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Abstract

The goal of this paper is to elaborate an empirical analysis of the relationship between Critical Raw Materials (CRMs) and environmental technologies. Using text mining techniques to parse and analyse patent descriptions, we provide a thorough empirical exploration of (i) the dependence of green technologies on CRMs; (ii) the countries that lead the demand of CRMs; and (iii) the countries that are more exposed to global demand for CRMs. Framed in the context of recent policy debates on the viability of the green transition, our study points to criticalities associated to both the evolution of green technology and to the spatial network of demand and supply of CRMs.

Keywords — Critical Raw Materials, Green Technologies, Text Mining
Jel classification — O33, Q55, O13

1 Introduction

The goal of this paper is to elaborate an empirical analysis of the relationship between Critical Raw Materials (CRMs) and environmental technologies. CRMs include a broad range of raw inputs that are necessary for the production of intermediate and final goods, and that are deemed critical on account of both their strategic importance for multiple sectors of the economy and of issues concerning availability and limited substitutability. The European Commission (EC) published the first comprehensive list of CRMs in 2011 (European Commission, 2011) and updated it every three years. For the purposes of the present study we rely on an expanded version on the 2020 list

(European Commission, 2020*a*) that includes crucial inputs for the green transition (Hund et al., 2020; International Energy Agency, 2021; Herrington, 2021; Kowalski and Legendre, 2023). Our analysis explores three questions:

1. Which green technologies rely more intensively on CRMs?
2. Which countries rely more intensively on CRMs via their own green inventive activities?
3. Which countries are more exposed to green technology-driven demand for CRMs?

To put matters in context, meeting the climate change goals outlined in the Paris Agreement (1.5-2°C or below) will require scaling up the development and deployment of green technologies which, in turn, entails a significant expansion of production and trade of raw inputs that are critical for their operation (International Energy Agency, 2021; Kowalski and Legendre, 2023). The problem is that green technologies are already more mineral intensive than the fossil fuel counterparts. The International Energy Agency (2021) estimates that a standard electric car needs six times the mineral input of a conventional vehicle and that, under the Sustainable Development Goals scenario, demand for lithium, nickel and graphite – all key inputs for electric vehicles – will grow up to almost 30 times relative to 2020 levels. Likewise, the World Bank (Hund et al., 2020) estimates that meeting the 2°C scenario by 2050 for energy storage alone will require a 450% increase in the production of graphite, lithium and cobalt. Therefore, while implementing the green transition may contribute to reduce global dependence on fossil fuels, keeping up with current demand levels will shift the pressure towards production and trade of raw materials, neither of which is exempt from complications.

On the one hand, the availability of minerals depends upon a wide range of physical and sociopolitical issues. As regards the former, empirical evidence shows that current global reserves of CRMs are not sufficient to match projected demand levels (Herrington, 2021). In addition, the processing yield (viz. ore) of several inputs that are crucial for green technology has been declining over time, thus resulting in higher unitary extraction costs (Heijlen et al., 2021). A second set of issues concerns geopolitical tensions – such as e.g. the ongoing conflict in Ukraine – whereby energy dependence on few supplier countries may turn into vulnerability to input shortages and price oscillations, with far reaching social and economic impacts (Kowalski and Legendre, 2023). Further, prior research shows that mineral extraction correlates with negative socioeconomic outcomes in source countries, to name a few: environmental harm (Norgate and Haque, 2010; Wanger, 2011; Romare and Dahllöf, 2017; Azadi et al., 2020), lower agricultural productivity (Aragón and Rud, 2015), increased physical and psychosocial occupational health hazards (Sovacool et al., 2020), as well as higher propensity towards violent conflicts (Berman et al., 2017; Church and Crawford, 2018; Christensen, 2018). What's more, these domestic issues often hamper suppliers' export security of minerals, thus adding to the globally uncertain outlook. Increasing secondary production of materials through reuse might be an alternative but the current recycling capacity of most CRMs remains inadequate (International Energy Agency, 2021; United Nations Environment Programme, International Resource Panel, 2011; Vikström et al., 2013; Jowitt et al., 2018), and there is still a long way to go before such an option becomes viable and profitable (Wang et al., 2014; International Energy Agency, 2023).

Another major complication is that meeting current, or higher, levels of demand for energy and transportation requires extraction and processing infrastructure that has yet to be built. Indeed, many CRMs required for the green transition have not been mined in bulk quantities so far, and doing so will likely confront scalability issues due to (i) the need for massive amounts of fossil-fuel energy, (ii) the complexity of the underlying component inputs and (iii) the uncertainty of operating untested large-scale distribution systems – e.g., supplying clean energy that matches current standards of security, continuity and regularity (Grandell et al., 2016; Valero et al., 2018; Azadi et al., 2020; Michaux, 2021). One solution may be increasing mineral extraction both by improving current mining activities and by opening new sites, as outlined in the EC's Action Plan on Critical Raw Materials (European Commission, 2020*a*). But, in addition to the foretold socioeconomic drawbacks, setting up new extraction activities would not solve pressing supply issues considering that the average lead times from discovery to production of new mines is nine years – five for construction and start of production alone (International Energy Agency, 2023). In sum, the problem is not just how much of each input is physically available but whether it is economically possible to extract, product and use them as intensively and rapidly as dictated by current policies — not least the European Green Deal.

These issues have surfaced in academic and policy debates only recently. A World Bank forecast casts a shadow on current projections of the timing of the switch to non-fossil fuel energy generation and storage due to global CRMs availability (Hund et al., 2020) and calls for closer collaboration between the climate community and mineral producers to facilitate 'smart mining strategies'. In a similar vein, a European Commission foresight exercise of the supply risks associated with the availability of and accessibility to CRMs (European Commission, 2020*b*) invokes a new industrial strategy based on the stipulation of strategic alliances to remove economic and technical barriers. Further, an International Energy Agency study on green energy technology supply chains identifies key bottlenecks to the scaling up of clean energy as per current policies (see i.e., International Energy Agency 2021, 2023), and advocates for international producer-consumer relationships to shape new environmental, social and governance standards for mineral production and processing. Last but not least, an OECD (Kowalski and Legendre, 2023) assessment of possible shortcomings for technology development due to export restrictions of raw materials recommends a product-specific approach to guide policies for preventing or closing gaps and inconsistencies along green value chains. Common to these recent reports, besides the focus on the emerging socio-technical barriers, is the emphasis on policy that identify and prevent cross national or cross sectoral barriers.

In spite of growing attention in the policy arena, the literature on innovation studies has barely kept up with mounting evidence of growing, and imminent, criticalities in the path towards the green transition. Iammarino and coauthors took a first step by providing thorough empirical evidence of the technological dependence of new inventions on rare minerals (Yunxiong Li et al., 2022) and of technological and geographical linkages between technological paradigms and some critical and conflict materials (Diemer et al., 2022). Taking the cue from these pioneering studies, we propose an exploratory analysis of how green innovation activities map onto the demand for critical raw materials. Bearing in mind that under the broad umbrella of 'green technology' stands a vast terrain of target-specific domains (i.e., energy generation, transport, manufacturing), understanding how technology and sub-technology developments shape input material demand is crucial to inform the viability of different low-carbon scenarios, especially in view of the trade offs that may emerge as a result of the aforementioned bottlenecks. Furthermore, such an exercise carries a dual geographical connotation considering that both inventive activities and material inputs availability are spatially concentrated in specific territorial clusters, which obviously may or may not coincide. This is to say, a directed mapping of clean technology onto critical materials indirectly captures the complex web of cross-country demand and supply connections, thus providing a critical entry point into the wider socio-political opportunities and challenges associated with the green transition.

The empirical analysis proposed here relies on various methodologies and data sources. First, we employ text mining techniques to parse green patents' abstracts – source: European Patent Office (2020) – over the period 1998-2017. This allows us to identify the green technology classes that are more intensively associated to CRMs, thus addressing the first research question. Our methodology follows the cue of cited works by Iammarino and coauthors (Yunxiong Li et al., 2022; Diemer et al., 2022), as well as the pioneering study by Biggi et al. (2022) on the toxicity of chemical patents. Subsequently, using information on granted status and filing countries, we map spatial demand of CRMs based on each country's green patenting activity, thus addressing the second research question. These two issues are further articulated by considering the relative scarcity of materials, measured by means of a spatial concentration index. Lastly, data on the annual production of critical raw materials (source: *World Mining Data* (2023)) allows us to geolocalise the spatial distribution of these inputs. This addresses the third research question and yields the other side of the map, namely of the territories with higher exposure to green technology development by virtue of their endowment of critical materials.

The remainder of the paper is organised as follows. Section 2 - Data & Methods describes the data and the methodology. Section 3 - Results outlines and discusses the results, and is articulated in sub-sections, one for each of the research questions addressed in this paper. Section 4 - Conclusion concludes.

2 Data & Methods

2.1 Data

2.1.1 Green Patents

The primary source of our analysis is the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT) (European Patent Office, 2020), a comprehensive repository of information on more than 100 million documents from patent offices around the world. In spite of well-known shortcomings — i.e. not all inventions are patented, or that among those patented it is difficult to determine their true intrinsic value — patent data is still a reliable source due to wide availability and granularity of information (Griliches, 1998; Lanjouw et al., 1998; Dechezleprêtre et al., 2011; Arts et al., 2013). In the case at hand, we rely on information on the nature of the invention, as detailed in the abstract, and on the geolocalisation of applicants and inventors (Dechezleprêtre et al., 2011). Finally, patent data can be disaggregated into increasingly fine-grained technological areas, which facilitates our task of running keyword searches in specific technological domains (Haščič and Migotto, 2015).

Associated to each patent application in PATSTAT are the Cooperative Patent Classification (CPC) codes assigned by patent offices depending on the relevant technological domain of the invention. The CPC system encompasses five hierarchical levels spanning from 9 sections to around 250000 subgroups: codes starting with the letters A to H represent a traditional classification of innovative activity in technological fields, while the Y section[1] tags new cross-sectional technologies. Inside the Y section, the Y02 class (*Technologies or applications for mitigation or adaptation against climate change*) contains more than 1000 tags organised in 8 sub-classes concerning a wide range of technologies related to sustainability objectives, such as energy efficiency in buildings, energy generation from renewable sources, sustainable mobility, smart grids and many others, details of which can be found at a more aggregated level (hereafter CPC1 level) in Table 1 and at more disaggregated level (hereafter CPC2 level) in Table 2.

