Critical Raw Materials and Renewable Energy Transition: The Role of Domestic Supply

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Abstract: Many critical raw materials (CRMs) – including rare metals and earth elements – are essential components in renewable energy products, and they work as an irreplaceable material basis for related technological innovation. However, global CRM supply chains are subject to significant risks, posing threats to the stability of the renewable energy industry. To address the challenges, a growing emphasis in both academic and policy circles is directed to de-risking supply chains through diversification and production reshoring. In this study, we investigate the relevance of domestic CRM production as a strategic measure to hedge against global supply shocks, providing competitive advantages for local renewable energy development and innovation. We explore this issue by focusing on two core renewable energy sectors: Wind and Solar energy. Analysing data from a panel of 128 countries spanning from 2007 to 2016, we examine the impact of domestic CRM supply capabilities on the competitiveness of the RE sectors and technological innovation, while controlling for various influencing factors. Our findings show that a stable CRM supply through domestic production significantly supports downstream RE product export and patent output, protecting local RE development from global material supply shocks. Using the case of renewable energy sector, this paper introduces the concept of "material-based technological regime" and underscores the critical importance of supply chain stability for key materials in bolstering national technological advantages. It provides valuable perspectives for both businesses and policymakers.

1. Introduction

Materials are the foundational elements of the world and a variety of products. Frontier technological advancements are increasingly anchored in the progress in material science (Hanson, 2018; Abraham, 2015). With their distinct physical and chemical properties, new materials (or new uses of old ones) usher in novel technological functions. Nevertheless, the field of innovation studies has largely overlooked the integral role of materials, along with the associated opportunities and constraints they present.

Technological progress in a specific sector follows a set of rules or trajectories, referred to as technological regimes (Nelson & Winter 1977, 1982; Dosi, 1982). We posit that certain technology groups adhere to a *'material-based technological regime*', meaning their functionalities are intrinsically tied to specific materials, with innovations often intersecting significantly with Material Technologies. Additionally, the incorporation of crucial materials is intimately linked to the key properties of technological regimes identified in the literature (Breschi et al., 2000), such as the underlying scientific "knowledge bases" and the "technological opportunities" spawned by advancements in material science and technology. Concurrently, the burgeoning reliance on specific materials renders emerging industries and innovations increasingly contingent on the availability and stable supply of these materials.

Supply chain management literature, on the other hand, highlights the increasing vulnerability resulting from deglobalization, which disrupts the previously established deep labour divisions and material flows through extensive global sourcing and offshoring. In response to this shift, the importance of supply chain resilience through diversification and increasing domestic supply is gaining prominence (Choudhary et al., 2022; Fernández-Miguel et al., 2022; Vivoda, 2023). Special attention has been directed toward a group of critical raw materials (CRMs), particularly rare metals and rare earth elements, which serve as the physical backbone of modern technologies and fuel the development of frontier technologies and emerging industries. These materials have become increasingly vulnerable to supply chain risks stemming from material scarcity and geographical concentration, trade disruptions, and geopolitical risks. Some countries have even 'weaponized' the export of CRMs to gain geopolitical leverage, as evidenced by China's rare earth embargo against Japan in 2010 and the recent export control over Gallium and Germanium in response to the US semiconductor embargo during the ongoing technology war (Reuters, 2023)[1], endangering the development of global high-tech sectors.

Against this background, in this paper, we attempt to answer the following question:

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[1] https://www.reuters.com/markets/commodities/china-flexes-critical-metals-muscles-with-export-curbs-2023-07-10/

for a sector technologically depending on specific materials, how does the material supply conditions influence the industry competitiveness and technological advantages at the national level? To do so, this paper builds on insights from both innovation and supply chain management literature, using the interplay between renewable energy (RE) technologies and critical rare metals (RMs) & rare earth elements (REEs)[2] as a case study. Wind and solar energies and electric vehicles represent a case of "material-based technological regime" as they strictly depend on diverse CRMs to achieve their functionalities: for example, the REE permanent magnets for wind turbines and semiconductor materials for solar panel. As a result, the energy transition shifts resource supply challenges from conventional energies to critical materials (IEA, 2021). Growing concerns surrounding CRM supply chain resilience arise from the inability of mining, metallurgy industries and diversified material manufacturers to meet the soaring demands for RE transition (e.g., European Commission, 2014; Campbell, 2020; Zhao et al., 2020). However, the demand side perspective overlooks the complex spatial configuration of supply chains: global-level shortage is often not the cause of resource scarcity, rather it arises from the unequal distribution of resources among different locations and the complex interactions with local institutional, industrial, and technological conditions (George, 2010). This spatial imbalance leads to value chain fragmentation and CRM supply chain uncertainties largely due to tariffs, resource policies and geopolitical risks usually defined by national borders. Domestic CRM supply, and its impact on the downstream activities, then becomes really crucial as it allows differentiating from global supply dynamics: this is clearly behind the very recent measures taken by the EU to become more self-sufficient in the CRMs needed to help power the clean energy transition.[3].

Empirically, this paper provides insights on the significance of the supply chain's spatial structure in the RE industry development and innovation by examining Solar and Wind, two major energy generation technologies, and the corresponding CRMs between 2007-2016. During this period, the patterns of both CRM supplies and RE manufacturing and innovation have undergone significant changes, and the degree of spatial clustering has deepened. Using data from the UN Comtrade and USPTO patent datasets, we employ econometric models to estimate the effect of domestic CRM supply on national RE competitiveness, measured by product exports and technological output. We find that domestic CRM supply (here defined as the production of processed CRM materials after metallurgy and refining rather than raw minerals and ores) positively correlates with RE competitiveness, after controlling for factors identified in the literature. Moreover, the impact of domestic supply mainly manifests in

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[2] Rare earth elements, an important subgroup of CRMs, are 17 elements at the bottom of the periodic table (Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu).

[3] https://www.consilium.europa.eu/en/infographics/critical-raw-materials/

mitigating international CRM supply shocks and is enhanced by the local competence in material technologies. To address endogeneity concerns, we use geological reserves of CRMs as an exogenously determined instrumental variable, positively associated with CRM domestic production and unrelated to downstream industrial and innovation dynamics.

We aim to contribute to recent research exploring the material base of modern technologies (e.g. Biggi et al., 2021; Diemer et al., 2022; Li et al., 2024). While innovation studies have traditionally focused on the recombination of technological elements and the principles underpinning it, the technological elements themselves, especially the tangible physical materials and resources, have received scant attention. Our case study on RE technologies illustrates how this material-based regime expands technological opportunities, at the same time introducing new constraints due to the heterogenous availability of specific materials. In addition, this paper integrates supply chain security into the innovation literature to explore how critical material supply shapes countries' industrial and technology trajectories in the context of RE transitions, shedding light on the actual importance of CRMs and the consequences of supply chain risks (Graedel, 2015; Nassar, 2015; Graedel & Reck, 2016). Third, this study expands the literature on the determinants and conditions of the green transition by delving into its physical material basis and resource supply chain, garnering growing attention from academia, industry, and national and international organizations (e.g., Viebahn et al., 2015; IEA, 2021; IMF, 2021; McKinsey, 2022; World Bank, 2022; EC, 2023).

The following Section 2 provides a conceptual background to the study by intertwining the literatures on innovation, resource science, economic geography, and supply chain management. Section 3 describes the spatial pattern of CRM supply and dynamics, whilst Section 4 details our sample, model and identification strategies. The findings, mechanisms analysis, and robustness tests are then presented in Sections 5 and 6; lastly, in Section 7 we draw our conclusions.

2. Literature background

2.1 Technological innovation and materials

Schumpeter (1934) defines innovation as a recombination process, to "produce means to combine materials and forces within our reach [...] To produce other things [...] means to combine these materials and forces differently" (p. 65). Following the Schumpeterian perspective, innovation studies have explored in depth the principles and mechanisms underlying this recombination process. Nelson and Winter (1977, 1982) and subsequent evolutionary economists have posited that technological evolution adheres to inherent properties that shape the creation and subsequent growth of innovation processes. A technological regime is defined as a particular combination of such properties: appropriability (of the returns to innovation), technological opportunities (likelihood to innovate, given the investment in research), degree of cumulativeness of technological advances (extent to which the amount of innovation produced in the past raises the probability of current innovation) and characteristics of the knowledge base (among others, Breschi et al., 2000).

Technological regimes manifest at various levels and are conceptualized as design hierarchies, encompassing overarching configurations, subsystems, and basic components, collectively achieving technological functions: any change in core elements have ripple effects throughout the entire system (Clark, 1985; Murmann & Frenken, 2006). The starting point of innovation are the basic elements (such as the “materials, forces” in Schumpeter’s language) involved in the recombination process, which lie at the bottom of the design hierarchies: such “technological components”, defined by Fleming & Sorenson (2004) as the “fundamental bits of knowledge or matter that inventor might use to build inventions” (p. 610), can be both physical or non-physical. The bulk of the innovation literature has focussed on the latter knowledge elements and their characteristics, such as complexity, codifiability and value (Cardinal et al., 2001; Lerner, 1990; Mewes & Broekel, 2022). On the other hand, physical materials are the basic building block of the world, working as the fundamental essence of technologies and primary constituents of products. Shifts in material usage, including the introduction of new materials and new use of existing ones, serve as primary catalysts for product enhancement. As Schumpeter (1934) argues, physical properties of materials set the basic conditions of production, and new modes of combinations may come from a new source of raw materials. Similar emphasis also appears in the classical work of Dosi (1982) on the “technological paradigm” which was defined in three dimensions — in parallel to the widely discussed science push & demand pull, he also emphasized the underlining material technologies to achieve technical progress. However, the interdependence between technologies and materials have not been fully explored in the following literature.

