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Low-emission hydrogen: global value chain opportunities for latecomers and industrial policy challenges

Tilman Altenburg¹ · Rita Strohmaier¹

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Abstract

To meet decarbonization targets, demand for low-emission hydrogen is increasing. A considerable share of supply will come from latecomer countries. We study how latecomer countries and firms participate in the emerging global low-emission hydrogen economy and how industrial policies can help maximize societal benefits. This requires a specific conceptualization of industrial policy: First, the latecomer condition calls for specific policy mixes, as latecomers typically cannot build on established innovation systems and network externalities, and rather need to combine FDI attraction with measures strengthening absorptive capacity and ensuring knowledge transfer from FDI to domestic firms; second, low-emission hydrogen is a policy-induced alternative that requires creating entirely new firm ecosystems while competing with lower-cost emission-intensive incumbent technologies. Hence, industrial policies need to account for enhanced coordination failure and internalization of environmental costs. We analyze the published national hydrogen strategies of 20 latecomer economies and derive a novel typology differentiating four hydrogen-specific industrial development pathways. For each pathway, we assess entry barriers and risks, identify the policies suggested in the country strategies, and discuss how likely those are to be successful. The novel pathway typology and comparison of associated policy mixes may help policymakers maximize the gains of hydrogen investments.

Keywords Low-emission hydrogen · Industrial policy · Latecomer economy · National hydrogen strategies · Industrial upgrading

Introduction

Low-emission hydrogen (LEH) has the potential to play an important role in the decarbonization of sectors where emissions are hard to abate. This is particularly the case for iron and steel, chemicals, cement, and long-haul transport, including aviation and maritime shipping (IEA, 2023). More than 140 countries, including the biggest greenhouse gas emitters, have committed to a net-zero target,¹ as have

many of the hard-to-abate industries (World Economic Forum, 2023). Global demand for low-emission hydrogen is therefore set to increase ten-fold by 2030 to 6 million tons per year with the current policy incentives, although this is only a tiny fraction of the 65 million tons needed annually by 2030 in a net-zero scenario (IEA, 2024a, p. 23). In fact, the number of announced investment projects has been continuously increasing, covering an annual LEH production of 49 million tons in 2030 if all projects were realized. Yet, only 7% of those projects already have a Final Investment Decision (IEA, 2024a, p. 61), highlighting the uncertainty inherent in the emerging LEH economy, and several major hydrogen projects have recently been canceled as offtakers shy away from long-term agreements as long as LEH prices are still high (Čučuk, 2024).

The shift to LEH has the potential to trigger profound changes in global value chains [GVCs] (Eicke & De Blasio, 2022; IRENA, 2024; Stamm et al., 2023) and in the way firms organize their operations (Baglieri, 2024).

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¹ <https://www.un.org/en/climatechange/net-zero-coalition>.

Hydrogen-based ecosystems would replace fossil fuel-based ecosystems with a very different set of technologies and firms aimed at exploiting solar and wind energy, capturing and storing carbon emissions and changing transport and transmission infrastructures. Moreover, its use in a variety of downstream industries requires deep changes in the production processes of heavy industries and technological and infrastructural adaptations in long-haul and heavy-weight transport (IEA, 2023).

These changes imply spatial reconfigurations of GVCs. Demand is concentrated in heavily industrialized regions. Some of those (including the USA and China) are expected to be able to produce sufficient LEH at home, whereas others will strongly rely on imports; the latter include Germany, Belgium, the Netherlands, Japan and South Korea (Hydrogen Council, & McKinsey & Company, 2023). Supply will come from countries with excellent energy endowments, many of those being latecomer economies in the MENA region, Southern Africa, South America and South Asia (IRENA, 2023). By 2050, the larger portion of LEH, i.e., 200 out of 375 MTPA required for net-zero, could be transported over long distances (Hydrogen Council & McKinsey & Company, 2023).

