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Conference Paper — Manuscript Version (Preprint)

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Suggested Citation: Caiafa, Clara R. (2025) : Industry Location Drivers in a Green Hydrogen Economy: Reorganization or Transformation?, Industrial decarbonization and hydrogen: The politics and economics of sustainable structural transformation, Potsdam, Germany, October 28th-29th, 2025., ZBW - Leibniz Information Centre for Economics, Kiel, Hamburg

This Version is available at:
https://hdl.handle.net/10419/343028

Industry Location Drivers in a Green Hydrogen Economy: Reorganization or Transformation?

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*This article accompanies an oral presentation held at the conference on "Industrial decarbonization and hydrogen: The politics and economics of sustainable structural transformation" in Potsdam, Germany on October 28th, 2025.

Abstract

While a growing body of literature has argued that the rise of a global green hydrogen economy can reshape global value chains and trade patterns, significant uncertainty remains about how transformative such reorganization would be. The economic geography literature has examined drivers of industry location and the potential benefits of different spatial organizations of industries, but a comprehensive application of these findings to a green hydrogen economy has so far been missing. This paper bridges the economic geography literature with research on green hydrogen value chains to identify how different drivers can influence the location of activities across the green hydrogen value chain, and the implications thereof for development opportunities across regions. The analysis concludes that most findings about the renewables-pull effect draw on cost-optimization perspectives rooted in classical and neoclassical location theory, overlooking many insights from post-1990s economic geography. Incorporating this broader perspective suggests that the transformational potential of green hydrogen is more limited than often assumed. Places with only factor input and transport cost advantages may attract simple, mature, activities, in industries where process innovation is incremental and led by large incumbents with the ability to exclude rivals, resulting in limited potential for knowledge-spillovers and self-sustained competitiveness. Meanwhile, regions with complex capabilities but limited renewable energy resources may retain high value added activities related to equipment manufacturing and knowledge development. This would mean that even if industry relocation leads to a reorganization of value chains, it would unlikely fundamentally transform prevailing uneven patterns of specialization and diversification.

Keywords: Industrial Decarbonisation; Industry Location; Global Value Chains; Economic Development; Green Hydrogen

JEL codes: O14, O19, O33, Q56, Q57

1 Introduction

Achieving climate goals may lead to the rise of a "Green Hydrogen Economy" (Wappler et al., 2022), where green hydrogen would be produced using renewable electricity and then used to decarbonize multiple industrial applications (Wappler et al., 2022)(Fig. 1). Given these multiple linkages between industries, a green hydrogen economy may create industrialization and employment opportunities throughout the value chain (Eicke and De Blasio, 2022).

In recent years, a growing body of literature has argued that the widespread use of green hydrogen as a industry decarbonization option may reconfigure global value chains (Egerer et al., 2024; Verpoort et al., 2024; Eicke et al., 2026). The higher costs and energy losses associated with the long-distance transport of green hydrogen and electricity compared to fossil fuels may prompt industries to move production closer to renewable energy sources - what has been called a "renewables-pull effect" (Samadi et al., 2023).

The idea of a renewables-pull effect has raised expectations for green industrialization in developing and emerging economies with high availability of renewables. These economies may diversify into the production and export of green hydrogen, but may also localize additional steps in the value chain (Eicke and De Blasio, 2022; Caiafa et al., 2026). Conversely, industrialized economies with limited renewables may lose competitiveness and see their industries leave (Egerer et al., 2024; Verpoort et al., 2024).

However, many techno-economic studies assessing the renewables-pull implicitly assume that relocation would be driven by optimization of production and transport costs, but location factors such as labor market dynamics and agglomeration effects could possibly counteract it (Colen and Mohnen, 2025; Samadi et al., 2025), especially for activities like research and development or equipment manufacturing. The limited availability of related capabilities could constrain the localization of these higher value added activities in developing economies (Eicke and De Blasio, 2022; Caiafa et al., 2024; Scholvin, 2023).

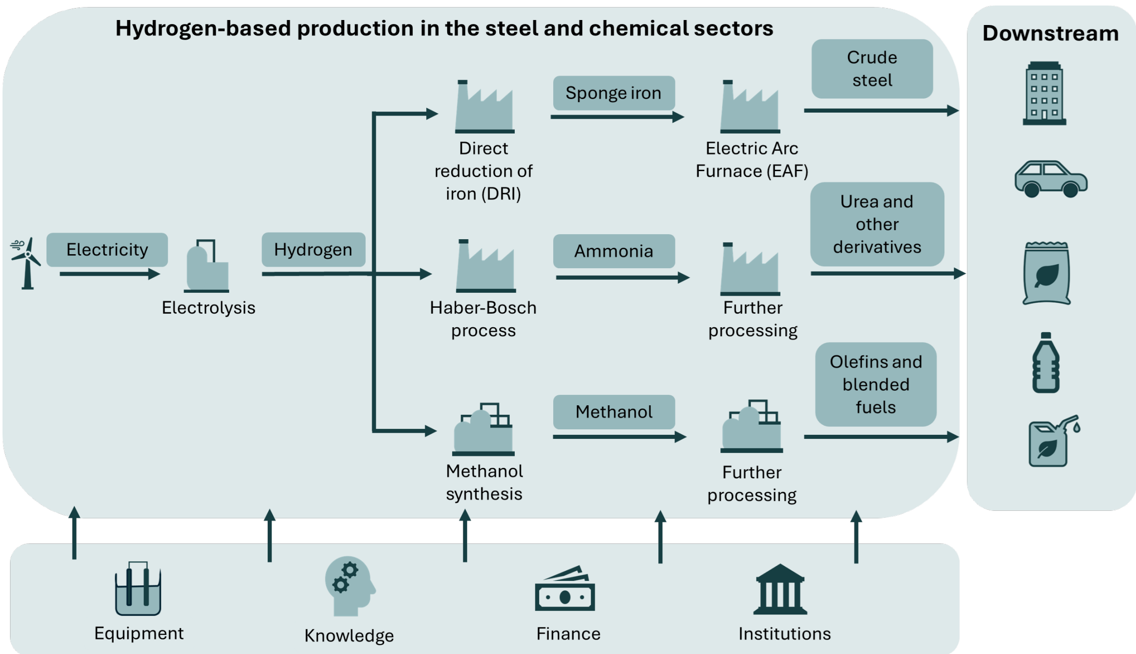

Figure 1: The green hydrogen value chain

Uncertainty remains not only regarding *whether* the rise of green hydrogen will reshape the geography of industrial production, but also concerning the potential implications for industrial development for different geographies if such shift occurs. In particular, it remains unclear whether green hydrogen would reshape global value chains in a way that would substantially transform the economic geography of industrial production, or rather reinforce existing uneven patterns of specialization and diversification.

