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Integrated Working Paper on one strategic value chain 2

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Summary

Energy-intensive industries have a great impact on carbon neutral development by reducing fossil-based carbon emissions into the atmosphere. This working paper provides insights into pathways towards carbon neutral industry from critical and strategic raw materials perspective. Here, carbon neutral industry refers to technologies that have a major contribution for decarbonising energy-intensive industrial sectors and their critical raw materials demand. First, we outline the current situation, understanding the industry pathways to carbon neutrality, and focusing more on critical raw materials in new technology transitions such as process changes and renewable energy, instead of incremental CO2 reduction.

Approval

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TOWARDS CARBON NEUTRAL INDUSTRY

A CRITICAL RAW MATERIALS PERSPECTIVE

Jyri HANSKI (VTT Technical Research Centre of Finland), Päivi KIVIKYTÖ-REPONEN (VTT Technical Research Centre of Finland)

Energy-intensive industries have a great impact on carbon neutral development by reducing fossil-based carbon emissions into the atmosphere. This working paper provides insights into pathways towards carbon neutral industry from critical and strategic raw materials perspective. Here, carbon neutral industry refers to technologies that have a major contribution for decarbonising energy-intensive industrial sectors and their critical raw materials demand. First, we outline the current situation, understanding the industry pathways to carbon neutrality, and focusing more on critical raw materials in new technology transitions such as process changes and renewable energy, instead of incremental CO_2 reduction.

TOWARDS CARBON NEUTRAL INDUSTRY

Introduction

The EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. EU policies empower Europe's industries to transition to digitisation and technological change, a resource efficient and circular economy and the development of less polluting and less energy-intensive technologies (European Commission, 2018).

One of the strategic priorities is industrial modernisation at the centre of a fully circular economy, covering both brown and greenfield investments: modernising existing installations and investing in new carbon neutral and circular economy compatible technologies and systems (Comisión Europea, 2018).

Industry accounts for 24 % of global and 15 % of European greenhouse gas (GHG) emissions (High-Level Group on Energy-intensive Industries, 2019; IPCC, 2023). The global figure excludes emissions from industrial electricity use and the European figure includes emissions from chemical, metallurgical, and mineral transformation processes.

An estimate for the global GHG emissions of the energy-intensive industries is 25 % (UNECE, 2022) and they make up more than 50 % of EU industry energy consumption (High-Level Group on Energy-intensive Industries, 2019). Therefore, energy-intensive industries are major contributors to transitions towards a sustainable future.

The key challenge for EU and the Member States is to to lower emissions while keeping industry competitive and enabling access to the global market for low-carbon technologies and services. Does industry reach carbon neutrality targets through incremental CO_2 reductions and energy efficiency or through new and alternative processes and technologies? The incremental energy efficiency, waste heat recovery and material efficiency have long traditions in industrial operations, and beside the greenhouse gas emissions, typically cost reductions play significant role. Alternative or new processes and technologies stand for higher internal or external risk and are more strategic and long-term actions.

This report covers the following sectors, pathways and key technologies towards carbon neutral industry:

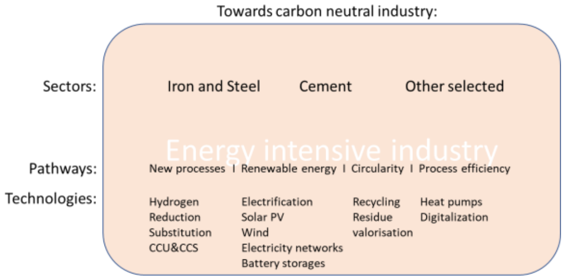

Figure 1. Outline of working paper with main sectors, pathways and technologies.

Framework boundaries for critical raw materials and carbon neutral industry

Critical raw materials are crucial for a wide range of technologies needed in EU strategic sectors such as the carbon neutral industry, ICT, space and defence. (Grohol and Veeh, 2023)

INFO BOX: Critical and strategic raw materials in the EU's assessment in 2023 (Grohol and Veeh, 2023) include (strategic raw materials bolded, copper and nickel with italics as they are considered strategic but not critical):

- Aluminium/Bauxite
- Antimony
- Arsenic
- Baryte
- Beryllium
- **Bismuth**
- **Boron/borate**
- **Cobalt**
- Coking coal
- Feldspar
- Fluorspar
- **Gallium**
- **Germanium**
- Hafnium
- **Heavy rare earth element (HREE)**
- Helium
- Light rare earth elements (LREE)
- **Lithium**
- **Magnesium**
- **Manganese**
- **Natural graphite**
- Niobium
- **Platinum group metals (PGM)**
- Phosphate rock
- Phosphorus
- Scandium
- **Silicon metal**
- Strontium
- Tantalum
- **Titanium metal**
- **Tungsten**
- Vanadium
- ***Copper***
- ***Nickel***

The **Critical Raw Materials Act** (European Commission, 2023a) has three main aims: 1) developing CRM value chains in the EU, 2) support the supply diversification and sustainable partnering in support of global production, and 3) promoting circularity. Concrete targets for SRMs by 2030 include: 10% of domestic demand for mining and extraction, at least 40% of domestic demand for processing and refining, at least 15% of domestic demand for recycling. Additionally, not more than 65% of the Union's annual consumption of each SRM at any relevant stage of processing should come from a single third country.

Net Zero Industry Act (European Commission, 2023b) defines eight strategic net-zero technologies for manufacturing industries: 1) Solar photovoltaic and solar thermal technologies, 2) Onshore wind and offshore renewable technologies, 3) Battery/storage technologies, 4) Heat pumps and geothermal energy technologies, 5) Electrolysers and fuel cells, 6) Sustainable biogas/biomethane technologies, 7) Carbon Capture and storage (CCS) technologies and 8) Grid technologies.

