defence applications								
4.8	Gallium		•	•	•	•	•							
4.1	Magnesium	•	•	•	•									
4.0	REE (magnets)		•	•	•	•	•	•	•	•	•	•		
3.8	Boron		•	•	•									
2.7	PGM		•	•	•	•	•		•					
1.9	Lithium		•	•	•	•		•	•	•			•	
1.9	Bismuth				•									
1.8	Germanium				•	•	•				•	•		
1.8	Natural graphite		•	•		•	•		•	•	•	•		
1.7	Cobalt	•	•	•	•	•		•	•	•				
1.6	Titanium metal	•	•	•	•	•	•	•	•	•		•		
1.4	Silicon metal	•	•	•	•	•		•						
1.2	Manganese	•	•	•	•	•	•		•	•	•		•	
1.2	Tungsten	•		•	•	•	•	•	•	•				
0.5	Nickel	•	•	•	•	•	•	•		•	•			
0.1	Copper	•	•	•	•	•	•	•		•	•	•		
5.3	HREE (rest)	•	•	•	•	•	•				•	•		
4.4	Niobium	•		•	•	•		•	•					
3.5	LREE (rest)		•	•	•									
3.3	Phosphorus				•									
2.4	Scandium	•			•									
2.3	Vanadium	•	•	•	•	•	•		•		•			•
1.8	Antimony		•	•	•									
1.8	Beryllium				•	•	•				•	•		
1.6	Arsenic				•									
1.5	Feldspar			•										
1.5	Hafnium	•		•	•	•	•		•					
1.3	Baryte				•	•			•	•				

[73] Detailed information concerning the most relevant alloys deployed in defence applications can be found in Pavel and Tzimas (2016).

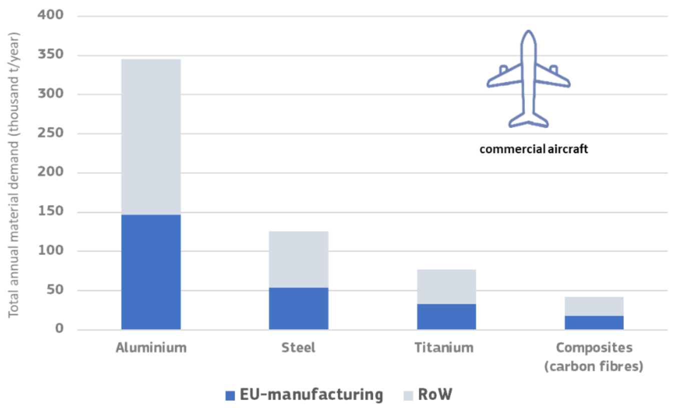
1.3	Tantalum			●	●	●	●	●			●	●		
1.2	Aluminium	●	●	●	●	●	●	●	●	●	●	●	●	
1.1	Fluorspar		●	●	●									
0.9	Tin		●	●		●								
0.8	Molybdenum	●	●	●	●	●	●	●		●	●			
0.8	Silver		●	●	●	●			●				●	
0.8	Zirconium	●			●	●		●					●	
0.7	Chromium	●	●	●	●	●	●	●	●	●	●		●	
0.4	Gold		●	●	●	●				●				
0.6	Indium		●	●	●	●	●				●	●		
0.5	Iron ore	●	●	●	●	●	●	●	●	●	●			●
0.3	Tellurium		●	●		●	●				●	●		
0.3	Selenium				●	●	●							
0.2	Cadmium					●	●				●	●		
0.2	Zinc		●	●	●	●	●							
0.1	Lead		●	●	●	●		●	●	●			●	

Source: JRC analysis for the dual-use technologies and based on Girardi et al. 2023 and Pavel and Tzimas (2016) for military equipment.

Drawing on innovations introduced over time in the aerospace and defence manufacturing sector, carbon fibres and aircraft-grade composites have become increasingly prominent. These represent a key constitutent of civil and military aircrafts as well as strategic rockets and satellites. For example, the Airbus A350 contains over 250 kg of CFRP (carbon-fiber-reinforced polymers) per passenger (Lefeuvre et al. 2017), and in new generations of light combat aircrafts and helicopters, carbon composite airframes (AMCA) account for 45% of the airframe weight (KPMG, 2020).

Commercial aircrafts, such as the Airbus A320's, are equipped with an airframe composed mainly of aluminium and Al-Li alloys (72%), steel (9%) and titanium (6%). The A350 is composed of 7% of steel by mass, titanium (14%), aluminium alloys (20%) and principally, CFPR (52%). On average, it is estimated that each one of the 2 213 commercial aircraft delivered in 2018 is composed of 53% aluminium, 10% steel, 8% titanium and 28% composites (Pierrat et al., 2021) (Figure 106).

Figure 106. Total annual materials demand in 2018 for commercial aircraft manufacturing (expressed in ktonnes per year). The figures includes manufacturing production losses.



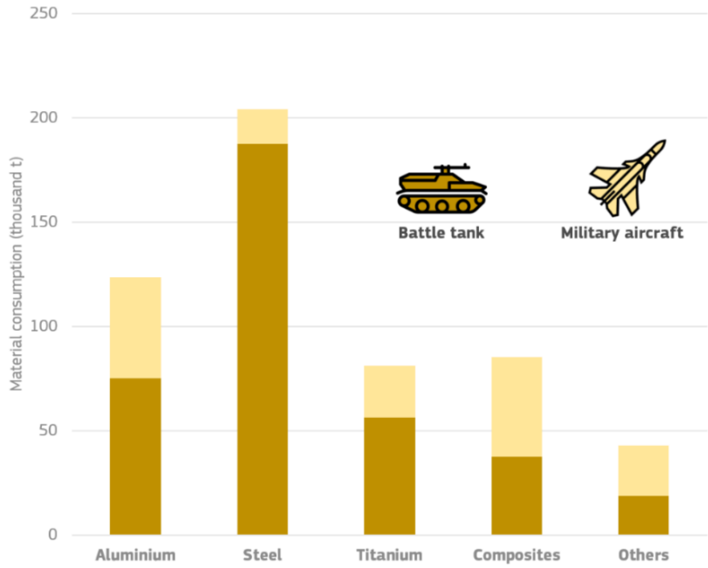
Source: datasets retrieved from Pierrat (2021) et al., for estimated low demand scenario. The EU share of the global demand is evaluated at 43%.

In the military sphere, given the size of common naval platforms (e.g. frigate/destroyer/corvettes) and the number of vehicles deployed, the naval and land military segments have the highest demand for steel, aluminium and titanium (Figure 107). Main battle tanks deployed in NATO fleets as of 2020 are estimated to contain 20% aluminium, 50% steel and 15% titanium. Composites, on the other hand, are comparatively more important in military aeronautics, including aircraft, helicopters, UAVs and missiles. On average, NATO aircraft fleets are made up of 30% aluminium, 10% steel, 15% titanium and 29% composites.

In the aerospace and defence sector as a whole, the ongoing demand for titanium metal is substantial. For example, about 81 000 tonnes of titanium is currently embedded in NATO fleets of aircraft and battle tanks as of 2022. In 2019, aerospace applications, in particular aircraft manufacturing, used about two thirds of the available titanium metal supplies in the EU.

Like space, the defence industry has a strong and ongoing need for rare earths. Lanthanum is, for example, used in night vision goggles and ammunition. Neodymium finds applications in targeting lasers, guidance systems (incl. precision guide munitions) and remotely piloted aircraft systems and communications (Figure 108). It was estimated by US governmental services in 2013 that each F-35 jet has embedded in it around 415 kg of yttrium, terbium and other rare-earth elements, mainly for advanced targeting systems, microwave emitters, lens coatings and other optical devices (Kenlan, 2020).

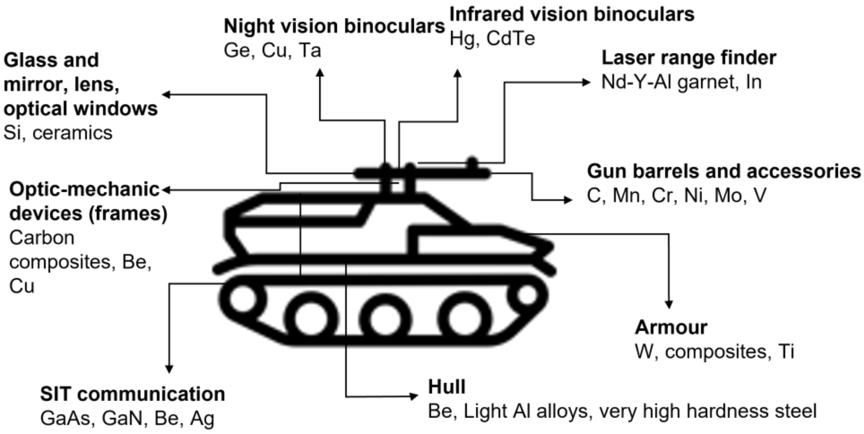
Figure 107. Demand for structural materials in NATO fleets of aircrafts and battle tanks as of 2022[74].



Source: JRC analysis (developed using data from Statista (2022b), Statista (2022c) and KPMG (2020).

[74] The fleets are composed of around 20 700 active combat aircraft and 15 000 battle tanks belonging to NATO countries, listed in military inventories worldwide.

Figure 108. Components and raw materials used in a main battle tank (e.g. Leclerc), but also representative of infantry-fighting and armoured fighting vehicles



Source: JRC adapted from Pavel and Tzimas, 2016

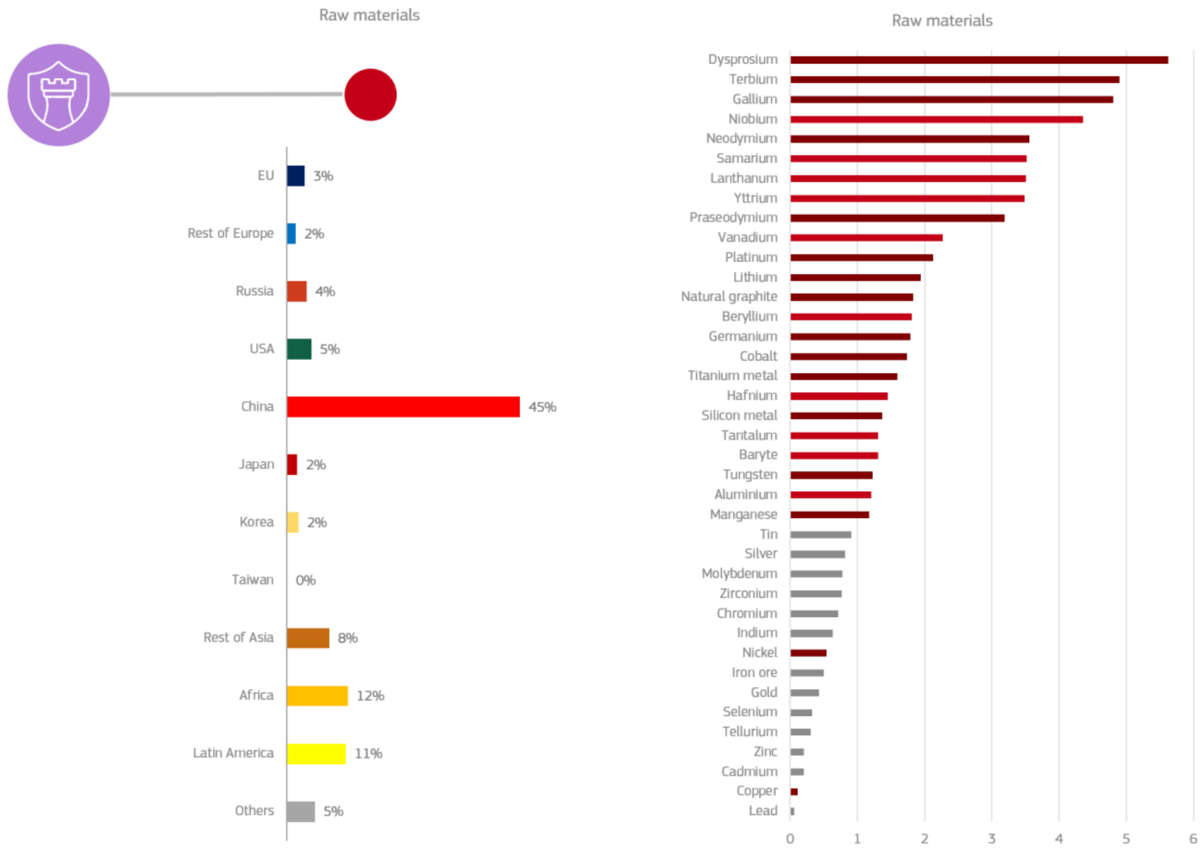
Potential supply bottlenecks

Europe's alloy industry is competitive, represented by companies engaged in the production, processing and supply of specialised high-performance alloys covering multiple end-uses, including defence and aerosopace. While manufacturing facilities for some of the key grades of materials are available in the EU, the region could be better positioned regarding advanced composites and ceramics (e.g. aerospace-grade silicon carbide), dominated by Japanese, and to a lesser extent, US suppliers.

In addition, titanium metal is identified as one of the main critical elements for the aerospace and defence ecosystem. Russia's invasion of Ukraine reveals important dependencies regarding titanium sponge and semi-finished titanium products. Indeed, Russian company VSMPO-Avisma used to supply about one third of the titanium used by the aviation sector globally and more than 45% of the world's aerospace titanium parts. Before the COVID-19 pandemic, Airbus (for airframes and space components) and Safran (for aircraft engines) both procured half of their titanium demand from this company, while Boeing estimated that one third of its demand originated from Russia before the war (JRC, 2022). The EU situation regarding titanium supply is now improving, with lower reliance on Russian products, particularly for defence applications (Barnier, 2022). However, stockpiling capabilities still need to be strengthened to avoid supply disruption at mid-term. Regarding aerospace-space grade titanium, the supply is shifting from Russia to Kazakhstan and Japan for titanium sponge (in the future Saudi Arabia might represent an alternative), and to the US and the UK for wrought titanium products.

In addition to titanium, the EU is also fully dependent on imports of tantalum, boron (as borates), REEs, magnesium, molybdenum and niobium. Overall, China accounts for a large majority of the production of the raw materials used in the construction of military equipment (Figure 109). Tungsten is also a source of concern since a substantial proportion of EU demand is covered by Chinese imports which use trade corridors and railways across Russian territory (Tirone and Nardelli, 2023). As in other sectors, aerospace and defence has suffered recently from increased aluminium and steel prices following the COVID-19 disruption and Russia's war in Ukraine.

Figure 109. An overview of bottlenecks, key producers, and Supply Risks for selected raw materials used in the defence sector supply chain

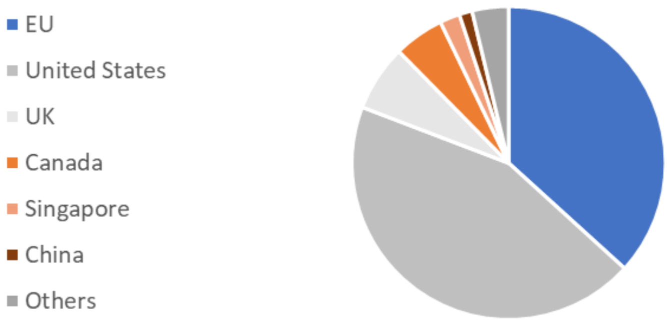


Source: JRC analysis.

Electrical, Electronic and Electro-mechanical (EEE) components containing silicon or gallium-based semiconductors are fundamental building blocks of any aerospace and defence system. The post-pandemic global shortage of such devices tightened the supply chains of the sector despite a higher willingness to pay premiums compared to the ICT or automotive sectors. According to ASD (2022b), applications for defence and aerospace differ from broader commercial chip production (which focuses on cost-efficiency at large volumes of demand) by requiring durability, reliable high performance under very demanding conditions, long-life supply, and security of information. Security is often considered more important than the use of next generation components, even if leading-edge technologies might increasingly be required for new defence and space programmes, e.g. satellite quantum communications. The sector is an important end-market for microcontrollers, programmable chips and signal processors. Guided rockets and missiles are particularly reliant on a large amount of chips and microprocessors. For instance, around 250 chips are embedded in a US-manufactured Javelin anti-tank missile (Vincent and Pietralunga, 2022). The US, via companies like Texas Instrument, Intel Corp, AMD and Analog devices inc., has a quasi-monopoly in the field, causing a high import reliance for all countries including Russia. However, the latter still succeeds, at least partly, in supplying such devices in spite of the sanctions (Gauthier-Villars et al. 2022). In Europe, STMicroelectronics and Infineon technologies are important players in specialised market segments with specific applications in defence and space, while the European Chips Act (EC, 2022b) recognises the importance of identifying critical sectors such as space and defence to prioritise orders in case of supply disruptions and to ensure better access to testing facilities.

