This is an Accepted Manuscript of an article published by Taylor & Francis in Industry & Innovation on August 14th, 2025, available at: https://doi.org/10.1080/13662716.2025.2522451.

Mapping Critical Raw Materials in Green Technologies

Francesco de Cunzo[1,*], Davide Consoli[2], François Perruchas[3], and Angelica Sbardella[1,4]

[1]Enrico Fermi Research Center (Italy)
[2]INGENIO CSIC-Universitat Politecnica de Valencia (Spain)
[3]Department of Business Management, University of Valencia (Spain)
[4]School of Finance and Management, SOAS University of London (UK)
[*]Corresponding Author: francesco.decunzo@gmail.com

Abstract

This paper provides an exploratory analysis of the relationship between critical raw materials (CRMs) and environmental technologies. Using text mining techniques to parse and analyse patent data, we explore: (i) the dependence of green technologies on CRMs; (ii) the countries that are more reliant on CRMs in their green patent portfolios; and (iii) the connections between major users and suppliers of CRMs. Framed in the context of recent policy debates on the viability of the sustainable transition, our study points to criticalities of both the evolution of green technology and of the spatial distribution of demand and supply of CRMs.

Keywords — Critical Raw Materials; Green Technologies; Text Mining; Sustainable Transition; Patent Data
Jel classification — O33, Q55, O13

1 Introduction

This paper elaborates an exploratory analysis of the relationship between critical raw materials (CRMs) and environmental technologies. These materials encompass a broad range of raw inputs for the production of intermediate and final goods, and are deemed as 'critical' by virtue of their strategic importance for key sectors as well as potential issues concerning their availability and limited substitutability. CRMs have become prominent in recent debates concerning the viability of the green and the digital transitions. To put matters in the context of the present study, 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, would entail a significant expansion of production and trade of essential raw inputs (International Energy Agency, 2021; Kowalski and Legendre, 2023). The problem is that these technologies are more mineral intensive than their fossil fuel counterparts. To illustrate, 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 inputs like lithium, nickel and graphite 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 sustainable transition may reduce global dependence on fossil fuels, keeping up with demand will likely shift the environmental pressure towards the production and the trade of raw materials, neither of which is exempt from complications.

On the one hand, the availability of raw materials depends on 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 amount that is available through extraction from mined rocks has been declining over time, making this process more energy intensive and, therefore, more costly (International Energy Agency, 2021). Another set of issues concerns geopolitical tensions that could trigger or exacerbate vulnerability to input shortages and price oscillations, with potentially far reaching social and economic impacts (Kowalski and Legendre, 2023). What's more, prior research casts doubts on the developmental benefits of the expansion of mining industries in sourcing countries (Fusillo et al., 2024; Pietrobelli et al., 2018; Sachs and Warner, 2001). Various strands of literature conclude that high levels of mineral extraction correlate with negative socioeconomic outcomes including environmental harm (Azadi et al., 2020; Norgate and Haque, 2010; Romare and Dahllöf, 2017; Wanger, 2011), lower agricultural productivity (Aragón and Rud, 2015), increased physical and psychosocial occupational health hazards (Sovacool, Ali, Bazilian, Radley, Nemery, Okatz and Mulvaney, 2020), as well as higher propensity towards violent conflicts (Berman et al., 2017; Christensen, 2018; Church and Crawford, 2018). Additionally, domestic issues often hamper suppliers' export security of raw materials, thus further contributing to uncertainty. 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; Jowitt et al., 2018; United Nations Environment Programme, International Resource Panel, 2011; Vikström et al., 2013), and there is still a long way to go before such an option becomes viable and profitable (International Energy Agency, 2023; Wang et al., 2014).

Another major complication is that meeting current, or prospectively increasing, demand for energy and transportation requires an infrastructure for extraction and processing that is still not in place. Indeed, many CRMs required for the green transition have not been mined in bulk quantities so far, and doing so would 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 that are expected to supply clean energy according to the standards of security, continuity, and regularity (Azadi et al., 2020; Grandell et al., 2016; Michaux, 2021; Valero et al., 2018). One option may be increasing mineral extraction both by improving current mining activities and by opening new sites, as outlined in the European Commission's (EC) action plan on critical raw materials (European Commission, 2020*a*, 2024). However, in addition to the foretold socioeconomic drawbacks, setting up new extraction activities would not solve supply issues considering that the average lead times from discovery to production of new mines requires around 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, produce, 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 relatively recently. In 2020, the World Bank questioned projections of the timing of the switch to non-fossil fuel energy generation and storage due to global CRMs availability, and called for closer collaboration between the climate community and mineral producers to facilitate 'smart mining strategies' (Hund et al., 2020). In a similar vein, an EC foresight exercise emphasises supply risks associated with the availability and accessibility of CRMs (European Commission, 2020*b*) and invoked a new industrial strategy based on the stipulation of strategic alliances to remove economic and technical barriers. Likewise, the International Energy Agency identified key bottlenecks to the scaling up of clean energy due to raw input availability (see, e.g., International Energy Agency 2021, 2023), and advocated 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. Besides the focus on emerging socio-technical barriers, common between these reports is the emphasis on the need for policy that identifies and prevent cross-national or cross-sectoral barriers.

In spite of growing attention in the policy arena, the debate on the sources and possible effects of these criticalities is still underdeveloped in innovation studies. Li et al. (2024) took a first step by providing thorough empirical evidence on the technological dependence of new inventions on rare minerals, while Diemer et al. (2022) focused on technological and geographical linkages between technological paradigms and some critical materials. 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' is a vast terrain of target-specific domains, such as energy generation, transport, and manufacturing (Barbieri, Marzucchi and Rizzo, 2020; Barbieri, Perruchas and Consoli, 2020; Perruchas et al., 2020), 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. In particular, we address three research questions (RQ):

1. Which CRMs are most prominent in green technology domains?
2. Which countries rely more intensively on CRMs via their green patenting profile?
3. What is the spatial distribution of demand and supply of CRMs associated with green patenting?

The exploratory analysis proposed here relies on various methodologies and data sources. To address RQ1, we employ text mining techniques to parse green patent abstracts and detect mentions of critical materials over the period 1998-2017 (Herrington, 2021; Hund et al., 2020; International Energy Agency, 2021; Kowalski and Legendre, 2023). For this task, we rely on patent data retrieved from PATSTAT database (European Patent Office, 2020), and on the 2020 update of the EC's list of CRMs (European Commission, 2020*a*). Our methodology follows the cited works of Iammarino and co-authors (Diemer et al., 2022; Li et al., 2024), as well as the pioneering study by Biggi et al. (2022) on the toxicity of chemical patents. To address RQ2, we combine information on patent grant status and filing countries to map spatial demand of CRMs based on each country's green patenting activity. These patterns are further contextualized by incorporating data on the annual production of critical raw materials,[1] which are used to capture the relative scarcity of materials, measured by means of a spatial concentration index. Finally, we draw again on production data to examine the geographical distribution of CRM supply and uncover spatial patterns of connected inventive activities and material input availability. This addresses the third research question and yields the other side of the map, namely territories with higher exposure to green technology development by virtue of their endowment of critical raw materials. Such an exercise captures the complex web of cross-country demand and supply connections, and provides an entry point into the wider socio-political opportunities and challenges associated with the sustainable transition.

The remainder of the paper is organised as follows. Section 2 provides an overview of the relevant context and literature. This is followed by Section 3 detailing the data and the methodology and by Section 4 outlining and discussing the results. Section 5 concludes.

2 Background

2.1 Critical raw materials and technology

In recent decades, the role of CRMs has risen to prominence in research and policy debates by virtue of their strategic role in both the green and digital transitions. These social and economic transformations involve a shift in the material basis of industrial productions, with CRMs being non-substitutable inputs for a wide range of strategic digital and sustainable technologies, from batteries to microchips (de Cunzo et al., 2022; Graedel et al., 2013; Herrington, 2021; International Energy Agency, 2021; Sovacool, Ali, Bazilian, Radley, Nemery, Okatz and Mulvaney, 2020). To illustrate, lithium and cobalt are crucial inputs for electric vehicle (EV) batteries, as well as for renewable energy storage systems and digital infrastructure. Rare earth elements (REEs) such as neodymium and dysprosium are essential for manufacturing high-performance permanent magnets used in wind turbines, EV engines and - along with other materials such as silicon metal, graphite, and cobalt - in components of data storage centres and digital devices like laptops, tablets, and smartphones (European Commission, 2023*b*;

[1] The main source for production data is World Mining Data, available at https://www.world-mining-data.info/?World_Mining_Data.

Hund et al., 2020).[2]

Many CRMs stand at the intersection of the green and digital transitions. Technologies like smart grids rely on renewable energy systems and digital control infrastructure, requiring materials such as gallium and indium. Similarly, EVs integrate digital navigation and battery management systems, all dependent on CRM-based electronics (Moss et al., 2011). Recent studies emphasise the need to align digitalisation with environmental goals, warning that a lack of coordination between the two transitions may amplify environmental pressures through increased energy use, electronic waste, and demand for critical raw materials (European Environment Agency, 2022*a*,*b*; European Commission, 2023*b*, 2024). Additionally, dependence on CRMs has become increasingly complex, as modern technologies incorporate a wider variety of materials, often within the same device, to meet higher performance and efficiency standards (Graedel et al., 2013; Greenfield and Graedel, 2013). These dynamics highlight the risk that uncoordinated technological development may intensify material bottlenecks and undermine sustainability objectives.

In the midst of growing reliance on CRMs, concerns about their future availability have intensified. Potential supply shortages pose a significant risk to the diffusion of new technologies and, further down the line, to the viability of digital and green transitions (International Energy Agency, 2024). The availability of CRMs is threatened by actual physical scarcity rather than mere market factors and price oscillations. In fact, many CRMs exist in limited quantities in the Earth's crust, raising questions about whether supply can meet future demand. Against this complex backdrop, many of these materials are by-products of other minerals and their availability depends on a delicate interplay of factors, including the production efficiency, the commercial viability, as well as the availability of primary minerals (Eggert, 2010; Nassar et al., 2015). Scholars have sought to identify CRMs with the highest supply risks by analysing projected demand under various policy scenarios alongside known geological reserves (Grandell et al., 2016; Valero et al., 2018) and production volumes (Moss et al., 2013). However, the challenge goes beyond sheer quantities, as also timing plays a pivotal role. This implies that, without adequate policy support, medium-term supply shortages could hinder technological innovation and deployment, even if long-term geological reserves were sufficient to meet future demand (International Energy Agency, 2024; Kushnir and Sandén, 2012). This temporal disconnect highlights the pressing need to tackle supply constraints.

A common counterpoint to the above is that increasing primary raw material extraction or improvements in recycling could mitigate supply shortages. However, even these avenues are problematic. On the one hand, opening new extraction sites is a lengthy and complex process, often requiring several years from resource discovery to operational readiness (Heijlen et al., 2021; International Energy Agency, 2023). On the other hand, despite widespread recognition of recycling potential to address potential supply shortages, recycling rates for CRMs remain persistently low due to several barriers (International Energy Agency, 2021). Technological limitations reduce the efficiency of recycling processes while lack of clear economic incentives makes extraction of

[2]For more details on the CRM content of specific green or electronic goods and technology, we refer to the infographics developed by SFA Ofxord available at: `https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-electronics`.

new materials more attractive. Furthermore, many CRM-containing technologies are at early stages of the lifecycle, meaning that a substantial volume of recyclable materials has yet to reach end-of-life (Binnemans et al., 2013; Castelvecchi, 2021; Jowitt et al., 2018; Wanger, 2011).

Such a fragmented backdrop calls for a clearer empirical understanding of how CRMs are embedded in different technological domains, thereby motivating our first research question (RQ1): Which CRMs are most prominent in green technology domains? Drawing on prior studies (Diemer et al., 2022; Li et al., 2024), we detect CRM mentions in patent abstracts and compare green versus non-green technologies. This exercise reveals a stronger association between CRMs and green technologies, consistent with the literature on the material intensity of the sustainable transition (Grandell et al., 2016; Junne et al., 2020; Watari et al., 2019). Subsequently, focusing on green technologies allows us to identify with high level of granularity which materials are most prevalent in specific climate change mitigation and adaptation domains, thereby contributing to a more detailed understanding of the material composition of green innovation.

2.2 The global supply chain and geopolitics of critical raw materials

The spatial connotations of demand and supply of critical inputs motivate RQ 2 and 3. While the entire global supply and demand of raw inputs faces geopolitical turbulence, CRM-intensive value chains are particularly vulnerable to disruption. This is, first, due to their fragmented and globally dispersed nature. Each stage of the chain – from extraction and processing to the production of CRM-dependent end-use products – often spans multiple countries, and is controlled by a few dominant players. Such a high degree of concentration adds fragility and uncertainty to global supply. Previous studies on these value chains estimate their material footprint (Wiedmann et al., 2013) and highlight how structural factors, such as their degree of fragmentation, can affect a country's resilience to supply shocks (Bontadini et al., 2023*b*). Aggressive trade policies in supplier countries, like i.e. trade restrictions, further exacerbate dependence. Trade struggles between China and the US exemplify this dynamic, whereby when the US imposed tariffs and restrictions on Chinese imports like EVs and solar panels, China restricted exports of certain CRMs with limited alternative sources (Fajgelbaum and Khandelwal, 2022).[3] Adding to these challenges, CRM supply chains are also weakened by political instability and governance concerns in producer countries. For instance, the Democratic Republic of Congo, the world's leading supplier of cobalt accounting for over 60% of global extraction, presents severe sources of concern in its mining sector practices. Many cobalt mines operate under poor conditions, frequently involving child labour and exposing workers to serious health hazards (Sovacool, Ali, Bazilian, Radley, Nemery, Okatz and Mulvaney, 2020).

Amid such a volatile landscape, intergovernmental initiatives such as the G7's Five-Point Plan for Critical Minerals Security presented in 2023, have promoted coordinated actions (G7 Ministers' Meeting on Climate, Energy and Environment, 2023). At the same time, various countries are devising strategies to secure access to critical raw materials. Some focus on boosting domestic production, both by expanding primary

[3]See also https://www.nytimes.com/2024/12/03/world/asia/china-minerals-semiconductors.html on China's CRM export restrictions to the US.

mining operations and enhancing secondary processes, such as recycling and substitution technologies. Others, especially in Europe, strive to strengthen their position by negotiating international supply agreements, thereby diversifying their suppliers of these essential materials. As part of the ambitious Open Strategic Autonomy framework and the Green Deal, the European Union (EU) is taking steps to secure access to CRMs for its member states, since many of these are vital for advancing strategic technologies but, crucially, are sourced from outside the Union. As a matter of fact, the EU is one of the few green innovation powerhouses that remains heavily dependent on external CRM supplies. China is not only the world's largest producer but also the EU's primary supplier of rare earth elements, magnesium, graphite, and vanadium. South Africa dominates the supply of platinum group metals, and lithium is primarily imported from Chile (European Commission, 2023*a*). The EC remains vigilant of these developments, as demonstrated by regular updates to its list of critical raw materials, which identifies those essential to the EU economy and particularly vulnerable to supply risks (European Commission, 2011, 2020*a*). In 2024, the EU took an extra step with the Critical Raw Materials Act, a comprehensive framework designed to ensure a secure and sustainable supply of CRMs by focusing on multiple key areas, namely: increasing internal mining exploration, expanding processing and recycling capacities, and reducing dependency on a limited number of third countries at all supply stages, from extraction to processing and beyond (Bontadini et al., 2023*a*; European Commission, 2024). These ongoing efforts speak to the concern that supply vulnerabilities may become a bottleneck for green and digital transitions for EU countries.

