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Material bottlenecks in the future development of green technologies

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ABSTRACT

Decarbonizing world economies implies the deployment of "green technologies", meaning a renovation of the energy sector towards using renewable sources and zero emission transport technologies. This renovation will require huge amounts of raw materials, some of them with high supply risks. To assess such risks a new methodology is proposed, identifying possible bottlenecks of future demand versus geological availability. This has been applied to the world development of wind power, solar photovoltaic, solar thermal power and passenger electric vehicles for the 2016–2050 time period under a business as usual scenario considering the impact on 31 different raw materials. As a result, 13 elements were identified to have very high or high risk, meaning that these could generate bottlenecks in the future: cadmium, chromium, cobalt, copper, gallium, indium, lithium, manganese, nickel, silver, tellurium, tin and zinc. Tellurium, which is mostly demanded to manufacture solar photovoltaic cells, presents the highest risk. To overcome these constraints, measures consisting on improving recycling rates from 0.1% to 4.6% per year could avoid material shortages or restrictions in green technologies. For instance, lithium recycling rate should increase from 1% to 4.8% in 2050. This study aims to serve as a guideline for developing eco-design and recycling strategies.

1. Introduction

In the 21st United Nations Framework Convention on Climate Change celebrated on December 2015 in Paris, it was agreed to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels. Besides, it was proposed that global peaking of greenhouse gas emissions (GHG) should be reached as soon as possible [1]. In this respect, the European Commission, via the Joint Research Centre (JRC), is exploring the most effective way to make the European economy more climate friendly. As it was published in the European low carbon economy roadmap, GHG emissions must be cut to at least 80% below 1990 levels and to accomplish this goal, all sectors must contribute [2].

Both, the electric and transport sectors have a great potential to achieve European targets. The electricity power sector has actually the largest potential for cutting down CO_2 emissions and even eliminating them totally by 2050 [3]. On the other hand, the transport sector, and especially private mobility, could reduce its CO_2 emissions by up to 60% in the same time frame [4]. These changes will imply a renovation in the energy sector towards using renewable sources and zero emission transport technologies.

During this transition period, green technologies like wind power, solar photovoltaic or electrical vehicles will be needed. According to the International Energy Agency projections [5], in 2050, installed power of wind and solar technologies[1] is expected to reach 2208 GW and 2613 GW, respectively in the Reference technology scenario and 3280 GW and 1739 GW, respectively in the 2 °C scenario. Yet this transition must be carefully accomplished as huge amounts of raw materials are going to be required, increasing the pressure on raw material availability.

Wind power demands important amounts of rare earth elements (REE) like neodymium and dysprosium to build permanent magnets for electric generators [6,7] and some studies have shown that demand of both elements might increase by 700% and 2600%, respectively, in the next decades [8]. Additionally, solar photovoltaic demands high quantities of silver for electrical connections, and other materials like

Abbreviations: **BEV**, Battery Electric Vehicle; **CdTe**, Tellurium Cadmium; **CIGS**, Copper, Indium, Gallium, Selenium; **CM**, Critical raw materials; **CRS**, Central Receiver System; **CSP**, Concentrated Solar Power; **d**, material demand; **D**, cumulative material demand; **EV**, Electric Vehicle; **GHG**, Greenhouse gases; **ICEV**, Internal Combustion Engine Vehicle; **LDV**, Light Duty Vehicle; **LIS**, Lithium ion-sieve technology; **m**, studied technologies; **t**, studied years; **N**, manufactured units; **Nns**, new units added to the global market; **Nrn**, units manufactured to renew installations; **PHEV**, Plug Hybrid Electric Vehicle; **PT**, Parabolic Trough; **PV**, Photovoltaics; **R**, reserves or resources; **r**, material share from recycling; **Re**, recycling quote; **REE**, Rare Earth Elements; **RES**, resources; **RSV**, reserves

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[1] Solar power technologies includes solar photovoltaic and solar thermal power.

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cadmium, tellurium, or indium are used for manufacturing p-n junctions in solar thin film technologies like CIGS or CdTe [9–11]. Solar thermal power (STP) requires also silver for manufacturing reflectors or nickel and molybdenum for manufacturing high strength steel alloys needed in structures [12].

In the field of mobility, Light Duty Vehicles (LDV) based on internal combustion engines will be progressively replaced by vehicles based on electromobility. For instance, it is expected that Plug Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) world sales will surpass Internal Combustion Engine Vehicles (ICEV) sales in 2029 and 2038, respectively [13]. This new generation of vehicles will require more electrical and electronic devices, which will demand materials like neodymium, praseodymium and dysprosium to build permanent magnets [14] and silver, indium, tantalum or lanthanum for electronic components [15]. Besides, electromobility will bring the development of high capacity batteries, which in turn will increase world lithium demand [16,17] and with it prices [18] as well as demand for other commodities such as nickel or cobalt [19,20].