Despite external vulnerabilities, EU companies contribute the most to aerospace exports markets (37%), just behind the US (44%) and followed by the UK and Canada (Figure 110). In 2021, European military exports totalled EUR 38 billion (own estimation excluding UK; derived from ASD statistics). Due to the relatively small size of EU home markets, these exports are said to be crucial for the industry to reach the production volumes necessary to maintain a competitive economic performance (ASD, 2022a).

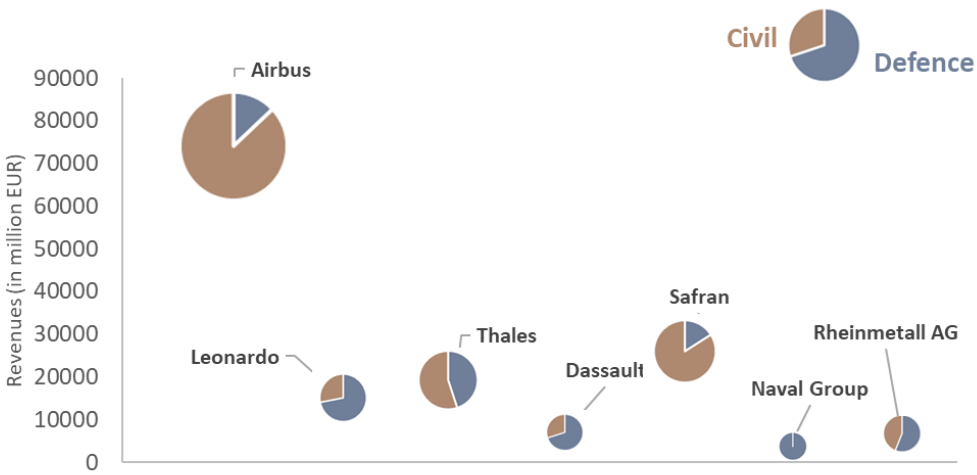
Figure 110. Leading countries with the highest aerospace exports in 2021[75]



Source: JRC analysis based on data from Statista (2023b).

Both aerospace and defence supply chains are organised around prime contractors (often called OEMs) which have the full responsibility to design, integrate and build civil or military platforms. These companies and their competitors normally supply both the defence and civilian markets, with the share of revenues generated from military and civilian supplies varying significantly between companies (Figure 111). The largest European prime contractors are located in France, Germany and Italy (ASD, 2022a) which together with the US, are ranked among the most important for aerospace products (Statista, 2023b). The US-based companies, Lockheed Martin and Boeing, are the largest prime contractors and military equipment producers in the world. In the EU, Airbus is the leading manufacturer, supplying the majority of domestic and international demand for aerospace platforms. The defence revenues of Leonardo and Airbus make them the leading manufacturers in Europe of military technology for air, land and sea defence. The four main civil and military aircraft engine manufacturers are the French Safran Aircraft Engines, the US-based GE Aviation (with production facilities in Europe such as Avio Aero), the UK-based Rolls Royce and the US Pratt & Whitney (subsidiary of Raytheon Technologies). A 50:50 joint venture between Safran and GE called CFM International, founded in 1974, is the largest commercial engine manufacturer with its LEAP series, representing around 40% of the global market in 2022.

Figure 111. EU's top aerospace and defence companies in 2019: total revenues from military and civilian supplies and corresponding market share.



Source: JRC with data from ASD (2022a).

Most of the prime contractors rely on tier-1 suppliers for the development and manufacturing of the systems and subsystems such as engines, electronics and avionics that are fitted into core defence platforms and general military equipment. The lower tiers of suppliers consist of a broad range of companies of different sizes and activities, but many of them generate only a small proportion of their revenues from the defence market

[75] Note: Others include China, Brazil, Israel, the Netherlands, Switzerland and Japan.

(ASD, 2022a). Given the need for certification and traceability, most OEMs have a list of approved direct suppliers with a robust quality management system (QMS) in conformity with the stringent requirements of the sector (KPMG, 2020). The specification, composition, and method of production, as well as the physical and chemical properties of any raw material used in any equipment, are pre-defined. This also means that not all finished and semi-finished materials from any supplier can be used interchangeably to produce a relevant military component, assembly, or system. Moreover, not all suppliers are able to provide the right purity required for a certain critical application. The market thus tends to concentrate around only a few large producers, increasing the vulnerability of the sector and associated obsolescence risks[76]. Continuous due diligence and implementation of monitoring system targeting the supply chains might prevent from severe supply disruptions. However, such instruments should particularly focus on the value chain's upstream suppliers (tiers of rank 3 or 4) which are probably the most at stake, and more particularly in the case of sudden production rates' increase (Davesne, 2023).

For military applications, companies and public authorities are also bound by commonly accepted standards that support and promote the greater interoperability of defence equipment. In the EU, the European Defence Standards Reference System (EDA, 2022a) is used by governmental organisations and the defence industry for the development, production and procurement of defence materials and equipment.

Due to the strategic nature of the sector, companies in space and defence normally operate in close collaboration with government agencies and the export, transit, brokering and technical assistance of dual-use products is regulated (EC, 2023a). In the coming decade, it is estimated that 75% of the value of satellite manucturing and launch markets will come from institutional and government funding (Euroconsult, 2021). The importance of public-sector procurement and research programme funding (from governement, institutions and agencies) leads to the establishment of captive/restricted markets that may limit the diversity of the supply and substitution potentials.

Recycling opportunities and associated end-of-life management

Development of systematic large-scale recycling practices in the sector remains challenging. To meet the performance requirements of aerospace alloys and product specifications (which include, for example, strict controls on impurities), the use of secondary material is currently disregarded for the huge majority of applications (Das & Koffman, 2007).

The sector is facing rather limited resource efficiency in manufacturing processes. The "Buy-to-fly" (BTF) ratio[77] is often low. For instance, more than 90% of the titanium alloys used for the cryogenic tank in space systems is scrapped during the manufacturing step. Pierrat et al. (2021) estimate a ratio of 16:1 for steel, 10:1 for titanium and 5:1 for aluminium alloys in conventional aerospace processes (except parts obtained via additive layer manufacturing). For CFRP, Lefeuvre et al. (2017) detail that 30% of the total mass is lost in production waste. These figures confirm the significant quantity of post-industrial scrap generated by the sector to reach the appropriate technical and safety requirements in the domain (the airworthiness qualification procedure). Metal and composite material scrap represent an important material share to be valorised. Recycling processes for CFRP still need to gain maturity, the current pilot-scale processes resulting in important downcycling of the fibres for both old and new scrap. Regarding titanium alloy scrap recycling, a first industrial-scale demonstrator is operating in France[78], producing aerospace-grade titanium ingots from reprocessed, post-industrial scrap. For non-aerospace applications, it is estimated in the literature that the demand for scrap represents 15% of the global production of titanium (JRC, 2022). Even if the recycling of future aircraft alloys such as aluminium-lithium (Al-Li), aluminium-scandium (Al-Sc) and aluminium-magnesium-lithium (Al-Mg-Li) remains challenging at the moment (Suomalainen et al. 2014), a systematic collection scheme in Europe, avoiding the export of scrap to third countries, would ensure sufficient availability of materials to secure the deployment of aeronautic-grade recycling processes.

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[76] Obsolescence risk in the sector can be defined as any possibility of impairment of quality and reliability or even loss of critical technologies for qualified materials and processes, which is induced by a chemical, material or component's unavailability or substitution threat.

[77] The BTF ratio is the weight ratio between the raw material used for a component and the weight of the component itself. The aeronautics industry often relies on production processes facing a low buy-to-fly ratio.

[78] *EcoTitanium*, a joint venture by Aubert&Duval and UKAD supported by the French State (ADEME) and Crédit Agricole, has operated in France since September 2017. The company produces ingots of titanium alloys (e.g. TA6V) by recycling new scrap from aircraft makers and subcontractors, most of which was previously *exported* to the US. According to the French professional association GIFAS, this secondary production of Titanium with forecast production capacity of 4 kt could ultimately cover 15-20% of EU aerospace and defence demand.

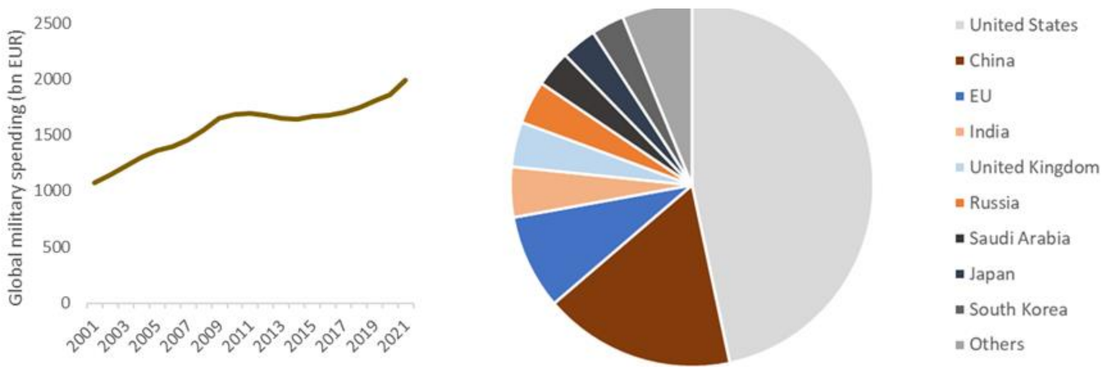
In terms of end-of-life management, the main waste stream is certainly end-of-life aircraft and to a lesser extent military naval ships and tanks. In civil aeronautics, unlike vehicles or white electronic goods, there is currently no legislation to compel aircraft owners or manufacturers to manage and recycle their aircraft fleet at end of life. For most commercial aircraft today, it is estimated that 80-85% can be recycled, depending on type. Airbus states that 92% of an aircraft's total weight and more than 99% of its engine parts can be recycled by the French company Tarmac Aerosave (Airbus, 2022), a specialised joint-venture company equally distributed between Airbus, Safran and Suez SA. However, in practice, the recovered metals are often downcycled, mainly to be used in ferroalloys or as an oxidant in electric steelmaking (Suomalainen et al. 2014).

3.5.4. Geopolitical dimension

The global political situation brings an entirely new dimension to the assessment of geopolitical and security risks in various sectors of the economy. Defence has gained greater prominence in European strategic thinking, with the protection of the external borders of the EU becoming a priority. In the EU, defence spending broke the EUR 200 billion threshold for the first time in 2021, just before Russia's invasion of Ukraine. Since then, Germany has announced additional expenditure of EUR 100 billion (EDA, 2022b). Worldwide, military spending amounted to EUR 1.97 trillion in 2021[79]. The United States accounted for 38% of the total spending (Figure 112). However, when compared to GDP, countries like Saudi Arabia, Israel, and Russia, take on greater prominence.

In the context of increased military budgets and associated defence spending across the globe, competition between countries and sectors is now more important than ever. As a result, disruptions in supply chains are likely to occur, whether fuelled by increases in the price of materials and parts, or by longer lead times (typically two to three times what they were pre-pandemic for microelectronics). Titanium, steel, electronic components and rocket engines for missiles seem to be facing more critical market conditions (Chávez et al. 2023). Overcoming difficulties has meant looking for new sources of materials and even redesigning electronic components as in the case of Stringer missiles (Chávez, S., 2022). However, competition between the US and Europe to supply critical materials and components might occur because of the necessity of replenishing ammunition stocks, but also partly reinforced by new orders from EU countries focusing on US defence material purchases such as F-35 aircraft, M1 tanks, AIM 9X Block II tactical missiles and multiple launch rocket systems (Coste, 2023; Bezat et al. 2022). Ultimately, long-lasting increased demand levels for defence applications will be detrimental to the commercial civil sector, especially aeronautics and space, which all compete for the same supplies.

Figure 112. Global distribution of military spending in 2020.



Source: JRC elaboration with data from Statista (2022a).

Defence space programmes are larger in the US, Russia and China. The increased capacity of these countries is evidenced by the multiple satellite launches in 2022, for space surveillance, optical imaging, radar imaging and signals intelligence (McDowell, 2023). Iran, Singapore and Israel are also active in the deployment of military space activities. The EU has several space projects for the purpose of increasing its security. In 2022, Germany

[79] Converted from USD dollars based on the exchange rate in effect as of 15/02/2023.

and Italy launched radar satellites for surveillance services, while IRIS², the new EU secure satellite constellation, was announced in late 2022, with an expected initial deployment in 2024 (reaching full capability in 2027).

Concerns about the militarisation of space are not new. Much of the growth in this area is led by China and the US, with 900 tonnes of military-oriented payloads launched over the last decade (2012-2021), up from 600 tonnes in 2002-2011 (ASD, 2022c). In recent years, countries such as Russia and China have developed counter-space technologies. India (in March 2019) and Russia (in Nov. 2021) have conducted several anti-satellite tests (ASAT), generating large clouds of debris. In December 2022, the UN General Assembly adopted a non-binding resolution to ban such tests, aiming to mitigate damage to the outer space environment and prevent an arms race in outer space. More regions and countries are building space-tracking abilities, including, for instance, the European Space Surveillance and Tracking network (EUSST). An EU strategy on Space traffic management was issued in February 2022 with the purpose of developing concrete initiatives (including operations and legislation) to ensure a safe and sustainable use of space. Reinforcement of space capabilities has been illustrated by the creation of a new national spaceforce or command by the US, France and the UK, while in 2019, NATO recognised outer space as a new operational domain alongside air, land, maritime and cyberspace.

However, the first threat concerning space remains cyberattacks or electronic jamming targeting space services, as was the case during the first weeks of Russia's invasion of Ukraine (OECD, 2022). This war, the first with "two-sided" space capabilities, has underlined the key role played by space infrastructures during modern conflicts and crisis. The novelty lies in the wide deployment and use of commercial space services to support the Ukrainian civil population and military troops (Beale, 2022). The availability of a tremendous amount of commercial imagery, e.g. from US-based Maxar and Planet labs companies, helps with the monitoring of material damages and casualties, surveillance of civilian and military troop movements and identification of ammunition dumps, thanks to synthetic aperture radar (SAR) satellite systems. Position navigation and timing (PNT) satellite systems, providing global navigation space services, are used, among others, to guide cruise missiles or umanned aerial vehicles. For the first time, communication satellites, more particularly the Starlink commercial service, provide constant and reliable off-grid, high-bandwidth internet access in conflict areas, maintaining communications and acting as a game-changer in the conflict (The Economist, 2023). Commercial companies can now provide more services to less wealthy nations than conventional spacefaring powers, leading *de facto* to a democratisation of space-based applications. In such a context, the roles of nations and corporations are likely to blur, as commercial space companies manage increasingly capable systems and directly influence national actors (Cheng, D. 2023). The success of Starlink's service deployment in Ukraine and its use by Iranian protesters to circumvent censorship, bring a new geopolitical dimension regarding the use of such technologies, for instance in the case of Taiwan's sovereignty.

Across the globe, policy-level initiatives by government entities and stakeholders are under way to build resilience and ensure sufficient capacity to respond to urgent and immediate needs. Many countries are focusing on tackling security risks related to the procurement of materials by military equipment and platform manufacturers, considered an important asset to maintain a certain autonomous capacity in this field. For example, the Indian Defence Procurement Procedure in 2020 points to the development of domestic military material sources as the most effective and strategically important action to achieve resilience. Phased material development by platform manufacturers and R&D organisations, using their resources or those of Indian industry, is therefore encouraged in exchange for Indian industry offsets. The DPP also specifies a procedure and incentives for platform manufacturers to use indigenously created materials in procurement. It proposes the creation of a national advanced manufacturing strategy focused on opportunities in advanced manufacturing and the adoption of Technology Development Fund (TDF) programmes for material development. Finally, it recognises the need to implement in India a unified standardisation procedure similar to the EDSIS (European Defence Standards Information System).

