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The hydrogen paradigms. Technologies, country patterns of specialisation and dependence

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The hydrogen paradigms. Technologies, country patterns of specialisation and dependence[*]

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Abstract

The adverse effects of the climate crisis call for a structural change in the economy toward less environmentally disruptive development pathways. To address decarbonisation, hydrogen seems to be the most promising element to complement renewable energy. However, the dominant technology for its production relies on hydrocarbons, while a radical transition would require the establishment of a green hydrogen technological paradigm. Green hydrogen production is also hampered by critical materials and geographic attributes that only some countries would meet. This may constitute a window of opportunity for latecomers' countries to pursue green industrialization or a condition for their exploitation. So, what are the drivers behind hydrogen technologies production? And, how do countries learn and consequently specialise? We tackle these questions investigating the technologies, products, and processes behind hydrogen production. Using trade data, we examine the pattern of countries' specialisation and dependence on raw materials. Our findings indicate that hydrogen technologies market is undergoing a transformation in their composition rather than expansion. Moreover, looking at the critical raw materials content of green hydrogen technology, we find a negative relationship between dependence on critical raw materials and the autonomous specialisation of countries in their related production.

Key-words: ecological transition, hydrogen paradigms, specialisation, dependency, mission-oriented policies

JEL codes: Q27, Q40, Q55, O1

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1 Introduction

The climate crisis (Crist, 2007) urges a structural change of the economy towards less environmental disruptive pathways of development, reducing pollution and resource depletion. Decarbonising the energy sector, which is responsible for a quarter of greenhouse gases emissions globally, and almost 40% of CO_2 emissions alone (IEA, 2022a), represents one of the high-priority objectives to alter the path towards environmental collapse (IPCC, 2022). So far, technological solutions with this aim have entailed the electrification of the economy, powered by renewables, and potentially complemented by other energy carriers. Nowadays, we are witnessing a momentous clash between two "constellations of technological paradigms" (Freeman, 2007), one based on fossil fuels and the other one based on renewable energy sources. It is indeed a "battle of the systems" with consequences enormously wider than those analysed by Paul David between AC and DC electric systems (David, 1992). However, also among the renewables there are competing paradigms. And they appear even within the hydrogen family of technologies. For sure, hydrogen seems to be the most promising bet for industry decarbonisation, used as fuel and feedstock for the hard-to-abate sectors, to ensure the resilience of the entire energy system (IPCC, 2022). At the current stage, hydrogen gas is not effectively part of the energy mix of countries and most of the production occurs at the consumption site, mainly to cater for the fertilizer and oil refinery industries. Hydrogen can be produced in different ways, from hydrocarbons (the so-called *black/grey hydrogen*, or *blue*, if coupled with carbon capture processes), or from water electrolysis, using electricity produced from renewable sources (*green hydrogen*. However, current production is derived almost exclusively from natural gas and coal, without including CO_2 sequestration. As such, hydrogen use so far contributes to global emissions (at least for 1.5%), rather than to their reduction (IEA, 2022a).

The boost of production for energy transition should lead to an increase in green hydrogen commercialization and obviously to some countries' specialisation in its production. Why does that matter? Green hydrogen, meant to negatively contribute to overall emissions, has to be produced in locations characterised by the conjuncture of abundant renewable resources, available land, access to water, and the ability to transport energy to large demand centres. This may represent an opportunity to specialise in green energy production for those developing countries having adequate physical attributes. Therefore, the establishment of a green hydrogen industry, coupled with a significant reduction of fossil-based energy, could unlock the potential to redefine the provision and distribution of clean energy on a global scale, with significant changes in terms of energy security and import dependence (IRENA, 2022). Here a question with crucial implications also for the prospects of development of emerging economies is whether the abundance of some critical mineral input can represent a window of opportunity (see for example Perez and Soete, 1988, and Perez, 2008 or, on the contrary, relatively sticky country-specific, technological capabilities will continue to represent the core driver of technological advantages and gaps

(Cimoli et al., 2008).

This study addresses the production and diffusion of green hydrogen, as a potential new clean energy paradigm, assessing the technological knowledge involved in its generation, in terms of processes and technologies, looking at the production and trade of the inputs and artifacts necessary for its production. To identify the technological knowledge bases, we reconstruct the alternative hydrogen production processes, each of them associated to a constellation of technologies (Freeman, 2007) at different maturity stages. Thus, grounded in the notion that countries' asymmetric positioning in international arena reflects technological differences arising from underlying processes of capabilities accumulation (Cimoli & Dosi, 1995), and given the lack of comparable national product-level datasets, we use trade data (BACI, CEPII database) for the empirical analysis. International trade flows are employed to examine the patterns of specialisation and diversification in green hydrogen of 119 countries over the period 1995-2020. Green hydrogen production is proxied by the international trade of the artifact more relevant for its production, namely the electrolyser. We build time-varying product-country level indicators that enable us to comparatively assess the positioning of each country in the domains of technology and trade. By coupling information from trade volume, and relative comparative advantages, we aim to identify the changing patterns of lags and leads. Remarkably, the role of China emerges as a new dominant player in the export space, competing with traditional leaders such as Japan, Germany and overcoming the United States.

To assess dependence patterns behind electrolyser production, merging classifications from European Commission (2020b) and US Department of Energy (2022), we get a comprehensive list of raw materials defined as critical (European Commission, 2017) in order to build the electrolyser. The attribute "critical" refers to a combination of importance and availability (production bottlenecks) of the material of interest. Next, we build a time-varying country-product indicator of raw material dependence. When we couple the positioning of each country in the electrolyser "space" vis-à-vis the raw material "space" a more nuanced picture emerges: many of the top specialised exporters present a relatively high degree of autonomy in the acquisition of raw materials essential for building and operating electrolysers. Over a twenty-five-year time horizon, we do find a pattern of negative comovement between specialisation in hydrogen production and dependence upon raw materials. This pattern is exemplified by countries like Japan, Korea and China, which present an ascending trend. On the contrary, Europe shows a downward trajectory: while some traditional players, such as Germany and Italy, maintain a stable position over time, others, like France and the Netherlands, are experiencing a decline. The U.S. presents both a relatively low degree of specialisation and a moderate dependence on raw materials. Finally, among small emerging economies in the electrolyser sector, we observe a few countries with an initial low dependence on raw materials associated to a subsequent path toward specialisation. This is the case of Estonia, Lithuania, Czechia, Philippine. However, we do not find any strong evidence that the abundance of critical raw materials paved the way for a "window of opportunity" for developing countries.

Our findings can be summarised as follows. First, the production of electrolysers is still at a relatively infant stage, although we record its presence in international trade since 1995. Throughout the period of analysis, we do not find any major expansion of trade flows. Moreover, their production appears rather scattered and mainly based on country-level positioning in the traditional energy arena. No clear convergent path toward green hydrogen production appears. Remarkably, some established dominant players in the Western part of the world fall behind as compared to the Asian Far East. In that, green hydrogen production is hardly becoming the dominant new emerging paradigm. On the contrary, a quite timid and delayed process in its technological advancements and production is underway, despite the urgency to tackle climate change.

Is the delayed production and diffusion of such a technology associated with inherent bottlenecks of the technology itself? Or is it possibly due to the strategy of the actors involved in the energy sectors? Or, finally, is its cause rooted in the lack of a "mission-oriented" policy (Dosi et al., 2024)? While this paper does not address in any detail the former two questions, we point out, in our conclusion, the role played by national industrial policies. Indeed, those countries presenting an emerging role in the electrolyser arena are both financing and implementing national plans for green hydrogen production. In particular, the EU has recently approved a community policy framework for hydrogen (European Commission, 2020a) to promote hydrogen production, but no specific attempt is made in the direction of green hydrogen.

The remainder of the paper is structured as follows: Section 2 discusses the emergence of hydrogen production as an ensemble of potential new technological paradigms, Section 3 nests our interpretation of the evidence within the structuralist and evolutionary literatures, Section 4 describes data and methodology, while Section 5 discusses our results. Our conclusions and policy implications are outlined in Section 6.

2 A new energy paradigm? History and technological trajectories of hydrogen

2.1 Hydrogen production: historical perspective

The evolution of the energy sources might be seen as a history of progressive decarbonisation (Rifkin, 2002). Considered as a stepwise process, the fossil sources of energy (coal, oil and gas) are molecules made by carbon and hydrogen. A progressive historical switching of the energy source regime from wood to coal, and then from oil to gas, has entailed a decline of the carbon to hydrogen ratio, towards more efficient sources, which also emit less CO_2. For example, the lightest hydrocarbon is methane (CH_4), having only one atom of carbon (C) over four atoms of hydrogen (H), while petrol (C_8H_{18}) has a much higher ratio. From this efficiency trajectory measured as C/H, hydrogen represents the missing stage towards the decarbonisation of the energy system, as it would entail zero carbon emissions in its use, and therefore it can potentially considered as the energy source for the future. A vision that contributes to the "hydrogen myth" (Szabo, 2021).

From a historical perspective, the use of hydrogen as energy carrier and chemical feedstock is not a recent discovery. It goes back to the early developments in chemistry. In 1761, Robert Boyle discovered hydrogen from reacting iron filings and dilute acids. In 1776, Henry Cavendish identified hydrogen (the "inflammable air") as a unique substance. In 1783, Antoine Lavoisier was able to extract it, naming the gas hydrogen. Since its discovery, different production methods and applications were developed. In 1835, Michael Faraday stated his laws of electrolysis, on the principles behind water decomposition by electric current, and around fifty years later, commercial electrolysis cells were available (Hoffmann, 2019).

Hydrogen was initially produced by water electrolysis, however, the process was quite inefficient and expensive. The industrial production and applications increased during the first half of the 20_{th} century, mainly after the expansion of the demand as an intermediate product for synthetic ammonia production, via the Haber-Bosh process. During this period, the more polluting processes of coal gasification and methane reforming came as cheaper alternatives (Gabriel et al., 2022), and they became the dominant technology. During World War II, hydrogen gained momentum for the production of explosives and synthetic fuels. Afterwards, the gas played a significant role in the Apollo mission. It was used to fuel the Saturn V rocket, which carried the spacecraft into space, and to generate electricity onboard via fuel cells releasing, as by-product, water that was consumed by the astronauts.

In the 1970s, interest in hydrogen grew as a consequence of the oil price shocks, petroleum shortages, and environmental awareness, particularly regarding the automotive-related pollution. This enthusiasm led to the creation of new projects and associations, including the International Energy Agency Hydrogen and Fuel Cell Technology Collaboration Programme in 1977, and the International Journal of Hydrogen Energy in 1976 (Scita et al., 2020). Hydrogen-powered aircrafts, automobiles and buses were produced during this period. However, these types of product have never achieved large-scale market penetration due to the high-cost barriers and the technological lock-in within the integrated system of production, distribution and utilisation based on fossil-fuels. As a matter of fact, private research efforts by leading players in the automotive and the oil sectors have materialised over time, exploring several hydrogen alternatives. General Motors in 1970 was the first company to use the expression "hydrogen economy" imaging the fuel of the future, a position that was remarked as corporate long-term vision in 2000 (Rifkin, 2002). Others, as Shell Group and Daimler-Chrysler in Iceland, created join ventures with public institutions to scout opportunities for hydrogen development.

During the 90s, some countries, particularly Japan, and institutions, as the Fraunhofer

Institute in Germany, have carried out investments for hydrogen projects. Also, attempts of hydrogen powered public transportation were performed at the end of that decade at the municipality level in some countries (Rifkin, 2002). In general, the “hydrogen utopia” emerges as an energy solution for the growth-decarbonisation trade-off (Szabo, 2021). The U.S., during the G.W. Bush presidency, launched the National Energy Policy Development Group in 2001 to explore and promote the potential of hydrogen as a fuel. However, shale gas soon provided an easier and relatively cleaner fossil fuel alternative, despite the overall environmental damage. Similarly, back into 2002, the European Union declared hydrogen as clean energy for growth and energy autonomy (Szabo, 2021).

2.2 State of the art and trajectories of hydrogen production technologies

Hydrogen seems to be an essential element for the decarbonisation of the economy. In an electrified system based on renewable energy, which is flow-based, hydrogen would be a stock element, storing the surplus of renewable electricity not absorbed by the grid. It would allow deferred consumption, increasing energy security and the resilience of the energy system (IEA, 2019a). Hydrogen would also decarbonise those energy-intensive sectors for which the electrification is not yet viable, especially cement and steel production, so called hard-to-abate industries, which are coal-based and account for the 7% of emissions worldwide (IEA, 2019b). The third application is the replacement of fossil sources as feedstock in chemical and fuel production, particularly ammonia, which is used by several industries and is an essential element for fertilisers production.

