D7.2. Sectors with highest CRM demand growth potential: a review of future critical raw material demand in 11 key technologies for transport, energy, electronics and telecommunication sectors

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Ref. Ares(2022)7572353 - 02/11/2022

Horizon 2020
Programme

SCRREEN2

Coordination and Support Action (CSA)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211.

Start date : 2020-11-01 Duration : 36 Months

Sectors with highest CRM demand growth potential

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SCRREEN2 - Contract Number: 958211

Project officer: Ugo Miretti

Document title	Sectors with highest CRM demand growth potential
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Number of pages	25
Document type	Deliverable
Work Package	WP7
Document number	D7.2
Issued by	Leiden University
Date of completion	2022-09-02 14:16:19
Dissemination level	Public

Summary

An array of technologies is expected to contribute to the energy and circular transitions in multiple sectors, such as transport, energy, and electronics and telecommunications. These sectors are considered key sectors for achieving climate targets due to their role on reducing greenhouse gas (GHG) emissions. The widespread use of technologies will require increased amounts raw materials and may strain the established supply chains for some of these. There is interest in critical raw materials (CRMs) that have major economic relevance and face comparatively high supply risks in specific economies. Identifying the future CRM demand in the key sectors is essential to implement strategies that can mitigate potential disruptions and helps to improve resilience in the relevant supply chains. This working paper provides an overview of the CRM demand of 11 key technologies that are expected to contribute to the development of transport, energy, electronics, and telecommunication sectors. Moreover, the working paper discusses the links between the selected sectors, and identifies further implications for the future CRM demand, such as overall CRM demand from other economic sectors and technologies, circularity potential, CRM demand from production and building infrastructure, future innovations, and supply/demand interactions.

Approval

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A REVIEW OF FUTURE CRITICAL RAW MATERIAL DEMAND IN 11 KEY TECHNOLOGIES FOR TRANSPORT, ENERGY, ELECTRONICS AND TELECOMMUNICATION SECTORS

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February, 2022

Abstract

An array of technologies is expected to contribute to the energy and circular transitions in multiple sectors, such as transport, energy, and electronics and telecommunications. These sectors are considered key sectors for achieving climate targets due to their role on reducing greenhouse gas (GHG) emissions. The widespread use of technologies will require increased amounts raw materials and may strain the established supply chains for some of these. There is interest in critical raw materials (CRMs) that have major economic relevance and face comparatively high supply risks in specific economies. Identifying the future CRM demand in the key sectors is essential to implement strategies that can mitigate potential disruptions and helps to improve resilience in the relevant supply chains.

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1. Introduction

Energy and circular transitions are crucial to achieving sustainability goals and climate change targets in the upcoming decades (IEA, 2021a; IRP, 2020). To enable such transitions towards sustainability, the development of technologies has a major role on contributing to mitigate greenhouse gas (GHG) emissions. For example, the EU has proposed to increase the share of renewable sources for electricity production to 80% in 2050 (Bobba et al., 2020). This has been reinforced through recovery strategies for the economic crisis during the COVID-19 outbreak (European Commission, 2021a; Zanoletti et al., 2021).

The transitions toward a sustainable future require an increasing volume of raw materials to build the infrastructure needed to develop renewable energies and circular strategies (IRP, 2020). Governments and practitioners have put important attention to the impacts of future technologies, and material criticality for those technologies that support a sustainable future (European Commission, 2014; Grilli et al., 2017). Security of supply for raw materials important to the energy transition have been discussed for the last decade (DOE, 2011; Moss et al., 2013). These focused reports complement the broader discussion around critical raw materials (European Commission, 2021b; NRC, 2008).

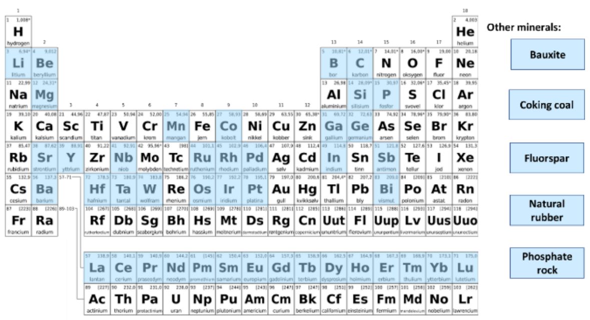

Figure 1: Critical raw materials for the EU (European Commission, 2020b)

CRMs are economically and strategically relevant for an economy and face comparatively high supply risks (European Commission, 2020b). In 2020, the EU reviewed its list of Critical Raw Materials, arriving at a selection of 30 raw materials and groups of raw materials, including 42 elements, and 5 industrial minerals and biotic materials (see figure 1).

The demand for CRMs depends on multiple factors, such as population growth, and technological development (Tercero Espinoza, 2012; Tercero Espinoza & Wittmer, 2015). Considering the energy and circular transitions, emerging technologies bring an extra pressure on CRMs demand, which varies depending on technology applications (Blanco et al., 2020; de Oliveira et al., 2021). Thus, it is important to identify the future demand of CRMs considering the technological shift or improvements in specific sectors.

CRM demand is driven by the material use in multiple sectors. However, transport, energy and electronics have been highlighted as key sectors necessary to achieving GHG mitigation targets by 2040 but generating significant new demand for CRM (EMF, 2017; IEA, 2021b; Monnet & Ait Abderrahim, 2018). The transport sector accounts for almost a quarter of the greenhouse gas (GHG) emissions

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worldwide (IEA, 2020b) and is being revolutionized by the broad introduction of electric vehicles. The development of renewable energy technologies plays is central to the energy transition (IRENA, 2019a) and implies a significant increase in critical raw material use for the energy sector. The electronics and telecommunications sector can facilitate the energy and circular transitions, but will itself require critical raw materials (Bobba et al., 2020; Eynard et al., 2020). Strongly increasing demand in even a single application can significantly impact the overall demand for raw materials (cf. Langkau & Tercero Espinoza, 2018 for some historical examples).

The CRM demand also depends on the links between these sectors, which can significantly increase the CRM requirements in the future. For example, the transport sector requires inputs from the energy sector, which implies that changes in the transport system would influence the energy sector and its future CRM demand. Thus, understanding the relation between the key sectors is crucial to identify the potential changes in CRM requirements.

This working paper aims to provide an overview of the most recent information on the CRM demand for technologies that are expected to have a major contribution to these key sectors (i.e., transport, energy, and electronics and telecommunication) by 2040. There are a number of studies that assess the CRM requirements and future demand of specific sectors and technologies (see, for example, Deetman et al., 2016; IEA, 2020a; Xu et al., 2020). Among the CRM literature, there are only a few studies that address the future CRM demand of technologies related to the selected sectors. For example, Bobba et al. (2020) provides CRM demand scenarios of foresight technologies in strategic sectors for the EU up to 2050. Likewise, Marscheider-Weidemann et al. (2021) brings global scenarios of technological development up to 2040, where scenarios for CRM demand are expressed per technology and relevant sectors. To the best of our knowledge, these two studies comprise the most recent scenario analysis of CRM demand for technologies linked to the selected sectors.

There are 11 technologies reviewed in this working paper, namely, traction motors, Li-ion batteries, solar photovoltaics, wind power, energy storage technologies, fuel cells, hydrogen production, digital technologies, photonics, 5G/6G, and quantum computing. These technologies are selected as some the most relevant technologies for future CRM demand based on their recurrence in the literature search. Figure 2 shows the structure of the document.

Other relevant technologies and sectors (e.g., food systems) were not considered in this working paper. The scope was narrowed down to the selected technologies and sectors in order to provide sensible links between the sectors. However, it is important to consider that there might be further implications for future CRM demand from other economic sectors and technologies (see section 5.2).

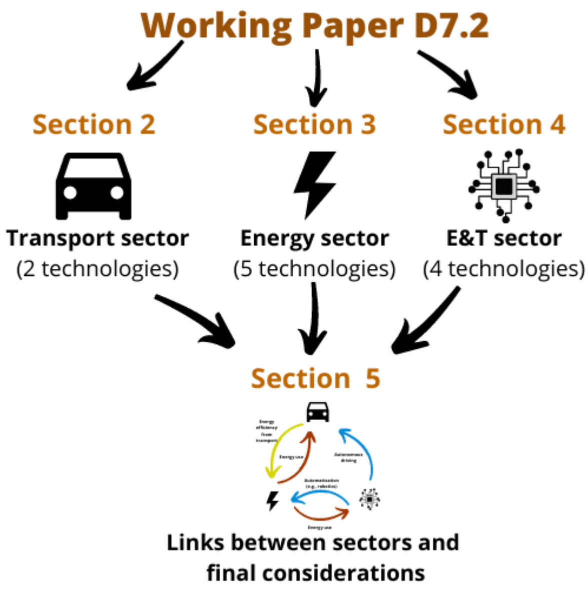

Figure 2: Outline of Working Paper D7.2. E&T = Electronics and telecommunication sector

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2. CRM demand for the transportation sector

2.1. Key technologies and CRM requirements

The development of sustainable transport technologies is a key aspect to achieve climate policy targets. The transport sector is one of the major contributors to GHG emissions (IEA, 2020b). In the EU, for example, the transport sector represents around 25% of total GHG emissions, where road transport contributes almost three-quarters of GHG emissions (European Commission, 2021c). Within this context, novel technologies offer opportunities to reduce impacts of the transport sector. The following sub-sections explore 2 key technologies for the transport sector and their CRM demand by 2040.