Pathways towards carbon neutrality

This working paper *towards carbon neutral industries* focuses on **energy and material-intensive industrial sectors with the highest share of emissions in the EU** that can reduce their emissions by implementing new processes and technologies, renewable energy, and circularity principles. This working paper covers iron and steel, cement, and selected other sectors such as chemicals and non-metallic minerals. For these energy-intensive industries, the key strategic technologies include hydrogen reduction technologies, carbon capture, utilisation and storage and heat pumps (JRC, 2023), new processes with reduced emissions and increased circularity. To support the transition, the carbon neutral industry needs low carbon energy production, electricity distribution and transmission networks and storage technologies.

Iron and Steel industry

Global annual consumption of iron ore and steel was about 2,200 and 1,700 Mt from 2017 to 2020, respectively. For the EU, the annual consumption of iron and steel were 127 and 148 Mt. (World steel association, 2022) Steel production is a significant source emissions in the EU with annual GHG emissions of 200 Mt CO_2 (Material Economics, 2019).

European iron and steel industry aims to reduce 80-95% of their GHG emissions by 2050 from 1990 emission level. This transition requires major investments in new technologies and 400TWh of new low carbon energy production. Iron and steel industry's strategic pathways are:

- carbon capture and storage (CCS) and usage (CCU)

- using renewable electricity and production of H2 to replace metallurgical carbon
- circular economy solutions such as recycling steel and side streams, and increasing resource efficiency (Eurofer, 2019)

The individual Member States are in line with European iron and steel industry pathways. In Germany the pathways include new and alternative technologies, such as direct reduction of iron based on hydrogen combined with the electricity regenerated from CO_2-free sources, but also in the short run incremental CO_2 reductions, energy efficiency actions such as heat recovery, scrap-based steel making and the use of by-products for the production of base metals (Arens *et al.*, 2017). Swedish steel industry case study considered the following pathway alternatives: top gas recycling blast furnace (TGRBF), carbon capture and storage (CCS), substitution of pulverized coal injection (PCI) with biomass, hydrogen direct reduction of iron ore (H-DR) and electric arc furnace (EAF), (Toktarova *et al.*, 2020).

Cement industry

Cement is used as the binding material in the production of concrete, the most widely used construction material The cement industry is responsible for about 7% of CO_2 emissions globally, and about 4% in the EU. (IEA, 2018; JRC, 2020)

High carbon intensity results from the clinker in Portland cement production, the active component that gives concrete its binding properties. This process involves the chemical reactions of calcium carbonate, which represents about 60-70 % of the total CO_2 emissions generated in the process, with the remainder of CO_2 emissions resulting from the combustion of fuels. (IEA, 2018) Cement industry's low carbon pathways include (Cembureau, 2020):

- improving energy efficiency
- switching to low carbon fuels and renewable electricity
- low carbon clinker, and reducing the clinker to cement ratio
- clinker substitution by using alternative binders and supplementary cementitious materials
- and integrating carbon capture into production.

The integration of emerging technologies like carbon capture and reducing of the clinker content in cement are identified to provide the largest cumulative CO_2 emissions reductions by 2050, with 48% and 37% contributions. (IEA, 2018; Nilsson *et al.*, 2020)

Pathways of selected other industries

Refining industry is one the largest CO_2 emitters. A recent CO_2 emission inventory estimates the CO_2 emissions of the refinery industry about 1.3 gigatonnes (Gt) in 2018, contributing 4% of the total global emissions. By counting the indirect emissions of refineries, the emissions total 42 % of global emissions (Beck et al., 2020). The share of EU refining industry of the total emissions was 17 % in 2018. (Lei et al., 2021)

Low carbon pathways for refining industry have been presented by Concawe, a division of the European Fuel Manufacturers Association, within its cross-sectorial Low Carbon Pathways (LCP) programme (Concawe, 2021). The identified technologies include, among others, energy efficiency, use of low-carbon energy sources (electrification, green hydrogen), CO_2 capture and storage, and the progressive replacement of crude oil by "low-carbon" feedstocks.

Glass and ceramic industry are both industries having typically high temperature processes and therefore also needing large amount to energy. Ceramic industry's measures for carbon neutrality include renewable energy (hydrogen, green electricity, biofuels), reduction of process emissions, efficient manufacturing process, CCUS and carbon removal and offsetting measures (Cerame-Unie, 2021). Glass industry's carbon neutrality measures include energy efficiency increase in glass production, increased use of recycled glass, waste heat recovery, carbon neutral energy sources and electric melting. Indirect measures include energy efficient glass for reducing emissions of buildings and lighter glass to save fuel costs. (Glass Alliance Europe, 2019)

For non-ferrous alloys, **aluminium industry**'s pathway focuses on energy and resource efficiency throughout the value chain. Suggested technologies include deployment of renewable energy sources. (European Aluminium, 2015). In the mid-term review of the roadmap in 2021, focus of aluminium industry has extended to more extensive circularity actions and increased recycling rate.

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Critical Raw Materials in key technologies for carbon neutral industry

The European Commission recognises the economic importance of ensuring a sufficient raw material supply to meet the demand. EU level critical raw materials listing arises from the growing concerns about securing valuable raw materials for the EU economy. In 2008, the Commission launched the European Raw Materials Initiative and one of its priority actions was to establish a list of Critical Raw Materials (CRMs) at the EU level. (European Commission, 2018)

There are many pathways to reduce carbon dioxide emissions, such as new processes or raw materials substitution, the use of renewable energy in production, increasing circularity and process efficiency. In the following, these strategies and their relationship to CRMs is discussed.