In spite of widespread consensus on the importance of multilateral actions (Ali et al., 2017; International Energy Agency, 2024), the competitive pursuit of CRM security at all costs raises additional concerns about physical and ethical constraints on primary and secondary production. Mining, in particular, must undergo a shift towards socially and environmentally responsible practices to mitigate its historically harmful practices, from massive greenhouse gas emissions (Azadi et al., 2020; Norgate and Haque, 2010) and biodiversity loss (Sonter et al., 2018), to highly exploitative labour conditions, and the intensification of local tensions and armed conflicts fuelled by resource extraction (Berman et al., 2017; Church and Crawford, 2018). Furthermore, the geographic distribution of CRM resources exacerbates global inequalities. Many major CRM producers, such as Chile, Bolivia, Argentina, the Democratic Republic of Congo, and Zambia are low-income economies where mining often leads to environmental degradation and social exploitation (Aragón and Rud, 2015; Christensen, 2018; Sovacool, Hook, Martiskainen, Brock and Turnheim, 2020). Additionally, extraction in these countries is often dominated by Western and Chinese multinational corporations (Castillo and Purdy, 2022).[4] Despite being primary CRM suppliers, these territories are among the least prepared for the green transition.[5] Their resources fuel green technologies that are predominantly developed, implemented, and adopted in wealthier, more technologically advanced nations.

The outlined backdrop of supply chain vulnerability in a polycrisis scenario connects to ongoing debates in the geography of innovation literature, in particular on the

[4]See also https://www.energymonitor.ai/sectors/power/the-countries-controlling-the-critical-minerals-supply-chain-in-four-charts/ for reference.

[5]See https://www.statista.com/chart/29789/map-of-countries-preparation-for-frontier-technologies/ for reference.

spatial concentration of high value-added activities (Iammarino and McCann, 2013). Innovative countries and regions are often home to clusters of inter-related firms, high-skilled workers and resources, all of which make them strategic nodes within global value chains. While institutional and technological capabilities in related domains together with the presence of global 'gatekeepers' are drivers of innovative capacity in general (Feldman et al., 2021; Lema et al., 2021; Martin and Trippl, 2017), CRM dependence adds a layer of complexity, as the ability of leading regions to create and capture value through green innovation depends on a host of largely exogenous forces, stemming from the geopolitics of resource-rich economies (Hayter and Patchell, 2017; Sachs and Warner, 2001). And even if those barriers were surmountable, aggressive extractive strategies with weak connections to local economies would hamper opportunities for learning and local appropriation of the relevant competences (Atienza et al., 2020; Bridge, 2008; Emel et al., 2011). In other words, failing to engage in local innovative activities in resource-intensive areas may prove unsustainable in the long term, a prospect that clashes with the urgency of implementing large-scale deployment of green technologies at different stages of life cycle development (see Barbieri, Perruchas and Consoli (2020)) according to extant policy frameworks, i.e. the European Green Deal.

In this context, we formulate our second and third research questions to explore the geography of CRM production and CRM-dependent green inventive activities. To address RQ2, we compute a country-specific index of CRM intensity in patent portfolios to uncover the spatial distribution of the demand for critical inputs related to green technology development. For RQ3, we build a network that connects CRM user countries with CRMs supplier countries. Such an exercise sheds light on the spatial imbalances between producers and consumers of critical inputs in the race towards widespread green technology diffusion.

3 Data & Methods

3.1 Data

3.1.1 Green Patents

The primary data source 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 (Arts et al., 2013; Dechezleprêtre et al., 2011; Griliches, 1998; Lanjouw et al., 1998). In the case at hand, we rely on information on the nature of the invention, as detailed in the patent abstract, and on the geolocalisation of patent applications (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 that patent offices assign on the basis of the relevant technological domain of the invention. The CPC system encompasses five hierarchical levels spanning 9 sections and around 250000 subgroups: groups A to H include traditional innovative activities in technological fields, while new cross-sectional technologies of interest for the present study are in the Y section.[6] The Y02 class (*Technologies or applications for mitigation or adaptation against climate change*) contains more than 1000 tags, organised into 8 sub-classes covering a wide range of climate change mitigation and adaptation technologies, such as energy efficiency in buildings, renewable energy generation, sustainable mobility, smart grids et cetera. A detailed breakdown is provided in Table 1. While there are several classifications of green patents, Y02 and ENV-TECH (OECD, 2022) are the most appropriate for PATSTAT (Favot et al., 2023), but we discard ENV-TECH because it includes also environmental and ocean management technologies and is updated less frequently.[7]

Our database includes 2.441.074 patent applications labelled with CPC codes under the Y02 class. Starting from this sample, we only consider patents registered in PATSTAT in the period 1998-2017,[8] a 20 year time span that is both as recent as patent data allows and that, also, encompasses dynamics unfolding around milestone climate agreements (European Commission, 2019; United Nations, 1997, 2015). Additionally, since an invention can be protected by several patent applications,[9] 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, the roughly 2.4 million applications correspond to 1.473.320 patent families. For each patent family, we retrieve information on the corresponding Y02 codes at different aggregation levels, the earliest filing year of the family - i.e., the filing year of the earliest patent application within the family - and the country where the family is filed, indicating where the invention's owners seek protection. We use the location of the patent office where the application is filed for two main reasons. First, it is a proxy of the country in which the patented invention is likely to be implemented, as well as a spatial marker for the associated CRMs. Second, this approach helps mitigate data coverage issues, as information on inventors or applicants - i.e., two potential alternatives for patent geolocalisation - is often missing in PATSTAT.

3.1.2 Production Data

From the World Mining Data (WMD) we extract information on countries' annual production at the mining stage for relevant CRMs (see Table 2), measured in metric tons over the period 1998-2017. To ensure consistency, we cross-check WMD with the British Geological Survey (BGS) and the US Geological Survey (USGS)[10], though we primarily use the former as it covers most materials of interest for our study. A key benefit of WMD is the systematic and standardized reporting of CRM production. In

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

[7] There is a 6 year gap between the 2nd and the 3rd issue of ENV-TECH published in 2022.

[8] We rely on the 2017 release of PATSTAT to account for lengthy lags between the compilation in patent offices and the data recorded and collected by EPO.

[9] For example, for each invention there are as many patent applications as the number of countries wherein the applicants seek intellectual property protection. Patent offices also offer tools to extend protection rights of an invention that often imply more patent applications.

[10] To have access to information on these data sources see the websites https://www.world-mining-data.info/?World_Mining_Data (WMD), https://www.bgs.ac.uk/mineralsuk/statistics/world-mineral-statistics/world-mineral-statistics-data-download/world-mineral-statistics-data/ (BGS), and https://www.usgs.gov/centers/national-minerals-information-center/minerals-yearbook-metals-and-minerals (USGS).

Y02 Class	
Y02A Technologies for adaptation to climate change	
Y02A10	Adaptation to climate change at coastal zones; at river basins
Y02A20	Water conservation; efficient water supply; efficient water use
Y02A30	Adapting or protecting infrastructure or their operation
Y02A40	Adaptation technologies in agriculture, livestock or agroalimentary production
Y02A50	Adaptation in human health protection
Y02A90	Having an indirect contribution to adaptation to climate change
Y02B Climate change mitigation technologies related to buildings	
Y02B10	Integration of renewable energy sources in buildings
Y02B20	Energy efficient lighting technologies
Y02B30	Energy efficient heating, ventilation or air conditioning
Y02B40	Improving the efficiency of home appliances
Y02B50	Energy efficient technologies in elevators, escalators and moving walkways
Y02B60	ICT aiming at the reduction of own energy use
Y02B70	Technologies for an efficient end-user side electric power management and consumption
Y02B80	Architectural or constructional elements improving the thermal performance of buildings
Y02B90	Enabling technologies or with a potential contribution to GHG emissions mitigation
Y02C Capture, storage, sequestration or disposal of greenhouse gases	
Y02C10	CO_2 capture or storage
Y02C20	Capture or disposal of greenhouse gases other than CO_2
Y02D Climate change mitigation technologies in ICT	
Y02D10	Energy efficient computing
Y02D30	High level technologies for reducing energy consumption in communication networks
Y02D50	Reducing energy consumption in wire-line communication networks
Y02D70	Reducing energy consumption in wireless communication networks
Y02E Reduction of greenhouse gas (GHG) emissions related to energy	
Y02E10	Energy generation through renewable energy sources
Y02E20	Combustion technologies with mitigation potential
Y02E30	Energy generation of nuclear origin
Y02E40	Technologies for an efficient electrical power generation, transmission or distribution
Y02E50	Technologies for the production of fuel of non-fossil origin
Y02E60	Enabling technologies or with a potential contribution to GHG emissions mitigation
Y02E70	Other energy conversion or management systems reducing GHG emissions
Y02P Climate change mitigation technologies in the production or processing of goods	
Y02P10	Technologies related to metal processing
Y02P20	Technologies relating to chemical industry
Y02P30	Technologies relating to oil refining and petrochemical industry
Y02P40	Technologies relating to the processing of minerals
Y02P60	Technologies relating to agriculture, livestock or agroalimentary industries
Y02P70	CCMT in the production process for final industrial or consumer products
Y02P80	CCMT for sector-wide applications
Y02P90	Enabling technologies with a potential contribution to GHG emissions mitigation
Y02T Climate change mitigation technologies related to transportation	
Y02T10	Road transport of goods or passengers
Y02T30	Transportation of goods or passengers via railways
Y02T50	Aeronautics or air transport
Y02T70	Maritime or waterways transport
Y02T90	Enabling technologies or with a potential contribution to GHG emissions mitigation
Y02W Climate change mitigation technologies related to wastewater treatment or waste management	
Y02W10	Technologies for wastewater treatment
Y02W30	Technologies for solid waste management
Y02W90	Enabling technologies or with a potential contribution to GHG emissions mitigation

Table 1: CPC Y02 tagging scheme: climate change mitigation and adaptation technology sub-classes.

fact, many CRMs are not found in pure form but as components of various minerals, with differing compositions that make direct comparisons challenging. For instance, lithium occurs in minerals with varying lithium content. While BGS and USGS report lithium production based on different source minerals depending on the country, WMD labels lithium production uniformly as lithium oxide content (Li_2O), thus allowing for more accurate cross-country comparisons.

That said, WMD lacks data for some CRMs such as phosphate rock minerals - the main global phosphorus resource according to USGS[11] – magnesium, silicon, and strontium. To fill these gaps, we supplement WMD data with BGS records. An additional caveat applies to silicon, whose production data is reported within ferro-alloys, a category that includes both silicon-free alloys - e.g., ferro-manganese, ferro-nickel, ferro-chrome - and alloys with variable silicon content - e.g., silicon metal, ferro-silicon, ferro-silico-manganese. We extract data only for silicon metal, as it is the primary source of high-purity silicon used in green technologies. Moreover, the European Commission (2020*a*) explicitly lists silicon metal, rather than generic silicon, as a critical material for Europe. Finally, since the United States reported silicon metal production together with ferro-silicon under "ferro-alloys" since 2011, we estimate annual US silicon metal production for 2011-2017 by weighting the reported ferro-alloys values with the average ratio silicon metal to ferro-silicon of the period 2001-2010.

3.2 Methods

3.2.1 Keyword search

Addressing RQ1 entails parsing green patent data to detect mentions of CRMs. As a first step, we compile a list of critical raw materials to be searched in patent abstracts. We rely on two sources. The first is the EC list of materials that are labelled 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 introduced in 2011 (European Commission, 2011), is updated every three years. For this study we use the 2020 update (European Commission, 2020*a*). The second source is the report of the International Energy Agency on the role of minerals in the transition to clean energy (International Energy Agency, 2021), which considers a broad spectrum of materials used in clean energy technologies.

Next, we run a keyword search for CRMs mentions in each patent abstract based on a newly created dictionary containing all the materials listed in the two sources (see the top panel *Disaggregated keywords* in Table 2)[12]. Each detected keyword establishes a direct association between a patent application and a CRM, signifying that the material is used in the patented invention[13]. Once we investigated all the CRM-related keywords,

[11] See `https://www.usgs.gov/centers/national-minerals-information-center/phosphate-rock-statistics-and-information`.

[12] We search for both the extended CRM names and their chemical symbols, except when symbols could be ambiguous - e.g. 'In' for indium, 'As' for arsenic, or single letter elements like B for boron and P for phosphorus. 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 (labelled as zirconium only in the results).

[13] We explore an alternative method to identify CRMs in patents using CPC classification, but the coverage is smaller. A comparison between the two methodologies is available in Appendix A.

we express our results with respect to the 39 CRMs reported in the bottom panel (*Aggregated keywords*) of Table 2.

At this point, an important caveat is in order. The detection of a CRM mention in a green technology abstract can signal a number of circumstances. For instance, a material may be mentioned because it is directly used by the patented green technology, but also because one of the purposes of the technology at hand is to recycle that material. On occasion a material is mentioned because the patented invention is a technology or technique for removing the material, for example to reduce environmental hazard. These instances bring to the fore a broad array of circumstances in which a CRM-patent association may not univocally signal the potential for negative environmental outcomes. On these grounds, and following prior literature (Biggi et al., 2022; Diemer et al., 2022; Fifarek et al., 2007; Li et al., 2024), we opt for a text mining approach to detect connections between CRMs and green technologies and to discern between the above circumstances as detailed in Appendix B. That said, future research should focus on refining these methods, perhaps by exploring the potential of natural language processing techniques (Montobbio et al., 2022; Rughi et al., 2023).

3.2.2 Geographic concentration of critical raw materials production

Addressing RQ2 and RQ3 calls for a spatial analysis of patterns of demand and supply of critical inputs for green patents. To measure geographic concentration, we compute an Herfindahl-Hirschman Index (HHI) that gauges the relative size and distribution of overall CRM quantities produced by countries over the period 1998-2017 at the mining stage. The HHI ranges between 0 and 1: it approaches zero when the CRM is produced in relatively equal size quantities by a large number of countries, while values closer to one indicate high concentration of CRM production in a few countries. 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.