2.1.1. Electric traction motors

E-mobility is considered a key technology for a sustainable transport system in the future. Several governments (such as China, US, and the EU) have proposed targets to extent the fleet of electric vehicles (EVs) and other electric transport equipment in the upcoming decades (Jones et al., 2020). Depending on the country, EV market share is expected to increase between 21-57% by 2030 (IEA, 2019).

The development of EVs has led to continuous improvements of electric traction motor technologies, which are an essential component to transform electric power from batteries into motion (Jones et al., 2020). The application of traction motors can be found in multiple transport equipment, for example e-bikes, electric passenger cars and heavy transport (Bobba et al., 2020).

Many compact and efficient electric motor designs use NdFeB permanent magnets that are well-known for driving the demand of rare earth elements, REEs (Pavel et al., 2017). (Elshkaki, 2020). Other REEs are used in the production of traction motors as well (Pavel et al., 2017). Dysprosium and terbium are used in NdFeB magnets to make them more stable towards temperature. For other CRMs in traction motors, boron is a component of NdFeB magnets, and silicon metal is used as an alloying material for the motor's structure (Bobba et al., 2020).

It is important to notice that there is an ongoing development of alternative motor designs aiming to reduce and/or replace the amount of REEs required for traction motor technologies. For example, induction machines, wound and reluctance motors are considered as alternate technologies and expected to contribute to the development of EVs (Widmer et al., 2015). However, the EV market is expected to be dominated by traction motor technologies with REE-containing permanent magnets in the next two decades (Mordor Intelligence, 2021).

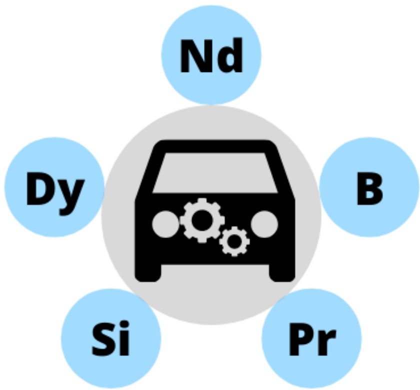

Figure 3: CRM requirements for traction motor technologies. B = Boron (borates), Dy = Dysprosium, Nd = Neodymium, Pr = Praseodymium, and Si = Silicon (metal).

2.1.2. Li-ion batteries

Li-ion battery technologies are key to the development of EVs and will continue to be an important technology in the upcoming decades. (Miao et al., 2019; Tsiropoulos et al., 2018). The application of Li-ion is not limited to transport systems but is also used in energy storage and electronics sectors (see section 3 and 4).

The production of Li-ion batteries requires multiple CRM materials (see figure 4). Natural graphite, silicon metal, and titanium (in future applications) are used in anodes in Li-ion batteries (Valero et al., 2018). Lithium and cobalt are applied to Li-ion cathodes, and niobium is expected to be used in future cathode development (Bobba et al., 2020). Phosphorous[1] and fluorspar components are also CRM materials that are used in the development of Li-ion batteries technologies (Valero et al., 2018).

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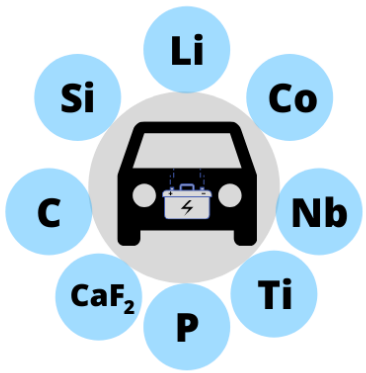

Figure 4: CRM requirements for Li-ion battery technologies. C = Carbon (natural graphite), CaF_2 = Calcium fluoride (fluorspar components), Co = Cobalt, Li = Lithium, P= Phosphorus[1], Nb = Niobium, Si = Silicon (metal), and Ti = Titanium.

Figure 5 brings an overview of the 12 CRMs requirement for transport technologies. The demand of silicon metal is shared by traction motors and Li-ion battery technologies, which might imply potential pressure on the future silicon metal demand.

2.2. Future CRM demand for the transportation sector

For traction motor technologies, the global CRM demand by 2040 will rise mostly for the REEs. Regarding light rare earth elements (LREEs), neodymium demand is forecast to increase 24 times compared to the demand in 2018[2] (for values in tonnes, see table 1, Annex). The demand for heavy rare earth elements (HREEs), such as dysprosium, is expected to increase by the same factor. Both LREEs and HREEs demands are related to the production of permanent magnets. In comparison with REE supply in 2018, the future REE demand for traction motors would require 5 times the global production in 2018 (see table 1, Annex).

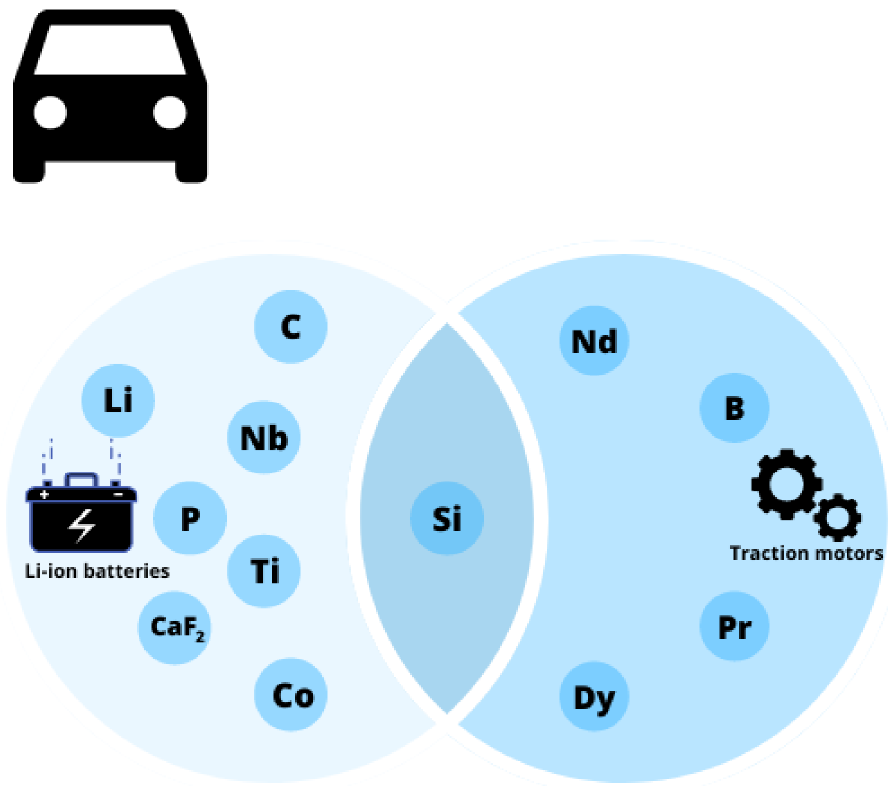

Figure 5: CRM demand for the transport technologies

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Global lithium demand is expected to rise more than 50 times by 2040 compared to demand in 2018[2] to satisfy the demand for Li-ion batteries from the transport sector. Compared to the global lithium supply in 2018, the future demand for Li-ion batteries would require 4 times the global lithium production in 2018 (see table 1, Annex). Cobalt demand is expected to increase 24 times compared to 2018 requirements[2]. The future demand of cobalt for Li-ion batteries would require 2 times the global cobalt supply in 2018. Natural graphite will also have the major increases, with an additional amount of 47 times compared to the CRM demand in 2018[2]. The future natural graphite for Li-ion batteries represents around 64% of the global natural graphite production in 2018.