A more comprehensive view of industry dynamics, going beyond cost-optimization as location driver, can enhance our understanding of this transformative potential, as it would enhance our understanding of not only the probability of relocation, but also of its potential patterns and dynamics (Colen and Mohnen, 2025; Eicke et al., 2026).

This paper contributes to fill this gap by drawing on insights from the literature on economic geography. This literature has studied how a wide variety of location drivers shape the geography of industrial production, as well as the implications thereof for the opportunity spaces countries and regions are faced with when pursuing economic development (e.g., Weber, 1929; Krugman, 1991; Glaeser et al., 1992; Duranton and Puga, 2001; Mccann and Sheppard, 2003; Bathelt et al., 2004; Frenken et al., 2007; Iammarino and McCann, 2006; Lankhuizen et al., 2011; Boschma, 2017; Balland et al., 2020). While this is not an empirical study, it contributes to the debate by showing how established theories of industrial location can refine the understanding of the emerging spatial dynamics of a green hydrogen economy.

This paper is organized as follows. Section 2 discusses the literature on location drivers while Section 3 explains the methods. Section 4 identifies how location drivers could influence a green hydrogen economy. Section 5 discusses the implications of different spatial organizations of industries for economic development. Section 6 discusses areas of uncertainty and areas for further research. Section 7 concludes.

2 Theoretical background

Classical (Weber, 1929; Launhardt, 1885) and neoclassical (e.g., Moses, 1958) perspectives on location theory explained the location of manufacturing industries as a production optimization problem. That is, location decisions would based on the cost minimizing conditions necessary to produce goods given a prespecified production function and to deliver this good from production to its consumer market, while accounting for transportation costs of inputs.

This perspective of the location problem as a cost optimization problem was also the focus of discussions within post-war trade theory (Helpman, 1984; Markusen, 1984). Here, the location choices of multinational firms were explained based on the *factor-proportions hypothesis*, which holds that firms integrate production vertically across borders to take advantage of factor price differences associated with different relative factor supplies (Helpman, 1984; Markusen, 1984).

In the perspectives above, agglomeration of economic activities in space would be the result of the optimization behavior of independent firms generating the same location choices for similar firms. The potential for agglomeration externalities was largely overlooked (McCann, 1995).

The 1990s and 2000s saw a growing interest in location theory in economic geography, which would lead to the incorporation of returns to scale, monopolistic competition, and externalities into the location decision (see e.g., Mccann and Sheppard, 2003; Boschma and Frenken, 2006; McCann, 2014). A first development was brought by the research program on New Economic Geography (NEG) (Krugman, 1991, 1995; Fujita et al., 1999), which developed a framework where the location problem was understood as a trade-off between enjoying economies of scale from concentrating production in space and spreading production to locate it closer to consumer markets and avoid transport costs – or, a *proximity-concentration trade-off.* The development of the NEG was met with criticism from geographers and institutionalists who argued that they saw locations as empty spaces, not considering differences in institutions or factor availability, and still overlooking externalities (Martin, 1999; Boschma and Frenken, 2006).

This criticism connects to a second core development in the field, which was brought by a literature focusing on agglomeration economies to explain the development of cities (Glaeser et al., 1992) and industrial districts (Markusen, 1996; Storper, 1995; Phelps, 1992). They paid special attention to the competition dynamics (Porter, 1998) and microeconomic logics of the co-located firms (Gordon and McCann, 2000; Mccann and Sheppard, 2003), the possibility to benefit from knowledge spillovers (Maskell, 1999; Bathelt et al., 2004), as well as the role of density (Henderson, 1986) in explaining location patterns. They also incorporated considerations such as life cycle stages in product and industry development (Duranton and Puga, 2001; Audretsch and Feldman, 1996;

Audretsch, 1998), the type of knowledge and capabilities required for different economic activities (Bathelt et al., 2004; Balland et al., 2020), and the importance of localized and cumulative learning (Iammarino and McCann, 2006; Boschma and Frenken, 2011), including the importance of existing related capabilities (Frenken et al., 2007; Hidalgo et al., 2018; Whittle and Kogler, 2020) for the generation and absorption of such externalities. This led to a greater recognition of how socio-institutional settings and inter-firm communication influenced innovation in clusters (Maskell, 1999; Gordon and McCann, 2000), and how the role of distance in industry location would go beyond geographical distance to also encompass cognitive, organizational, institutional and social distance (e.g., Boschma, 2005).

3 Methods

This paper assesses how the main location drivers from the literature discussed in Section 2 can influence a global green hydrogen economy, by drawing on the literature on green hydrogen value chains (Samadi et al., 2025; Eicke et al., 2026, see, e.g.). The aim of this paper is not to provide a systematic assessment of the entire renewables-pull literature (for such a study, please see Samadi et al. (2025) and Eicke et al. (2026)). Rather, the aim is to map which concepts of the economic geography literature have been well reflected in the renewables-pull debate and which aspects may need additional research. The literature review is therefore structured around two research questions:

RQ1) How can different location drivers influence the location of economic activities across the green hydrogen value chain and thereby reshape the current geography of industrial production?

RQ2) What would be the implications of this spatial reorganization for economic development patterns across regions participating in this value chain?

The approach to answer the research questions was deductive, taking the economic geography literature as the conceptual starting point. That is, for each research question, the economic geography literature was first reviewed to identify relevant concepts. These were then mapped against insights from the green hydrogen value chain literature. The latter was identified through a set of core papers, including two recent literature reviews (Samadi et al., 2025; Eicke et al., 2026) and subsequent snowballing of backward and forward citations.

Research question RQ1 is answered in Section 4, while research question RQ2 is addressed in Section 5.