Our database includes 3.003.748 patent applications containing abstracts written in English and labeled with CPC codes under the Y02 class. Since an invention can be protected by several patent applications[2], we avoid multiple counting by grouping applications in *inpadoc* patent families, each representing a collection of documents related to the same invention. In our case, 3 million applications correspond to 1.839.600 patent families for each of which we retrieve information on the corresponding Y02 codes at CPC1 and CPC2 levels, the country of origin of the inventors, the country where the family is filed (i.e. where the owners of the invention want to protect it), and the earliest filing year of the family (i.e. the filing year of the earliest patent application belonging to the family). Regarding the latter, we only consider patents registered in PATSTAT no later than 2017 to account for lengthy lags between the compilation in patent offices and the data recorded and collected by EPO.

2.1.2 CRM Production Data

The other major source for our analysis is the World Mining Data (WMD) dataset (*World Mining Data*, 2023), from which we extract information on the annual production of all the relevant CRMs (see Table 3) to focus, in particular, on the annual material content in metric tons produced by each country for the period 1984-2020. Moreover, we compare WMD data with data from the British Geological Survey (BGS) (British Geological Survey, 2023) and the US Geological Survey (USGS) (U.S. Geological Survey, 2023) to cross-check for consistency. We consider WMD our main source because it covers most of the materials of interest. In fact, several CRMs are not found in elemental form but alloyed together with other elements in some minerals. Data on these CRMs can be expressed in terms of the produced quantities of the corresponding minerals: however, depending on the mineral, the CRMs are present in different percentages, which entails that it would be inaccurate to compare production data between countries. For example, lithium can be extracted from minerals with different lithium content. In BGS and USGS lithium production data is reported in terms of these minerals, which can be different depending on the producer country; in WMD on

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[1] `https://www.uspto.gov/web/patents/classification/cpc/html/cpc-Y.html`

[2] For example, for the same invention there are as many patent applications as the number of countries or geographical organisations where the applicants want their invention protected. Legal frameworks of patent offices also offer mechanisms to extent the rights of protection over an invention, which lead to more patent applications.

CPC label	Title and description
Y02	**TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE**
Y02A	Technologies for adaptation to climate change
Y02B	Climate change mitigation technologies related to buildings, e.g. housing, house appliances or related end-user applications, including the residential sector
Y02C	Capture, storage, sequestration or disposal of greenhouse gases
Y02D	Climate change mitigation technologies in information and communication technologies, i.e. information and communication technologies aiming at the reduction of their own energy use
Y02E	Reduction of greenhouse gas (GHG) emissions, related to energy generation, transmission or distribution, including renewable energy, efficient combustion, biofuels, efficient transmission and distribution, energy storage, and hydrogen technology
Y02P	Climate change mitigation technologies in the production or processing of goods
Y02T	Climate change mitigation technologies related to transportation, e.g. hybrid vehicles
Y02W	Climate change mitigation technologies related to wastewater treatment or waste management

Table 1: CPC1 Y02 tagging scheme: green technology main classes

the other hand, lithium production data is expressed in terms of lithium oxide content (Li_2O) for all countries, which make it more accurate as a measure to compare.

However, WMD does not provide information for some CRMs, for example phosphate rock minerals, the only significant global resources of phosphorus according to USGS (U.S. Geological Survey, 2023), magnesium, silicon and strontium. To make up for these gaps, we rely on data from the BGS. An additional caveat is in order for silicon. Production data are included within the ferro-alloys, which comprise alloys that do not include silicon (like ferro-manganese, ferro-nickel, ferro-chrome and so on) or that have a variable and uncertain silicon content (like silicon metal, ferro-silicon, ferro-silico-chrome, ferro-silico-manganese). From all the ferro-alloys, we extract production data on silicon metal only, since it is from it that the high-purity silicon used in green technologies is typically obtained; in addition, in the list by the European Commission (2020*a*) silicon metal, and not generic silicon, is explicitly mentioned among the critical materials to be monitored for Europe. Finally, since starting from 2011 USA production data on silicon metal is reported together with ferro-silicon under the name "ferro-alloys", we estimate the annual silicon metal quantities produced by USA in the period 2011-2020 by weighting the reported ferro-alloys values with the average ratio silicon metal to ferro-silicon of the period 2001-2010.

2.2 Methods

Our analysis focuses on 1.473.320 patent families over the period 1998-2017, thus covering a 20 year time span that is both as recent as patent data allows but that also captures dynamics unfolding around milestone climate agreements (United Nations, 1997, 2015; European Commission, 2019).

CPC label		Description
Y02A	**10**	Adaptation to climate change at coastal zones; at river basins
	20	Water conservation; efficient water supply; efficient water use
	30	Adapting or protecting infrastructure or their operation
	40	Adaptation technologies in agriculture, livestock or agroalimentary production
	50	Adaptation in human health protection
	90	Having an indirect contribution to adaptation to climate change
Y02B	**10**	Integration of renewable energy sources in buildings
	20	Energy efficient lighting technologies
	30	Energy efficient heating, ventilation or air conditioning
	40	Improving the efficiency of home appliances
	50	Energy efficient technologies in elevators, escalators and moving walkways
	60	ICT aiming at the reduction of own energy use
	70	Technologies for an efficient end-user side electric power management and consumption
	80	Architectural or constructional elements improving the thermal performance of buildings
	90	Enabling technologies or with a potential contribution to GHG emissions mitigation
Y02C	**10**	CO_2 capture or storage
	20	Capture or disposal of greenhouse gases other than CO_2
Y02D	**10**	Energy efficient computing
	30	High level technologies for reducing energy consumption in communication networks
	50	Reducing energy consumption in wire-line communication networks
	70	Reducing energy consumption in wireless communication networks
Y02E	**10**	Energy generation through renewable energy sources
	20	Combustion technologies with mitigation potential
	30	Energy generation of nuclear origin
	40	Technologies for an efficient electrical power generation, transmission or distribution
	50	Technologies for the production of fuel of non-fossil origin
	60	Enabling technologies or with a potential contribution to GHG emissions mitigation
	70	Other energy conversion or management systems reducing GHG emissions
Y02P	**10**	Technologies related to metal processing
	20	Technologies relating to chemical industry
	30	Technologies relating to oil refining and petrochemical industry
	40	Technologies relating to the processing of minerals
	60	Technologies relating to agriculture, livestock or agroalimentary industries
	70	CCMT in the production process for final industrial or consumer products
	80	CCMT for sector-wide applications
	90	Enabling technologies with a potential contribution to GHG emissions mitigation
Y02T	**10**	Road transport of goods or passengers
	30	Transportation of goods or passengers via railways
	50	Aeronautics or air transport
	70	Maritime or waterways transport
	90	Enabling technologies or with a potential contribution to GHG emissions mitigation
Y02W	**10**	Technologies for wastewater treatment
	30	Technologies for solid waste management
	90	Enabling technologies or with a potential contribution to GHG emissions mitigation

Table 2: CPC2 tagging scheme: green technology sub-classes

2.2.1 CRMs keyword search

As a first step in our analysis, we compile a list of critical raw materials that will be parsed in green patent abstracts. To do so, we rely on two main sources. The first is the European Commission's list of materials that are labeled as 'critical' in view of their importance for the future of European economies, especially in light of the commitments outlined in the Green Deal (European Commission, 2020*a*). This list, first created in 2011 (European Commission, 2011), is regularly updated every 3 years. For this study we use the 2020 update. The second source is the report of the International Energy Agency (IEA) on the role of minerals in the transition to clean energy sources (International Energy Agency, 2021), in which a wide range of minerals used in clean energy technologies is considered.

Using these resources as references, we run a keyword search of CRMs mentions in each patent's abstracts based on a newly created dictionary containing all the materials in the aforementioned reports (see the top panel *Disaggregated keywords* in Table 3). Each detection of a listed term implies an association between a patent application and one of the CRM[3]. The list of 39 CRMs with respect to which we express our results, is reported in the bottom panel (*Aggregated keywords*) of Table 3.

At this point, a caveat is in order. A green technology-CRM connection can signal a number of circumstances. For example, an input may be mentioned because it is directly used by the patented green technology but also because the technology is used in the manufacturing or refining processes of that material. Furthermore, a green patent might mention a material as the patented invention corresponds to a technology aimed at removing the material because it is harmful to the environment. The latter is especially important for our analysis. That said, following prior literature (Fifarek et al., 2007; Yunxiong Li et al., 2022; Diemer et al., 2022; Biggi et al., 2022) we consider that text mining is a reliable first approximation to detect the connection between CRMs and green technologies. In this spirit, we have also carried out additional checks as reported in Appendix A - Manual Exploration of Patent Abstracts. No doubt, future research should be devoted to refining these methods, perhaps by adopting natural language processing techniques (Montobbio et al., 2022; Rughi et al., 2023).

2.2.2 Herfindahl–Hirschman Index

We consider the time interval 1998-2017 both as a whole and divided into five-year blocks. Regardless of the time aggregation, the pre-processing of CRMs production information is the same, that is, we sum up the production data of the years included in the time interval considered. Therefore, for each period, and for each country-CRM couple, we consider the amount of CRM produced by the country in the years considered. In addition, from the summed data we compute the Herfindahl–Hirschman Index (HHI). Normally, HHI is a commonly accepted and used measure of market concentration computed by summing the squared market shares of all firms in a particular

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[3] We perform a keyword search of both the extended names of CRMs and their element symbols when they have one, except when the latter may be associated with other meanings — e.g. 'In' which is the symbol for indium, 'As' for arsenic, single letter elements like B (boron), P (phosphorus), and so on. Moreover, we merge the results corresponding to materials that are grouped together when we look at their production information: these include rare earth elements (REEs) — for which we search both for the single materials and the 'rare earth' terms in the abstracts — platinum group metals (PGM), and hafnium with zirconium (labeled as zirconium only in the results).