The enormous anticipated demand for LEH therefore provides new opportunities for latecomer firms and countries tapping into, and potentially upgrading in, GVCs. Very little has been published thus far, given the nascent stage of the LEH market. Research gaps exist both with regard to *how value chain configurations and technological requirements change*; and the *mix of policies* that public authorities can design to shape cross-border business transactions and allow for economic upgrading in the related industries.

Addressing these gaps promises new insights for the GVC, the international business and the industrial policy literature, as LEH displays two important characteristics that set it aside from most other GVCs. First, as an energy carrier that can be used as both a fuel and feedstock, LEH is versatile, with ramifications for many industries and therefore a plethora of options for specialization and economic upgrading (Stamm et al., 2023; UNIDO et al., 2023). Second, the global hydrogen market is essentially policy-induced and dependent on socio-political preferences and settlements. Market ramp-up strongly depends on import countries' political priorities – e.g., how ambitious their decarbonization plans are, how much they regulate and incentivize domestic industrial transformation, and how they structure their trade policies to confront carbon leakage. This policy-induced characteristic significantly affects latecomer's upgrading opportunities, setting LEH aside from most previous industrial transformations that have essentially been driven by technological innovations (Schmitz et al., 2015). Policy-induced industrial transformations are subject to political contestation and potentially unstable national and

international socio-political settlements. Latecomers have to deal with the resulting uncertainty in aligning their policy frameworks internationally and searching for upgrading opportunities under different scenarios.

Against this background, this paper addresses two research questions: How can latecomer countries and firms tap into, and upgrade in, the emerging global low-emission hydrogen economy? And: How can industrial policies contribute to shaping these pathways and exploiting the potential development benefits they offer?

Based on a content analysis of 20 national hydrogen strategies and backed by several in-depth country studies, we propose a typology of four industrial development pathways for latecomers in the emerging global hydrogen economy. These pathways vary by purpose and initial country conditions and entail very different industrial activities and upgrading opportunities. At the same time, each pathway requires a very specific set of industrial policies. The challenges associated with each pathway and the policy responses provided in latecomer strategies are subsequently summarized and discussed.

The remainder of this paper consists of six sections. The first section develops a “**Conceptual framework**” section develops a conceptual framework that helps to structure our empirical sections. It distinguishes two specific characteristics with profound implications for the design of industrial policies: the specific challenges of latecomer development; and the policy-induced character of green industries, such as LEH. The “**Methodology and research design**” section provides an overview of how the emerging hydrogen economy affects a wide variety of industries and induces considerable change in upstream and downstream activities. This excursus is indispensable to understand the multiplicity of (potential) GVC configurations and serves as the groundwork for our subsequent typology of industrial development pathways. The “**Building the LEH ecosystem: main sector components**” section presents the methodology employed for the following two empirical chapters. In the “**Industrial development pathways of latecomers: exploiting opportunities in LEH value chains**” section, we analyze 20 national hydrogen strategies of latecomer countries and the emerging body of literature on LEH to develop a typology of four industrial development pathways, characterize each of them and compare them in terms of upgrading opportunities. The “**Pathway-specific industrial policies compared**” section then analyses the industrial policy content of these national strategies, assigning policy packages to the four pathways. Moreover, we draw on insights from the industrial policy literature to address trade-offs and implementation challenges associated with these policy packages. The final section concludes and identifies promising research avenues for scholars of international business policy.

Conceptual framework

Countries pursue industrial policies to reinforce or counteract the allocative effects of markets with the aim of restructuring economies towards better outcomes (Rodrik, 2004). Hence, they address market failures, for example, due to incomplete information, insufficient appropriability of the benefits of R&D investments, the market's inability to ensure optimal investment coordination, or because purely market-based allocation may forego dynamic knowledge spillovers (Chang, 1994).