3.2.3 Countries' exposure in critical raw materials

Next, we define a measure of each country's exposure to critical raw materials as the weighted contribution of CRM-related patents to its green patent portfolio, where the weights reflect the geographic concentration of each material. Specifically, we focus on CRMs with above-average presence in at least one green technology over the period CRMs that do not meet this criterion - namely: tungsten, cadmium, germanium, antimony, arsenic, beryllium, fluorspar - are excluded from the analysis.

Formally, the green patent portfolio exposure to CRMs for a country c is defined as follows:

$$Exposure_c = \frac{\sum_m (NPAT)_{mc} * HHI_m}{NPATc} \tag{2}$$

where $NPAT_{cm}$ represents the number of patent families with detections of the CRM m filed in the country c, $NPAT_c$ denotes the total number of patent families filed in the

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 2: *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 (labelled under zirconium after the aggregation).

country c, and HHI_m is the geographic concentration of material m, as given by the Herfindahl–Hirschman Index defined in the previous section. In the remainder of the paper, we use the Exposure Index to proxy the CRM dependence of countries via their green patenting activity, which is the main goal of RQ2. An important proviso is that the observed patterns are at best approximations because, being our index based on patent data, it captures national technological protection rights that do not necessarily reflect the rate of adoption of the technologies under analysis.

4 Results

4.1 Comparing green and non-green technology CRM dependence

In the first part of our study, we draw a comparison between the CRM intensity of green and non-green technologies over the period 1998-2017. Since patents can be classified with both green and non-green technological codes, to compare the presence of CRMs in all domains, and to avoid double counting, we consider all patents tagged with at least one Y02 code as belonging only to the green domain. Table 3 details the incidence of CRM patents in green and non-green technological classes. As expected, the non-green patent dataset is substantially larger, with 25.708.295 non-green patent families compared to 1.473.320 green patent families from 1998 to 2017. However, the relative presence of critical raw materials in green technologies is nearly twice as high relative to the non-green group (11.43% vs 6.63%), thus confirming the stronger connection between CRMs and green technologies that emerges from reports on current trends in mineral demand (International Energy Agency, 2024).

	CRM Families	**Tot Families**	**Avg CRM Presence**
Green	168.354	1.473.320	11.43%
Non-green	1.705.304	25.708.295	6.63%

Table 3: CRM presence in green and non-green technologies. In particular, column *CRM families* refers to the number of patent families with at least one CRM detection; column *Tot Families* refers to the total number of patent families classified as green and non-green technologies; column *Avg CRM Presence* refers to the average presence of CRMs, and it's given by the ratio of the other two column values.

While green technologies exhibit consistently higher CRM intensity - see also Figure 13 in the Appendix C, where additional comparisons with non-green technologies are discussed - reflecting the specific material needs for renewable energy generation and electrification, the trends for both domains are strikingly similar. This similarity in trend shapes suggests a transversal distribution of CRMs across technological domains, implying that the underlying dynamics driving CRM usage are similar for both green and non-green technologies, with green technologies simply having a higher overall incidence of CRMs. This motivates a closer examination of how CRMs are distributed across different green technology domains, which we explore in the next section.

4.2 Critical raw materials presence in green technologies

We begin by presenting the results of our text analysis identifying the presence of CRMs in green technologies.[14] Over the period 1998-2017, the keyword search in green patents yields 295.041 CRM returns in 168.354 inpadoc families on a total number of families of 1.473.320, that is, 11.4% of green patent families display at least one CRM detection. Figure 1 breaks down these findings by critical raw material, sorted by the total percentage of detections in green patents. Additionally, thirteen CRMs[15] are highlighted in the figure with darker bars. These materials exhibit both an above the median level of geographical concentration in production, as measured by the Herfindahl-Hirschman Index, and an above average number of detections in at least one green technology. CRM detection shares and CRM production concentration levels are compared in Table 4.

The distribution of CRM observations in Figure 1 is notably skewed, with the top 10 CRMs representing 62% of all observations, and the darker-coloured bars accounting for 40% of all observations. This indicates that CRM mentions in green patents are not only concentrated in a small number of materials, but also that a significant amount of CRM detections involve materials that are highly vulnerable to supply disruptions, as their production is concentrated in just few countries.

To illustrate, silicon, lithium, and base metals such as aluminium, copper, zinc and nickel are among the most prominent. This resonates with their broad applicability across both green and non-green technologies. In fact, crystalline silicon is essential in solar photovoltaic technology; lithium is a key component in battery production; electricity networks rely heavily on 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 (European Commission, 2023*b*; Hund et al., 2020; International Energy Agency, 2021, 2024). In terms of material concentration, in addition to silicon - whose production in its purest form (i.e., silicon metal) is highly concentrated - and lithium - which is primarily extracted in Chile, Argentina and Australia - we also observe a significant number of patents mentions of rare earth elements (REEs) that are extracted and processed exclusively by China. Other materials of interest for the development of green technologies are magnesium, platinum group metals (PGMs), cobalt, and graphite.

Figure 2 illustrates the evolution of relative CRM mentions in green technology patents over the period 1998-2017, divided into four 5-year intervals: 1998-2002, 2003-2007, 2008-2012 and 2013-2017, with 1998-2002 serving as the base period. For each CRM and 5-year interval, the figure shows the difference between the total number of CRM detections for each sub-period (divided by the total number of patented green technologies) and the same value for the base period (1998-2002). The majority of CRMs exhibit a stable pattern, bar a few exceptions. One notable case is lithium, which exhibits a consistent increase from 2002 to 2012, followed by a slight decrease in 2013-2017. Additionally, lithium presence in green technologies grew by 84.7% over the entire period. As previously mentioned, lithium is crucial for batteries for clean energy storage and electric vehicles, which raises concerns due to the ongoing surge of demand (Hund et al., 2020; International Energy Agency, 2021, 2023; Kushnir and

[14]To reinforce our findings, some of the results presented here and in the next section are also replicated in Appendix D, where we incorporate patent citations as a measure of patent quality.

[15]silicon, lithium, magnesium, rare earth elements, platinum group metals, cobalt, graphite, boron, vanadium, gallium, indium, niobium, bismuth.

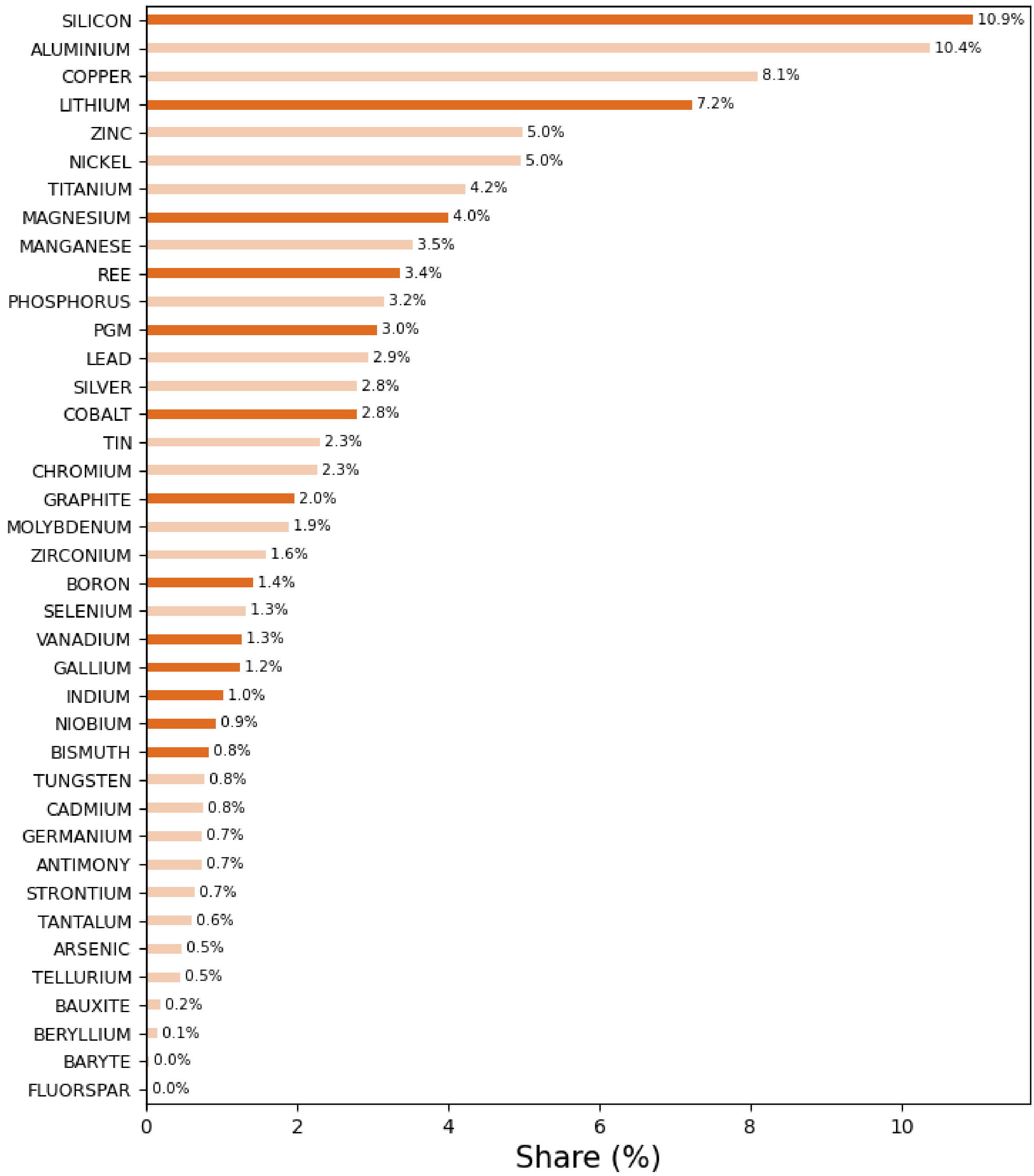

Figure 1: CRMs in green patents, breakdown by material. Dark orange bars indicate CRMs with more geographically concentrated production (above the median HHI) and with an above the average number of detections in at least one green technology.

CRM (label)	Rank HHI	HHI value	Rank Detections	% Detections
Niobium (Nb)	1	0.855	26	0.93%
REE (REE)	2	0.832	10	3.35%
Tungsten (W)	3	0.667	28	0.77%
Beryllium (Be)	4	0.662	37	0.15%
Antimony (Sb)	5	0.649	31	0.73%
Magnesium (Mg)	6	0.611	8	4.00%
Germanium (Ge)	7	0.461	30	0.73%
Gallium (Ga)	8	0.441	24	1.24%
Graphite (Gph)	9	0.415	18	1.97%
Bismuth (Bi)	10	0.411	27	0.83%
PGM (PGM)	11	0.406	11	3.05%
Fluorspar (F)	12	0.379	39	0.01%
Silicon (Si)	13	0.344	1	10.94%
Vanadium (Va)	14	0.319	23	1.26%
Arsenic (As)	15	0.309	34	0.47%
Indium (In)	16	0.29	25	1.02%
Lithium (Li)	17	0.281	4	7.23%
Cobalt (Co)	18	0.276	14	2.79%
Boron (B)	19	0.267	21	1.41%
Chromium (Cr)	20	0.255	17	2.26%
Zirconium (Zr)	21	0.254	20	1.59%
Strontium (Sr)	22	0.254	32	0.65%
Baryte (Ba)	23	0.244	38	0.03%
Molybdenum (Mo)	24	0.228	19	1.89%
Tin (Sn)	25	0.219	16	2.31%
Lead (Pb)	26	0.199	15	2.94%
Tellurium (Te)	27	0.194	35	0.45%
Phosphorus (P)	28	0.185	12	3.16%
Aluminium (Al)	29	0.168	2	10.38%
Bauxite (Bx)	30	0.157	36	0.18%
Selenium (Se)	31	0.148	22	1.33%
Tantalum (Ta)	32	0.142	33	0.60%
Copper (Cu)	33	0.14	3	8.10%
Manganese (Mn)	34	0.135	9	3.53%
Zinc (Zn)	35	0.13	5	4.98%
Titanium (Ti)	36	0.123	7	4.23%
Cadmium (Cd)	37	0.114	29	0.76%
Nickel (Ni)	38	0.101	6	4.96%
Silver (Ag)	39	0.094	13	2.80%

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.

Sandén, 2012; Valero et al., 2018). Another noteworthy trend is the sharp rise in silicon mentions during the first sub-period followed by an equally strong decline. Over the entire period, silicon presence in green technologies grew by 10.7%. This pattern is likely tied to the evolution of solar panel patenting - included in the Y02 class *Energy generation through renewable energy sources* (Y02E10) - with silicon remaining the dominant input for solar panels due to its abundance in minerals such as silica or quartz. However, factors such as high manufacturing costs or sub-optimal reflection properties have driven efforts to enhance solar cell performance (Suman et al., 2020), thus leading to higher use of alternative materials in solar panels to the detriment of silicon. This leads us to conclude that the observed growth at the beginning of the period reflects the full maturity of technologies like monocrystalline or polycrystalline silicon photovoltaic (PV) cells, while the subsequent decline likely signals the emergence of alternative materials. Other CRMs such as copper, phosphorus, and zinc exhibit increasing trends in recent years. While for copper and zinc this may attributed to their broad applicability in various green technology domains - i.e., wind turbines, solar panels, and batteries - the growth of phosphorus is likely driven by mentions in technologies that are designed to monitor its presence in wastewater processes.[16] Lastly, while the trends of aluminium, rare earth elements, lead and nickel appear stable or mildly decreasing, this does not imply that these materials are less relevant for green technologies, nor that supply concerns are absent, as previously highlighted by the patterns of Figure 1 and Table 4.