New processes and raw materials
New processes and raw materials have high potential for reducing emissions. In current working paper we focus on iron hydrogen reduction, substitution of metallurgical carbon and substitution of limestone for clinker, substitution of cement with supplementary cementitious materials for concrete or alkali-activated materials. These two sectors are linked together through iron and steel industry side-streams that are potential substitutes for concrete or concrete like products. *Potential impact on CRMs: substituting metallurgical carbon (coking coal) increases demand for CRMs in the hydrogen value chain.*

Renewable energy
The evident strategy towards fossil free production and climate neutral industry is to change needed energy source to renewable ones, such as solar or wind energy, and electrification of the processes. In this working paper we focus on renewable energy generation, transmission and distribution, and storage.
Potential impact on CRMs: increasing demand on CRMs used in solar and wind electricity production, electricity networks and storage (e.g., batteries) and electrification, e.g., electric motors that include permanent magnets.

Current processes and process efficiency
Improving current processes and their efficiency is typically a constant and incremental process, including improved energy efficiency and material efficiency. In this working paper we focus on carbon capture, utilisation and storage (CCUS), energy recovery and digitalization of industry that enables optimization, and supports traceability of raw materials.
Potential impact on CRMs: CCUS and heat pumps, savings in production asset wear and spare parts, raw materials for production, increase in digital technologies hardware that often have much shorter lifespan compared to industrial processes.

Circularity
Improving circularity can cover circular economy strategies through rethinking the system and reducing raw material consumption, lifetime extension strategies and recycling and recovery strategies. In current working paper we focus on using recycled materials and critical raw materials recycling and recovery from residues.
Potential impact on CRMs: using recycled materials and CRMs, recycling CRMs and recovery of CRMs from side-streams and residues.

New processes and raw materials: Hydrogen technologies for steel

Substitution of fossil-based metallurgical coal for iron oxide reduction will have a radical effect on reducing carbon dioxide emissions for the sector. Fossil-based coal can be substituted with hydrogen as reducing agent or bio-based (or waste-based) reducing agent. Substitution with hydrogen, especially, has a relevant impact on the demand for CRMs.

Hydrogen as reducing agent

There are two primary production routes for iron and steel industry. First route takes place in blast furnace where iron ore is reduced to iron by using coke. Iron is refined to steel in basic oxygen furnace. This route is very CO_2 and energy intensive. The second route is direct iron reduction by hydrogen and carbon monoxide followed by steelmaking in electric arc furnace with oxygen and lime. If low carbon hydrogen source and energy mix are used the process can be close to carbon neutral. (Carrara *et al.*, 2023)

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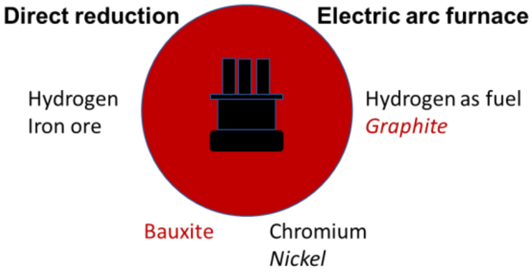

Figure 2. Raw material needs in direct iron reduction and electric arc furnace. Red colour = critical raw materials. Italics = strategic raw materials.

Use of critical raw materials in iron and steel production is related to CRMs need for industrial furnaces and raw material need for steels themselves (Figure 2). Hydrogen reduction process of steel is followed by electric arc furnace (EAF), where also scrap can be used as raw material. Concerning critical raw materials, graphite electrodes are typically used for EAF, while high temperature refractory materials are typically containing alumina (aluminum oxide) and other oxides such as magnesia (magnesium oxide), silica or zirconia. Nickel and chromium are the raw materials for stainless steel.

Supplying clean hydrogen with electrolysers

Hydrogen is expected to play a key role in transition to low-carbon industry. It has the potential to reduce the CO_2emissions of industrial processes used as raw materials and fuel and can be used as a fuel in the transport sector and as a combustible for heat supply. RePowerEU targets both EU production and import of 10 Mt of clean hydrogen to tackle import reliance on Russian energy and reach strict GHG emission reduction targets of 55% by 2030 and net-zero by 2050 (European Commission, 2023c).

Globally, hydrogen demand was 94 Mt (SCRREEN2, 2023). Industry consumed 51 Mt hydrogen in 2020. Chemical production, mainly oil refining, consumed 46 Mt and steelmaking 5 Mt. For the EU, hydrogen consumption was 9.3 Mt in 2021, divided into 4.8 in refining, 4.4 in chemicals, 0.1 in metal and 0.02 other uses (SCRREEN2, 2023). However, hydrogen is mainly produced from fossil fuels and has close to 900 Mt annual CO_2 emission. Low-carbon hydrogen met only 0.3 Mt of 2020 industry demand. The global production of low carbon hydrogen is expected to rise considerably to 21 Mt in IEA's 2030 low carbon scenario. (IEA, 2022a)

Main hydrogen production methods include natural gas reforming, gasification, electrolysis, renewable liquid reforming and fermentation. Hydrogen is typically produced at or close to where it is used. Hydrogen distribution infrastructure may consist of pipeline, high-pressure tube trailers transported by trucks, trains or ships for less than 300 km distances or liquefied hydrogen tankers for longer distances. (US Department of Energy, 2021). This study focuses on the use of electrolysers for producing clean hydrogen or fossil fuels linked with carbon capture, storage and utilization (CCUS).

