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Strategic mineral resources: Availability and future estimations for the renewable energy sector

Guiomar Calvo *, Alicia Valero

Research Centre for Energy Resources and Consumption (CIRCE Institute), Universidad de Zaragoza, Calle Mariano Esquillor Gómez, 15, 50018, Zaragoza, Spain

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A B S T R A C T

To keep the increase in global average temperature below 2 °C the use of renewable energy sources is essential. There are various scenarios for this energy transition depending on the amounts and types of renewable energies implemented. However, the material requirements to build new renewable power systems is rarely considered. It is key to understand the impact that the increasing demand of materials for renewable technologies could have on mining and mineral availability and so avoid potential disruptions. Thirteen strategic elements for the renewable energy sector have been analyzed which could generate supply shortages in the medium to long term. From the supply side, production, current resources and data related to future production have been compiled. From the demand side, element use in solar power (PV and CSP), wind energy (on and off-shore), and electric vehicles have been analyzed, as well as the demand of each element in other sectors from 2018 to 2050. Of the 13 elements included in this study, cobalt, lithium, tellurium, and nickel are the most critical of all. Technologies should be more effective in their use. Governments and companies should incorporate policies related to the conservation and extension of its life through recycling and servitisation to avoid resource depletion.

1. Introduction

To achieve the global objective of keeping the increase in global average temperature well below 2 °C, one of the best options is to enhance the use of renewable energy sources, such as wind, solar energy, photovoltaics or concentrated solar power plants for electricity generation.

Different scenarios and pathways have been developed for this energy transition to 2050, considering the installed power that is going to be needed in renewables to cover the global demand (International Energy Agency, 2017; Teske et al., 2015; Valero et al., 2018b). According to Energy Agency projections, in 2050, there will be 3280 GW and 1739 GW of installed power wind and solar technologies, respectively, in the 2 °C scenario (International Energy Agency, 2017). Additionally, the transport sector is responsible for more than 24% of total world CO_2 emissions (International Energy Agency, 2018). Moreover, this sector is the one that is expected to grow at a faster rate than any other. Therefore, decarbonization, via electric mobility, can produce a significant impact. Electric vehicle sales will reach 44 million vehicles per year by 2030 (International Energy Agency, 2019) and the sales of battery electric vehicles (BEV) and plug hybrid electric vehicles (PHEV) will surpass those of conventional vehicles in 2038 and 2029, respectively (ANFAC, 2014).

* Corresponding author.
E-mail address: gcalvose@unizar.es (G. Calvo).

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Even if this transition will be gradual in the coming years, the main question remains. Will there be enough materials available to build these technologies? Renewable technologies are more intensive in their use of raw materials than conventional energy sources. While a conventional power plant needs one ton of copper per megawatt of installed capacity, a solar power plant needs four (Villena, 2019). To build the electric generators for wind turbines, between 5 kg/MW and 14 kg/MW of dysprosium and between 61 kg/MW and 183 kg/MW of neodymium are needed (Valero et al., 2018a). Solar panels need other elements, such as silver, cadmium, tellurium or indium, and electric vehicles need lithium, nickel or cobalt for batteries. Most of these elements are extracted in only a few regions of the world, a factor which makes them critical according to several studies (European Commission, 2020a; Palacios et al., 2018a; U.S. Department of Commerce, 2019). For instance, 62% of tellurium is produced in China and 71% of cobalt in the Democratic Republic of the Congo (DRC). Additionally, in many cases these elements are extracted in regions where societal and environmental conditions are less restrictive and whose impact in greenhouse emissions can be more considerable. This situation, linked with the decrease of ore grade than can be observed in many places, either due to increase in extraction technology or to depletion, can increase the pressure on the mining sector (Calvo et al., 2016).

Analyzing the impact that the future demand of elements to build these technologies is then crucial to identify possible supply shortages. After a bottom-up and a top-down approach, in Valero et al. (2018a), a risk analysis was carried out for 32 elements, of which 13 showed very high or high risk of generating supply shortages in the long term. This paper's main goal is to carry out a review of those elements which are strategic for the renewable energy sector.

2. Method and data sources

The methodology that was followed to obtain the list of strategic elements for the renewable sector is fully developed in Valero et al. (2018a). A combination of various factors was carried out, using a bottom-up and a top-down approach. In the bottom up approach, data regarding reserves and resources from relevant sources such as the United States Geological Survey (USGS) or the British Geological Survey (BGS) was used. Other estimations carried out by different authors were also considered (Table 1). This information was combined with future production estimations. This term was calculated by means of applying the Hubbert model to current production, which provides production predictions based on current trends and total resources data. These curves always present a Gaussian distribution, providing information of when a maximum production peak in production could be reached.

On the other hand, in the top-down approach, each selected renewable technology's material requirements was analyzed and coupled with future implementation trends to estimate future material demand. For this endeavor, different documents were analyzed. First, data regarding which elements are used in each renewable technology as well as in which amount. This information is summarized in Valero et al. (2018a). A study regarding recycling and repowering was conducted as well, considering its impact on primary extraction. Then, projections and scenarios to 2050 of implementation of renewable energies, such as those carried out by the International Energy Agency (International Energy Agency, 2013, 2014, 2017, 2019), were combined with this data to calculate future material demand of the sector.