4 Spatial organization drivers in a green hydrogen economy

Section 4.1 discusses the role of input availability. Section 4.2 discusses the proximity-concentration trade-off, including the role of multiple dimensions of distance for trade and investment decisions. Section 4.3 focuses on the role of agglomeration economies.

4.1 Factor proportion hypothesis: availability of low cost inputs

Location theory has long acknowledged the role of input cost minimization in location decisions (Weber, 1929; Launhardt, 1885). Similarly, the factor proportion hypothesis from trade theory argues that firms locate production across borders in order to benefit from factor price differences across locations, deriving from different relative abundance of factor supplies (e.g., Helpman, 1984).

Historically, the relative abundance of low-cost energy resources such as coal, oil, and natural gas has been a driver for locating energy intensive production (Grether et al., 2014; Manderson and Kneller, 2020; Gerlagh et al., 2015). The literature on green hydrogen value chains has argued that, while energy availability is expected to remain an important location driver in a green hydrogen economy, a shift in the location advantages of regions is expected (Samadi et al., 2023; Eicke et al., 2026). Since renewable energy sources have a different geographical distribution than fossil fuels, a transition to a green hydrogen economy would reshape regional advantages, shifting the attractiveness from regions rich in fossil fuels to those with high availability of renewables (Samadi et al., 2023; Egerer et al., 2024; Eicke et al., 2026).

Renewable energy availability can be a major driver for cost competitiveness of green hydrogen production, together with land and water (IRENA, 2022b). Green hydrogen is produced using electricity from solar and wind to split water into hydrogen and oxygen. Densely populated areas, like most of the European continent, and places facing water scarcity, like Northern Africa, face constraints for large-scale production (Fig. 2).

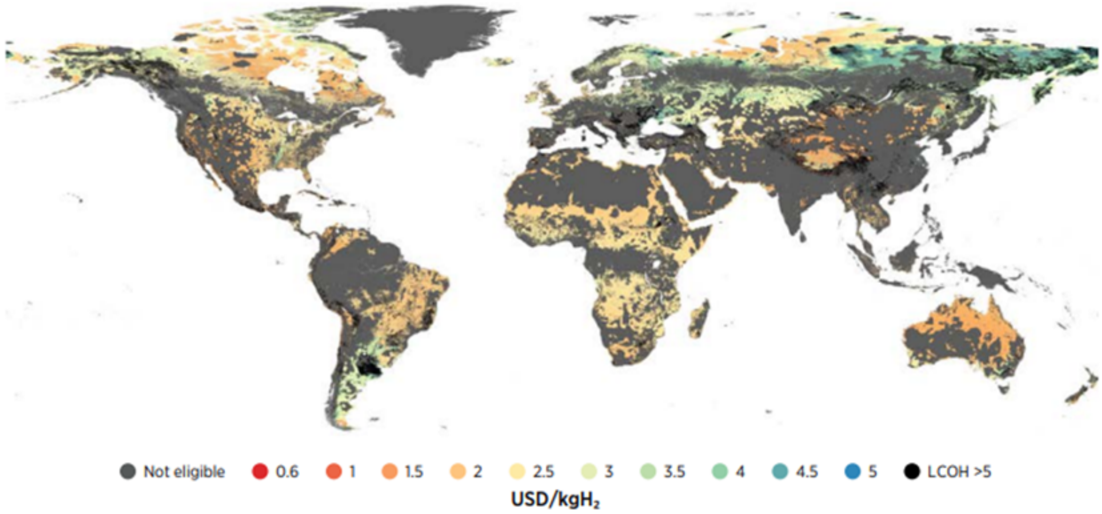

Figure 2: Global map of levelized cost of green hydrogen in 2030 considering water scarcity
Source: IRENA (2022b)

Input availability could also influence location decisions of green hydrogen consumer firms in steel and chemical industries. The renewables-pull literature has argued that exceptional renewable energy conditions and availability of green hydrogen as feedstock can work as a pull factor for green industrial production in energy-intensive sectors like steel and ammonia production (e.g., Samadi et al., 2023; Verpoort et al., 2024; Samadi et al., 2025; Caiafa et al., 2025, 2026). Competitive renewables-based steel production depends on the combination of renewable energy, including green hydrogen and biomass feedstock, high-quality iron ore, and lower wages (Trollip et al., 2022; Devlin et al., 2023; Caiafa et al., 2025). Renewable energy costs are also a significant for ammonia (e.g., Armijo and Philibert, 2020; Arnaiz del Pozo and Cloete, 2022) and methanol synthesis (Wan et al., 2024; Arnaiz del Pozo et al., 2022; Kaiser et al., 2021). For methanol synthesis and urea, however, the availability of CO_2 from point-sources can be another important cost driver, given the higher costs for direct air capture (DAC) (Arnaiz del Pozo et al., 2022; Wan et al., 2024).

While the availability of low-cost inputs could be an important driver for energy-intensive production, they may not be a driver for value chain functions beyond production. Activities across value chain functions such as corporate, finance, research and development, or marketing, rely significantly less on renewable energy. Multinational firms can locate corporate headquarters and production plants in different markets to exploit factor cost differences (Helpman, 1984).

The renewables-pull effect is hence unlikely to be as important for R&D and other corporate activities that are not as energy intensive. Here, the availability of human capital and appropriate institutions could play a more important role (see Section 4.3). However, this has been an aspect less explicitly discussed in the renewables-pull literature, which has focused on the energy-intensive production steps.

4.2 Proximity-concentration trade-off and multiple roles of distance

Even when factor price differences are not substantial, firms need to decide between spreading production to locate in proximity to different consumer markets and concentrating production in space to benefit from economies of scale (Brainard, 1997). This "proximity-concentration trade-off" implies the additional variable costs of trading over long distances is balanced against the fixed costs of opening an additional plant (Brainard, 1997). The costs of trading over long distance include the transport costs of goods, but also trade and investment barriers. Transport costs and trade barriers create incentives for location in proximity of consumers, while investment barriers and scale economies at the plant level incentivize concentration (Brainard, 1997).