DERA reports that critical raw materials for hydrogen production through water electrolysis could become scarce. Iridium and scandium are in greatest supply risk due to high demand, concentration of supply and small markets for these raw materials. Water electrolysis increases the demand of yttrium which is used as electrolyte material. Yttrium oxide and scandium oxide are substitutes in stabilising zirconium dioxides. Other raw materials important for water electrolysis include titanium, nickel, zirconium and cerium. (DERA, 2022). For specific technologies, the strategic and critical raw materials contained in Polymer electrolyte membrane technology (PEM) are iridium and platinum and in Alkaline electrolysis (AEL) cobalt, platinum and nickel (Gavrilova and Wieclawska, 2021). Other relevant technologies include Solid oxide (SO) and Anion exchange membrane electrolysers (AEM) (Carrara *et al.*, 2023). Water electrolysis technologies' raw material needs are presented in Figure 3 (Gavrilova and Wieclawska, 2021; DERA, 2022; Carrara *et al.*, 2023).

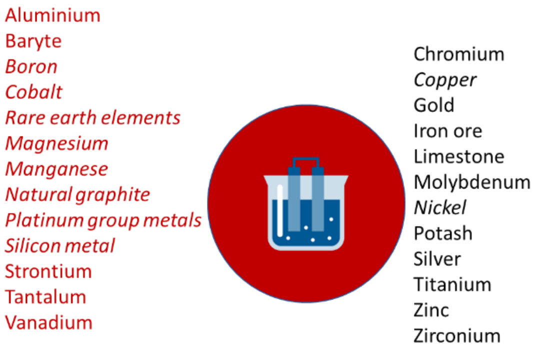

Figure 3. Raw material needs in water electrolysis technologies. Red colour = critical raw materials. Italics = strategic raw materials.

Critical, strategic and non-critical materials in water electrolysis are located in electrodes (cobalt), catalysts

(PGMs), coatings (gold), current collectors (silver), sealants (boron and REEs), interconnectors (iron ore and REEs) and bipolar plates (natural graphite) (Carrara *et al.*, 2023).

Alternative materials for cement production

Traditional clinker production in a rotary kiln requires energy for chemical reaction, calcination. This chemical reaching results 60-65% of cement manufacturing emissions, rest being mainly the energy needed for heating up to 1450 °C.

Clinker can be partially substituted by so-called supplementary cementitious materials, such as fly ash from coal power plants and blast furnace slag from steelmaking (JRC, 2020). However, in steel making, the hydrogen reduction process substitutes the traditional blast furnace. Fossil-based coking coal substitution strategies in steel making significantly impact cement industry pathways towards carbon neutrality through the relative high volumes of metallurgical slag streams utilization in downstream industries. According to Eurofer, total slag utilization was 34,1 Mt in 2019, and from blast furnace slag (22,3 Mt in 2019) 80.3 % was used for cement and concrete addition (Eurofer, 2020). This is because slag composition and structure change with process changes and its feasibility as raw material for clinker production or as supplementary cementitious material in cement, concrete or alkali-activated materials need research and development investments. In 2019, only 5.4 % of other types of slags were utilized for cements and other concrete additions (Eurofer, 2020).

Another option for reducing carbon dioxide emissions is carbon capture, utilization and storage (CCUS) discussed in the following chapter. It is estimated that the use of CCUS techniques will reduce carbon dioxide emissions by 42 % by 2050 (Cembureau, 2020).

Carbon capture, storage and utilisation (CCUS)

Carbon capture, storage and utilisation (CCUS) aims to capture CO_2 emissions from large emission sources such as power plants and either store or utilise the CO_2 in products. Main applications for CCUS include fossil power generation or emission-intensive industrial processes in industries like cement, iron and steel and refineries. Pilot projects for CCUS exist but large-scale CCUS plants have not been built yet (Carrara *et al.*, 2023).

Figure 4 presents the raw material needs in carbon capture, storage and utilization technologies.

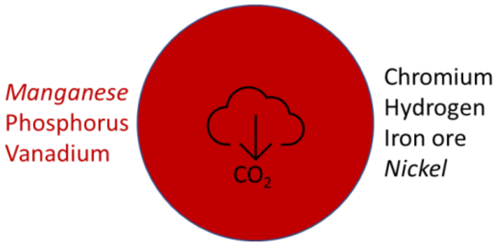

Figure 4. Raw material needs in carbon capture, storage and utilization. Red colour = critical raw materials. Italics = strategic raw materials.

Main critical raw materials needs are related to components such as pumps and compressors, and their raw materials and selected chemical. (Carrara *et al.*, 2023). Typical stainless steel contains nickel and chromium, for improved corrosion resistance molybdenum is added around two to three percent. Vanadium on the other hand improves strength and toughness properties of stainless steels.

Electrification and renewable energy

Industry electrification is a significant pathway towards carbon neutral production. Electrification and energy-intensive industry requires considerable amounts of energy for high temperature processes, therefore transition to renewable energy is a crucial pathway towards carbon neutrality.

Cross-cutting technologies for carbon neutral industry covered in this report include electrification related technologies such as electric motors and robots, and technologies for low carbon electricity generation, storage and transmission. These technologies have substantial needs of critical and strategic raw materials. For electricity generation, the specific technologies covered include solar photovoltaics (Solar PV) and wind turbines.

Other key electricity generation technologies for low carbon industry include nuclear power and hydropower. Key raw material needs in these technologies are aluminium, chromium, manganese, molybdenum, titanium and zinc for hydro and aluminium, chromium, copper, hafnium, indium, nickel, REEs, vanadium and zirconium for nuclear (IEA, 2022; USGS, 2023).