Material usage is closely related to key properties of the technological regime. Fundamentally, specific materials define the “knowledge base”, i.e. the scientific axioms underpinning technological regimes, bestowing unique physical and chemical traits to actualize technological functions. For example, semiconductors (silicon and germanium) achieve photoelectric effect, and uranium achieves nuclear fission: changing materials leads to change in the scientific principles. Secondly, the technological functions enabled by these materials create new "technological opportunities." Subsequently, the "appropriability" or, more broadly, the commercialization of these technologies is shaped by the availability of the materials necessary for these technologies. The changing science principles related to material shifts trigger profound systemic transformations, herald new technological possibilities and reshape wide technological landscapes. As a result, material technologies are usually regarded as general-purpose technologies (GPTs), contributing to changes in various fields (Aithal & Aithal, 2018). On the other hand, advanced technologies and high-tech sector operations are increasingly contingent on advanced and specific material resources, making the commercialization opportunities of new technologies a function of the supply conditions of CRMs.

Technological evolutions across various sectors are governed by unique sets of principles, with some sectors more prominently aligning with the material-based characteristics. The case of the RE sector exemplifies a typical “material-based technological regime”. At the basic level, the scientific foundations and technological breakthroughs in the RE sector largely depend on advancements in scientific discovery on materials (Sovacool et al., 2020). For example, the evolution of solar photovoltaics is rooted in Einstein's seminal work on semiconductor materials and the photoelectric effect. This foundational discovery set the principles for Photovoltaics (PV) innovation attempts, emphasizing the exploration of materials with superior conversion efficiencies and cost-effectiveness. Such regime is observed in the subsequent technology changes in photoelectric, from monocrystalline silicon cells to polycrystalline ones, then to thin films using CRMs like gallium and cadmium. Similarly, the use of rare earth permanent magnets and the lithium iron phosphate materials have substantially enhanced the efficiency of wind turbines and electric vehicle. On the other hand, physical availability (amount, quality and price) of such critical materials paves the way for production and commercialization of RE technologies, enabling their efficiency, affordability, and competitiveness, empowering renewables to challenge traditional energy sources. As a result, cutting-edge discoveries in new materials and the availability of CRMs provide the RE sector “the sense of potential, of constraints, and of not yet exploited opportunities” (Nelson & Winter, 1977, p. 57).

To illustrate this material-based nature of RE, in Figure 1, we compare the differences between RE technologies and all other technologies in terms of overlapping rates of patent classification with material technologies and the use of CRMs. The figure on the left shows that, compared to other technologies, RE technologies have a higher degree of overlap with material technologies, which means that a lot of RE patents are also material technologies identified in the patent classification. On the right, the analysis of CRM keywords in the patent text indicates that a significantly higher proportion of RE technologies uses CRMs than non-RE technologies.

[Insert Figure 1 here]

2.2 Innovation and development of the RE industry

Green and renewable energy technologies have been extensively analysed in innovation studies, revealing distinctions from other technological domains. They are found to exhibit characteristics such as heightened novelty, externalities, complexity, uncertainty, as well as broader knowledge scopes. These unique features, as seen also in the previous section, define the specific technological regime and research approach within RE sector —the novelty is deeply rooted in the close linkages to foundational science, their externality-driven nature renders them more policy-responsive (Cleff & Rennings, 1999; Jaffe et al., 2002), and the inherent complexity, diversity and uncertainty mandate greater collaboration with external partners (De Marchi, 2012).

Such features are reflected in the spatial patterns of the RE industry discovered in empirical studies of economic geography, innovation, and energy economics. To develop the RE sector, countries and regions should own competencies, resources, and institutional structures matched with the RE technological regime — geographies develop their RE foundations based on related industries (Costantini & Crespi, 2009; Barbieri et al., 2020; Santoalha, 2021; Perruchas et al., 2022) and input of basic science (Johnston et al., 2010). In addition, the inherently public-good characteristics of the green technologies and its underlying policy imperative imply that the RE industry is considerably influenced by varying degrees and modalities of government interventions (e.g., Johnstone et al., 2017; Santoalha & Boschma, 2021). Furthermore, it is also found to be influenced by other external forces, such as knowledge spillovers from FDI and international trade (Popp, 2002; Huang et al., 2016; Papież et al., 2018; Shubbak, 2019; Castellani et al., 2022), as well as competition with traditional energy sources (Binswanger 1974; Nordhaus & Popp, 1997).

A gap appears in the literature when considering the material-driven essence of the RE technological regime — the deep dependence on material technologies as well as the availability of crucial materials. The prevalent understanding of location capabilities neglects other pivotal capabilities, notably a country's access to and/or control over the material supply. Consequently, the association of RE sectors with their most immediate related industries – arguably, the suppliers of vital material inputs – has been overlooked, leaving the physical basis of the RE supply chain unclear. Some notable exceptions are Hanson (2018) that, using the case of PV and silicon metallurgy industry, illustrates how the new technological opportunities in RE sectors are enabled by the innovation along the particular trajectory of silicon material refining. Similarly, De Marchi (2012) shows that eco-innovation patents depend mostly on new materials components and collaborations with suppliers. CRM dependence in fact becomes even more relevant in a time of supply chain disruptions.

2.3 CRM supply chain for RE transition

Resource studies explore the supply chain security through combined indicators to gauge the degree of criticality for metals and minerals and identify the bottleneck factors (Graedel, 2015; Nassar, 2015). Numerous studies focus on the case of rare metals essential for green technologies and its supply security at different spatial scales and value chain stages to achieve decarbonization goals (e.g., European Commission, 2014; IMF, 2021; Campbell, 2020; Zhao et al., 2020). Such perspectives lead us to integrate the RE development into the full material supply chain, as illustrated in Figure 2.

[Insert Figure 2 here]

At the beginning of this chain, RM geological scarcity poses significant constraints: clean energy technology demand, which allows new products, necessitates a strong rise in current CRM mining production, estimated by over five times by 2050: the global reserve and production of some RMs may not meet future demands at the current depletion rate (IMF, 2021). In addition, such risks are also more serious considering CRM by-product nature and low recycling rates. Some key metals (e.g. Cobalt, Vanadium, and Nickel) are forecasted to face over two-third gap deficits in relation to demand (IMF, 2021; World Bank, 2021). The EU study by Moss et al. (2011), labelled five CRMs – three RMs, Tellurium, Indium, Gallium, and two REEs, Neodymium, and Dysprosium – as most critical for the electric vehicle, wind, and solar sectors. Increasing supply risks clash with the soaring RE demand to meet the ambitious 2°C carbon reduction goals set by the IPCC (Grandell et al., 2016).

In addition to the global-level challenges to the availability of materials, even more important are the supply risks related to the spatially unequal accessibility of CRMs which goes directly into the downstream RE sector as crucial inputs. Spatial differences are initially shaped by the distribution of CRM reserves, which however, does not necessarily translate into domestic CRM supply as it is influenced by countries' conditions, including industrial capabilities – especially technological levels and scale economies in metallurgy and smelting sectors – institutional frameworks on resources and environment, as well as the abilities to control the resource ownership and international flows through FDI and trade networks (Zhu, 2022).

Large concentrations of CRM deposits are in only a few countries. For example, more than 60% of world’s cobalt reserves are in the Democratic Republic of the Congo (and concentrated in the southern Lualaba and Haut-Katanga provinces), however, due to the lack of industrial capabilities and adequate institutional settings, DRC has not benefitted much from it and suffers from a severe resource curse (Calvo, 2021). On the other hand, some developed economies, like the US, Canada and Denmark with abundant resources restrict or even prohibit exploitation due to stringent environmental regulations. Coupled with years of offshoring and domestic de-industrialization, their capabilities to produce materials competitively have been partially lost. This discrepancy results in a situation where countries or regions with abundant mineral resources fail to provide reliable supply of processed industrial materials for downstream high value-added activities and to boost local industrial development (Canh et al., 2020). In stark contrast, countries such as China have successfully capitalized on both domestic and international resources. Not only do they exploit local reserves efficiently, as in the case of China’s REEs, but they also exert control over foreign resources through proactive global trade networks and investments abroad (Leruth et al., 2022). This control of mineral resources, combined with the country's robust production capabilities in metallurgy and materials, has solidified its domestic supply capacity for key raw materials. Consequently, production and refining of many CRMs are highly concentrated in a few countries, and especially in China. This pattern is depicted in Figure A1, which delineates the disparity between CRM material reserves and CRM material production .

The highly uneven geographical distribution of CRMs and their production has led to intensive global trade flows. Such trade networks are under significant threats due to the asymmetrical power relationships among partners, and potential supply risks come from monopoly of supply sources, geo-political risks and trade conflicts (e.g. Klimek et al., 2015; Sun et al., 2018; Tian et al., 2021; Zhu et al., 2021; Diemer et al., 2022). Therefore, the literature emphasizes over dependence on CRM imports as a significant risk factor for downstream industries (Graedel, 2015; Nassar, 2015).