Hydrogen (chemical symbol H) is one of the most abundant elements in the universe, but it exists mainly in molecular form, combined with other elements, such as water, H_2O, and all the hydrocarbons, like methane CH_4. It is an energy carrier, that means that is not an energy source *per se*, but it embeds energy, allowing its storage and transport. Similarly to fuels, to be used as power sources, it must be burned or transformed into electricity by a Fuel Cell (FC), producing as residual emission only water. The production process consists of the separation of the molecules of water or hydrocarbons and the isolation of the element. Production is energy-intensive and the use requires some conversion steps resulting in energy losses. To enable the use via FC, hydrogen would be rather pure, as obtained from the most advanced techniques, otherwise purification is an additional stage in the value chain, before compression, storage and transport. Moreover, hydrogen is very light and volatile, and safe to handle only in a strict range of physical conditions (temperature and pressure) due to its high flammability. Therefore, the phases of storage and transport are more difficult, inefficient, and energy-consuming with respect to other gases, and so they require the development of new and more technically advanced solutions. However, it could be combined with other elements such as carbon and nitrogen to make hydrogen-based fuels (like e-fuels and ammonia) that are easier to handle for transport and that can be used as feedstock in industry (IEA, 2019a). By enabling the conversion of the grid electricity into other energy carriers – gases, liquids, and chemical feedstock (defined as $Power - to - X$, where the X can be hydrogen or other carriers), hydrogen has the potential to connect different segments of the energy system, a process known as *sector coupling*, increasing the total efficiency (IEA, 2019a). The gas is also more powerful and efficient with respect to the other energy carriers. Most of all, its application as power source entails a significant reduction of the environmental externalities from energy use, given the absence of greenhouse gases emissions during consumption, and also in the production phase when it occurs via electrolysis (IEA, 2019a). Therefore, it has both a huge potential for decarbonisation, together with some important drawbacks that increase inefficiencies and cost, hampering the rollout in use and production.

Today, hydrogen is almost exclusively produced from fossil fuels without carbon capture, as a consequence, it is responsible for around 1.5% of the total CO_2 emissions (IEA, 2022a), approximately the emissions of Indonesia and United Kingdom combined (IEA, 2019a). This emission contributions are just due to catering almost exclusively for the conventional applications (refinery and chemicals) and not for energy consumption. At the current stage, the conventional methods of hydrogen production are from fossil fuels: gas reforming and gasification of coal and biomass. The dominant technique is steam methane reforming (SMR) which alone accounts for the 75% of production worldwide, while coal gasification is the most diffused process in China. Water electrolysis, that is, the “green” technique, constitutes only 4% of total production (Gabriel et al., 2022).

A proper market for hydrogen as an energy source still does not exist, although the hydrogen industry is well-established and caters for several industrial sectors that employ it as a feedstock, therefore the production often occurs on-site. The main applications are the production of ammonia (which account for the majority of the current hydrogen demand), methanol and steel. Other industrial applications include various processes in electronics, especially semiconductors, glassmaking, and downstream chemical industries. A significant demand comes from the refining sector that uses hydrogen to remove impurities and to upgrade heavy oil fractions into lighter products. China and the U.S. account for half of the hydrogen demand for refining, which is raising due to their increase in the unconventional oil production, which requires more refining (IEA, 2022b). Demand for hydrogen in new applications, such as heavy industries, transport, fuels and power generation, account for less than 1% of the final demand (IEA, 2024). In 2024, demand for refinery increased by 4% compare to the record year of 2022. While the total demand grows due to industry trends for traditional applications, rather than policy effectiveness (IEA, 2024).

Relying on specialised literature (Gabriel et al., 2022; Kovač et al., 2021) and institutional reports from IEA (International Energy Agency) and IRENA (International Renewable Energy Agency), we proceed to a synthetic description of the current, most common hydrogen production technologies. The hydrogen resulting from different processes is labelled with different colours, according to the taxonomy proposed by policy-makers (Erbach

& Svensson, 2023), deriving from the overall contribution to CO_2 emissions.

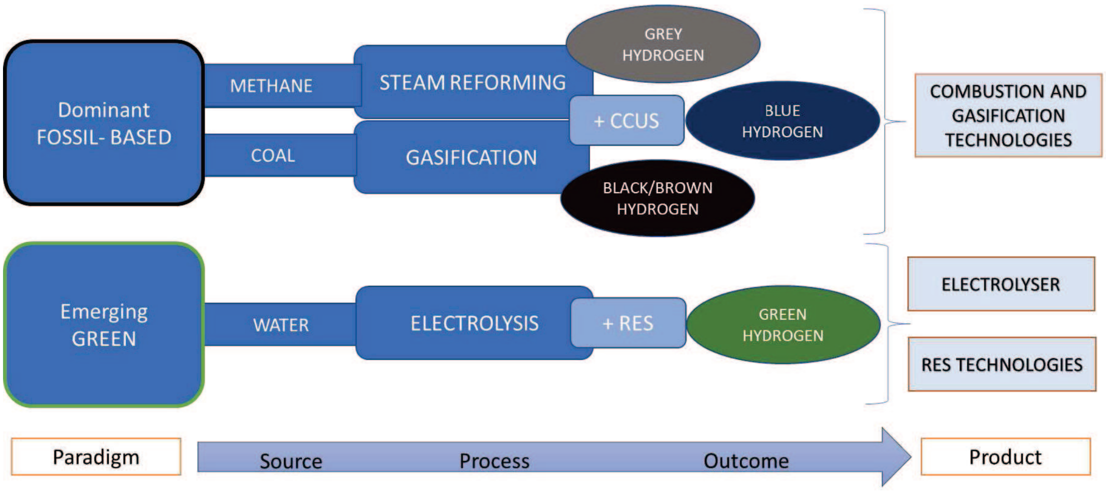
Hydrogen can be produced using a potential constellations of technologies and procedures, including:

- Steam Methane Reforming (SMR): it involves reacting natural gas (methane) with high-temperature steam to produce hydrogen gas and carbon dioxide as a by-product. It is the most common technology for producing the so-called *grey hydrogen*. If the CO_2 emission at the end of the process are captured (by CCUS technologies), we referred to the product as *blue hydrogen*.
- Electrolysis: it exploits electric current passing through water to split it into hydrogen and oxygen. It is the only viable way to produce *green hydrogen*.
- Biomass and Coal Gasification: coal or biomass feedstocks, such as agricultural residues, energy crops, or organic waste, are heated in the absence of oxygen to produce a gas mixture called syngas. Coal gasification produces *black hydrogen* from bituminous coal, or *brown hydrogen* from lignite. When the CO_2 of the process is captured and stored by CCUS technologies, the outcome is part of the *blue hydrogen* mix.
- Pyrolysis of hydrocarbons: it produces *turquoise hydrogen* and solid CO_2 as by-product, without emission; it is not yet a mature technology.
- Nuclear Hydrogen: uses high-temperature nuclear reactors to produce heat, which is then used in various processes like electrolysis or thermochemical processes to generate hydrogen, called *pink* or *purple hydrogen*.

There is a variety of hydrogen colours associated to different production processes and sources. Other production techniques, as photolysis and thermochemical water splitting, are promising for their environmental impact, but still in the early stages of development. When hydrogen is fund pure in nature, it is called *white*. Given the underlying production process above described, we consider the production of hydrogen from hydrocarbons (coal gasification and SMR producing the *black* or *brown*, and the *grey* hydrogen) and from water electrolysis (*green* hydrogen) as two competing technological paradigms, where the former is part of the dominant polluting paradigm and the latter is embedded into an emerging decarbonised one. The different types of electrolysis are instead the alternative technological trajectories within the green paradigms, characterised by different readiness levels and trade-offs in terms of efficiencies and resources requirements. Figure 1 presents a synthetic descriptions of hydrogen trajectories, sources, processes, outcomes, and technologies.

2.3 In search of a new paradigm: green hydrogen trajectories and critical raw materials dependence

Green hydrogen is produced by water electrolysis through electricity from renewable energy sources (RES). Water electrolysis associated to electric current of the grid, usually produced by fossil fuels, is not considered in the analysis, since it would have a higher environmental



Source: Authors' elaboration on the base of IEA information.
CCUS refers to Carbon Capture Usage and Storage processes, RES refers to Renewable Energy Sources powering the Electrolysis process. The fossil-paradigm uses hydrocarbons associated to different process that are powered by those called by the authors ”Combustion and Gasification technologies”, producing Grey and Black hydrogen. When the emissions from these productions are captured by CCUS, hydrogen is called blue and considered as low-carbon. Associated with the emerging green paradigm is the process of water electrolysis powered by RES, which produces green hydrogen.

Figure 1: Technological paradigms of hydrogen: processes and technologies

impact than the direct use of hydrocarbons (Bhandari et al., 2014). There are several types of electrolysis that can be used for hydrogen production, each of them associated to different levels of efficiency, technological readiness, raw material use, purity of the gas, temperature and stability of the electricity flow.

- Alkaline Electrolysis: is the most diffused method of hydrogen production from water, accounting for 60% of the current manufacturing capacity (IEA, 2022b). It is a mature technology, suitable for large scale production, which produces hydrogen 99.9% pure (not enough for the majority of applications), that can be increased with a purification process (Bhandari et al., 2014). However, it is the least efficient and the most energy-intensive available process.
- Proton Exchange Membrane (PEM) Electrolysis: is more efficient than the alkaline type, it requires less electricity and responds well to power fluctuations typical of renewable sources, while producing very pure hydrogen that does not require supplementary purification steps. However, it has higher investment costs due to the need for noble metals in the production of the electrolyser, and a shorter lifetime due to high temperature requirements. The technology is less mature, and the production capacity needs to be increased . PEM electrolysis is often used for smaller-scale hydrogen production, such as domestic use and fuel cell vehicles. A variant of the process is the Anion Exchange Membrane (AEM) electrolysis, which does not require noble metals as catalysts (IEA, 2022b).

- Solid Oxide Electrolysis (SOE): it could be more efficient than PEM, but it requires very high temperatures, which entails a fast deterioration of the materials and a resulting shorter life-cycle of the artifact. SOE is appealing especially coupled with high heat sources like geothermal energy. It currently operates in a laboratory scale.
- High-Temperature Electrolysis (HTE): HTE is similar to SOE, but it uses a different type of solid oxide electrolyte and operates at even higher temperatures. HTE would be the most efficient electrolysis technology, but is still at the research and development phase.

Overall, alkaline and PEM electrolysis are the most diffused methods while, as technology advances, other methods such as SOE and HTE would become preferable options for large-scale production. The projection shows that, by 2030, alkaline electrolysers should account for 64% of manufacturing capacities, followed by PEM (22%) and SOEC (4%) (IEA, 2022b).

Different types of electrolysis are associated to different costs and supply risks, given the presence of some critical raw materials for their production and use. Some of them, like the alkaline type, do not have stringent requirements in terms of raw materials for production, however, they must be integrated in a RES energy system and supplied with a stable electrical flow; so (lithium) batteries are required to integrate the electrolyser into the RES system. Other types of electrolysis, such as PEM, deploy some critical raw materials for their components, characterised by higher cost, but less stringency on other characteristics, as the stability of the electric flows (Patonia & Poudineh, 2022). While alkaline electrolysis is not exposed to significant risks, the presence of some rare earth elements and precious metals may hamper the large scale development of PEM electrolysis (Kiemel et al., 2021). The different electrolysis trajectories, their efficiency, raw material requirements and technological readiness are summarised in Table 1.

Type	Efficiency	Raw materials	Technological Readiness
Alkaline	Medium	Low	Mature
PEM	Medium	High	Commercially available
AEM	Medium	Medium	Demonstration phase
SOEC	High	High	Market uptake
HTE	High	High	R&D

Table 1: Different trajectories of electrolysis for green hydrogen production.
Source: authors' elaboration based on IEA information

Among the raw materials required for the production of electrolysers, there are some that are not yet in short supply, as copper or nickel, but would be used more intensively with the spread of electrification. Others, however, are already scarce or subject to major production bottlenecks (European Commission, 2020b). Overall, it seems that the raw materials requirement is as stringent as the novelty and the efficiency of the proposed technological solution, as common feature of ‘green’ technologies (De Cunzo et al., 2023; Yunxiong Li et al., 2022). This raises serious doubts about the sustainability of these technologies that produce no emissions in use but have a disruptive impact on territories and communities in the raw materials extraction phase (Dorn et al., 2022).

2.4 Actors behind the transition and their resistance: the role of policy

After the first National Hydrogen plan by Japan in 2021, more than 30 countries have adopted or prepared national strategies. Several national recovery packages from the pandemic include measures to foster hydrogen production, including most of the European countries, and European Union, Australia, Canada, Chile, Morocco, and China. National strategies are heterogeneous in terms of resources, targeted emissions reduction, and source of hydrogen (Cheng & Lee, 2022). The US launched, in 2022, the Inflation Reduction Act (IRA) which contains some elements of industrial policy, as long-term subsidies for clean technologies deployment, discriminating for foreign products (Kleimann et al., 2023). IRA allocates subsidies for hydrogen production, designed to be higher for green hydrogen with respect to the fossil-based kind. The European response to IRA is the Net-zero Industry Act (Kleimann et al., 2023), proposed as an industrial policy for green manufacturing which should be coupled with the RePowerEU act (European Commission, 2022), the energy policy design aiming to accelerate the rollout of renewable energy and to build strategic autonomy with reference to both fossil fuels and raw materials supply. Europe is boosting hydrogen market expansion providing several instruments, subsiding schemes within the REpowerEU, the Just transition founds, and the European Hydrogen Bank. Within the European Hydrogen Bank it has been launched a mechanism to match suppliers and consumers and help the creation of a market for hydrogen. The European Commission fosters public-private partnership like the Clean Hydrogen Alliance to guide the transition to low-carbon hydrogen, however, hydrogen lobbying in Europe seems quite strong and guided by the major oil corporations (Szabo, 2021). While it is important to include the actors effected by the policy in the process of technical change (Chang & Andreoni, 2020), the emerging of green hydrogen is hampered not only by high costs and uncertainty, but also by the incumbent fossil-based industry. Notably, the power of the actors involved in the process of technical change influences its direction (Dosi, 1984).