In contrast, there are scenarios that suggest a significant higher future CRM requirement for transport sector. For example, lithium, cobalt, and graphite increasing 818, 620, and over 2000 times, respectively, in 2050 compared to the 2018 demand[3]. In this case, the large differences between multiple scenarios come from the assumptions made to determine the future energy requirements for transport sector (for more details, see Michaux, 2021).

3. CRM demand for the energy sector

Renewable energy technologies have been developed rapidly in the last decades because of their importance to achieve climate change targets. Several technologies are expected to support the energy transition (Moss et al., 2013; Ubaldi et al., 2019). The following sub-sections review 5 key technologies in the energy sector and their CRM requirements by 2040.

3.1. Key technologies and CRM requirements

3.1.1. Solar photovoltaics

Solar photovoltaics (PV) is one of the key technologies for the energy transition. With the decrease of production cost and rapid technological development, solar PV is expected to grow in the coming decades (IRENA, 2019a). Current commercial application comprises crystalline silicon and thin-film technologies. The latter is considered the most important for the future demand of solar PV by 2030. Thin-film will have the largest market share by this period as thin-film has been economically feasible and represents already the large share of solar PV market (IRENA, 2019a). Thin-film includes amorphous silicon, copper-indium-gallium-(di)selenide (CIGS), and cadmium-telluride (CdTe).

Solar PV comprises a variety of materials depending on the technology type (see figure 6). For instance, silicon metal is a crucial material for solar PV, in particular, in recent times where there has been a major disruption of semiconductor supply chain due to the impact of COVID-19 pandemic on global supply chains (Garrington, 2020). Likewise, the production of CIGS and CdTe involve the use of CRM, such as indium (Valero et al., 2018). Moreover, demand for gallium arsenide (GaAs) adds pressure to the future demand of gallium by 2040 (IEA, 2021a; Monnet & Ait Abderrahim, 2018). Other CRMs are used in silicon-based wafers (e.g., boron) and as semiconductor materials (e.g., germanium). It is important to notice that cadmium and tellurium are considered as non-critical in 2020 EU criticality list, thus, these elements excluded from this report.

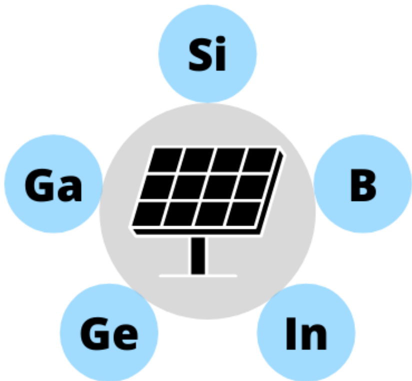

Figure 6: CRM requirements for solar PV technologies. B = Boron (borates), Ga = Gallium, Ge = Germanium, In = Indium, and Si = Silicon (metal).

3.1.2. Wind power

Another well-known technology that contributes to the energy transition is wind power. The investment on wind farms is expected to increase in the coming decades, with a higher development of offshore (i.e., at sea) wind than onshore (i.e., in land) technologies. By 2030, the EU offshore wind power is expected to contribute to 30-40% share of all wind power production (Rabe et al., 2017).

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Wind power requires REEs, such as neodymium, dysprosium, praseodymium, and terbium, to build the permanent magnets used in wind turbines (Valero et al., 2018). Furthermore, boron is used in these neodymium–iron–boron magnets (Bobba et al., 2020), and niobium is used as a microalloying element in high strength structural steel for wind towers (cf. Figure 7).

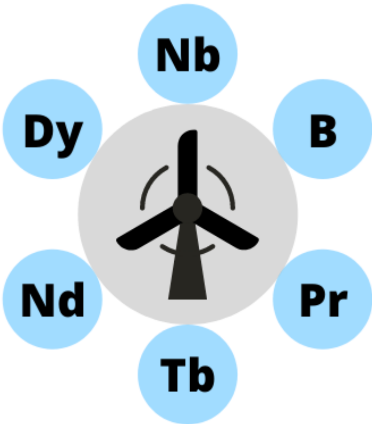

Figure 7: CRM requirements for wind power technologies. B = Boron (borates), Dy = Dysprosium, Nb = Niobium, Nd = Neodymium, and Pr = Praseodymium, and Tb Terbium.

Neodymium and dysprosium are considered more relevant for the development of wind power, as these elements are required intensively in wind turbines (12 – 180 t/GW for neodymium and 2 – 17 t/GW for dysprosium), and present high supply risk (Marscheider-Weidemann et al., 2021).

3.1.3. Energy storage technologies

It is well-known that solar PV and wind power are not constant renewable sources as these energy technologies fluctuate along with daytime and weather conditions. This means that the application of technologies to store the energy captured by the intermittent energy sources is crucial.

The development of energy storage application has led to improved battery technologies that can support renewable energy systems (Hache et al., 2019). Depending on the storage application, several types of battery technologies are on development, such as Li-ion batteries and redox flow batteries (Ait Abderrahim, A. Monnet, 2018; Tsiropoulos et al., 2018).

As mentioned in Section 2, Li-ion batteries are expected to contribute significantly to a sustainable energy transition. The application of Li-ion is not limited to transport systems, but also used in energy storage and electronics. Recapping from Section 2, the production of Li-ion batteries requires multiple CRM materials: cobalt, lithium, natural graphite, niobium, titanium, phosphorous, and fluorspar components (see figure 8).

Redox flow batteries are also a mature technology that can be applied to large-scale energy storage. Currently, the market of redox flow batteries consists of vanadium redox flow batteries, which implies a significant use of vanadium as CRM (Ait Abderrahim, A. Monnet, 2018). Furthermore, it is expected that all-iron redox flow batteries will contribute to the application of redox flow technologies in the upcoming decades. However, this technology is still not commercially available (Marscheider-Weidemann et al., 2021).

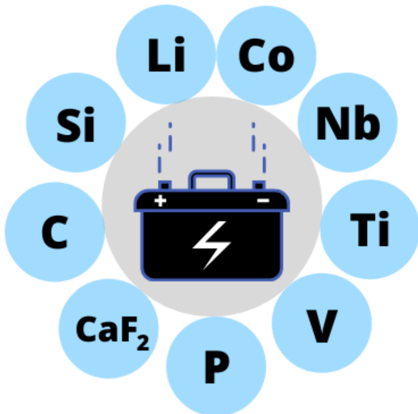

Figure 8: CRM requirements for battery technologies. C = Carbon (natural graphite), CaF2 = Calcium fluoride (fluorspar components), Co = Cobalt, Li = Lithium, P = Phosphorus[1], Nb= Niobium, Si= Silicon (metal), Ti = Titanium, and V = Vanadium (for Redox flow batteries).

3.1.4. Fuel cells

Fuel cells are a clean energy alternative for the energy transition. Fuel cell technologies use a fuel (such as hydrogen) to convert chemical energy into electricity without combustion through an electrochemical cell (Marscheider-Weidemann et al., 2021; Moss et al., 2013).

There are multiple types of fuel cells that vary depending on the type of fuel, operational system, and application. The technology is expected to have an important contribution to mobility applications (Hache et al., 2019). However, fuel cells are currently more used for stationary

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power generation, which covers more than 65% of the market (Bobba et al., 2020).

Considering stationary fuel cells, CRM requirements vary depending on the type of technology. Most common electrolyte materials for fuel cells are yttria-stabilized zirconia, scandium-stabilized zirconia, and gadolinium-doped cerium (Marscheider-Weidemann et al., 2021). From the CRM perspective, the development of fuel technologies relies on the use of lanthanum, yttrium, cobalt, and scandium (see figure 9). Furthermore, natural graphite is used for the construction of bipolar plates, platinum and palladium as electrocatalytic components, as well as titanium and strontium as components for the fuel cell anodes (Bobba et al., 2020).

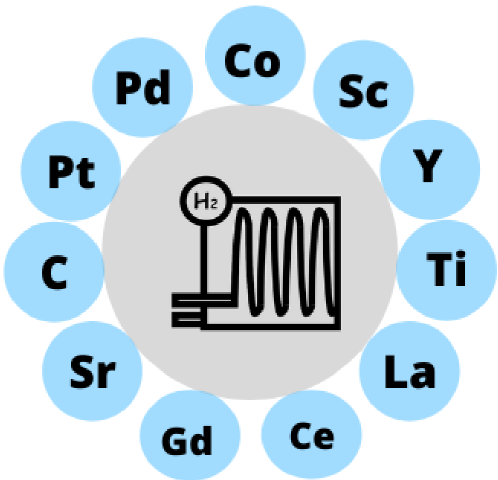

Figure 9: CRM requirements for fuel cell technologies. C = Carbon (natural graphite), Ce = Cerium, Co = Cobalt, Gd = Gadolinium, La = Lanthanum, Pd = Palladium, Pt = Platinum, Sc = Scandium, Sr = Strontium, Ti = Titanium, and Y = Yttrium.