On the other hand, current recycling rates of some of these materials are almost negligible because more often than not the specific required recycling processes do not pay off. That is the case for indium, gallium, cadmium and tellurium in solar modules [21]. Indeed, and even if it has been demonstrated that recycling has a huge improving potential by including pre-recycling processes to recover the metals, current recycling rates are still very low [22]. For instance, less than 3% of the lithium contained in a battery is currently recycled [23] and only 42% of the total battery waste mass can be recycled with current available technology [24]. And even if at least 95% of a car's weight must be recycled or recovered, this only covers the most common metals such as iron, aluminum and copper [25]. As a result, the concern regarding the impact of green technologies on raw material availability is becoming an important issue for countries aiming at guaranteeing their sustainability [26,27] and for the development of green technologies [28,29].

The criticality of materials has been extensively studied using different points of view. These assessments can include several dimensions related to vulnerability, economic importance, supply or ecological risks [30,31], being one of the most relevant the one provided by the European Commission, recently updated [32,33]. Most of these factors are very influenced by geopolitical and socioeconomic elements. This is why critical raw materials (CRM) lists need to be constantly updated. In this respect, geological availability could constitute a more stable factor. Still, as it currently depends on demand, exploration efforts and technological progress, all of which related to the economic interest of the commodities, it also presents a high level of incertitude.

Historically, fluctuations and shortages in demand have generated increases both in price and in geological exploration. One of the most recent examples of mineral shortages can be found in China, with REE trade restrictions that took place during the 2005–2012 period [34,35]. Another example was associated to cobalt production in the early 1970s. Due to political instability of the Democratic Republic of Congo, mining activities were slowed down while demand increased sharply. Besides increasing market prices, this situation also triggered the search for alternatives, such as reducing the use of cobalt or finding substitutes in key applications [36].

Leaving questions related to geopolitical risk aside, material constraints from a geological point of view can be assessed by comparing future demand with current production capacity [37,38] or by comparing reserves with production capacity [39]. Nevertheless, these approaches consider that production is static and that it does not change over time, a trend that has been proven wrong over the years.

Thus, it is an interesting first approach but a dynamic behavior must be incorporated to provide more realistic values. For instance, in the case of the energy sector, models that provide dynamic data, like TIMES-MARKAL or LEAP, can be used to assess the impacts related to fossil fuel supply, emissions and encourage the development of energy policies [9,40–42].

As for non-fossil fuels, several dynamic models have been developed for specific minerals, such as copper [43], lithium [44] or aluminum [45], that rely on information regarding ore grade, production rates or market prices, among other factors, to make future predictions. However, these models need very specific data, definition of variables and functions to estimate future projections, which partly need to be based on numerous assumptions.

Indeed, creating a model that estimates future raw material production is a challenge. Nevertheless, in the case of fossil fuels, the Hubbert peak methodology is admitted as a useful and reliable model [46–48] and has also been applied to non-fuel minerals [49]. This approach considers that production evolution is a function of reserves (or resources), therefore production is not considered to be constant. Obviously the model has weaknesses related to data availability and to unpredictable changes in future production, as it presents a business as usual scenario [50]. That said, it is more reliable than those models which consider a constant yearly production.

To assess raw material constraints related to the growth of green technologies, this paper presents a methodology that identifies possible bottlenecks based on: 1) cumulative raw material demand with current available reserves and resources and 2) expected raw material demand and raw material production projections. With this approach, it is possible to identify which materials could create constraints in the medium to long term for each green technology analyzed. Once this task has been carried out, the recycling improvements that should take place before 2050 to avoid these constraints are calculated.

This information can then be used to promote possible alternatives related to increase geological knowledge, substitutability, investment in new technologies to increase recycling rates, etc. It should be stated that it is not the intention of the authors to propose a new CRM list, but rather to point out which green technologies might be at risk of not achieving current deployment targets due to possible raw material supply shortages.

2. Methodology

When talking about green technologies, many types of technologies come into play, from solar power to geothermal. In this paper, the green technologies considered are: wind power, solar photovoltaic (PV), concentrated solar power (CSP) and the mobility sector, with special emphasis on Electric Vehicles (EV) including Plug Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV). For this endeavor, the identification of bottlenecks is done using a combination of bottom-up and top-down approaches, defined as follows:

- Bottom-up approach: assessment, on a global basis, of the reserves, resources and estimated production trends from 2016 to 2050 for each commodity (assuming a Hubbert-like production trend).
- Top-down approach: assessment of material requirements for manufacturing green technologies assuming state of the art developments and competition for materials with the rest of sectors, in the 2016–2050 time period.

2.1. Bottom-up

As extraction is ultimately limited by the amount of minerals present in the crust with sufficient concentration, it is important to identify raw material availability in terms of reserves and resources.

According to the USGS (United States Geological Survey), resources (RES) are concentrations of naturally occurring materials on the Earth's crust in such form that economic extraction is currently or potentially feasible. Reserves (RSV) in turn are the portion of resources which can be economically extracted or produced at the time of determination. Reserves figures are thus lower than resources and more dynamic, since identified resources can be reclassified as reserves when commodity prices rise or when there is a decrease in production costs. Different