Development of green hydrogen requires actions quite beyond the infant industry argument, starting from the end of fossil production subsidies together with cost reduction policies for renewable electricity (Andreoni & Roberts, 2022; Bianco & Blanco, 2020). Despite regulation might constraint technological development (Jaffe et al., 2003), it is a strong industrial policy that allows for a radical transformation of the productive system, mixing technological push and demand pull instruments. Above all, climate policy should abandon the principle of technology neutrality (Jacobsson et al., 2017), which would implicitly favour technical development inside the carbon locked-in system (Unruh, 2000) and, relatively to hydrogen technologies (Aisbett et al., 2021), would oust the green one. Well designed industrial policy is also of the *anticipatory* type, with a clear announcement of public priorities and the promotion of a transition where not only technical change is fostered encouraging the entrance of new actors, but also challenging the incumbent to exit (Andreoni & Roberts, 2022; Chang & Andreoni, 2020). For example, Germany early subsidies to the RES industry, stimulated production and created also a strong segment in the energy industry advocating for clean energy policy, which now is a powerful stakeholder against conservative interventions compliant towards fossil fuels (Jaakkola et al., 2023; Zimmer & Hoffmann, 2023). Power constellations shift policy focus from green to low-emission hydrogen (Dorn, 2024). Low-emission hydrogen is also the blue kind, produced from coal or methane collecting the carbon dioxide emissions by Carbon Capture, Usage and Storage (CCUS) processes (Noussan et al., 2020). Part of the scientific literature warns about the risk of underestimating the emission embedded in blue hydrogen production, especially the fugitive methane emissions, and those needed to power the CCUS process (Bauer et al., 2022; Riemer, 2022). Others find no justification on climate grounds for blue hydrogen given the higher costs and emissions with respect to the direct burning of gas or diesel (Howarth & Jacobson, 2021). Moreover, blue hydrogen is not disruptive but embedded in fossil-based processes (Kovač et al., 2021), and therefore part of the dominant technological paradigm, which is the main obstacle to the establishment of green hydrogen.

3 The evolutionary and structuralist perspectives on the decarbonisation transition

The technological and market boundaries of the decarbonisation transition, together with its socio-economic implications can be framed inside earlier contributions in the evolutionary and structuralist literature. A central attribute of industrialisation has been the increasing utilization of energy. Industrial revolutions may be read as a widespread introduction of techniques for the exploitation of the newest energy source, and technical change as a mediator between the energy supplies and the changing needs of the industrialised society (Rosenberg, 1982). The change of the energy regime in history is accompanied by a constellation of innovations around the new energy source and has been supported by a series of new institutions (Freeman & Louçã, 2001). As shown by the transition from traditional energy sources to fossil fuels, energy shifting is not a single event, but rather a complex phenomenon, involving numerous sectors and services which change at different paces (Fouquet, 2010). This interconnection (*feedback loops* among industries, and their interrelations with society and institutions, makes the system reluctant to change, and an ensuing decarbonised energy transition more difficult to reach (Perez, 2016).

Although a phase of technological transition might open a window of opportunities for latecomers (Perez & Soete, 1988), the emergence of new countries in the sectoral arena depends on their response on the base of their local knowledge and capability accumulation patterns (Bell & Pavitt, 1993; Cimoli & Dosi, 1995; Lee & Malerba, 2017). Moreover, the outcome of a technological transformation is deeply influenced by the economic interest of the actors participating to the R&D process, and more generally to the innovation arena (Dosi, 1984). The historical case of the development of electrical infrastructures over the late 19_{th} century, the so-called "battle of the currents" (Hughes, 1983); David, 1992, reveals a striking similarity to the current failure in decarbonising the system. During that period, the established and more efficient direct-current (DC) technology was challenged by the introduction of the less efficient and more dangerous alternating-current (AC) technology. In the end, the latter won the technological race also because it was suitable for long-distance transmission, allowing for centralised energy generation, and therefore the emergence of large monopolies in production and distribution (Unruh, 2000). This is an example of competition between alternative technologies characterised by increasing returns and a consequent lock-in of the system due to network effects and path dependence dynamics (Arthur, 1989).

Technological progress is a discontinuous process, alternating between periods of accumulation of knowledge and capabilities for the advancement on a technological trajectory, around the established technological paradigm, and periods of "creative destruction", reshuffling capabilities and power around a new paradigm (Dosi, 1982; Malerba & Orsenigo, 1995; Nelson & Winter, 1982). Learning is essential to the innovative process, and it is mainly an attribute of individuals and organizations. The firm is the locus in which individuals can access, absorb and exploit knowledge, within mechanisms of codification and learning by doing and using, the formation of routines and heuristics, and the building of capabilities at the organizational level (Cohen & Levinthal, 1990; Dosi et al., 2008). Therefore, the ideal dimension to study technical change is the firm (Rosenberg, 1982).

However, the differences in technological levels and innovative capabilities are factors that explain trade performance of countries (Cimoli & Dosi, 1995; Dosi et al., 1990). The traded products, i.e. the technological *artifacts*, are the firm-, sectoral-, country-specific results of the organizational transformations of the technological knowledge (Pavitt, 1998). The presence of country-specific institutions and organizational arrangements of the economic relations, that support and shape technical change, allows for the assessment of capabilities and technical change at the country level. The Evolutionary perspective suggests that absolute advantages is the privileged measure which accounts for country-specific capabilities to exploit the innovative efforts (Dosi & Tranchero, 2021). However, grounding international performance on evolutionary dynamics at the micro level, relative measures, such as comparative advantage, might reflect the learning process, which includes innovation, imitation and organizational learning, that are heterogeneous across countries and sectors (Dosi et al., 1990). Comparative advantages can be a measure of productive capabilities, as their are acquired through the production for domestic market, according to the theory of representative demand (Linder, 1961), and they do not necessary result from countries factors' endowments (Cimoli et al., 2008).

The evolutionary theory shares with part of the structuralist literature the foundation of growth and development on the innovative capacity, which result from learning capabilities (Cimoli et al., 2008; Dosi et al., 1990). When the system changes, the pattern of structural change can be observed from a country perspective (Cimoli & Dosi, 1995), given that countries positioning in international trade reflects their technological differences, which ultimately stems from the accumulation of capabilities by countries and firms (Dosi et al., 1990). It is, therefore, the capability and knowledge accumulation processes, upon which the expansion of the manufacturing sector relies, that leads to countries development and affects the structure of trade (Dosi & Tranchero, 2021).

Indeed, countries specialisation in economic activities characterised by greatest opportunities of learning and demand growth seems to be a good recipe for development (Dosi et al., 2021). This is a good recipe also according to the structuralist-dependency school, that focuses on the power asymmetries in the international arena, as structural determinants of the type of specialisation (Kay & Gwynne, 2000). The specialisation in technological poor products and primary commodities lead to structural dependency of these countries from foreign import, given the lower income elasticity of demand for those products (Prebisch, 1962). This is especially relevant considering the importance of raw materials for the decarbonisation technologies and the fact that they are located mostly in the South of the world (Kowalski & Legendre, 2023). In a South-North or Center-Periphery dual view of the world, countries in the Global South produces primary commodities catering for the need of the most complex economies. Primary commodities specialisation could lead to Dutch disease, as an increasing demand for raw materials might induce rapid price growth for the exporting country due to the depreciation of its currency, resulting in a loss of competitiveness in other sectors with larger productivity gap (Cimoli & Porcile, 2014). Unequal terms of trade penalise the periphery not only in terms of economic exchange, but also in terms of ecological exchanges of those countries specialised in extractive activities (Hickel et al., 2022; Piñero et al., 2020).

In the following, structuralist and dependency theories are adopted as lenses to interpret the asymmetric relationship among countries (Arsel & Dasgupta, 2015; Fischer, 2015; Kay & Gwynne, 2000; Kvangraven, 2021) to study the transition towards decarbonisation. This choice is also motivated by the fact that also hydrogen specialisation could be a latecomer development strategy (Pegels & Altenburg, 2020). Learning, for a less developed country, starts with the adoption of foreign technology. The development of the capabilities through learning-by-using, and then imitation are fundamental features of late successful industrialisation (Cimoli & Dosi, 1995; Dosi et al., 1988).

4 Data and Methods

Studies on the emergence of green technologies are abundant. Those employing trade data map green products space, examining the pattern of diversification and specialisation of countries (Mealy & Teytelboym, 2022; Vona & Bontadini, 2022) and, using also patents to map the innovative capacity (Sbardella et al., 2018). Recent developments of the literature are going towards the understanding of the role of critical raw materials in influencing the direction of technical change (Yunxiong Li et al., 2022), and the production of "green" technologies (De Cunzo et al., 2023). The bottleneck of critical raw materials is also addressed, in line with the European policy, to phrase the terms of strategic autonomy and technological sovereignty (Caravella et al., 2021; Caravella et al., 2023) for mitigation technologies and solar panels, using empirical evidences from both trade and patent data.

With regard to hydrogen, instead, there are very few empirical analyses, mainly because there is no established market and there is no clarity on the future of the industry in relation to the energy transition, as some models try to project (Antweiler & Schlund, 2023). For instance, some studies (Moreno-Brieva et al., 2023) use patents to show that the fossil-based production techniques are still the most subject to innovation. Some policy analyses, focusing on production, examine the emerging regional geographies of the global hydrogen rush (Eadson et al., 2022) and countries' internationalisation strategy (Quitzow et al., 2024). Other studies focus on future application of hydrogen, such as Sadik-Zada et al. (2023), which discuss the potential of hydrogen as greener alternative to the lithium-based solutions for powering mobility. At the current stage there is, however, a lack of large-scale empirical detection of the positioning of countries in the technological-trade space of green hydrogen, to understand the development of the market and country specialisation and dependence for its production.

4.1 Trade data for energy transition

We employ trade data from the BACI, CEEPI database (Gaulier & Zignago, 2010) at 6-digit level. We select the following products on the base of their HS code, as retrieved by different sources:

- Energy technologies components from Wind (2008);
- Electrolyser from APEC (2021);
- Raw materials for electrolyser production: we combine two sources from US Department of Energy (2022) and European Commission (2020b) to build a complete list of materials for electrolyser production and integration, we compare it with the list of critical raw material as defined by European Commission (2017) on the base of their supply risk and economic importance. Finally we retrieve the corresponding HS product codes from a source by OECD (2022).

We aim to cover the longest time span available in the dataset, therefore, we use the

RAMON Eurostat tables to convert the HS codes gathered from the listed sources - primarily HS 2007 - to the 1992 HS classification, thereby accounting for the longest temporal range of CEEPI data from 1995 to 2020.

Our methodology is meant to characterise the international positioning of countries with respect to hydrogen production technologies. We identify the electrolyser as the key technology to produce green hydrogen, mapped into exported flows. Given our empirical framework, the revealed comparative advantage, RCA (Balassa, 1965), is employed. We look at the relative positioning of countries as proxy for productive capabilities, with the caveat that these types of indicators do not fully represent countries productive heterogeneity. To address the biases due to the RCA information, we modify the traditional Balassa index to take into account the level of countries diversification, by discounting for the Entropy index (De Benedictis et al., 2009), as a down-weight of the specialisation measure. We then classify countries along the absolute dimension of export volume and the relative one of comparative advantage. In this respect, we identify leader, laggard and transitioning countries in green hydrogen space.

We then move to analyse dependency on raw materials, as autonomous or import-dependent source of specialisation. We consider raw materials needed to build the electrolyser and integrate it in a system of RES grid. We define a comprehensive list of materials defined as ”critical”, according to their economic importance and availability, by the EU Commission and the US Department of Energy. We build a class of products related to raw materials as described in the Appendix 4.2. Then, we construct an index of import dependence mirroring our specification of the RCA for import, that we adopt to classify countries along the dimensions of dependence on critical raw materials and specialisation in green hydrogen (electrolyser), to detect the degree of raw materials’ autonomy in the specialisation pattern.

4.2 Product identification

By making use of the BACII dataset, we proxy green hydrogen production with electrolyser products and compare the underlying trade flows with other potential substitute or complement energy technologies. Three groups of 6-digit products are used as benchmark.

- Combustion and Gasification technologies, which account for the carbon-intensive production of grey and black hydrogen;
- Electrolyser technology, for the Electrolysis process, accounting for green hydrogen production;
- Renewable energy technologies, which are complementary to green hydrogen, generating the electricity needed for electrolysis process.

The combustion and gasification technologies “bundle” would cover both Gasification and Steam Methane reforming processes of hydrogen productions (respectively *black* and *grey* hydrogen, both considered as *blue* hydrogen when coupled with CCUS processes). It has to be noted the lack, at least to our knowledge, of a list uniquely classifying the products behind such processes. Therefore, we adopted the list of products for biomass combustion and gasification, included among the renewable sources of energy in (Wind, 2008), given the close similarities of processes and products behind.