Historically, minimization of transport costs has been a key driver for the formation of steel and chemical clusters (e.g., Iammarino and McCann, 2006), due to energy losses and the requirement of extreme temperatures and storage conditions for intermediate products (Schneider, 2022; IEA, 2021). In turn, high transport costs for steel (Schneider, 2022) and chemical (IEA, 2021) products led this clusters to locate close to consumer markets, while being close to transport infrastructure such as ports, storage facilities, and pipelines in order to access imported inputs such as coal, iron ore, and natural gas.

The literature on green hydrogen value chains argues that transport costs are expected to continue to play a key role in a green hydrogen economy (see, e.g., Samadi et al., 2025; Eicke et al., 2026), but a change in relative transport costs between inputs and outputs can lead to a reconfiguration of these value chains (Schneider, 2022; Day, 2022; Verpoort et al., 2024).

Regarding green hydrogen, current hydrogen production happens mostly in-locu in chemical clusters, using mainly natural gas as input for the Steam Methane Reforming (SMR) process (IEA, 2023a). For green hydrogen production, electricity would be the main input, but it is more difficult to transport over long distances than fossil fuels (Day, 2022). Economies of scale are expected at the level of the electrolysis plant (Caiafa et al., 2024) as well as at the liquefaction and storage and transport steps IRENA (2022a). High transport costs for electricity inputs combined with economies of scale suggest a concentration of green hydrogen production in space, and close to the renewable electricity production.

High transport costs for hydrogen compared to previous fossil industrial inputs such as coal an natural gas would incentivize co-location of industrial processes with green hydrogen production. “Green iron” and “green ammonia” production would use low-carbon hydrogen as inputs, but are products comparatively easier to transport. Co-locating their production with hydrogen production and then transporting the green iron or green ammonia can reduce transport challenges (Gielen et al., 2020; Trollip et al., 2022; Armijo and Philibert, 2020; Egerer et al., 2024; Fasihi et al., 2021; Rhee et al., 2024; Pawar et al., 2021; Zhao et al., 2022; Caiafa et al., 2026, 2025; Verpoort et al., 2024; Samadi et al., 2025).

That is, industries could locate production steps directly using green hydrogen closer to where the green hydrogen and the renewable energy are available, and then trade the intermediate products of hot briquette iron (HBI), green ammonia, and green methanol for final processing into steel, urea, and ethylene, respectively, in current locations (Verpoort et al., 2024). While relocating the entire production of steel, urea, or ethylene could lead to the largest cost-savings, partial relocation already grants substantial savings compared to trading hydrogen (Verpoort et al., 2024; Caiafa et al., 2026).

An important aspect regards whether the geographical distribution of future demand for steel and basic chemicals will change compared to current patterns. Demand for these products is projected to come mainly from developing and emerging economies, with consumption saturating in many advanced economies like Europe (IEA, 2021, 2020; Bashmakov et al., 2023). If these patterns continue, full relocation could become an option for steel and chemical industries to locate closer to growing demand centers.

Regarding investment barriers, firms are less likely to invest in or trade with a market not only when they are geographically distant from that market, but also when they are unfamiliar with the local culture and institutions (Lankhuizen et al., 2011; De Groot et al., 2004). This would mean that places located geographically further away from demand centers or not well integrated in existing investment and trade networks could face difficulties in attracting investments. International donors and ports have been actively supporting green hydrogen projects in developing countries like Brazil, Chile, Morocco, and Namibia by sharing information, providing training and funding (Lindner, 2022). This means that from an organizational and institutional perspective, green hydrogen hubs supported by international donors would be closely connected to Europe, despite the geographical distance (Caiafa et al., 2024), and may hence more easily attract funding.

Additionally, institutional quality can is an important determined for both trade and foreign direct investment (De Groot et al., 2004; Adegboye et al., 2020), including for green hydrogen value chains (Colen and Mohnen, 2025). Some developing economies with lower institutional quality may hence face challenges in attracting activities in the green hydrogen value chain (Dagnachew et al., 2025; Colen and Mohnen, 2025). Differences in capital costs arising from higher perceived risks can substantially decrease cost-savings from relocation (Caiafa et al., 2026; Kaiser et al., 2021). Increasing institutional capacity and local leadership can help developing economies attract and benefit from investments in green hydrogen (Caiafa et al., 2024; Scheffler et al., 2025; Scholvin and Kalvelage, 2025).

Regarding trade barriers, Eicke et al. (2026) points out that the current geopolitical condition characterized by trade disruptions through tariffs and wars creates incentives for countries and regions to keep production at home or prioritize "friend-shoring" strategies. Such geopolitical concerns may counteract incentives from cost-minimization.

Therefore, high transport costs for renewable electricity and economies of scale at the plant level could incentivize the concentration of green hydrogen production in places with high availability of renewable energy. Costs and energy losses associated with green hydrogen transport could then incentivize the concentration of consumer industries close to green hydrogen production. A change in the global distribution of demand for steel and basic chemicals may incentivize the relocation of semi-finished and finished products. This could lead to the formation of green hydrogen clusters. This concentration of economic activity would tend to happen in economies that are well-embedded in international trade and investment networks and that present sufficient institutional quality.

4.3 External economies of agglomeration

Firms can benefit from simply co-locating with other firms (e.g., Frenken et al., 2007; Combes and Gobillon, 2015) by *sharing* indivisible facilities and infrastructure, enjoying a higher probability of quality *matching* with suppliers and labor, and *learning* through spying, imitating, and interacting (Duranton and Puga, 2004).

Benefits from co-location are called external economies, and vary depending on whether the agglomeration is characterized by *specialization*, *diversity*, or *density* (Glaeser et al., 1992; Frenken et al., 2007). *Localization economies* arise from specialization through labor market pooling, the creation of specialized suppliers, and knowledge spillovers between similar firms. *Jacobs externalities* (Jacobs, 1969), conversely, arise from knowledge spillovers between firms in different industries, relying on diversity. Finally, *urbanization economies* arise from savings from large-scale operation in a given agglomeration or city as a whole, independently of the particular industry structure. More populous localities have larger local markets (Henderson, 1986) and are more likely to house not only the economic, but also the social, political, and cultural organizations that support the production and absorption of know-how and support innovative behavior (Frenken et al., 2007).

The importance of these agglomeration externalities for industry location decisions are expected to vary with the degree of similarity between activities, industry-specific innovation dynamics, the stage of the product and industry life cycle, as well as the micro-economic logics for clustering.