Critical Raw Materials full list

Disaggregated keywords

Aluminium	Antimony	Arsenic	Baryte	Bauxite
Beryllium	Bismuth	Boron	Cadmium	Chromium
Cobalt	Copper	Dysprosium*	Fluorspar	Gallium
Germanium	Graphite	Hafnium***	Indium	Iridium**
Lanthanum*	Lead	Lithium	Magnesium	Manganese
Molybdenum	Neodymium*	Nickel	Niobium	Phosphorus
Palladium**	Platinum**	Praseodymium*	Samarium*	Scandium*
Selenium	Silicon	Silver	Strontium	Tantalum
Tellurium	Terbium*	Tin	Titanium	Tungsten
Vanadium	Yttrium*	Zinc	Zirconium***	

Aggregated keywords

Aluminium	Antimony	Arsenic	Baryte	Bauxite
Beryllium	Bismuth	Boron	Cadmium	Chromium
Cobalt	Copper	Fluorspar	Gallium	Germanium
Graphite	Indium	Lead	Lithium	Magnesium
Manganese	Molybdenum	Nickel	Niobium	PGM
Phosphorus	REE	Selenium	Silicon metal	Silver
Strontium	Tantalum	Tellurium	Tin	Titanium
Tungsten	Vanadium	Zinc	Zirconium	

Table 3: *Top panel*: list of all materials searched in patent abstracts. *Bottom panel*: list of 39 CRMs after aggregation. Legend: * rare earth elements (REE); ** platinum group metals (PGM); *** zirconium and hafnium (labeled under zirconium after the aggregation).

market. The resulting index ranges from 0 to 1: the higher the HHI, the greater the market power of the largest firms in the market. Here we employ the HHI to measure the concentration of producing countries for each CRM. In our case, the HHI takes into account the relative size and distribution of the CRM quantities produced by countries and it approaches zero when the CRM is produced in relatively equal size quantities by a large number of countries. Therefore, the higher the HHI, the greater the share of material output from the largest producing country. In formula:

$$HHI_m(t) = \sum_c \left(\frac{q_{mc}(t)}{\sum_c q_{mc}(t)} \right)^2 , \tag{1}$$

where $q_{cm}(t)$ is the produced quantity (expressed in metric tons) of the CRM m from country c in time period t.

2.2.3 Network Construction

The last part of the analysis brings together all the preceding insights to explore jointly the network of relationships between (i) CRMs and green technologies (based on keyword search), (ii) countries and green technologies (based on where patents are filed), and (iii) between countries and materials (based on production data).

Depending on the relationship at hand, we follow different rules for the link construction between two nodes. In particular, we connect a CRM with a green technology when the number of detections in that green technology is greater than the average number of detections of all CRMs in the same green technology. We also connect a CRM with a country when the latter produces more than the average global production of that CRM. Lastly, we connect a country with a green technology when the number of filed green patent families corresponding to that green technology in the country is above the average number of filed families across all countries. The outcome of such an exercise is an undirected network of CRMs, green technologies and countries wherein each link represents a connection to which we associate different meanings: green technologies are connected with the materials on which they are most dependent and with the countries in which they are deployed, while a country is connected with a material if it is a major producer worldwide.

3 Results

Through a keyword search of materials over more than 3 millions green patent abstracts we examine at a very fined grained level the dependence of green technologies on the 39 CRMs listed in Table 3 (bottom panel) over the period 1998-2017. Searching for green patents in this time window yields 1473320 inpadoc documents. Overall, all the materials are detected at least once, while looking at the families where we have found at least one material, the only green technology to which none of them corresponds (and therefore the only one with which we find no connection to any material) is *Y02B6 - ICT aiming at the reduction of own energy use*, which is also the green technology least present in the entire dataset and has been removed from the CPC since 2018 (European Patent Office and U.S. Patent and Trademark Office, 2018).

3.1 CRMs presence in green technologies

We start by examining the outcome of the keyword search in green patents which yields 292689 CRM returns in 167236 inpadoc families; considering the total number of families in the period 1998-2017 (i.e. 1473320) this means that about 11.4% of patent families have at least one detection. Figure 1 shows these inputs ordered and labeled on the y-axis according to the total (in percentage terms) of detections in green patents. As expected, silicon and base metals like aluminium, copper, zinc and nickel are the most prominent, which resonates with their wide applicability in various sectors, both green and non-green. To put matters in context, crystalline silicon is key in the solar photovoltaic technology; electricity networks require a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies; zinc is used in wind turbines as a protective coating against corrosion; nickel has an important role in energy storage technologies (Hund et al., 2020; International Energy Agency, 2021). In addition, we find a high number of returns for lithium, REE, cobalt, and graphite, all extremely important for the development of green technologies.

Figure 2 shows the evolution of CRM mentions in green technology patents over the period 1998-2017. In particular, we divid the time period into four 5-year intervals: 1998-2002, 2003-2007, 2008-2012 and 2013-2017. Subsequently, for each CRM and for each 5-year interval, the figure plots the total number of detections divided by the total number of patented green technologies. Finally, we report each CRM evolution using 1998-2002 as the base period. Therein the majority of CRMs exhibit a stable pattern, bar a few exceptions. One is lithium, which exhibits a constant increase from 2002 to 2012 and a slight decrease in 2013-2017. Such an input is known to be crucial for many green technologies like batteries for electric vehicles, which is a source of concern given the ongoing booming demand (Kushnir and Sandén, 2012; Valero et al., 2018; Hund et al., 2020; International Energy Agency, 2021, 2023). Another noticeable feature is the rapid acceleration of silicon in the first sub-period followed by an equally strong decline afterwards. This can be ascribed to the evolution of patenting in solar panels – included in *Energy generation through renewable energy sources (Y02E1)* – following a pattern similar to that of silicon, which remains the dominant input for solar panels due to its abundance in the form of minerals such as silica or quartz in the Earth's crust. However, factors such as high manufacturing costs or sub-optimal reflection parameters of silicon have spurred efforts towards enhancing solar cell performance (Suman et al., 2020) thus increasing the range of materials used in solar panels and, consequently, reducing the relative importance of silicon. Therefore if the initial growth coincides with the full maturity of technologies such as monocrystalline or polycrystalline silicon photovoltaic (PV) cells, the recent decline reflects the emergence of technological alternatives to silicon. Other CRMs such as copper, phosphorus and zinc exhibit increasing trends in recent years. While for copper and zinc this may be due to wide applicability in various domains (i.e., wind turbines, solar panels, batteries) the growth of phosphorus might be due to technologies aimed at controlling its presence in wastewater processes (see also the focus on phosphorus in Appendix A - Manual Exploration of Patent Abstracts). Lastly, even if the trends of CRMs such as aluminum, rare earth elements, lead and nickel are constant or mildly decreasing, this does imply that they are less relevant for green technologies, as shown in Figure 1.

Taking a closer look at green technology categories, Figure 3 shows the relative presence of CRMs in the first (1998-2007) and second (2008-2017) periods. For reference, the grey dashed line shows the size of each green technology patent class in the dataset. With very few exceptions, dependence on CRMs has increased between the first and the second period, with highest prevalence in *Mitigation technologies in the production or processing of goods (Y02P)*, *Energy generation, transmission or distribution (Y02E)* and *Capture, storage, sequestration or disposal of GHG (Y02C)*. Conversely the subgroup of *Technologies for Information and Communication Technologies (Y02D)* are at the bottom of this ranking. As expected, among the top ten green technologies are flagship domains often cited in the technical literature (European Commission, 2020*a*; International Energy Agency, 2021), such as *Energy generation through renewable energy sources (Y02E1)*, *Technologies for road transport of good or passengers (Y02T10)* and *Enabling technologies (Y02E60)*. Surprisingly, we also observe two adaptation technologies and four technologies related to the production of goods, three of which with significant higher dependency than the average on CRMs. Overall, the average dependence on CRMs of the top ten technologies in terms of number of patent families is higher than the mean of all technologies (16.6% versus 8.7% in the first period, 18.8% versus 9.4% in the second one). Moreover, these technologies are mostly in a mature stage of the life cycle, which indicates a broader geographical diffusion of their development (Barbieri et al., 2020; Perruchas et al., 2020) and use. This lends support to the argument that policies for the development of green technologies should account for increases in demand for CRMs, either through the increase of primary production or the development of recycling in combination with the eco-design of processes and products.