In addition, these groups of technologies are treated as if they were a homogeneous class of products. The electrolyser is instead an integrated system, embedding its components, so green hydrogen technological cluster is made only by one single product category. The other technological clusters are instead composed of pieces of technologies concurring to the production of renewable energy production processes (solar, wind, ocean, hydropower) and of biomass energy productions (combustion, gasification, biodiesel, bioethanol). To make the technological bundles comparable, we aggregate product-level data considering a weighted average of the grouped products (see the Appendix, A for more details). The Combustion and gasification cluster of technologies and the electrolyser are to be considered as competing processes and, thus, as *substitute* technologies. While the renewable energy bundle is a *complementary* technology to the electrolyser.

In the second part of the analysis, we look at the critical raw materials content of green hydrogen technologies (electrolysers and fuel cells). We combine the lists of critical and non critical raw materials from US Department of Energy (2022) and European Commission (2020b), necessary to build the different types of electrolyser, to integrate it in the electricity grid from RES, and used for fuel cells production. We retrieve the codes of the traded products from an official document (OECD, 2022) and build our final list of raw materials for green hydrogen production. For the empirical analysis, we select only materials defined as "critical" by the European Commission (European Commission, 2017), on the base of their economic importance and supply risk. Then, we compute the weighted average of critical raw materials (CRMs) products. Note that we include also those CRMs needed to integrate the electrolyser in the electric grid, and therefore to produce hydrogen from RES. For example, in the list, reported in the Appendix B, appears lithium, needed for the accumulation of electricity, but not for electrolysis in itself, since some electrolysis' processes require a stable electric current, as described in the previous section.

5 Results

5.1 International trade volumes, concentration and specialisation in the markets for energy

We start the empirical analysis by looking at the evolution of the international market of electrolysers, as a proxy of green hydrogen technology. As benchmark comparison, we include the renewable source (RES) energy technologies and the Combustion and Gasification technologies. The worldwide export flows of the three technologies of interest is presented in Figure 2. Over twenty five years, a stable and almost decreasing pattern in the last decades, in export flows of electrolysers is observable. After an increasing volume of electrolysers' trade from 2002 to 2011, the trend stabilises. While the overall slow-down in export flows after 2008 is line with the worldwide export trend, the volume of electrolyser trade as percentage of the world trade is 0.01%, while decreases in 2020 at 0.008%. We notice also a flat trend for renewable energy technologies trade, in line with the evidence related to their decreasing innovation rate (Caravella et al., 2021).

We then examine export concentration, looking at the number of exporting countries in each product/technology market. We calculate the Herfindahl- Hirschman Index (HHI) looking at the share of export of each country i of the total export of product k over time, according to the following equation:

$$HHI_{t,k} = \sum_{i=1}^{N} (\frac{x_{i,t,k}}{x_{t,k}})^2 \tag{1}$$

The evolution of the HHI for each of the three segments is presented in Figure 3. During the initial period, the three industries show a low to moderate degree of concentration, with an HHI between 0.1 and 0.2. Then, during the uptake of the market for renewables, we observe a divergence in the patterns of concentration, with renewable energy products reaching almost 0.5. The spike in renewable technologies is probably led by the solar sector. For that production, just a handful of countries, especially Korea at the beginning of the period and China afterwards, dominate the market of crucial inputs (IEA, 2022c). However, after a peak in 2008 the HHI of renewables returns to levels below 0.2.

To detect the reason of the almost stable, or declining, concentration, we study the global market shares composition of exports in electrolysers, in three selected points in time, 1999, 2008 and 2020. Results are presented in Figure 4. We observe that, over time, the number of exporting countries increases. The quota for some European countries (Swiss and France) shrinks, while for others (Italy, United Kingdom) remains stable. At the end of the period, the general picture is an erosion of Western countries shares, partly due to the rise of China's export growth. In addition, a more distributed representation of OECD countries, and the entrance of some developing ones emerge.

To examine the relationship between country income level and export of electrolysers, we plot the evolution of the shares of trade over time, considered as 5-year moving average, in Figure 5a by country income classes, top, and World Regions, bottom. In general, the export of energy products/technologies is dominated by high income countries. However, since 2008, a growing share originates from upper-middle income countries, that correspond to countries located in East Asia and Pacific. The Chinese export expansion drives the dynamics of the East Asia and Pacific Region, which shows growing international penetration, particularly in the electrolyser and renewable energies markets. While the other two industries are well established, the market for electrolyser is still at a relatively infant stage,

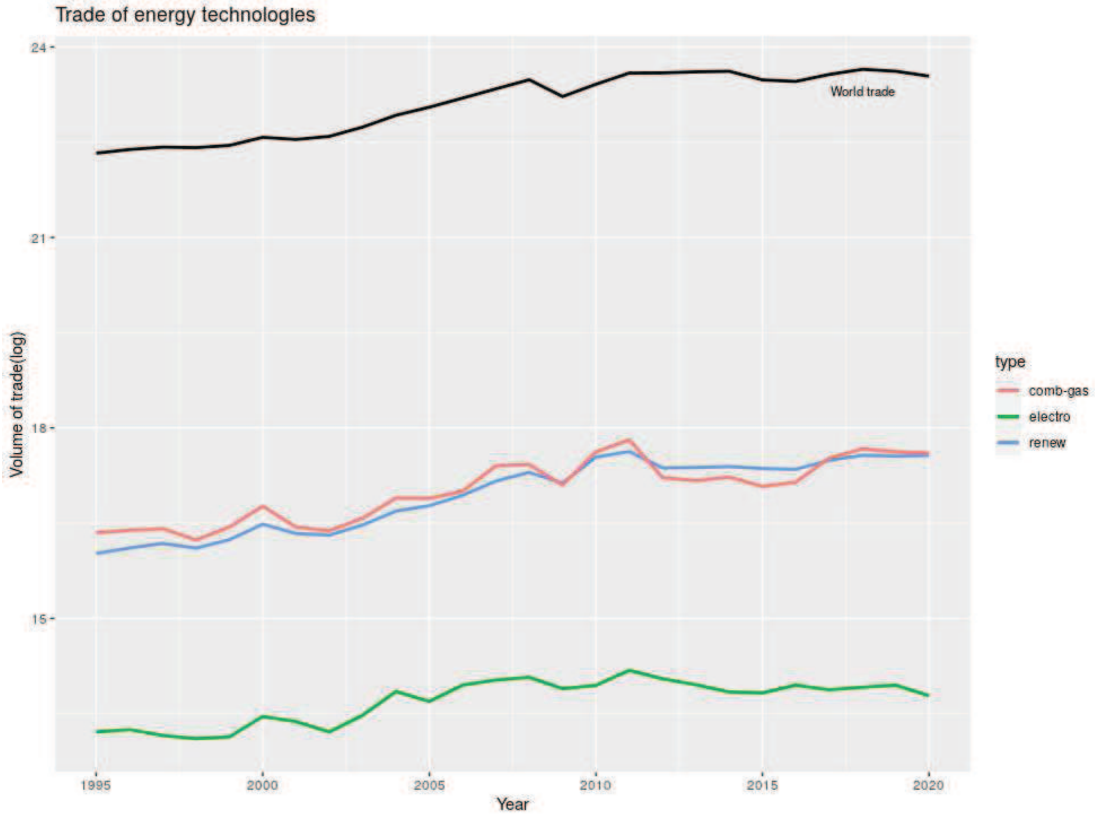


Figure 2: Worldwide export flows in energy technologies

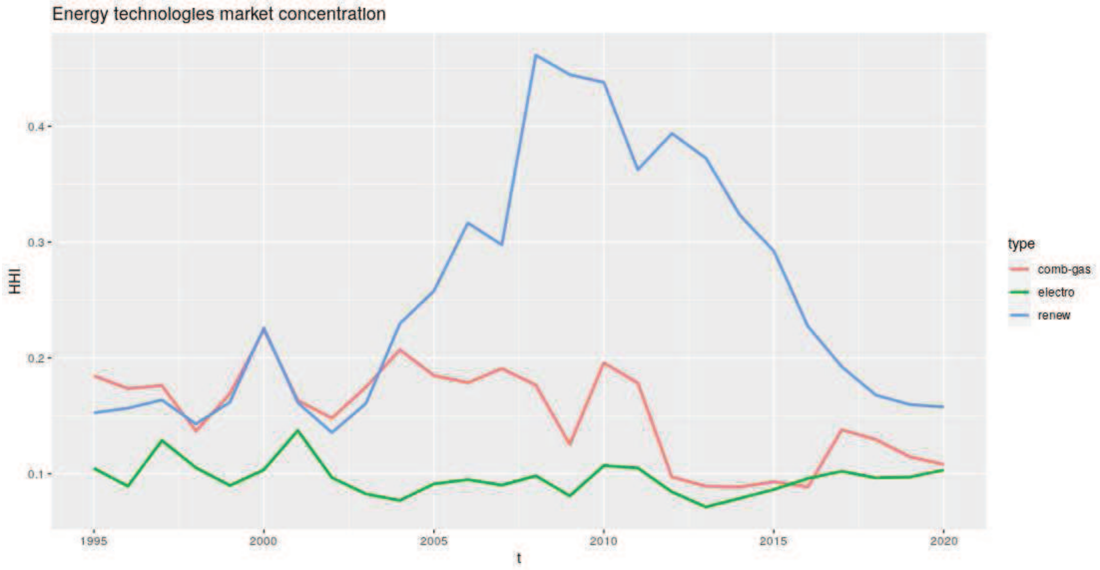


Figure 3: Export market concentration of energy technologies. HHI time evolution

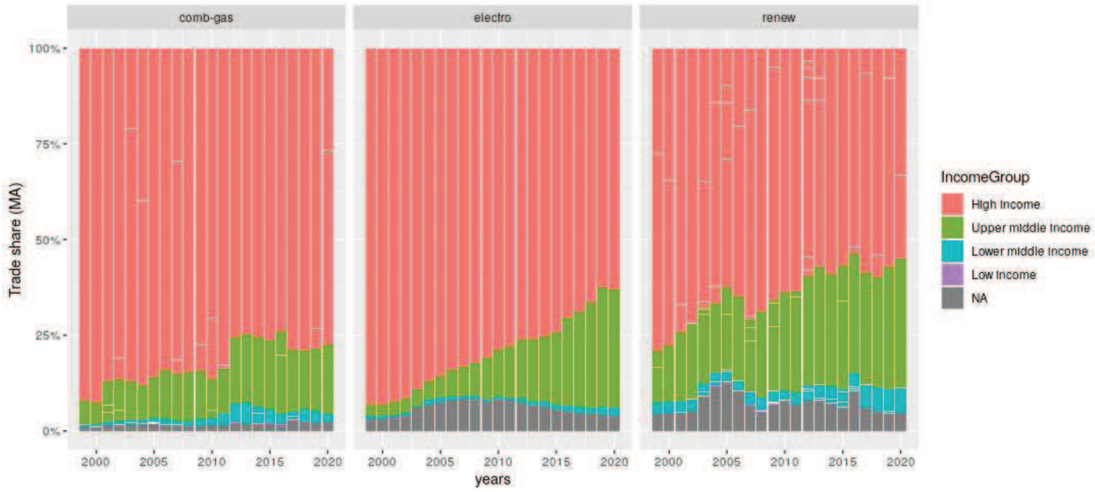
given the small fraction of its export volume. However, the composition of exporters in the renewable industry is similar. Remarkably, China and Japan are expanding their shares.

Figure 4: Shares of electrolyser export

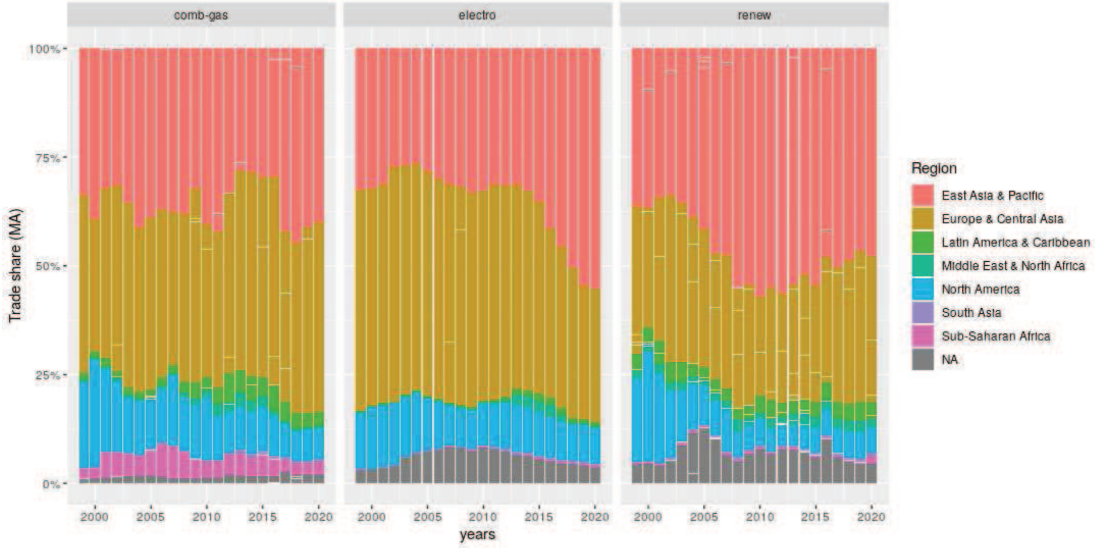
To assess the degree of specialisation, we calculate the Balassa index (Balassa, 1965), accounting for the Revealed Comparative Advantage of exporting countries in the international market. For each export value x, from country i of product k, at time t, considering X the country-level aggregation of x, the Revealed Comparative Advantage reads as:

$$RCA_{i,k,t} = \frac{\frac{x_{i,k,t}}{\sum_k x_{i,k,t}}}{\frac{X_{k,t}}{\sum_k X_{k,t}}} \tag{2}$$

Given the volatility of trade data, particularly when examining a single 6-digit product class such as electrolysers, we use a 5-year moving average (MA) of $log(1 + RCA)$. The Balassa index measures relative specialisation, influenced by a country's export structure and the global specialisation in a specific traded product. A spike in this index may indicate either an export surge for that product or a shock that reduces exports in other sectors (Hidalgo & Hausmann, 2009). To mitigate the impact of potentially spurious specialised countries, we adjust the RCA using an entropy index at the country level, which accounts for the structural diversification of a country's exports. We adopt the entropy specification by De Benedictis et al. (2009).