2.4 CRM supply chains and domestic supply in the RE industry

Supply chain management literature discusses the trade-off between offshoring and domestic sourcing. Global outsourcing and offshoring have been prevalent strategies for firms to gain cost advantages and higher efficiency by leveraging labour and material costs in other countries (Razzaque & Sheng 1998). However, these strategies also entail higher transportation costs, loss of control and coordination costs over the offshored activities and inputs (Juras, 2008; Larsen et al., 2013), and the costs of border crossing such as regulatory compliance, currency fluctuations as well as the hidden costs from risks, such as political uncertainties, or loss of intellectual property rights (Holweg et al., 2011). Supply disruption risks can result in significant and far-reaching consequences, impacting the downstream industries and decreasing firm revenues and profits through rising operation costs. Such risks also lead to loss of trust of customers, partners and stakeholders, and cause market share shrinks and disinvestments (Lockamy & McCormack, 2010; Jacobs et al., 2022). Recent events, such as the disruptions to medical goods during the Covid-19 pandemic, the shortage of natural gas due to the Ukraine war, and the input price increases during the Sino-US Trade War, have highlighted the hidden costs of global sourcing and the risks associated with the supply chain for essential goods. This has prompted a re-evaluation of supply chain strategies, leading to a shift towards domestic and regional sourcing options (Ellram et al., 2013; Peter & Rathgeber, 2017).

The risks associated with global sourcing become notably pronounced when it comes to complex, customized and strategically important inputs, whose suppliers are highly geographically concentrated: this is the case of CRMs, because of technological criticality and low substitutability. Supply limitations, price spikes, or even a complete cut-off of crucial inputs may jeopardize entire sectors and substantially reduce returns. Past events serve as sobering reminders of the supply risks inherent in depending on foreign sources of CRMs. In the 1970s, for instance, conflicts in the Congo led to a cobalt supply shortage which was followed by massive spikes in cobalt prices, speculation, government stockpiling, and massive disruption in the electronics industry (Alonso et al., 2007). More recently, the price of some important base metals, nickel and aluminium, climbed to a record high during the Ukraine war.

Beyond the economic aspects, the increasing focus on corporate social responsibility and Environmental, Social, and Governance (ESG) factors highlights additional risks associated with global sourcing. Ethical, social, and environmental concerns arise, particularly when sourcing materials from locations lacking secure institutional environments for ecological and human rights protection. These risks have broader implications for the entire value chain, introducing potential liabilities and costs. The CRM value chain, in particular, has witnessed numerous cases exemplifying these risks, such as, for example, human rights abuses related to conflict mineral mining in the Congo (Calvo, 2021). In response to such issues, a number of legislative measures – from the Dodd Frank Act introduced by the US in 2010 (subsequently weakened under Trump's administration), to the EU Conflict Minerals Regulation of 2021, have tried to ban and/or regulate the sourcing of minerals from countries such as the DRC and neighbours (Hofmann et al., 2018). Domestic sourcing, on the other hand, when available offers better opportunities for supplier monitoring and serves the purpose to mitigate serious ethical and social issues. All the above may have serious impacts on firms, consumers, and industries worldwide, significantly deterring the green transition (Gaustad et al., 2018).

Against this background, in this paper we argue that domestic supply of CRM materials plays a key role for the development of the RE sector, helping to diversify supply sources and enabling the downstream RE competitiveness.

First, for downstream countries reliant on CRMs, especially advanced economies with substantial high-tech industries, embracing available domestic sourcing of CRMs is paramount to reducing dependence on foreign suppliers and bolstering self-reliance and security. Supply chain management research underscores the significance of supply chain flexibility and diversification for enhancing firm performance. Building redundancy and preparedness for supply chain uncertainty are crucial aspects that firms need to consider (Talluri et al., 2013). As an alternative to global sourcing, domestic sources of CRMs, when available, offer greater reliability compared to foreign suppliers. The benefits stem from reduced transportation costs, shorter lead times, and less exposure to potential disruptions or shortages arising from political conflicts, trade disputes, sanctions, or embargoes. Consequently, domestic supply provides more stable and timely inputs to domestic downstream RE sectors. Additionally, in situations where supply shocks or disruptions have occurred, domestic supply capabilities contribute to enhancing supply chain resilience (Tukamuhabwa et al., 2015). This, in turn, alleviates the negative impact of international shocks and facilitates quicker recovery.

On the other hand, for upstream countries that are endowed with rich CRM resources, having control over them and developing local capabilities in both extraction and production could enhance their bargaining power and exerts greater influence over prices and conditions for material access. The local accruing of benefits can occur only if the institutional framework – at various levels of governance, international, national and local – is strong enough to prevent ethical, environmental and social disruptions and promote fairness in supply chains. As a result, these economies would be better positioned to develop downstream industries and extract more value from their resource, thereby attracting high-value FDI and technology transfer. Countries possessing ample CRM deposits – often developing economies – can strategically leverage domestic sources to create competitive advantages and foster opportunities for their local industries. For instance, during the 2010 “Rare Earth crisis”, the reduction of export quotas led to a more than tenfold increase in REEs prices (Eggert et al., 2016), resulting in a significant price gap between China and other economies and a large-scale relocation of downstream foreign firms reliant on REEs (Pitron, 2020).

In conclusion, bolstering domestic supply capabilities on CRMs can yield stability and bring or enhance competitive advantages for the renewable energy industry, thus also fostering a conducive environment for technological advancement and collaboration, promoting innovation in RE. First, domestic CRM supply conditions change the incentives and trajectory of RE innovation. As discussed above, material supply risks related to global sourcing make firms face increased operational costs and less profitable, influence researchers' expectations by altering commercialization opportunities for their inventions. Thus, firms encounter additional constraints in R&D budgets and have less incentive to take risks. Moreover, resource scarcity from supply risks may eventually prompt changes in the orientation of technology progress (Cunha et al., 2014), inducing inventors to divert their R&D efforts towards material cost reduction through material recycling, conservation, and substitution. Although the latter are all per se positive activities, abrupt shifts may happen at the expense of interrupting existing innovation directions, such as RE functional improvements: such changes of R&D directions may bring additional learning and experimentation costs as inventors hastily adjust their trajectories. Moreover, such innovation faces the trade-off between material cost reduction and innovation output, in terms of novelty, production performance and research speed— reports find that material-saving R&D efforts and investments typically require long research cycles and are challenging to achieve in the short term (EU, 2013), resulting in potentially adverse effects on innovation outputs and technological competitiveness. Second, domestic production of CRM provides supply chain agility to external technological changes. This is particularly relevant for RE technologies which are radical innovations on the frontier, i.e. less standardized, having tacit nature, requiring face to face collaborations among supply chain partners (Fifarek, 2008; Lo et al., 2013). For the development of emerging technological innovation systems (TISs), it is important to attract suppliers who provide complementary inputs (Bergek et al., 2008). Breakthroughs in material science or related new technology trajectories emerge, destructing old trajectories. Proximity to and collaboration with domestic material producers brings supply chain agility, enabling quick adaptation by redesigning the system of products and keep abreast of the technology frontiers. Thus, domestic CRM supply can further boost RE innovation by fostering synergies and strengthening local innovation capabilities.

3. CRM supply dynamics for RE transition during 2007-2016

Our cases, solar energy and wind energy depend on various materials which are categorized into two groups: base metals (e.g. Copper, Iron, Zinc, etc.) and rare metals (and rare earth elements). In this paper, we specifically focus on the second group, as RMs and REEs are of much greater criticality. First, they are used in small quantities but provide unique and essential chemical, electrical or mechanical properties able to serve specific technological functions (e.g., Abraham, 2015; Li et al., 2024). Second, they are not traded in formal exchanges and their supply is highly vulnerable to disturbance and risks of various nature. In contrast, the base metals, although also important, are considered general inputs whose mining and production processes are widely geographically distributed and whose trade is standardized through global markets, such as the London Metal Exchange.

To investigate the supply chain dynamics of these sectors, we have selected six rare metals and two rare earth elements intensively used within them, following Moss et al. (2011), as shown in Table 1.[4]

[Insert Table 1 here]

First, we describe the global supply dynamics by calculating the sector level $Global\ \ price\ shocks_{j,t}$, which varies with sector j (solar or wind) and time t, and is the sum of costs for all CRMs, denoted by r used to produce a unit of RE products (products per MW of power):

$$Global\ \ price\ shocks_{j,t} = \sum_{r=1}^{\mathrm{R}} Global\ Price_{r,t} \cdot Utilization\ intensity_{r,j} \qquad (1)$$

During our research period, global CRM costs for the RE sectors have witnessed great shocks, as illustrated by Figure 3: we observe significant cost fluctuation due to the price changes: for example, the price shocks in Wind energy comes from 1. the high price of Molybdenum from 2007 and 2008 and 2. the price increase of REEs between 2011 to 2013 due to China’s export quota reduction; the Solar energy sector experienced price shock in 2011when all material had price spikes.

[Insert Figure 3 here]

Figure 4 illustrates the geography of production of the selected CRMs (the materials after refining which can be used for downstream sectors), presenting the aggregated shares for each of them. East Asia, particularly China, emerges as the dominant supplier, accounting for 44% of global CRM production and possessing a significant share of RMs such as Gallium, Indium, Molybdenum, and most REEs. Notably, China stands out as the sole country capable of producing the whole set of the selected CRMs, which may be an essential yet often overlooked factor contributing to the fast growth of China's RE sectors. Other countries exhibit specialization in the production of specific RMs with smaller shares: in East Asia, also Japan, Korea, Kazakhstan, and Taiwan (region) contribute to the production of many of the selected CRMs, whilst some Central and Latin America countries such as Mexico, Peru and Chile specialize in Silver and Molybdenum production. Additionally, the United States, Canada, Germany and Poland maintain strong capabilities in producing a few specific RMs.

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[4] The materials considered in Table 1 are all classified as CRMs in the main existing official lists (EU, US, Japan, Australia, Canada) but silver: the latter was added here on the basis of the EU report by Moss et al. (2011) on the RE industry.