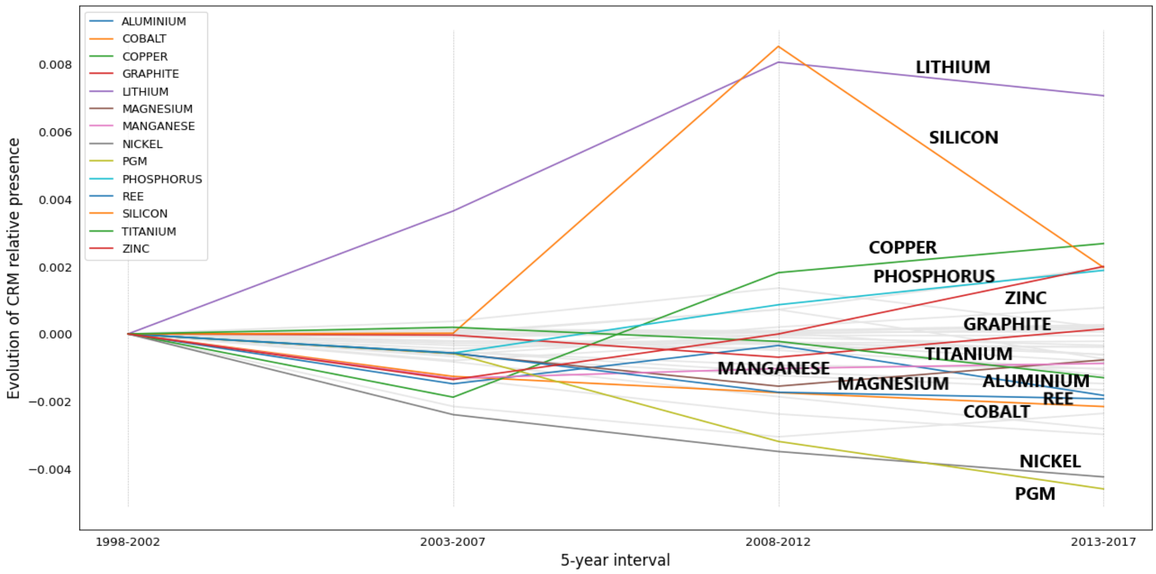

Figure 2: Evolution of CRM relative presence in green technologies over 5-year periods relative to their presence in 1998-2002.

4.3 Which green technologies rely more intensively on which CRMs?

Figure 3 illustrates the relative presence of CRMs in the green technology sub-classes of Table 1, relative to the time periods 1998-2007 and 2008-2017. The empirical regular-

[16]See more details about this in Appendix B.

ities underlying this graph address RQ1. For reference, the grey dashed line indicates the size of each green technology patent sub-class in the dataset. With few exceptions, dependence on CRMs has increased between the first and the second period, with the 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). Among them, when considering their size in the dataset, all except Y02C have a significant share of patents, indicating that their high CRM content may have a greater influence on material demand. Conversely, the subgroup of *Technologies for Information and Communication Technologies* (Y02D), covering a smaller share of patents in our dataset, exhibits the lowest CRM presence. As expected, among the top ten green technologies are prominent domains often cited in the technical literature (European Commission, 2020*b*; International Energy Agency, 2021), such as *Energy generation through renewable energy sources* (Y02E10), *Technologies for road transport of good or passengers* (Y02T10) and *Enabling technologies* (Y02E60). Additionally, we observe significant material dependence in two adaptation technologies and four technologies related to the production of goods, three of which show notably higher CRM dependency than the average. Overall, the average CRM dependence of the top ten technologies in terms of the number of patent families is higher than the average across all technologies (16.1% versus 8.1% in the first period, 18.2% versus 8.8% in the second). Moreover, these technologies are mostly in a mature stage of the life cycle, suggesting a broader geographical diffusion of their development and use (Barbieri, Perruchas and Consoli, 2020; Perruchas et al., 2020; Sbardella et al., 2018).

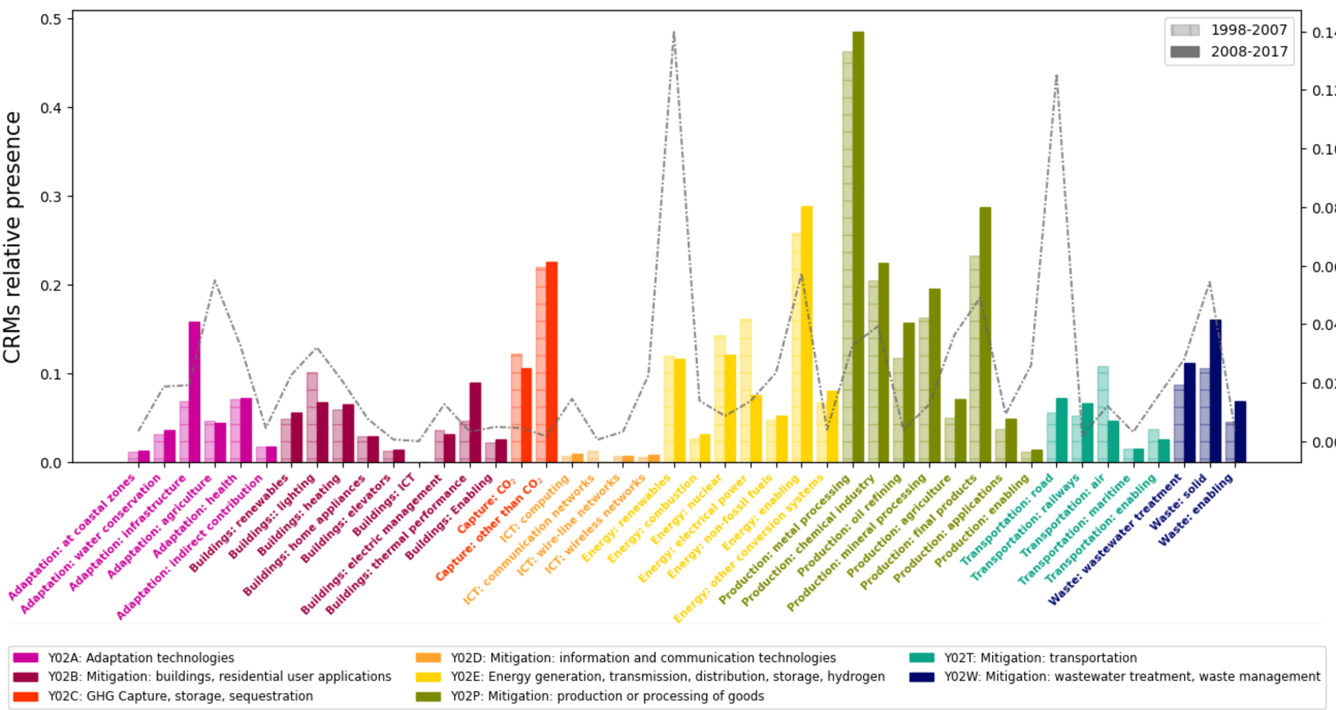

Figure 3: Relative CRM presence in the Y02 green technology domains (barplot) and green technology distribution (grey dashed line). Bars: left-hand side=1998-2007; right-hand side=2008-2017. Y02 green technology colour-coding in the legend.

Figure 4 brings it all together by providing a breakdown by material of the CRM dependence of Y02 green technologies. Therein the connections between CRMs and green technologies are depicted considering the concentration of CRM production and the size of each green technology sub-class. In particular, materials (rows) are ordered on the y-axis by increasing geographic concentration of production activities (from bottom to top), while green technologies (columns) are arranged on the x-axis by increasing patenting intensity (from left to right). Each CRM-green technology pair cell is colour-coded according to the percentile of CRM detections in each green technology, with dark red indicating high importance and yellow indicating low importance. A quick glance at the graph reveals more clustering (red cells) on the right-hand-side of the figure, suggesting that higher patenting frequency correlates with greater material intensity. Additionally, clustering is more prominent towards the centre to bottom-right of the figure, thus suggesting that, generally, more in-demand CRMs tend to be less geographically concentrated.

When examining individual rows, some CRMs stand out as more 'general purpose' materials than others, exhibiting strong connections with multiple green technology domains. Bearing in mind that CRMs are ranked by HHI (see Table 4 for reference), silicon, magnesium, and lithium are among the most widely used CRMs with spatially concentrated production (HHI above the median, at the top of the figure). In contrast, aluminium, zinc, copper, lead, titanium and nickel are also in high demand but their production is more geographically dispersed (low HHI, at the bottom half of the figure). These patterns align with the policy issues raise in the introduction, whereby green tech-CRM pairings associated with potential shortages tend to appear in the top-right centre of the graph. Some of these problematic connections are well known.

The first is the co-occurrence of silicon (above the median HHI, as per Table 4) and the Y02 sub-class *Renewable energy* (Y02E10), which includes photovoltaic energy and, consequently, crystalline and amorphous silicon PV cells (Suman et al., 2020). A second clear connection exists between silicon and *Enabling technologies for energy* (Y02E60), which primarily cater to energy storage technologies such as batteries, where silicon metal is increasingly being explored for use in anodes to boost their density (Eshetu et al., 2021; European Commission, 2020*b*). Lastly, silicon ranks high also in green patents related to *Solid waste management* (Y02W30), a domain that recent literature considers as a side effect of the rapid expansion of the photovoltaic industry (Guo et al., 2021).

Lithium is also of interest due to the peculiarity of being strongly represented in green technologies that are more material-specific, that is, that rely on average on fewer CRMs relative to other technologies in Figure 4. One example is *Road transport* (Y02T10), where batteries and energy storage devices rely extensively and almost exclusively on lithium (Graham et al., 2021). Other lithium-intensive green technologies include *Energy efficient heating, ventilation or air conditioning (Y02B30)* and *Water conservation technologies (Y02A20).* Finally, lithium is in high demand among the leading green technology patent domains that rely extensively on silicon, namely *Renewable energy* (Y02E10), *Enabling technologies for energy* (Y02E60), and *Technologies for solid waste management* (Y02W30). The common denominator between lithium and silicon is their role in batteries, by far the most important enabling component. Batteries are essential for energy storage in renewable energy plants, and their recovery through effective waste management is crucial to prevent shortages as well as environmental and health hazards (Richa et al., 2014; Scrosati and Garche, 2010).

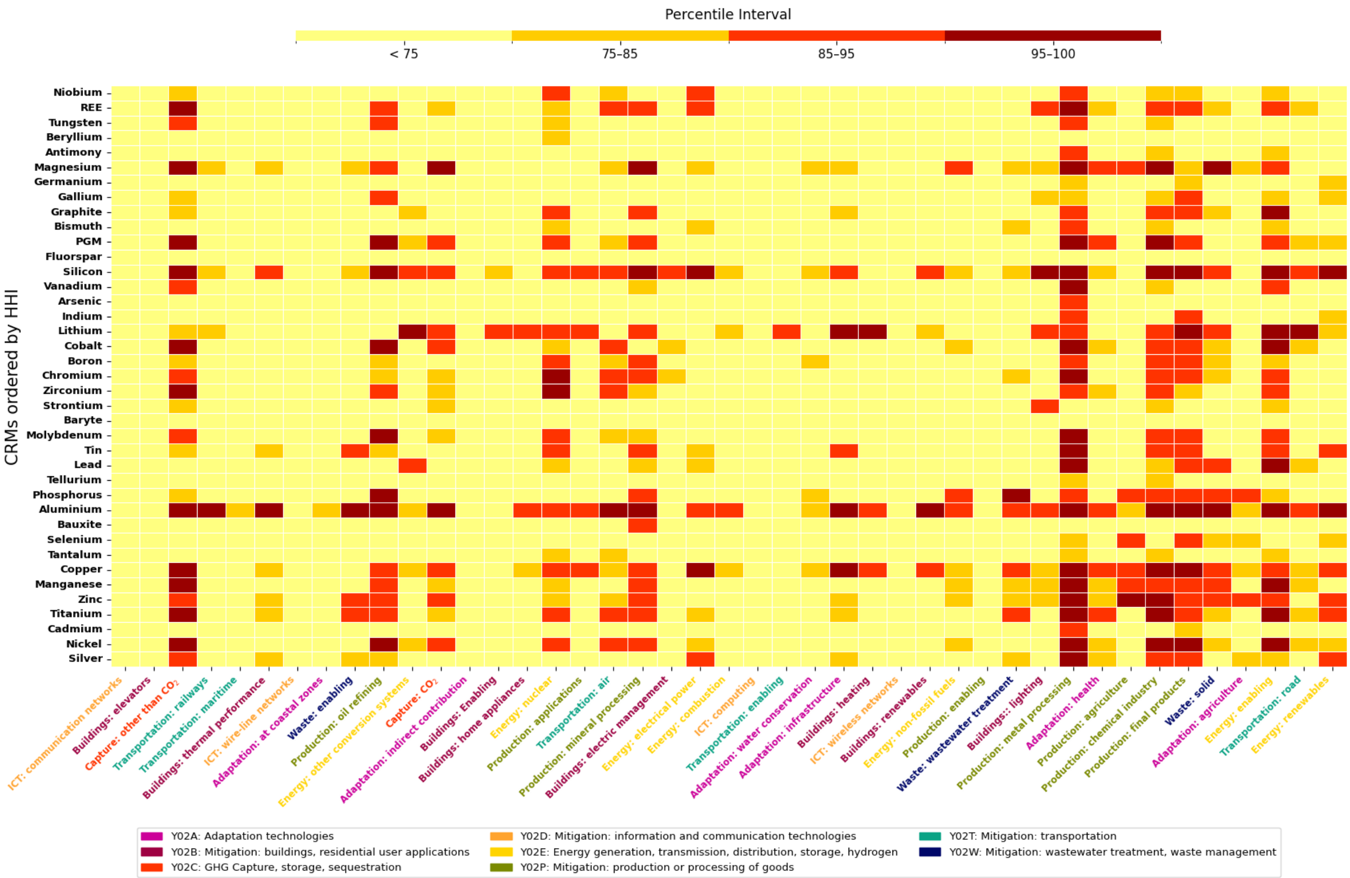

Figure 4: Relative presence of CRM in green technology patents. CRMs are ordered by HHI (see Table 4). Green technologies are ordered by the frequency of each sub-class in the dataset, colour-coding in the legend. Cells are coloured according to the relative importance of CRMs in each sub-class: dark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

Focusing on the green technology domains (columns), *Production or processing of goods* (Y02P) emerges as the most material-intensive class, which is to be expected given that sub-domains include *Metal processing* (Y02P10), *Chemical industry* (Y02P20), *Oil refining and petrochemical industry* (Y02P30), and *Final consumer products* (Y02P70). Other notable Y02 domains are *Capture or disposal of GHGs other than* CO_2 (Y02C20) and *Enabling technologies for energy* (Y02E60). The high dependence of these technologies on CRMs has important implications. As noted, Y02P comprises green technologies for processing metals, minerals, chemical compounds, et cetera, which naturally leads to a high number of detections in the patent abstracts.[17] Instead, the CRM dependence of enabling technologies (Y02E60) like batteries, energy storage devices, and fuel cells is well documented (Hund et al., 2020; International Energy Agency, 2021). Finally, with respect to the high CRM dependence of Y02C2, the World Bank report by Hund et al. (2020) notes that materials involved in all stages (i.e., capture, transport and storage) of the GHG capture process can vary, and are used in different ways. Examples are nickel and manganese, which are involved both in the capture process and in the steel alloys needed for the capture plant. However, as the limited number of patents associated with Y02C in our dataset (less than 1%, see Figure 3) evidences, carbon capture and storage is still at early-stages. This uncertainty raises questions about its future role in the green transition, particularly regarding the quantities of CRMs that will be required for its development and deployment.