Lastly, combining the bottom up and the top-down approach and Hubbert estimations, a series of bottlenecks were identified using three risk categories. Cumulative demand exceeding current resources (very high risk), where it exceeded current reserves (high risk), or where annual demand was higher than annual primary production (medium risk).

In this study only one element, tellurium, presented a very high risk, as cumulative demand from 2016 to 2050 surpassed current known resources Valero et al. (2018a). A total of 13 elements were labelled as "high risk": silver, cadmium, cobalt, chromium, copper, gallium, indium, lithium, manganese, nickel, tin, and zinc (Fig. 1). In all these elements, cumulative demand (demand of renewable energy sources plus demand of other sectors) exceeded current known reserves. The demand of non-renewable sectors was treated as constant.

3. Strategic elements for the renewables sector

Different information regarding the thirteen elements considered as strategic will be presented here in detail: zinc, cadmium, indium, chromium, nickel, cobalt, copper, silver, tellurium, gallium, lithium, manganese, and tin. It is relevant to notice that some of these elements are extracted only as by-products of other base metals; therefore, their production is strongly linked. Total world production, main producing countries and resources for all these elements are summarized in Table 2.

Table 1
Sources used in this study.

Content	Sources
World mineral extraction	USGS (2020); Brown et al. (2020)
Reserves and resources	USGS (2020); Sverdrup and Ragnarsdottir (2014); Werner et al. (2017); Mudd and Jowitt (2018); Kesler et al. (2012); Nickel Institute (2016); Mudd et al. (2017)
Recycling rates	UNEP (2011)
End use	USGS (2017); European Commission (2017); Calvo et al. (2017a); Moss et al. (2011); U.S. Department of Commerce (2019)
Criticality studies	European Commission (2017, 2020a, 2020b); Iglesias-Émbil et al. (2020); Moss et al. (2011, 2013); Ortego et al. (2020)

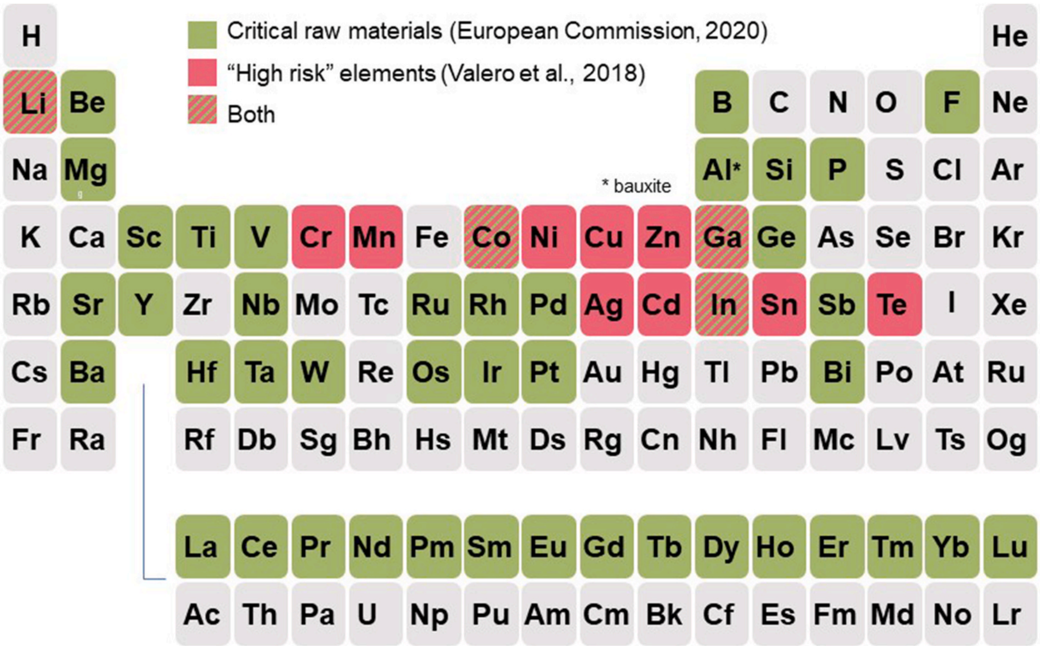

Fig. 1. List of very high and high risk elements (Valero et al., 2018a) compared to the critical raw material list of the European Commission (European Commission, 2020a).

Table 2
Summary of 2019 production, including main producing country, and estimated resources. Sources are indicated in the table.

	2019 production (t) USGS (2020)	Main producing country (% share) USGS (2020)	Resources (t)
Ag	27,000	Mexico (23%)	NA
Cd	25,000	China (33%)	660,000 (USGS, 2010)
Co	140,000	DR Congo (71%)	Terrestrial: 25,000,000 Deep-sea nodules and crusts: 120,000,000 (USGS, 2020)
Cr	44,000,000	South Africa (39%)	>12,000,000,000 (USGS, 2020)
Cu	20,000,000	Chile (28%)	3,035,000,000 (Mudd and Jowitt, 2018)
Ga	320	China (97%)	>1,000,00 (less than 10% potentially recoverable) in bauxite (USGS, 2020)
In	760	China (39%)	356,000 (Werner et al., 2017)
Li	77,000	Australia (55%)	31,000,000 (Kesler et al., 2012)
Mn	19,000,000	South Africa (29%)	NA
Ni	2,700,000	Indonesia (30%)	130,000,000 (USGS, 2020) 300,000,000 (Nickel Institute, 2016)
Sn	310,000	China (27%)	NA
Te	470	China (62%)	NA
Zn	13,000,000	China (31%)	610,000,000 (Mudd et al., 2017)

NA: not available.