Electrification

The low temperature processes with industrial heat pumps, and electric arc furnaces in steel production show much promise for industrial electrification. Electric motors are used in many industrial applications such as in pumps, fans, machine and power tools and in compressors. Increasing automatization of production increases the number of robots in industries. Electric motors and robots contain permanent magnets that are rich in strategic and critical raw materials.

Figure 5 presents the raw material needs for electrification exemplified by traction motors, permanent magnets and robots (Carrara *et al.*, 2023).

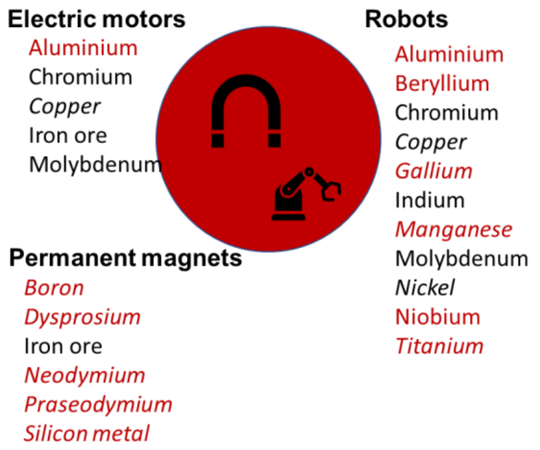

Figure 5. Raw material needs in electrification. Red colour = critical raw materials. Italics = strategic raw materials.

Electric motors contain Al in casings, Fe, Cr and Mo in stainless steel, and Cu in cables. Robots contain Fe, Mo, Ni, Nb, Ti, Mn and Cr in steels, Be, Ga and In in electro-optical systems, and Al as an alloy in many components. Permanent magnets contain B, Dy, Fe, Dy, Pr and Si. (Carrara *et al.*, 2023)

Solar photovoltaics (Solar PV)

Solar PV plants consist of modules, inverters, trackers, mounting structures and general electrical components. Currently, the main module types include c-Si (silicon, copper, silver), CdTe (cadmium, tellurium), CIGS (indium, gallium, selenium) and amorphous silicon (a-Si). (IEA, 2022b)

Assuming dominance of c-Si modules for solar PV applications, copper demand is expected to rise from 350 kt in 2020 to almost 1000 kt in 2040 in sustainable development scenario. Similarly, silicon demand is expected to rise from 400 kt in 2020 to 800 kt in 2040. Silver demand is expected to stay at around 2 kt from 2020 to 2040.

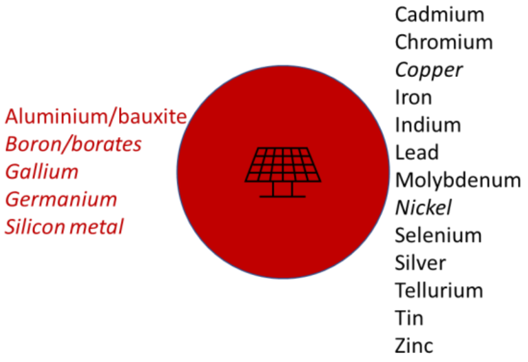

Figure 6. Raw material needs in solar PV (JRC 2013, IEA (2022), OECD 2022, Factsheet (2020) to be updated to 2023). Red colour = critical raw materials. Italics = strategic raw materials.

Panel frame contains of elements such as Al, Cu, Fe, Pb, Mo, Ni, Sn and Zn, semiconductors and connectors contain elements such as B, Ga, Ge, Si, and Ag, whereas solar cells or modules may contain following elements: Cd, Cu, Ga, In, Mo, Se, Sn, and Te (IEA, 2022b; Carrara *et al.*, 2023).

Wind turbines

In 2020, global wind power capacity was 732 GW, of which 698 GW was onshore wind and 34 GW offshore wind. The global installed capacity is expected to rise to 5,000 GW by 2040 based on sustainable development scenarios. (Carrara *et al.*, 2023)

Wind turbines consist of a tower, a nacelle and rotors and a foundation. Raw materials intensity in turbines is dependent on turbine type and size, e.g., direct-drive permanent magnet synchronous generator (DD-PMSG) contain larger amounts of REE than gearbox permanent magnet synchronous generator (GB-PMSG) turbines (IEA, 2022b).

In sustainable development scenario, the global demand for REE is expected to rise from 4 kt in 2020 to about 12 kt in 2040 in wind power applications (onshore and offshore). Similarly, copper demand is expected to rise from 200 kt in 2020 to 600 kt in 2040, and zinc demand from 300 kt in 2020 to 800 kt in 2040. (IEA, 2022b)

Raw material needs of wind power generation is presented in Figure 7 (IEA, 2022b; Carrara *et al.*, 2023).

Figure 7. Raw material needs in wind power generation. Red colour = critical raw materials. Italics = strategic raw materials.

Wind turbines contain B, Dy, Fe, Nd, and Pr in permanent magnets, Al, Cr, Fe, Mn, Mo, Nb, Ni, and Si in tower, nacelle, rotor, blades and foundation, Zn in corrosion coatings and Cu and Pb in soldering, cables and other components. In addition to these raw materials, wind turbine blades may contain materials such as balsa wood, glass fibre, carbon fibre, polymers or plastics. (Carrara *et al.*, 2023)

Electricity transmission and distribution networks

Electricity transmission and distribution networks connect electricity generation and end users with lines, substations, and other necessary equipment. Introduction of intermittent electricity generation, such as solar and wind, and increased reliability requirements have greatly increased the amount of digital measurement and control equipment and other advanced information and communication technology in the electricity networks. In addition to integrating renewable production to the network, these smart grids enable the integration of electricity storage, electric vehicles and various devices to the network (Ketter et al., 2018). Smart grids and integration of renewables requires doubling of the extent of electricity networks by 2040 in the sustainable development scenario (IEA, 2022b).