The map clearly illustrates a pronounced spatial heterogeneity in CRM production worldwide. The selected CRMs are extracted from diverse locations and specific subnational regions, driven by the distribution of resource reserves (USGS, 2019). Subsequently, these ores are predominantly exported to China for smelting and refining processes. The resulting metal products are used both within China and exported abroad for the manufacturing of final goods (Zhu et al., 2022; Liu et al., 2023). The concentration of CRM production in specific economies, particularly China, highlights the importance of understanding the dynamics and risks associated with such spatial patterns.

[Insert Figure 4 here]

Figure 5 below shows the dynamics of the selected CRM production patterns, illustrated by changes in the share of CRMs produced by the top eight countries over the decade 2007-2016 (China's share, which stands significantly higher than the others, is displayed separately on the right axis). Whilst China's share experienced an impressive increase, from 30% in 2007 to 50% in 2016, other key metal producers like Japan, the United States, and Canada witnessed a decline in their respective shares during the same period: the production of CRMs essential for the RE industry is clearly shifting towards China.

[Insert Figure 5 here]

4. Econometric analysis

4.1 Sample and model specification

We use a panel model to estimate the effect of domestic production of CRMs on countries' competitiveness in the two RE sectors and technologies, denoted by *j*. The sample includes all countries in the UN Comtrade dataset from which find the RE product export values during the period 2007-2016, including 128 countries[5], denoted by *i*. Patents granted are utilized to assess national-level RE technologies, with data sourced from the United States Patent and Trademark Office (USPTO) dataset. The estimated model is reported in equation (2):

$$RCA/RTA_{i,j,t} = \beta_k Domestic\ CRM\ production_{i,j,t} + \sum_{k=2}^{8} \beta_k X_{i,j,t} + Country\ FE + Sector\ FE + Year\ FE + \varepsilon_{i,j,t} \qquad (2)$$

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[5] We also exclude countries whose main variables for the analysis are missing: the list is reported in Table A4.

The dependent variables, RE industrial and technological competitiveness[6] are measured by the indices of revealed comparative advantage (RCA) and revealed technological advantage (RTA) respectively, indicating how competitive a country is in exporting a certain product or in a certain sector and in innovating in a specific technological field, relative to the world.[7] Both indexes are widely used in the trade and geography literature (e.g. Laursen, 2015). If a country has a comparative advantage in a product/sector/technological domain, then the RCA/RTA is greater than 1, meaning that it exports/innovates more than the world average.

The variable of interest is domestic production of CRM materials which is the sum of the share of each CRM over the world total production[8] of this metal, denoted by r, used by each RE sector j produced in country i.[9] As discussed in Section 2, this variable experiences significant changes during the research period.

$$Domestic\ CRM\ production_{i,j,t} = \sum_{r=1}^{\mathrm{R}} RM\ production\ share_{i,j,r,t} \quad (3)$$

In addition to domestic CRM supply, we include two key control variables. First, we control for global CRM supply dynamics by $Global\ price\ shocks_{j,t}$ as defined in formula (1). A sudden price rise suggests a shock in the relevant international CRM market, which may come from the supply side, such as material export bans, or from the demand side, such as competition for the same CRM from other sectors. Such shocks are expected to have negative impacts on the RE competitiveness in exports and technology. The second key control is technological capabilities in $Material\ technologies_{i,t}$, measured by the share of granted patents in the fields of Material Technologies (WIPO's definition) over all patents whose inventors are located in country i.

Other control variables cover factors relevant to the RE industry and innovation, following previous literature (e.g., Horbach, 2008; Johnstone et al., 2010; Popp et al., 2011). Feed-in tariffs[10] are used to control for governmental support; factors related to country-level demand conditions, such as the demand for renewable energy supply, measured by the share of

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[6] RE products are identified by the 6-digit HS code in the UN Comtrade dataset, following the definition of related studies (Costantini & Crespi, 2009). See the Table A1 in the Appendix for details.

[7] RCA, and similarly RTA, are calculated by the following formula (for country = i; product/sector j; t = 2007-16):

$$RCA_{i,j,t} = \frac{EXP_{i,j,t/}\ EXP_{i,t}}{EXP_{j,t/}\ EXP_{t}}$$

[8] By "production," we refer to production of the CRM materials that have undergone processes such as refining and purification, including pure metals and chemical compounds rather than minerals and ores before processing.

[9] In the baseline model, all CRMs are regarded equally; an alternative weighted measure is discussed in the robustness tests.

[10] The Feed-in Tariff (FIT) is a policy designed to encourage the development of renewable energy sources by providing energy producers with long-term contracts and financial incentives. The FIT rate, which determines the level of support for renewable energies, is a crucial mechanism in this policy, offering a fixed price for the energy generated from renewable sources.

population with access to electricity and the existing deployment of RE; general economic and industrial development, such as GDP per capita, share of employment in industry, and share of exports over GDP; oil rent is included to control for the competition from conventional energy supplies. Only for the RCA models, total patent number and share of RE patents are included to consider country general technological capabilities and specialization. Country, year and RE sector fixed effects are included to control for other invariant national, sectoral features and time trends. In the RCA model, domestic CRM production and control variables are lagged by one year to account for the time lag in the production decisions' impact, attributable to significant investments and sunk costs associated with the Renewable Energy (RE) manufacturing sectors. In the RTA model, considering the lags between R&D activities and patenting, all independent variables are lagged by 3 years. The detailed description, summary and correlation matrix of all variables are reported in Table A2 and A3 in the Appendix.

4.2 Endogeneity and identification

Endogeneity issues arise from our variable of interest, $Domestic\ production\ of\ CRMs_{i,j,t}$, due to various reasons. The first is that the development of RE sectors may stimulate local metallurgy and smelting industries, subsequently increasing the local production of CRM materials, leading to a reverse causality issue. Furthermore, confounding factors such as industrial policies, proximity to other countries producing CRMs and RE products, and related industrial activities may simultaneously influence both the dependent and independent variables, adding to the endogeneity concern. These issues potentially bias our estimations.

We employ a method to capture exogenous shocks to domestic CRM supply by considering countries' reserves of CRMs. Since the total amount of mineral reserves in each country are predetermined by geological structures that formed millions of years ago, they are unlikely to be influenced by the dependent variable, RE export competitiveness and innovation dynamics, or any other confounding factors. The construction of the instrumental variable is similar to that of the dependent variables. $CRM\ \ Reserve_{i,j,t}$ is the sum of the share of country i's mineral reserve for each selected RM/REE r over the world total, as in formula (4):

$$CRM\ Reserve\ _{i,j} = \sum_{r=1}^{\mathrm{R}} CRM\ \ Reserve\ share_{i,j,r} \qquad (4)$$

5. Regression results

5.1 Baseline results

Table 2 presents the regression results for the RCA model: columns 1 and 2 display the results of the OLS regressions, including only the core independent variables and all controls, respectively. Columns 3 and 4 present second-stage instrumental variable regression results, with variable settings consistent with those in columns 1 and 2. The first-stage regression results are provided in Table A4 in the Appendix.

The coefficient of the lagged Domestic CRM production is significantly positive, irrespective of whether other factors affecting the RE industry are controlled for or not, indicating that domestic CRM production enhances the competitiveness of RE sectors and has a positive impact on downstream manufacturing. Moreover, after accounting for endogeneity, the effect of domestic production remains significant, and the coefficient's significance increases. This suggests that the OLS regression may underestimate the impact, likely due to the correlation of this variable with some unobservable confounding factors that also influence the RE industry's development. For instance, a country's strict environmental regulation may negatively affect metallurgical mining and other industries (Söderholm et al., 2015), while directing more attention and support to energy transition industries (Zhao et al., 2022).

Most of the control variables are insignificant, yet their directions are consistent with our expectations and the conclusions from existing literature. For instance, the share of material technologies positively influences the RE competitiveness. The global price of rare metals/earth elements at the RE sector level shows a negative sign, aligning with previous studies that have identified material costs as a critical factor for the RE industry's development. For example, Sandor et al. (2018) finds that the price fluctuation of photovoltaic materials eroded the advantages of downstream solar cell manufacturing. Additionally, access to electricity has negative impacts, suggesting that a shortage of energy supply can serve as an incentive for RE development. The RE patent share exhibits a positive sign, while with this control the total number of patents becomes negative, possibly indicating that specialisation may occur even without strong general technological capabilities. Lastly, the feed-in tariff shows a positive sign, consistent with existing research on government subsidies and the ability of local REs to innovate (Johnstone et al., 2017).

[Insert Table 2 here]

In Table 3, the results for the RTA model mirror those of the export RCA, with the coefficient of the 3-year lagged Domestic CRM production highly significant and positive across specifications. This suggests that a country's technological advantage in RE technologies benefits from domestic production of CRMs, comforting the idea that the supply of key critical materials' influences the entire RE value chain.