3.1. Zinc

Zinc is the sixth most produced metallic element at the world level. The extraction of this metal is linked to the extraction of many other elements that appear as by-products or during the refining stages (Verhoef et al., 2004). The main zinc ore-bearing mineral is sphalerite, which appears in hydrothermal deposits along with lead and often with copper, among other elements. In 2019, China was the main leading producer of this element, with a share higher than 30% (Table 2).

More than half of zinc production is used for galvanizing. The second primary use is for alloys and, third, for electrical equipment (European Commission, 2017). For its abundance at the global level and the diversity of its main end uses, zinc is not usually included in criticality studies.

In renewable energy sources, zinc is used in solar cells (around 86 kg/MW in Copper Indium Gallium Selenide - CIGS), in solar thermal power (between 650 t/GW and 1400 t/GW), among others (Valero et al., 2018a). Additionally, each electric vehicle will need around 6 kg of zinc for various components (Iglesias-Émbil et al., 2020). This demand is not expected to change considerably in the coming decades. Therefore, as in this analysis the demand of the remaining sectors is kept constant, total demand in 2050 will not be much different from current demand (Fig. 2).

As reported by the International Zinc Association, the end-of-life recycling rate of zinc is over 45%, while other studies show an average of 31% (International Zinc Association, 2015; UNEP, 2011). Due to this situation and the low expected increase in demand, there are likely not going to be problems related with availability, as it can be substituted by other metals, such as aluminium in galvanized plates.

3.2. Cadmium

Cadmium is a frequent by-product of zinc processing and refining. Even if it is present in many minerals in low concentration (1–200 ppm), some zinc minerals, such as sphalerite or smithsonite, can present up to 5% cadmium content (Schwartz, 2000). As with zinc, the leading world producer of cadmium in 2019 was China (Table 2). As it is a by-product of zinc production, cadmium resources data are closely linked to zinc resources data, hence, the uncertainty linked to these values.

Cadmium is primarily used in nickel-cadmium (NiCd) batteries, containing between 6% and 18% of cadmium. Due to its toxicity, cadmium is not usually considered critical by any organization or country as its use in the future is going to suffer from restrictions, as it happened with mercury or arsenic in the last decades.

This element is present in different amounts in almost all types of solar cells, such as in cadmium-tellurium (CdTe). Still, these solar cells require higher amounts, around 65 kg/MW. Compared to current demand, in 2050 it will only increase by 2% and only in the solar photovoltaic sector (Figs. 2 and 3).

All waste management legislations include a section specifying that batteries containing cadmium must be properly recycled due to its toxicity, and even include recommendations regarding its recollection process. In the case of solar panels that contain cadmium, they are treated as general or industrial waste except in the European Union, which has specific PV waste regulation (IRENA, 2016). As PV wastes could reach more than 60 million tons in 2050, recycling is one of the best options to avoid shortages in the medium to long term (IRENA, 2016). Usually only a few major elements, such as aluminium or copper are recovered in those recycling processes. Still, there are several experiences that demonstrate that it is technically feasible to recover other elements. This process could also improve in the future, including thermal treatments (Ardente et al., 2019). However, the issue remains regarding economic and environmental aspects (Chowdhury et al., 2020; Müller et al., 2005). Nevertheless, in the medium term, there are likely not going to be problems related with cadmium availability.

3.3. Indium

Globally, zinc concentrates are currently the main source of indium. Resource data of both elements are closely linked (Table 2). Production in 2019 was slightly lower than 800 t, being China responsible for almost 40% (USGS, 2020).

It is widely used in certain compounds, such as indium tin oxide (ITO), in many flat panels displays and in screens and touchscreens as the transparent conducting film (65%). Other uses include low-melting alloys, semiconductor materials for LEDs and laser diodes (USGS, 2017). Indium is considered critical in almost all the regional and sectoral studies due to its end uses and for its correlation with zinc extraction (European Commission, 2020a; Stanek et al., 2017; U.S. Department of Commerce, 2019).

Indium is used in efficient photovoltaic cells. CIGS approximately requires 23 kg/MW of this element (Valero et al., 2018a). It is also used in light-duty vehicles, specifically in electronic components. One vehicle can contain up to 0.4 g of indium which is not