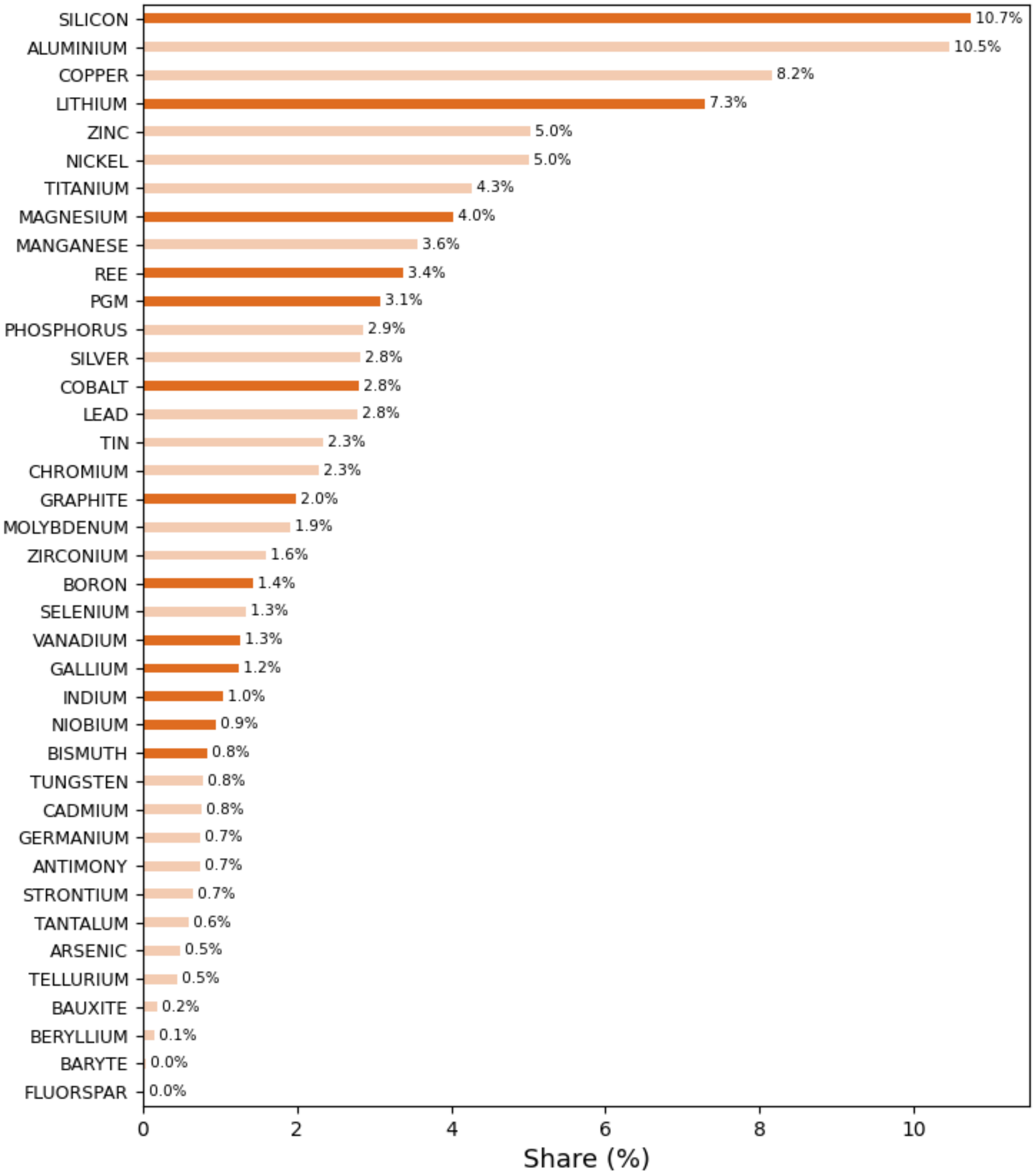

Figure 1: Shares of returns for each CRM in green patents. Dark orange bars indicate CRMs with HHI above the median, i.e., more geographically concentrated production, and connected to at least one green technology according to the methodology described in Section 2.2.3 - Network Construction.

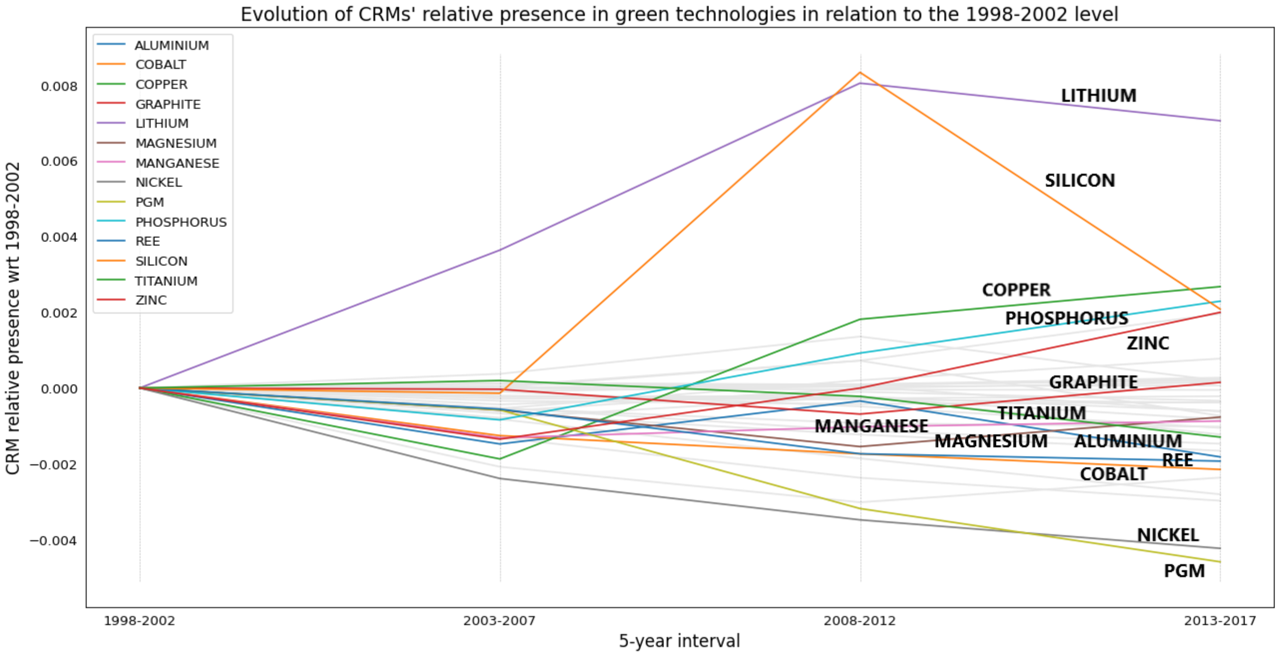

Figure 2: Evolution of CRMs' relative presence in green technologies over 5-year periods – base period: 1998-2002.

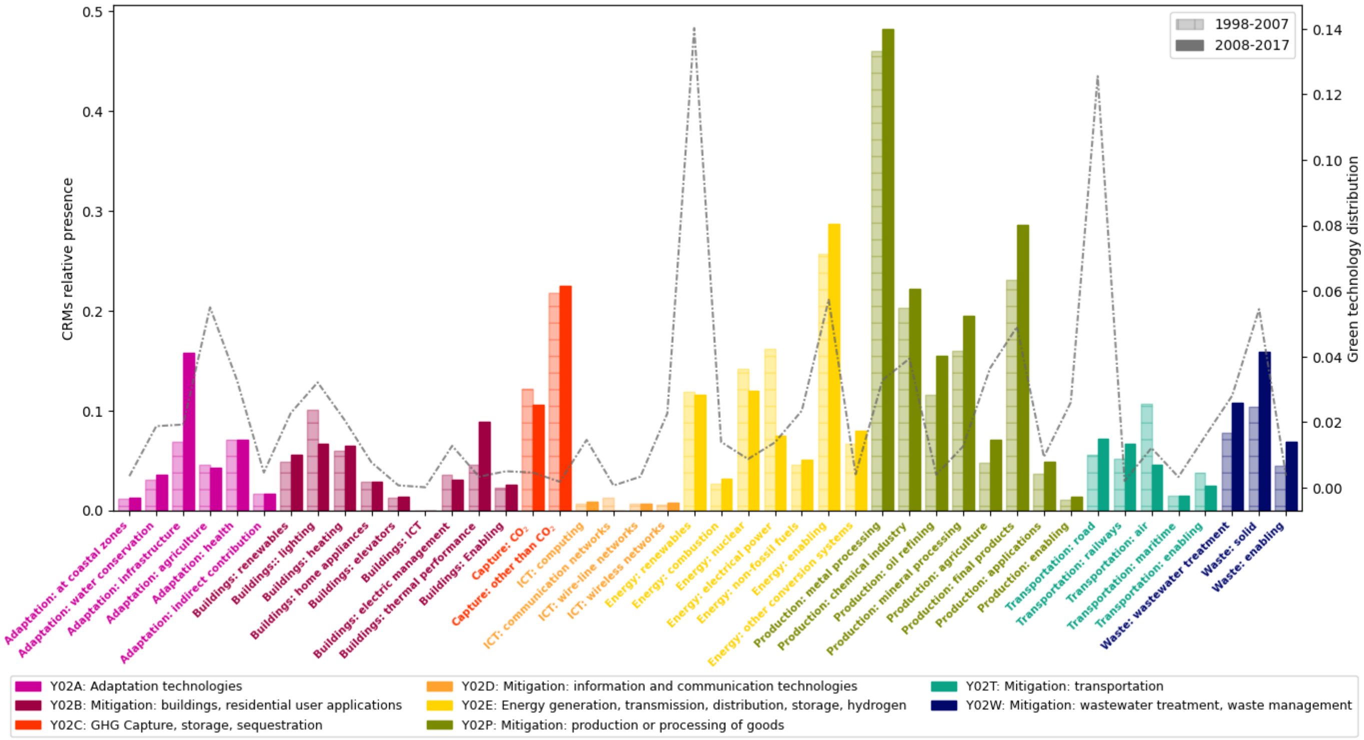

Figure 3: Relative presence of CRMs in green technologies (barplot) and green technology distribution (grey dashed line). Bars: left-hand side=1998-2007; right-hand side=2008-2017. Colour coding in the legend (see also Table 1 and 2).

3.2 Which green technologies rely more intensively on CRMs?

Using information on the annual production data allows us to compute CRM specific HHI index to measure the spatial concentration of material production. Table 4 shows

CRMs ranked by concentration (columns 1 and 2) as well as information on their share of detections in green patent abstracts (columns 3 and 4) – see Figure 1 for reference. Although most raw inputs mentioned in green patents exhibit a fairly wide geographical distribution, a closer look at the first half of the ranking (from boron upwards) indicates that even some of the most concentrated materials play a non negligible role. Among these are rare earth elements (REEs) – mostly produced in China –, silicon – the production of which in its purest form (i.e. silicon metal) is highly concentrated – , lithium – mostly concentrated in Chile, Argentina and Australia – and others like graphite, platinum group metals (PGMs), magnesium and cobalt. We will now focus on these materials that are not very diversified and yet play an important role in green technologies.