Some authors hold that the market failure rationale is insufficient or even misleading (Bleda & del Río, 2013), as it is based on unrealistic welfare theorems of neoclassical theory, overestimating the allocative functions of markets and underestimating the pervasiveness of non-market institutions (Cimoli et al., 2009). This led to the notion of systems failure which accounts for a range of economic and non-economic factors preventing entire systems from transitioning to a new stage (Klein Woolthuis et al., 2005).

In any case, industrial policies are employed when there is a gap between *private and social returns* to investments. This justifies a wide range of interventions that are in fact widely used across countries and sectors and which we here call *generic* industrial policies. These include support for R&D, coordination of actors, norm and standard-setting, subsidies and investment guarantees and other instruments in a wide variety of forms (Altenburg & Lütkenhorst, 2015; Rodrik, 2009).

We argue that the specific subject of this paper – the upgrading opportunities and policies of latecomers in the LEH economy – requires a specific conceptualization of industrial policy. Countries here face additional challenges that call for tailored upgrading strategies and industrial policies beyond the generic set of policies. First, challenges stemming from the latecomer context; and second, challenges related to the specificities of “green” industrial transformation.

Latecomer industrial development, GVC upgrading and the required industrial policies

The term “latecomer” is used here for firms and countries that integrated in global markets later than their competitors (Mathews, 2006). Early industrializers are in an advantageous position. They have accumulated knowledge and invested in production at scale and network externalities with business partners and customers over decades, or even centuries. New Trade Theory (Krugman, 1987) underlines the centrality of increasing returns to scale and network effects for self-reinforcing competitive advantage. When latecomers start their development journey, they do so without similar

scales and network externalities, with lower levels of economic complexity, lower R&D shares in GDP, fewer competitive firms and weaker institutions than their international competitors. Their main comparative advantage lies in classical natural resource endowments and/or low labor costs. In exploiting those, however, they can benefit from what Gerschenkron (1962) called the “advantage of backwardness”: Business models can be copied, foreign technologies licensed, and globally leading firms can be attracted to undertake investments in the latecomer economy. From this perspective, trade liberalization, open-door policies for foreign direct investment (FDI) and participation in GVCs can help latecomers increase their productivity without having to repeat all the trial-and-error processes that early movers had to undergo (Lin, 2016).

Empirical evidence confirms both latecomer advantages and disadvantages. A number of studies show that liberalizing trade, using FDI and participating in GVCs can increase output, productivity, value added, and employment through a variety of channels (Gereffi, 2019; Taglioni & Winkler, 2016). Yet, research also consistently shows that not all countries gain from attracting FDI (Görg & Greenaway, 2004) and participating in GVCs (Kümmritz et al., 2017). For developing countries in particular, Pipkin and Fuentes (2017) state a wide range of variation in benefits from GVC participation.

Gains from trade and GVCs are not automatic because the relevant knowledge does not disseminate in an easy and frictionless way (Saviotti, 1998), given limited codifiability, lack of absorptive capacity and deliberate strategies of foreign investors to prevent leakage of competitive advantage (Berry, 2017; Contractor, 2019; Rao et al., 2024). Moreover, borrowing technology and inviting firms with superior performance may hamper domestic competition.

These observations triggered a substantial amount of research focusing on the determinants of economic upgrading in GVCs (Gereffi, 2005; Gibbon & Ponte, 2005). GVC upgrading is understood as “the process by which economic actors (...) move from low-value to relatively high-value activities in GVCs” (Gereffi, 2005). Humphrey and Schmitz (2002) identified four types of upgrading that firms or groups of firms can achieve in GVCs, differentiating between product, process, functional and chain upgrading. Kaplinsky and Morris (2001) emphasized the relevance of asymmetric power relations between lead firms and suppliers and how those impact on the distribution of rents across value chains. Gereffi et al. (2005) took this one step further, introducing a typology of power relations in GVCs that helps to understand which types are more conducive to upgrading.