3.1.5. Hydrogen production technologies

There are several technologies for hydrogen production. However, the production of green hydrogen (i.e., production based on renewable energies) is considered the most sustainable option that can contribute to future energy systems (IRENA, 2020).

By 2040, it is expected that the use of water electrolysis powered by renewable energies will be the largest technology for hydrogen production (IRENA, 2020). This is because water electrolysis technologies are reaching a point of development where their large-scale application will be feasible technically and economically.

There are several CRM requirements for water electrolysis that depend on the technology type (see Figure 10). For example, proton exchange membrane electrolysers (which have become commercially available in recent years) require platinum, iridium, ruthenium as well as titanium (Kiemel et al., 2021; Shiva Kumar & Himabindu, 2019). Other novel water electrolysis is high temperature electrolysis (also known as solid oxide electrolysis), which requires strontium and REEs, such as yttrium and lanthanum (Kiemel et al., 2021). Other CRMs used in water electrolysis technologies are scandium, and cobalt (Marscheider-Weidemann et al., 2021). Furthermore, the use of cerium contributes to improve electrocatalytic activity and to reduce the amount of iridium and ruthenium (Shiva Kumar & Himabindu, 2019).

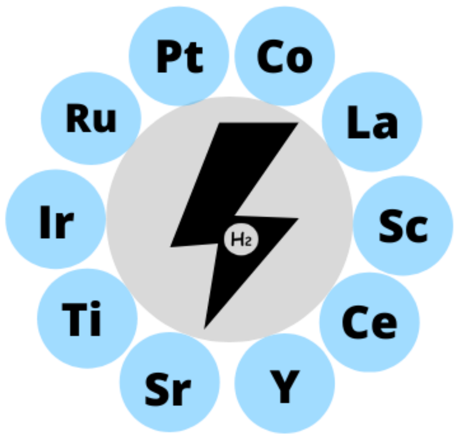

Figure 10: CRM requirements for water electrolysis technologies used in hydrogen production. Co = Cobalt, Ir = Iridium (as part of platinum metal group), La = Lanthanum, Pt = Platinum Sc = Scandium, Sr= Strontium, Ti = Titanium, and Y = Yttrium.

Figure 11 shows an overview of the 28 CRMs required for energy technologies. Platinum, titanium, scandium, strontium, lanthanum, cerium, and yttrium demand are shared by fuel cells and hydrogen production technologies. Furthermore, cobalt demand will be driven by fuel cells, hydrogen, and battery technologies. Boron demand is shared by solar PV and wind power, while silicon metal demand is shared by solar PV and battery technologies. The demand for natural graphite is allocated to fuel cells and battery technologies. Moreover, niobium demand is shared by wind power and battery technologies.

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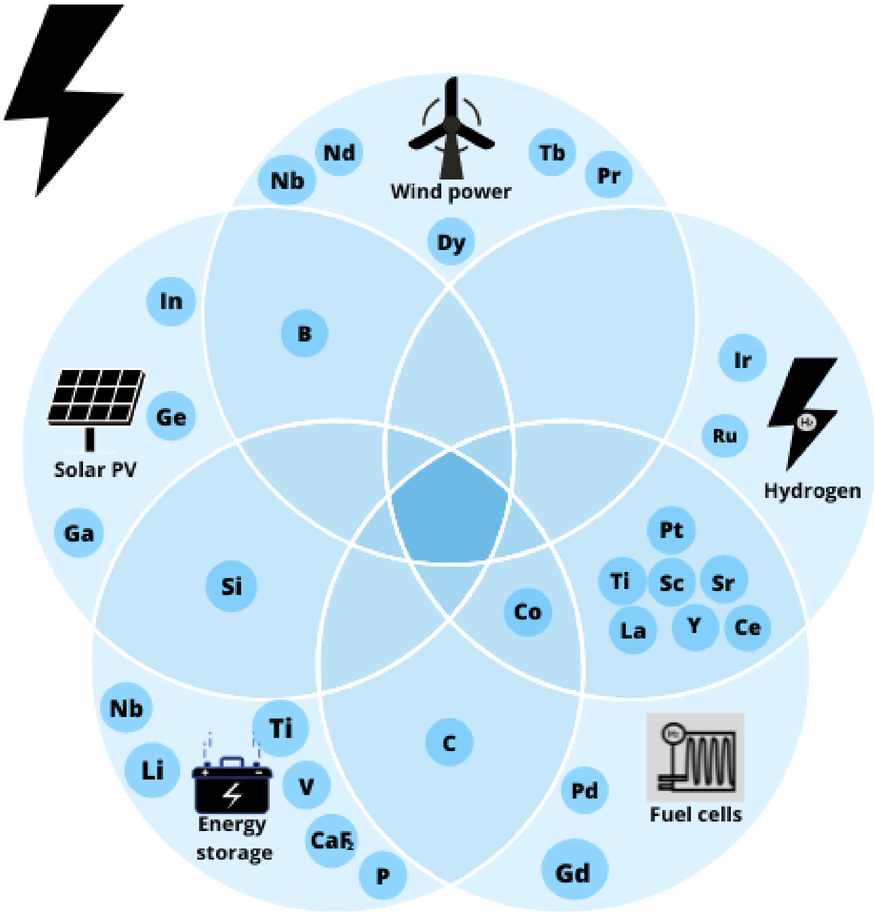

Figure 11: CRM demand for the selected energy technologies. Niobium is shared by wind power and battery technologies[5]

3.2. Future CRM demand for energy sector

By 2040, the global demand of REEs in wind power plants will exceed more than 6 times the requirements in 2018[2] (for values in tonnes, see table 1, Annex). This includes Light Rare Earth Elements (such as neodymium and praseodymium) as well as Heavy Rare Earth Elements (as dysprosium and terbium). In comparison with the global supply in 2018, the future demand of REEs for wind power represents around 9% of the global REEs production in 2018 (see table 1, Annex).

For solar PV, the global demand of gallium and indium is expected to increase between 5 to 10 times compared to 2018 requirements[2,4]. The future demand of gallium for solar PV represents 0.01% of the global gallium supply in 2018, while the future indium demand represents around 13% of the global production of indium in 2018.

Fuel cells will present the highest changes in CRM demand by 2040. This additional amount of CRM for fuel cells are caused by a large-scale production of fuel cells in the 1.5°C scenario. Cobalt will present the highest increases of CRM demand in energy technologies, which will increase consumption 63 times[2] due to the increasing demand of fuel cells. Nevertheless, the future cobalt demand for fuel cells represents 0.04% of the global cobalt supply in 2018 (see table 1, Annex).

Regarding energy storage technologies, Li-ion batteries demand will change the CRM demand by the same proportion as in battery technologies for the transport sector, where CRM demand increase more than 50 times by 2040 compared to 2018 (see section 2.2.). It is important to notice that the values of Li-ion batteries for energy and transport sectors are equivalent in relative

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terms. However, the absolute values are different as it is expected that the share of Li-ion batteries for energy storage will represent around 20% of total energy and transport market for 2070, having 80% of share for transport applications[6] (IEA, 2020a).

Hydrogen production through water electrolysis technology presents the highest changes in CRM demand by 2040. The demand of REEs (such as lanthanum and yttrium) will be over 3000 times more than the demand in 2018[2]. Similarly, demands for titanium, scandium, platinum metal group (including platinum and iridium), and cobalt are expected to increase 3800, 2400, 4000, and 4000 times[2], respectively. Although these factors can be seen extremely large, it is important to notice that there was no large-scale application yet in such scenarios, as the electrolysis technology was not commercially available in 2018. Moreover, the future demand of REEs, titanium, and platinum for hydrogen represent less than 2% of the global production of these elements in 2018 (see table 1, Annex). Therefore, growth rates are very large while total amounts are not as significant. Furthermore, the large factors do not mean a significant amount in absolute terms as the CRMs might be required in small amounts (for absolute values in tonnes, see table 1, Annex).

Hydrogen and fuel cell technologies are expected to contribute significantly to the transport sector, which means that the CRM demand scenarios for these technologies will also depend on future demand from transport systems. For example, hydrogen is a clean fuel alternative for transport sector applications, which can be used directly through the integration of fuel cells in EVs or indirectly through stationary fuel cells and battery-based EVs (IEA, 2019).

As hydrogen production technologies contribute simultaneously to the energy and transport sectors (IEA, 2019; IRENA, 2019b), hydrogen production is classified in this working paper as key technology for energy sector, but keeping in mind that it is key for the transport sector as well.