4.4 Which green patenting countries rely the most on CRMs?

Turning to RQ2, we now examine the geographical patterns emerging from our study, aiming to identify where CRM-related green inventions are patented. Therefore, while the previous sections mapped the presence of CRMs in green technologies, this section and the next will provide insights into the dual role of countries as both demanders and suppliers of CRMs in relation to green inventive activities. To this end, we geolocalise patents based on the application authority, such as patent offices, where they are registered. As detailed in Section 3.2, to obtain a more accurate proxy for the successful deployment of each invention, and of the link between CRM presence in green patents and their actual demand, we limit our analysis to granted green patents only.[18] As a result, the sample is reduced to 941.878 patent families, about 64% of the total number of families over the period 1998-2017. Additionally, we consider only CRMs with above the average presence in at least one green technology domain, focusing on the geographical dependence related to the most prominent CRMs in green technologies.

Overall, 103.153 geolocalised patent families mention at least one CRM, corresponding roughly to an 11% world average relative presence of CRMs in green technologies. As a proxy of country green invention dependence on CRMs, we compute the CRM

[17]It is important to note that materials in patent abstracts might be mentioned not only as inputs but also for their functional role in the technology, such as refining, recovery, recycling, etctera. Therefore, our count method may overestimate the actual dependence of Y02P.

[18]The 'granted' status means that the patent office accepted the submission and granted exclusive property rights to the applicant with no limitation of use in volume. In the case of international patent offices like EPO, where the information on granted status can be sometimes inaccurate, we consider a patent application granted in a country when it is explicitly reported in PATSTAT or when the patent fees have been paid at least once in the country. We acknowledge that even this information is ridden with uncertainty, for example about applicants' motivations for filing patents in specific countries and the extent to which a patented invention is actually implemented or used.

Exposure index defined in Section 3.2.3. Figure 5 shows that CRM exposure is negatively correlated with GDP per capita, and therefore that higher-income countries are on average less exposed to supply risks.

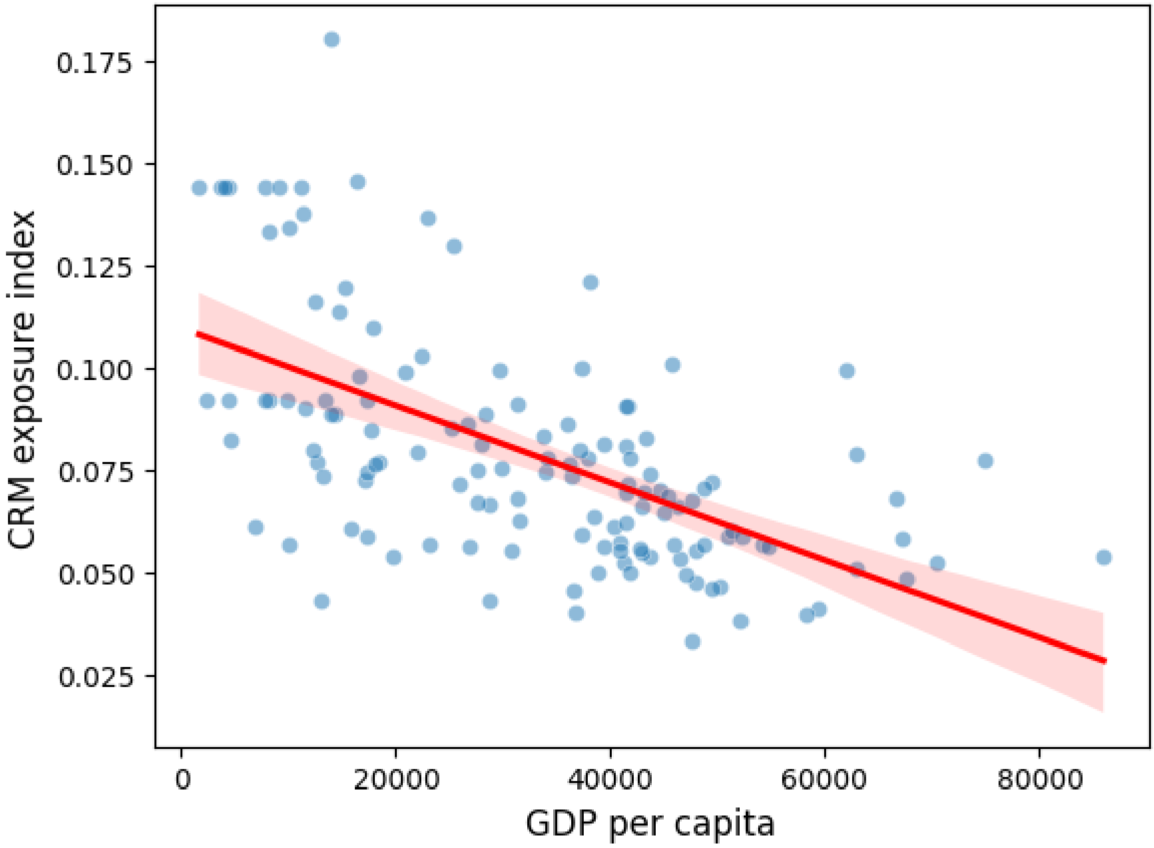

Figure 5: Scatter plot of country CRM exposure versus GDP per capita. Each point refers to a country in one 5-year interval (1998-2002, 2003-2007, 2008-2012, and 2013-2017) and plots the country's average GDP per capita (USD millions) and the CRM exposure index. The red line depicts the overall fit, with a negative correlation coefficient of -0.59.

To illustrate the evolution of CRM exposure across countries, Figure 6 presents the ranking of countries' CRM exposure over four 5-year intervals: 1998-2002, 2003-2007, 2008-2012, and 2013-2017. To mitigate the influence of countries with a high level of CRM exposure driven by a few geographically concentrated patents, we apply a minimum threshold for patent families in each period.[19]

[19]The threshold is set at 0.5% of all the patent families in each 5-year interval, which reduces to more than 433 patent families in 1998-2002, 693 in 2003-2007, 1516 in 2008-2012, and 2065 in 2013-2017.

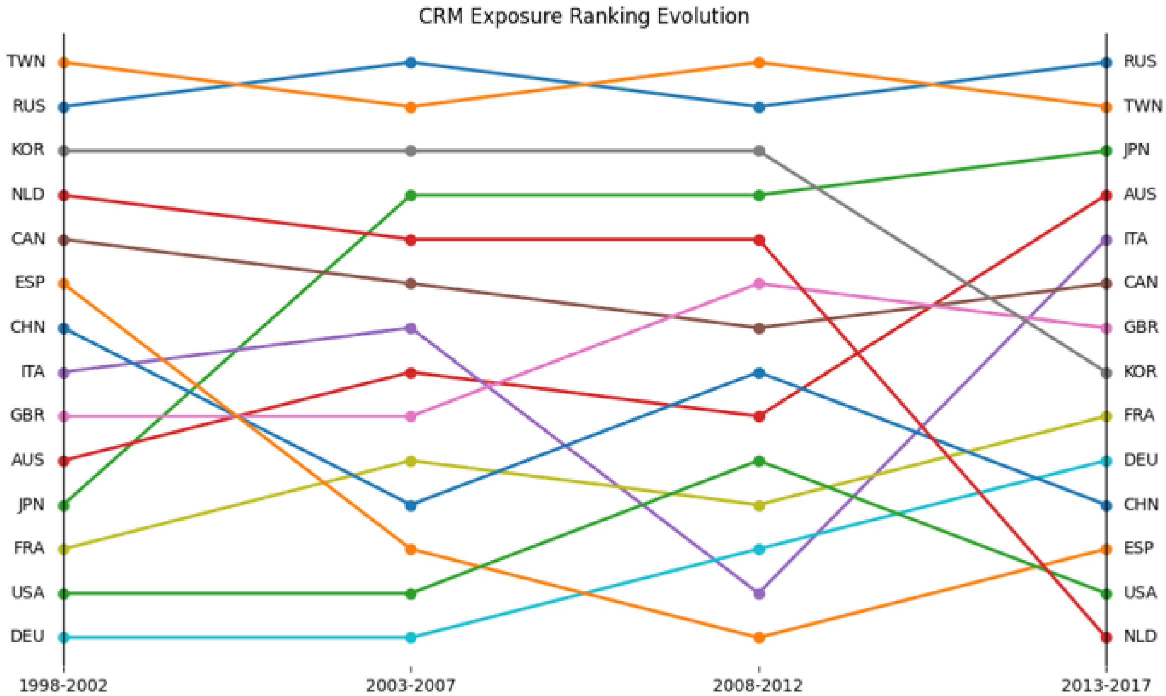

Figure 6: Evolution of the ranking of country CRM exposure index over the period 1998-2017 (divided into 5-year intervals).

The diagram shows that the trends of Russia, Taiwan, Japan and Australia are consistently high in the ranking throughout the period. We posit that in the case of Russia and Australia the patterns reflect established leadership in production and processing of several CRMs - which will be discussed in the next section - while high CRM dependence of Taiwan and Japan is mostly due to their leading role in the manufacture of advanced digital and computing technologies, such as microchips and semiconductors, that rely heavily on concentrated CRMs like REEs, silicon, gallium, and germanium. Conversely, the longitudinal patterns of countries with lower exposure tend to be more unstable with the exceptions of China, the United States, France and Germany, i.e. countries that maintain consistently low levels of CRM exposure, likely a reflection of their highly diversified patent portfolios.

Breaking down country exposure to CRM by Y02 sub-class further reinforces our findings (Figure 7). In particular, higher levels of exposure are driven by the most CRM intensive technological domains. High CRM-dependent countries like Russia, Taiwan, Japan, and, to a lesser extent, Australia, exhibit particularly high levels of dependence (well above average) in the related domains of *Production* (Y02P), where Russia exhibits the highest exposure, *Energy generation* (Y02E) and *Carbon capture* (Y02C), with Taiwan and Japan standing out in both. In contrast, countries with lower CRM dependence, such as China, the United States, and Germany, display below-average CRM exposure across all technology domains.

	Y02A	Y02B	Y02C	Y02D	Y02E	Y02P	Y02T	Y02W
Russia	0,043	0,040	0,121	0,005	0,076	0,179	0,052	0,069
Taiwan	0,034	0,057	0,130	0,005	0,132	0,158	0,097	0,062
Japan	0,032	0,034	0,084	0,003	0,117	0,146	0,050	0,042
Australia	0,027	0,031	0,059	0,015	0,062	0,136	0,054	0,056
Italy	0,036	0,026	0,099	0,008	0,086	0,121	0,051	0,047
Canada	0,035	0,026	0,062	0,010	0,072	0,133	0,057	0,052
United Kingdom	0,039	0,032	0,095	0,004	0,091	0,131	0,054	0,052
South Korea	0,023	0,038	0,100	0,004	0,109	0,132	0,066	0,049
France	0,031	0,030	0,090	0,006	0,094	0,130	0,044	0,046
Germany	0,031	0,029	0,081	0,004	0,087	0,123	0,040	0,041
China	0,021	0,025	0,088	0,004	0,054	0,104	0,033	0,038
Spain	0,028	0,027	0,078	0,008	0,052	0,125	0,048	0,041
United States	0,028	0,027	0,074	0,002	0,097	0,119	0,040	0,046
Netherlands	0,029	0,033	0,102	0,007	0,068	0,134	0,086	0,044
Average	0,031	0,033	0,090	0,006	0,085	0,134	0,055	0,049

Figure 7: Breakdown of the CRM exposure index by technology class. The levels of exposure refer to the entire period 1998-2017 and the reported countries are the same displayed in Figure 6.

4.5 Which countries lead the global supply of CRMs?

In this final section, we identify global producer countries of CRMs and connect them to global demand of materials via green patenting. Figure 8 shows a global ranking of countries based on their share of CRM global production over the period 1998-2017 summed across all CRMs and normalised to scale. This visualization highlights a globally heterogeneous landscape of CRM production. At the top of the ranking are not only high- and middle-income countries such as China, the United States, Canada, and Australia, but also emerging economies like South Africa, Mexico, and Brazil. The first group combines high CRM production volumes with significant patenting activity in green technology domains. For instance, China's dominance in both CRM production and green technology patents positions it as a critical player in the green innovation landscape. In contrast, countries such as Brazil, Mexico and South Africa, despite relatively low levels of green patenting, are major producers of essential CRMs required for green technologies, underscoring their strategic importance in the global green transition. A notable finding is the minimal contribution of European countries to global CRM production: Germany, France, Italy, and the United Kingdom - leaders in green technology patenting - are conspicuously absent from the top CRM producers. This disparity underscores Europe's reliance on external suppliers for critical raw inputs to its green innovations.