Another important strand of research points to the role of technological discontinuities: The more an industry builds on increasing returns and network effects, the more difficult it is for latecomers to catch up. Technological

discontinuities, in contrast, may erode the value of specific investments and established network externalities (Anderson & Tushman, 1990), thereby creating space for catching up or even leapfrogging ahead (Lee & Malerba, 2017). In practice, however, changes are rarely so radical that they devalue all existing assets and capabilities; some of those built for the previous industrial paradigm help to transition to the next one (Schmitz & Altenburg, 2016). Understanding the relatedness of old and new capabilities (Boschma et al., 2017; Hidalgo, 2021) is therefore crucial for assessing upgrading and leapfrogging opportunities.

Studies consistently highlight the importance of industrial policy for economic upgrading within GVCs (De Marchi & Alford, 2022; Gereffi & Sturgeon, 2013; Kaplinsky & Morris, 2016; Morris & Staritz, 2019). What is often overlooked is that early industrialized countries and latecomers require *different sets of industrial policies* (Kaplinsky, 2014). Early movers mainly aim to push the technological frontier to stay ahead of competitors. Hence, they invest e.g., in R&D, pilot applications, venture capital, and university–industry cooperation. At the same time, their industrial policies erect barriers to prevent leakage of their know-how, e.g., via intellectual property rights, standards, and trade policies. Latecomer industrial policy, in contrast, revolves around three sets of policies (Altenburg, 2000): First, those to attract FDI through improving the general investment climate, negotiating trade agreements and strategically targeting the most attractive investors in terms of domestics spillover; second, those aimed at improving the absorptive capacities of domestic firms and institutions (Bell & Pavitt, 1993; Chen & Sun, 2023); third, policies aimed to break into the proprietary knowledge assets of foreign investors and accelerate technology transfer. The latter may entail using local content requirements, joint ventures, technology-sharing agreements and supplier development programs. All these actions are ideally packaged to gradually shift beyond the original comparative advantages into higher-value activities (Gereffi, 2019).

When it comes to strategy, it is important to distinguish between latecomer “countries” and latecomer “firms” (Sinkovics & Sinkovics, 2019). Subsidiaries of Multi-National Enterprises (MNEs) may play an important role in latecomer countries’ firm ecosystems, thus it matters to understand MNE strategies (Buckley & Ghauri, 2004) and headquarter–subsidiary relations (Kostova et al., 2016). Also, the level of competitiveness of firms within a country, and their upgrading opportunities and strategies, may diverge considerably. Firms may design very specific upgrading strategies, e.g., using firm alliances, mergers and acquisitions (Lema & Lema, 2012). A considerable strand of research therefore explores upgrading strategies at the firm level (Awate et al., 2015; Hobday, 1995; Mathews, 2002). Country governments, however, need to adopt a broader

perspective on promoting structural change and consider societal objectives.

The specificities of “green” industrial policy

The structural transformation towards “greener” industries involves additional challenges that call for a rethinking of industrial policy. This applies to industrial policies in the pursuit of decarbonization (Meckling, 2021). “Green” industrial policies differ considerably from industrial policies in a business-as-usual setting (Altenburg & Rodrik, 2017). Most importantly, the push for greener industries is not induced by the superiority of green solutions in commercial terms, but by a societal objective to align production with planetary boundaries. National governments and international institutions are pushing this transformation against unsustainable dominant designs (Andersen & Tushman, 1990) that remain more competitive as long as environmental externalities are not accounted for. “Directionality” (Mazzucato, 2016; Yap & Truffer, 2019) is thus a key feature of green industrial policy, as governments make an ex-ante distinction between “good” and “bad” technologies and not only push new industries, but in parallel proactively incentivize the phasing-out of undesirable technologies and business models (Altenburg & Rodrik, 2017). A range of instruments is applied to steer investments towards sustainable alternatives, from environmental taxes and cap-and-trade systems for emissions to subsidies, penalties, and regulatory requirements. Often, long-term support is required to create the scales of production and learning effects needed to bring costs of green alternatives below those of unsustainable dominant designs (Gambhir et al., 2014).