[Insert Table 3 here]

5.2 Mechanism analysis

The findings above provide support to the significant impact of domestic CRM production on RE industrial and technological competitiveness. Next, we further explore the mechanisms through which this impact occurs and the factors strengthening/mitigating it by introducing the cross terms of domestic CRM production with other variables. As we expected, Table 4 shows that a major role played by local CRM production is to mitigate the fluctuation of international material prices, serving as an alternative supply. As shown in column 1, the cross term of CRM domestic production and global price is significantly positive, while after introducing the interaction the sign of domestic production becomes insignificant. This indicates that the impact of domestic CRM supply on RE product competitiveness is mainly to be attributed to containing the negative effect of international price variations; on the contrary, it suggests that the importance of domestic production diminishes when the CRM global supply is stable. Hence, global sourcing of critical materials remains irreplaceable for RE manufacturing due to several reasons, among which the high dependence of many major economies on CRM imports, the geographical concentration of resource locations and production facilities, and the dominance of CRM trade networks by large multinational firms. All these factors are not easily modifiable in the short term. Importing CRMs continues to be the primary source for many countries' RE industry, especially those with very strict environmental regulations which discourage mining and smelting activities (Söderholm et al., 2015). Nevertheless, our finding suggests that having domestic production as a backup supply option can substantially support the development of local RE manufacturing, particularly during periods of international price volatility and supply risks. This also aligns with the existing literature on supply chain dynamics, emphasizing a shift from decoupling to de-risking strategies (Remko, 2020). On the contrary, as from column 2 in Table 4, the importance of domestic production remains significant for the RTA model after introducing the cross term with CRM global price dynamics, suggesting that RE technological innovation is more dependent on domestic CRM supply regardless of global supply dynamics.

In columns 3 and 4, we introduce the interaction of domestic CRM production with Material Technologies: a positive effect, though not strongly significant, is observed on the RTA, while the effect in the RCA model is insignificant. As previously discussed, we established that domestic access to CRMs enhances RE technological output, and this positive influence is further augmented by specialization in material technologies. This implies that merely possessing the materials is not sufficient; it is equally crucial to have the necessary advanced capabilities to fully exploit them. The existing literature posits that material science and technologies are GPTs that have broad spillover effects across various technological domains, particularly in the RE industry. For instance, Huenteler et al. (2016) finds that material technologies are among the top five external knowledge sources for different subsystems of wind energy. Our findings reinforce this argument, elucidating how material technologies act as a crucial link between the availability of CRMs and the technological innovations that rely on these materials.

[Insert Table 4 here]

In summary, these findings further highlight the importance of domestic production of critical raw materials for the competitiveness of the renewable energy industry and innovation. While global procurement of critical rare metals remains crucial, having domestic production as a backup option can enhance supply chain stability for RE manufacturing. For RE technological innovation, this impact can be further enhanced by the material technologies.

6. Robustness checks and further analysis

6.1 Alternative measures for the dependent variables

We modify our approach for measuring the dependent variables representing RE competitiveness, looking for alternative metrics for gauging country specialization in specific sectors and technologies. Instead of using RCA and RTA, we calculate the share of RE product exports in a country's total export value and that of RE patents in a country's patent portfolio, respectively. The results are presented in Table 5, where we observe generally consistent outcomes, with the exception that the RE export IV model loses significance.

[Insert Table 5 here]

6.2 Considering heterogenous criticality

In the baseline regression, we assume that all the selected CRMs are equal. However, the heterogeneity of their relevance is undeniable, as some are more critical or account for higher proportion of costs in the RE industry. So, we use a measure to consider this heterogeneity, in which the CRM Production share over the world total of this metal, which is weighted by the criticality level of each CRM:

$$Weighted\ \ Domestic\ CRM\ production_{i,j,t} = \sum_{r=1}^{\mathrm{R}} CRM\ criticality_{r,j,t} \cdot \mathrm{C}RM\ Production\ share_{i,r,t} \tag{5}$$

In such a weighted regressor, a country will have a high level of domestic production for RE sector j if it produces more CRM used by this sector, or if this metal has high degree of criticality (driven by global price increase), as defined by the literature on resource criticality. $CRM\ criticality_{r,j,t}$ is determined by both supply and demand side factors: is the first is availability, measured by the global average price;[11] an increasing price is a reflection of less availability; on the demand side, criticality is also influenced by CRM importance in each RE sector measured by the utilization intensity, as from Moss et al. (2011) and shown in Table 1. The variable $CRM\ criticality_{r,j,t}$ is expressed in the unit of price (thousand dollar) per megawatt, measuring the criticality of each metal for each RE sector at the global level, i.e. the cost of metal needed to produce a unit of the RE product: in other words, it is determined by amount of materials use and price of each metal.

$$CRM\ criticality_{r,j,t} = Global\ Price_{r,t} \cdot Utilization\ intensity_{r,j,t} \quad (6)$$

In accordance, the instrumental variable in this case is the share of each CRM reserve weighed by this criticality index. The regression results are consistent by the new measurement of variable, after considering this heterogenous criticality, as shown in Table 6.

[Insert Table 6 here]

6.3 Excluding major RE producing countries

A further concern is that the domestic CRM supply capacity shows high heterogeneity also across countries. Some large ones, like China, have monopolized the market of many CRMs and can affect international prices by controlling output; at the same time, they influence the dynamics of the global product market through their monopoly position: China's embargo on REEs and Indonesia's export tariff on nickel ores influence both global metal prices and RE industries. Therefore, we further test whether our findings above are mainly caused by a few superpowers that dominate the production of certain metals by excluding the major CRM suppliers, i.e. those producing more than 10% of any CRM during the research period, including Australia, Chile, China, Finland, Germany, Japan, Korea, Russia and USA. As shown in Table 7, the results are generally consistent with our baseline findings. This means that the impact of domestic CRMs supply capacity is not entirely driven by the monopoly of the major producers. For smaller countries, having a certain domestic capacity can effectively promote the competitiveness of downstream industries and technologies, even without having market-dominating positions.

[Insert Table 7 here]

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[11] Price data for RM is from WIND Trading Terminal for the RMs (https://www.wind.com.cn/en/wft.html), whilst price information for REEs is obtained from USGS historical mineral price statistics.

7. Conclusion

The RE industry plays a vital role in the decarbonization and sustainable development of human society. The literature highlights the pivotal roles of both green energy technological capabilities and manufacturing capacity in ensuring this shift. While the former offers decarbonization solutions, the latter materializes these solutions by producing and supplying RE infrastructure and products, including solar panels, wind turbines, and batteries. The specific technological regime properties of the RE transition have been studied mostly focusing on factors such as market conditions, policy intervention, and technological bases and transfers (Horbach, 2008; Johnstone et al., 2010; Popp et al., 2011; Castellani et al., 2022), whilst less attention has been directed to the material basis of RE developments.

CRMs have been regarded as the key inputs of modern industries, and especially for REs, their unique characteristics are crucial to achieving technological and production functionality. The ambitious shift of the global energy sector towards zero-carbon will result in an increasing demand for CRMs whose supply chains are subject to significant supply risks, an issue first recognized by resource criticality studies and currently attracting increasing attention in public debates (IEA, 2021). However, to the best of our knowledge, no study has so far addressed the question of whether and to what extent the supply dynamics of critical metals influences the competitiveness of the RE industry exports and technological innovation. Answering this questions can help governments and firms design an effective supply chain configuration to improve the resilience of the downstream industries and ensure a successful transition to renewable energy. Given the dependence of emerging technologies on material resources, it is important to understand how RE industries are linked to the dynamics of material supply. A significant research gap persists regarding the spatial structure of material value chains and supply and their fundamental influence on downstream RE activities.

The significance of these materials in RE technologies, combined with their susceptibility to geopolitical tensions and conflicts, emphasizes the importance of establishing a robust and resilient supply chain configuration. By linking the ongoing debates on the RE transition and CRM sourcing in supply chain management, we assert that domestic CRM supply presents considerable advantages in bolstering supply chain stability and mitigating risks, ultimately contributing to the enhanced stability and competitiveness of the RE industry. Empirically, we present the assessment of how national-level availability of CRM impacts the development of the renewable energy industry, distinguishing between domestic and international availability. Our empirical findings demonstrate that, at the country level, both RE product exports and patent output are affected by the localization of the CRM supply, with a positive impact of domestic CRM production on the RE industry overall competitiveness, especially during periods of international supply risk.

Our theoretical contribution first responds to the vast literature on RE innovation. Scholars have provided insights on RE innovation by explaining the distinct features of green and RE technologies, in terms of higher originality and complexity, more diversified knowledge sources and deeper impacts on subsequent technologies (e.g., De Marchi, 2012; Ghisetti et al., 2015; Barbieri et al., 2020). Through introducing the material perspective, we broaden this discussion to a rarely-discussed but equally important aspect — the shifting physical basis and material demands related to the technological transition paradigm shift. Second, our attempts cast light on the whole system in which RE innovation happens. Our perspective explores the entire RE supply chain by linking different activities across geographies, adding to previous literature mainly focusing on the location of R&D and innovation activities, but overlooking the material flows behind them as a necessary condition fuelling those activities. More generally, the case of RE and CRM also helps to rediscover the importance of natural resources in industrial development and economic growth. This perspective facilitates a broader understanding of the RE transition, revealing potential resource traps and their implications for resource-criticality in various economies. It also highlights the redistributive welfare and development opportunities among countries and regions amid technological shifts in the RE value chain, from resource extraction to product manufacturing and technology innovation. Furthermore, we provide insights to the current policy debates on the supply chain dynamics and adjustments — the case of CRM supply chain and RE development emphasizes the infeasibility of complete decoupling global supply chain, on the other hand underscoring the significance of de-risking through domestic production capabilities.