(a) By Income



(b) By World Region

Figure 5: Composition of export shares by income and geographical location

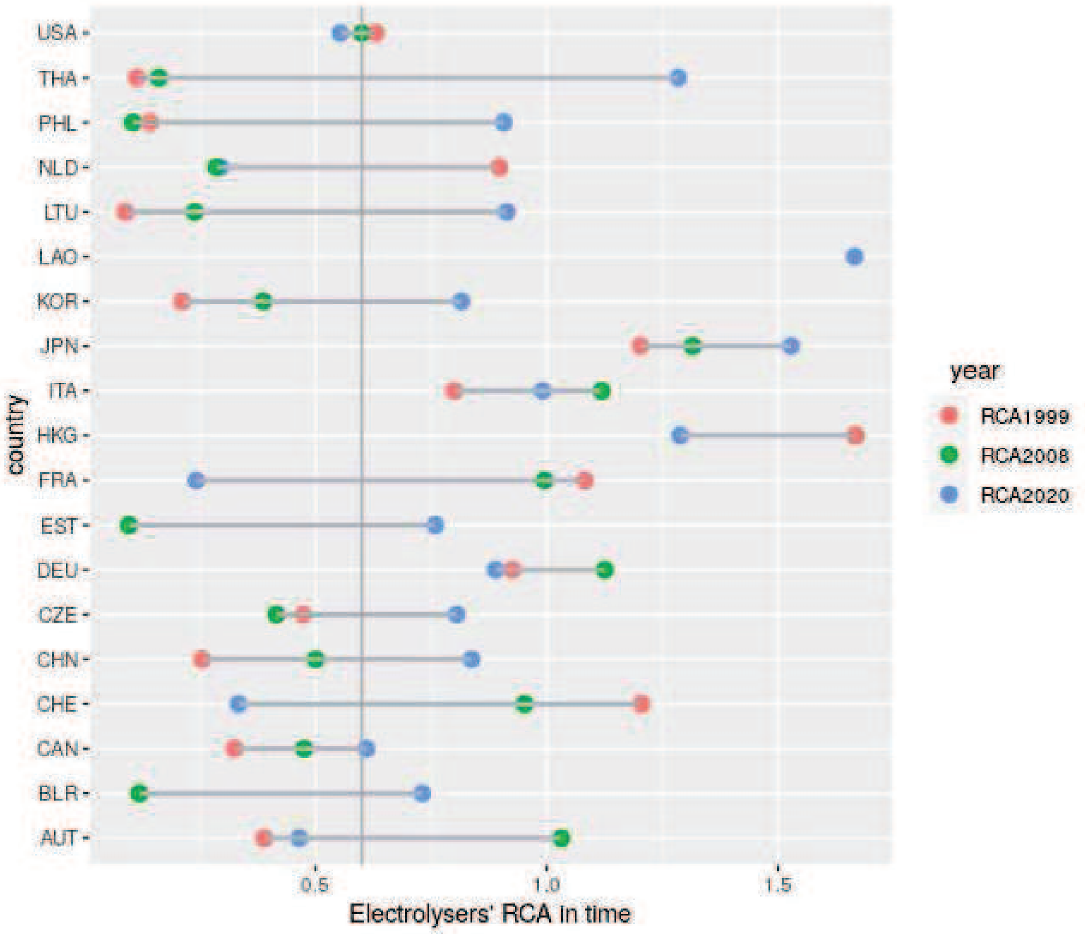
$$Entropy_{i,t} = \sum_{k=1}^{n} \left\{ \frac{x_{i,k,t}}{\sum_k \ x_{i,k,t}} \ ln \left[\frac{\frac{x_{i,k,t}}{\sum_k \ x_{i,k,t}}}{\frac{X_{k,t}}{\sum_k \ X_{k,t}}} \right] \right\} \tag{3}$$

The entropy index is introduced in the RCA, using the min-max normalisation of its 5-year moving average (MA). Thus, we adjust the RCA index by down-weighting countries by entropy. This implies that, if high specialisation in electrolysers emerges by the lack of exporting activities in other industries/products, indicating poor diversification in the country's export structure, the RCA is penalised. The adjusted RCA, RCA^{adj}, reads as follows:

$$RCA^{adj}_{i,t,k} = log(1 + RCA^{MA}_{i,t,k}) \times (1 - entropy^{MA,norm}_{i,t}) \tag{4}$$

The temporal pattern of RCA^{adj} is presented in Figure 6, that reveals some shifts in specialisation from 1999 to 2020. Initially, in 1999 (red dots), specialised countries in electrolysers export were primarily Western economies, including Switzerland, France, Germany, the United States, the Netherlands, Italy, Sweden, Japan, and the United Kingdom. Over time, China's RCA has grown significantly, reaching the threshold of specialisation, 0.6, after 2008. After 2008, there is a remarkable increase in the number of specialised countries, with some latecomers gaining competitive capacities. These emerging countries are primarily from Eastern Europe-such (Czech Republic, Slovenia, Estonia, Belarus, Serbia) and East Asia (Korea, Thailand, and the Philippines). Recently, Laos has also shown increased specialisation, although it may be an outlier of the statistical sample as no manufacturing producing firms were found to justify such competitive position. No African country appears to have developed a significant comparative advantage in electrolyser exports. Among OECD countries, some exhibit erratic RCA patterns, while Italy shows a growing and stable specialisation trajectory. Japan stands out with the strongest specialisation pattern over time, indicating robust capabilities and a substantial knowledge base. This is supported by Japan's early adoption of a National Hydrogen Strategy in 2017, and its longstanding investments and policy interventions dating back to the 1990s (Lundin & Eriksson, 2016). Our findings align with the evidence that Japan dominates patented inventions related to key technologies in fuel cells and electrolysers (IRENA & EPO, 2024).

To study the relationship between export specialisation and country size, proxied by the value of export, in Figure 7 we present the electrolyser space with respect to the dimensions of export value (as proxy of size) and the specialisation level. We picture the distribution of countries clustered in the four quadrants along the two dimensions, as the combinations of large/small size (larger/smaller then the median) and high/low specialisation (above/below 0.6). The top-right quadrant groups *leading* countries, characterised



The RCA considered in our specification is adjusted for entropy, as the 5-year moving average of the $log(1 + RCA)$. The vertical line is the specialisation threshold of 0.6. The colours of the dots correspond to the value of the index at the beginning (1999) middle (2008) and end (2020) of the period. For Netherlands the values for 2008 and 2020 coincide. For Hong Kong, the RCA of 1999 and 2020 are the same. Estonia and Belarus enter as electrolysers' exporter before 2008 and Laos before 2020.

Figure 6: Evolution in time of countries specialisation in electrolyser

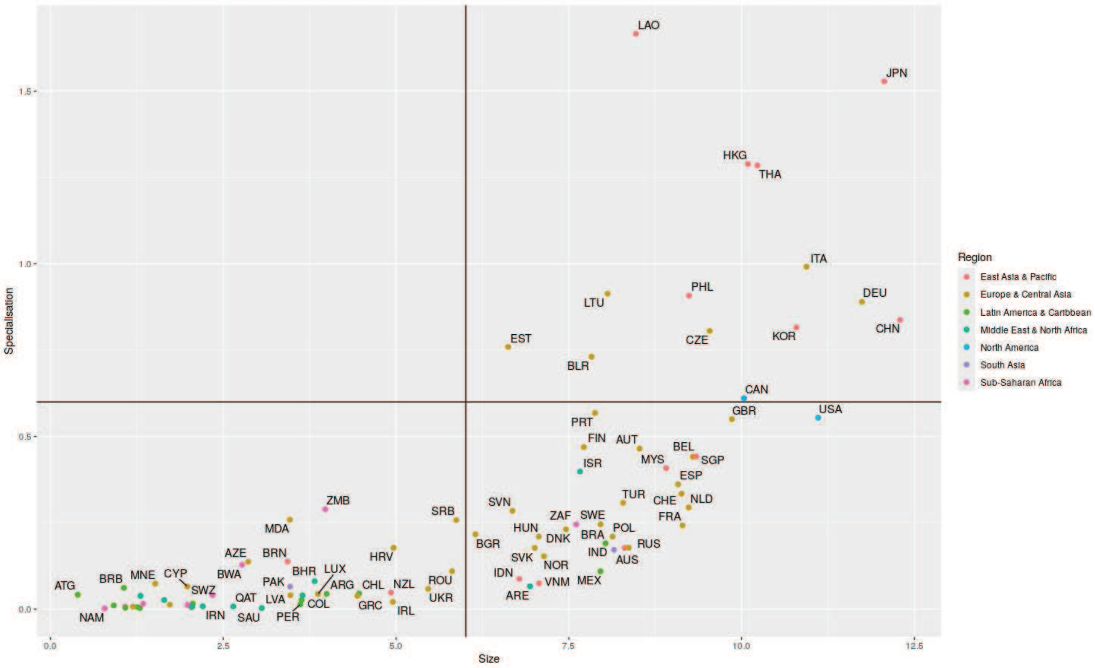
both by high value of trade and high specialisation. Positioning in this quadrant indicates the presence of high-level of country capabilities in producing and exporting electrolysers, showing both competitive advantage and relatively high market shares. Leaders are mainly Asian countries: Japan, with a high level of specialisation, and China with a high value of export. European leading countries are Germany and Italy. Among the group of leaders, some small-size countries emerge, such as Estonia, Lithuania and Czech Republic for Europe, Philippines and Thailand for Asia. The presence of less diversified economies among the leading countries suggests that the entry barriers in the electrolysers market are not very strong, and that there is room for small countries like Czech Republic, which, although not competitively, have developed some capabilities in hydrogen technologies in the past (Kochanek, 2022), to become relevant in the international arena.

The bottom-left quadrant groups *laggard* countries, characterised by both a low value of export and a low degree of specialisation, and thus lacking techno-economic capabilities in the production and export of electrolysers. The bottom-right quadrant represents *transitioning* countries, which export a large value of electrolysers, but are associated to a low level of specialisation. Transitioning countries can include large diversified exporters, like the US, new middle-income entrants with strong potential for hydrogen, such as South Africa, characterised by a low cost of RES energy (Andreoni & Roberts, 2022), which may enter the market as imitators while developing the capabilities to innovate. Part of this transitioning group includes old incumbents, such as some European countries, which are losing their initial competitive advantage, consistently with their market share decline shown in Figure 4. Considering the infant phase of the market, these countries may transition both to the leader or laggard cluster, according to their ability to specialise. The top-left quadrant represents small specialised leaders; however, the value of export below the median is not enough to enable the emergence of small specialised countries.

5.2 Raw materials dependence

As a final step, we examine the extent to which the production of electrolyser relies on forms of import dependence or, alternatively strategic autonomy, looking at the raw materials required to build and install electrolysers. We consider the raw materials needed to build the electrolyser and integrate them in a system of RES grids, according to US Department of Energy (2022) and European Commission (2017). The included raw materials are those defined 'critical' by European Commission (2020b), according to their economic importance, relevance for strategic sectors (energy and high-tech), and supply-chain risks. We repeat the same analysis done for the electrolyser, presenting concentration, market shares and an index of import dependence, rather than of comparative advantage.

Starting with concentration, the CRMs (Critical Raw Materials) market is highly concentrated, as shown by the HHI (Herfindahl-Hirschman Index) for exports presented in Figure 8a, which exhibits a spiky behaviour with frequent peaks, indicating significant pro-



The figure shows countries distribution in the electrolyser space, between size (value of export), on the x-axis, and specialisation, according to the authors' formulation of the RCA, on the y-axis. Four quadrants result from the intersection of two axes identifying the specialisation threshold of $RCA_{adj} = 0.6$ and the median of the export dimension. The time reference is 2020, considered as 5 years average.