For the steel and chemical industries, sharing and matching have been important mechanisms explaining spatial clustering. Firms in these clusters often rely on similar inputs - such as natural gas, electricity, coal, and industrial gases - for their production process. Clusters offer shared pipelines, storage infrastructure, and utilities services for electricity, steam, air, water, and industrial gases, and may provide a framework for joint lobbying and regulatory activities (Janipour et al., 2022; Bashmakov et al., 2023). In addition, there are strong buyer-supplier relationships between the firms. By-products of certain production processes are regularly used as inputs for other processes. For example, cement uses slag, a by-product of ironmaking in the blast furnace, while fossil hydrogen production during ammonia production offers CO_2 to urea production (Bashmakov et al., 2023; IEA, 2021).

A shift to hydrogen-based production would reduce some of these synergies, weakening incentives for co-locating ironmaking and ammonia production with existing clusters. Blast-Furnace slag would not be a direct co-product in hydrogen-based direct reduction of iron, decreasing synergies between ironmaking and cement production (Margutti et al., 2026). If ammonia is produced from green hydrogen, CO_2 for derivatives would be sourced from another source (e.g., biomass with carbon capture or direct air capture) (IEA, 2021).

The prospect of benefiting from widespread knowledge spillovers between firms has been a limited driver for spatial clustering in chemical and steel clusters. In this industries, innovation is mostly led by large incumbents through in-house R&D. Knowledge is protected via secrecy and patenting limiting the potential for knowledge spillovers. Innovation is mostly process-focused, with technological innovation being carried out mostly by equipment suppliers (Pavitt, 1984; Iammarino and McCann, 2006; Castellacci, 2008; Martins et al., 2021).

A history of specialization in similar activities can still be an important location driver for steel and chemical industries (Cole et al., 2021; Eicke and De Blasio, 2022). When activities rely on the same knowledge base, on similar skills and institutional frameworks, or require similar inputs in the production process (see e.g., Whittle and Kogler, 2020) the costs and risks for diversification can be lowered (Neffke et al., 2011; Hidalgo et al., 2007, 2018; Boschma et al., 2015). This is especially important considering the knowledge base of these industries is characterized by high degrees of cumulativeness and tacitness (Pavitt, 1984; Iammarino and McCann, 2006). Tacit knowledge is acquired by experience and interaction and hence highly contextual. While codified knowledge can be more easily diffused globally, tacit knowledge transfer would be more localized, requiring either geographical proximity (Maskell, 1999; Maskell and Malmberg, 1999; Malmberg and Maskell, 2006) or the the establishment of multi-scalar networks and communication channels (Bathelt et al., 2004; Binz and Truffer, 2017). However, as multinationals in those sectors have intra-firm multi-scalar networks and communication channels that can compensate for physical distance when sharing knowledge and expertise (Bathelt et al., 2004; Binz and Truffer, 2017).

This path-dependency associated with relatedness could lead to a tension with the renewables-pull effect, since many places with the best availability of renewable energy inputs do not possess related capabilities (Eicke and De Blasio, 2022). Existing industrial capabilities could in fact incentivize green hydrogen production to locate where fossil-based hydrogen is currently produced and used (Eicke and De Blasio, 2022; Griffiths et al., 2021). Since once green hydrogen is produced it is simply hydrogen gas, the required skills, jobs, infrastructure, assets and business models could be "transferable" from incumbent sectors. Gas pipelines, storage facilities, and liquefied natural gas (LNG) terminals in ports could be repurposed for green hydrogen and derivatives like ammonia and synthetic fuels (Griffiths et al., 2021; IRENA, 2022c).

Moreover, existing markets for steel and chemicals can offer less risky off-takers, since they are more likely to have the knowledge and skills required for the application of hydrogen in their production processes, having a competitive advantage when compared to new market entrants (Eicke and De Blasio, 2022). The availability of specialized suppliers and labor can create incentives for these industries to remain in existing clusters (Colen and Mohnen, 2025). However, a high level of relatedness may lead to lock-ins. Some have hence argued that places with capabilities unrelated to fossil fuels could instead be better positioned to offer the institutional support needed for green technologies (Boschma et al., 2017).

Regarding the supply of equipment for green hydrogen electrolysis plants, a branch of the economic geography literature assessing the emergence of the clean technology industry has found that the manufacturing of products such as electrolyzers, solar photovoltaic panels and power supply equipment relies on a relatively complex set of capabilities (Müller and Eichhammer, 2023), and require the existence of related capabilities (Li et al., 2020; Tanner, 2016). Moreover, renewable energy technologies have a higher degree of knowledge cumulativeness (Barbieri et al., 2020), a more substantial science base (Persoon et al., 2020), and higher skills requirements (Consoli et al., 2016) than fossil technologies. Since complex sets of capabilities tend to be more concentrate in space (Balland et al., 2020), equipment manufacturing would tend to concentrate in few locations. Current manufacturing of clean energy technologies is heavily concentrated, with only four countries and the European Union account for around 80-90% of global manufacturing capacity for solar photovoltaic (PV), wind turbines, batteries, electrolyser and heat pumps (IEA, 2023b).

While relatedness has been found important to explain the emergence of renewable energy technologies at a country level (Li et al., 2020; Tanner, 2016), innovation dynamics differ across renewable energy technologies (Binz et al., 2021). Technologies like solar photovoltaics and solar heaters manufacturing are more footloose, with manufacturers creating highly standardized products for global mass markets. Others like wind turbines and water recycling are more spatially sticky, as innovation is based on doing, using, and interacting (DUI) and products are customized to user preferences and local institutions (Binz et al., 2021). The geographical distribution of industries with footloose innovation systems is more prone to shift quickly, while there is stronger inertia in spatially-sticky ones (Binz et al., 2021). While there is some initial evidence suggesting electrolysers may be similar to solar photovoltaics (Caiafa et al., 2024), more research is needed across the entire value chain.