Moreover, the green transformation sometimes requires the establishment of complex not-yet-existing production systems. In our case, hydrogen-using technologies often require major process changes, several hydrogen production technologies are still in their infancy, pipeline, transmission grids and specialized tank ships need to be built, and technical standards agreed to ensure interoperability. On the supply side, green and blue hydrogen can only become cost-competitive once economies of scale and technological progress kick-in, yet initial investments are held back as offtakers are unwilling to accept the initial high initial prices. Ramping-up the hydrogen market thus requires multiple coordinated interventions, requiring “strategic investments and public policies that aim to create and shape markets, rather than just ‘fixing’” them (Mazzucato, 2016, p. 140).

What these policy-induced markets should look like, however, is politically contested (Marquardt et al., 2022), especially when measures increase costs for industries and consumers and phase out commercially successful industries. Internationally, jurisdictions diverge in terms of environmental ambition, and different interpretations exist,

for example regarding what to classify as “low-emission”, which technological risks (e.g., nuclear, carbon storage) are acceptable, and whether emissions embedded in traded goods should be accounted for by producing or consuming countries (Steininger et al., 2018). Lack of agreed standards then leads to fragmented and distorted markets (Agora Industry, 2024). Ambitious national decarbonization risks carbon leakage (Jakob, 2021), which governments try to contain by an additional layer of industrial policies, either imposing standards and penalising imports from jurisdictions with lower standards; or compensating national industries with project-based carbon contracts-for-difference (Richstein & Neuhoﬀ, 2022) or other subsidies. Recent years have witnessed an increasing subsidy race between China, the US, and Europe to attract or retain green investments (Gehrke, 2022; Tagliapietra et al., 2023), to the detriment of those countries that cannot afford similar subsidies.

This entire set of transformational policies needs to be designed in ways that enhance, or do not harm, traditional industrial development and welfare objectives, such as competitiveness and employment creation (Altenburg & Rodrik, 2017). All in all, steering a green transformation requires a very proactive government approach.

In sum, latecomer countries trying to tap into emerging green markets thus need to design industrial policy package that combine

- *Generic* industrial policies with

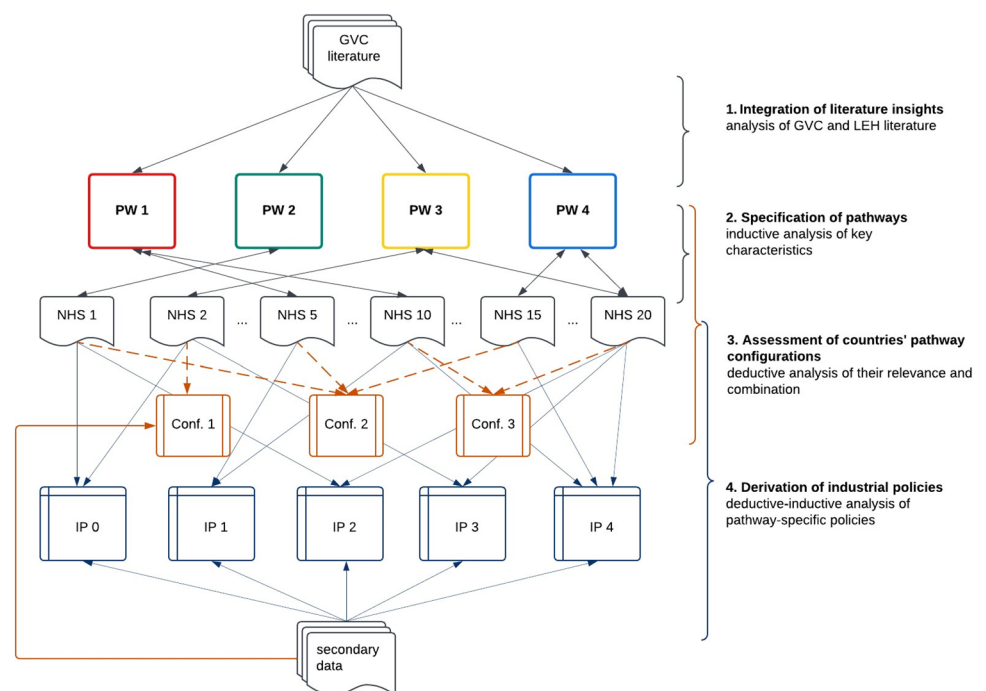
- Specific policies aimed at overcoming the *latecomer* condition and account for the
- Specific challenges of *green* industrial transformations.