Figure 7: Countries clustered by specialisation and export in electrolyser

duction bottlenecks. Although a declining trend in concentration emerged during the early 2000s, it began to rise again in the following decade, also because of the increasing strategic importance of these materials.

Given that we consider CRMs as a single product class, to be comparable with the analysis of energy sources production technologies, this choice prevents us from capturing the underlying heterogeneity at a more granular level. In fact, export concentration of specific raw materials quite probably has experienced different patterns. For instance, the export concentration of rare-earth elements has decreased in recent years, while it has increased for others like cobalt and lithium. Notably, lithium is experiencing a high and growing export growth rate (Kowalski & Legendre, 2023).

Figure 8b presents the composition of export shares by country for the years 1999, 2008, 2020. The most remarkable pattern is the declining quota of South Africa (from 70% to 44%), but also the recomposition in terms of market shares, with some emerging countries, such as Chile that appears in the last period, exactly because of the relevance of lithium export.

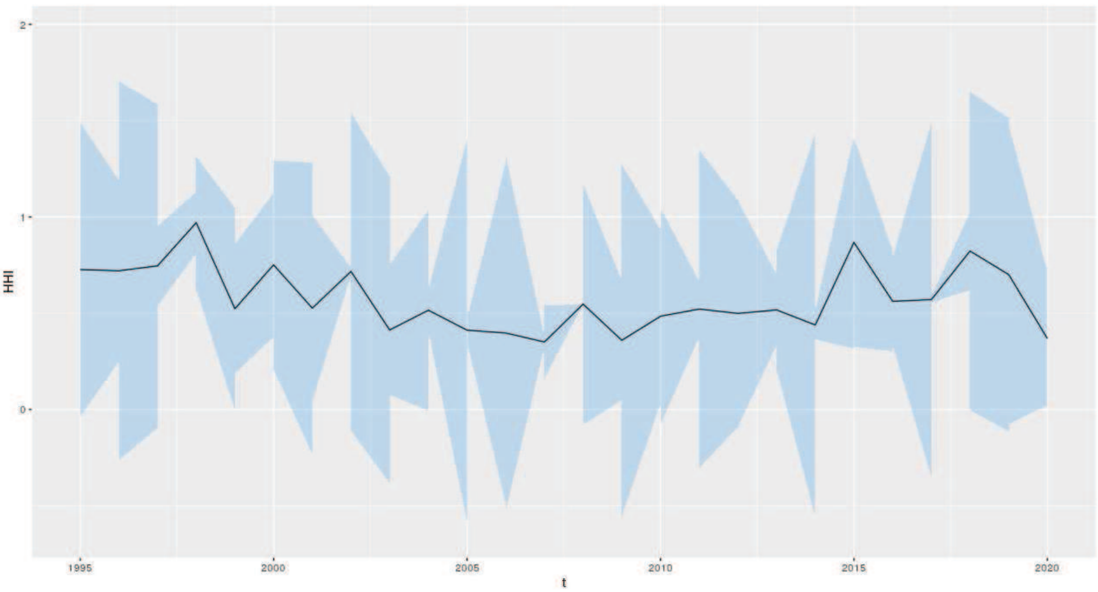
To evaluate countries' dependence on raw materials necessary to build the electrolysers or produce hydrogen, we adopt the Revealed Import Dependence index (RID) (Taneja & Wani, 2014), which is constructed as the Balassa index, but including, in this case, the relative import intensity with respect to the rest of the world. Considering each import value y, from country i of product k, for each year t, with respect to the World total import Y, the Revealed Import Dependence reads as:

$$RID_{i,k,t} = \frac{\frac{y_{i,k,t}}{\sum_k y_{i,k,t}}}{\frac{Y_{k,t}}{\sum_k Y_{k,t}}} \tag{5}$$

The index is then adjusted, as the RCA for export, to account for the diversification structure of the country, so that we have a comparable index for raw materials dependence. As higher entropy indicates poorer diversification, the intensity of import dependence is discounted by an entropy factor for less diversified economy. This is motivated, besides comparability, by the fact that import dependence is structurally higher for small countries compared to large ones, considering the lack of available raw materials in small territories.

$$RID^{adj}_{i,t,k} = log(1 + RID^{MA}_{i,t,k}) \times (1 - entropy^{MA,norm}_{i,t}) \tag{6}$$

Figure 9 presents the import dependent countries and the time evolution of their specific RID. Like RCA, RID indicates the relative importance of that imported good for the specific country with respect to the rest of the world. Critical raw materials for electrol-



(a) Export concentration in critical raw materials

(b) Export share composition

Figure 8: Market for Critical Raw Materials (CRM)

yser is considered as single product class, thus we cannot appreciate the product-countries differences in importing behaviour, as we estimate the weighted averages among several materials. Furthermore, we are also including materials from recycling and from some initial raw processing. Therefore, it is likely that the same country appears among top exporters among import-dependent countries, as the case of South Africa.

Figure 9 shows how the relative importance of import for the countries changes over time (referring to the years 1999, 2008, 2020). Some countries, like Italy, France, Estonia, and Japan, despite some differences in the pattern, show an increasing import dependence on CRM from 1999 to 2020. Which can also mirroring the importance of the CRM input for their electrolyser production comparatively to the rest of the world, when is coupled with high level of specialisation. Some other countries, like US, Finland and the Netherlands show a reduction of import dependence on CRM in time, which can imply both an increase of domestic production or a decreasing of the importance of these imported input for their manufacturing. Therefore, we assess the relationship between CRM import dependency and electrolyser specialisation in Figure 10. In the figure, countries are positioned according to the dimensions of RID index from CRM, on the y-axis, and the RCA index for electrolyser on the x-axis. We observe in the top-right quadrant the specialised dependent countries, that are characterised by both high specialisation and high dependency. Here we find historical market players in hydrogen production, such as Japan, Germany and Italy, but also new emerging players, such as Estonia, the Philippines and Hong-Kong. The top-left quadrant groups autonomous specialised countries, which experience the most favourable conditions for leading the market, having low reliance on import of raw materials and being specialised in electrolysers production. In this quadrant leader countries, according to Figure 7, appear, including China, Korea, Thailand. The majority of countries, lacking any specialisation, are located in the bottom-left quadrant. The bottom-right quadrant, on the other hand, presents countries that lack specialisation in electrolysers export and exhibit high dependence on CRM, possibly because of other CRM-intensive technologically advanced production. To be noted that Laos disappears from the picture, meaning that is not a critical material importer. Therefore, it could be considered as an outlier among specialised country in GH2 production as it does not import any of the materials needed to build an electrolyser. We, then, look at the evolution of country positioning along the specialisation and import dependency dimensions. Figure 11 presents the same picture of Figure 10 but it repeats the country observations for the years 1999, 2008, and 2020. The observations for each country are of the same colour, and linked with an arrow pointing to the most recent position, enabling the tracing of their temporal evolution. Specialised latecomer countries can be identified as those that appear above the specialisation threshold at the endpoint of their oriented segment that connects their positions over time. These include China, Thailand, Estonia, Lithuania, Czechia, Korea, and the Philippines. Conversely, some countries, like Austria and the Netherlands, lose their specialisation status over time, along with their dependency on critical raw materials (CRM) for electrolysers. However, for countries like France, the decrease in specialisation is not accompanied by a decrease in CRM dependency. At the beginning of the period, the latecomers were generally positioned in the bottom-left quadrant, indicating both low specialisation and low dependency. Some of these countries, such as China, Thailand, and Czechia, managed to achieve specialisation without significantly increasing their CRM dependency. Korea even reduced its import dependency while increasing specialisation over time, as it first appears in the bottom-right quadrant. Other countries, like the Philippines and Estonia, became specialised in electrolyser exports while increasing their CRM dependency. In general, an inverse relation emerges between export specialisation at the end and raw materials dependence at the beginning of the period.

6 Conclusions and policy implications

Hydrogen as energy carrier is progressively considered as a part of the solutions to overcome the growth-decarbonisation trade-off. However, at the current stage, its market, measured by international export flows over the past twenty-five years, remains in its infancy. Based on our findings, in 2020, electrolysers accounted for just 0.0008% of total exported products, even declining from their initial share in 1995. This trend is coupled with a market characterised by low concentration, and also the entry of latecomer developing countries. In that, our analysis support the potential of green hydrogen for the growth of low and middle income countries that managed to produce and export the technological artifact for its production. Our evidences suggest that China's emergence as a dominant market player has reconfigured the position of high-income countries like Japan and Germany, while small emerging economies from East Europe and East Asia are entering the market. Notably, some of these countries, such as Korea, China and Thailand, experience also a high degree of autonomy in the acquisition of critical raw materials. However, exporting a complex technological product like the electrolyser requires advanced knowledge and capabilities. In their absence, the opportunities created by the infancy of the market or the countries' resource endowments cannot be realised. Although the potential arising from the establishment of a new global production and distribution of clean energy is highly significant, bottlenecks still hamper the development of green hydrogen as energy source. The first bottleneck is represented by the technological lock-in in fossil-fuels dependence. Hydrogen, to be green, should be produced out of water electrolysis, and, thus, uncoupled from fossil extraction, whose drop is imperative to tackle climate change (IPCC, 2022). Energy derived from hydrocarbons relies on mature technologies, and their learning curves are such that they remain more cost-effective than cleaner alternatives (Kovač et al., 2021). Nevertheless, the price of renewable energy has declined dramatically over the last few decades, especially for energy from solar PV which, in 2023 for new utility-scale plants, was 56 % cheaper than

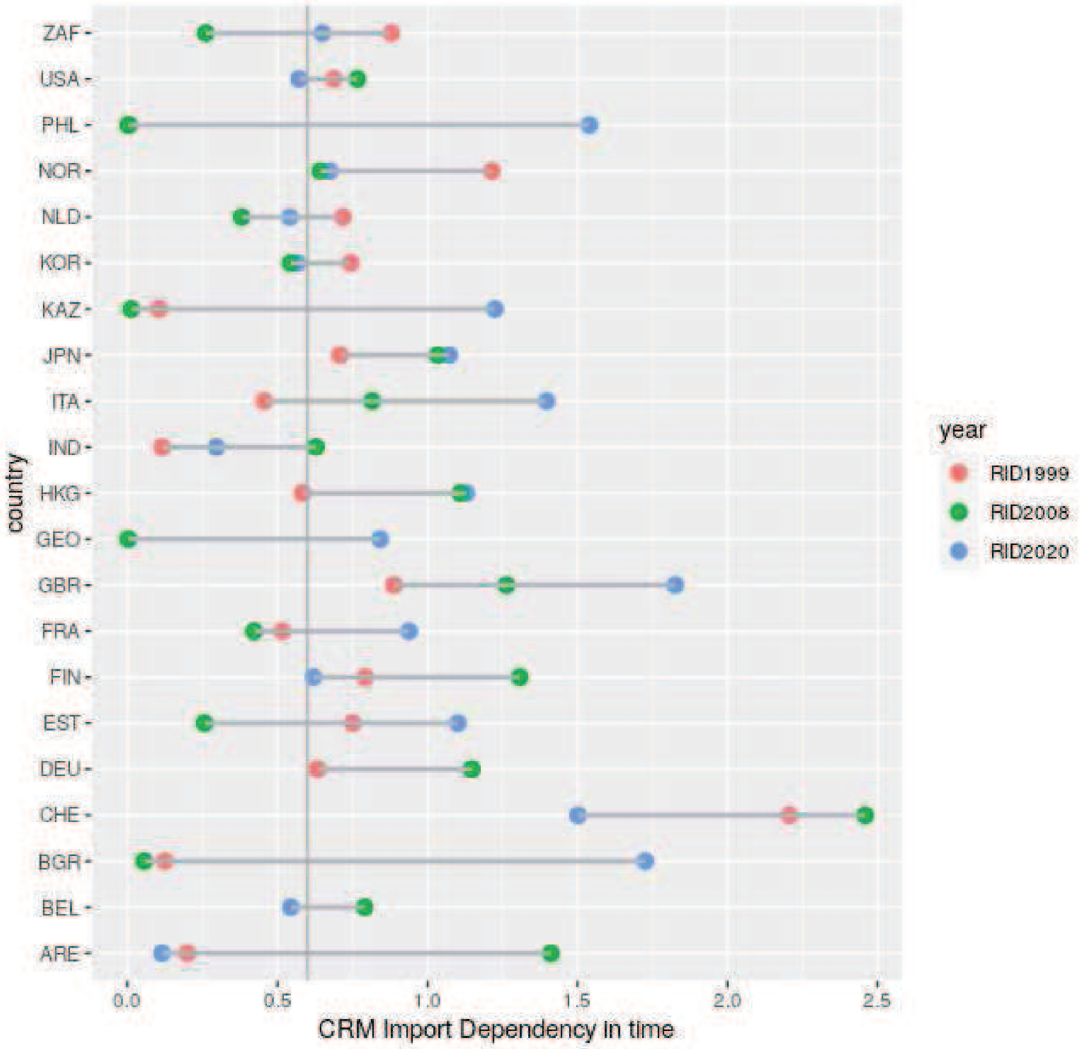
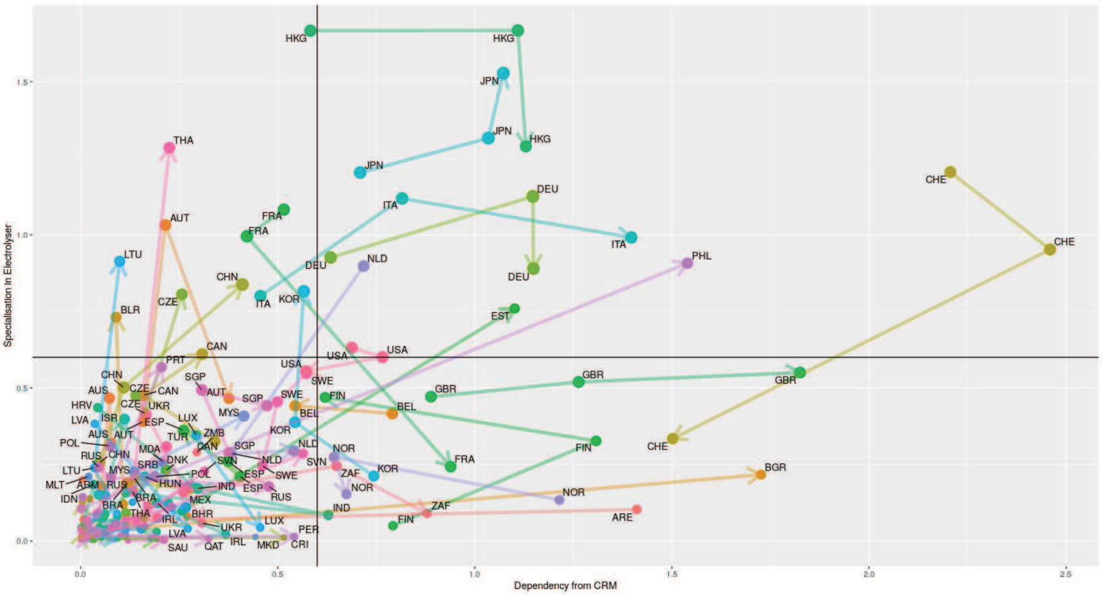