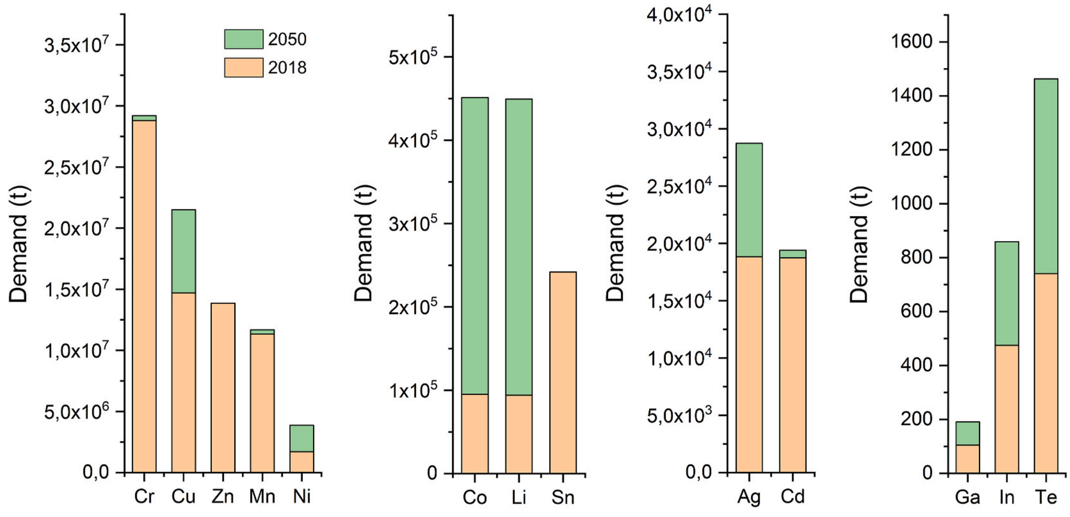

Fig. 2. Comparative analysis between total material demand in 2018 and estimated material demand increase in 2050 according to Valero et al. (2018a). For visibility purposes, the Y-axis has a different scale on each graph.

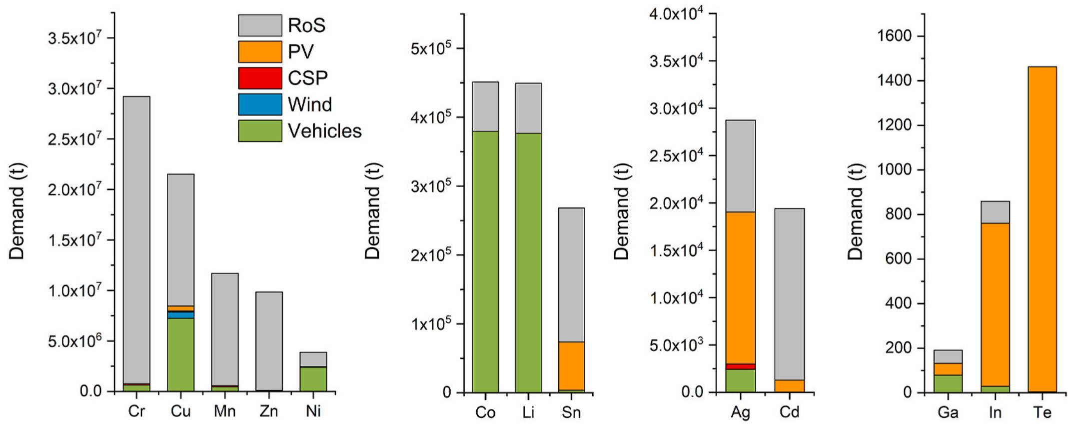

Fig. 3. Estimated material demand for strategic elements by technology and sector in 2050. Vehicles: includes internal combustion engine vehicles (ICEV), battery electric vehicles (BEV) and plug hybrid electric vehicles (PHEV). Wind: includes onshore and offshore turbines; CSP: concentrated solar power; PV: solar photovoltaic; RoS: rest of sectors). For visibility purposes, the Y-axis has a different scale on each graph.

recovered during the vehicle recycling process (Ortego et al., 2018). The increase in demand for renewable energies is expected to be considerable, compared to the current demand, around 40%, mainly due to its use in solar panels (Fig. 3).

Due to the low indium concentration in final products, its average end-of-life recovery is almost negligible, but it can be recovered from the recycling of manufacturing waste (European Commission, 2017). Some experiences have shown that this element can be substituted by other compounds in flat panel displays, such as antimony tin oxide or carbon nanotube coatings (Tolcin, 2013). As CIGS uses indium and gallium, recycling is needed to ensure a future supply of both elements and maintain production costs down. For example, a preliminary method able to recover via oxidation and then selective electrodeposition of the various elements used in CIGS was developed at Chalmers University of Technology and resulted in almost complete separation (Gustafsson et al, 2014, 2015). Urban mining, the recovery of metals from discarded waste electrical and electronic equipment (WEEE), could also be an option. For instance, Ciacci et al. (2019) estimated that the amount of indium present in urban mines is around 500 t. The question remains if this recovery process could be profitable or feasible in the future.

3.4. Chromium

Chromium ranks third in worldwide metal production, after iron and aluminium. The main chromium-bearing mineral is chromite, which has a Cr_2O_3 content between 25% and 60%. There are two main products that can be obtained from this mineral, ferrochromium and chromium metal. The main producer was South Africa (Table 2). Precisely, Bushveld Igneous Complex is the richest deposit at world level, where, in addition to chromium, other scarce elements such as platinum, palladium, osmium or rhodium are found (Bustillo Revuelta, 2018).

Chromium is mainly used in form of ferrochromium in products made of stainless steel to increase the hardness of the steel. Final steel products can reach almost all end-use sectors (European Commission, 2017). It is also used for special alloy steels, in jet engines and aircrafts to cope with extreme conditions, in chemicals, tanning agents, wood preservatives, etc. Since the European Commission, 2017 report of critical raw materials, chromium is no longer considered critical (European Commission, 2017). Nevertheless, it is included in the critical raw material list of the U.S. Government (Department of the Interior, 2018).