4. CRM demand for the electronics and telecommunication sector

The electronics and telecommunication sector covers a broad range of goods and services that use electrical components. This sector includes the manufacture of durable products, such as laptops, smartphones, home appliances, displays, optical fibres and so on. Their applications have been speeded up in the past decades, where electrical devices can be found in multiple sectors (Ait Abderrahim, A. Monnet, 2018). The following sub-sections explore 4 key technologies for the electronics and telecommunication sector and their CRM demand by 2040.

4.1. Key technologies and CRM requirements

4.1.1. Digital technologies

Digital technologies can be seen as auxiliary technologies to enable a cost-effective energy and circular transition. These technologies comprise several digitalization and automatization areas, such as information and communication technology (ICT) devices, and advanced electronics.

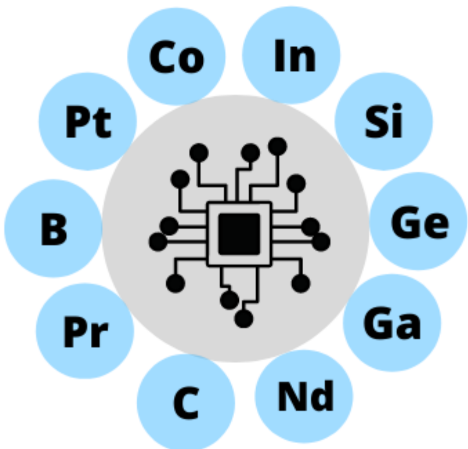

Figure 12: CRM requirements digital technologies. B = Boron, C = Carbon (natural graphite), Co = Cobalt, Ga = Gallium, Ge = Germanium, In = Indium, Nd = Neodymium, Pr = Praseodymium, Pt = Platinum, and Si = Silicon (metal).

Digitalization and automatization are already having a significant contribution to energy systems. For instance, there are applications of robotic automatization in solar PV and wind turbines production, in which automatization

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allows the development of complex structural components (European Commission, 2017; Ubaldi et al., 2019). Furthermore, 3D printing and additive manufacturing are expected to be applied in the development of renewable energy infrastructure (e.g., in components used by offshore wind turbines), which will facilitate the production of certain renewable energies (Bobba et al., 2020).

Regarding CRM, digital technologies require a variety of materials, which are mostly used to produce advanced electronic devices. For example, 3D printing requires cobalt and natural graphite (Bobba et al., 2020). Furthermore, platinum, neodymium, praseodymium, and boron are required in the production of hard disk drive. Gallium and silicon metal are required for semiconductors (IEEE, 2021). Germanium is also required for semiconductors, as well as to produce fiber-optic cables. Indium is used as indium oxide for the development of screens (European Commission, 2020a).

4.1.2. Photonics

Photonics technologies provide a suitable way to transmit information through light signals. These technologies use photonic devices to produce, detect, and interact with light, which can be found in multiple high-tech applications (Flik, 2021). For example, photonic devices are key components of data transmission in telecommunication systems, which use optical fibers and optoelectronic devices to transfer information efficiently (Amiri et al., 2018).

Regarding CRM requirements, photonics devices have a different CRM demand depending on the type of application. Considering telecommunication applications, photonics technologies are constituted by three main components: transmitter, sender and receiver (Marscheider-Weidemann et al., 2021). These components use multiple devices, such as lenses, photonic integrated circuits, and optical fibers. Thus, photonics technologies requires a significant amount of CRMs (Flik, 2021). For telecommunication applications, there are key CRMs that are expected to be crucial in future demand (see figure 13). The use of beryllium, gallium, and indium are required for electro-optical systems (Bobba et al., 2020; Marscheider-Weidemann et al., 2021). Furthermore, germanium is used in the manufacturing of optical fibers (Ait Abderrahim, A. Monnet, 2018).

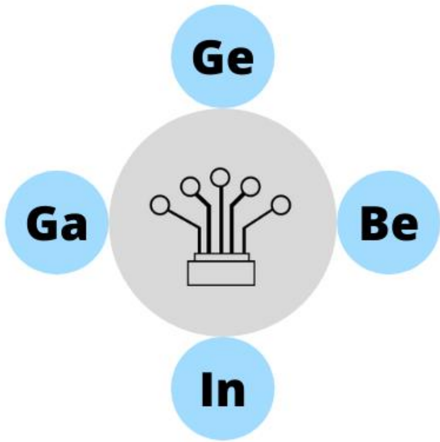

Figure 13: Key CRM requirements for photonics technologies in telecommunication application. Be = Beryllium, Ga = Gallium, Ge = Germanium, and In = Indium.

4.1.3. 5G/6G

5G refers to the 5th generation for broadband cellular network, which provides high speed connectivity and data transmission (Marscheider-Weidemann et al., 2021). 5G is expected to contribute to enhance resource and energy efficiency (Juneja et al., 2021). For example, 5G is required for the development of the Internet of Things (IoT) where multiples devices are interconnected and interact in real-time, which is key for applications such as smart energy systems (HUAWEI, 2021; Marchese et al., 2019).

5G is expected to have a major coverage in sustainable technologies between 2025 and 2030 (UN, 2021). However, it is also expected to be replaced quickly by 6G applications, which will provide even faster connectivity for network systems.

The CRM demand of 5G/6G comes from the equipment types on these network applications, which include antennas, base stations, and remote radio units (Flik, 2021). Gallium is used in based amplifiers for base stations, and mobile devices. Lithium niobate, and lithium tantalate are required for their transmission properties (Marscheider-Weidemann et al., 2021). Indium phosphide is also required in optical transceivers in base stations (Marscheider-Weidemann et al., 2021). Moreover, erbium and scandium (for RF filters) are also CRM required for the development of 5G/6G technologies (Ecclestone, 2019; Song et al., 2021; Yan & VanHeerden, 2021).

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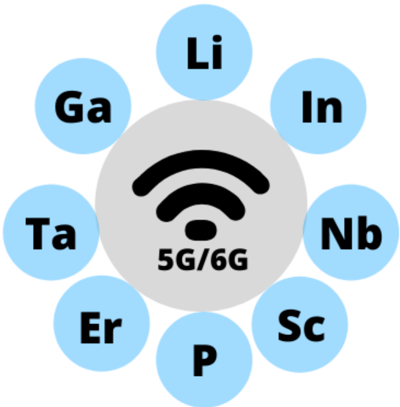

Figure 14: CRM requirements for 5G/6G applications. Er = Erbium Ga = Gallium, In = Indium, Li = Lithium, Nb = Niobium, P = Phosphorus[1], Sc= Scandium, and Ta = Tantalum.

4.1.4. Quantum computing

Quantum computing is considered a key technology for the development of communication services. The computational power generated by quantum systems bring unprecedented possibilities for digital technologies compared to a traditional computing systems (Marscheider-Weidemann et al., 2021).

Quantum computing provides significant improvements in security and data processing, which are expected to have positive impacts on digital technologies (Appas et al., 2021; Giustino et al., 2020). For example, quantum networks are expected to enhance the security network for operators and users in telecommunication systems (Flik, 2021).

With the current development of quantum computing, there are some CRM requirements that can be already identified. This technology includes three main devices: quantum router, quantum sender, and quantum receiver (Flik, 2021). The CRM requirements for quantum devices present 70% of the elements in the EU's CRM list, such as REEs, gallium, germanium, niobium (Flik, 2021). Figure 15 shows 13 CRMs used in quantum computing devices considering the current technological development.

It is important to notice that the field of quantum materials with quantum computing applications is changing constantly (Giustino et al., 2020). Thus, the CRM demand for quantum computing might be different with novel quantum materials and their potential commercial applications.

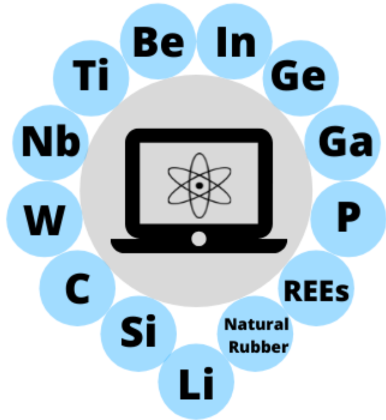

Figure 15: CRM requirements for quantum computing. Be = Beryllium, C = Carbon (natural graphite), Ga = Gallium, Ge = Germanium, In = Indium, Li = Lithium, Nb = Niobium, P = Phosphorus[1], REEs = Rare Earth Elements including light REEs (as praseodymium) and heavy REEs (as dysprosium, holmium, erbium, and gadolinium) Si = Silicon (metal), Ti = Titanium, and W = Tungsten.