In terms of aerospace and defence technologies trade, specific EU export control rules apply for dual-use items, military equipment and weapons. The EU legislative framework reflects commitments agreed upon in key multilateral export control regimes. The export of dual-use items is governed by regulation EU 2021/821, amended in January 2023 (EU, 2023) to update the control list of items, while EU arms exports are regulated by the Common Position 2008/944/CFSP, amended in 2019 by the Council of the EU (EUCO, 2019) to enhance transparency and information exchange among Member States. In the US, the International Traffic in Arms regulations (ITAR) restrict and control the export of dual-use and military related technologies. The presence of components targeted by the ITAR regulation in EU-manufactured aerospace and defence equipment could therefore hamper the EU's strategic autonomy. In a changing international context, ensuring that the EU is not dependent on ITAR components would improve the aerospace industry's supply chain resilience and its position on export markets. Hence, the development of "ITAR-free" equipment is an emerging trend in Europe (Meddah,

H. 2023). For instance, the company MBDA embarked upon the redesign of an air-air missile in 2018 in order to exclude ITAR-controlled components, while the joint European defence programmes take this constraint into account in the development of the Future Combat Air System (FCAS), Eurodrone and Main Ground Combat System (MGCS), to improve EU strategic autonomy in the field.

Finally, the new geopolitical situation is leading to a global race in which the mastery of dual-use technologies is central, focusing on computing power, quantum technologies, advanced manufacturing, energy carriers (e.g. hydrogen and batteries) and space capabilities. In this power struggle, the control of the development and transfer of emerging and cutting-edge technologies is key. In the EU, ensuring open strategic autonomy and technological sovereignty through secure and sustainable supply chains is a political priority (EC, 2022c, 2023b). Economic intelligence mechanisms are today used extensively by the US, based on strict export controls and the extraterritoriality of its law and regulations. The central role of dollars and data management through digital platforms located in the US and ruled by the US Cloud Act drives this trend (Guiliani, 2023). Until recently, the digital transition increased the EU Member States' dependence on US commercial big tech companies (Alphabet, Amazon, Apple, Meta, Microsoft and to a lesser extent Space X), and their associated platforms (Pannier, 2023). This appears even more critical for the defence sector as flagged by the EU's new Cybersecurity Strategy (EU, 2020) and for which one of the responses could take the form of common European cloud projects. Beyond digital, financial flows with foreign direct investments (FDI) also need to be monitored to prevent increasing industrial dependence and the associated loss of sovereignty. Regulation (EU) 2019/452, establishing a framework for the screening of foreign direct investments into the Union, created a cooperation mechanism for Member States and the Commission. This legislation identifies cutting-edge technologies, dual-use items and raw materials as key critical elements. FDI has been identified as a powerful tool to support the voluntary and involuntary transfer of technologies (Nowens and Legarda, 2018). To counter unauthorised transfer of dual-use technologies, the US widely applies export restrictions (including embargoes and sanctions) and filters outbound investment in sensitive areas. In October 2022, just before 20th Congress of the Chinese Communist Party, the US announced new export controls on semiconductors that could severely hamper efforts by Chinese companies to develop advanced dual-use technologies. In early 2023, Japan and the Netherlands also agreed with the US to restrict exports of chip manufacturing tools to China (Fabry, E., 2022; Sugiura, E., 2023). The US *Entity List,* a trade restriction list published by the US Department of Commerce's Bureau of Industry and Security (BIS), has recently been enlarged to include six additional companies supporting Chinese aerospace programs, including airships, balloons and related materials (BIS, 2023). China's response is a set of export control measures and the publication of a similar list of *unreliable entities*, banning them from import and export activities related to China, which includes US defence companies Lockheed Martin and Raytheon technologies(Munroe and Chen, 2023).

3.5.5. Key observations and recommendations

In view of the strategic importance of the aerospace and defence sector for Europe's security and competitiveness, it is imperative that the related manufacturing industries operate under uninterrupted conditions. The European aerospace and defence industry needs to secure the supply of a number of raw materials from international sources, maintain its global leadership in the manufacture of high-performance alloys and special steels, and further develop capabilities to produce speciality composite materials.

Despite the overall competitiveness of the sector, difficulties and gaps exist.

Enhancing European strategic autonomy means to retain in Europe the industrial and technological base that underpins key strategic military capabilities. Decreasing European dependencies and securing global supply chains requires mainly a four-fold approach: increasing stockpiling capacities in the short term, diversifying supply (especially from complete dependency on sources of supply in politically unstable countries), increasing domestic supply (achieve indigenisation/self-reliance on some critical defence parts and especially raw materials; increasing mining capacity in Europe is part of a long-term solution to reduce foreign dependence) and further developing resource efficient and circular practices which enable the recycling and re-use of raw materials and components.

The following strategic objectives could be advocated for the European aerospace and defence sector:

- **Boost raw material stockpiling strategies and replenishment of military equipment stocks**. Stockpiling could be one of the options to mitigate short- to medium-term supply disruptions in the event of a crisis. For instance, titanium stockpiles, built during the pandemic, eased the management of supply disruption for titanium products during the first months of Russia's invasion of Ukraine. Going further, some European companies operating in the defence domain have already prepared themselves to protect their business from skyrocketing prices and potential shortages, through the purchase of large material stocks (e.g aluminium and important plastics) (Zachová, 2022). Beyond commercial companies, governments and public bodies might play a major role by strengthening the industry's stockpiling capabilities. In Japan, state bodies ensured a 48-day stockpile stock for certain materials and strategic electronic components on top of mandatory stocks to be established by industry; in the US, stocks are managed by the Defence logistics agency which oversees the setting up of strategic stocks of antimony, lithium, tungsten and REEs, mainly for defence sector (Davesne, S., 2023). In Europe, such an approach was suggested in the Versaille declaration in March 2022 (EUCO, 2022) and could be included in the EU framework for defence joint procurement adopted in 2022 (EC, 2022d**).**

The legislative framework, the European Defence Industry Reinforcement through common Procurement Act (EDIRPA) for 2022-2024, is associated with a EUR 500 million instrument released by the Commission (EC, 2022d). Boosting joint procurement practices should foster the replenishment of weapons stocks by avoiding fragmentation of the market and competition between Member States in the context of ongoing arms deliveries to Ukraine. The objective is also to speed up the adaptation of the aerospace and defence industry to structural changes, including the ramping up of its manufacturing capacities.

- **Diversification of the supply**. The diversification of supply is one of the main mitigation measures contributing to de-risking aerospace and defence value chains. A global reorganisation of the sector's supply chains is ongoing, considering the current shortage of components and material, including items potentially targeted by export controls and sanctions. This reorganisation is triggering lead-time increases and paradoxically may lengthen the chains (Fabry, E. 2023). Diversifying suppliers and sourcing critical raw materials can be achieved with a "dual sourcing"[82] strategy (also enabling maintenan EU manufacturers presence in some export-restricted markets), bearing in mind that the stringent certification and qualification processes of the sector could be a major obstacle. For some commodities where countries have a quasi-monopoly (e.g., refined REEs and specific space-grade electronic components), this diversification including potential redundancy of suppliers will be more complex in the short-term. The establishment of a *friendshoring* strategy in this critical sector might allow the EU to secure strategic supplies. This is mainly the case for raw materials for which the EC has proposed the creation of a critical raw materials club to work with like-minded partners (from the US to Ukraine) to collectively strengthen supply chains (EC, 2023b). The substitution of materials remains challenging for aerospace and defence applications as the very high level of performance and special properties of the materials cannot be matched by readily available substitutes.

- **Support to the EU space and defence industrial base**. As specific material grades and qualified components for aerospace and defence have restricted purchase quantities, supply bottlenecks could be mitigated by targeted public investment to ensure an adequate production capacity and to respond to sudden spikes in demand. Often, the orders are typically below a firm's lucrative minimum order quantity, and manufacturers refrain from investing in dedicated facilities or in extra capacity to produce certain special alloys. Demand incentives such as assurance of long-term orders under agreements concluded with relevant government agencies, and minimum order guarantees, could unlock investment and sustain the development of indigenous capabilities and materials (Linganna, 2022). Supporting fragile suppliers in the lower tier of the industrial base could also help mitigate single points of failure, e.g. with the financing of industrial machinery and infrastructure (KPMG, 2021). In the case of a sudden surge in demand, production in civilian aerospace companies (more particularly in the case of dual-use components and systems) could be redirected to meet defence and security purposes (Bezat et al. 2022). Such an approach is already implemented in the US through the *Defense Priorities and Allocations System Program* (DPAS).

  Improving synergies between the civil, defence and space industries is also crucial, as highlighted by the Action Plan released by the EC in 2021 (EC 2021). The action plan initiates three flagship projects targeting dual-use items: drone technologies, space-based secure connectivity and a space traffic management framework. Investing in defence and space technologies brings economic and technological dividends for European citizens. There are also numerous applications of defence components and sub-systems for civilian and commercial purposes and the larger market size will attract domestic manufacturers. The smaller defence market benefits from the larger civil market in terms of innovation (i.e. *spin-ins)* and cost for the development of current breakthrough technologies, such as Artificial Intelligence, 5G and cyber. Significant opportunities are expected to open up for material manufacturers (e.g., increased order numbers and associated economies of scale where specific material grades have dual-use potential).

- **Promoting investment in R&D programmes and joint development programmes**. The EU should build on industrial successes and know-how in the field, such as the consolidation of the European aerospace industry through Airbus commercial success or the deployment of emblematic space programmes including Ariane 5, Galileo and Copernicus. For defence, the joint development of the Eurofighter typhoon can be mentioned. The Permanent Structured Cooperation (PESCO), first initiated in 2017 (EU, 2017), offers a legal framework to jointly plan, develop and invest in shared capability projects (e.g. Eurodrones, Eurocopter Tiger, and European Secure Software-defined Radio). The new IRIS^2 European space programme will also enhance Europe capabilities for secure connectivity, offering both civil and military applications. Maintaining know-how and domestic industrial capabilities, while addressing emerging security challenges, will require strong investment in R&D. The European Defence Fund (EDF), complementing and amplifying Member States' efforts, supports competitive and collaborative projects throughout the entire cycle of research and development, having an impact on the European defence capability and industrial landscape. In Europe, the bulk of the defence industry is concentrated in a few Member States which invest most in defence. However, innovative, and competitive SMEs and mid-caps exist throughout the European Union (ASD, 2022a). The EDF should help to open the defence supply chains, linking the large system integrators with the entire defence SMEs ecosystem, which is key to foster competitive supply chains.
- **Further developing resource-efficient technologies and the recycling of advanced materials**. Innovative technologies such as additive manufacturing, advanced welding process and surface treatment could greatly increase the resource efficiency of the production process and associated buy-to-fly ratio while avoiding the sourcing of primary material from third countries. Lightweighting is a long-standing trend in the sector which results in the wide adoption of advanced composite materials for structural parts. This uptake goes together with a greater use of titanium alloys due to the excellent compatibility between composite and titanium alloys. Consequently, increased demand is expected for both materials in the future. The recycling of carbon fibres still needs to gain maturity before being deployed at industrial scale, while substantial efforts are still required to enhance the collection and reprocessing of metal (post-industrial and post consumption) scrap to reach aerospace-grade qualification. For example, in the case of titanium, discussions are under way in France to develop a recycling industry targeting aerospace and defence application (Bezat et al., 2022). Avoiding exports of metal scrap to third countries would boost domestic capabilities and generate economies of scale in the development of recycling processes.
- **Improving the knowledge base and providing early warning**. Monitoring and information systems focusing on critical production of the materials, components and assemblies used is crucial to ensure the resilience of aerospace and defence supply chains. This can be done, for example, by promoting information-sharing between all relevant stakeholders (despite the sensitivity and confidential nature of such activities), enhancing the ability to analyse, assess and monitor vulnerabilities in the industrial base, and reducing information asymmetry in the available market capabilities. Several Member States have already developed and implemented monitoring systems, for example for titanium, steel, rare metals and certain electronic components. In parallel, in 2021, the European Commission launched the Observatory of critical technologies in the context of the Action Plan on synergies between civil, defence and space industries (EC, 2021c). The objective is to provide regular monitoring and analysis of critical technologies, their potential applications, value chains, the needed research and testing infrastructure, the desired level of EU control, and existing gaps and dependencies.

4. Conclusions and recommendations

The European Union needs undisrupted access to critical raw materials and to many products which contain them to achieve its ambitious targets on the twin digital and green transition, its industrial strategy and its security agenda. This challenge is set against a changing geopolitical context, marked by supply shortages during and following the COVID-19 pandemic, the supply chain repercussions of the Russian invasion of Ukraine, and competition between many sectors and countries for the same raw and processed materials. As countries all over the world move towards decarbonisation and the digitalisation of their economies, demand for these materials is expected to increase rapidly in the future. Green transition technologies make much more intensive use of materials and metals than their fossil-fuelled counterparts. In the long term, these materials have the advantage of not being consumed upon use and therefore remaining available for recycling. In the short term, the European Union must find a way to secure access to the materials needed for the massive deployment of key technologies such as wind turbines, solar PV panels, batteries and electrolysers.

This foresight study has presented a systematic and detailed analysis of the complete values chains for 15 key technologies across the five strategic sectors (renewables; electromobility; industrial; digital; and space/defence) responsible for the delivery of the EU's twin transition and security agenda. It assessed supply chain dependencies and forecast materials demand until 2050 in the EU, economic regions and the world. It also assessed the EU's materials needs and vulnerabilities now and in the future. As such, the study provides a forward-looking basis to help identify strategic raw materials for key technologies and applications, to identify bottlenecks and to pinpoint the segments of supply chains which need strengthening and how. It also provides scientific evidence to underpin the Critical Raw Materials Act and other relevant initiatives announced by President von der Leyen in her State of the European Union speech in September 2022.

Main findings of the Foresight study

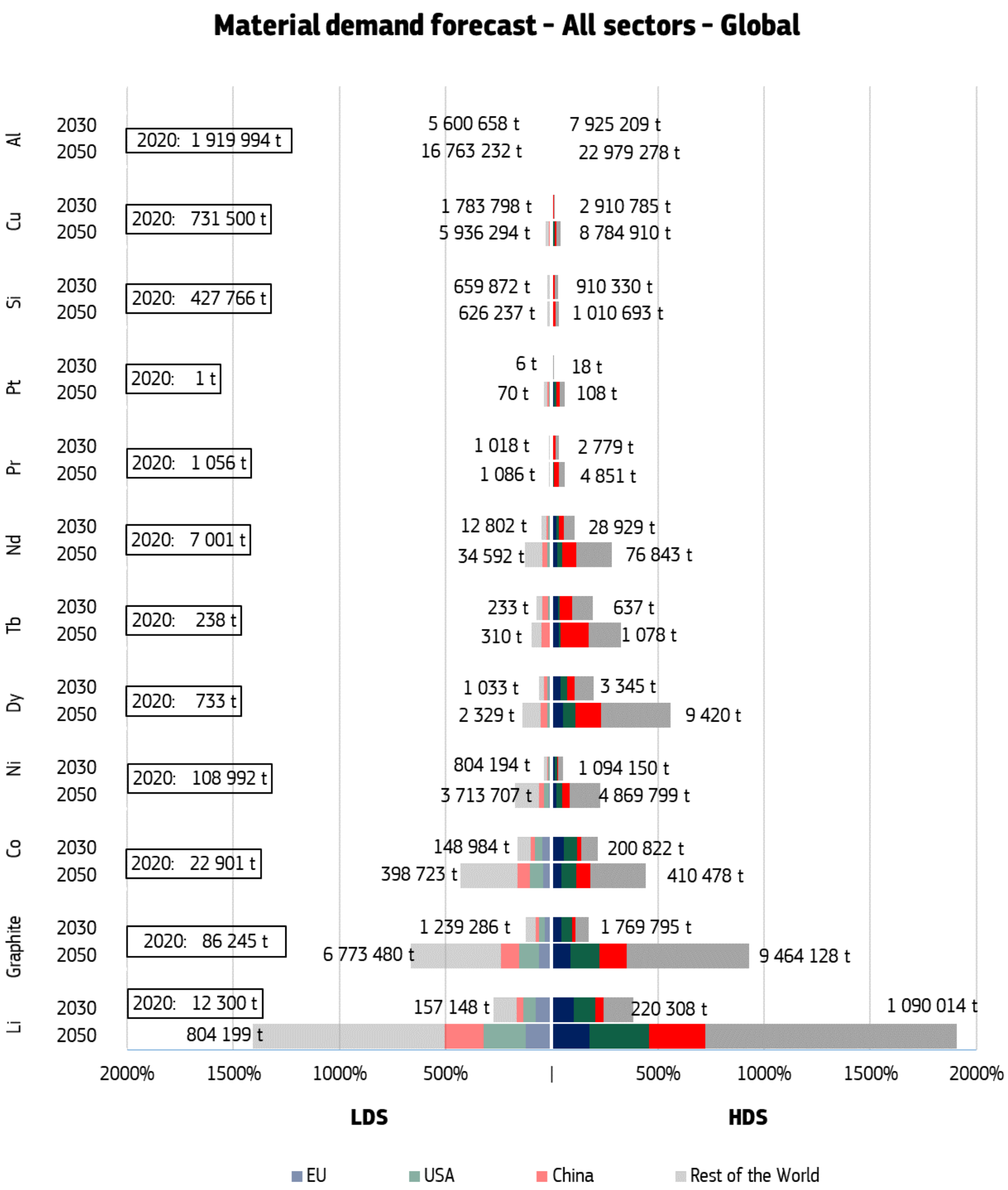
- All of the key technologies and strategic sectors in scope rely extensively on critical raw materials to deliver the goals of the twin transitions and the defence/aerospace agenda.
- Table 12 summarises, for each technology, the main strategic and critical raw materials used.
- Meeting the EU's ambitious policy targets will drive an **unprecedented increase in materials demand** in the run up to 2030 and 2050. For example, in order to meet the REPowerEU targets for 2030, **for the permanent magnet needs of wind turbines alone, EU demand for rare earth metals will increase almost fivefold**. **Lithium demand for the batteries in electric vehicles will also increase 11 times**. Looking to the 2050 horizon, in the High Demand Scenario (HDS), EU demand in all the explored sectors for raw materials such as neodymium, dysprosium (the two main rare earths), nickel, lithium and graphite is projected to increase 6, 7, 16, 21 and 26 times compared with the current values, respectively**.**
- The demand forecast takes into consideration innovation, circularity and substitution possibilities and, for the low demand scenario (LDS), it allows enough space for demand mitigation, e.g. through behavioural changes. Even for the low demand scenario, which takes the most pessimistic view of technology growth (moderate or even reverse growth in some technologies, and well below the REPowerEU targets) and the most optimistic view of innovation and market choices for less material-intensive technologies, materials demand still tends to increase significantly over time.
- **Global demand** is also projected to increase significantly, as many other countries and regions follow similar energy and digital transitions, **competing for the same pool of raw materials**. Moreover, there is **sectorial competition** for these same resources: rare earths are not only used in wind turbine generators, for example, but also in other key technologies such as electric vehicle traction motors and digital applications, whose markets are also projected to grow. International and cross-sectorial competition therefore require close attention (see Figure 113).