Figure 4 shows the connections between CRMs and CPC2 green technologies. Materials (rows) are ordered on the y-axis by increasing levels of geographic concentration of production activities (bottom to top) while green technologies (columns) are listed on the x-axis by increasing levels of patenting intensity (left to right). Each CRM-green technology pair cell is coloured according to the percentile range of CRM detections in each green technology, from dark red (high importance) to yellow (low). A cursory look at the graph reveals more clustering (red cells) on the right hand side, which indicates that the higher the frequency of patenting, the higher the material intensity. Further, clustering is higher on the centre to bottom right of the figure, thus suggesting that, in general, more in demand CRMs are also the less geographically concentrated.

Looking at individual items (rows), some CRMs stand out as more 'general purpose' than others, and thus exhibit strong connections with multiple green technology categories. Bearing in mind that CRMs are ranked by HHI (see Table 4 for reference), silicon, magnesium, lithium are among the most widely used CRMs with more spatially concentrated production (HHI above the median, top part of the figure). Conversely, aluminium, zinc, copper, lead, titanium and nickel are also in high demand but their production is more widely distributed in space (low HHI, bottom half of the graph). These findings resonate with the policy issues mentioned in the introduction, whereby green tech-CRM pairings that may be associated with shortages are in the center-top right hand side of the graph. Some of these problematic connections are well known.

The first is the co-occurrence of silicon (above median HHI as per Table 4) and *Renewable energy (Y02E1)*, which includes among its subclasses photovoltaic energy, thus also including crystalline and amorphous silicon PV cells (Suman et al., 2020). A second renowned connection is between silicon and *Enabling technologies for energy (Y02E6)*, including mainly energy storage technologies such as batteries, for which the use of silicon metal in the anodes is recently being ventured to increase their density (European Commission, 2020*b*; Eshetu et al., 2021). Lastly, silicon ranks high in patenting activities related to *solid waste management (Y02W3)*, which recent literature considers as a side effect of the rapid expansion of the photovoltaic industry (Guo et al., 2021).

Another critical cluster of potentially problematic pairings concerns lithium, which exhibits the peculiarity of being strongly represented in green technologies that are more material specific, meaning that they rely on average on less CRMs compared to other technologies in Figure 4. One instance is *Road transport (Y02T1)*, whereby batteries and energy storage devices rely extensively and almost exlusivey on this input (Graham et al., 2021). Other lithium-intensive green technologies are *Energy efficient heating, ventilation or air conditioning (Y02B3)* and *Water conservation technologies (Y0A2).*

CRM (label)	Rank HHI	HHI value	Rank Detections	% Detections
Niobium (Nb)	1	0.855	26	0.94%
REE (REE)	2	0.832	10	3.38%
Tungsten (W)	3	0.667	28	0.78%
Beryllium (Be)	4	0.662	37	0.15%
Antimony (Sb)	5	0.649	31	0.74%
Magnesium (Mg)	6	0.611	8	4.03%
Germanium (Ge)	7	0.461	30	0.74%
Gallium (Ga)	8	0.441	24	1.25%
Graphite (Gph)	9	0.415	18	1.99%
Bismuth (Bi)	10	0.411	27	0.84%
PGM (PGM)	11	0.406	11	3.08%
Fluorspar (F)	12	0.379	39	0.02%
Silicon (Si)	13	0.344	1	10.74%
Vanadium (Va)	14	0.319	23	1.27%
Arsenic (As)	15	0.309	34	0.48%
Indium (In)	16	0.29	25	1.03%
Lithium (Li)	17	0.281	4	7.29%
Cobalt (Co)	18	0.276	14	2.81%
Boron (B)	19	0.267	21	1.42%
Chromium (Cr)	20	0.255	17	2.28%
Zirconium (Zr)	21	0.254	20	1.60%
Strontium (Sr)	22	0.254	32	0.65%
Baryte (Ba)	23	0.244	38	0.03%
Molybdenum (Mo)	24	0.228	19	1.91%
Tin (Sn)	25	0.219	16	2.33%
Lead (Pb)	26	0.199	15	2.78%
Tellurium (Te)	27	0.194	35	0.45%
Phosphorus (P)	28	0.185	12	2.85%
Aluminium (Al)	29	0.168	2	10.46%
Bauxite (Bx)	30	0.157	36	0.18%
Selenium (Se)	31	0.148	22	1.34%
Tantalum (Ta)	32	0.142	33	0.60%
Copper (Cu)	33	0.14	3	8.16%
Manganese (Mn)	34	0.135	9	3.56%
Zinc (Zn)	35	0.13	5	5.02%
Titanium (Ti)	36	0.123	7	4.26%
Cadmium (Cd)	37	0.114	29	0.76%
Nickel (Ni)	38	0.101	6	5.00%
Silver (Ag)	39	0.094	13	2.82%

Table 4: For each CRM, this table reports information on its HHI (rank and value) and on the corresponding number of detections (rank and shares in percentage) which are also shown in Figure 1

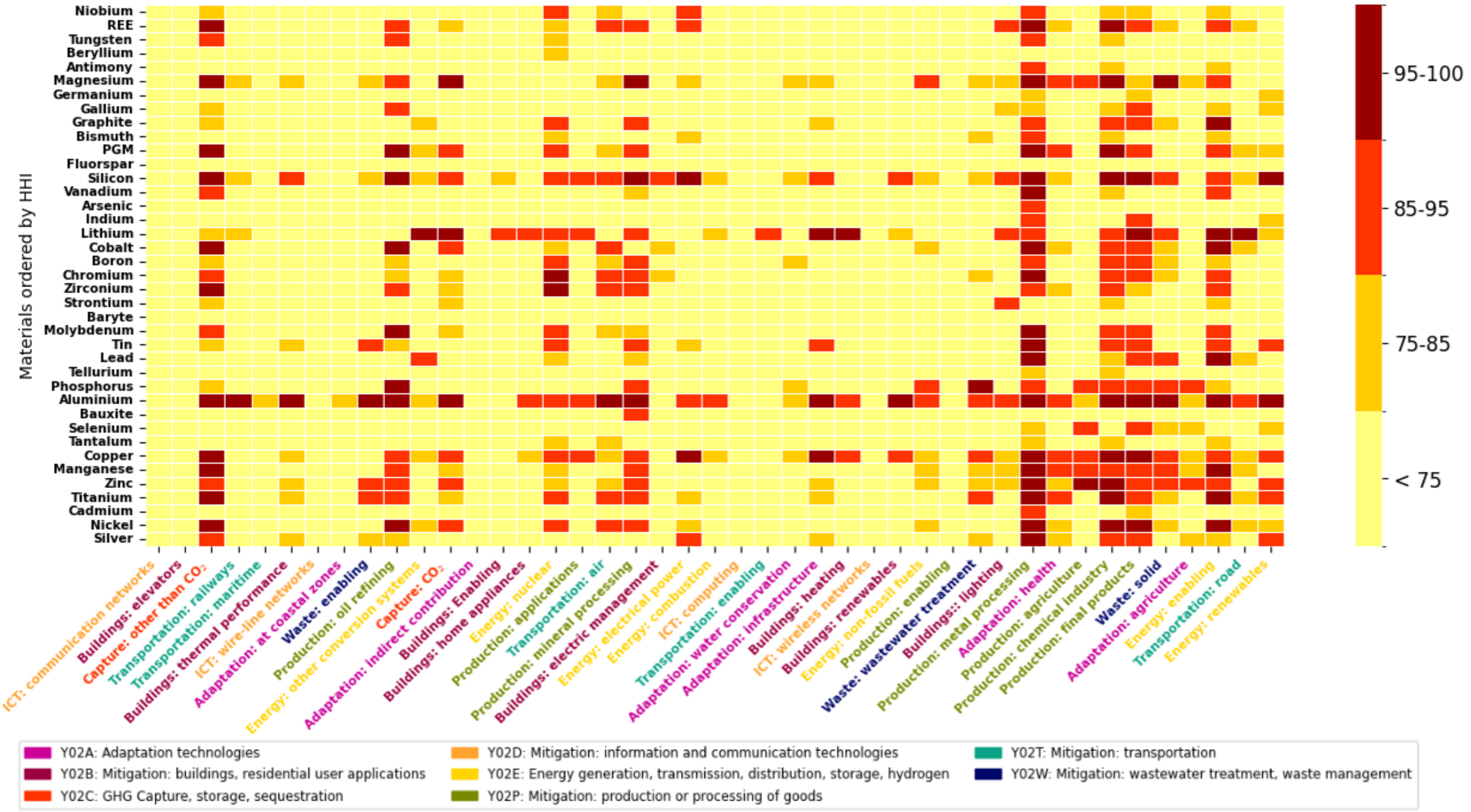

Figure 4: Relative presence of CRM in green technology patents. CRMs are ordered by HHI (see Table 4). Green technologies are ordered by the frequency of each sub-class in the dataset, colour coding in the legend. Cells are coloured according to the relative importance of CRMs in each sub-class: dark red= above 95^{th} percentile; red=85^{th}-95^{th}; orange=75^{th}-85^{th}; yellow= below =75^{th}.

Finally, lithium is in high demand among the leading green technology patent categories that rely extensively on silicon, namely *Renewable energy (Y02E1)*, *Enabling technologies for energy (Y02E6)* and *Technologies for solid waste management (Y02W3)*. The common ground of the two inputs is batteries, by far the most important enabling component, which is crucial as a storage system in renewable energy plants and whose recovery through careful waste management is essential to avoid both shortages and environmental and health hazards (Scrosati and Garche, 2010; Richa et al., 2014).

Focusing on the green technology categories (columns), *Production or processing of goods (Y02P)* emerges as the most 'material intensive' class, which is plausible considering that sub-components domains include *Metal processing (Y02P1)*, *Chemical industry (Y02P2)*, *Oil refining and petrochemical industry (Y02P3)* as well as *Final consumer products (Y02P7)*. Other categories that stand out are *Capture or disposal of GHGs other than* CO_2 *(Y02C2)* and *Enabling technologies for energy (Y02E6)*. The high dependence of these technologies on CRMs has many connotations. As mentioned, *Y02P* comprises green technologies for processing metals, minerals, chemical compounds, etc, which clearly leads to a high number of detections in the abstracts.[4] Regarding other patenting domains, the dependence of enabling technologies like batteries and energy storage devices in general as well as fuel cells' on CRMs is well documented (Hund et al., 2020; International Energy Agency, 2021). Finally, regarding the high dependence of *Y02C2*, according to the World Bank report (Hund et al., 2020) the materials involved throughout all the steps (i.e. capture, transport and storage) of the GHG capture process can be manifold and used in a variety of ways, such as nickel and manganese used either in capturing and in the steel alloys needed for the capture plant. However, as evidenced also by the limited number of patents associated with Y02C in our dataset (see Figure 3), carbon capture and storage is still at early-stages, which casts uncertainty as to the role it will play in the green transition, not least in terms of the actual quantities of CRMs that will be required for its development and deployment.