Figure 9: Import dependency on Raw Materials in time

The Figure illustrates the positioning of countries along the dimensions of CRM dependency, measured by the authors' specification of RID, and Electrolyser specialisation, measured by authors' specification of RCA, in the year 2020. The indices are presented as their 5-year moving average. The vertical and horizontal lines represent the specialisation/dependency threshold of 0.6. The colour of the points corresponds to the different world regions to which the countries belong.

Figure 10: Import dependency on CRM and specialisation in electrolyser export in 2020



The Figure illustrates the temporal evolution of countries' positions along the dimensions of CRM dependency and electrolyser specialisation. Each country is represented at three points in time, corresponding to its positions in 1999, 2008, and 2020 as result of 5-year moving average. For each country, these positions are connected by a line with an arrow pointing to the final year, indicating the direction of their evolution.

Figure 11: Temporal evolution of import dependency on CRM and specialisation in electrolyser

fossil-based electricity (IRENA, 2024). This will facilitate the diffusion of green hydrogen production in a more cost-competitive way (IEA, 2024). The second bottleneck is the lack of a clear strategy to overcome such technological lock-in, through industrial policies designed for this purpose. Cost-effective and widely distributed green hydrogen represents both a technological and societal mission, that could serve to decarbonise the system (Nelson, 2011) by means of a mission-oriented environmental program (Dosi et al., 2024; Dosi & Soete, 2022). Given the current infant stage of such technologies and market, innovation and industrial policies might effectively foster the creation of institutions, but also of private market players (Dosi et al., 1990). In that, policy should be solid in pursuing societal needs and influencing the direction of change also against particular interests (Chang & Andreoni, 2020). As a matter of fact, although several countries have proposals or national plans for hydrogen development, the existing policy framework appears too timid in its scope to effectively boost green hydrogen take-off. The strong advocacy power of the oil & gas industry would direct the energy political agenda in their favour (Szabo, 2021), avoiding the cannibalization of their business, in absence of a pervasive transformative policy. The third bottleneck is the extent to which pursuing green hydrogen diffusion might induce negative effects in terms of environmental and societal sustainability. Its production heavily depends on natural resources and raw materials, for manufacturing the electrolysers and for the production process itself, which requires land, water, and renewable energy. Additionally, renewable energy is produced through technologies that are intensive in raw material use. The extraction and control of raw materials are quite often managed by foreign companies operating in less developed countries, leading to lack of transparency of the extractive process and raising several environmental, social, and governance (ESG) concerns (Leruth et al., 2022). Countries rich in resources may face extensive exploitation, while advanced economies risk compromising their strategic autonomy (Caravella et al., 2021; Dillman & Heinonen, 2022; Dorn, 2024).

Overall, the diffusion of green hydrogen is not just a matter of access to technologies, raw materials and the development of capabilities. It is part of the much bigger energy-transition picture, implying profound transformations in the structure of socio-economic relations, which are hindered by the path-dependent and self-reinforcing structure of the dominant fossil-based paradigm. Establishing a global clean hydrogen market will require the creation of entirely new value chains, including technology used, locations of production and consumption (Van de Graaf et al., 2020), the role of market players and energy providers. In this work, we present new evidence on the hydrogen production processes and technologies, outlining alternative trajectories, production processes, market maturity stage vis-à-vis complementary or substitute technologies, and, ultimately, country positioning in the specialisation arena. Although the export market is small, the entry of new latecomers is emerging, However, reliance on raw materials import may hamper the possibility of autonomous specialisation of the countries. This aspect raises important policy implications in terms of strategic autonomy, especially for Western countries.

The global transformation towards decarbonisation could provide a significant opportunity for latecomer countries, despite the higher uncertainty associated with emerging technologies like green hydrogen. However, developing countries rich in raw materials often face exploitation and power imbalances in the international arena, hindering their ability to develop the productive capabilities necessary for more complex specialisations and higher levels of development. Technical cooperation and global partnerships are crucial to foster green hydrogen industry in developing countries. Without tailored and comprehensive policy interventions, this industry risks being dominated by foreign investors (UNCTAD, 2023; UNIDO, 2022).

Further developments of the study include the identification of the conditions for specialisation and the opportunities for technological catching-up. Another line of research should focus on investigating the role of the actors involved in the energy transition, particularly the incumbent industry.

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A Appendix

A.1 Data construction

We consider the technological groups as bundles of products. To do so, we aggregate by weighting the sum of each product, part of a given technological bundle, by its share in the volume of trade of the specific cluster. We calculated the weighted average for each year (t) and country (i), specific trade information (value of export or import) of the product p, $x_{i,t,p}$, as follows:

$$\bar{x}_{i,t}^{tech} = \sum_{k=1}^{n} x_{i,t,k} \times s_{i,t,k} \tag{7}$$

Where for each cluster *tech*, considered as the sum of p products, the share is defined as:

$$s_{i,t,p} = \frac{x_{i,t,p}}{\sum_{p=1}^{n} x_{t,i,p}} \tag{8}$$

In the analysis performed, we considered $\bar{x}_{i,t}^{tech}$ as a product k, using the notion $x_{i,t,k}$.

We adopt the same method of aggregation when considering trade variables of raw materials.

To show the comparability among the different technological clusters, we plot the density of export distribution at country, Figure12, and product level, in Figure 13 .

The difference in the shape of the distribution may be due to the different maturity of the technologies and markets. Given that the market for electrolyser is not well established and the electrolyser types are at different stages of maturity, there might be room for the presence of low-value, small-size exporting behaviour leading a bimodal distribution of the observations. This is confirmed also at the product level. The distance of the electrolyser product distribution is due to the lower value of trade, in absolute terms, with respect to the other technologies.

A.2 Summary statistics

In the section are reported the descriptives statistics of the export and the indices. In Table 2 are reported the summary statistics of the export value by product class. Then, a comparison of the RCA indices in electrolyser is reported both as summary statistics in Table 3 and distributions in Figure 14. The comparison is among the log transformation of the index, its 5-year moving average and the authors' specification, RCA_{Adj}, which is the 5-year MA adjusted for the entropy index of the country to be downgraded for poorly diversified exporters. The comparison is also performed considering the begin, middle and the end of the period examined, referring to the years 1999, 2008 and 2020. The descriptive statistics of the Entropy index of the countries in the data is reported in Table 4. In general we can observe that the authors' formulation of the specialisation index RCA_{Adj}

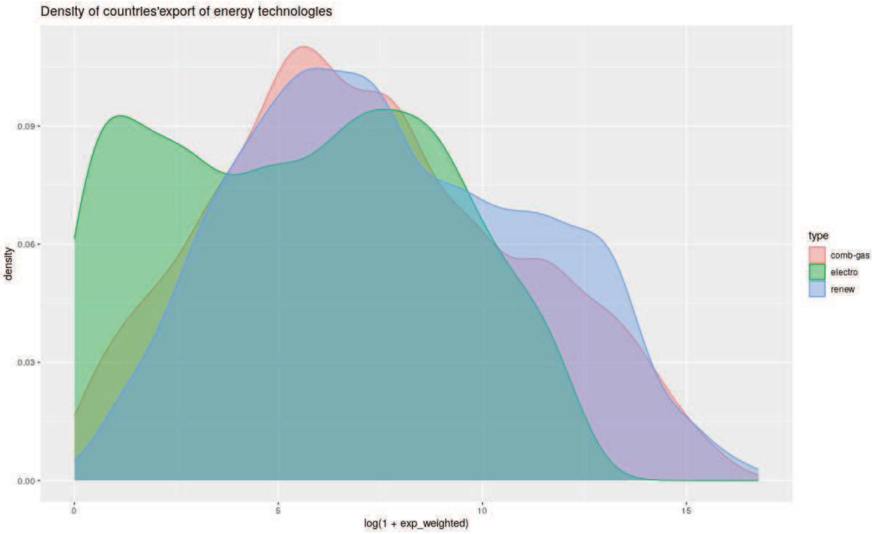


Figure 12: Density of export at country level

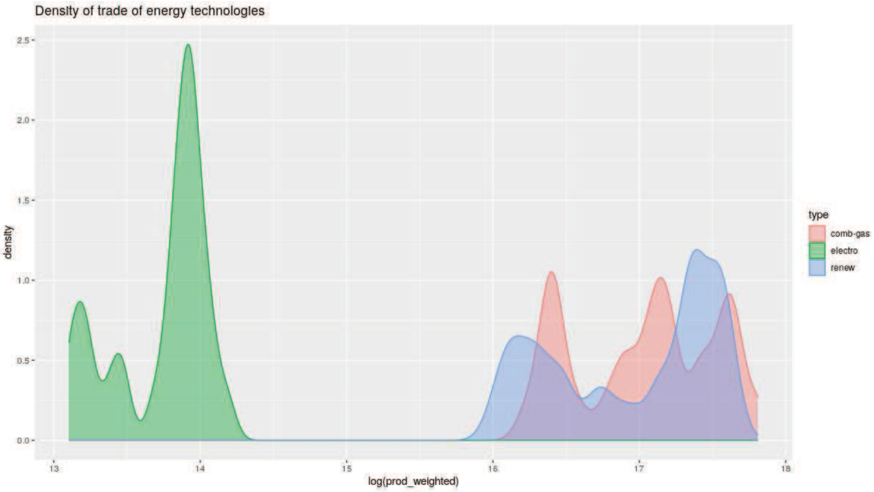


Figure 13: Density of trade at product level

reduces data dispersion, decreasing variance and outliers distance from the mean, while better representing the complexity of specialisation in electrolyser production. Figure 15 reports the rank of the top 20 specialised countries in electrolyser according to the different specifications of the RCA index, at the beginning and the end of the period. From the Figure, it is clear how the RCA_adj closely resembles the 5-year moving average specification of the index, but penalises poorly diversified countries. The specular index of Revealed Import Dependence, RID, is considered for critical raw material (CRM) dependency. The summary statistics of the natural logarithm transformation and the authors' formulation embedding entropy RID_{Adj} is reported in Table 5.

type	n	Mean	Min	Max
CRM	2777	7.095	0.109	14.947
Comb-Gas	4251	7.708	0.604	16.647
GH2 (electrolyser)	1634	6.071	0.134	12.374
RES	4271	8.445	1.022	16.667

Summary statistics of the export as 5-year MA of log(1+exp) of the entire sample, as grouped in the different exported product class. The number of observations is due to the number of exporting countries of that product in the years 1995-2020. The panel is not balanced.