The supply of CRMs could become a potential bottleneck factor for the energy transition, echoing the concerns of Grandell et al. (2016) that “renewable energy scenarios presented by the IPCC Fifth Assessment Report seem partly unrealistic from the perspective of critical metals” (p. 53). From this perspective, the RE transition seems less sustainable. Policymakers should consider all stakeholders of the RE transition, especially, critical material suppliers, and ensure stable and fair supplies of CRM materials through domestic production or cross-national cooperation between developing and developed countries, and strong governance and regulation concerted scheme. On the other hand, it is important to prepare for potential CRM supply crises from black swan events, such as political unrest and instability, natural disasters and trade conflicts, etc. In the foreseeable future, one significant threat may come from the decoupling strategies of the US, with China which has supplied more than half of the world’s CRM materials. Such implications are vital to the RE industry and could also be applied to other strategic sectors, like ICT, defence and AI, which also heavily rely on different groups of critical raw materials. For moving up the global value chain for the developing countries, owning resources is enough, provided that a process of building capabilities in transforming resources into input for downstream activities is allowed and protected by international regulations. In doing so, they can leverage their comparative advantage in these activities and diversify into more complex and innovative ones.

More research is needed to further explore the relationship between RE and CRMs. One direction we are exploring is the competition for the same CRMs between RE and other industries and across geography. For example, solar energy requires indium and gallium as inputs, but at the same time these two metals are also vital elements in screens and semiconductors. RE may be at disadvantage considering its global political imperative against the high profit of the advanced electronic industry, highly concentrated both geographical and in market shares, which erode the cost advantage of thin film technologies (Wolden et al., 2011). Future research can expand the discussion to other industries, which are also heavily dependent on different groups of CMs but are in different technological and institutional conditions.

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Tables and Figures

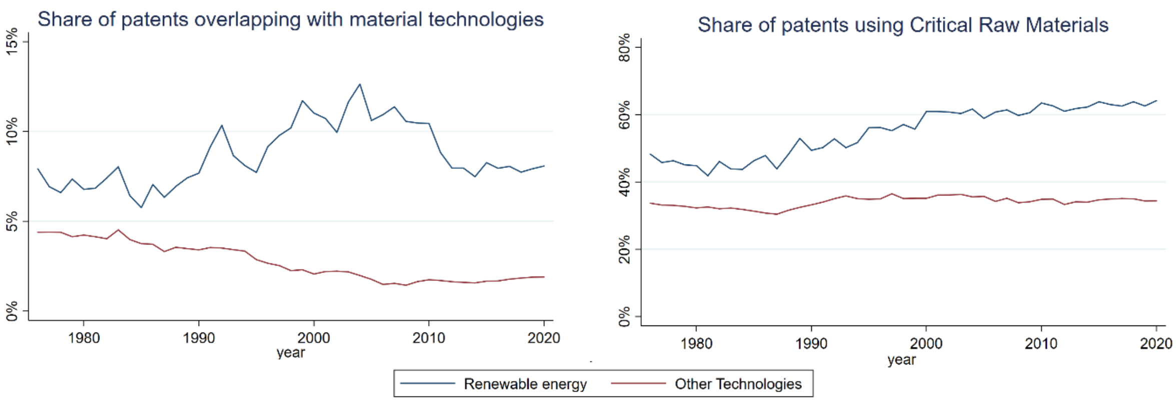


Figure 1. Overlapping rates in patent classification with Material Technologies (left) and dependence on CRMs (right), RE technologies VS. others*

*Note: A patent may belong to different technological classes which reveal the knowledge composition (Barbieri et al., 2020): the left figure measures the overlapping rates with material technologies, measured by the share of patents also belongs to the Material Technologies (defined by WIPO classification) at the subgroup classification level, indicating the degree of dependence on material technologies. The right figure follows Li et al. (2024), identifying technological dependence on CRM by text mining patent texts. The CRM list used here combines the CRM lists of the EU (2018 version) and that of the US geological survey.

Figure 2. Critical material supply chain for the RE sector

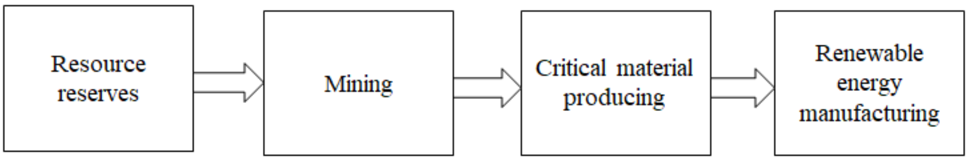
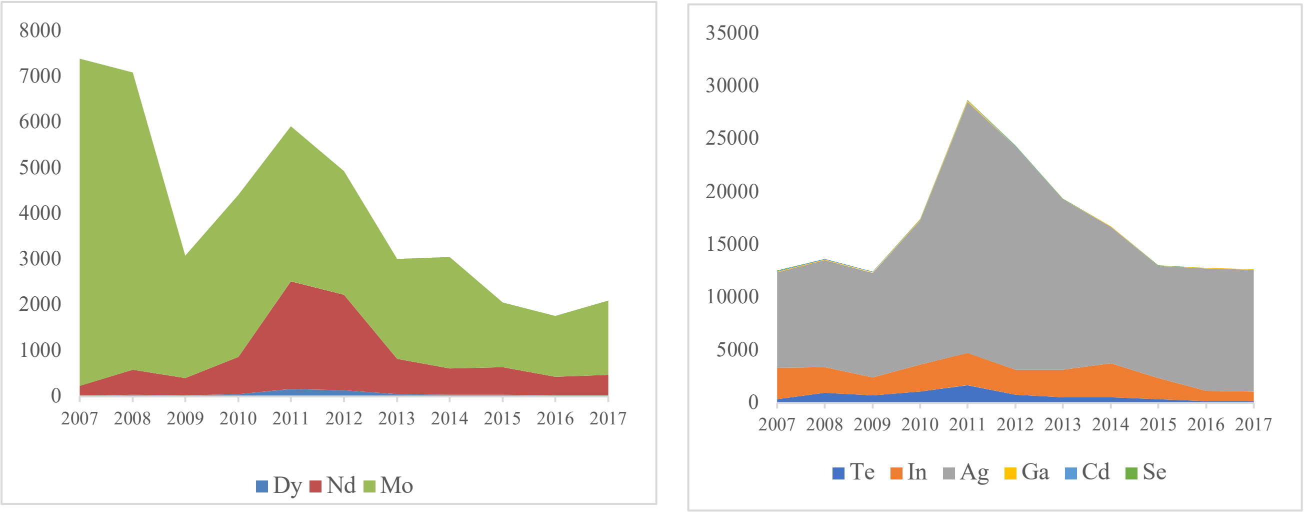
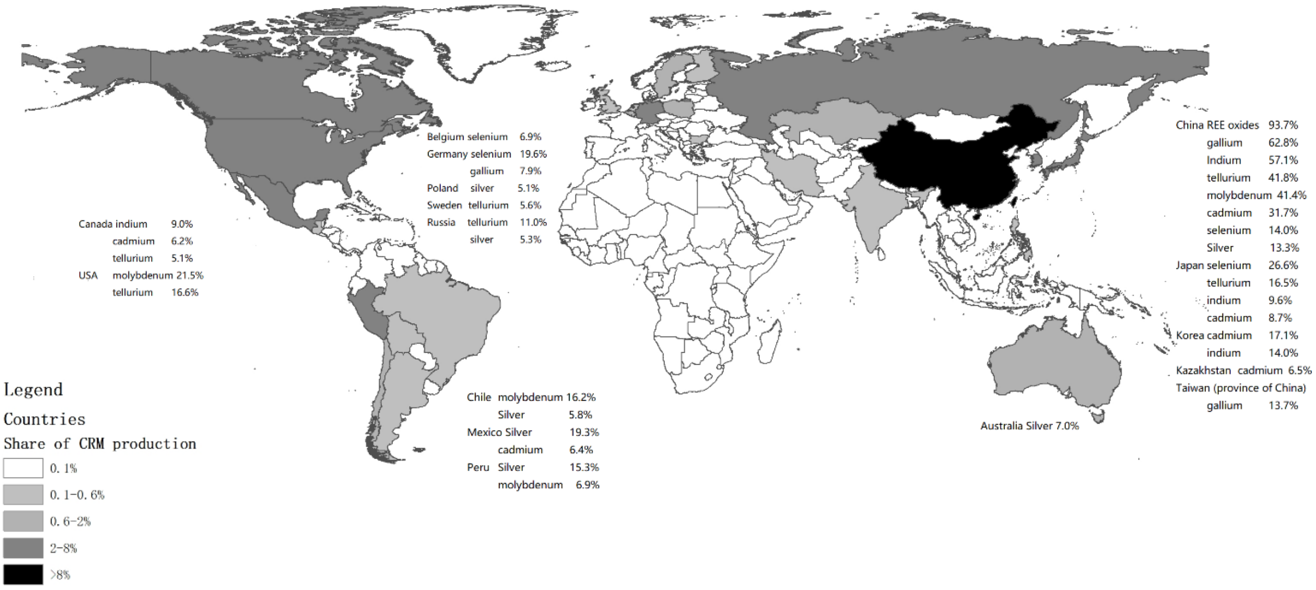