Figure 16 provides an overview of the 19 CRM demand for electronics and telecommunication technologies. Gallium and indium demands are shared by all four selected technologies. Lithium, phosphorus[1], and niobium demand will be driven by 5G/6G and quantum computing. Natural graphite and silicon metal are shared by quantum computing and digital technologies. The demand of germanium is shared by digital technologies, quantum computing as well as photonics. Furthermore, beryllium demand is allocated to photonics and quantum computing.

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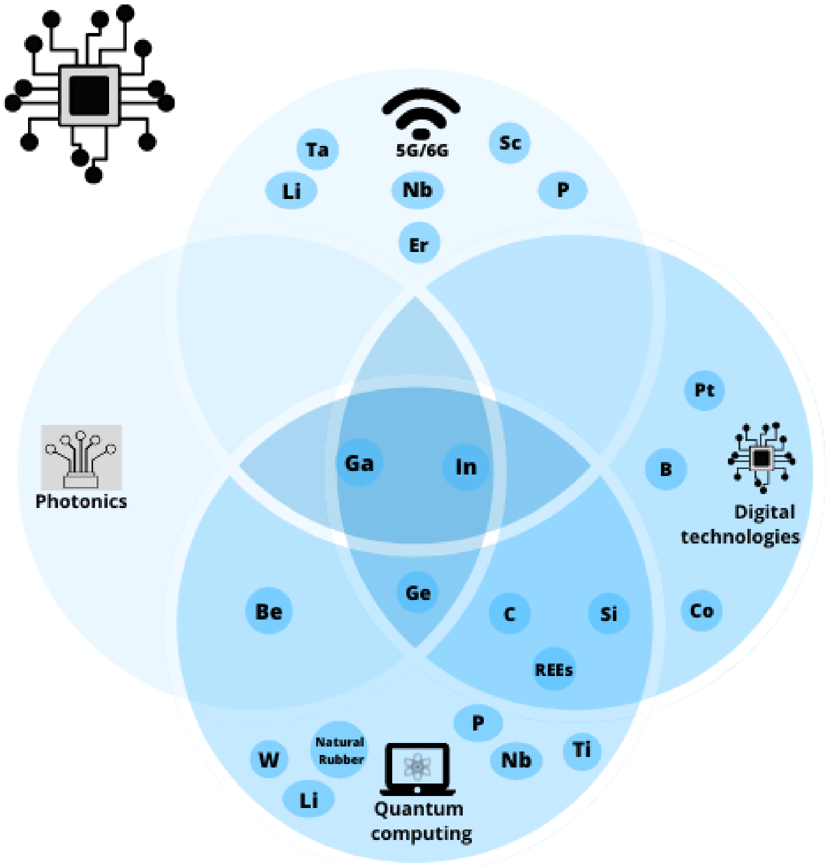

Figure 16: CRM demand for the selected electronic and telecommunication technologies. Niobium, phosphorus[1], and lithium are shared by 5G/6G and quantum computing technologies[5]

4.2. Future CRM demand for electronics and telecommunication

As in section 2.2. and 3.2, CRM demand for electronics and telecommunication technologies has been modelled based on multiple scenarios by 2040 (see, for example, IEA, 2020a, 2021b; IRENA, 2019a; Monnet & Ait Abderrahim, 2018; Tsiropoulos et al., 2018; Xu et al., 2020).

By 2040, the global CRM requirement for photonics technologies will double the CRM demand compared to 2018[2] (for values in tonnes, see table 1, Annex). It is expected that demand for gallium for photonics in 2040 will be 2 times larger than the corresponding requirements 2018[2]. However, in comparison with the global gallium supply, the demand of gallium for photonics represents less than 0.001% of the global production in 2018 (see table 1, Annex). Likewise, the demand for indium is expected to increase 3 times in 2040 compared to 2018[2]. The future indium demand for photonics represents 2% of the global production of indium in 2018.

For 5G/6G applications, the global demand of CRM will also double by 2040 compared to the use in these applications in 2018[2]. Gallium, lithium, and tantalum are expected to rise to 2 times the demand in 2040 compared to the 2018 requirements[2]. Meanwhile, indium is expected to have a slightly higher increase, in which the indium demand for 5G/6G application is expected to be 3 times higher than the indium requirement in 2018[2]. In comparison with the global supply in 2018, the future demand of gallium, lithium, and indium for 5G/6G represent less than 2% of the global production of these elements in 2018, while the future demand of tantalum represents around 20% of the global tantalum production in 2018 (see table 1, Annex).

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5. Implications for future CRM demand

The previous sections brought together an overview of the CRM requirements and future demand for the selected technologies in the transport, energy, and electronics and telecommunication sectors. There are several CRMs used in multiple technologies, as well as a nexus between key sectors. The following sub-sections explore the links between the 3 key sectors, and further implications for future CRM demand.

5.1. Links between key sectors

There are several CRMs that are required in different applications. Figure 17 (a) shows the relation between the CRM requirements in transport, energy, and electronics and telecommunication sectors based on the 11 reviewed technologies.

The total CRM requirements in the selected technologies correspond to 33 materials, of which 11 out of 33 CRMs are required simultaneously by the three selected sectors. Among others, cobalt, lithium, silicon metal, and REEs (such as dysprosium and praseodymium) are some of the key CRMs in all three sectors.

The transport and energy sectors share 16 out of 33 CRMs in the selected technologies. The CRMs used by transport and energy sectors are mostly those associated with batteries, which are used for energy storage as well as energy source for EVs. Besides lithium, fluorspar components are crucial for the development of Li-ion batteries. Furthermore, the transport and energy sectors share the use of REEs, such as neodymium. This element is required for the manufacturing of permanent magnets, which are used for wind turbines in the energy sector and traction motors for transport applications.

The energy and electronics and telecommunication sectors share 14 out of 33 CRMs. This means that CRM requirements of energy, electronics and telecommunication technologies could together generate a significant pressure on the CRM demand for almost half of the CRM required for the respective technologies. There are 3 CRMs that are allocated only to energy, and electronics and telecommunication sectors. Gallium, germanium, and indium present important applications for photonics, 5G/6G, quantum computing, as well as for PV technologies.

The future demand of CRMs in each technology also depends on the links between the key sectors (see figure 17(b)). This means that each sector could drive indirectly the future CRM demand from another sector. For instance, it is well-known that the application of electronics and telecommunication technologies can contribute to improve energy systems. Automatization with digital technologies can support the manufacturing of energy equipment, making these devices technically and commercially feasible. Furthermore, quantum computing applications can be used to enhance the scenario development of energy systems, in which it can be improved the performance intermittent energy sources, such as solar and wind.

Considering a sustainable transition for the transport sector, any advancement in transport technology will be supplemented by renewable energies (IEA, 2020b). This implies that transport sector contributes indirectly to the demand for new energy technologies and, consequently, for CRM demand. The increasing demand of electricity should be satisfied through renewable sources.

Electronics and telecommunication also play a key role in the future transport sector. For example, electrical components are crucial for future transport systems, as those components are used to enhance the energy efficiency and driving security. Likewise, autonomous transport will require a high level of connectivity between transport equipment and its surroundings, which implies further advancement on 5G/6G applications (HUAWEI, 2021). Thus, future transport systems will drive the CRM demand from electronics and telecommunication applications as well.

In general, the electronics and telecommunication sectors are considered an enabler for the energy and circular transitions. However, electronics and telecommunication applications also push the demand of energy from a production and use side. To produce electronic devices, energy is required, which should be produced from sustainable energy technologies (Castellani et al., 2015). Moreover, operating network systems requires reliable sources of energy that are expected to be supported by the current and emerging energy technologies. Considering the CRM demand by 2040, the nexus between the key sectors could generate an increasing pressure on CRM demand thereby further pushing criticality of these materials.