3.3 Which green patenting countries rely more intensively on CRMs?

The next step of the analysis focuses on the geographical dimension to identify where CRM-dependent green inventions are patented. To obtain a better proxy of the future successful deployment of each invention, we consider only granted green patents[5] which is a sample of 941878 patent families – about 64% of the total number of families over the period 1998-2017. In turn, these families correspond to 1672966 observations of filing countries. If instead we look only at patent families mentioning at least one CRM, we obtain 104028 granted families corresponding to 193585 filing country observations. Therefore, when looking only at granted inventions, the world average relative presence of CRMs in green technologies is 11% (i.e., 104028/941878).

Table 5 shows the top 20 countries that jointly account for 92% of total filing country observations (i.e. 1540643 out of 1672966): for each country we report the total

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[4] It is important to reiterate that materials might be mentioned in patent abstracts both as inputs but also because of the functionality the technology is aimed at, for example refining, recovery, recycling, etc. Therefore, our count method might overestimate the actual dependence of *Y02P*.

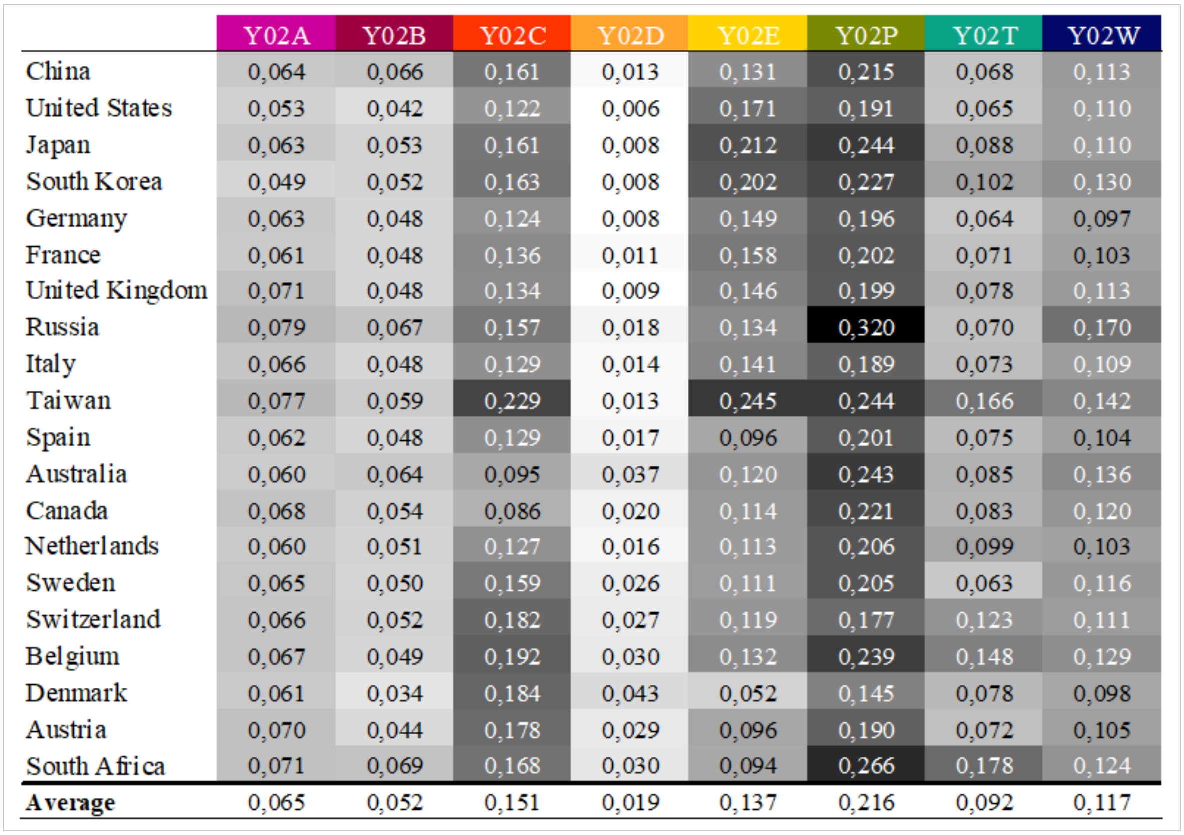
[5] In the case of international patent offices such as WIPO or EPO, we consider a patent application granted in a country when it was reported in PATSTAT or when the patent fees were paid at least once in the country.

green patent families (column 2), the number of families with at least one CRM detection (column 3) and the relative presence of CRMs in the country's patenting activity (column 4). Therein, China emerges as the global leader by a margin followed by the United States (US), Japan, South Korea and Germany (cumulatively, they account for 69% of all country observations). The next block includes France, the United Kingdom, Russia, Italy, Taiwan and Spain (cumulatively, 84% of all country observations). On the whole, this ranking highlights the dominance of Asian countries (4 in the top 10) together with the US, as well as the lower profile of Northern European countries, the majority of which are at the bottom of the table – jointly accounting for 5% of country observations – Netherlands to Austria in Table 5. A closer look reveals that average CRM dependence is higher in the top 10 relative to the bottom half (12% vs 11.3%). Therein, Russia and Taiwan stand out with the highest relative presence of CRMs in green patents (about 16-17%, well above the world average of 11% and the top 20 average of 11.7%), followed by South Africa and Belgium (about 14-15%), Japan and South Korea (about 13%). The more 'virtuous' countries are Denmark, Germany, France, UK, Sweden, Austria and the US (all around 10%).

Country	**TOT families**	**TOT families with CRMs**	**Relative presence of CRMs**
China	548723	64241	11.7%
United States	212267	19729	9.3%
Japan	184653	23913	13.0%
South Korea	115360	15131	13.1%
Germany	95452	9024	9.5%
France	71207	7139	10.0%
United Kingdom	60050	6002	10.0%
Russia	34422	5771	16.8%
Italy	29160	3040	10.4%
Taiwan	27120	4352	16.0%
Spain	25052	2559	10.2%
Australia	23372	2885	12.3%
Canada	22681	2629	11.6%
Netherlands	20081	2213	11.0%
Sweden	14699	1483	10.1%
Switzerland	13077	1412	10.8%
Belgium	11632	1646	14.2%
Denmark	11083	854	7.7%
Austria	10929	1100	10.1%
South Africa	9623	1462	15.2%

Table 5: Descriptive of filed green patents by country

To gain further insights into the spatial distribution of material intensity, we break down information on the relative presence of materials in the top 20 countries by green technology domain (see Figure 5). Looking at green patent portfolios by *Y02* subclasses it is possible to observe that the highest levels of CRM dependence of countries are driven by the most intensive technological categories. High CRM dependent countries like Russia, Taiwan, South Africa, Japan, South Korea and Belgium show multiple high level of dependence (far above average) in the related domains of *production (Y02P)* (Russia, South Africa, Taiwan and Japan in particular), *energy generation (Y02E)* (Taiwan, Japan and South Korea), and *carbon capture (Y02C)* (Taiwan). Russia exhibits high dependence in *waste management (Y02W)*, while Taiwan, Belgium and South Africa in *transportation (Y02T)*. Countries with lower CRM dependence, such as China, Australia and Canada (about 12-13%, see Table 5), display average levels of dependencies across all technology domains. Finally, countries such as the US, Germany, France and United Kingdom exhibit a more balanced level of CRM dependence in their green patent portfolios, with fewer technology domains featuring higher levels of dependence, that usually do not significantly exceed the average values reported in the last row of the figure.



	Y02A	Y02B	Y02C	Y02D	Y02E	Y02P	Y02T	Y02W
China	0,064	0,066	0,161	0,013	0,131	0,215	0,068	0,113
United States	0,053	0,042	0,122	0,006	0,171	0,191	0,065	0,110
Japan	0,063	0,053	0,161	0,008	0,212	0,244	0,088	0,110
South Korea	0,049	0,052	0,163	0,008	0,202	0,227	0,102	0,130
Germany	0,063	0,048	0,124	0,008	0,149	0,196	0,064	0,097
France	0,061	0,048	0,136	0,011	0,158	0,202	0,071	0,103
United Kingdom	0,071	0,048	0,134	0,009	0,146	0,199	0,078	0,113
Russia	0,079	0,067	0,157	0,018	0,134	0,320	0,070	0,170
Italy	0,066	0,048	0,129	0,014	0,141	0,189	0,073	0,109
Taiwan	0,077	0,059	0,229	0,013	0,245	0,244	0,166	0,142
Spain	0,062	0,048	0,129	0,017	0,096	0,201	0,075	0,104
Australia	0,060	0,064	0,095	0,037	0,120	0,243	0,085	0,136
Canada	0,068	0,054	0,086	0,020	0,114	0,221	0,083	0,120
Netherlands	0,060	0,051	0,127	0,016	0,113	0,206	0,099	0,103
Sweden	0,065	0,050	0,159	0,026	0,111	0,205	0,063	0,116
Switzerland	0,066	0,052	0,182	0,027	0,119	0,177	0,123	0,111
Belgium	0,067	0,049	0,192	0,030	0,132	0,239	0,148	0,129
Denmark	0,061	0,034	0,184	0,043	0,052	0,145	0,078	0,098
Austria	0,070	0,044	0,178	0,029	0,096	0,190	0,072	0,105
South Africa	0,071	0,069	0,168	0,030	0,094	0,266	0,178	0,124
Average	0,065	0,052	0,151	0,019	0,137	0,216	0,092	0,117

Figure 5: Relative presence of Y02 sub-classes in national green patent portfolios, x-axis ranked by total green patent families filed in the country (left to right).