Figure 3. International CRM costs for the RE sector by CRM, 2007-2016



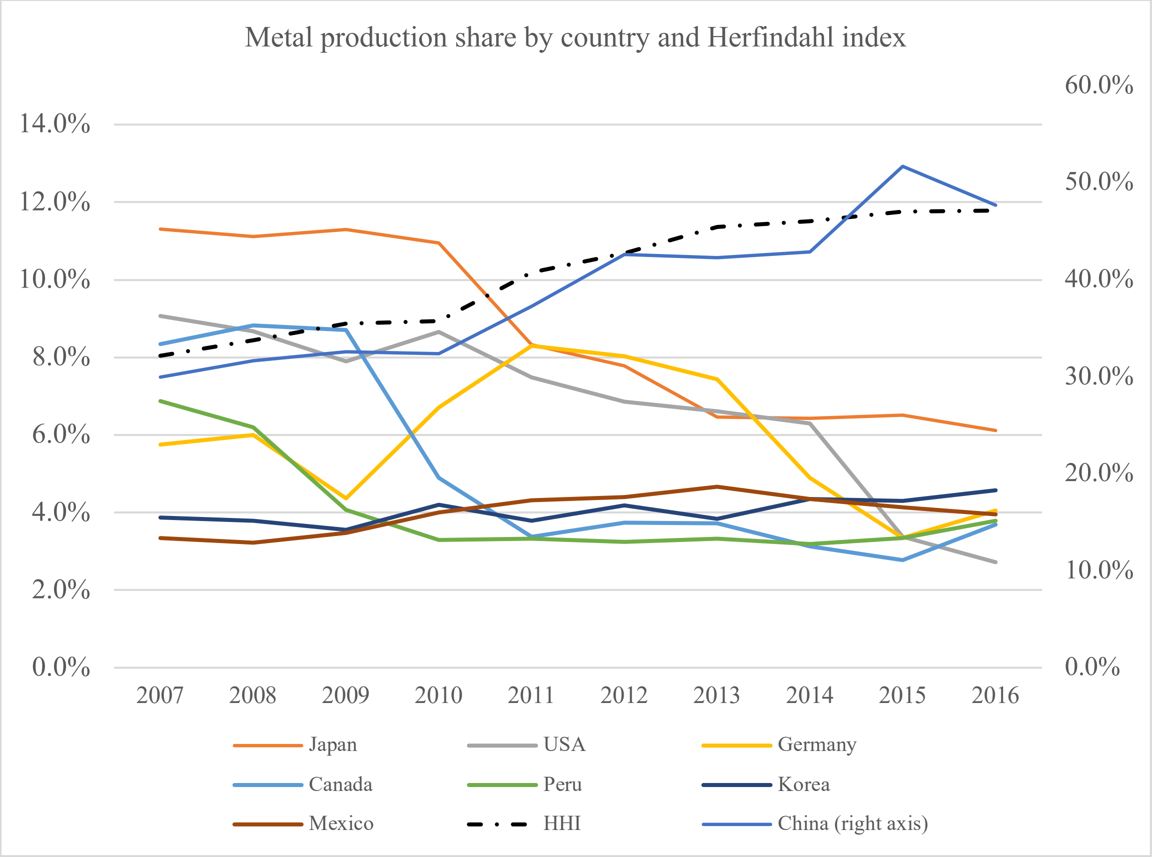
Metal price source: WIND financial platform

Figure 4. The geography of the selected CRM production, 2007-2016



Source: data from British Geological Survey and US Geological Survey

Figure 5. Trends in the selected CRM production, 2007-2016



Source: data from British Geological Survey and US Geological Survey

Table 1. CRM utilization intensity by renewable energy sectors

Renewable Energy Sectors	Critical rare metals	Utilization intensity (kg)*
Solar energy	Cadmium (Cd)	6.1
	Gallium (Ga)	0.12
	Indium (In)	4.5
	Selenium (Se)	0.5
	Silver (Ag)	19.2
	Tellurium (Te)	4.7
Wind energy	Dysprosium (Dy) Rare earth	2.8
	Neodymium (Nd) Rare earth	40.6
	Molybdenum (Mo)	135.3

* The material use intensity for each sector (in kg/MW) comes from the estimate of the EU report by Moss et al. (2011).

Table 2. Results for the RE product export model (RCA)

Model	(1)	(2)	(3)	(4)
VARIABLES	RCA (OLS)	RCA (OLS)	RCA (IV)	RCA (IV)
L.Domestic CRM production	2.980**	2.821**	6.525**	6.184*
	(1.499)	(1.424)	(3.181)	(3.146)
L.Material technologies share		0.337		0.360
		(0.300)		(0.303)
Global price shocks		-0.0280		-0.0295
		(0.100)		(0.100)
L.Feed-in tariff		0.675		0.539
		(0.915)		(0.938)
L.Patent number log		-0.136*		-0.137*
		(0.0728)		(0.0732)
L.RE patent share		13.49		13.45
		(11.70)		(11.66)
L.Access to electricity		-2.047*		-2.055*
		(1.161)		(1.178)
L.Oil rents		0.861		0.939
		(1.127)		(1.142)
L.GDPpc log		0.720		0.739
		(0.935)		(0.935)
L.RE deployment		-0.504		-0.453
		(0.589)		(0.591)
L.Exports share of GDP		-0.396		-0.464
		(0.576)		(0.570)
L.Employment in industry (%)		0.126		0.163
		(1.931)		(1.930)
Constant	0.383**	-3.792		
	(0.163)	(8.771)		
Country FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	2,304	2,268	2,304	2,268
R-squared	0.101	0.103	0.000	0.002

L. indicates lagged variables. Standard errors clustered at the country-sector level. Robust standard errors reported in parentheses.

Table 3. Results for the RE technology innovation model (RTA)

Model VARIABLES	(1) RTA (OLS)	(2) RTA (OLS)	(3) RTA (IV)	(4) RTA (IV)
L3.Domestic CRM production	4.146***	4.242***	6.457***	6.793***
	(1.393)	(1.386)	(2.273)	(2.304)
Constant	1.079***	58.02		
	(0.171)	(49.42)		
Control	No	Yes	No	Yes
Country FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,792	1,764	1,792	1,764
R-squared	0.123	0.126	0.000	0.004

L. indicates lagged variables. Standard errors clustered at the country-sector level. Robust standard errors reported in parentheses.

Table 4. Results for the mechanism analysis

Model	(1)	(2)	(3)	(4)
VARIABLES	RCA	RTA	RCA	RTA
L.Domestic CRM production	2.117	4.164***	2.874**	3.743***
	(1.417)	(1.413)	(1.409)	(1.328)
L.Domestic CRM production* Global price shocks	0.110**	0.00114		
	(0.0521)	(0.0610)		
L.Domestic CRM production* Material technologies share			-1.518	12.61*
			(2.346)	(8.32)
Constant	-3.692	28.19	-3.826	28.44
	(8.782)	(40.82)	(8.808)	(40.82)
Control	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	2,268	1,764	2,268	1,764
R-squared	0.460	0.126	0.459	0.126

L. indicates lagged variables. Standard errors are clustered at the country-sector level. Robust standard errors are reported in parentheses.

Table 5. Robustness tests 1 (alternative dependent variable)

Model VARIABLES	(1) RE export share (OLS)	(2) RE export share (IV)	(3) RE patent share (OLS)	(4) RE patent share (IV)
L.Domestic CRM production	2.694***	3.157	0.0149***	0.0211***
	(0.849)	(2.733)	(0.00505)	(0.00758)
Constant	-9.036		0.207	
	(9.028)		(0.157)	
Control	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	2,268	2,268	1,764	1,764
R-squared	0.339	0.047	0.117	0.004

L. indicates lagged variables. Standard errors are clustered at the country-sector level. Robust standard errors are reported in parentheses.

Table 6. Robustness tests 2 (CRM criticality heterogeneity)

Model VARIABLES	(1) RE export share (OLS)	(2) RE export share (IV)	(3) RE patent share (OLS)	(4) RE patent share (IV)
L.Weighed Domestic CRM production	0.000641*	0.00155**	3.71e-05*	0.00171**
	(0.000343)	(0.000761)	(2.08e-05)	(0.000704)
Constant	-3.628		2.344	
	(8.738)		(2.340)	
Control	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	2,268	2,268	1,640	1,640
R-squared	0.459	0.020	0.378	0.005

L. indicates lagged variables. Standard errors are clustered at the country-sector level. Robust standard errors are reported in parentheses.

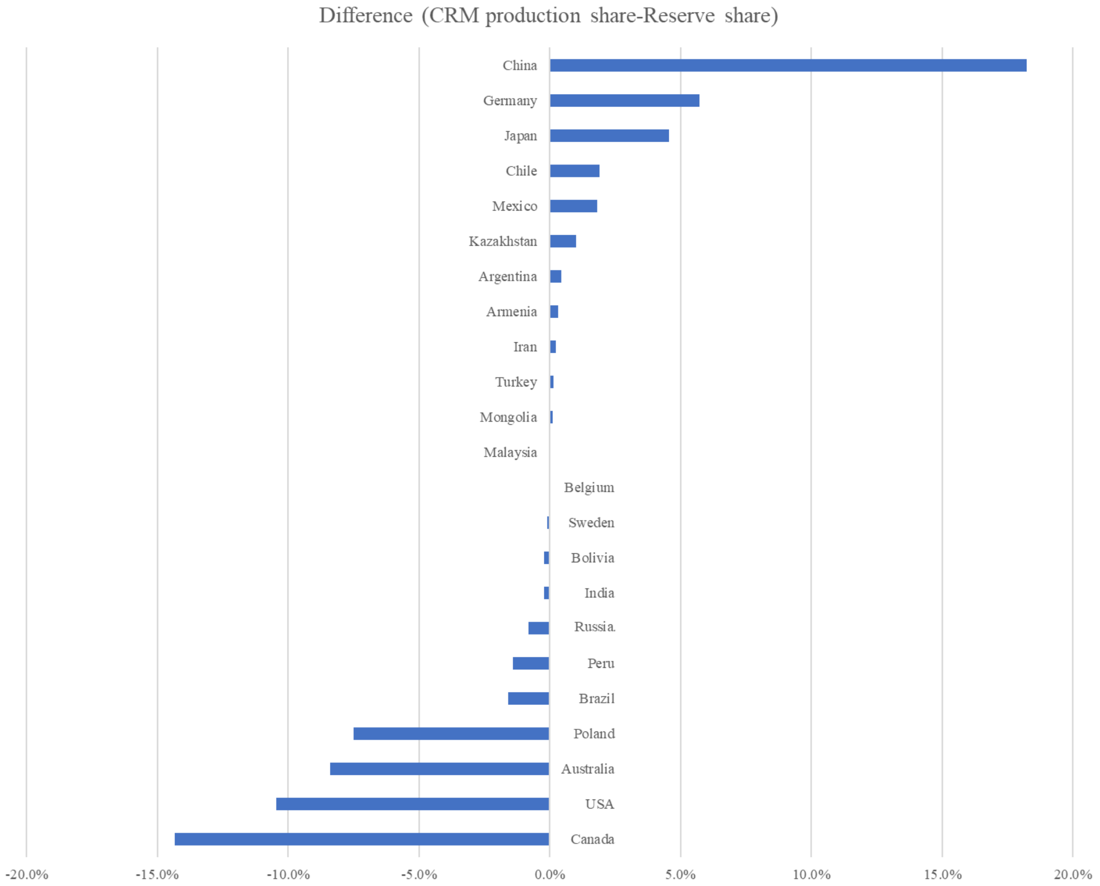
Table 7. Robustness tests 3 (country heterogeneity)