In the “**Pathway-specific industrial policies compared**” section, we incorporate this distinction into our analytical framework.

Methodology and research design

Against the conceptual background provided in the previous section, the remainder of this paper explores the potential and envisioned industrial development pathways for selected latecomer countries in the context of LEH. “Below, we develop” a typology of these pathways, based on the systematic review of 20 national hydrogen strategies and roadmaps (NHS). Although these documents vary considerably in detail, ranging from eight to approximately 150 pages, they generally follow a similar structure, first stating comparative advantages, followed by specific objectives (with or without timelines) and then outlining the envisaged policies to realize them. For two of them (Egypt and Indonesia), we relied on secondary sources, in particular media articles and official presentations, as the hydrogen strategies were not accessible. To derive a typology of industrial development pathways, we used an inductive approach, also drawing on insights from theoretical and empirical GVC and LEH literature. Figure 1 presents our mixed-method research design.

Fig. 1 Research design Source: Own elaboration



We used World Energy Council-Germany (2024) data to identify all NHS available in January 2024. From that database, we selected all latecomer economies for our sample, drawing on the economic complexity index for 2019 (Simoes et al., 2025). The index is based on commodity trade data and is seen as a proxy for a country's production capabilities, as it measures the diversity and sophistication of a country's exports. We classified economies with a complexity score below 0.6 as latecomers. This resulted in a sample of 20 countries considered for the empirical analysis.² Within this group of latecomers, we established threshold levels to distinguish between “very low”, “low”, “modest”, and “moderate” complexity (see Table A.1). The respective threshold levels were defined to produce balanced subgroups of comparable size, while aligning with conventional practices in ECI classification. To build our typology, two researchers independently collected, iteratively reduced and clustered the key characteristics into specific industrial development pathways, broadly following Mayring (2008) and Steininger et al. (2021). Atlas.ti was used to code and analyze the data. Insights from the literature on GVCs and latecomer countries (see “Conceptual framework”) and selected social science studies on LEH supported the analysis. Subsequently, we assessed each country's orientation regarding the different pathways, applying a coding scheme (again using Atlas.ti) constructed from the inductively derived and theoretically informed characteristics. We categorized the four pathways for each country into three classes: highly relevant, relevant, not relevant/not mentioned.

Whether the strategies assign a high relevance to a pathway was mainly inferred through explicit or implicit (for example: envisaged quantities of production or shares in global trade) statements on their importance and broadly cross-checked against the density of related characteristics in the NHS (i.e., the frequency of their mentions). *Ranking* the importance of pathways for a given country, however, proved impossible, as there is no uniform measure that would allow to compare e.g., a quantitative export target with a qualitative technology development target.

The results were corroborated using nine country studies conducted during field research from 2022 to 2025, featuring over 100 expert interviews in total.³ Additionally, the

findings were collaboratively discussed among the authors and further refined by consulting colleagues involved in those country studies. Our analysis also informed the industrial policy discussion in the “Pathway-specific industrial policies compared” section. We extracted information from the selected NHS regarding industrial policies that have been enacted or are envisaged and assigned the respective statements to five categories: generic hydrogen-related industrial policies; and those that could be associated with the priorities and industrial activities of any of the four industrial development pathways. We triangulated the information from the strategies and roadmaps again with insights from expert interviews and secondary documents.