Figure 9 provides further insights into the geographical distribution of CRM-related green innovations. The scatter plot compares each country's CRM exposure introduced above with their CRM production rankings, whereby each dot represents a country, with size proportional to GDP per capita in 2017, allowing for a multidimensional analysis of their roles in CRM-related innovation and CRM production. Based on the scatter plot, countries are grouped into four quadrants, differentiated by their relative positions above or below the median values for CRM exposure and production, with distinct colour coding:

i *Low CRM exposure and low CRM production (green):* Predominantly European,

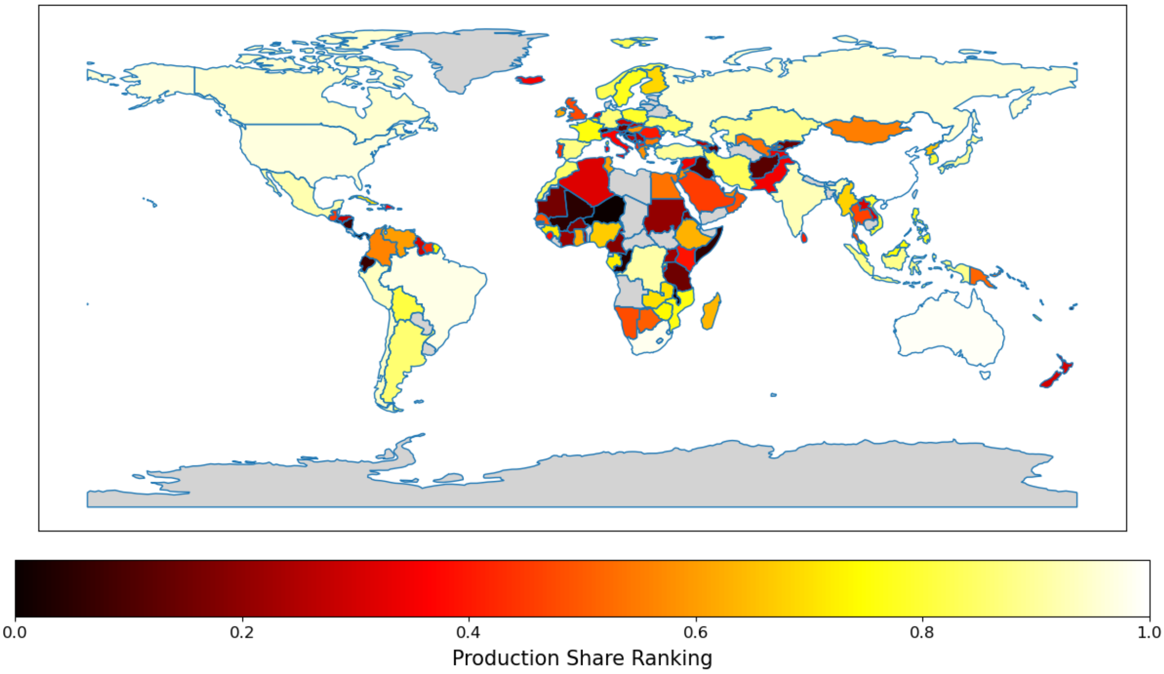

Figure 8: CRM production map. Countries are coloured according to their position in the ranking of the sums of their CRM production global shares (lower purple, higher yellow).

these nations are likely benefiting from diversified strategies in the composition of their patent portfolios, reducing the exposure on CRMs.

ii *Low CRM exposure but high CRM production (blue):* Resource-rich countries like China, Australia, the United States, and Canada, demonstrating independence in the CRM supply chain. Some European countries, such as Germany and Spain, also fall into this group.

iii *High CRM exposure and high CRM production (yellow):* Countries like Russia and South Africa, where natural resource abundance significantly shapes innovation strategies and economic specialisation.

iv *High CRM exposure but low CRM production (red):* The most critical quadrant is predominantly populated by European countries, including Austria, Czechia, Switzerland, and Portugal. These countries are specialised in CRM-intensive green technologies but do not have domestic CRM resources, making them extremely vulnerable to CRM supply risks. The presence of Eastern European countries in this quadrant is likely driven by their increasing role as electric vehicle manufacturers integrated in the European automotive value chains (Oxford Analytica, 2023; Pavlínek, 2023).

Addressing RQ3, Figure 10 further elucidates the dual role of countries as both green innovator and producers along the CRM supply chain. Here we focus on CRMs with high production concentration – e.g., boron and above as per Table 4 – that are also proactive above average in at least one domain. These crucial materials for green technology development are of interest because they carry elevated supply risks. The figure shows an undirected network connecting countries, green technologies, and

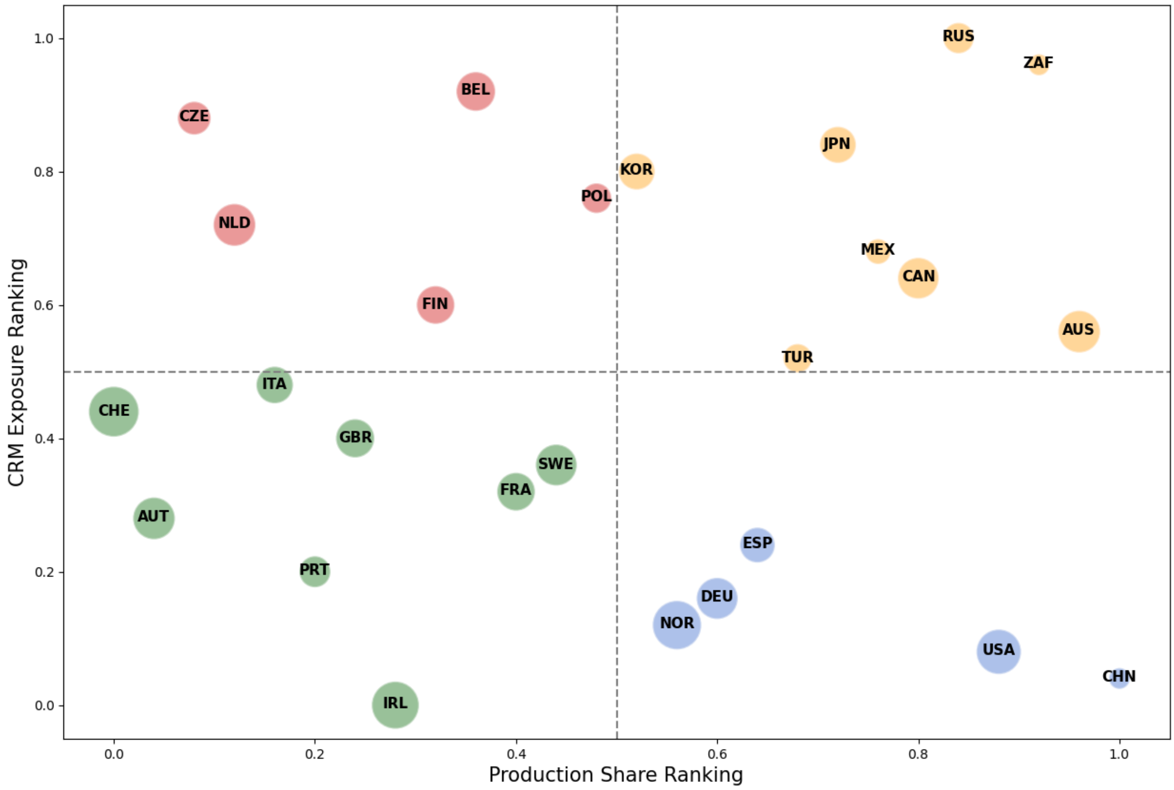

Figure 9: Four quadrant country taxonomy representing ranking of CRM global production shares vs ranking of the CRM exposure index (1998-2017). Each dot represents a country and its size is proportional to the country's level of GDP per capita in 2017, measured in millions of US dollars. Countries that do not produce CRMs or with no CRM-related patents are not included in the plot.

CRMs. The network is organised in four clusters. On the left-hand side are the countries where green patent applications are filed. Adjacent to this, the second cluster displays green technologies, which are grouped and colour-coded according to the Y02 green patent sub-categories listed in Table 1. The third cluster captures CRMs that are mentioned in green technology patents. Finally, on the right-hand side are placed countries linked to the CRMs they produce. The size of the nodes is proportional to its degree viz. the number of connections each shares with other nodes. For countries and CRMs, nodes with highest degrees are at the centre of the clusters. For each grouping, links in the network are established based on specific thresholds: CRMs are connected to green technologies when they have an above-average presence compared to other materials, and to countries that are above-average producers. Instead, countries and green technologies are linked when the number of green technology inventions filed in a country exceeds the global average.

The network highlights the dual role of countries as both green innovators (1^{st} cluster) and producers (4^{th} cluster) as well as their position in the global demand and supply dynamics of green technology inputs. With the exception of China (CHN), a global leader of both green technologies and critical material production, a clear divide emerges between countries at the two extremes of Figure 10. On the left-hand side, the largest nodes connected to green technologies are predominantly high-income Global North countries, including the United States, Germany, France, the United Kingdom, Japan and South Korea. A second tier of high patenting countries includes Italy, Spain, Australia, Russia, Canada and Taiwan. In contrast, on the right-hand side of the figure is a cluster of countries producing the most spatially concentrated CRMs featuring a diverse mix of both top patenting countries - i.e., China, the United States, Russia, and Australia - and of countries with weaker or no connections to green technology nodes - i.e., Argentina, Chile, Cuba, India, the Democratic Republic of Congo, Turkey, and Zambia. Brazil is a good case in point. It is the second largest producer of the most concentrated 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 4.3. The only other producers of silicon (intended as silicon metal) besides Brazil, are China, the US and, to a lesser extent, Norway. Despite this, Brazil's green patenting is limited to *Oil refining and petrochemical industry* (Y02P30), a relatively small class of technologies (see Figure 4). Likewise, South Africa is the top producer of highly sought-after and relatively scarce platinum group metals (PGMs) together with Russia. While this input is used in a wide range of technologies, most notably in climate change mitigation technologies relating to *Chemical industry* (Y02P20) (8^{th} technology domain by patent intensity - see Figure 4), South Africa exhibits few links with green technologies in the network. Additionally, the diagram shows that, coherently with the policy reports cited earlier (European Commission, 2020*a*; European Commission, 2023*a*), European countries are rather absent from the right-hand side of the diagram, and the only country that is present, Norway, is not connected to green technologies as prominently as leading players like France, Germany, and the United Kingdom.

Finally, we draw attention to a handful of countries (highlighted in a red font on the right-hand side of Figure 10) that are mere producers and thus are present in the network only by virtue of their capacity to supply CRMs to other patenting countries. These include Argentina, Cuba, Chile, the Democratic Republic of Congo, India, Turkey

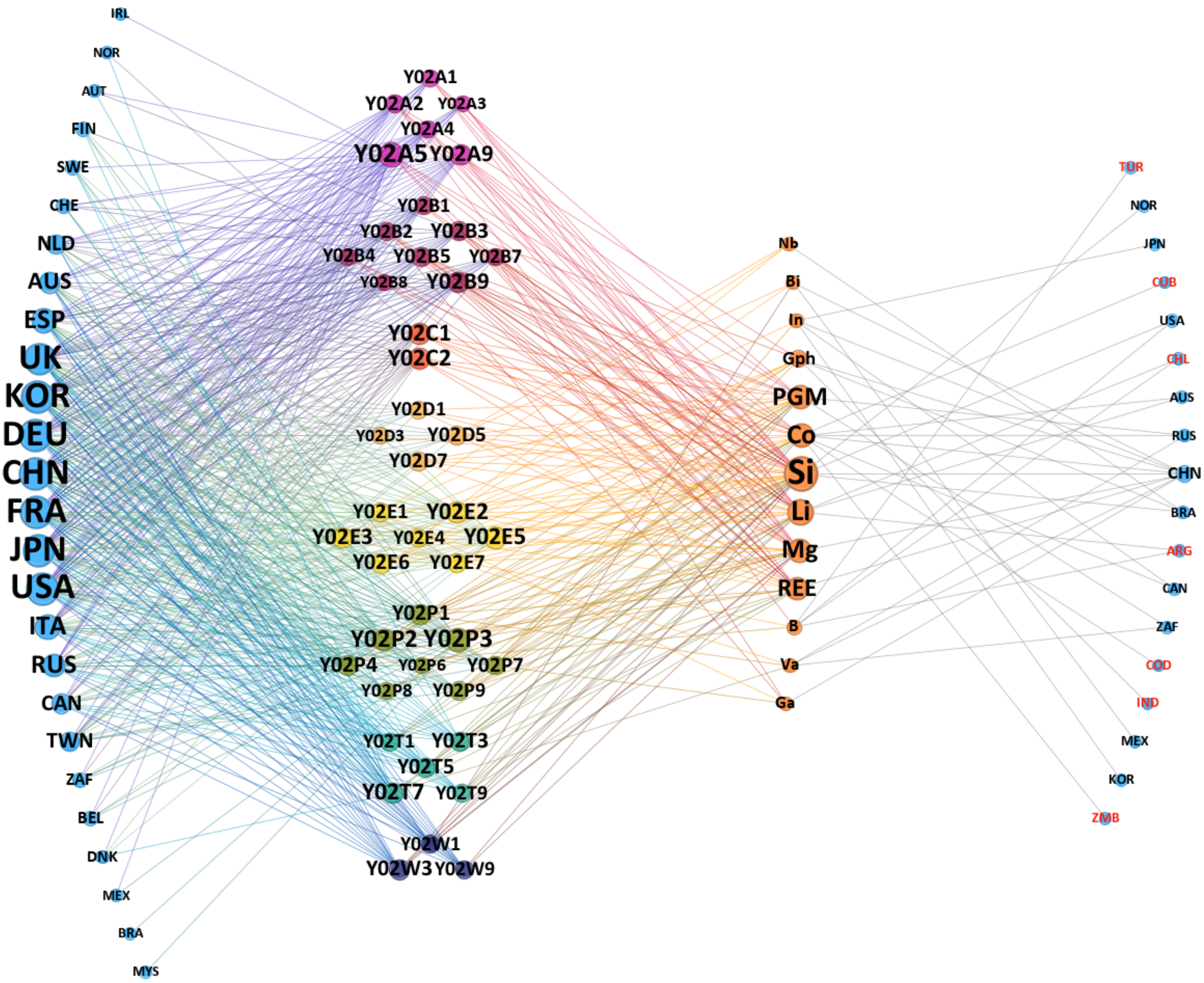

Figure 10: Network of CRMs-green technologies-countries. Node size is proportional to their degree (the number of links each node has to other nodes in the network). Green technologies: from top to bottom according to Y02 green patent class. Only above median HHI critical raw materials (i.e., above Boron in Table 4) are shown. Countries and materials are organised so that the higher the degree of the node, the closer to the centre of the respective column. The 1^{st} (left) column reports the countries connected to green technologies in the 2^{nd} column; the 3^{rd} column represents CRMs and the 4^{th} column the countries that produce them.

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 a crucial role in the green technology supply chain. An illustrative example is lithium, of which Chile and Argentina are the only producers together with Australia. Cobalt is another notable input produced solely by non green innovator countries in the network, including the Democratic Republic of Congo, Cuba, and Zambia, while graphite is produced by India, Brazil and China only. Lithium, cobalt and graphite are therefore relatively scarce materials (i.e., high HHI) produced by countries that, with the exception of China, 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, pointing to a dimension of inequality that is intrinsically embedded into the sustainable transition.

5 Conclusion

This paper has elaborated an exploratory analysis of the relationship between critical raw materials and environmental technologies. The main motivation for our analysis is the growing debate concerning the viability of the sustainable transition which, in its current form, relies heavily on rapid and sizeable scaling up of green technology development and deployment. As the literature shows, 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 do not seem to warrant. While the policy debate has started to address these issues, the literature on innovation studies still lags behind. We fill this gap by addressing three research questions focusing on (i) the connection between green technologies and CRMs, (ii) the countries that, by virtue of their green patenting efforts, exhibit higher dependence on CRMs, and (iii) the spatial map of global supply and demand of these critical inputs.

Our study shows that CRMs are more predominant in green technology domains when compared with non-green ones. This aligns with current trends where clean energy applications are the main driver of demand growth for several CRMs (International Energy Agency, 2024). In absolute terms, mature green technologies such as 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 (IPCC, 2022; Jacobson, 2019). When resource production concentration (proxied by the HHI) enters the equation, we identify critical input-green technology pairings (European Commission, 2023*b*; Grandell et al., 2016; Valero et al., 2018). 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 codependence between these two CRMs, as both lithium and silicon are essential to flagship domains such as renewable energy and solid waste management.