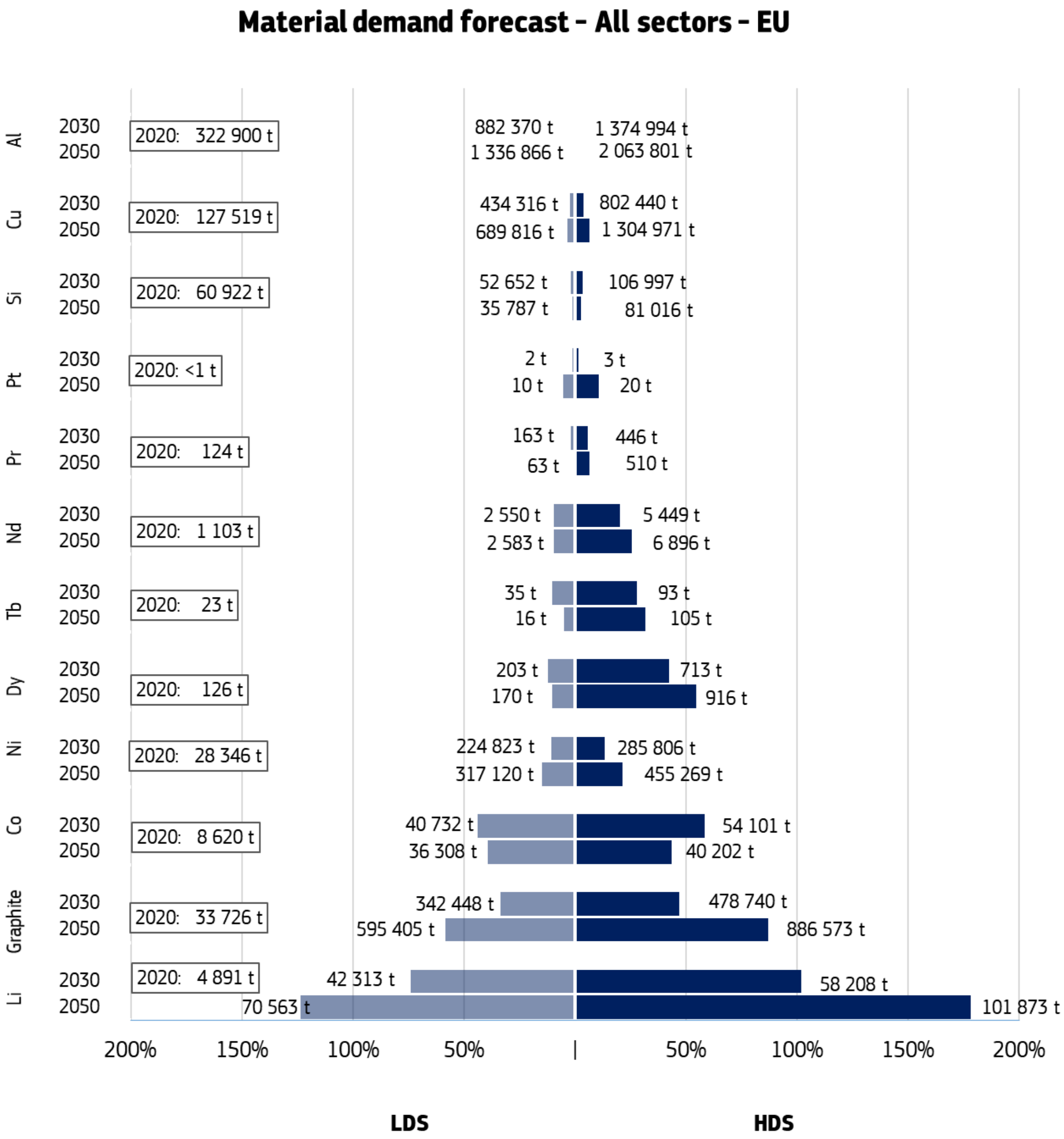
Table 12. Strategic and critical raw materials used in the technologies in scope.

Supply Risk	Raw material															
4.8	Gallium						•			•	•	•		•	•	•
4.1	Magnesium			•							•	•	•	•	•	•
4.0	REE (PM)		•	•	•	•		•		•	•	•		•	•	•
3.8	Boron		•	•	•	•	•	•		•	•	•		•	•	•
2.7	PGM		•	•						•	•	•		•	•	•
1.9	Lithium	•								•		•		•	•	•
1.9	Bismuth									•	•	•				•
1.8	Germanium						•			•	•	•				•
1.8	Natural graphite	•	•	•					•	•		•		•	•	
1.7	Cobalt	•	•	•						•		•	•	•	•	•
1.6	Titanium metal											•	•	•	•	•
1.4	Silicon metal		•	•	•	•	•	•	•	•	•	•	•	•	•	•
1.2	Manganese	•	•	•	•			•	•	•	•	•	•	•	•	•
1.2	Tungsten			•								•	•		•	•
0.5	Nickel	•	•	•	•		•	•	•	•	•	•	•	•	•	•
0.1	Copper	•	•	•	•	•	•	•		•	•	•	•	•	•	•
5.3	HREE (rest)		•	•						•	•	•	•	•	•	•
4.4	Niobium			•	•					•			•		•	•
3.5	LREE (rest)		•	•						•		•		•	•	•
3.3	Phosphorus	•					•		•		•	•				•
2.6	Strontium		•	•						•		•				
2.4	Scandium			•							•		•			•
2.3	Vanadium		•	•					•	•			•	•	•	•
1.8	Antimony						•			•	•	•		•	•	•
1.8	Beryllium										•	•				•
1.6	Arsenic						•			•	•	•				•
1.5	Feldspar		•												•	
1.5	Hafnium										•		•		•	•
1.3	Baryte		•	•						•	•	•				•
1.3	Tantalum			•						•		•			•	•
1.2	Helium										•					•
1.2	Aluminium	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
1.1	Fluorspar	•					•	•		•		•		•	•	•
1.0	Phosphate rock									•						

Source: JRC analysis. Although it is a critical material, coking coal does not appear in the table as it is not used in any technology.

Figure 113. Material demand forecast for all sectors: global (this page) and focus on the EU (next page)





Source: JRC analysis (Li = lithium, Co = cobalt, Ni = nickel, Dy = dysprosium, Tb = terbium, Pr = praseodymium, Pt = platinum, Si = silicon metal, Cu = copper, Al = aluminium).

- The EU is heavily **dependent** on third countries, and in particular on **China**, at various stages in all supply chains, which poses a serious risk to the success of the twin transition. For example, the rare earths needed for the permanent magnets in wind turbines are mined, refined and processed in China. Most of the modules and cells for solar photovoltaics are imported from China. China currently dominates all stages of the battery supply chain, and while the EU does well in most steps of the supply chain for hydrogen electrolysers, raw materials supply is a big issue. Together with China, the US holds a dominant position in the global markets for digital technologies assemblies and super-assemblies. While in some technologies there are alternative suppliers, allowing measures for diversification of supply (e.g. South Africa for electrolysers), in many other cases, Chinese dominance is almost monopolistic. Moreover, ownership of mining facilities in third countries is an issue. For example, 70% of cobalt mines in the Democratic Republic of the Congo are owned by China and supply exclusively to Chinese refineries.

- **Dependencies and vulnerabilities are present in various steps of the value chain**. The supply of raw materials is not the only challenge, but also their processing, refining and manufacturing. Sometimes, as in the case of solar PV and digital technologies, dependencies extend throughout the complete value chains. In identifying and managing vulnerabilities and bottlenecks, attention should be given to the fact that the development of capacity at one stage of the value chain cannot happen without ensuring sufficiency in the previous steps.

- **Risk of losing global leadership**: Traditionally, for some of the technologies, such as wind power, the EU has enjoyed global leadership in the production of the overall technology. However, while it remains self-sufficient in manufacturing, it has recently lost its leading position to China. A gradual loss of competitiveness and decline in production has also been observed in semiconductors, while in heat pumps, Chinese manufacturers are claiming an increasing share of the European market.

- Concerns about a **gap between demand and supply**: In normal markets, supply follows demand relatively quickly. For raw materials, the supply tends to grow much more slowly – even if the market signals increased demand through, for example, a rise in prices, it takes a relatively long time to increase mine capacity and years to open a new operation. Therefore, the risk is high of demand outpacing supply for selected materials and technologies relevant to the twin transition. This is aggravated by domestic growth in demand for critical and scarce materials, combined with a similar increase globally, technological and sectoral competition, and the initial lack of material available for recycling. In the case of batteries, the JRC forecasts, based on known and planned mining development projects for lithium, cobalt, manganese and nickel, that demand will outstrip known potential supply after 2029-2030, unless sufficient investment is made in time to bridge the gap. The supply of rare earths will also struggle to meet global demand, if no new production projects are implemented.

- In terms of **geopolitics**, the risk of supply disruptions is extremely high in various value chains and for selected materials and components. This is due to natural and environmental events, such as epidemics and damage to facilities; geopolitical risks, as demonstrated by the Russian invasion of Ukraine; and trade distortions, such as we have seen with the market restrictions imposed by China on materials and components.

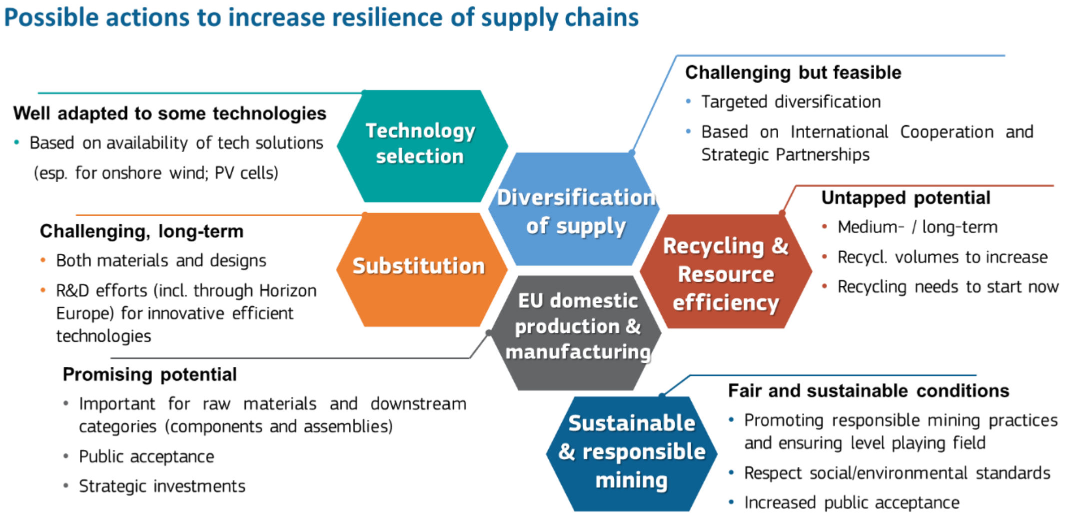
Recommendations for strengthening the supply chains

The EU currently lacks a mechanism to address **both short-term and long-term disruptions**. Among the responses employed by other economies, possible strategies include **stockpiling** and the **joint procurement** of strategic materials.

Complementary risk mitigation strategies which can be considered to further **reduce dependencies** include: 1) diversifying materials supply and establishing long-term agreements/partnerships; 2) increasing component manufacturing capacity in the EU; 3) enhancing recycling and reuse for a stronger circular economy; and 4) substitution and alternative solutions. Figure 114 schematically presents an overview of these strategies.

It is clear that one size does not fit all. Each one of the supply chains analysed has its own issues and requires tailored solutions for short-term and long-term reinforcement.

Figure 114. Overview of actions to increase the resilience of supply chains



Source: JRC analysis.

- **Diversification of supply** is often considered an easy solution, but it is not always possible, due to geological and geopolitical constraints. It requires the availability of resources and a willingness on the part of the other parties to enter into partnerships or trade agreements. It is therefore best, where possible, to work with like-minded countries. Practices such as development assistance, promoting ESG (Environmental, Social, and Governance) standards and international cooperation and partnerships, appear to be most effective.

- **Recycling, reuse, resource efficiency** and demand mitigation through **behavioural change**: this should be sought in the application of any technology and throughout the complete value chain. Behavioural change has untapped potential worth exploiting and incentivising. While recycling and re-use of materials is a more medium-term measure (i.e. after 2030 when sufficient end-of-life recycling input volumes will become available), secondary raw materials are an asset for the EU and can play a major role. The development of domestic processing capacity and technological feasibility for recovering materials for recycling needs to start now.

- **Substitution and innovation**: Although a longer-term prospect, innovative solutions offer both technological leadership (especially where substitutes are advanced innovative materials with enhanced performance and better technical properties) and security in supply chains. In addition to materials substitution, alternative technologies can also be selected which might be less efficient but equally effective and less materials-intensive. Investment in R&I efforts is necessary in this area.

- **Development of EU domestic production and processing capacities**: Although public acceptance can be an issue, there are many benefits to exploiting domestic resources. This includes mine waste in old and abandoned mines, which should also be exploited. The development of capacity should not be restricted to mineral extraction alone, but should also extend to other steps of the value chains, namely processing and components manufacturing, to provide integrated solutions. An increase in processing and manufacturing capacities for high-spec materials and components for the space/defence sector would make a significant contribution to the EU's **open strategic autonomy**. As noted above, for each segment of the supply chain, it is necessary to ensure the resilience of the preceding segments.

The objective of these solutions is not total self-sufficiency, which is impossible, but rather the strengthening of supply chains and a reduction of dependency on concentrated supply.

Skills and access to highly skilled talent are deemed critical not only for the twin transitions, but also for a number of specialised and R&D-intensive supply chain elements (e.g. semiconductors and aerospace). Educational capacities to provide this specialised workforce are also required for a range of disciplines relevant to the envisaged transition to a low-carbon economy, as well as for performing R&I activities to reduce the use of materials and substitution.

Further attention should be given to research and innovation in material sciences, geosciences and metallurgy to remain internationally competitive. When developing resource diversification strategies, skills and innovation are a core ingredient for the realisation of environmentally, economically and socially efficient processes, material efficiency and successful substitution strategies. These key elements on materials and skills are to be taken into account when developing and coordinating the R&I Implementation Plans for the different technologies of the European Strategic Energy Technologies Plan[80] of the future.