Model VARIABLES	(1) RCA (OLS)	(2) RCA (IV)	(3) RTA (OLS)	(4) RTA (IV)
L.Domestic CRM production	3.419*	3.078*	3.925*	4.272**
	(2.033)	(1.789)	(1.994)	(1.866)
Constant	-4.111		59.38	
	(9.120)		(52.01)	
Country FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	2,142	2,142	1,666	1,666
R-squared	0.460	0.022	0.126	0.004

L. indicates lagged variables. Standard errors are clustered at the country-sector level. Robust standard errors are reported in parentheses.

Appendix

Figure A1. Difference between CRM production and domestic CRM mineral reserves



Data source: British Geological Survey and US Geological Survey

Table A1. Identification of RE products and technologies

Sector	HS code for RE products	Title	CPC code for RE patents	Title
Wind	850231	Wind-powered electric generating sets	Y02E 10/50 Including: Y02E 10/50, Y02E 10/52,Y02E 10/541,Y02E 10/542, Y02E 10/543, Y02E 10/544, Y02E 10/545,Y02E 10/546, Y02E 10/547,Y02E 10/548,Y02E 10/549,Y02E 10/56	Photovoltaic [PV] energy
Solar	854140	Electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light emitting diodes	Y02E 10/70 Including: Y02E 10/70,Y02E 10/72,Y02E 10/727,Y02E 10/728, Y02E 10/74,Y02E 10/76	Wind energy

The identification of RE products and technological class follows previous studies:

Algieri, B., Aquino, A., & Succurro, M. (2011). Going “green”: trade specialisation dynamics in the solar photovoltaic sector. Energy Policy, 39(11), 7275-7283.

Wind, I. (2008). HS Codes and the Renewable Energy Sector. Research and Analysis, International Centre for Trade and Sustainable Development (ICTSD).

Cao, X., Rajarshi, A., & Tong, J. (2018). Technology evolution of China’s export of renewable energy products. International journal of environmental research and public health, 15(8), 1782.

Table A2. Definition of variables and data sources

Variable	Definition	Source
Country RCA RE	Revealed comparative advantages of RE products	UN Comtrade dataset
Country RTA RE	Revealed technological advantages of RE patents	USPTO
Country domestic CRM production	Sum of production of each CRM over the world total	British Geological survey
Global price shocks zscore	Average CRM price dynamics weighted by use intensity	US Geological survey, WIND Platform
Country feed-in tariff	Values of FIT (in USD/kWh)	OECD.Stat
Country patent number log	Number of patents granted to inventors located in each country	USPTO
Country RE patent share	RE patent number over all patent (RE capabilities/specialisation)	USPTO
Country material technologies share	Share of material patents over all patents (material technology capabilities)	USPTO
Country access to electricity (%)	Share of population with access to electricity	World Bank development indicator
Country RE deployment (%)	Electricity production from renewable sources, excluding hydroelectric (% of tot production)	World Bank development indicator
Country oil rents (%)	Difference between the value of crude oil production at regional prices and total costs of production over GDP	World Bank development indicator
Country GDPpc log	GDP per capita	World Bank development indicator
Country exports share of GDP (%)	Exports of goods and services	World Bank development indicator
Country employment in industry (%)	Share of population employed in industry (mining and quarrying, manufacturing, construction, and public utilities) over total population	World Bank development indicator
Country CRM reserve	Sum of shares of reserve for each selected CRM on world total	US Geological Survey

Table A3. Summary of variables and the correlation matrix

Variable	Observation	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11	12	13
1. RCA RE	2560	0.477609	3.650833	1												
2. RTA RE	2560	0.9994204	7.176798	0.2638	1											
3. Domestic CRMs production	2560	0.0323951	0.098525	0.0283	-0.0105	1										
4. Global price shocks zscore	2560	-2.78E-18	1.000015	-0.0373	-0.0531	0.1043	1									
5. Feed-in tariff	2560	0.05179	0.126363	0.0747	-0.0081	0.1068	0.1535	1								
6. Patent no. log	2560	3.288558	2.924758	0.1372	0.0468	0.4694	0.0008	0.3292	1							
7. RE patent share	2560	0.005127	0.028905	0.1872	0.0806	-0.0056	0.0117	0.02	0.0479	1						
8. Material patent share	2560	0.0238233	0.080791	-0.0017	-0.0062	0.0666	0.0174	0.0264	0.0489	-0.0075	1					
9. Access to electricity (%)	2560	85.72985	27.09878	0.0674	0.0551	0.1505	0.0004	0.1924	0.4844	0.0894	0.1176	1				
10. Oil rents (%)	2560	2.93209	7.690009	-0.038	-0.0161	-0.0453	0.0148	-0.1001	-0.0675	0.0104	0.1002	0.126	1			
11. GDP pc log	2514	8.907698	1.494923	0.1292	0.0693	0.1683	0.001	0.2699	0.6824	0.0954	0.0665	0.7546	0.1303	1		
12. RE deployment (%)	2560	3.767292	6.99619	0.2096	0.0773	-0.0054	0.0379	0.1286	0.2661	0.0424	-0.0084	0.1631	-0.1861	0.2668	1	
13. Exports share of GDP (%)	2560	44.21379	32.91147	0.0396	0.0015	-0.141	0.0151	0.0149	0.1493	0.0311	0.0323	0.3072	0.0751	0.4038	0.0291	1
14. Employment in industry (%)	2560	21.04239	8.649175	0.0199	-0.0236	0.1173	-0.0054	0.1678	0.3232	0.0315	0.0433	0.5861	0.2091	0.3922	0.0744	0.2065

Table A4. List of 128 countries (regions) in the sample

Albania
Algeria
Andorra
Argentina
Armenia
Australia
Austria
Azerbaijan
Bahamas
Bahrain
Bangladesh
Belarus
Belgium
Belize
Bolivia
Bosnia Herzegovina
Brazil
Brunei Darussalam
Bulgaria
Burkina Faso
Burundi
Cambodia
Canada
Chile
China
China, Hong Kong SAR
China, Macao SAR
Colombia
Costa Rica
Croatia
Cyprus
Czechia
CÃ´te d'Ivoire
Denmark
Dominican Rep.
Ecuador
El Salvador
Estonia
Ethiopia
Fiji
Finland
France
French Polynesia
Georgia
Germany
Greece
Greenland
Guatemala
Guyana
Honduras
Hungary
Iceland
India
Iran
Ireland
Israel
Italy
Jamaica
Japan
Jordan
Kazakhstan
Kenya
Kuwait
Kyrgyzstan
Latvia
Lebanon
Lithuania
Luxembourg
Madagascar
Malawi
Malaysia
Mali
Malta
Mauritius
Mexico
Mongolia
Montenegro
Morocco
Mozambique
Namibia
Netherlands
New Caledonia
New Zealand
Nicaragua
Niger
Nigeria
North Macedonia
Norway
Oman
Pakistan
Panama
Papua New Guinea
Paraguay
Peru
Poland
Portugal
Qatar
Rep. of Korea
Rep. of Moldova
Romania
Russian Federation
Rwanda
Saudi Arabia
Senegal
Serbia
Singapore
Slovakia
Slovenia
South Africa
Spain
Sri Lanka
Sweden
Switzerland
Thailand
Togo
Trinidad and Tobago
Tunisia
Turkey
USA
Uganda
United Arab Emirates
United Kingdom
United Rep. of Tanzania
Uruguay
Viet Nam
Yemen
Zambia
Zimbabwe

Table A5. First stage regression results

Model VARIABLES	(1) L.Domestic CRM production	(2) L3.Domestic CRM production
L. CRM Reserve	0.0733***	0.0699***
	(0.0223)	(0.0216)
Controls	Yes	Yes
Country FE	Yes	Yes
Year FE	Yes	Yes
Sector FE	Yes	Yes
Kleibergen-Paap rk LM statistic	31.215***	26.600***
Kleibergen-Paap rk Wald F statistic	42.012	32.691
Stock-Yogo weak ID test critical values: 10% maximal IV size	16.38	16.38
15% maximal IV size	8.96	8.96
20% maximal IV size	6.66	6.66
Constant	-1,229	-2,690
	(1,120)	(1,739)
Observations	2,238	1,738
R-squared	0.746	0.749

L. indicates lagged variables. Standard errors are clustered at the country-sector level. Robust standard errors are reported in parentheses.