Table 2: Descriptive statistics of export by product

		n	Mean	Min	Max
log(1+RCA)	Full Sample	1634	0.341	0.000	3.631
	1999	42	0.413	0.008	1.496
	2008	73	0.343	0.000	1.845
	2020	91	0.366	0.000	2.969
5y-MA log(1+RCA)	Full sample	1634	0.330	0.000	2.597
	1999	42	0.399	0.031	1.840
	2008	73	0.314	0.000	1.821
	2020	91	0.339	0.004	2.597
RCA_{Adj}	Full sample	1634	0.294	0.000	1.770
	1999	42	0.364	0.029	1.667
	2008	73	0.285	0.000	1.668
	2020	91	0.290	0.002	1.666

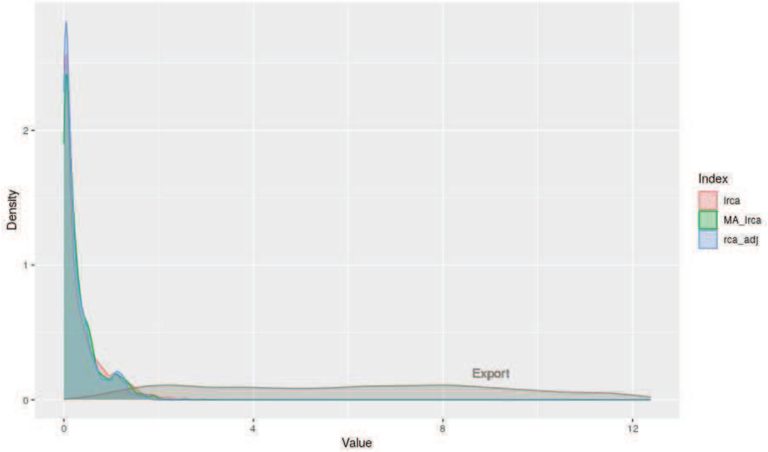
Summary statistics of the RCA related to the product electrolyser in different specification. The number of observations varying according to the number of exporting countries of electrolyser in the year, the full sample contains the years 1999-2020. The years 1999, 2008 and 2020 are the reference years for the beginning, middle and end of the observed period. RCA_{Adj} is the RCA index weighted for entropy as authors' specification, it is considered as a 5 year moving average of the natural logarithm as well.

Table 3: Summary statistics, RCA indices comparison

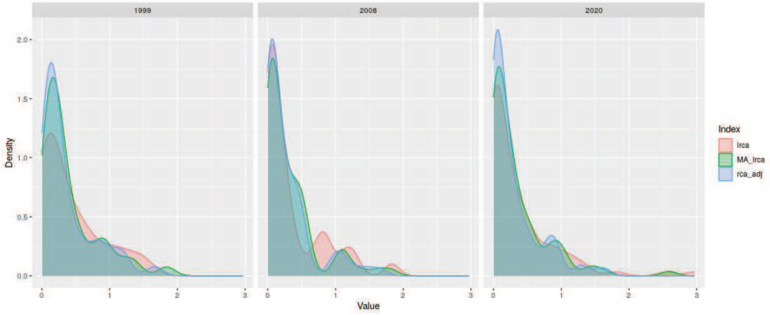
		n	Mean	Min	Max
Entropy	Full sample	4271	3.025	0.334	8.868
	1999	163	2.961	0.376	7.072
	2008	202	3.055	0.439	8.745
	2020	198	3.027	0.334	7.456

Entropy is a country-time varying indicator, the number of observations per year is due to the number of countries in the sample (countries that export a value¿0 in at least one of the product considered). As the other indexes, Entropy is considered at the 5 year moving average. The specification of the index adopted is the one formulated by (De Benedictis et al., 2009).

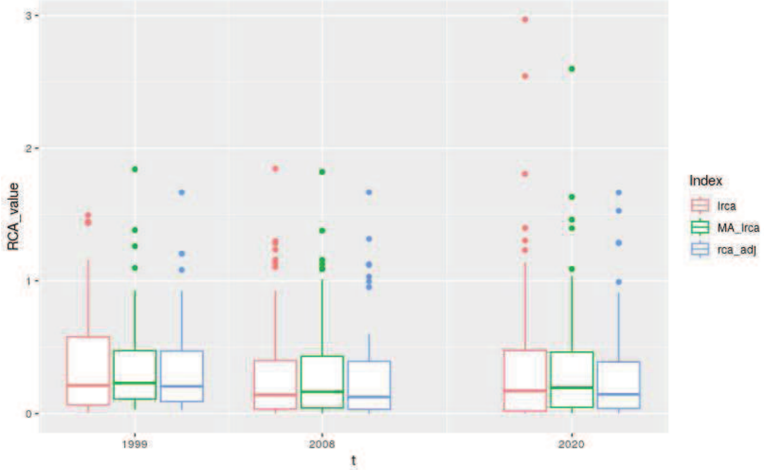
Table 4: Descriptive statistics of the Entropy index



(a) Full sample

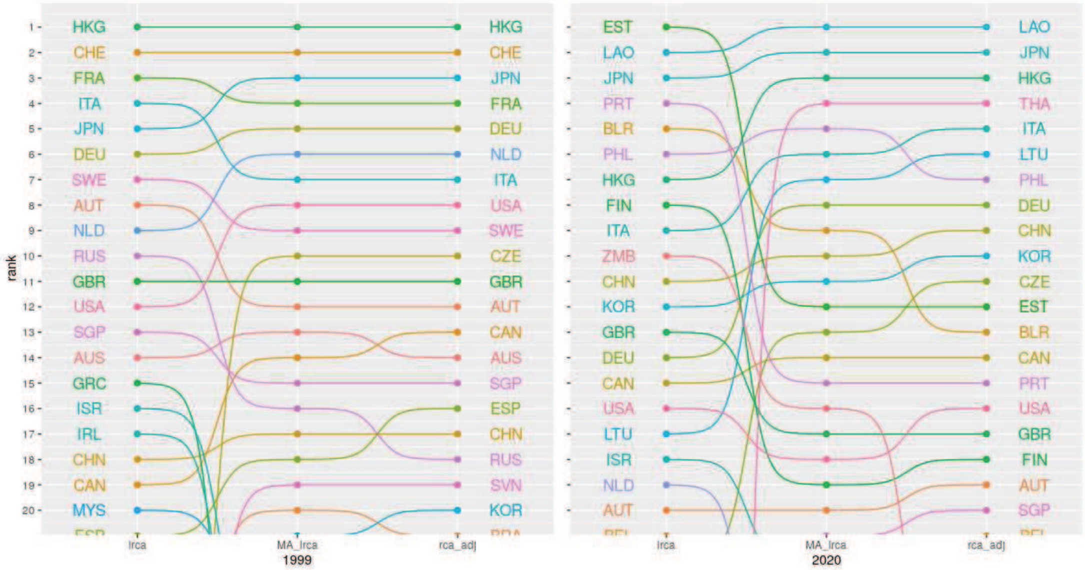


(b) By year



(c) Boxplot

Figure 14: Distribution of different specifications of the RCA in electrolyser



The Figure reports the difference in the rank of the top 20 specialised countries in electrolyser export, according to the different formulations of the RCA index. Respectively, log(1+RCA) as $lrca$, the 5-year MA of log(1+RCA) as MA_lrca and authors' formulation adjusted for entropy RCA_Adj as rca_adj. On the left is reported the ranking in 1999, as the beginning of the 5-y MA observed period, to the right the rank relatively to 2020, the end of the observed period.

Figure 15: Countries positioning according to different specifications of the RCA index

	t	n	Mean	Min	Max
$log(1 + RID)$	Full sample	2777	0.260	0.000	3.207
	1999	82	0.305	0.007	2.696
	2008	131	0.223	0.001	2.989
	2020	136	0.330	0.001	2.036
RID_{adj}	Full sample	2777	0.200	0.000	2.666
	1999	82	0.233	0.000	2.206
	2008	131	0.178	0.000	2.459
	2020	136	0.258	0.000	1.825

Table 5: Summary statistics of different RID indexes

B Appendix: list of raw materials

RAW MATERIALS FOR ELECTROLYSER	HS 2007	HS 1992 only	Critical
Aluminium (housing)	260600		
	760711		
	760719		
	760110		No
	760120		
	760200		
	760310		
	760320		
Boron	281000		Yes
Cerium (HT)	284610		Yes
Chromium (SS)	261000		
	811221#		No
	811222#	262091	
	811229		
Cobalt (HT)	260500		
	810520#		Yes
	810530#	810510	
	810590		
Copper	260300	740110	
	262030	740120	No
	282550		
	282741		
	283325		
	740100#		
	740200		
	740311		
	740312		
	740313		
	740919		
	740400		
Feldspar	252910		No
Graphite (BPP)	250410		Yes
	250490		
Iridium	711049		Yes
Iron (HT)	260111		No
	260112		
Kaolin	250700		No
Lanthanum (HT)	280530		Yes
	284690		
Limestone	252100		No
Lithium	282520		Yes
	283691		
Magnesium	281610	280519	
	282731	280522	Yes
	283321		
	810411		
	810419		
	810420		
	810430		
	810490		
Manganese (HT)	260200		
	284161#		No
	284169#	284160	
	811100		
Molybdenum	261310		
	261390		No
	282570		
	284170		
	810210		
	810297#		
	810296#	810291	
	810295#	810292	
	810294#	810293	
	810299		
Nickel (SS)	260400		
	750210		No
	750220		
	750300		
	750400		
PGM-containing ore	261690		
PGM concentrate	261690		Yes
PGM (Pt) (catalyst)	711011		
Pt-based catalyst	711019		
Potash	310420		
	310430		No
	310490		
	310410		
Silicon	280461		
	280469		
	281122		Yes
	283911		
	283919		
	283990	283920	
	284210	382390	
Silver	261610		
	284310		
	284321		No
	284329		
	710610		
	710691	262090	
	710692	391590	
	710700	711210	
	711230#	711220	
	711299#	711290	
Strontium (HT)	280519		Yes
	281640		
	283692		
Titanium (ore, metal TiCl)	261400		Yes
	810820#	810890	
	810890		
	810830#	810810	
Yttrium (HT)	280530		Yes
	284690		
Zirconium (HT)	261510		
	810920#	810910	No
	810930#		
	810990		

The raw materials are retrieved from US Department of Energy (2022) and European Commission (2020) the correspondent 2007 HS codes are from OECD (2022). The UE RAMON tables are employed for the conversion from 2007 to 1992 HS classification. The 2007 HS codes followed by "#" are those present in the 2007 classification only, the correspondent 1992 version is reported in the next column. In red are the materials defined as critical (supply risk and economic importance) by the European Commission (2017).

C Appendix: additional empirical evidence and robustness checks

C.1 Evolution of market shares for renewables and combustion and gasification

We report the evolution of market shares for the complementary industry to green hydrogen (technologies for renewables) and the substitute one (combustion and gasification technologies).

Figure 16: Shares of export for Renewable technologies

Figure 17: Shares of export for Combustion and Gasification technologies

C.2 Alternative reference time

In our study, we consider 2020 as reference year, as the last available in the data. However, 2020 is the year of the COVID-19 pandemic which is a shock on countries supply-chains. Since trade data are volatile, especially when the product considered is narrow (6-digit), we use a 5-year moving average, so that 2020 is a valid reference year. We report the evidence, shown for 2020 in the paper, referring to 2019 to point that the main picture observed in the study is not biased by the selection of 2020 as baseline year.

Figure 18: Specialisation in electrolyser and size - 2019

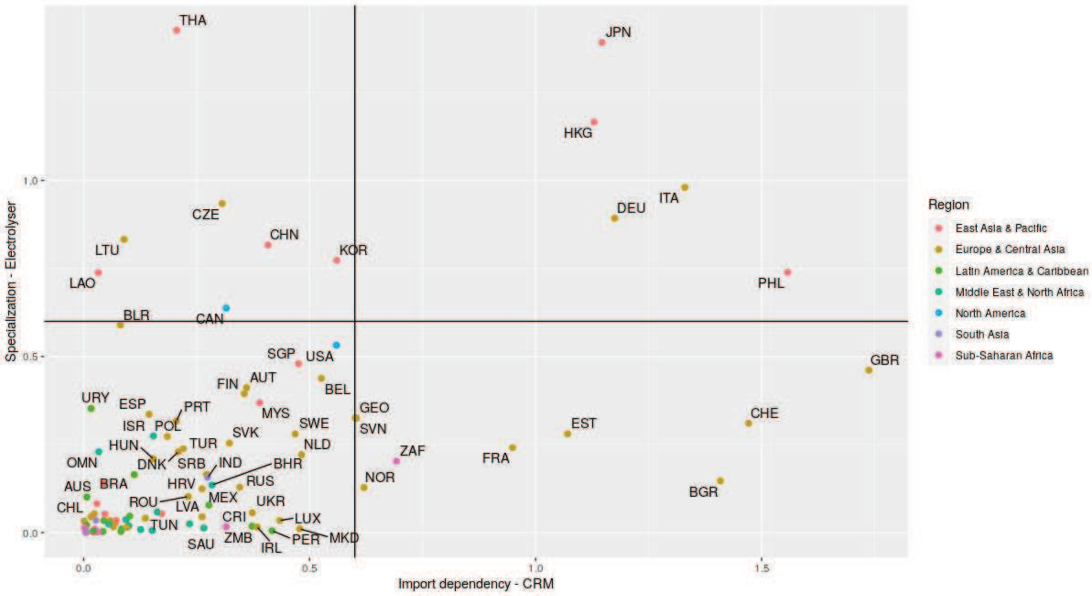


Figure 19: Specialisation in electrolyser and dependence on CRM - 2019

The year 2019 presents a picture similar to that of 2020. The only exception is the absence of Laos in the 2020 assessment related to specialisation in electrolyser export and dependency on Critical Raw Materials. This is because the index of import dependence for Laos could not be assessed in 2020 due to a lack of import data.