Besides attention to the physical origins of materials, components and assemblies, **the protection of valuable intellectual property should also be safeguarded**. In many of the cases in this analysis, concerns have been raised by experts regarding the protection of intellectual property for innovations originating in the EU.

Recommendations for policy and methodological developments

- **Foresight methodology** has shown itself to be a powerful tool for analysing supply chains, forecasting materials demand and supply chain bottlenecks, and providing a **forward-looking basis supporting the policy decisions** of the Commission and Member States. Foresight studies, focusing both on the forecast of the demand and of the supply of critical materials can now be established as an accepted practice, performed on a regular basis, and used to inform CRM policy alongside the more traditional criticality assessments. Furthermore, it is necessary to perform **deep dive assessments** at a deeper level of detail for selected strategic technologies, which will provide insights into the vulnerabilities of supply chains and the options for addressing them (see, for example, the US DOE Assessments in Response to Executive Order 14017 "America's Supply Chains"). These assessments could also include enabling technologies, such as electric networks, inverters, controllers and switch gears, along with energy efficiency measures.
- **Strategic materials**: The European Commission has introduced the concept of strategic raw materials in its proposal for a European Critical Raw Materials Act. Whereas a *critical raw material* is characterised by a high risk of supply disruptions and its importance for the overall EU economy, a *strategic raw material* is additionally characterised by its importance for strategic areas such as renewable energy, digital, aerospace and defence technologies, its projected demand growth and current supply, and the difficulties of scaling up production. Strategic raw materials have properties that make them very difficult to replace in the relevant technologies without significant loss of performance. Examples of strategic materials include the rare earth elements found in the permanent magnets used to manufacture wind turbine motors, lithium used for batteries, copper for electrification, and silicon used for semiconductors and solar PV modules. Monitoring the supply chains of strategic raw materials is necessary to ensure the undisrupted course towards the twin transition. At the same time, it is necessary **to carry out foresight studies, such as the 2020 and this study, with demand and supply forecasts, on a regular basis** to inform the list of strategic materials.
- **Monitoring capacities and risk assessment tools need to be developed for strategic supply chains,** with the capacity to take into account geopolitical risks and impacts and to update the assessed level of risk quickly. Such tool(s) can be used as an **early warning** mechanism for potential upcoming supply disruptions (dynamic assessment), thus assisting risk management measures.
- **The knowledge-base and scientific evidence for policy** can be further developed. The EC's Raw Materials Information System[81] and the various analyses of supply chains performed by the JRC and other organisations have provided valuable information. Continuing to build the relevant knowledge-base is essential.

[80] Strategic Energy Technologies Plan (SET Plan): https://setis.ec.europa.eu/

[81] European Commission's Raw materials Information System (RMIS): https://rmis.jrc.ec.europa.eu/

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List of abbreviations and definitions

AAS	Advanced antenna system
AATiD	Advanced Additive Titanium Development Consortium
AC	Alternating Current
ACIM	AC induction motor
AEM	Anion Exchange Membrane
ALM	Additiive layer manufacturing
AM	Additive Manufacturing
AMCA	Advanced Medium Combat Aircraft
APOAT	Association of the Industry of Additive Technologies
ASAT	Anti-satellite tests
ASD	Aerospace, Security and Defence Industries Association of Europe
AWE	Alkaline Water Electrolyser
BB	Broadband
BEV	Battery electric vehicle
BF	Blast furnace
BFR	Brominated flame retardants
BIL	Bipartisan Infrastructure Law
BIPV	Building-Integrated PV
BJ	Binder Jetting
BOF	Basic oxygen furnace
BoP	Balance of Plant
BTF	Buy-to-fly
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CATV	Cable Television
CC	Carbon capture
CCAM	Connected, cooperative, and automated mobility
CCS	Carbon Capture and Storage
CdTe	Cadmium telluride
CETO	Clean Energy Technology Observatory
CFB	Circulating fluidised bed
CFC	Carbon Fibre Reinforced Carbon
CIGS	Copper indium gallium (di)selenide
CIndECS	Climate-Neutral industry Competitiveness Scoreboard
CMC	Ceramic matrix composite component
CMIC	Critical Minerals Intelligence Centre (UK)
CMOS	Complementary metal-oxide semiconductor

CNT	Carbon Nanotubes
COTS	Commercial off-the-shelf
CPU	Central Processing Unit
CRM	Critical raw material
c-Si	Crystalline silicon
DAO	Discrete, analogue, and other semiconductor
DC	Direct Current
DD	Direct-drive
DD-EESG	Direct-drive electrically excited synchronous generator
DD-PMSG	Direct-drive permanent magnet synchronous generator
DED	Directed Energy Deposition
DFIG	Double-Fed Induction Generator
DG GROW	Directorate General for Internal Market, Industry, Entrepreneurship and SMEs
DHC	District Heating and Cooling
DOE	United States Department of Energy
DPP	Defence Procurement Procedure (India)
DR	Direct reduction
DRAM	Dynamic random-access memory
DRI	direct reduced iron
DTN	Data Transmission Networks
E&M	Entertainment & Media
EAF	Electric arc furnace
EASA	European Aviation Safety Agency
EC	European Commission
ECB	External controller based disk
EDF	European Defence Fund
EDFA	Erbium-Doped Fibre Amplifier
EDSIS	European Defence Standards Information System
EDTIB	European Defence Technological and Industrial Base
EEE	Electrical, Electronic and Electro-mechanical
EESG	Electrically Excited Synchronous Generator
EHPA	European Heat Pump Association
EI	Economic Importance
ELV	End-of-life vehicles
EOL_{RIR}	End-of-life recycling input rate
EPO	European Patents Office
ERMA	European Raw Materials Alliance
ESA	European Space Agency
ESG	Environmental, Social, and Governance

ESS	Energy Storage System
ETCS	European Train Control System
ETIP	European technology and innovation platform
EU	European Union
EUSST	European Space Surveillance and Tracking network
EV	Electric vehicle
FC	Fuel Cell
FCEV	fuel cell electric vehicles
F-gas	Fluorinated gas
FPGA	field-programmable gate array
FRP	Flat-rolled aluminium products
FYP	Five-Year Plan
GaAs	Gallium Arsenide
GaInP	Gallium indium phosphide
GB	Gearbox
GB-DFIG	Gearbox double-fed induction generator
GB-SCIG	Gearbox squirrel cage induction generator
GCCA	Global Cement and Concrete Association
GDC	Gadolinium doped ceria
GDL	Gas diffusion layer
GDP	Gross domestic product
GECO	Global Energy and Climate Outlook
GEO	Geosynchronous Equatorial Orbit satellites
GHG	Greenhouse Gas
GPU	Graphics Processing Unit
GS	Global supply
H2DRI	Hydrogen direct reduced iron and electric arc furnaces
HDD	Hard Disk Drive
HDS	High Demand Scenario
HHI	Herfindahl-Hirschman Index
HJT	Heterojunction technology
HPA	High-Purity Alumina
HREE	Heavy Rare-Earth Element
HTS	High-Temperature Superconductors
IC	Integrated circuit
ICAO	International Civil Aviation Organisation
ICT	Information and Communication Technology
IDC	International Data Corporation
IEA	International Energy Agency

ILR	Inverter Loading Ratio
IMU	Inertial Measurement Unit
IoT	Internet of Things
IP	Internet Protocol
IPCEI	Important Project of Common European Interest
IR	Import reliance
IRA	Inflation Reduction Act
IREDA	Indian Renewable Energy Development Agency
IRENA	International Renewable Energy Agency
ISTAR	intelligence, surveillance, target acquisition, and reconnaissance
IT	Information technology
JRC	Joint Research Centre
LCD	Liquid Crystal Display
LCO	Lithium cobalt oxide
LDS	Low Demand Scenario
LED	Light-emitting diode
LEO	Low Earth orbit
LFP	Lithium iron phosphate
LIB	Lithium-ion batteries
LME	London Metal Exchange
LMO	Lithium-manganese-oxide
LREE	Light Rare-Earth Element
LSC	Lanthanum strontium chromite
LSCF	Strontium-doped lanthanum cobaltite ferrite
LSI	Large system integrators
LSM	Strontium-doped lanthanum manganite
MaaS	Mobility-as-a-service
ME	Material extrusion
MEA	Membrane electrode assembly
MeitY	Ministry of Electronics and Information Technology of India
MEO	Medium Earth orbit satellites
METI	Ministry of Economy, Trade and Industry of Japan
MIC	Market Intelligence & Consulting Institute
MJ	Material Jetting
MMIC	Monolithic Microwave Integrated Circuit
MoU	Memorandum of Understanding
MSP	Minerals Security Partnership
NAND	Flash memory
NCA	Nickel Cobalt Aluminium Oxide

NdYAG	Neodymium-doped yttrium aluminum garnet
NEV	New energy vehicle
NiMH	Nickel metal hydride
NMC	Nickel-Manganese-Cobalt-Oxide
NOES	Non-grain oriented electrical steel
NUTS	Nomenclature of Territorial Units for Statistics
NZEB	Near-Zero Energy Buildings
OCP	Open Compute Project
ODM	Original design manufacturers
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturers
OLED	Organic light-emitting diode
PAN	Polyacrylonitrile
PbA	Lead-acid batteries
PBF	Powder Bed Fusion
PCB	Printed circuit board
PEM	Proton Exchange Membrane
PEMFC	Proton exchange membrane
PERC	Passivated emitter and rear contact solar cell
PFAS	Perfluorosulfonic acid
PFR	Phosphorus flame retardants
PGM	Platinum-Group Metals
PHEV	Plug-in electric vehicle
PM	Permanent Magnet
PMAR	Permanent magnet assisted reluctance motor
PMSG	Permanent Magnet Synchronous Generator
PMSM	Permanent magnet synchronous motor
PNT	Position navigation and timing
PSU	Power supply unit
PTFE	Polytetrafluoroethylene
PU	Polyurethane
PV	Solar Photovoltaics
PVC	Polyvinylchloride
R&D	Research and Development
R&D&I	Research, development and innovation
R&I	Research and Innovation
RAM	Random Access Memory
RE	Rare Earth
REE	Rare Earth Element

RF	Radio frequency
RMIS	Raw materials Information System
RNSS	Radionavigation-satellite services
RoHS	Restriction of hazardous substances
rPET	recycled polyethylene terephthalate
RPS	renewable portfolio standards
SAF	Submerged arc furnace
SAR	Synthetic aperture radar
SARP	Standards and Recommended Practices
SASAC	State-owned Assets Supervision and Administration Commission (China)
SCIG	Squirrel Cage Induction Generator
SECI	Solar Energy Corporation of India
SET Plan	Strategic Energy Technologies Plan
SI	Substitution index
SiC	Silicon carbide
SME	Small and medium-sized enterprises
SMIC	Semiconductor Manufacturing International Corporation
SO	Solid Oxide
SOFC	Solid oxide fuel cell
SR	Supply Risk
SRIA	Strategic Research Innovation Agenda
SSD	Solid-state drive
STEM	Science, technology, engineering, and mathematics
TDF	Technology Development Fund (India)
TIM	Thermal interface materials
TRAFAM	Technology Research Association for Future Additive Manufacturing
TSMC	Taiwan Semiconductor Manufacturing Company
UAV	Unmanned Aerial Vehicles
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
USV	Unmanned Surface Vehicles
UV	Unmanned Vehicles
WEEE	Waste from Electrical and Electronic Equipment
WGI	World Governance Index
WRSM	Wound rotor synchronous motor
WTO	World Trade Organization
xEV	Electric Vehicle
YSZ	Yttria-stabilised zirconia

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Annexes

Annex 1. Raw materials and technologies

Table 13 lists the 87 candidate raw materials considered in the Criticality Assessment exercise 2023 (EC, 2023). Raw materials are divided into three categories: strategic, critical, and non-critical materials. Within each category, materials are reported in descending order of Supply Risk as calculated in EC, 2023.

The table specifies in which technologies the raw materials are utilised. The most widespread raw materials are aluminium and iron ore (used in all 15 technologies), copper, nickel, silicon metal (14), and manganese (13). Nine materials do not appear in any technology.

Table 13. Strategic, critical, and non-critical raw materials used in the technologies in scope.

Supply Risk	Material															
5.6	Dysprosium				•	•		•			•	•		•	•	•
4.9	Terbium				•						•			•	•	•
4.8	Gallium						•			•	•	•		•	•	•
4.1	Magnesium			•							•	•	•	•	•	•
4.0	Cerium		•	•								•		•	•	•
3.9	Iridium		•	•												•
3.8	Boron		•	•	•	•	•	•		•	•	•		•	•	•
3.8	Ruthenium		•	•						•	•	•		•	•	
3.6	Neodymium				•	•		•		•	•	•		•	•	•
3.5	Samarium									•				•	•	•
3.3	Gadolinium		•	•						•		•		•	•	•
3.2	Praseodymium				•	•		•		•	•	•		•	•	
2.4	Rhodium			•						•						•
2.1	Platinum		•	•						•	•	•		•	•	•
1.9	Lithium	•								•		•		•	•	•
1.9	Bismuth									•	•	•				•
1.8	Germanium						•			•	•	•				•
1.8	Natural graphite	•	•	•					•	•		•		•	•	
1.7	Cobalt	•	•	•						•		•	•	•	•	•
1.6	Titanium metal											•	•	•	•	•
1.5	Palladium		•	•						•	•	•		•	•	•
1.4	Silicon metal		•	•	•	•	•	•	•	•	•	•	•	•	•	•
1.2	Manganese	•	•	•	•			•	•	•	•	•	•	•	•	•
1.2	Tungsten			•								•	•		•	•
0.5	Nickel	•	•	•	•		•	•	•	•	•	•	•	•	•	•
0.1	Copper	•	•	•	•	•	•	•		•	•	•	•	•	•	•
5.6	Erbium									•				•	•	
5.6	Europium											•		•	•	
5.6	Holmium									•				•	•	
5.6	Lutetium													•	•	
5.6	Thulium									•				•	•	

Supply Risk	Material															
5.6	Ytterbium									•				•	•	
4.4	Niobium			•	•					•			•		•	•
3.5	Lanthanum		•	•						•		•		•	•	•
3.5	Yttrium		•	•						•		•				•
3.3	Phosphorus	•					•		•		•	•				•
2.6	Strontium		•	•						•		•				
2.4	Scandium			•							•		•			•
2.3	Vanadium		•	•					•	•			•	•	•	•
1.8	Antimony						•			•	•	•		•	•	•
1.8	Beryllium										•	•				•
1.6	Arsenic						•			•	•	•				•
1.5	Feldspar		•												•	
1.5	Hafnium										•		•		•	•
1.3	Baryte		•	•						•	•	•				•
1.3	Tantalum			•						•		•			•	•
1.2	Helium										•					•
1.2	Aluminium	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
1.1	Fluorspar	•					•	•		•		•		•	•	•
1.0	Coking coal															
1.0	Phosphate rock									•						
1.7	Natural Teak wood															
1.3	Sapele wood															
0.9	Natural cork															•
0.9	Natural rubber															
0.9	Tin			•			•			•	•	•		•	•	
0.8	Kaolin clay															
0.8	Molybdenum			•	•	•	•	•		•		•	•	•	•	•
0.8	Perlite															
0.8	Silver			•			•	•		•	•	•		•	•	•
0.8	Xenon										•	•				•
0.8	Zirconium		•	•					•	•			•			•
0.7	Chromium		•	•	•	•		•	•		•	•	•	•	•	•
0.7	Krypton										•	•				•
0.7	Neon										•	•				
0.7	Potash			•										•	•	
0.6	Gypsum									•						
0.6	Indium						•			•	•	•		•	•	•
0.6	Magnesite								•							
0.5	Hydrogen								•			•				•
0.5	Iron ore	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
0.5	Rhenium									•				•	•	
0.5	Titanium		•	•							•					

Supply Risk	Material															
0.4	Gold			•				•		•	•	•		•	•	•
0.4	Bentonite															
0.3	Tellurium						•			•				•	•	
0.3	Diatomite															
0.3	Limestone			•					•					•	•	
0.3	Selenium						•			•						•
0.3	Silica				•		•		•			•				•
0.3	Sulphur															•
0.2	Cadmium						•					•				
0.2	Talc											•				
0.2	Zinc			•	•		•	•		•	•	•		•	•	•
0.2	Aggregates				•											
0.1	Lead				•		•			•		•		•	•	•
0.1	Roundwood															

Source: JRC analysis.

Annex 2. Supply chain steps and elements

Table 14. Definitions of the supply chain steps.