In concentrated solar power plants, chromium is used in solar selective coatings, in form of black chromium, for the efficient conversion of solar energy into thermal energy (Nunes et al., 2018). The total amount of chromium per installed GW can vary between 2200 t and 3700 t (Pihl et al., 2012). Regarding mobility, one light duty vehicle can contain between 6.5 kg and 11.8 kg per unit of chromium, in form of different alloys (Iglesias-Émbil et al., 2020). Nonetheless, material demand for the renewable energy sector represents less than 3% of the total current demand. Even if chromium demand of this sector could double from 2018 to 2050, from a global perspective, this increase is probably going to be negligible (Figs. 2 and 3).

Chromium is a strategic element as it currently does not have possible substitutes in stainless steel production or superalloys. Nevertheless, functional recycling of stainless steel ranges from 70% to 92% (European Commission, 2017). On the other hand, in many other applications, this element is downcycled or even totally dispersed (Ortego et al., 2018).

3.5. Nickel

Nickel is mainly obtained from two different ores: magmatic sulphides and lateritic ores. Around 60% is produced from sulphides, and the nickel concentration can range from 0.15% to 2%, although there are deposits where it can reach 8% (Neukirchen and Ries, 2020). Pentlandite is the most common mined mineral, which is frequently intergrown with pyrrhotite. Indonesia and Philippines were the leading providers of this element in 2019 (Table 2). As the demand of this element for stainless steel increases, these territories have recently started to implement trade bans which has caused raises in the metal price (McRae, 2018).

Approximately two-thirds of the nickel produced is used for stainless steel, as nickel contributes to longevity to ensure resistance against acids and corrosion (Nickel Institute, 2016). In other steel alloys, it is used to improve hardness and malleability. It is also used in other applications such as plating, foundry, batteries, etc. It is not frequently considered a critical element as the total resources are very high and production is geographically dispersed (Department of the Interior, 2018; European Commission, 2020a).

According to the estimations based on renewable energy growth, in 2050, nickel demand will almost double (Fig. 2), corresponding this significant increase to the electric vehicle sector (Fig. 3). There are many vehicle components that demand nickel, being the most important ones the battery, body and electrical and electronic systems (Iglesias-Émbil et al., 2020).

According to United Nations Environmental Programme (UNEP) figures, approximately 68% of nickel is recycled, with a recycled content that can vary between 29% and 41% (UNEP, 2011). New stainless steel containing nickel can be made using stainless steel scrap or high-purity recycled steel (Crundwell et al., 2011). Yet, in many cases, special alloys are recycled as mono-material, losing the initial quality and metal concentration they had, being downcycled (Ortego et al., 2018). Regarding substitution, nickel is used for its specific properties in alloys but can be partially replaced by other metals (European Commission, 2017).

3.6. Cobalt

Most cobalt is produced as a result of the refining process of nickel and copper-bearing ores. In 2015 around 43% of world cobalt production was from copper mining, and 44% from nickel mining (Shedd et al., 2017).

Cobalt is currently used in chemical and metallurgical applications, such as rechargeable battery components, catalysts, pigments, superalloys, and hard metals (Cobalt Institute, 2018). It is considered critical for the European Union and the US as both regions' supply mainly relies on China and the Democratic Republic of Congo (Department of the Interior, 2018; European Commission, 2020a).

Of all the renewable technologies analyzed, cobalt is only used in the mobility sector, approximately 21% of the total demand in 2018 was destined to this end. Electric vehicles can require between 6 kg and 22 kg of cobalt per unit and the increase in the sales of this type of vehicles will considerably affect total cobalt demand (Iglesias-Émbil et al., 2020; Ortego et al., 2020). In 2050, demand is expected to increase more than 260% (Figs. 2 and 3). Some studies even show that cobalt demand is expected to exceed production by 2030 (Schüler et al., 2018).

Even if cobalt is currently recycled from catalysts and superalloys, the most significant opportunities for recycling cobalt are in the battery sector (Cobalt Institute, 2018). The recycling input rate for cobalt is around 35%, while the estimated end-of-life recycling rate can reach 68% (UNEP, 2011). Cobalt-containing batteries could be changed by other batteries, such as lead-acid, lithium manganese oxide or lithium iron phosphate. However, their performance is considerably lower, and this could have consequences in the final battery size. Yet, some improvements are being made related to performance and reducing cobalt content in batteries (Iglesias-Émbil et al., 2020). More emphasis must be made in improving recycling rather than in substitution (Crundwell et al., 2011).

3.7. Copper

Copper is the fourth most mined element worldwide. There are several minerals from where it can be extracted. The most common ones are chalcopyrite, bornite, covellite, and chalcocite (Neukirchen and Ries, 2020). Relevant worldwide deposits are porphyry copper, volcanogenic massive sulfide deposits, among many others, where copper concentration can range from 0.2% to 6%. Chile and Perú were the leading copper producers in 2019 (USGS, 2020). Global copper resources were recently estimated at 3035 Mt after evaluating more than 2000 mineral deposits (Mudd and Jowitt, 2018).

This metal is used in pure form in wiring to conduct electricity and heat, but it can also form alloys with other elements, with zinc to form brass, in tin for bronze, etc. Other main uses are in building construction or transportation. It is rarely labelled as critical as, even if its economic importance is high for many economies, its use is widespread in many sectors and its geological availability is also very high.