It is also important to consider the different maturity stages across the value chain. First, because location decisions change with product and industry life cycle. In early product and industry development stages, activities tend to locate in places with a diverse set of capabilities, allowing them to learn from a variety of sources. As they mature and move to mass-production stages, activities tend to move to specialized clusters, to benefit from spillovers from similar industries and reduce costs through sharing and matching (Henderson et al., 1995; Duranton and Puga, 2001; Audretsch and Feldman, 1996; Audretsch, 1998). Second, because emerging industries face a window of locational opportunity (Boschma, 1997): technologies are not yet standardized, markets are fluid, and rules and preferences still forming. This also means that they depend on places capable of active market construction and strategic policy support (Bergek et al., 2008; Quitzow, 2015).

Maturity stages differ across industries and products in the green hydrogen value chain. Solar and onshore wind are becoming mature technologies for electricity production, but the integration of these variable sources remains a challenge for hydrogen production. While green hydrogen is still emerging (IEA, 2023a), the electrolysis process itself is widely known in chemistry. Electrolysis has already been used to produce hydrogen for ammonia production, but this was using dispatchable hydropower (IEA, 2021). Ammonia synthesis using hydrogen in the Haber-Bosch process has been the established route since 1930 and has presented limited improvements since 1990 as the technology is close to a theoretical maximum of energy efficiency (IEA, 2021). Conversely, steel is already a mature industry with mature markets, but the shift to hydrogen-based steel would require a significant shift to a immature production technology (IEA, 2023a; Martins et al., 2021; Gielen et al., 2020). The use of hydrogen directly or as derivatives in the transport sector would require significant technological innovation, both in the production and user side (IEA, 2023a). As current fossil-based hydrogen production is mostly in-locu via steam methane reforming (SMR) and not globally traded, development in hydrogen shipping technologies would be required if hydrogen would be internationally traded (IEA, 2023a).

The immaturity and higher costs of hydrogen-based production routes compared to fossil based alternatives would mean that the availability of subsidies, climate policies, and the required institutional capacity can influence location decisions (Colen and Mohnen, 2025). Here, it is unclear whether a history of specialization in these industries would facilitate or hinder the establishment of such enabling conditions from a political economy perspective.

Differences can therefore be expected between industries. Applications that are more mature may be more prompt to relocate to specialized clusters in the near future. Applications that still require substantial innovation and development may first prioritize locations with a variety of capabilities available, to only later consider relocation to specialized clusters. Additionally, for industries like green hydrogen where the greatest room for technological development lies on equipment development, production may relocate while equipment suppliers remain concentrated in few places. The degree of inertia in spatial development in industries would also depend on whether they present more footloose or spatially-sticky innovation dynamics.

Emerging work has begun to examine how relatedness, technological complexity, specialized suppliers, and supportive policies may shape industrial location in a green hydrogen economy (e.g., Eicke and De Blasio, 2022; Müller and Eichhammer, 2023; Colen and Mohnen, 2025). Yet, these factors remain far less explored than input availability and transport costs, offering a promising avenue for future research.

Table 1 summarises the main findings from Section 4.

5 Industry organization patterns and economic development

This Section reflects on the transformative potential of green hydrogen clusters based on three aspects: the potential for agglomeration externalities, the implication of specialization versus diversity for growth, and the spatial scale where externalities materialize.

Table 1: Summary of implications from location drivers for organization of industries in a green hydrogen economy and relation to the renewables-pull literature

Location drivers	**Sub-category**	**Pattern**	**Green hydrogen production**	**Industrial users (steel, chemicals)**	**Equipment manufacturing**	**Knowledge development**	**Overall implication**
Factor proportion hypothesis (Sec. 4.1)	Availability of low-cost inputs	Historical pattern	Produced from fossil fuels (mainly natural gas via SMR), typically in industrial clusters	Steel and chemical clusters historically located near fossil fuels	—	—	Change in patterns
		In a green hydrogen economy	Availability of renewable electricity, water, land, and labour can pull production to renewable-rich developing countries; high capital costs may offset some advantages	Availability of green hydrogen plus other inputs (iron ore, labour) can pull hydrogen-using production steps, enabling partial or full green relocation	Limited evidence linking input availability to equipment manufacturing location	Knowledge development depends more on high-skilled labour than energy inputs; less driven by renewables availability	
		Evidence in renewables-pull literature	High	High	Low	Medium	
Proximity – concentration trade-off (Sec. 4.2)	Transport costs, economies of scale	Historical pattern	Chemical products had higher transport costs than fossil fuels; industries concentrated near consumers and port/gas infrastructure	Chemical and steel products had higher transport costs than fossil fuels; industries concentrated near consumers and port/gas infrastructure	Economies of scale and transport costs vary by equipment type; large-scale/low-transport-cost equipment tends to concentrate	Tacit knowledge benefits from proximity, but international networks can compensate for distance	Change in patterns for production and industrial uses; path-dependency for knowledge and equipment
		In a green hydrogen economy	Higher transport costs for renewable energy carriers incentivize production near renewable electricity sources	Higher transport costs for hydrogen incentivize co-location of hydrogen with iron and ammonia production; less strong for later processing steps (steel, urea)	Electrolyzers: modularity and economies of scale lead to concentration, not necessarily near hydrogen production; limited evidence for hydrogen-use equipment	Limited importance of green hydrogen transport costs; advanced economies dominate patents; international projects do not share knowledge locally	
		Evidence in renewables-pull literature	High	High	Low	Low	

Table 1: (continued) Summary of implications from location drivers for organization of industries in a green hydrogen economy and relation to the renewables-pull literature

Location drivers	Sub-category	Pattern	Green hydrogen production	Industrial users (steel, chemicals)	Equipment manufacturing	Knowledge development	Overall implication
Agglomeration economies (Sec. 4.3)	Sharing, matching, learning	Historical pattern	Sharing of infrastructure and buyer–supplier matching drove clustering in steel and chemicals; knowledge spillovers limited due to intra-firm R&D	Same as previous column	(Insert findings from equipment literature if available)	(Insert findings from knowledge literature if available)	Some change for early processing steps; path-dependency for later steps, equipment, and knowledge
		In a green hydrogen economy	Hydrogen-based production reduces some synergies (e.g., no BF slag for cement; CO_2 for ammonia derivatives must come from elsewhere), weakening co-location incentives	Same as previous column	Varies by technology; not all equipment manufacturing behaves the same	—	
		Evidence in renewables-pull literature	Low	Low	Low	Low	
	Specialization, diversity, density	Historical pattern	Specialized clusters with tacit, cumulative knowledge; specialized suppliers and workers important	Same as previous column	Equipment manufacturing requires diverse capabilities but also cumulative knowledge	Early-stage innovation concentrates; process innovation spreads as industries mature	Path-dependency
		In a green hydrogen economy	Relocation requires prior specialization or strong integration in international networks; early-stage applications need diversity and density (e.g., ammonia as fuel)	Same as previous column	Concentration where capabilities already exist; fossil-related knowledge still relevant	—	
		Evidence in renewables-pull literature	Medium	Medium	Low	Low	