Summing up, these insights on the relative input intensity and on the portfolio composition of green patenting, uncover the existence of three blocks. The first includes countries with *high CRM intensity* driven by high CRMs presence in multiple technology domains: Japan, South Korea, Russia, Taiwan, Belgium and South Africa. In the second are countries with *medium CRM intensity* driven by average CRMs presence over all the technology domains: China, Canada and Australia. Finally, the last block consists of countries with *low CRM intensity*, exhibiting below average CRM presence in multiple technology domains: US, Germany, France, United Kingdom, Italy, Spain, Netherlands, Sweden, Switzerland, Denmark, Austria.

3.4 Which countries are more exposed to global demand for CRMs?

Following the procedure detailed in Section 2.2.3 - Network Construction we build a network of connections between CRMs, green technologies and countries wherein countries can be green technology inventors and/or suppliers of materials (Figure 6). To construct such a network, we average over green technologies to establish links with CRMs and countries, focusing only on materials with high HHI concentration (CRMs from boron upwards according to Table 4) that are connected to at least one green technology. This leads us to a reduced list of 13 CRMs, i.e., the materials highlighted with darker bars in Figure 1.

In the network layout nodes are grouped in four columns, from the left to the right: countries (1^{st} column, left-hand side), green technologies (2^{nd} column), CRMs (3^{rd} column), while in the right-hand side (4^{th} column) countries are connected to the network by virtue of CRM input production activities. The size of the nodes is proportional to their degree – i.e., each node's number of links with other nodes in the network – and, for the country and CRM columns, the highest degree nodes are at the center of the corresponding column. Instead, green technologies, positioned in the second column of the network, are grouped and colour coded according to the CPC1 sub-classes listed in Table 1.

Given the rules we follow to build the network links (see Section 2.2.3 - Network Construction) the main insights coming from this exercise center around the dual role of countries as both green innovator (1^{st} column) and producer (4^{th} column) actors. In fact, for what concerns the other 2 columns (green technologies and CRMs), it is important to note that they exhibit only minimal variation in their degree, and consequently in their importance in the network. This is due to the way we build the links. In fact, when we link a country or a CRM to a green technology, we first take each green technology, second look at the average number of filed green patents or of CRM detections, and third take the countries and CRMs that exceed these averages. Similarly, when we link CRMs to countries, for each CRM we link the countries that produce it more than the global average. Therefore, given the characteristics of this process, it is expected that, despite small variations, the nodes over which we average will have a similar number of connections[6].

Hence, while in the previous sections we focused on shaping the presence of CRMs in green technologies, the network provides insights on the role of countries in the global network of demand and supply for green technology inputs. With the exception of China, the global leader in terms of both green technologies and materials production, a divide emerges between countries at the two extremes of Fig. 6. The largest nodes connected to green technologies on the left-hand side are mainly high-income Global North countries – including the US, Germany, France, United Kingdom, Japan and South Korea – while the second tier of leading patenting countries, below the US in the first column of the network, comprises Italy, Spain, Australia, Russia, Canada and Taiwan.

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[6] To stress more on this, look e.g. at the $1^{st} - 2^{nd}$ column connections: for each green technology, we investigate the same set of countries and keep only those with a number of filed patents above the average. Therefore, since the set of countries is the same, the degree (number of countries) of each green technology will be similar, while the composition of its links (which countries) could potentially differ

On the left-hand side of the figure is a cluster of the producers of the most spatially concentrated CRMs. This features a diverse mix with both top patenting countries – such as China, US, Russia and Australia – and countries weakly connected or not linked at all to the green technology nodes, e.g. Turkey, Chile, Argentina, the Democratic Republic of Congo, and India. Brazil (BRA) is a good case in point. It is the second largest producer of CRMs behind China, top supplier of niobium but also of two pivotal and yet relatively scarce inputs like graphite and silicon – the reader will recall their importance from Section 3.2 - Which green technologies rely more intensively on CRMs?. The only other producers of silicon (intended as silicon metal) besides Brazil are China, the US and, to a lower extent, Norway. Yet Brazil's participation in green patenting is limited to *oil refining and petrochemical industry (Y02P3)*, a relatively small class of technologies (see Fig. 4). Likewise, South Africa (ZAF) is the top producer of highly sought after and relatively scarce platinum group metals (PGM) together with Russia. While this input is used in a wide range of technologies, most notably *chemical industry (Y02P2)* (8th technology domain by patent intensity – see Fig. 4), South Africa is only weakly connected to the green patents cluster. Last but not least, the diagram shows that, coherently with the policy reports cited earlier (European Commission, 2020*a*), European countries are rather absent from the right-hand side of the diagram, and the only two that are present, Austria and Norway, are not connected to green technologies as prominently as leading players like France, Germany and United Kingdom.

Let us conclude by drawing attention to a handful of countries that are mere producers and thus exist in this network only by virtue of their capacity to supply CRMs to other patenting countries (red font on the right-hand side of Fig. 6). These include Argentina, Cuba, Chile, the Democratic Republic of Congo, India, Turkey and Zambia. With the exception of a few marginal inputs for green technologies – i.e., Boron produced by Chile, Argentina and Turkey – in most cases these countries play an important role in the global green technology enterprise. A striking example is lithium, of which Chile and Argentina are the only producers together with Australia. Yet another is cobalt, produced by various countries including the Democratic Republic of Congo, Cuba, and Zambia, which are not among green technology inventor countries. Finally is graphite, produced by India together with Brazil and China. Lithium, cobalt and graphite are therefore relatively scarce materials (i.e., high HHI) produced by countries that are at best marginal in the domain of green patenting. Therefore, a clear divergence emerges between the countries producing the CRMs necessary for the development of green technologies and those where such technologies are developed.

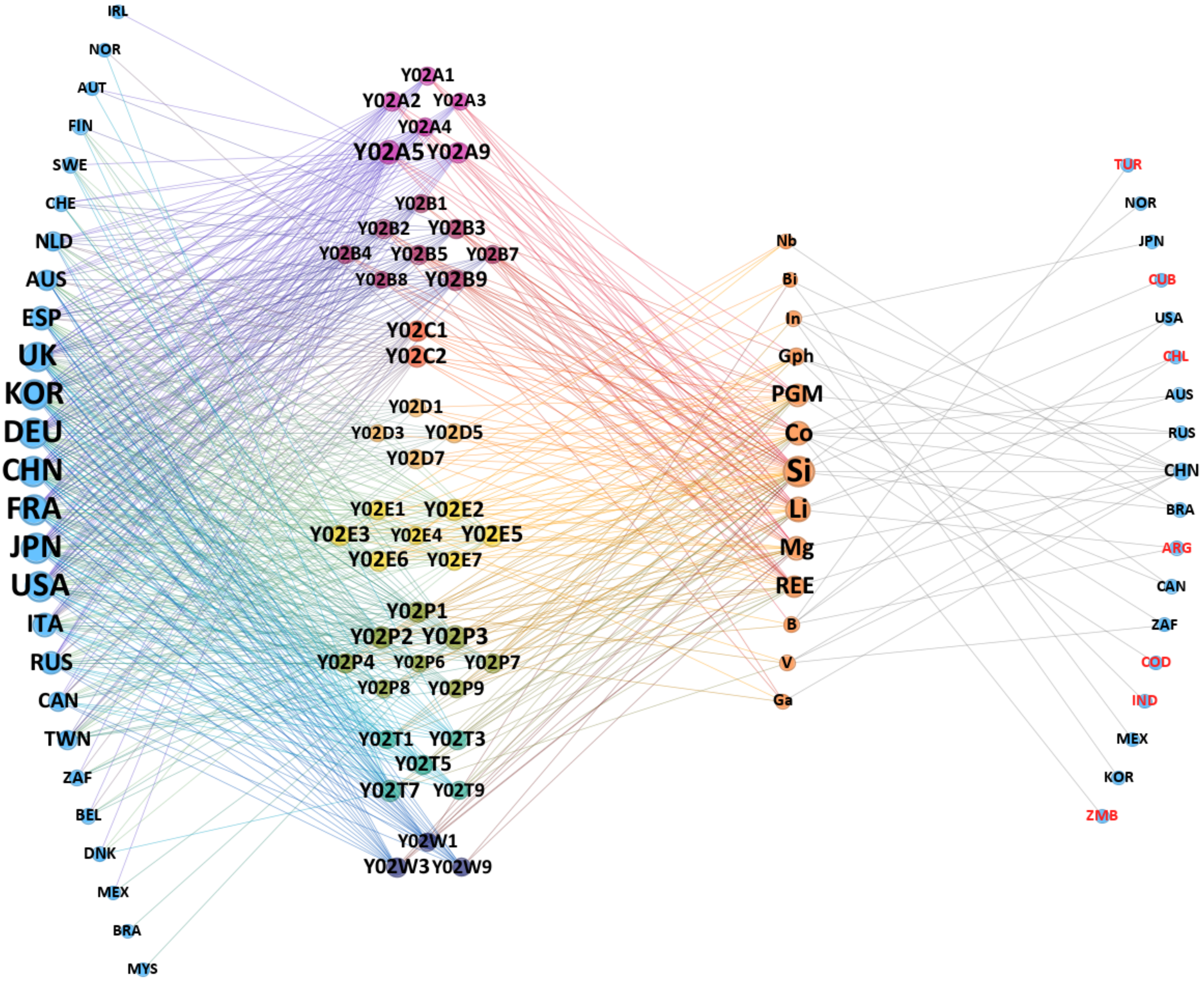

Figure 6: Network of CRMs-green technology-countries. Node size is proportional to their degree. Green technologies: from top to bottom according to CPC1 class. Materials: we select only those with above median HHI (i.e. above Boron in Table 4). Countries and materials are organised so that the higher the degree of the node, the closer to the centre of the respective column. 1^{st} (left) column reports the countries connected to green technologies (2^{nd} column; 3^{rd} column is the CRMs and the 4^{th} is the countries that produce them.