It is expected that the total world copper demand from 2018 to 2050 increases around 34% (Fig. 2). As non-renewable sectors' demand is considered constant, this increase in demand would be solely caused by the energy transition. In the case of the renewable energies considered in this study, the mobility sector has the highest consumption regarding copper as a single vehicle can contain between 60 kg and 150 kg of this metal (Fig. 3). Wind generators demand an average of 2822 kg/MW and c-Si solar panels around 1413 kg/MW (Valero et al., 2018a).

Of the 28 Mt that the Copper Alliance estimates that are being used each year, almost 35% comes from recycling (Copper Alliance, 2017). At general level, around 20%–37% of copper is recycled (UNEP, 2011). For its unique properties, copper is an element that can be hardly be substituted by others. Still, in electrical applications aluminum can be used instead (European Commission, 2017).

3.8. Silver

Silver is mainly obtained from argentiferous ores, such as argentiferous lead, lead-zinc and, in the most frequent case, from copper deposits. It is commonly extracted by smelting or chemical leaching or during the electrolytic refining of copper, using the Parkes process (Valero and Valero, 2014). Currently, there are no estimates of silver world resources (Table 2). However, some studies account for the ultimately recoverable reserves of silver between 2.7 Mt and 3.1 Mt (Sverdrup et al., 2014).

This metal is widely used in jewelry and coinage but also in electric and electronic applications, medicine, or alloys. In criticality studies, silver usually has a low value since its uses are very wide and diverse. Only in certain analysis it is considered critical due to its use in some low-carbon technologies (Moss et al., 2011).

The demand for this element between 2018 and 2050 is expected to increase 37%. Even if silver is used in all renewable technologies, c-Si solar panels are the most relevant users, with an average of 133 kg/MW (Valero et al., 2018b).

Silver recycling rates vary widely between sectors, between less than 5% in the automobile industry to more than 60% in industrial applications or 90% in coins (UNEP, 2011). Compared to all the elements present in c-Si solar cells, silver is the most valuable one, and several studies have focused on different ways to recover it after disposal, using electrochemical processes, among other options (Hiskey and Sanchez, 1990; Kuczynska-Lazewska et al., 2018; Lee et al., 2018). Besides recovery, another option is to diminish the use of silver in c-Si solar cells or even replace it with another metal. Copper could be used as an electrode material instead. This change could lower the lifetime of solar cells (Appleyard, 2012). Other substitutes could be the use of cheaper metals, such as nickel or zinc, but this would imply changes in the conductivity or resistivity (Rudolph et al., 2013).

3.9. Tellurium

Around 75% of tellurium is obtained during electrolytic copper refining, from anode slimes, and during smelting process of various elements (Anderson, 2018; Goldfarb et al., 2017). The primary producer of this element in 2019 was China (Table 2). As it is only found as a by-product, there are no estimates of global tellurium resources but reserves estimations made by the USGS indicated 24,000 t. Other studies present data around 48,000 t (Green, 2009; USGS, 2015).

The main use for tellurium is for solar panels (CdTe solar panels), around 40%, another 35% in thermoelectric applications and 10% for metallurgical uses (Anderson, 2018). It is labelled as critical in almost all analysis, either by region or technologies, due to its end uses (Achzet et al., 2011; Department of the Interior, 2018; Moss et al., 2011; UKERC, 2014). As it happens for other by-products, tellurium production can be directly affected by copper extraction and refining. Geological knowledge is also scarce, preventing future estimations or calculations of future production trends.

In renewable technologies, tellurium is mainly used in solar PV, specifically in CdTe solar cells, although c-Si solar cells also have some small amounts of tellurium. For this reason, tellurium demand could increase an average of 85%, due to the expected increase of this type of technology.

Most of the end uses of this element are dissipative, meaning that it cannot be recovered through recycling. Tellurium could be recovered from CdTe modules after crushing and hydrometallurgical or pyrometallurgical processing (Fthenakis and Duby, 2006; Zhang et al., 2020).

3.10. Gallium

The production of gallium is linked to the extraction of bauxite. Around 90% of the gallium recovered at the world level comes from alumina (Zhao et al., 2012). It can also be obtained as a by-product of sediment-hosted lead-zinc deposits. Other sources include fly ash collected from burning coal (Frenzel et al., 2016) and certain minerals in pegmatites (Neukirchen and Ries, 2020). In 2019, a total of 320 t of gallium were produced, 310 t coming from China (USGS, 2020) (Table 2). There are no accurate resource estimates for this element. Still, gallium contained in world bauxite resources could exceed 1 Mt but only around 10% could be potentially recoverable (USGS, 2020). Other estimations state that this number could even reach 4 Mt (Dittrich et al., 2011).

Gallium is used for its semiconducting properties, in form or gallium arsenide and gallium nitride. These compounds are used in integrated circuits, DVS's, laser diodes, and many other electronic applications and lighting, in LED, and in CIGS. It is considered critical by many regions, being the EU and US two of them (Department of the Interior, 2018; European Commission, 2020a). In other studies, gallium was considered to have a high risk of generating bottlenecks due to the growth in demand in the PV sector (Moss et al., 2011).