The second research question focuses on the spatial distribution of CRM-related green technologies in leading green patenting countries. By constructing an index that measures countries' exposure to CRMs via their green patent portfolios, we identify notable patterns. First, we find that green inventive activity is less exposed to CRMs dependence in high income countries. Second, the evolution of countries' CRM exposure rankings alongside the breakdown of exposure levels in green technology domains reveals distinctive national patterns. Higher ranking countries like Russia, Taiwan, Japan, and Australia are exposed in technology domains related to mineral and metal processing, likely due to established leadership in both upstream (Russia and Australia) and downstream (Taiwan and Japan) stages of the CRM value chain. In contrast, countries with large and diversified technology portfolios like the United States, China, the Netherlands, France, and Germany exhibit lower CRM dependence.

Finally, we compare the geographical exposure to CRMs via green technology specialisation with the spatial distribution of CRMs, by considering the dual role of countries in the demand (via patents) and supply (via production activities) of CRMs. 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, which are necessary to meet the demand for inputs needed by high income countries 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 in any significant innovation activity.

While our study provides a novel and broad perspective on the relationship between green technologies and critical raw materials, some limitations should be acknowledged. First, using countries as the unit of analysis enables the identification of broad patterns but may obscure firm-level dynamics - such as ownership structures, supply chain positioning, and intra-firm trade - which can significantly shape both innovation and material use. Second, while patent data represent a fundamental tool for empirical research, they have well-known limitations as a proxy for innovation. This is especially relevant to our case, as they may underestimate the innovation capacity of developing countries, where technological progress is often adopted or take place through non-patented channels: as a result, our analysis may understate the actual demand for CRMs in some resource-producing countries. Lastly, our keyword-based patent identification strategy does not allow us to distinguish the functional role of CRMs in the inventions - whether they are used, recycled, or refined for instance. Addressing this limitation is a priority for future work through the integration of large language models (LLMs), which can more accurately classify material functions in patent texts. In this regard, recent studies have employed LLMs to improve the identification of CRMs in patent texts, revealing different innovation strategies and patterns of sectoral and regional exposure (de Cunzo et al., 2025; Fusillo et al., 2025; Manera et al., 2025).

In conclusion, the present paper has strived to identify criticalities and provide a roadmap for future research on a yet underdeveloped thread in the innovation literature. 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, for example, renewable energy or electric vehicle transport, may well run into bottlenecks. The first problem is that some critical minerals are scarce, 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, remains largely 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 mineral 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 sustainable transition.

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 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://www.bgs.ac.uk/mineralsuk/statistics/world-mineral-statistics/world-mineral-statistics-data-download/world-mineral-statistics-data/.

Acknowledgments

Davide Consoli acknowledges the financial support of Ministerio de Ciencia e Innovación (PID2020-119096RB-I00/MCIN/AEI/10.13039/ 501100011033).
François Perruchas acknowledges Ramón y Cajal funding from MICIU/AEI/10.13039/ 501100011033 and the European Union NextGenerationEU/PRTR (funding reference RYC2021-032691-I).
Francesco de Cunzo and Angelica Sbardella acknowledge the financial support under the

National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 1409 published on 14.9.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – Next Generation EU – Project Title "Triple T – Tackling a just Twin Transition: a complexity approach to the geography of capabilities, labour markets and inequalities" – CUP F53D23010800001 – Grant Assignment Decree No. 1378 adopted on 01.09.2023 by the Italian Ministry of Ministry of University and Research (MUR).
Angelica Sbardella acknowledges the financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – Next Generation EU – Project Title "WECARE – WEaving Complexity And the gReen Economy" – CUP 20223W2JKJ by the Italian Ministry of Ministry of University and Research (MUR).

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Appendices

A Alternative method to detect critical raw materials in patents

In patents, a description of the invention is available in the form of text with the abstract, in the form of drawings, or using the technological codes that are assigned to the patent, either with IPC or CPC. While we text mine terms in the abstract to identify mentions of CRM, another possibility is to use a technological classification.

PATSTAT provides two technological classifications: International Patent Classification (developed by WIPO) and Collaborative Patent Classification (developed by EPO and USPTO), the latter being an extension of the former. Each CPC level (section, class, group, subgroup, symbol) is associated with a description; their concatenation provides a phrase that describes the invention. For example, symbol "C07F9/94" would describe the inventions as "Chemistry; Metallurgy, chemistry, organic chemistry, acyclic, carbocyclic or heterocyclic compounds containing elements other than carbon, hydrogen, oxygen, nitrogen, sulfur, selenium or tellurium, Compounds containing elements of Groups 5 or 15 of the Periodic Table, bismuth compounds".

For this exercise, we use the CPC symbol and description to obtain associations between symbols and CRMs. We first search CRM terms in descriptions, then we assign to each patent tagged with a symbol the CRM mentioned in the description. In doing so, we are able to identify 2980 CPC symbols that mention at least one CRM. All CRM terms except two (bauxite and fluorspar) are present in the CPC symbol descriptions. In a second phase, we associate with patent families the CRM detected in the description of their CPC codes.

To assess the coverage of this alternative methodology, we created a database of patent families identified through text mining, CPC symbols, or a combination of both. Figure 11 provides a graphical representation of this data. The boxes illustrate the number of patent families for each CRM, with those identified via text mining shown on the left and those detected using CPC symbols on the right. The "not found" boxes on each side represent patent families identified exclusively through the other methodology. While nearly all patent families detected via CPC symbols are also captured through text mining, over 2.8 million patent families remain undetected when relying solely on CPC symbols.

In conclusion, although using CPC descriptions might seem promising to identify CRM in patents, results show that this methodology would under-represent CRM presence.

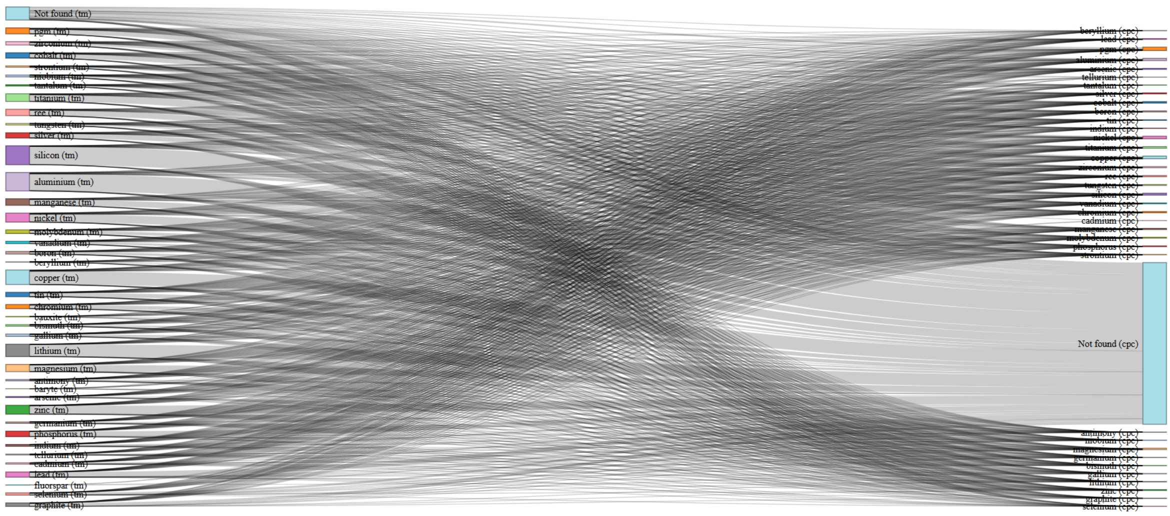

Figure 11: Sankey diagram showing the difference between identifying CRMs in patent using text mining (left side) and CPC (right side).

B 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 3.2.1, 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 read the corresponding abstract and we classified CRM mentions in 4 different categories:

- **Use**: the CRM is used by the invention.
- **Recycle/Refine**: the invention is useful to either recycle or refine the CRM.
- **Remove**: the patent describes a methodology to remove a CRM.
- **False positive**.

Table 5 summarises the results of the manual exploration.

Category	Outcome (Share)
Use	89.1%
Recycle/Refine	7.8%
Remove	1.7%
False positive	1.4%

Table 5: Results of the manual exploration of green patents for each category.

The 89.1% of all the manual classification observations are associated to the "use" category: this result gives robustness to our analysis, and specifically to the assumption according to which the CRMs mentioned in the abstracts are needed to develop the green technology. The second category with the highest number of observations (7.8%) is "recycle/refine", while the rate of the "remove" category classifications is 1.7%. Including the category "false positive" (1.4%) helped us validating and improving the text mining queries. In particular, reading each of the abstracts led us to detect a high number of false positives for lead and beryllium - this is especially due to the dual usage in English of the worlds "lead" and of "Be" which is also the chemical symbol of beryllium - for which we made several adjustments in the text mining strategy[20]. Finally, it is important to note that these percentages refer to all the validation we performed, therefore covering all the CRMs. However, there could be special cases with rates for specific CRMs or green technologies with particular categories diverging from the averages reported in Table 5, such as the just mentioned "false positive" cases of "lead" and "beryllium". In the following, we further elaborate on some of these special cases, especially with respect to the case of phosphorus and the green technologies that exhibit the highest levels of CRMs incidence.

B.1 On the use of phosphorus

Phosphorus is among the most mentioned CRMs that displays increasing frequency over time but is rarely mentioned in technological reports as a key input for climate change mitigation or adaptation technologies. Hence, as a robustness check, we checked a random sample of 204 patent abstracts (2.2% of the phosphorus observations in green patents) across all Y02 technologies to understand how phosphorus is effectively referred to in the documents. We found out that only 72.5% mentions refer to usage, while the second most frequent mentions (14,2%) concern inventions that involve a methodology for actually removing phosphorus. These instances are mainly in technology processes aimed at managing phosphorus content in water, grouped in the patent sub-classes Y02W10 - *Technologies for wastewater treatment* - and Y02A20 - *Adaptation technologies in water conservation; efficient water supply; efficient water use*. Finally, 10.8% of the inventions recycle or refine phosphorus, mainly in *Technologies for the production of fuel of non-fossil origin* (Y02E50), *Solid waste management* (Y02W30) and *Technologies related to metal processing* (Y02P10). Only 5 patents out of 204 were false positive, with an accurate rate of detection of 97,50%.

B.2 Technologies with high critical raw material content

We checked technologies with high presence of CRMs in order to verify how the use of materials occurrences in patent abstracts is a robust measure of CRM dependence. By restricting the sample to the patents with highest CRM incidence, we created random samples of patent families for the following technological domains:

[20]For instance, 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 it appeared at the beginning of a sentence.

- *Capture or disposal of greenhouse gases other than CO_2* - Y02C20 (21 patent families, 3.2% of the population)
- *Enabling technologies related to Energy, Technologies with a potential or indirect contribution to GHG emissions mitigation* - Y02E60 (785 patent families, 2.9% of the population)
- *Climate Change Mitigation Technologies related to metal processing* - Y02P10 (644 patent families, 2.4% of the population)
- *Climate Change Mitigation Technologies related to chemical industry* - Y02P20 (392 patent families, 2.7% of the population)
- *Climate change mitigation technologies in the production process for final industrial or consumer products* - Y02P70 (699 patent families, 3% of the population).

The rate of inventions mentioning the use of CRM is above 97% in all the selected technologies except in the case of Y02P10, where 58.5% of CRM mentions are related to the use category, while 36.6% 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 1% in all other technologies, it represents 4.5% of Y02P10 patent families. The rate of false positives is between 0.4% and 1.4% across the technology domains.

Delving into mentions of CRMs in Y02P10, we observe that the ratio between use and refine/recycle in not stable across materials. The highest mention of use is detected for graphite, silicon, bauxite, and titanium (above 80% of Y02P10 patent abstracts mentioning these CRMs use them). The highest mention of refine/recycle is observed for cobalt, platinum group metals (PGMs), silver, vanadium, and zinc (above 35% of Y02P10 patent abstracts mentioning these CRMs is for refining or recycling), potentially signalling new technological developments aimed at increasing the overall availability of these materials.

Finally, in the other green technology domains, the distribution of these ratios is stable across CRMs, with above 90% of use detected for almost all materials.

C Further comparisons of critical raw material dependence in green vs non-green technologies

In this section, we add some insights to the comparison between the presence of CRMs in green and non-green technologies. Table 6 lists the aggregate 8 CPC technology sections labelled with single letters from A to H.

As already pointed out in Section 4.1, to avoid double-counting the same patents in both categories, we consider patents tagged with at least one green technological code only in the green technology dataset. Figure 12 plots the evolution of the number of green and non-green patent families relative to their numbers in the period 1998-2002. As highlighted by the plot, despite having more patent families in the non-green dataset (25.708.295 vs 1.473.320 in the green one, see Table 3), in the last years we observe a faster growth of patented inventions in green technology domains.

Label	Description
A	Human necessities
B	Performing operations; Transporting
C	Chemistry; Metallurgy
D	Textiles; Paper
E	Fixed constructions
F	Mechanical engineering; Lighting; Heating; Weapons; Blasting
G	Physics
H	Electricity

Table 6: Non-green technology sections. The first column lists the letters from A to H with which each section is labelled, while the second column lists the corresponding descriptions.

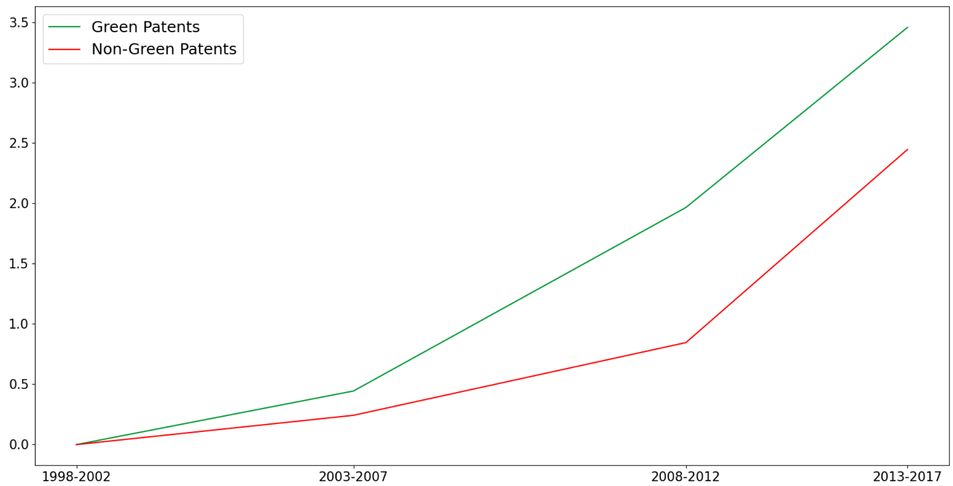

Figure 12: 5-years percentage increase of the number of green and non-green patent families with respect to the value in the initial period 1998-2002.