Material needs for electricity distribution and transmission networks are introduced in Figure 8 (Wellmer *et al.*, 2019; Deetman *et al.*, 2021; IEA, 2022b). This report focuses on transmission and distribution lines and transformers. In addition, these networks require a considerable number of digital technologies in smart meters, switches, servers, routers and optical cables and various technologies for electricity storage.

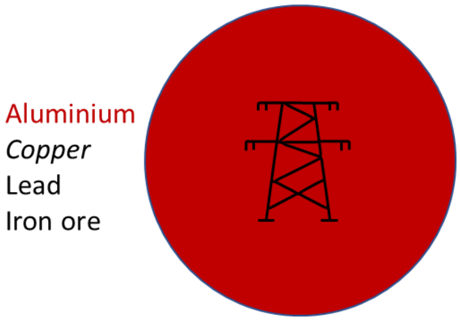

Figure 8. Raw material needs in distribution and transmission networks. Red colour = critical raw materials. Italics = strategic raw materials.

The demand for raw materials is expected to increase from 9 to 16 Mt (aluminium) and from 5 to 10 Mt (copper) by 2040 in the sustainable development scenario (IEA, 2022b). For reference, global refined aluminium consumption in 2020 was about 65 Mt and copper cathode 25 Mt (International Copper Study Group, 2022; World Bureau of Metal Statistics, 2022).

Electricity storage in electricity networks

Battery storage capacity connected to electricity networks was around 15.5 GW at the end of 2020 and is expected to increase 25-fold by 2040. The most important part of batteries are cells that contain active cathode materials such as lithium, nickel, cobalt and manganese, anode material (e.g., graphite) and current collector (e.g., copper). Other key raw materials in batteries include aluminium and steel. (IEA, 2022b)

Lithium iron phosphate (LFP) is considered as one of the most important battery chemistries for stationary electricity network applications. The key raw materials in this chemistry are copper, lithium and graphite. Other important chemistries include nickel manganese cobalt oxide (NMC) containing copper, lithium, nickel, cobalt manganese and graphite and nickel cobalt aluminium oxide (NCA) containing copper, lithium, nickel, cobalt and graphite. Other relevant chemistries for current and future stationary solutions include vanadium flow batteries, solid state batteries and sodium ion batteries. (IEA, 2022b)

Key raw materials in stationary battery applications for electricity networks are presented in Figure 9 (IEA, 2022b; Carrara *et al.*, 2023).

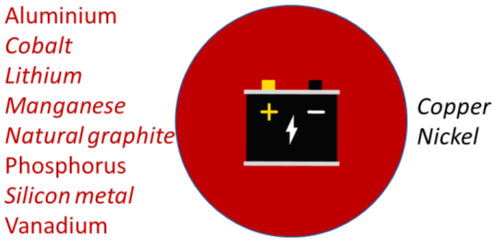

Figure 9. Raw material needs in stationary battery applications. Red colour = critical raw materials. Italics = strategic raw materials.

Demand for minerals in stationary batteries is expected to grow from 26 kt to 850 kt between 2020-2040. Nickel demand in stationary batteries is expected to grow from 0.4 kt in 2020 to 57 kt in 2040, while cobalt and manganese demand are expected to be 70 and 58 times higher in 2040. (IEA, 2022b)

Process efficiency

Key technologies for increasing process efficiency include widespread adoption of industrial heat pumps and various digital solutions for optimization of production processes, product life cycle performance and maintenance.

Industrial heat pumps

A heat pump is a device that transfers heat from a lower to a higher temperature using a refrigeration cycle. Heat pumps are typically used as a heat or cooling source in residential buildings, but it can also be used for industrial applications. Industrial heat pumps can decarbonise industrial process heat at temperatures above 70°C and below 180°C. For carbon neutral industry application potential include cement, chemicals and metals still have several low-temperature processes and waste heat streams. (Carrara et al., 2023)

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).

Industrial heat pumps, consists of a frame, piping, compressor, heat exchangers, ICT, permanent magnets and refrigerants which contain various critical, strategic and non-critical raw materials. Figure 8 presents the raw material content in industrial heat pumps (Carrara *et al.*, 2023):

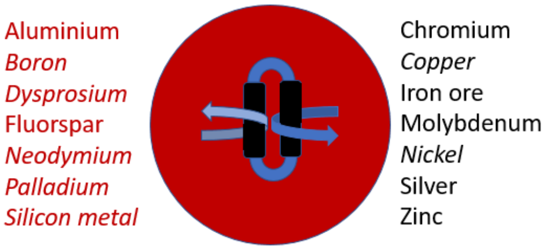

Figure 10. Raw material needs in industrial heat pumps. Red colour = critical raw materials. Italics = strategic raw materials.

Heat pumps contain Fe, Mo, Cr, and Ni in steels, Zn, Ag, Al, and Cu in housing, piping and heat exchangers and Pd, Si and Ni in electric components. B, Dy, and Nd in used in permanent magnets. F is used in refrigerants. (Carrara *et al.*, 2023)

Currently, industrial heat pumps are in their infancy and there are no large-scale projects in the EU. However, there are estimates of industrial heat pumps replacing the fossil fuels in below 500 °C applications by 2035 (Carrara *et al.*, 2023).