5.1 Logics for clustering and potential for agglomeration externalities

The benefits from clustering vary across cluster types, which in turn differ depending on the main logic for clustering. Clusters that are driven by transport cost minimization and input-output relations such as steel and chemical clusters are known as production complexes and tend to present limited potential for knowledge spillovers and radical innovation (Iammarino and McCann, 2006) (see also Section 4.3).

If industries relocate production steps driven primarily by minimizing transport costs of renewable electricity and green hydrogen, and innovation continues to be driven by large incumbents via in-house R&D, it would be unlikely that the industrial clusters formed around green hydrogen *production* would lead to significant knowledge spillovers and opportunities for diversification through radical innovation.

Conversely, the parts of the value chain related to the development of new equipment and knowledge for novel applications or to the provision of financial and consulting services could locate in clusters in the form of urban agglomerations or new social networks (Iammarino and McCann, 2006) to benefit from knowledge spillovers from a larger variety of industries. This implies that the activities with the greatest potential for knowledge spillovers and radical innovation may not be located at the same place as the green hydrogen production cluster.

5.2 Specialization, diversity, and growth

Regarding diversity versus specialization, localization economies lead mainly to productivity increases through incremental innovation and process innovation, but do not necessarily enable employment growth since process innovation can be labor-saving. Jacobs externalities, conversely, facilitate "break-through" innovation through the combination of diverse capabilities, which enables the creation of new markets and products resulting in employment growth (Frenken et al., 2007; Glaeser et al., 1992).

Moreover, diversification into activities that draw upon a broad set of capabilities can enhance the relatedness density of an economy, thereby expanding its opportunity space for further diversification. By contrast, diversification into activities that rely on one a small set of capabilities limit the range of capabilities that can subsequently be leveraged for additional diversification (Iammarino et al., 2019; Pinheiro et al., 2022).

Regarding timing, early maturity stages are characterized by fewer competitors and higher potential for innovation rents. These technological opportunities tend to decrease as a sector matures (Perez and Soete, 1988; Lee and Malerba, 2017; Hartmann et al., 2021). Hence, entering an economic activity when this activity is already mature would present significantly lower potential for economic growth than early entrance.

If developing economies offer low cost inputs but have lower levels of economic complexity, presenting relatedness to a limited set of capabilities (Pinheiro et al., 2022; Growth Lab at Harvard University, 2024), it could be that only the activities focusing on low-cost mass production in specialized clusters would be attracted to these locations. Activities focusing on early innovation or requiring a broad set of capabilities would be less likely to locate in these places. As a result, green hydrogen production clusters would have limited potential to foster subsequent diversification in developing economies, but more complex activities in the value chain could still become a source of economic competitiveness for advanced economies. This would reinforce - rather than transform - current patterns of specialization and diversification.

5.3 Spatial scale of externalities

Regarding the spatial scale, industry agglomerations where externalities are present locally through value chain input-output linkages or knowledge spillovers tend to enable the processes of social reproduction and sustained urbanization (Phelps et al., 2015). Conversely, in highly specialized and spatially bounded agglomerations that rely on few large multinational firms with often fly-in fly-out workers, externalities seldom materialize at the local level (Phelps et al., 2015).

The absence of local knowledge spillovers can be a constrain for long term competitiveness in a context where labor and capital are globally mobile (Maskell and Malmberg, 1999; Phelps, 2004;

Iammarino and McCann, 2013). This would result in enclave-types of industrial agglomerations, which present large short term gains, but net negative economic benefits in the long run (Phelps et al., 2015).

Green hydrogen production clusters may offer limited opportunities for self-sustained economic development. As explained, these clusters would likely resemble the production complex type, where innovation is dominated by large incumbents, intrinsically presenting limited potential for knowledge spillovers locally. More specifically for the case of ongoing international projects in developing countries, projects are mostly located in isolation in out-of-town, sparsely populated littoral port lands (Scholvin, 2023; Caiafa et al., 2024; Notteboom and Haralambides, 2023). This geographical disconnection with other centers of economic activity can decrease the potential for knowledge spillovers to indigenous companies. Interests from large incumbents and international donors could further constrain this potential through an active effort to protect their competitive advantage (Caiafa et al., 2024). While these clusters could still lead to employment and income through value chain linkages, these could be limited at the local scale as multinational firms opt for importing equipment, direct employment in renewable electricity and green hydrogen electrolysis is relatively low, and companies have been asking for tax exemptions (Scholvin, 2023; Caiafa et al., 2024). And, since some of these activities are highly capital intensive with modular equipment that can be relatively easily transported (Caiafa et al., 2024), benefits may not be guaranteed in the long run. This all would limit the social reproduction of the cluster and hinder long term competitiveness, leading to industrial formations closer to enclaves than dynamic agglomerations.

6 Discussion

6.1 Implications for development strategies in different geographies

There are two implications worth highlighting in terms of regional development. First, if the renewables-pull effect is to be sufficiently strong to incentivize relocation of activities, this will more likely be for the energy-intensive production steps, especially in applications at more mature stages. This implies that the type of cluster formation would be of a relatively specialized production complex with incremental innovation. While this could lead to employment creation and increase in industrial output in the short term, the potential for leading to the dynamic externalities that the literature has associated with long-term competitiveness and growth would be limited. In fact, these dynamic externalities are more likely to be captured by places with already existing related, complex, capabilities. Additionally, it would be activities in footloose industries that would be more likely to change their geographical patterns, but these are precisely those that are characterized by rapid innovation cycles. This fast-pace of innovation dynamics may make it even harder for developing economies without pre-existing capabilities to accompany the pace of innovation.