Stage of the supply chain	**Elements**
Raw materials	In accordance with the CRM study, raw materials are the results of one of the following two stages: • Extraction stage: process of obtaining raw materials from the environment. • Processing/Refining stage: processing operations to obtain purified substances used to make semi-finished and finished products (post-mining or post-harvesting stage). When information is available for both stages, the one with the higher SR is taken.
Processed materials	Processed materials are a combination of two or more materials (e.g., alloys or mixed powders) or a relatively pure material that has been processed (via casting, rolling slitting, etc.) in a specific fashion for its further use to manufacture a part of a technology (semi-fabricated or semi-finished products). Semi-production processes encompass the processing of refinery shapes into semi-finished metal and metal alloy products (e.g. aluminium semis include sheet, strip, plate, profiles, rod and bar, tube, wire and forgings; copper semis include wire rod, ingot for castings, master alloy, brass and electrodeposited copper foil).
Components	A component is the smallest part of a technology that is manufactured and traded by a company starting from processed materials. As an example, ball bearings are a component manufactured starting from chrome steel semi-fabricated products. The rings, the balls and the retainer parts of a bearing are not components since they are not manufactured and traded by a company starting from processed materials. These parts are manufactured by the same company producing the complete bearing, they are not purchased and assembled. Similarly, the metal casing of a smartphone is not a component. The casing is manufactured using aluminium semis, but there is no market for it since it is produced by the same company putting together the smartphone components and parts.
Assemblies	An assembly is a set of components purchased by a company, put together, and sold to other companies. In this process, a company might use also processed materials for manufacturing some parts. As an example, an electric motor is an assembly where components (e.g. the permanent magnets) and processed materials (e.g. copper semis used for the stator windings) are put together. Another example of assemblies is represented by a fuel cell or an electrolyser stack. Also in this case, the company producing the stack can purchase components (e.g. the bipolar plates) from an external company, and manufacture some parts (e.g. the glass gaskets used in solid oxide stacks) starting from processed materials.
Super-assemblies	A super-assembly is a set of assemblies and components purchased by a company, put together, and sold to other companies. In this process, a company might use also processed materials for manufacturing some parts (e.g., casings manufactured from aluminium semi-fabricated products) that are used in the super-assembly. Smartphones, tablets, and laptops are an example of super-assemblies. These technologies are the result of putting together assemblies (e.g. the fan used for cooling or the batteries), components (e.g. magnets or transistors) as well as parts

Stage of the supply chain	Elements
	manufactured by the same company making the super-assembly (e.g. plastic or aluminium casing).
System	A system is a set of components, assemblies, and super-assemblies. Space launchers and satellites are an example of systems. Super-assemblies, such as the propulsion and the control sub-system, are developed by separate companies putting together assemblies (e.g., nozzles and propellant tanks) and components (e.g., injectors and thruster).

Source: JRC analysis.

Section 2.1 Li-ion batteries

Table 15. Elements considered in the Li-ion batteries supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, cobalt, copper, fluorspar, iron ore, lithium, manganese, natural graphite, nickel, phosphorus.
Processed materials	LCO (lithium cobalt oxide) active material, LFP (lithium iron phosphate) active material, LiPF6 (lithium hexaflurophosphate), LMO (lithium manganese oxide) active material, natural graphite anode material, NCA (nickel cobalt aluminium oxide) active material, NMC (nickel manganese cobalt oxide) active material, Cu semis, synthetic graphite anode material. *Not assessed: PE (polyethylene), PP (Poplyprolylene), Steel (crude).*
Components	Anodes Li-ion, cathodes Li-ion, electrolyte, separators Li-ion. *Not assessed: Cell casing*
Assemblies	Cell

Source: JRC analysis.

Table 16. Main raw materials in the Li-ion battery technology and their application.

	Raw materials	Precursor materials for battery components / *Key intermediate materials for the production of battery precursors*	Components				
			Cathode	Anode	Electrolyte	Separator	Other
1	Aluminium	Aluminium sulfate / *Aluminium trihydrate (hydrated alumina), bauxite*	X				
		High-purity alumina (HPA) / *High-purity Aluminum*				X (coating)	
		Semi-finished aluminium (extrusions and sheet)					X (casing)
		Semi-finished aluminium (batt-grade aluminium foil)					X (current collector)
2	Cobalt	Refined cobalt (cobalt sulphate and cobalt oxide)	X				
3	Copper	Semi-finished copper (batt-grade copper foil) or electro-deposited copper					X (current collector)
4	Fluorspar	Fluorinated chemicals / *Hydrofluoric acid, Fluorine*			X		

	Raw materials	Precursor materials for battery components / *Key intermediate materials for the production of battery precursors*	Components				
			Cathode	**Anode**	**Electrolyte**	**Separator**	**Other**
		Fluorinated polymers (PVDF and PTFE) / *Hydrofluoric acid, Fluorine*					X (binder)
5	Iron	Iron phosphate / *iron powder*	X				
6	Lithium	Refined lithium (battery-grade lithium carbonate and lithium hydroxide)	X				
		lithium salts			X		
7	Manganese	High purity manganese sulphate (MSM) / *High-purity electrolytic manganese (EMM)*	X				
8	Graphite (natural)	Purified spherical graphite (PSG) / *Flake natural Graphite*		X			
	Graphite (synthetic)	Battery-grade synthetic graphite / *petroleum coke, coal-tar pitch, or oil*		X			
9	Nickel	Nickel sulphate / *Class I nickel or nickel's metallurgy intermediate*	X				
10	Phosphorus	Iron phosphate / *High-purity phosphoric acid*	X				
		Phosphorus pentachloride			X		
Next Generation Technologies							
	Raw materials	**Precursor materials for battery components / Key intermediate materials for the production of battery precursors**	**Components**				
			Cathode	**Anode**	**Electrolyte**	**Separator**	**Other**
11	Lithium	Lithium metal / *Refined lithium (lithium chloride and carbonate)*		X			
12	Niobium	Battery-grade niobium oxide		X			
13	Silicon metal	Electrical-grade silicon		X			
14	Sulphur	Sulphur	X				
15	Tin	Sn-based intermetallics, SnO2		X			
16	Titanium	Titanium dioxide / *Titanium chemicals, powder or foil*		X			

Source*:* JRC analysis.

Section 2.2 Fuel cells

Table 17. Elements considered in the fuel cells supply chain.

Stage of the supply chain	**Elements**
Raw materials	Aluminium, baryte, boron, cerium, chromium, cobalt, copper, feldspar gadolinium, iridium, iron Ore, lanthanum, manganese, natural graphite nickel, palladium, platinum, ruthenium, silicon, strontium, titanium, vanadium, zttrium, zirconium.
Processed materials	Carbon paper/ cloth, Carbon nanotubes, Ceria, gadolinium dopped, Glass ceramic sealant materials, Graphene, Pt-Ru alloys, LSC (lanthanum

Stage of the supply chain	Elements
	strontium chromite), LSCF (lanthanum (Sr-dopped) cobaltite ferrite), LSM (lanthanum (Sr dopped) manganite), Mica, NiO, PFSA (perfluorosulfonic acid), stainless steel, stainless steel high temp, yttria stabilized zirconia. *Not assessed: boron silicate glass sealant, LaGaO3 (lanthanum gallate), La2NiO4 (lanthanum nickelate), Ni-Y2O3_ZrO2 cerment, SrTiO3/ABO3 (perovskite).*
Components	Aggregated data for components including: Anode and cathode PEMFC, Anode SOFC, Bipolar plate, Catalyst layer, Cathode SOFC, Cooling plate, Electrolyte ceramic SOFC, Electrolyte PEMFC (Membrane), End plate, GDL (Gas diffusion layer), MEA (membrane electrode assembly), Seal. *Not assessed individually: Anode and cathode PEMFC, Anode SOFC, Bipolar plate, Catalyst layer, Cathode SOFC, Cooling plate, Electrolyte ceramic SOFC, Electrolyte PEMFC (Membrane), End plate, GDL (Gas diffusion layer), MEA (membrane electrode assembly), Seal.*
Assemblies	Stack

Source: JRC analysis.

Section 2.3 Electrolysers

Table 18. Elements considered in the electrolysers supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, Baryte, Borate, Cerium, Chromium, Cobalt, Copper, Gadolinium, Gold, Iridium, Iron ore, Lanthanum, Limestone, Magnesium, Manganese, Molybdenum, Natural graphite, Nickel, Niobium, Palladium, Platinum, Potash (K), Rhodium, Ruthenium, Scandium, Silicon metal, Silver, Strontium, Tantalum, Tin, Titanium metal, Tungsten, Vanadium, Yttrium, Zinc, Zirconium
Processed materials	Acrylonitrile butadiene styrene, Aluminium oxide, Aramid fibers, Barium Yttrium Zirconate, Benzyltrimethylammonium hydroxide, Carbon black, Carbon cloth/paper, Cerium Gadolinium oxide, Elastomers, Ethylene propylene diene monomer, Expanded polytetrafluorethylene, Graphene, Graphite composites, High-temperature stainless steel , Iridium black, Iridium oxide, Lanthanum (Strontium) Manganites, Mild steel, Nickel alloys (e.g. Ni-Al-Mo, Ni-Cu, Ni-Fe-Co, Ni-Mn alloys), Nickel foam, Nickel nanopowder, Nickel oxide, Nickel-Cobalt alloys, Nickel-Chromium alloys, Nickel-Iron alloys, Nickel-Molybdenum alloys, Perfluorosulfonic acid, Platinum black, Platinum on Carbon support (Pt/C), Polybenzimidazole, Polyetheretherketone, Polyethersulfone, Polyphenylene (low density), Polyphenylene Sulfide, Polystyrene, Polysulfone, Polytetrafluoroethylene, Potassium hydroxide, Raney Nickel, Rhodium oxide, Ruthenium oxide, Silver brazing alloy, Stainless steel, Styrene-ethylene-butylene-styrene copolymer, Synthetic graphite, Thermoplastics (sealants), Titanium alloys, Titanium fiber felt, Titanium foams, Vermiculite, Yttria doped ceria, Yttria stabilised zirconia, Zirconium oxide *Not assessed due to lack of data on suppliers: Nickel-Cobalt-Zinc alloys, Nickel-Zinc alloys, Iron-Zinc alloys, Lanthanum strontium cobaltite, Lanthanum strontium cobalt ferrite, Glass ceramic sealant materials,*

Stage of the supply chain	Elements
	Cerium-Manganese-Iron alloys, Nickel supported on mixed oxide & carbon material, Copper-Cobalt alloys
Components	Bipolar plates, catalysts, diaphragm, electrodes, electrolyte (liquid and ceramic), frames, gaskets/sealants, interconnectors, membranes, porous transport layer/current collectors
Assemblies	Stack

Source: JRC analysis.

Table 19. Elements considered in the four electrolyser technologies.

	Raw materials	Alkaline electrolysers	PEM electrolysers	SO electrolysers	AEM electrolysers
1	Nickel	X	X	X	X
2	Iron ore	X	X	X	X
3	Manganese	X	X	X	X
4	Cromium	X	X	X	X
5	Aluminium	X		X	X
6	Cobalt	X		X	X
7	Copper	X		X	X
8	Lantanum	X		X	X
9	Molybdenum	X	X		X
10	Natural graphite	X	X		X
11	Zirconium	X	X	X	
12	Potash	X			X
13	Strontium	X		X	
14	Cerium			X	X
15	Titanium		X	X	
16	Silicon metal			X	X
17	Tin	X			
18	Vanadium	X			
19	Zinc	X			
20	Baryte			X	
21	Boron			X	
22	Gold		X		
23	Iridium		X		
24	Platinum		X		
25	Paladium		X		
26	Rhodium		X		
27	Ruthenium		X		
28	Gadolinium			X	
29	Magnesium			X	

	Raw materials	Alkaline electrolysers	PEM electrolysers	SO electrolysers	AEM electrolysers
30	Niobium			X	
31	Scandium			X	
32	Silver			X	
33	Tantalum			X	
34	Tungsten			X	
35	Yttrium			X	
36	Limestone			X	

Source: JRC analysis.

Section 2.4 Wind turbines

Table 20. Elements considered in the wind turbines supply chain.

Stage of the supply chain	Elements
Raw materials	Aggregates, aluminium, boron, chromium, copper, dysprosium, iron ore, lead, manganese, molybdenum, neodymium, nickel, niobium, praseodymium, silica, silicon metal, terbium, zinc
Processed materials	Balsa wood, carbon fibres, cement, Cu semis, epoxide resins, glass fibres, NdFeB permanent magnet alloys, Polyurehtane, PE (polyethylene), PET, (Polyethylene terephthalate), PS (Polystyrene), steel (crude) *Not assessed: cast iron, steel (high-alloyed)*
Components	Bearings, blades, gearbox, nacelle casing, NdFeB permanent magnets, shafts, tower (concrete), tower (steel) *Not assessed: brushes, cables, foundation, monopiles (offshore wind), spinner (wind turbine), transformer (wind plant), transformer (wind turbine)*
Assemblies	Power generator
Super-assembly	Wind turbine

Source: JRC analysis.

Section 2.5 Traction Motor

Table 21. Elements considered in the traction motor supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, boron, chromium, copper, dysprosium, iron ore, molybdenum, neodymium, praseodymium, silicon metal
Processed materials	Al semis, Cu coils, NdFeB permanent magnet alloys, non-grain oriented electrical steel/silicon steel with 0-6.5% of silicon content, Steel (crude)

Stage of the supply chain	Elements
Components	NdFeB permanent magnets, Traction motor components (rotor, stator, housing, end shields, bearings)
Assemblies	Traction motor

Source: JRC analysis.

Section 2.6 Solar photovoltaics

Table 22. Elements considered in the solar PV supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, antimony, arsenic, borate, cadmium, copper, fluorspar, gallium, germanium, indium, iron, lead, metal, molybdenum, nickel, ore, phosphorus, sand, selenium, silica, silicon, silver, tellurium, tin, zinc.
Processed materials	Ag paste, Al alloys, Al paste, AsH3, Backsheets, BBr3 (Boron tribromide), CdS (cadmium sulfide), Cu semis, Encapsulants, GaAs wafer (Gallium arsenide wafer), GaN, Ge wafer (Germanium wafer), Glass (low iron), PH3, POCl3 (Phosphoryl chloride), Polysilicon, Si wafer (Silicon wafer), Steel, TMAl (Trimethylaluminum), TMG (Trimethylgallium), TMI (Trimethylindium).
Components	Crystalline Si cells, Connectors, Frames (all types), III-V group compounds cells, Inverter, Junction box.
Assemblies	Crystalline Sillicon modules (c-Si); Thin film modules (CdTe; CIGS)

Source: JRC analysis.

Section 2.7 Heat pumps

Table 23. Elements considered in the heat pumps supply chain (partial analysis).

Stage of the supply chain	Elements
Raw materials	Aluminium, boron, chromium, copper, dysprosium, fluorspar, gold, iron ore, manganese, molybdenum, neodymium, nickel, praseodymium, silicon metal, silver, zinc
Processed materials	*Al semis, Cu semis, elastomers, galvanised sheet metal with zinc coating, NdFeB permanent magnet alloys, nodular cast iron, polyolester oil lubricants, PVC (polyvinyl chloride), refrigerants, steel (crude)*
Components	*AC/DC converter bearings, compressor motor and drive, drier, fan motor and drive, NdFeB permanent magnets, piping, piston, refrigerant storage vessel, seals, sheet metal components valves, wiring*
Assemblies	*Compressor, controller, fan, heat exchangers, housing*
Super-assembly	Heat pump

Source: JRC analysis.

Section 2.8 Hydrogen direct reduced iron and electric arc furnace

Table 24. Elements considered in the direct reduced iron supply chain (partial analysis).

Stage of the supply chain	**Elements**
Raw materials	Bauxite, chromium, hydrogen, iron ore, limestone, magnesite, manganese, natural graphite, nickel, phosphorus, silica, silicon, synthetic graphite, vanadium, zirconium.
Processed materials	*Common carbon and stainless-steel grades, High alumina refractory lining material, Nickel/Chromium based steel alloys.*
Components	*Direct reduction shaft furnace vessel (shell), High-temperature cast pipes, Valves.*
Assemblies	*Blower, Compressor, Direct reduction shaft furnace, Fan, Gas recovery system, Process gas heater, Pump.*
Super-assembly	Hydrogen direct reduced iron plant

Source: JRC analysis.

Table 25. Elements considered in the electric arc furnace (EAF) supply chain (partial analysis).