World total demand is expected to grow by 22% (Fig. 2). This increase will be mainly in the automobile and solar photovoltaic sectors (Fig. 3). An electric vehicle can contain between 0.4 g and 1.1 g of gallium and CIGS demands almost 5 kg per MW installed.

Current recycling and recovery rate of gallium is almost negligible due to the high dispersion. It is used in many different applications in minimal amounts and current recycling processes are focused on base or easy to recover metals (UNEP, 2011). Still, industrial scrap of manufacturing processes that require gallium could be a secondary source for this element if residues are adequately managed. As gallium applications are also very specialized, it does not currently have viable substitutes. Nonetheless, recycling options for CIGS are being analyzed to try to recover the raw materials used in them (Gustafsson et al., 2014). In the case of lighting, organic compounds can be used to substitute gallium in visual display in LED (Moskalyk, 2003).

3.11. Lithium

Of all the strategic elements needed in renewable energy sources, few have been so present in scientific literature such as lithium with more than 840 lithium-related publications in the last forty years (Agusdinata et al., 2018). This growing interest confirms that this element is going to be crucial in the energy transition.

Lithium can be found in different forms, as, for instance, brines and salt lakes, where lithium carbonate can be obtained, or in pegmatites, where lithium-bearing minerals, such as spodumene or amblygonite can be found. At the world level, lithium is only extracted in a few countries, even if there are deposits spread throughout the world. Even if Australia is the leading producer, Chile is one of the largest lithium brine producers, producing 24% of the total lithium in the world in 2019 (Table 2). This country also has almost half of the total world identified resources (USGS, 2020). Additionally, other Latin-American countries, such as Bolivia and

Argentina, could be main sources of easily extractable lithium (Palacios et al., 2018b). According to other studies, total lithium world resources could be around 31 Mt (Kesler et al., 2012). Lithium is not only found in land, but also in seawater. Specifically, the theoretical resource of lithium is sea water has been estimated at 230 billion tones (Yaksic and Tilton, 2009). Yet, not all this lithium can be economically or technically extracted. Even if only 20% could be recovered, vast quantities of water should be processed to produce a significant lithium amount, and it is currently not feasible (Calvo et al., 2017b).

Around 39% of total world lithium demand is currently intended for lithium-ion batteries (Gil-Alana and Monge, 2019). It has high energy density and, contrary to other types of batteries, no memory effect. For this reason, its use is widely spread in mobile phones, cameras, laptops, and, in the case of renewable technologies, in electric vehicles. Other relevant uses of lithium are in ceramics, in form of lithium oxide (30%), greases (8%) and casting mold flux powders (5%) (Jaskula, 2017). This element is considered critical by many studies precisely due to its end uses (British Geological Survey, 2015; Moss et al., 2012). It is also included in the list of 35 critical minerals of the USA (Department of the Interior, 2018). For the European Union, this element was considered critical for the first time in 2020 (European Commission, 2020a).

According to Fig. 2, by 2050 lithium yearly demand is going to increase more than tenfold, considering that the lithium demand in non-renewable sectors is going to remain constant. This increase is mostly going to correspond to the demand in the automobile manufacturing sector (Fig. 3). An internal combustion engine vehicle needs 4 g of lithium, whereas an electric vehicle demands almost 7 kg (Iglesias-Émbil et al., 2020). In the next 30 years it is expected that the lithium production is going to be ten times larger than the current one to transform the fleet of cars (García-Olivares et al., 2012). Some authors even state that global lithium demand only for lithium-ion batteries for electric vehicles could reach more than 500,000 t in 2050 (Månberger and Stenqvist, 2018; Schüler et al., 2018).

Table 3 shows resources to demand ratios (R/D) for 2018 and 2050. Comparing the R/D ratio for 2018 and for 2050, future availability can be assessed. That said, it provides information on the best-case scenario, as it does not consider growth in non-renewable sectors or changes in world resources. In 2018, considering the current consumption rate, there was enough lithium for more than 700 years. However, as the consumption trend increases, in 2050, this number goes down to only 66 years.

The increase in lithium demand could be compensated with alternatives focusing on eco-design measures, encouraging leasing of the batteries in the vehicle sector, or even substituting. Currently, several technologies are being analyzed to build batteries for electric vehicles based on carbon dioxide, graphene, or sodium (Lee et al., 2017; Mizuno et al., 2014). Today, less than 3% of the lithium used in batteries is recycled and, according to UNEP, the average lithium recycling rate is less than 1% (UNEP, 2011). The main reason behind these lower numbers is that lithium is usually used in a dissipative manner, with no technology able to recover it from lubricants, ceramics, glasses, etc. Therefore, as lithium-ion batteries could be the only source from where recovery is profitable, more efforts should be made in this direction (Pagliaro and Meneguzzo, 2019). If the lithium average recycling rate grew up to only 5% in 2050, shortages in supply in the coming decades could be easily avoided (Valero et al., 2018a).

3.12. Manganese

The most important manganese ore is pyrolusite though there are several other manganese and iron minerals from which this element can be extracted. South Africa was the main producer and a large amount of known world manganese reserves are in this country (USGS, 2020). Currently, there are no reliable manganese world resources estimations (Table 2), but ultimately recoverable reserves (URR) estimates for metal extraction are 1440 Mt (Sverdrup and Ragnarsdottir, 2014).