Second, if relocation does happen, not only the renewables-pull effect will play a role. Path-dependencies in trade, investment, and industrial specialization patterns would be expected to influence relocation destinations, since existing networks and local capabilities would contribute to reduce non-geographical dimensions of distance. Especially for spatially-sticky industries, inertia would likely be present. This means that paces that combine availability of factor inputs, existence of consumer industries within short distances and availability of related capabilities are in relatively more favorable position to become leaders in a green hydrogen economy.

This suggests a more nuanced interpretation of claims that relocation will be highly transformational. While relocation would lead to a more drastic reorganization of value chains compared to importing green hydrogen to current production locations, it would not necessarily alter broader patterns of specialization and diversification: regions with complex capabilities are expected to remain best positioned to diversify into complex activities, whereas regions with limited capabilities are more likely to attract simple, mature, mass-production ones.

Whether green hydrogen can be a leverage for development for a particular developing economy will depend on its specific context — including existing capabilities, alternative development options, and the governance mechanisms in place. Localizing relatively simpler functions in the value chain may still increase the economic complexity and related density of some developing economies, depending on their pre-existing activities. Moreover, diversification into new export sectors can help reduce dependence on a narrow rage of commodities, and new jobs and income - even if relatively limited - can help meet urgent short-term development needs. Nevertheless, hoping that "green hydrogen valleys" will naturally evolve into the next Silicon Valley is a misguided expectation. For green hydrogen production clusters to support economic development in the long-run, policy makers should ensure local suppliers are engaged and that local learning is maximized. The enclave-risk can be further mitigated by leveraging tax revenues from these activities to support redistributive policies, education, and programs for promoting economic diversification. However, governments in developing economies may not have the capabilities to devise and implement these policies because of a lack of knowledge and experience, power dynamics in value chains, or even interests of local incumbent sectors and groups.

6.2 Implications for green hydrogen value chain research

The literature review in this paper indicates that while techno-economic aspects are well-covered in the renewables-pull literature, aspects related to agglomeration externalities, characteristics of the knowledge base, industry innovation dynamics, and product and industry life cycle are not as widely discussed. As a result, most conclusions about the renewables-pull effect reflect cost-optimization perspectives aligned with classical and neoclassical location theory, but overlook many of the insights from economic geography literature developed after the 1990s, providing only a partial view of industry dynamics.

A first area for further research would be to conduct empirical analysis of the green hydrogen economy using an integrated global value chain perspective combining all the different location drivers. That is, to assess importance of factor input not only for production of electricity and hydrogen, but also for equipment manufacturing, for instance. Research could assess the relative importance of different location drivers for how firms in green hydrogen value chains locate their different activities - from corporate to R&D -, not only the energy-intensive production steps. Here, it would be interesting to disentangle how different aspects of relatedness - input, infrastructure, knowledge, skills, and institutions - may influence different activities.

A second area for further research concerns how the green transition may alter innovation and inter-firm dynamics in chemical and steel clusters. Most of the evidence on innovation dynamics in these clusters are from past decades, when these activities were already relatively mature. The need to develop new production technologies and applications for existing products may impact how innovation happens in these clusters, affecting the relative importance of knowledge spillovers, diversity, and existing institutions as location drivers.

Third, understanding how location drivers may evolve over time would be important, particularly as hydrogen transport costs may fall with technological learning.

7 Conclusions

This paper integrated the literature on economic geography with the literature on green hydrogen value chains to identify how location drivers in a green hydrogen economy may reorganize global value chains and to understand the implications for economic development patterns across regions.

This study suggests that, while availability of factor inputs and transport costs could incentivize relocation of hydrogen-based production steps to places rich in renewable energy, water, and land resources, the high requirements in terms of knowledge complexity and cumulativeness could push the location of more innovative and complex steps in the value chain to places with existing related capabilities. The relative importance of lower factor input prices, savings from transport costs, economies of scale, and the availability of related capabilities is expected to vary across activities in the green hydrogen value chain. More complex and innovative activities would more likely take place in corporate headquarters and in regions that are relatively specialized in knowledge production and invention of new technologies. Conversely, more energy-intensive and mature steps of the production process could locate closer to factor inputs to take advantage of lower input-output transport costs, but even here, a history of specialization in similar activities would be important given the levels of tacitness, cumulativeness and reliance on specialized suppliers.

Finally, if industries do relocate, they are more likely to move to more familiar than unfamiliar places.

The implications for regional development come from the specialization patterns that could arise. Places combining all three elements (availability of factor inputs, existence of consumer industries within short distances and availability of related capabilities) would be in the most favorable position to become leaders in a green hydrogen economy. Conversely, those that have only relative abundance of factor inputs would likely only be able to localize more mature and less complex activities, while those that have related capabilities but no relative abundance of factor inputs would likely localize the more immature and more complex activities, with higher competitiveness gains.

Additionally, green hydrogen clusters in developing economies risk becoming enclave-like production complexes. The co-location of renewable electricity, hydrogen production, and hydrogen consumer industries would be primarily driven by cost minimization and economies of scale. The dominance of large incumbent multinational firms restrict knowledge transfer and capability building opportunities for domestic actors, while a reliance on foreign suppliers limits local value chain linkages. Given low direct employment, reliance on imported equipment, and limited spillovers to domestic firms, such clusters would generate limited pecuniary and technological externalities at the local level. Consequently, in contexts of low economic complexity, as in many developing economies, green hydrogen clusters are unlikely to promote sustained diversification, resembling enclaves rather than dynamic agglomerations.

Therefore, while green hydrogen has been widely promoted as an opportunity for developing countries to promote "green industrialization" and "green growth", the insights in this study urge caution. Relative abundance of natural resource inputs is one of the drivers for industry relocation, but not the only one. And even if relocation happens, the activities to be relocated driven exclusively by input availability are likely to be less complex, more mature, and hence with less opportunities for promoting the kind of long-term dynamic benefits that have been associated with economic growth. Moreover, relocation will be more likely to happen to places that are already well-connected in global trade and investment networks, offering limited possibilities for very marginalized regions. Hence, despite expectations that green hydrogen can lead to a reorganization of global value chains, path dependencies impose an important constraint to the degree of transformation.

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