Stage of the supply chain	**Elements**
Raw materials	Coking coal, magnesite, natural and synthetic graphite.
Processed materials	*Refractory lining material: Magnesia bricks, Synthetic graphite.*
Components	*EAF furnace vessel (shell), Graphite electrodes.*
Assemblies	*EAF furnace*
Super-assembly	EAF plant

Source: JRC analysis.

Section 2.9 Data transmission networks

Table 26. Elements considered in the data transmission networks supply chain.

Stage of the supply chain	**Elements**
Raw materials	Aluminium, antimony, arsenic, baryte, bismuth, borate, cobalt, copper, erbium, fluorspar, gadolinium, gallium, germanium, gold, gypsum, holmium, indium, iron ore, lanthanum, lead, lithium, manganese, molybdenum, natural graphite, neodymium, nickel, niobium, palladium, phosphate rock, platinum, praseodymium, rhenium, rhodium, ruthenium, samarium, selenium, silicon metal, silver, strontium, tantalum, tellurium, thulium, tin, vanadium, ytterbium, yttrium, zinc, zirconium.
Processed materials	Al2O3 (alumina), aramid fibres (kevlar), carbon fibres, carbon nanotubes (CNTs), epoxy resin, FR-4 laminates, GaAs (gallium arsenide), GaAs wafer (gallium arsenide wafer), GaN (gallium nitride), glass fibres, graphene, PEEK (Polyetheretherketone), PPS (Polyphenylene sulphide), PS (Polystyrene), PTFE (Polytetrafluoroethylene) - expanded, PTFE (Polytetrafluoroethylene) - teflon, PU (Polyurethane), Si wafer (silicon wafer), steel, steel (stainless), thermoplastics, Ti oxide, Zr oxide *Not assessed: BaCO3 (barium carbonate), BaO (barium oxide), BaS (barium sulfide), BTO (barium titanate), Bi2O3 (Bismuth trioxide), BixTixOx (Bismuth titanate), CaTiO3 (Calcium titanate), CZ (calcium zirconate), cobalt oxide (II)(II,III), CuBe alloys, GaP (gallium phosphide), InP (indium phosphide), InP wafers (indium phosphide wafers), LaTiO3 (lanthanum titanium trioxide), La2Ti2O7 (dilanthanum dititanium heptaoxide), liquid crystal, LCP polymer, LiNbO3 (lithium niobium oxide), LiTaO3 (lithium tantalate), LTCC (low-temperature co-fired ceramics), metal oxide nanoparticles, MgO (magnesium oxide), Mn-Zn ferrite, MoO3 (molybdenum trioxide), MXene, Nb2O5 (diniobium pentaoxide), Nd2O3 ((di)neodymium trioxide), Ni-Zn ferrite, optical fibre cladding material (fluorinated polymer), PC - polycarbonates (plastics), PP (polypropylene), PVC, PrO (praseodymium oxide), RuO (ruthenium oxide), Sb2O3 (antimony trioxide), Sb2O5 (antimony pentoxide), SmO (samarium oxide), SiO2 (silicon oxide), SiN (silicon nitride), SnO (tin oxide), SrO (strontium oxide), TaN (tantalum nitride), Ta2O5 (ditantalum pentaoxide), TiN (titanium nitride), V2O5 (divanadium pentoxide), vitreous enamel, WO3 (tungstic trioxide), YBCO (yrium barium copper oxide), Y2O3 (yttrium(III) oxide, yttria)*
Components	Antenna elements, PCB (printed circuit boards), fibre cables, opto/optoelectronics, semiconductors (analogue), logic semiconductor chips <45 nm, semiconductors (memory), sensor chips, passive components, RF components (as a component group), submarine cables *Not assessed: PCB antenna elements, semiconductors (discrete, and other chips)(DO), add/drop multiplexer (ADM), baluns, circulators, ferrites, generators, low noise amplifiers (LNAs), mixers, modulators, power amplifiers (PAs), power wave modulators (PWMs), receivers, relays, resonators, switches, thyristors, transceivers, transformers, transistors, transmitters, tubes, waveguides*

Stage of the supply chain	Elements
Assemblies	Ethernet switch, antenna/AAS units, microwave systems, antenna/AAS integrated radio units *Not assessed: Access routers, access switches, baseband units, CCAP equipment, customer premises equipment (CPE), CWDM equipment, DWDM equipment, IP/MPLS metro/core routers, mobile core nodes: partially/fully equipped server rack, MSAN equipment, OLT equipment, optical transmission/terminal equipment, radio units / remote radio units, ROADM equipment, submarine branching units, submarine repeaters*
Super-assemblies	*Not assessed: Multi-service access node (MSAN), optical line terminal (OLT), access switches/routers, frontend nodes/sites (optical nodes/sites), base stations (BS), mobile core nodes/network, IP/MPLS metro/core nodes/sites, optical transport network (OTN or TN) nodes/sites, CWDM (course wavelength division multiplexing), remote operation add drop multiplexing (ROADM), landing station, shallow water cable, deep sea cable*
Systems	Fixed broadband (BB) access network, mobile / wireless / cellular access network, data transmission and IP core network

Source: JRC analysis.

Section 2.10 Data storage and servers

Table 27. Elements considered in the data storage and servers supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, antimony, arsenic, baryte, beryllium, bismuth, boron, chromium, copper, dysprosium, gallium, germanium, gold, hafnium, helium, indium, iron ore, krypton, magnesium, manganese, neodymium, neon, nickel, palladium, phosphorus, platinum, praseodymium, ruthenium, scandium, silicon metal, silver, terbium, tin, titanium, xenon, zinc
Processed materials	Aluminium alloys and semis, ceramic dielectric materials (incl. barium titanate), copper semis, Cu-Be alloys, epoxide resin, flame retardant chemicals, FR-4 laminates, GaAs (gallium arsenide), GaN (gallium nitride), GeCl4 (germanium tetrachloride), glass fibres, NdFeB permanent magnet alloys, nickel alloys, optical fibre cladding material (fluorinated polymer), photomask chemicals, photoresistant chemicals, platter substrate materials, semiconductor dopant materials, semiconductor wafer (all sizes), SiCl4 (silicon tetrachloride), silicon carbide, solder materials, specialised aluminas, steel, surface finish for printed circuit boards, TIM (thermal Interface Materials), wet chemicals, zinc semis
Components	<10 nm logic chips, >45 nm logic chips, 10-22 nm logic chips, 28-45 nm logic chips, analogue chips, capacitors, connectors, cooling fans, CPU heatsinks, ethernet cables, housing/chassis, inductors, linear resistors, memory chips, NdFeB permanent magnets, PCB (printed circuit board), read & write head actuator, spindle motor
Assemblies	CPU (central processing unit), DRAM (dynamic random access memory), ethernet switch, expansion card/graphic card, GPU (graphics processing unit), HDD (hard disk drive), motherboard, NAND memory module, power supply unit, router, SSD (solid-state drive)

Super-assemblies	Enterprise network, enterprise server, enterprise storage system

Source: JRC analysis.

Section 2.11 Smartphones, tablets and laptops

Table 28. Elements considered in the smartphones, tablets and laptops supply chain.

Stage of the supply chain	**Elements**
Raw Materials	Aluminium, antimony, arsenic, baryte, beryllium, bismuth, boron, cadmium, cerium, chromium, cobalt, copper, dysprosium, europium, fluorspar, gadolinium, gallium, germanium, gold, hydrogen, indium, iron ore, krypton, lanthanum, lead, lithium, magnesium, manganese, molybdenum, natural graphite, neodymium, neon, nickel, palladium, phosphorus, platinum, praseodymium, ruthenium, silica, silicon metal, silver, strontium, talc, tantalum, tin, titanium metal, tungsten, xenon, yttrium, zinc
Processed material	Al alloys, Al sheet, Al2O3 (alumina), Cu alloys and semis, epoxy resin, flame retardant chemicals, GaAs (Gallium Arsenide), GaN (gallium nitride), glass (hardened), LCO (Lithium Cobalt Oxide) active material, LiPF6 (Lithium Hexaflurophosphate), Mg alloys, natural graphite anode material (batteries), NCA (Nickel Cobalt Aluminium Oxide) active material, NdFeB permanent magnet alloys, NMC (Nickel-Manganese-Cobalt-Oxide) active material, PET, photomask chemicals, photoresistant chemicals, sapphire substrate, Si wafer (Silicon wafer), solder paste, steel (crude), synthetic graphite anode material (batteries), Ti oxide, wet chemicals *Not assessed: Aromatic polyimide polymer, Au-Pt-Pd coating, Benzenedicarboxylic acid polymer, BTO (Barium titanate - IV), Cu plating chemicals (Cu, Ni, Cr), ferrite powder, fibrous-glass-wool, fused silica, Hva-2 (PDM), insulating laminate, ITO (Indium-tin oxide), LCP polymer, LiF (Lithium fluoride), MoO3 (molybdenum trioxide), Ni plating chemicals, Ni-Au finish layer, PeDOT (pyrole, conductive polymer materia), Pegoterate- (inn), PFO (poly(9,9-dioctylfluorene), Phenol polymer, phosphors (incl. REE), pigment black 28, Polycarbonate, PU (Polyurethane), PVDF additives - polyvinylidene fluoride, silicones, SiO2 (silicon oxide) - glass fibre (silica), steel coating, vinyl silicone oil, W alloy (tungsten alloy), ZnO (Zinc oxide)*
Components	Analog chips, anodes Li-ion, cathodes Li-ion, CMOS Sensor chip, copper parts: screws, plating, coil, CPU logic chips (laptops), electrolyte, EMI shields (steel sheets), glass substrates and organic layers (ETL, active layer, HTL), cathode, GPU logic chips (laptop), LED chips, liquid crystal, logic semiconductor chips, memory chips, NdFeB permanent magnets, passive components, PCB, sensor chips, separators (Li-ion) *Not assessed: Au connectors, common Electrode (ITO), connectors, display frame, gold bond wires, host interface (logic chips in SSD), membrane foil, metal cover, metal-based housing for smartphones, tablets, and notebooks, midframe, other mechancial parts, including Tungsten, plastic adhesive, plastic housing for smartphones, tablets, and notebooks, reflector sheet, light guide plate (LGP), diffuser sheet, prism sheet, bottom polarizer, thin film transistor*

Stage of the supply chain	Elements
Assemblies	Baseband processor, CPU (Central Processing Unit) – Laptops, CPU (Central Processing Unit) – Smartphones, CPU (Central Processing Unit) – Tablets, LED light, Front and rear camera, GPU (Graphics Processing Unit), LCD Screen, LED chips, Li-ion batteries cells, NAND Flash memory, OLED display, radio frequency power amplifier, RAM (Smartphone and Tablet), RAM (Laptops), speakers and microphone, SSD (Solid-State Drive) *Not assessed: Fan, hard disk drive (declining market share), fan, keyboard and trackpad, other Ics, e.g. gyroscope, accelerometer, GPS module DAO/Analog semiconductors, MEMS, optical disk drive (declining market share), oower supply unit (not considered fundamental for the technology), vibration alert*
Super-assemblies	Smartphones, tablets and laptops

Source: JRC analysis.

Section 2.12 Additive manufacturing (3D printing)

Table 29. Elements considered in the additive manufacturing supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, chromium, cobalt, copper, hafnium, iron ore, magnesium, manganese, molybdenum, nickel, niobium, scandium, silicon metal, titanium metal, tungsten, vanadium, zirconium
Processed materials	Al semis, Ni alloys, Other alloys, Stainless steel, Ti alloys
Components	-
Assemblies	-
Super-assembly	3D printer (metal)

Source: JRC analysis.

Section 2.13 Robotics

Table 30. Elements considered in the robotics supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, antimony, boron, cerium, chromium, cobalt, copper, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, gold, holmium, indium, iron ore, lanthanum, lead, limestone, lithium, lutetium, magnesium, manganese, molybdenum, natural graphite, neodymium, nickel, palladium, platinum, potash, praseodymium, rhenium, ruthenium, samarium, silicon metal, silver, tellurium, terbium, thulium, tin, titanium metal, vanadium, ytterbium, zinc

Stage of the supply chain	Elements
Processed materials	Al alloys, Ni-Ti alloys, magnesium alloys, specialty steels, polymers, CFC (carbon fibre composites), aramid fibres (kevlar), advanced ceramic & glass, carbon paper/ cloth, carbon nanotubes (CNTs), Cu semis, graphene, NMC (nickel-manganese-cobalt-oxide) active material, NCA (nickel cobalt aluminium oxide) active material, LFP (lithium iron phosphate) active material, LCO (lithium cobalt oxide) active material, LMO (lithium manganese oxide) active material, natural graphite anode material (batteries), mica, LSC (lanthanum strontium chromite), LSCF (strontium-doped lanthanum cobaltite ferrite), LSM (strontium-doped lanthanum manganite), NdFeB permanent magnet alloys, Ni alloys, Ni oxide, PTFE (polytetrafluoroethylene) - teflon, Pt-Ru alloys, steel, steel (stainless), synthetic graphite anode material (batteries), Ti oxide, ZrO2/Y2O3 (yttria stabilised zirconia)
Components	Aggregated components for fuel cells - PEM, aggregated components for fuel cells - SO, anodes Li-ion, cathodes Li-ion, catalysts, electrolyte, gears, separator, electrolyte (ceramic, SO), NdFeB permanent magnets, semiconductors (avg.), semiconductors (memory), semiconductors (logic < 10 nm), semiconductors (logic 10-22 nm), semiconductors (logic 28-45 nm), semiconductors (logic > 45 nm), semiconductors (DAO) discrete, analogue, and other chips
Assemblies	Actuators, CPU (central processing unit), fuel cells, GPU (graphics processing unit), Li-ion batteries cells, sensors
Super-assemblies	Industrial and service robots

Source: JRC analysis.

Section 2.14 Drones

Table 31. Elements considered in the drones supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium/bauxite, antimony, boron, cerium, chromium, cobalt, copper, dysprosium, erbium, europium, feldspar, fluorspar, gadolinium, gallium, gold, hafnium, holmium, indium, iron ore, lanthanum, lead, limestone, lithium, lutetium, magnesium, manganese, molybdenum, natural graphite, neodymium, nickel, niobium, palladium, platinum, potash, praseodymium, rhenium, ruthenium, samarium, silicon metal, silver, tantalum, tellurium, terbium, thulium, tin, titanium metal, Tungsten, vanadium, ytterbium, zinc

Stage of the supply chain	Elements
Processed materials	Aluminium-magnesium alloys, Ni-Ti alloys, magnesium alloys, titanium alloys, specialty steels, high performance alloys, refractory metal powder, CFC (carbon fibre composites), aramid fibres (kevlar), ferroniobium, Al sheet, carbon paper/ cloth, carbon nanotubes (CNTs), Cu semis, graphene, NMC (nickel-manganese-cobalt-oxide) active material, NCA (nickel cobalt aluminium oxide) active material, LFP (lithium iron phosphate) active material, LCO (lithium cobalt oxide) active material, LMO (lithium manganese oxide) active material, natural graphite anode material (batteries), mica, LSC (lanthanum strontium chromite), LSCF (strontium-doped lanthanum cobaltite ferrite), LSM (strontium-doped lanthanum manganite), Ni alloys, Ni oxide, PTFE (polytetrafluoroethylene) - teflon, Pt-Ru alloys, steel, steel (stainless), synthetic graphite anode material (batteries), thermoplastics, Ti oxide, ZrO_2/Y_2O_3 (yttria stabilised zirconia)
Components	Aggregated components for fuel cells - PEM, aggregated components for fuel cells - SO, anodes Li-ion, cathodes Li-ion, catalysts, electrolyte, electrolyte (ceramic, SO), gears, NdFeB permanent magnets, semiconductors (avg.), semiconductors (memory), semiconductors (logic < 10 nm), semiconductors (logic 10-22 nm), semiconductors (logic 28-45 nm), semiconductors (logic > 45 nm), semiconductors (DAO) discrete, analogue, and other chips, separators
Assemblies	Actuators, communications system, CPU (central processing unit), fuel cells, GPU (graphics processing Unit), IMU (inertial measurement unit), Li-ion batteries cells, LiPo (lithium polymer) batteries, navigation and control systems, sensors
Super-assemblies	Drones

Source: JRC analysis.

Section 2.15 Space launchers and satellites

Table 32. Elements considered in the space launchers & satellites supply chain.