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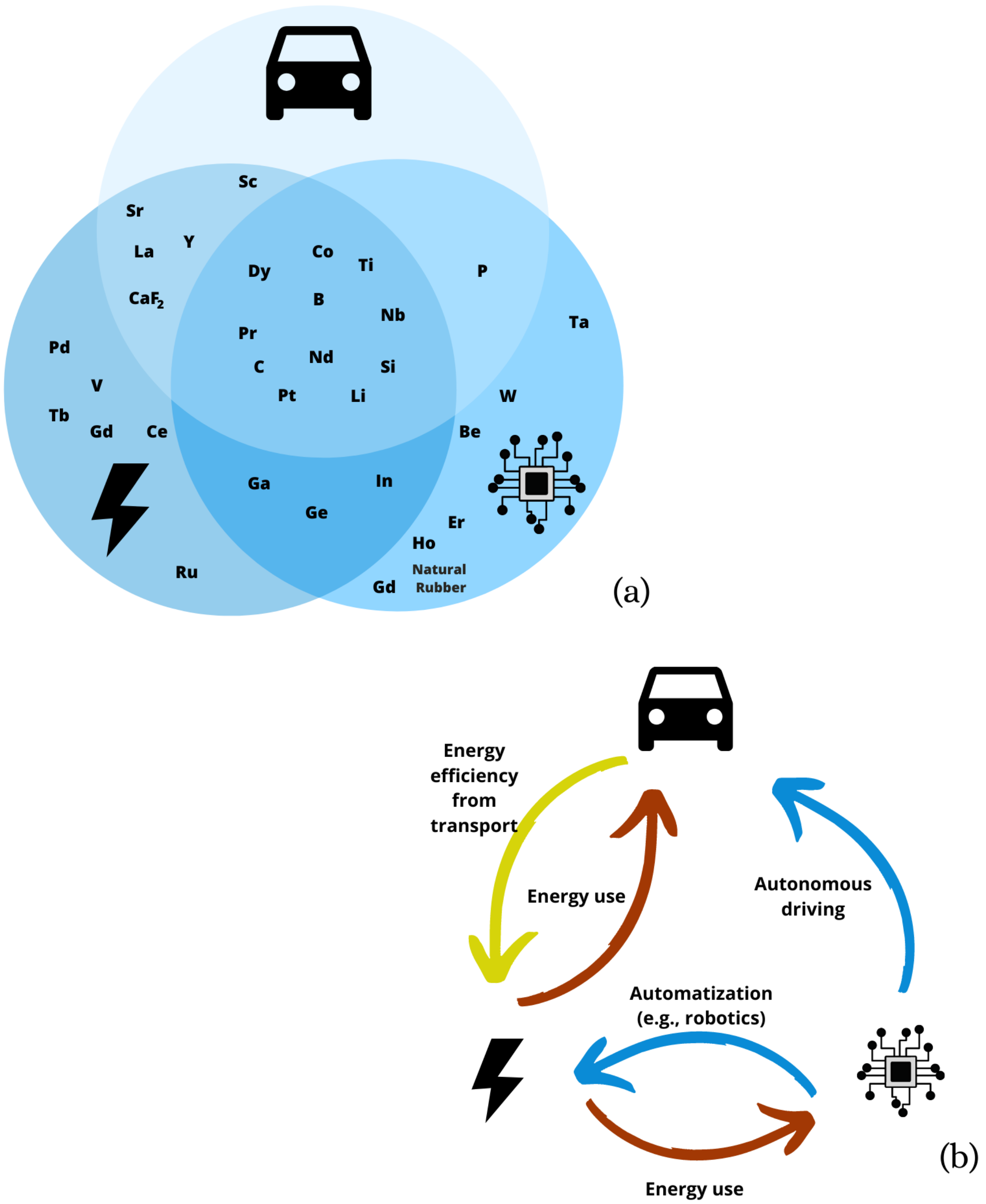

Figure 17: CRM demand for the 11 selected technologies across key sectors, and (b) links between the sectors for future CRM demand

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5.2. Further considerations for future CRM demand

Within the reviewed technologies, the scenarios of CRM demand consider a sustainable pathway to achieve climate change targets. Several studies suggest the need for energy and circular transitions, as well as the CRM demand for technologies that enables such transitions (Valero et al., 2018; Zanoletti et al., 2021). Nevertheless, there are still several implications from a system viewpoint that should be considered for providing a broader insight on the potential demand for CRMs. Here, we reflect on six main aspects that have direct and indirect implications for the CRM demand by 2040.

5.2.1. Current CRM demand and scale from other sectors

Future CRM demand will not only depend on new technologies used by the selected sectors, but also depend on the current demand from the rest of the economy (de Koning et al., 2018). For example, lithium is used in multiples sectors, such as ceramic glass, and polymer productions (European Commission, 2020a). It is expected that the lithium demand share for these sectors will be between 10-20% of the total lithium demand in 2070 (IEA, 2020a) [4].

Although the share of lithium on battery applications will present the highest value (in volume) for 2070, its application in other sectors might still have major impacts on the future demand. A comprehensive assessment of CRM demand should consider the overall change in CRM demand to be able to estimate the future availability and accessibility. This also means that the CRM demand scenarios for the selected technologies can be seen as an extra factor that affects future CRM demand.

For cobalt, the current use is very limited in EVs application. In 2020, over half of cobalt is used for batteries, mostly in LCO batteries for portable electronic equipment (Cobalt Institute, 2021). However, the predicted growth in EVs will change this in the coming years, and likely dominate demand.

Another example is the use of tantalum. Currently, more than 40% of tantalum use is for the production of capacitors, which are used in high-value electronics, along with superalloys. These types of applications for CRMs should be considered to determine the overall impact on future CRM demand.

The scale of CRM requirements is also an important aspect to consider. There are CRMs crucial for certain technologies that might not have major influence on total demand when comparing with the demand from other sectors. For instance, the amount of CRMs required by 5G/6G technology (see table 1, Annex) will be much less than the CRM demand for in the steel industry, which requires CRMs to produce steel alloys, such as niobium (Tuttle, 2018).

5.2.2. CRM demand from applications connected to the selected sectors

With the development of new technologies (especially those related to the energy transition), there are multiple applications that might impact the CRM from other sectors. For example, fire safety is a key industry for transport and energy sectors because of specific fire risks in high-current cables exposed to UV and weathering, in inverters and battery charging stations (Aram et al., 2021; Carrol, 2020; IFP, 2016). The relevance of fire safety industry will increase of CRM demand, such as phosphorus[1] (ESPP, 2020).

5.2.3. CRM demand from CRM production and infrastructure

The future demand of CRMs will also depend on the materials requirements on the CRM production and infrastructure. For example, the product of cobalt (as well as other metals) requires the use of phosphorus[1], as P4 is used in the separation of cobalt from nickel (ESPP, 2020). Thus, the production of certain CRMs could drive the demand for other CRMs directly or indirectly.

Increasing the CRM demand would imply the investment in building factories and infrastructure that are required to satisfy the expected demand (Sprecher & Kleijn, 2021). This might turn into a potential increase of raw material demand to build the infrastructure. For example, hydrogen distribution for energy sector would require converting a gas pipeline to a hydrogen pipeline, which implies special application of steels containing niobium in new pipelines. Among raw materials for infrastructure, there could be potential hidden CRM demand that has not been considered to-date (to the best of our knowledge).

5.2.4. Circularity potential

Material circularity might have major implications on future demand of CRMs. Circular strategies include

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interventions that are related to waste management, closing supply chains, product lifetime extension, and resource efficiency (Aguilar-Hernandez et al., 2018; Bocken et al., 2017; Peck et al., 2015).

Within the CRM context, circular strategies are interesting as an alternative to reduce future CRM demand. This has brought an increasing advancement in recycling processes to recover CRMs at the end-of-life stage, for example, from e-waste (Auerbach et al., 2019; Deetman et al., 2018; Deetman et al., 2018). For instance, novel technologies for the recovery of gallium and REEs from e-waste have been developed to reduce the amount of primary CRM extraction (de Oliveira et al., 2021).

Thus, circular strategies might contribute to reduce the CRM primary demand in certain sectors (European Commission, 2018). However, the implications of circular strategies in CRM demand would depend on how fast recycling and recovery technologies will be commercially available in the upcoming decades and how fast relevant waste streams become available to feed recycling processes, especially for these new technologies.

5.2.5. Future innovations and emerging CRMs

Technological development and innovations might have an important contribution to the future CRM demand. In this working paper were reviewed only a few technologies from several potential innovations in the next 2 decades. For example, battery technologies are developing constantly, and, with multiple battery formulations, it is difficult to establish whether there is a specific technology that will dominate the market in the next 10-20 years. Although it is ideal to have a broader perspective on which will be the future innovations that will support the energy and circularity transition, this working paper only included those technologies that were recurrent on the literature, and on which a connection between the selected sectors and CRM requirements were made.

Furthermore, the reviewed CRMs in this working paper include those materials that are considered critical from the 2020 EU's list (European Commission, 2021b). This means that potential emerging CRMs are not considered, however, they might be relevant for future CRM demand. For instance, copper is not currently on the EU's CRM list, however, this element might become more critical in the future due to their economic relevance and potential supply chain risks (de Koning et al., 2018; Dong et al., 2019). The selection of possible CRM candidates is an ongoing discussion, in which the SCRREEN2 network offers valuable information to explore which materials might become part of the future CRM list (see https://scrreen.eu/).