4 Conclusion

This paper has elaborated an empirical analysis of the relationship between Critical Raw Materials and environmental technologies motivated by a growing debate about the feasibility of the green transition which, in its current form, relies heavily on rapid and sizeable scaling up of green technology development and deployment. But this requires an expansion of production and trade of raw inputs which, in spite of policy proclaims, physical availability and state-of-the-art mining capacity simply do not warrant. While the policy debate has started to address these issues, the literature on innovation studies still lags behind. We propose to fills this gap by addressing three questions: (i) which green technologies rely more intensively on CRMs? (ii) which countries rely more intensively on CRMs via their own green inventive activities? And (iii) which countries are more exposed to green technology-driven demand for CRMs?

Our empirical analysis shows that in absolute terms mature green technologies, such as are Metal Processing, Production of goods and Enabling technologies for energy generation, are also more CRM intensive. This is not surprising considering that these were designed and developed when limited resource availability due to excess demand was not an issue. Yet another material intensive domain is the relatively less mature carbon capture, a highly contentious activity due to the uncertainty surrounding both input intensity as well as the observed environmental benefits (Jacobson, 2019; IPCC, 2022). When resource availability (proxied by the HHI index) enters the equation, we identify critical input-green technology pairings. The first is the use of silicon in renewable energy, both for generation and storage, as well as solid waste management. The second concerns the employment of lithium, which is prominent in green technology domains that exhibit higher dependency on specific inputs, namely: batteries and energy storage devices, energy efficient air conditioning and water conservation. Crucially, we also find co-dependence between these two CRMs, as both lithium and silicon are essential to flagship domains such as renewable energy and solid waste management.

Addressing the second question reveals the spatial distribution of green technology specialisation brings to the fore interesting peculiarities. In the top 20 patenting countries are two main groups: one with high CRMs dependence and narrower green tech specialisation, the other with low CRMs dependence and more balanced green technology portfolios. By and large, global leaders in the top 10 have more balanced patent portfolios, with higher prominence of less CRM intensive domains. Interestingly, the top 3 countries exhibit different patterns whereby China, the global leader, is a hybrid (i.e., the only one with high critical input intensity but also a balanced portfolio), the US (2^{nd} ranking) belongs to the former group while Japan (3^{rd} ranking) to the latter. On the whole such an exercise underlines the leadership of the US, the established role of Asia (three countries in the top 5, four in the top 10) as well as the consolidated role of some European countries – albeit only one EU country appears in the top 5.

Lastly, we focus on the geographical exposure to green patenting by considering the dual role of countries in the demand (via patents) and supply of CRMs (via production activities). Such an exercise brings to the fore a noticeable divide between innovators and predominantly low or middle income countries that participate in the global CRMs network only by virtue of their endowment of natural resources that are necessary to meet the demand for inputs that high income countries need to push the green technology frontier. In this picture, Europe stands out primarily as a user of CRMs due to its small volume of production. In contrast, 'mere suppliers' like Argentina, Cuba, Chile, the Democratic Republic of Congo, India, Turkey and Zambia are in the front line of providing critical inputs such as lithium (Chile and Argentina), cobalt (Democratic Republic of Congo, Cuba, and Zambia) and graphite (India) but do not engage any innovation activity.

Before concluding we reiterate that the goal of this paper was to identify criticalities and provide a roadmap for future research on topics that have received so far little attention among innovation scholars. While limits to the physical availability of critical minerals are not new, what has changed is that recent policy pledges have shortened the time frame of the green transition so that ambitious plans to accelerate the shift to e.g., renewable energy or electric vehicle transport may well run into bottlenecks. The first problem is that some critical minerals are in scarce supply, and for some of them mining in bulk quantities is still untested. Even if established targets of new recycling schemes and new extraction activities were met, supply issues would still stand in the way. The second problem is of scalability. Building and operating the infrastructures that are necessary to extract and process the desired volumes of materials, and to subsequently employ them in specific domains of use, is by and large unexplored territory. This uncertainty casts doubts on the feasibility of environmental targets that rely on efficient large-scale systems, especially if subjected to strict standards of security, continuity and regularity as is the case for clean energy supply. The last problem concerns the spatial distribution of natural inputs which connects with, on the one hand, the role of geopolitical relations in the trade of critical materials and, on the other hand, with the importance of accounting for socioeconomic and labour market outcomes in source countries. The lack of balance between the global demand of materials from more industrialised countries and resource availability raises ethical concerns, especially for European producers of green technologies whose future prospects depend on mining resources in other, often less developed, world regions that are already coping with substandard environmental and socioeconomic circumstances. The compelling evidence concerning the uncertainty and the high costs associated with CRM extraction indicate that current green policies are on track to exacerbate disparities and, further down the line, possibly undermine the perceptions and the commitment to tackling climate change. These are complex issues which cannot be addressed by a single paper, but we hope that the present study will contribute to spur such an important debate within the flourishing stream of literature on the green transition.

A Manual Exploration of Patent Abstracts

Part of our methodology consists in the detection of a list of CRM keywords in patent abstracts, the presence of CRM implying that there is a connection between CRM and green technologies. As discussed in Section 2.2.1 - CRMs keyword search, while the literature considers text mining of CRMs in patents a good proxy for how much technologies relies on them, we checked for possible inconsistencies or bias in the findings by reading a sample of abstracts. This process helped us to gain clearer understanding of the connection between CRMs and green technologies, and to refine the queries.

In each case, we selected a sample of patent abstracts randomly stratified by technologies and CRMs so as to have the same distribution of technologies and CRMs relative to that of the population. For each patent, we classified CRM mentions in 4 different categories:

- the CRM is used by the invention.
- the invention is useful to either recycle or refine the mineral.
- the patents describes a methodology to not use anymore or to remove a CRM.
- false positive.

The last category helped use to validate and improve queries. Reading each of the abstracts led us to detect a high number of false positives in lead and beryllium, due to the use of "lead" and beryllium symbol ("Be") in English. After several corrections[7], we concluded that the rate of incorrect detection is less than 3% in all the cases presented below. In the following, elaborate on special cases such as phosphorus and on the green technologies with the highest number of detections.

A.1 Use of phosphorus

Phosphorus is among the most mentioned CRM, with increasing frequency over time but rarely mentioned in technological reports as a determinant for the development of climate change mitigation or adaptation technologies. Hence, we checked a random sample of 208 patent abstracts (2.5% of the population) stratified by technologies to understand how phosphorus is effectively referred to in the documents. We found out that only 71,2% mention it for usage, and the second most frequent mention (14,4%) concern inventions that involve a methodology for actually removing the material. Such instances are mainly in adaptation technologies related to water quality and agriculture (*Y02W1 - Technologies for wastewater treatment*, *Y02A5 - Water conservation; Efficient water supply; Efficient water use*, *Y02A4 - Adaptation technologies in agriculture, forestry, livestock or agroalimentary production*) and aim at preventing excessive amounts of phosphorus coming from soil fertilization. Finally, 12% of the inventions recycle or refine phosphorus, mainly in *technologies for the production of fuel of non-fossil origin (Y02E5)*, *solid waste management (Y02W3)* and *technologies related to metal processing (Y02P1).* Only 5 patents out of 208 were false positive, which gives an accurate rate of detection of 97,60%.

A.2 Technologies with a high presence of CRM

We checked technologies with high presence of CRM in order to verify how robust is the use of minerals occurrences in patent abstracts as the measure of CRM dependence. We obtained random samples of patent abstracts for the following technologies:

- *Capture or disposal of greenhouse gases other than* CO_2 *- Y02C2* (22 abstracts, 3.4% of the population)
- *Enabling technologies related to Energy, Technologies with a potential or indirect contribution to GHG emissions mitigation - Y02E6* (800 abstracts, 2.8% of the population)

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[7] for example, we further examined the preceding and subsequent words of lead in the corresponding abstracts to exclude the detections where 'lead' was used as a verb or denoted tools like lead wire, lead screw, etc., while for 'Be' we eliminated the abstracts where 'Be' was detected at the beginning of a sentence

- *Climate Change Mitigation Technologies related to metal processing - Y02P1* (652 abstracts, 2.4% of the population)
- *Climate Change Mitigation Technologies related to chemical industry - Y02P2* (396 abstracts, 2.7% of the population)
- *Climate change mitigation technologies in the production process for final industrial or consumer products - Y02P7* (711 abstracts, 3% of the population)

The rate of inventions mentioning a use of CRM is above 96% in all these technologies except in the case of *Y02P1*, where 63.1% of CRM mentions are related to a use, while 30.7% are related to recycling or refining CRM. The specificity of metal processing explains these differences. This difference is also present in abstracts proposing a method to remove CRM. While it is less than 2% in all other technologies, it represents 5.2% of *Y02P1* abstracts. The rate of false positives is between 0.8% and 1.5%.

Delving into *Y02P1* mentions of CRM, we found out that the ratio between use and refine/recycle in not stable across minerals. The highest mention of use is in the case of graphite, silicon, bauxite and titanium (above 85% of patent abstracts mentioning those CRM use them), while the highest mention of refine/recycle is for silver, lithium, cobalt and germanium (above 55% of patent abstracts mentioning those CRM is for refining/recycling). The latter could indicate technological developments to improve the availability of some minerals.

In other technologies, the distribution of these ratios is stable across CRM. Above 90% of use for all minerals except for cadmium in *Y02P7*, where 11.8% of patents of this technology propose a process to remove it, and for arsenic in *Y02P2* where this ratio is 25%, although the size of the sample (8 abstracts in Y02P2 mention arsenic) calls for caution. In the cadmium case, the development of cadmium-free products is related to its high toxicity for humans even at low exposure rate.

Data Statement

Patents are not publicly available but can be accessed through PATSTAT (`https://www.epo.org/en/searching-for-patents/business/patstat`) upon payment of a subscription fee.

Production data from World Mining Data are publicly available upon request at `https://www.world-mining-data.info/?World_Mining_Data`.

Production data from British Geological Survey can be downloaded using the tool available at `https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS`.

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