Digitalization of industry

Digitalization of industry enables optimisation of production processes, maintenance, and product performance and, therefore supports reaching carbon neutrality targets. The entire value chain of a product from extraction to processing, manufacturing, and end of life activities is being digitalized to collect more data and analyse it for optimal performance of products and production assets. Consequently, more sensors, data processing units, data storages and servers, digital control

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systems, data transmission networks and end devices such as laptops, mobile phones and displays are installed or used in production facilities. The assets are tracked to identify their location, for monitoring their condition and status and to plan for their optimal maintenance routine. The products themselves are embedded with sensors.

Digitalization of industry leads into increase of installed ICT components in data transmission networks, end devices and data storage and servers.

Digital technologies cover almost the entire period table of elements. Key CRMs in digital technologies include antimony, bismuth, cobalt, chromium, copper, gallium, germanium, gold, indium, molybdenum, natural graphite, nickel, magnesium, PGMs, REEs, selenium, silver, tantalum, tellurium, tin and vanadium. Raw materials of digitalization represent only a tiny fraction of the total use of all metals, but for some of them such as gallium, germanium, indium and tellurium, digital technologies accounts for 80–90% of total usage (Eerola *et al.*, 2021).

Figure 11 covers raw materials needs for data storage, servers, data transmission networks and end devices including displays and smart devices (Eerola *et al.*, 2021; Carrara *et al.*, 2023).

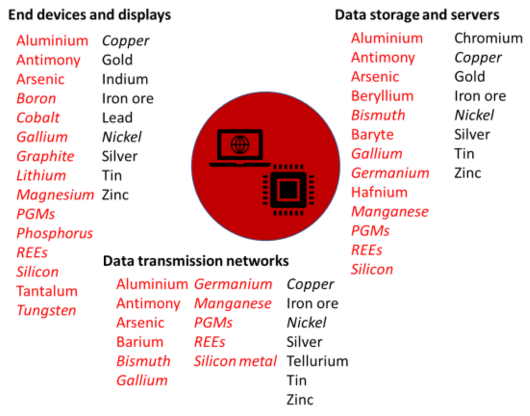

Figure 11. Elements commonly used in digitalization of industry. Red colour = critical raw materials. Italics = strategic raw materials.

Raw material needs of data storage and servers include Cr, Fe, Mn, Ni in steels, Zn and Cu in cabling and Al in contact pads of integrated circuits and thermal interface material. Ag, Au, Bi, Ba, PGMs, REE, Sb and Si are used in, e.g., printed circuit boards and Sn in solders. As, Be, Ga, Ge, Hf and Si are used in other key semiconductor components such as connectors, memory and optical coatings (Carrara *et al.*, 2023).

Raw material needs for smart devices and displays include Si, As, B, Ga, In, P and Sb in chips, whereas wiring and microelectronics contain Ag, Au, Cu and Ta. For instance, printed circuit boards contain Au, Cu, Ga, In, PGMs and Ta. Solder contains tin, silver, copper and lead even though lead-free alternatives are preferred. Microphone, cameras, vibration units and speakers contain B, Fe, Ga, REEs. Displays contain, for instance, Al, In, Si, Sn and REEs. Batteries contain Co, Graphite and Li. (Eerola *et al.*, 2021)

Raw material needs of data transmission networks include Ag, As, Ba, Bi, Ga, Ge, Si and Sb in e.g., printed circuit boards and capacitors and Sn in solders. Ge, Er and In are used in power amplifiers, REEs in permanent magnets, PGMs in various components and Cu, Fe, Mn and Ni in steels. Zn is used in cables, Te in optical fibres and Au in connectors. (Carrara *et al.*, 2023)

Circularity

Circularity is covering several R-strategies: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover energy. Many circular economy strategies through rethinking the system and reducing, lifetime extension strategies and recycling and recovery strategies decrease the demand for primary materials and improve material efficiency, also in case of critical raw materials and strategic raw materials. Circularity strategies also highlight substituting fossil raw materials.

In current working paper mentioned already substitution impacts of fossil-based carbon used for reducing agent in metallurgical industry that has impacts on CRMs needs on the other hand needed for hydrogen value chain. All the R-strategies impact on material value chain and raw material demand, however circular strategies and their impacts that cover directly raw materials processing are shortly discussed here, such as use of recycled materials, recycling and residue valorisation.

Using recycled materials and recycling

Pressure to increase the use of recycled materials may result in shortage of recycled materials, but at the same time, it may boost the development of recycling technologies and the recovery of critical raw materials from side-streams and process residues. The following elements cycle in steel value chain related to various steel grades and production infrastructure e.g., refractories in furnaces (Figure 12). Steel is an example of material-to-material recycling that is typically more cost and environmentally efficient than material-to-element recycling. Still, many streams lack material-to-material recycling routes due to various reasons. There are cases where single or selected valuable elements are recovered from the end-of-life waste streams or from industrial residues.

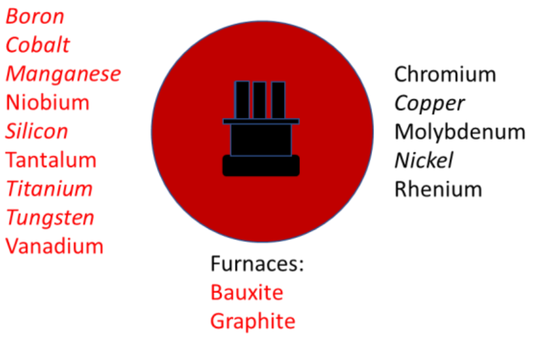

Figure 12. Elements commonly used in various steel grades. Red colour = critical raw materials. Italics = strategic raw materials.