Regarding the comparison of the overall presence of CRMs in green an non-green technologies, the 86.5% correlation of the CRM trends plotted in Figure 13 suggests a similarity in the CRMs that guide both green and non-green CRM dependence.

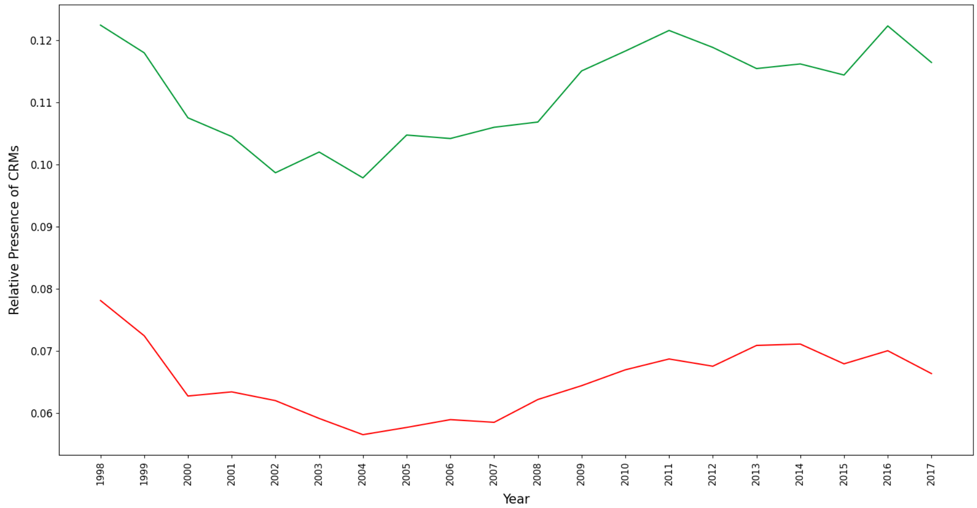

Figure 13: Trends of CRM presence in green (green line) and non-green (red line) technologies. Each line plots the yearly share of patent families with at least one CRM detection.

To further investigate the emergence of potential similarities, we explore the CRM intensity of non-green technologies, similarly to what we did in Section 4.3. Table 7 reports the level of CRM intensity of the 8 non-green A-H technology sections.

Label	Description	Section Share across all A-H technologies	CRM intensity
A	Human necessities	15.2%	3.1%
B	Performing operations; Transporting	20.8%	6.4%
C	Chemistry; Metallurgy	9.8%	21.6%
D	Textiles; Paper	1.4%	6.2%
E	Fixed Constructions	5.0%	3.2%
F	Mechanical engineering; Lighting; Heating; Weapons	10.2%	3.8%
G	Physics	19.5%	2.9%
H	Electricity	18.0%	8.3%

Table 7: CRM intensity of non-green technological domains. For each technology section labelled with the code in the 1^{st} column, we report the corresponding description (2^{nd} column), the share of the patent families grouped in it with respect to the enire dataset (3^{rd} column), and the relative presence of CRMs, given by the ratio between the number of patent families with at least 1 CRM observation and the total number of patent families in the section (4^{th} column).

With the exception of section *C-Chemistry; Metallurgy*, where 21.6% of patent families depend on CRMs, the other technology sections display a below 10% CRM intensity. The high number of CRM detections in section *C* is not surprising, as technological categories such as the manufacture and treatment of e.g. metallurgy alloys, or specific inorganic and organic compounds, are covered by this section. Following section *C*, the second highest CRM intensity is observed in section *H-Electricity*, which also accounts for a significant share of the non-green dataset (18%). In Figure 14 we break down the CRM dependence of these two technological domains.

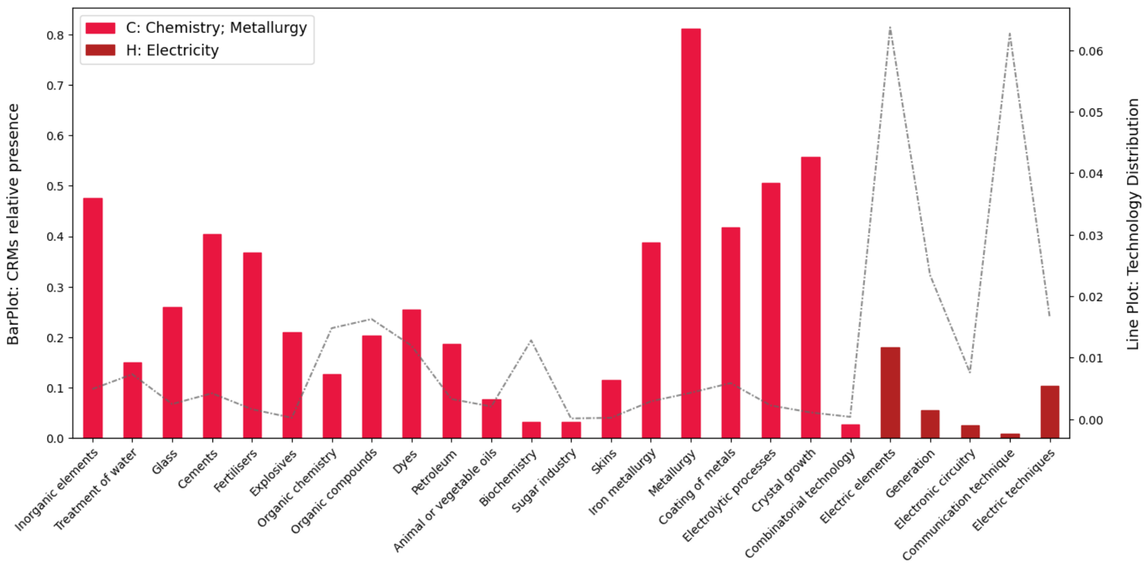

Figure 14: relative presence of CRMs in non-green technologies. Focus on section *C-Chemistry; Metallurgy* and section *H-Electricity*.

What emerges from the figure further reinforces a signal of interdependence between green and non-green CRM intensive technological domains. In fact, if we exclude technologies that are directly related to metal and material processing – such as *Metallurgy*, *Coating of metals* and *Inorganic elements* – which record very high levels of CRMs observations, there are other material-intensive technologies that connect to specific green technology areas. For instance, this can be observed in the technical domains: *Cristal growth* (55.7% CRM intensity), covering inventions related to the production and treatment of crystalline materials, which are key processes in the manufacture of solar panels, or *Electric Elements* (18%), in which, among others, crucial components for the development of several key green technologies, such as magnets, semiconductors, solid state devices and batteries, are included.
Thus, in shaping the CRMs dependency non-green technologies, while a quantitative distinction is evident in terms of overall material presence with respect to green technologies, we detect structural similarities in the most material intensive green and non-green domains, that are often related to similar types or interconnected technologies. In a broad sense, the existence of these similarities in the CRM dependence of the two domains align with previous studies that have shown how the development of green technologies often relies on advances in specific non-green technology domains (Barbieri, Consoli, Napolitano, Perruchas, Pugliese and Sbardella, 2023; Barbieri, Marzucchi and Rizzo, 2023).

D Critical raw materials in high-quality patents

The quality of a patent - intended as the technological and economic value of the corresponding patented invention and its possible impact on subsequent innovations - can be proxied using various patent indicators (Squicciarini et al., 2013). In this section, we assess the quality of CRM-related green inventions by considering the number of citations each green patent receives within three years of its registration in PATSTAT.

Citation count serves as a well-established proxy for both the economic value of a patented invention and its technological significance in the development of subsequent technologies (Hall et al., 2005). However, considering 3-year citations constrains the time window that we can examine. This is due to potential lags in patent registration in PATSTAT, which usually can take up to three years after initial filing at a patent office. As a result, we restrict our analysis to patents registered between 1998 and 2014. Our focus is on patents that receive at least one citation within 3 years of registration - referred to as cited patents - to analyse whether the main results hold when considering only the highest-quality inventions. We revisit some of the findings presented earlier to identify any differences or similarities when narrowing the focus to this subset of patents.

Out of 581.667 green inventions that received at least one citation, 68.362 are CRM-related, resulting in a roughly 11.75% relative presence of CRMs. This is closely aligned with the overall presence of CRMs in green patents during the period 1998-2017, which was 11.43%. Figure 15 replicates the histogram presented in Figure 1, this time considering only cited green patents. The distribution of CRMs remains similar to the previous result. Additionally, the share of patents associated with highly concentrated CRMs that also have an above-average presence in green technologies (represented by darker bars in the plot) increases slightly by 1.6% (from 40% to 41.6%). This increase is primarily driven by key materials such as silicon, lithium, rare earth elements (REEs), platinum group metals (PGMs), and cobalt. This result reflects in what emerges from Figure 16, which replicates the results from Figure 3. In particular, we observe small increases in the predominance of CRMs in key green technology domains, such as *Energy generation through renewable energy sources* (Y02E10), and *Road transport* (Y02T1).

In conclusion, the analysis of CRMs in high quality green technologies reinforces the main findings of our study. In fact, the replication of results for the subset of cited green patents yields nearly identical outcomes. If anything, focusing on high-quality inventions highlights a slightly greater predominance of highly concentrated CRMs in crucial green technology domains, further underscoring the potential risks associated with CRM supply constraints in green technology development.

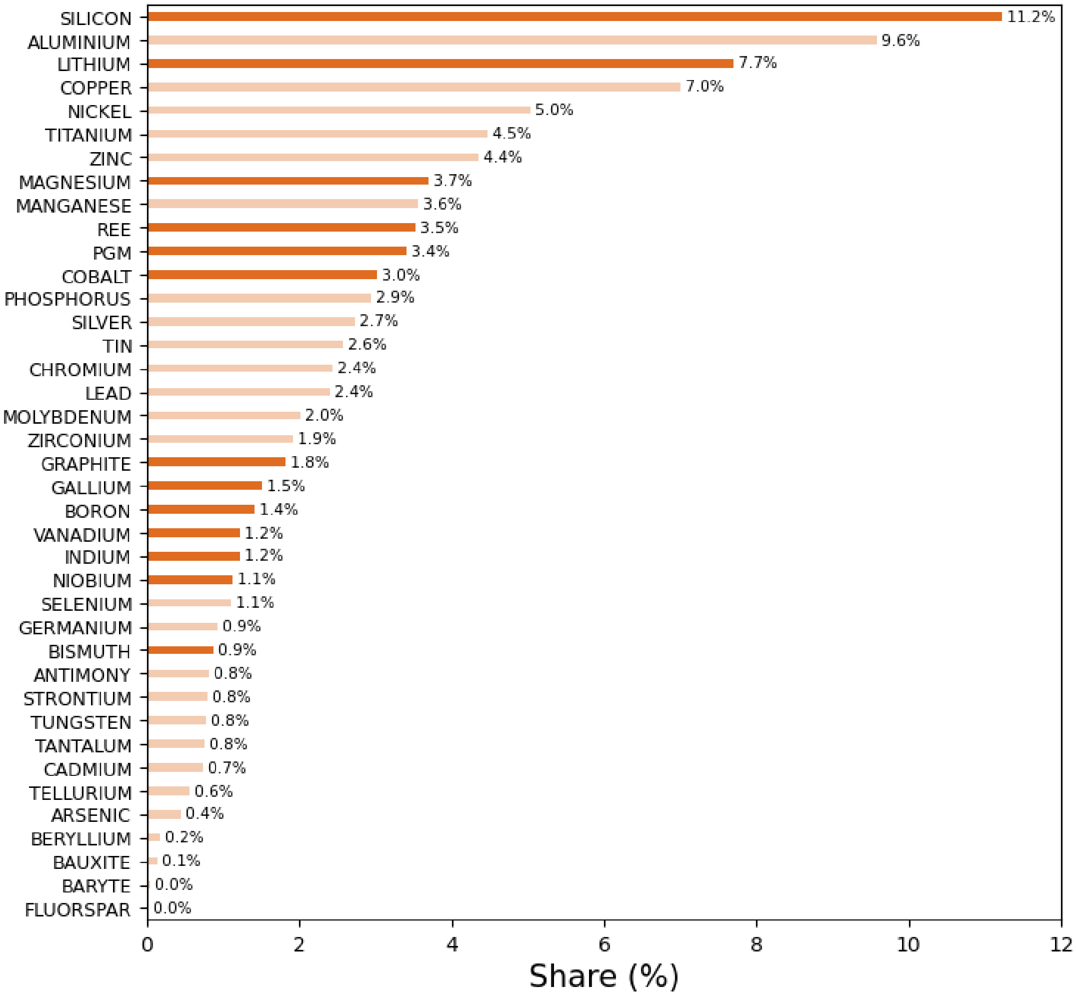

Figure 15: Replica of Figure 1 when considering only cited green patents.

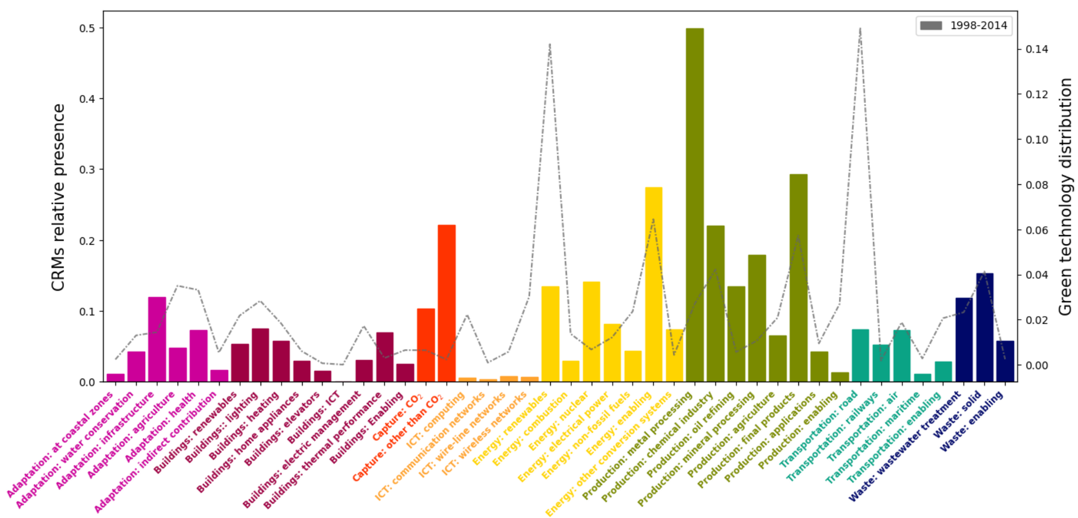

Figure 16: Replica of Figure 3 when considering only cited green patents.