There are other CRMs from the current EU list that were not included in this working paper. For instance, coking coal is a current CRM that is key for steel production. Furthermore, other CRMs might appear from a forward-looking CRM demand evaluation. This is the case of zooming in within the select sectors. For example, when considering lightweighing for the transportation sector, steel in vehicles is currently being replaced by magnesium and aluminium-magnesium alloys to reduce fuel consumption and emissions. Thus, magnesium will play a major role in lightweighing. Likewise, the demand of beryllium is equally important in this application as each magnesium alloy requires 5-15 ppm of beryllium to be used and produced safely.

Considering the potential missing CRMs in this working paper, we acknowledge that the reviewed CRMs represent only some of the key CRMs for each technology based on the literature search. Thus, there are more CRMs from other sectors and technologies that might drive the future CRM demand.

5.2.6. Supply and demand interactions

Exploring future CRM demand should be aligned with the supply side, and whether the future supply will be enough to satisfy the potential demand. From the reviewed literature, there are several publications that address the CRM reservoirs and potential supply for CRMs (see, for example, IEA, 2019; Michaux, 2021; World Bank, 2021). However, this working paper focuses on CRMs the demand side exclusively.

The reason to exclude the supply perspective is because this working paper is presented as one piece of a working paper series from the SCRREEN2 project, in which the supply perspective and supply/demand interaction will be addressed in the upcoming works from SCRREEN2 working paper series.

5.3. Concluding remarks

This working paper brought an overview of the CRM demand for 11 technologies that are expected to contribute to the energy and circular transitions in transportation, energy, electronics, and telecommunication sectors. The working paper considered the CRMs requirements for technologies in transport,

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energy, and electronics and telecommunication sectors in the upcoming two decades (i.e., up to 2040). The demand for the selected technologies will drive an increase in demand for 33 CRMs, which are used for the production and development of each technology.

From the CRM future demand and potential implications, it is important to consider the dynamic aspect of the CRMs. The changes in technology (as well as raw material demand) are not static, which implies that some raw materials might become critical in the future with the development of new technologies. The dynamic aspect of CRM is crucial to understand the future CRM demand that should be considered in the ongoing CRM assessments to anticipate potential changes in CRMs.

Furthermore, the dynamic of the CRM demand for new technologies will have an impact the raw material markets. It is expected that some the reviewed technologies will change the respective CRM markets. For instance, Li-ion battery technologies have led to market changes for lithium, cobalt and nickel, which will continue to change the markets. Likewise, e-mobility will have an impact on the copper market, in which market changes might be marginal in comparison with other copper applications. Thus, the evolution of CRM demand can be linked to the future market changes for certain raw materials.

This working paper also examined the links between the 3 selected sectors and future CRM demand, and the main implications for CRM demand by 2040. Among further implications, this working paper highlighted the importance of future CRM demand from other sectors and technologies, CRM demand from production and building infrastructure, circularity potential, future innovations, and supply/demand interactions. This work only explores the demand side as it is part of a working paper series from SCRREEN2 project, in which it will be available relevant information for the CRM supply perspective and opportunities to develop the future CRM assessment (for updates on the SCRREEN2 working paper series, see: https://scrreen.eu/).

Acknowledgements

The authors would like to thank the following experts from the SCCREEN2 network who brought their valuable feedback on this working paper: Carlos Frias, Chris Thornton (ESPP), Elisabeth Prieto Strobl (CRM Alliance), Fabrizio Corti, Genevieve Metson (LiU), Gonzalo Mayoral Fernández, Gustavo Macedo (CBMM), Henryk Karaś, Lekshmi Nair (IRSG), Manuel Regueiro, Martin Tauber (IMA), Matti Kinnunen (GTK), Nadia Vinck (EMEAA), Navaraj Perumalsamy, Nourredine Menad, Patrick Friedrichs (GTK), Rebecca Lentini (BeST), Simon Michaux (GTK), Tom Fairlie (Cobalt Institute), and Vjaceslavs Lapkovskis (Riga Technical University).

Footnotes

1. Phosphorus is used in the EU CRM List to mean P4 (white phosphorus) and derivatives, and Phosphate Rock is used to mean the element phosphorus in any form (ESPP, 2020). In this working paper, Phosphorus refers to P4 and derivatives.
2. Values were retrieved from ambitious scenarios in Marscheider-Weidemann et al. (2021). These scenarios consider ambitious climate policy targets, following the SSP1 sustainability scenario by the IPCC (Marscheider-Weidemann et al., 2021). Methodologically, in this working paper, the 2040 values were divided by the CRM requirement of the respective technology in 2018 to determine how much CRM demand will be required in comparison with the most recent requirements (i.e., 2018). This approach is equivalent to the estimation reported by Bobba et al. (2020), but with the difference that this report shows values for the global demand instead of only the demand for the EU.
3. Values were retrieved from Scenario F in Michaux (2021). This scenario considers the extra power generation capacity required to phase out fossil fuels completely worldwide.
4. Values were retrieved from Sustainable Development scenarios in IEA (2020a). These values were retrieved from the figures, thus, the values represent an approximation of the reported data in in IEA (2020a).
5. Elements were allocated to the respective areas only for graphical purposes.
6. Values were retrieved from both Stated Policies and Sustainable Development scenarios in IEA (2020a).

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6. Annex

Table 1. Global production (in tonnes), total requirements per technology (in tonnes), future demand (in tonnes), and future demand factors

Material	Global production for 2018, in tonnes*	Sector	Technology	Total requirements for 2018, in tonnes	Future demand for 2040, in tonnes	Future demand factor (i.e., future demand/total requirements)	Future demand /Global production for 2018 (%)	Reference
Cobalt	140000	Transport	Li-ion battery	12750	311000	x24	222%	Marscheider-Weidemann et al. (2021)
			Li-ion battery		7900000**	x620	5642%	Michaux (2021)
		Energy	Fuel cells	1	63	x63	0.04%	Marscheider-Weidemann et al. (2021)
			Hydrogen	01	370	X3700	0.3%	Marscheider-Weidemann et al. (2021)
Gallium	410000	Energy	Solar PV	5	26	x5	0.006%	Marscheider-Weidemann et al. (2021)
				5	50***	x10	0.01%	IEA (2020a)
		E&T	Photonics	1	2	x2	0.0005%	Marscheider-Weidemann et al. (2021)
			5G/6G	77	122	x2	0.03%	Marscheider-Weidemann et al. (2021)
Indium	720	Energy	Solar PV	17	92	x5	13%	Marscheider-Weidemann et al. (2021)
				17	170***	x10	24%	IEA (2020a)
		E&T	Photonics	5	16	x3	2%	Marscheider-Weidemann et al. (2021)
			5G/6G	5	16	x3	2%	Marscheider-Weidemann et al. (2021)
Graphite	1600000****	Transport	Li-ion battery	21900	1019000	x47	64%	Marscheider-Weidemann et al. (2021)
					62200000**	x2840	388%	Michaux (2021)
Lithium	85000	Transport	Li-ion battery	7460	377300**	x51	443%	Marscheider-Weidemann et al. (2021)
					6100000**	x818	7176%	Michaux (2021)
		Energy	Li-ion battery	476	24083	x51	28%	Marscheider-Weidemann et al. (2021)
		E&T	5G/6G	8	15	x2	0.02%	Marscheider-Weidemann et al. (2021)
Platinum	160000	Energy	Hydrogen	1E-02	40	x4000	0.02%	Marscheider-Weidemann et al. (2021)
REEs	170000	Transport	Traction	34630	834050	X24	491%	Marscheider-Weidemann et al. (2021)
		Energy	Wind	2820	15890	X6	9%	Marscheider-Weidemann et al. (2021)
			Solar PV	3168	17740	x5	10%	Marscheider-Weidemann et al. (2021)
			Hydrogen	8E-01	3170	x3000	2%	Marscheider-Weidemann et al. (2021)
Scandium	-	Energy	Hydrogen	1E-02	24	x2400	-	Marscheider-Weidemann et al. (2021)
Tantalum	1800	E&T	5G/6G	194	356	x2	20%	Marscheider-Weidemann et al. (2021)
Titanium	11500	Energy	Hydrogen	3.5	13600	x3800	118%	Marscheider-Weidemann et al. (2021)

*Global production includes all the material production in 2018. Data retrieved from USGS (2022)

**Estimated demand for 2050

***Values retrieved and rounded from the report's figures

**** Value retrieved from Zhou and Damm (2020)

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