CRMs cycle in steel value chain within various grade of low carbon steels, manganese steels, stainless steels and tools steels for mentioning some type of steels. Each element has a vital function for improving the properties of the steel grades, such as strength, toughness, fatigue, wear, corrosion or heat resistance, and these elements are typically difficult to substitute with element-to-element substitution strategies.

Discussion – Raw material needs towards carbon neutral industry

Transition towards carbon neutral industry is dependent on many different raw materials. Table 1 presents elements that are crucial for technologies needed for transition towards carbon neutral industry. Raw materials are divided into critical, strategic and non-critical.

Table 1. Elements in technologies needed for carbon neutral industry.

Technology	Critical	Strategic	Non-critical
Direct reduction and EAF	Bauxite	Graphite, Ni	Cr, Fe, H
Water electrolysis	Al, Ba, Sr, Ta, V	B, Co, REEs, Mg, Mn, graphite, PGMs, Si, Ti, Cu, Ni	Ag, Au, Cr, Fe, limestone, Mo, potash, Zn, Zr
CCUS	P, V	Mn, Ni	Cr, H, Fe
Electrification	Al, Be, Nb	B, Ga, Mn, Ti, REEs, Si	Cr, Fe, In, Mo
Solar	Al	B, Ga, Ge, Si, Cu, Ni	Cd, Cr, Fe, In, Pb, Mo, Se, Ag, Te, Sn, Zn
Wind	Al	B, Co, REEs, Mn, Si, Cu, Ni	Cr, Fe, Pb, Mo, Zn
Electricity networks	Al	Cu	Fe, Pb
Electricity storage in networks	Al, P, V	Co, Li, Mn, graphite, Si, Cu, Ni	
Industrial heat pumps	Al, fluorspar	B, Dy, Nd, Pd, Si, Cu, Ni	Cr, Fe, Mo, Ag, Zn
Digitalization of industry	Al, As, Ba, Be, Hf, Sb, Ta	B, Bi, Co, Ga, Ge, graphite, Li, Mg, Mn, P, PGMs, REEs, Si, W, Cu, Ni	Ag, Au, Cr, Fe, In, Pb, Sn, Te, Zn
Common steel grades	Bauxite, Ta, V	B, Co, graphite, Mn, Si, Ti, W, Cu, Ni	Cr, Mo, Re

Based on their emergence on the table, the key strategic raw materials for carbon neutral industry include boron/borate, cobalt, graphite, silicon, rare earth elements, manganese, nickel, and copper. These elements are important for batteries, permanent magnets and information technology needed in many key technologies as well as alloying elements in steel production.

For carbon neutral industry, critical raw materials include aluminium and bauxite, tantalum and vanadium, which are used in various applications in metallurgy, electronics, and batteries. Key non-critical raw materials such as chromium, iron ore, molybdenum and niobium are crucial for steel production. Consumption of hydrogen is expected to increase substantially in steel industry, and energy production and storage. Other important non-critical materials such as indium, lead, silver, tin, and zinc are used in various applications such as in electronics, solar PV, wind, and corrosion coatings.

Table 2 presents global production, EU consumption and EU import reliance for these key raw materials (SCRREEN, 2023).

Table 2. Global production, EU consumption and EU import reliance in 2016-2020 for the key raw materials for carbon neutral industry.

Raw material	Global production (t)	EU consumption (t)	Import reliance
Ag	27 476	19 514	54 %
Al	64 075 391	5 042 008	56 %
B	4 130 000	51 450	100 %
Bauxite	336 197 330	16 146 077	89 %
Co	136 385	15 000	100 %
Cr	14 058 733	577 336	18 %
Cu	20 538 727	2 054 007	48 %
Fe[1]	1 515 358 230	88 448 784	78 %
Graphite	1 019 167	77 340	97 %
H	90 000 000	1 100 000	0 %[2]
In	845	6.5	2.5 %
Mn	18 900 000	270 393	97 %
Mo	275 899	9 018	96 %
Nb	72 528	13 484	98 %
Ni	2 331 612	77 781	30 %
Pb	4 736 352	1 237 388	41 %
REEs	280 0003	4 734[3] + 683[4]	100 %
Si	2 979 470	440 968	74 %
Sn	300 440	49 000	73 %
Ta	1 867	5005	100 %
V	91 400	12 931	94 %
Zn	12 428 181	2 544 295	71 %

1) iron ore, 2) at processing stage, based on natural gas imports 3) REO equivalent, 4) REE metals and interalloys 5) Tantalum concentrates and pentoxide average for 2012-2016

Conclusions

Industry pathway towards carbon neutrality requires new processes and raw materials. In this working paper, we focus on steel and cement industries, as well as selected other industries such as refineries, glass, ceramics and aluminium industries that have large energy consumption, emission footprint, and production volumes. These industries have identified the needs of hydrogen as raw materials and technologies such as electrification and carbon capture, utilization and storage.

Industry pathways to carbon neutral production requires renewable energy. Therefore, it also increases the demand for raw materials needed to produce, distribute, store, and use green electricity. Consequently, carbon neutral industry is also dependent on the same raw materials as other sectors such as transportation and construction for reaching climate targets.

Beside the new processes and materials, the process efficiency and increasing circularity plays a role in climate neutral production. Examples of process efficiency technologies include widespread adoption of digital technologies and industrial heat pumps. An example of circularity is material-to-material recycling of steel products.

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