Stage of the supply chain	Elements
Raw materials	Aluminium, antimony, arsenic, barite, bauxite, beryllium, bismuth, boron, cerium, chromium, cobalt, copper, dysprosium, fluorspar, gadolinium, gallium, germanium, gold, hafnium, helium, hydrogen, krypton, indium, iridium, iron ore, lanthanum, lead, lithium, magnesium, manganese, molybdenum, natural cork, neodymium, nickel, niobium, palladium, phosphorus, platinum, rhodium, samarium, scandium, selenium, silica, silicon metal, silver, sulphur, tantalum, terbium, titanium metal, tungsten, vanadium, xenon, yttrium, zinc, zirconium
Processed materials	Aluminium semis, anode-grade grade materials, aramid fibre (Kevlar), carbon nanotubes, carbon fibres, cathode-grade materials, gallium nitride, gallium arsenide, germanium wafer (space grade), laser crystal (Yttrium), magnesium alloys, magnets, metal powders (Ti, Ni), nickel alloys, silicon carbide (space-grade), titanium products (semi finished products), Xenon/Krypton (space grade).
Components	Chemical propulsion thrusters, combustion chamber, electrodes for batteries (space-grade), generic electronics and passive components (space

Stage of the supply chain	**Elements**
	grade), hall effect thrusters, high-power Laser instruments (Nd:YAG or cooling applications), honeycomb panels structure, injectors, nozzles (launchers), tank components and mettalic structures, tubes and cryogenics lines, turbo-pumps
Assemblies	Active thermal control, actuators, additive layer manufacturing structures (space-grade), antennas (space-grade), batteries (space-grade), central processing unit, deployable and steering mechanisms, engines (satellites), engines (launchers), interface ring, modem (space), primary structures and tanks, sensors.
Super-assemblies	Attitude and orbit control systems, communication and tracking systems, launch interface, mechanical systems, on-board data handling system, payload, power sub-systems, propulsion, structure, telemetry and command systems, thermal systems
Systems	EU-manufactured satellites Launchers: Ariane 5, Vega C, Soyuz

Source: JRC analysis.

Annex 3. Additional methodological notes

This annex reports additional methodological notes on selected sections.

Executive summary and Chapter 3 Sectors – Sankey diagrams

The Sankey diagram is organised in three different rows. The upper row represents three different classes of raw materials, non-critical, critical andstrategic. Among the critical raw materials, 25 are also strategic raw materials. The middle row represents the fifteen technologies analysed; the bottom row represents the five sectors addressed in this study. The arrows are coloured with three different colours, corresponding to the colours of the criticality of the materials (critical = bright red and strategic = dark red). The thickness of the arrow represents the proportion of each type of raw material. The sum of each raw material along the different technologies is constrained to a constant amount that depends on the number of different raw materials in that material category.

The thickness of the arrows that flow from the upper row (raw material) to the top of the middle row (technologies) represents the proportion of raw material needed in a technology, e.g., niobium is used in batteries, wind turbines, data transmission networks, data storage and servers, additive manufacturing, drones, and space launchers and satellites. The thickness of the arrows in the final row represents the proportion of the raw material used by each sector, e.g., solar PV contributes to renewables, ICT, and aerospace & defence sectors. The sum of all contributions is constrained to sum the same as the upper row.

Section 1.2.1 Methodology for the supply chain analysis

In the Criticality Assessment, the Supply Risk for raw materials is calculated according to the following formula (EC, 2017):

$$\boldsymbol{SR} = \left[\left(\boldsymbol{HHI_{WGI,t}}\right)_{\boldsymbol{GS}} \cdot \frac{\boldsymbol{IR}}{\boldsymbol{2}} + \left(\boldsymbol{HHI_{WGI,t}}\right)_{\boldsymbol{EUsourcing}} \left(\boldsymbol{1} - \frac{\boldsymbol{IR}}{\boldsymbol{2}}\right)\right] \cdot (\boldsymbol{1} - \boldsymbol{EoL_{RIR}}) \cdot \boldsymbol{SI_{SR}} \tag{1}$$

Where:

- *SR = supply risk;*
- *GS = global supply, i.e. global suppliers countries mix;*
- *$EU_{sourcing}$ = actual sourcing of the supply to the EU, i.e. EU domestic production plus other countries importing to the EU;*
- *HHI = Herfindahl-Hirschman Index (used as a proxy for country concentration);*
- *WGI = scaled World Governance Index (used as a proxy for country governance);*
- *t = trade parameter adjusting WGI;*
- *IR = import reliance;*
- *EOL_{RIR} = end-of-life recycling input rate;*
- *SI_{SR} = substitution index related to supply risk.*

Source: EC, 2017.

The $HHI_{WGI,t}$ parameter expresses the concentration of supply and is calculated as follows (EC, 2017):

$$\boldsymbol{(HHI_{WGI,t})_{GS\ or\ EUsourcing}} = \sum_c (S_c)^2 \boldsymbol{WGI_c} * \boldsymbol{t_c} \tag{2}$$

where:

- *S_c = the share of country c in the global supply mix or in the EU sourcing mix of the raw material considered;*
- *WGI_c = the scaled World Governance Indicators of country c;*
- *t_c = the trade-related variable of country c for a candidate raw material (RM).*

Source: EC, 2017.

The WGI is used as a proxy for country governance. This indicator is produced by the World Bank aggregating six dimensions of governance: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption (World Bank, 2022). This analysis considers the average between the six parameters from 2016 to 2020. The original parameter is comprised between -2.5 and -2.5. The final parameter is scaled up to between 0 and 10.

The t_c trade parameter quantifies how the trade conditions contribute to increasing or diminishing the Supply Risk related to a specific country for a candidate raw material. These conditions may include export restrictions and trade agreements between countries. This parameter is calculated according to detailed instructions reported in EC, 2017 and can amount to 0.8 (EU countries) or between 1 and 2 (non-EU countries, depending on the actual trade conditions).

The import reliance is calculated according to the following formula (EC, 2017):

$$\boldsymbol{Import\ Reliance\ (IR)} = \frac{\boldsymbol{Net\ Import}}{\boldsymbol{Apparent\ Consumption}} = \frac{\boldsymbol{Import - Export}}{\boldsymbol{Domestic\ production + Import - Export}} \quad (3)$$

Source: EC, 2017.

EoL_{RIR} is the end-of-life recycling input rate. It quantifies the material demand share covered with secondary sources. The substitution index (SI_{SR}) quantifies the possible substitution routes which may reduce the supply risk. This parameter is calculated according to detailed instructions reported in EC, 2017 and can range between 0.8 and 1.

In this work, the Supply Risk values for the raw materials are directly sourced from the 2023 Criticality Assessment (EC, 2023). Instead, values are directly calculated in this study for the elements in the supply chains steps following raw materials. In these steps, the same Supply Risk formula has in principle been applied. Practically, some information needed to calculate the Supply Risk according to Equation 1 is very hard to gather for the vast majority of the elements beyond raw materials. In particular, it is very hard to assess in detail the actual sourcing in the EU as well as the import reliance. Also, it is very difficult to assess the substitution routes for these elements. Therefore, the following simplified formula based on global supply and derived from Equation 1 has been applied for these steps:

$$\boldsymbol{SR} = \left(\boldsymbol{HHI_{WGI,t}}\right)_{\boldsymbol{GS}} \cdot (\boldsymbol{1} - \boldsymbol{EoL_{RIR}}) \quad (4)$$

Also, the t_c trade parameter for non-EU countries is simply set to 1 (corresponding to no specific export restrictions or regulations).

Two further adjustments are carried out in order to provide a more realistic picture of the Supply Risk for the EU in the light of its domestic production.

First, if only the aggregate EU production share is available and no further details are known on the actual distribution among Member States, the share is distributed among all Member States weighed on their GDP share in the EU economy. According to Equation 2, this lowers greatly the Supply Risk. This is done in order to avoid concentration of supply in one single actor, when it is likely not the case in the absence of specific information.

However, there are some cases where even applying the condition above, the Supply Risk is critical even if the EU domestic production is higher than 20%, typically because the remaining production is concentrated in one single third country (e.g China). If this is the case, the Supply Risk is artificially fixed to 0.95, provided that the EU quota is not concentrated in one single country. The latter condition is needed as the concentration of supply, even in one EU Member State, is in principle source of potential risk. In this case, no adjustment is applied.

The 20% threshold derives from the consideration that the average EU demand for the fifteen technologies analysed in this work is around 20% of the global demand, which is not surprising as the EU quota in the global GDP is about 18%. This implies that an EU production share higher than 20% for a certain material or product can broadly be interpreted as self-sufficiency of supply for the EU.

Section 2.3 Electrolysers

EU electrolyser capacity

The Strategic Research Innovation Agenda (SRIA) (Clean Hydrogen Joint Undertaking, 2022), and RePowerEU European Commission (EC) (2022c), (European Clean Hydrogen Alliance, 2022) are used as scenarios for the deployment of electrolyser technologies in the EU by 2030. In 2021, the SRIA stipulated the deployment of 80 GW of electrolysers, which includes 40 GW deployed in the EU and 40 GW to be built and deployed outside the EU by 2030. In 2022, The European Commission's RepowerEU Communication proposed a Hydrogen Accelerator, setting out a strategy to double the previous EU renewable hydrogen target to 10 million t of annual domestic production, plus an additional 10 million t of annual hydrogen imports. According to industry estimates, producing 10 million t of renewable hydrogen in the EU would require an installed electrolyser capacity of 90-100 GW (low heating value), depending on utilisation factors and efficiency rates.

Since the targets are given in terms of renewable hydrogen output, the 80 GW target translates into 114 GW, taking into account the 70% average efficiency of electrolysers. The 100 GW in RePowerEU translates into 143 GW of actual electrolyser capacity following the same assumptions. Such capacity should ensure the production of 10 million t of renewable hydrogen by 2030.

The forecast demand for hydrogen in 2050 of 32 million tonnes according to the "Fit for 55" package is used as a low demand scenario, and 75 million tonnes according to Hydrogen for Net-Zero scenario (McKinsey&Company and Hydrogen Council, 2021) as high demand scenario to calculate the capacity needed in 2050. While the first target is more in line with the forecast EU demand for hydrogen according to the IEA (International Energy Agency, 2022b), the second target aligns with the seven-fold increase in hydrogen demand predicted on a global level (World Bank, 2022). A summary of the capacity values and the hydrogen demand in 2030 and 2050 is given in Table 33.

Table 33. Target capacity in 2030 and hydrogen demand in 2030 and 2050 according to several sources.

Year	Installed electrolyser capacity (GW) (given in H2 output)	Assumed average efficiency of electrolysers (%)	Estimated electrolyser capacity considering electrolysers efficiency of 70% (GW)	H2 demand, MtH2
2030 (Low demand)	80 (40 + 40) - SRIA	70%	114	10
2030 (High demand)	100 - REPowerEU	70%	143	10
2050 (Low demand)	Fit for 55	70%	365	32
2050 (High demand)	McKinsey	70%	1073	75

Source: JRC analysis

US electrolyser capacity

The DoE has published targets of around 140 GW of installed capacity by 2030 and 1 000 GW by 2050. No other data are found for the deployment of electrolysers in the US (DOE, 2022).

China electrolyser capacity

An Energy Sector Roadmap to Carbon Neutrality in China provides data for every five years between 2025 and 2050, namely 23 GW to be installed by 2030 and 539 GW by 2050. The China Hydrogen Alliance has estimated that China's hydrogen demand will reach 35 million tonnes per year by 2030, from 20 million tonnes now, reaching 60 million tonnes by 2050 (International Energy Agency, 2021), (Xu M. et al., 2022).

More ambitious targets were recently announced by the National Development and Reform Commission, namely to produce up to 200 000 tonnes per year of carbon-free green hydrogen by 2025, which means scaling up capacity tenfold (Brown, A. et al., 2022). Almost all provinces and regions in China have included hydrogen in their development plans. More than 120 green hydrogen projects are under development. Some major firms such as Sinopec, Baosteel and GCL have also expanded into hydrogen production, using natural gas and renewable energy, building hydrogen filling stations and using hydrogen in steelmaking and transportation.

While in 2020 the installed electrolysis capacity in China was less than 20% of the European capacity, today China is ambitious to take the lead in producing the technology vital for green hydrogen, claiming to be able to produce electrolysers at a third of cost than in the US and Europe (Brown, A. et al., 2022).

Worldwide electrolyser capacity

Globally, the total installed capacity reached 0.5 GW in 2021 and is expected to grow to over 1 GW by the end of 2022. Data for global electrolysers deployment are taken from IEA (LDS) and IRENA (HDS). The IEA estimates that the global electrolysis capacity will be close to 200 GW by 2030 and 1400 GW by 2050. The IRENA 1.5°C (IRENA, 2022) scenario gives capacity close to 700 GW by 2030 (anticipated also by an IEA study (International Energy Agency (2022b)) and 5000 GW by 2050.

Market shares evolution of electrolyser technologies until 2050

For the EU, current market shares are taken from (Hydrogen Europe, 2022), namely: 40% alkaline, 59% PEM and <1% for both SO and AEM. A gradual decrease in alkaline and PEM technologies is assumed until 2050 to make space for SO and AEM technologies. The technology shares in 2050 for the EU, US and China are calculated based on number of existing companies in these countries. IEA data on global technology shares for 2020 are available, while 2030, 2040 and 2050 predictions are based on developments in the EU, US and China. Linear interpolation is carried out to obtain the values for the years in between. Constant shares are assumed for China due to the fact that the alkaline type is foreseen to remain the predominant technology and no Chinese companies were found developing SO and AEM electrolysers.

Average lifetime of electrolysers: 15 years.

Annual operational time: 5 000 hours.

Materials loading / intensity (material usage per unit power).

The current materials usage in unit power (per GW) are taken mainly from the IEA (International Energy Agency, 2020), as well as SRIA (Clean Hydrogen Joint Undertaking, 2022), which also gives targets up to 2030 for the use of PGMs in particular, such as iridium, platinum, ruthenium and rhodium. The same materials efficiency was assumed for the period 2030 – 2050.

Sources used for supply chain analysis

Various sources are used to identify companies along the supply chain: (Fuel Cells and Hydrogen Observatory, 2022), (HyTechCycling, 2018), (Hydrogen Electrolyzer, 2021), as well as company websites and research pulications.

Section 2.10 Data storage and servers

Technology Scope

For the purposes of the current assessment, the scope and boundaries of the data servers and storage technology are defined as follows:

1. The proposed scope includes all types of servers and storage systems intended for corporate use or when providing services for individual end-users (e.g. in a cloud application environment) are operated directly by businesses and the public sector. Portable data storage products intended for domestic users are excluded.
2. All types of data centres ranging from server rooms (traditional enterprise data centres) to hyperscale designs, including data centres providing digital services in the cloud, are considered.
3. Only ICT equipment is considered within scope. Support infrastructure/equipment necessary for operation not actually handling data is out of scope (i.e. undisruptive power supply (UPS), batteries, power distribution units (PDU), cooling and air conditioning infrastructure (CRAC/HVAC), safety, monitoring and control equipment).

4. The building itself (i.e. physical structure of the building and its respective building materials) is also not included in the proposed scope.

Methodological details

Estimations concerning raw materials usage in data servers and storage are based on the compositions of an average rack server and a virtual storage unit, as presented in the ecodesign preparatory study on enterprise servers and data equipment (EC, 2016) (see Table 34). Data concerning PCBs, fans, HDD magnet, controller board and PSU was further disaggregated into its individual raw materials, based on Talens Peiró and Ardente (2015) and references therein. The composition of cables, brass and steel was inferred internally based on multiple sources.

Table 34. Summary and technical specifications of reference equipment for the analysis of materials usage in data storage and servers.

Average rack-server
Technology level: Year 2012 2CPU socket (Intel E5-26XX), typical configuration according to SERT (average 2,3 GHz) Memory: 96 GB Storage: 4HDDs Internal cooling: heat sink material Heat pipes 4 fans with power consumption of 4-5 Watt at 25-50% load and 12-15 Watt per fan at max load or higher temperatures (30ºC) PSU (80 plus silver)/redundancy: 2 x 400 W (AC/DC) No extra power management Power consumption according to SERT (idle: 150 W / 25% Load 200W) Infrastructure Overhead/PUE: 2.0
Virtual storage unit (hybrid system)
Technology level: year 2012 1/2 Controller Media mix: 3.5 HDD, 2.5 HDD, SSD / total capacity ca. 40 TB 2 Disk Area Enclosures (DAE) containing a mix of 3.5 inch and 2.5 inch HDDs as well as SSDs Components: PCB (controller), connectors, PSU, Fans, Houing Power consumption according to SNIA averages Infrastructure Overhead / PUE: 2.0

Source: EC, 2016.

Annex 4. Global material supply and detailed results of the demand forecast analysis

Data can be retrieved online at the following link:

https://zenodo.org/record/7736782

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