Manganese is a crucial element for iron and steel production, as small amounts of manganese improve the workability of steel at high temperatures and decrease embrittlement. Usually, a ton of steel needs between 6 kg and 9 kg (USGS, 2014). The second largest application is in aluminum alloys, to increase corrosion resistance. Other uses include battery cathodes, electronics, and water treatment chemicals (USGS, 2014). This element is usually not considered critical, yet it is included in the list of 35 critical minerals of the USA, as the country relies 100% on imports (Department of the Interior, 2018).

As shown in Fig. 2, total material demand between 2018 and 2050 is not expected to increase dramatically. Manganese is only used for alloying steels for the manufacturing of electric vehicles and in CSP (Fig. 3). The non-renewable sectors are those that are going to demand more manganese, but in our approach this demand is considered constant. Therefore, the increase is not considerable (2%).

Secondary manganese sources are quite relevant. According to UNEP (2013), end-of-life recycling from ferrous and non-ferrous scrap is greater than 50%. Manganese can also be recovered from slags generated during the steel production process. That said, currently there are no satisfactory substitutes for this element in iron and steel production (European Commission, 2017).

Table 3
Resources to demand ratio (R/D) for 2018 and 2050 for some of the high-risk elements.

	R/D (2018)	R/D (2050)
Cd	25	24
Cr	368	363
Cu	154	114
In	382	270
Li	709	66
Ni	113	62
Zn	44	45

3.13. Tin

Tin can be extracted from various ores, cassiterite being the most commercially important source. China is currently the leading tin producing country (Table 2). Even if there are no resources estimates, ultimately recoverable reserves might be around 96 Mt (Sverdrup and Ragnarsdottir, 2014).

At world level, tin is in demand for use in electronic solders found in circuits and in the industrial sector, for automotive radiators, joining lead pipes, alloys, chemicals, packaging, etc. (European Commission, 2017). It is rarely considered a critical element due to its abundance, geographic distribution, and the availability of secondary sources (tinplate, beverage cans…). Nonetheless, it is included in the US's federal strategy (U.S. Department of Commerce, 2019).

As shown in Fig. 2, total material demand between 2018 and 2050 is expected to increase to around 10%, mainly due to the increase in demand for solar PV (Fig. 3). For instance, around 520 kg/MW of tin are needed in c-Si (Valero et al., 2018a).

There are some applications where tin can be substituted by other elements, the main one being food and beverage containers (by glass, plastic, and aluminum) and solders (by epoxy resin) (European Commission, 2017). In solar energy, other types of solar panels can be used that demand less tin, such as CdTe or CIGS. Yet this would imply to rely on the availability of other elements.

4. Conclusions

Renewable energy sources shall become the main energy providers in the near future. Even sectors that consume large amounts of energy, like the mining industry, are implementing renewable technologies in their operations.

As seen in this paper, the elements that are likely going to experience a more significant increase in demand in the coming decades, compared to current levels, are lithium, cobalt, tellurium, nickel, and indium. Other elements, such as silver or copper, will also experience a moderate increase.

Certain of these elements are currently produced in countries which have a far from desirable situation regarding environmental laws, human rights, reliability and future stability in production. The resource dependency of many regions could even compromise the future of the energy transition, being the elements limited to only a few. This should also be combined with geological availability. The amount of ore that can be profitably extracted in each deposit is finite. The exponential increase in demand could soon lead to mineral depletion.

Another issue that the renewable sector could face shortly is related to recycling opportunities. As we have seen, renewable technologies demand a considerable amount of scarce or critical elements, but currently, there are no feasible or profitable processes to recycle these modern devices. Solar panels, and many other technologies mentioned in this paper, lack standards that facilitate disassembling and recovering the elements that are dispersed in them in appreciable quantities. Economically, recovery processes and plants for these materials are so expensive that they require very significant and major investments. At a global level, China is the leading global recipient of electronic scrap. And in Europe, only one country, Belgium, has a company capable of recycling the minerals that sustain the decarbonized and digital society. Regarding lithium, recycling batteries is one of the best alternatives to ensure its availability, combined with leasing, so the users are not the batteries' owners, but the industry itself.

On the other hand, all opportunities to increase by-products production (i.e. cobalt), are limited by the demand of the primary metal (i.e.: copper or nickel). Metal recovery from stockpiles or partially refined materials, mine dumps and tailings, etc., can be an alternative option. Recovery technologies have improved in the last decades, enabling higher metal recovery rates, as it is being done with niobium and tantalum in Penouta (Rodríguez et al., 2020).

There are three lines of action that could be implemented and should be explored to avoid these bottlenecks that threatens to stifle the future of the ecological transition. First, a much stricter legislative and regulatory framework, consistent with the technical principles of the circular economy. Imposing design and manufacturing standards designed for the recycling of critical minerals and eliminating administrative and legal barriers so that wastes can become raw materials. Second, promoting research and development related to circular economy, creating alliances between the public and the private sector to design metallurgical plants to recover those critical elements. Lastly, the most complex challenge is transforming the economy into a less compulsive and expansive one, prioritizing shared uses and exploring demand control policies. The amount of mineral resources of the Earth is finite. Even if the elements we currently extract are rather dissipated than lost, we cannot solely rely on mines to cover our needs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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