Building the LEH ecosystem: main sector components

Developing an ecosystem for LEH creates a formidable coordination challenge, as it requires a fundamental change in systems of production and consumption in terms of actors, technologies, infrastructures and institutions. It is therefore essential to examine the “sectoral configuration” (Bakhuys et al., 2024), i.e., the sectors linked to the value chain. In large technical systems such as LEH, involving a multitude of different technologies, these value chains necessarily become coupled as well (see, e.g., Meynard et al., 2017). This section briefly thus describes the main elements of the LEH ecosystem on the sector level, outlining the industry groups involved in orchestrating hydrogen supply, demand, and infrastructure.

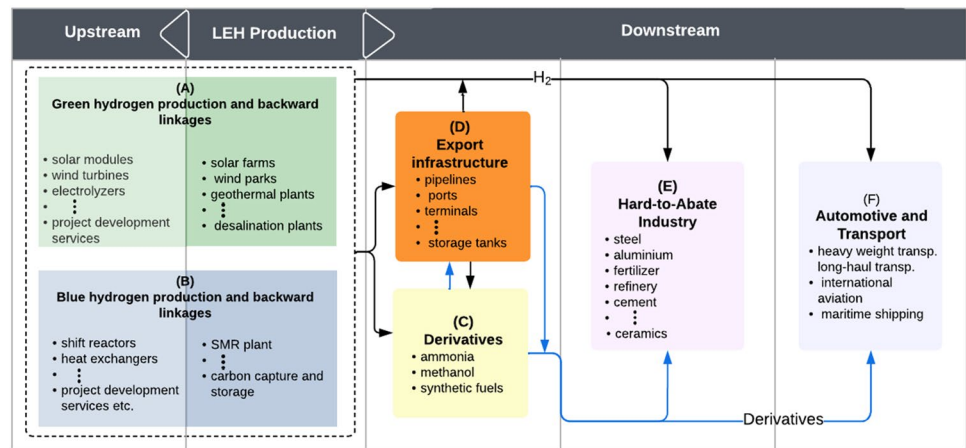
LEH is usually understood to encompass green and blue hydrogen. Green hydrogen is generated through electrolysis, using renewable energy to split water into oxygen and hydrogen. Blue hydrogen is mainly produced from natural gas via steam methane reforming, where most of the carbon emissions are then absorbed and stored or reused using carbon capture, storage and use technologies (CCUS). Blue hydrogen involves higher emissions, but is currently less expensive and therefore seen as a bridge technology. Of the announced projects⁴ for 2030, 55% are based on electrolysis and the rest on natural gas with CCUS, with investors increasingly refocusing their attention to blue hydrogen, driven by the recent drop in natural gas prices (IEA, 2024a, 2024b). Most of these projects, however, are still in their

² We used January 31, 2024 as the cut-off date for the publication of the national hydrogen strategy, considering all cases reported by the World Energy Council - Germany (2024) up to that point. To our knowledge, this should encompass *all* strategies by latecomers published by then. Note that while Indonesia's NHS was published in December 2023, it has not been accessible. Egypt's hydrogen strategy, on the other hand, had been under preparation since 2022, but was officially launched only in August 2024. Nevertheless, due to sufficient media coverage and official policy presentations, we included both countries in our analysis.

³ See Stamm et al. (2023) for South Africa, Altenburg and Kantel (2024) for Namibia; Aboushady and Jaroudi (2024) for Algeria, Stamm et al. (2024) for Costa Rica; Oyan (2024) for Türkiye, Oyan and Kantel (2025) for Kenya, as well as Strohmaier et al. (2024) for Argentina and Uruguay, and Strohmaier et al. (2025) for Brazil.

⁴ This means either with a final investment decision or are under construction.

Fig. 2 Value chain of low-emission hydrogen Source: Own elaboration



nascent phase. Following, we differentiate six groups of industrial activities, here called “sector components A–F” (Fig. 2).⁵

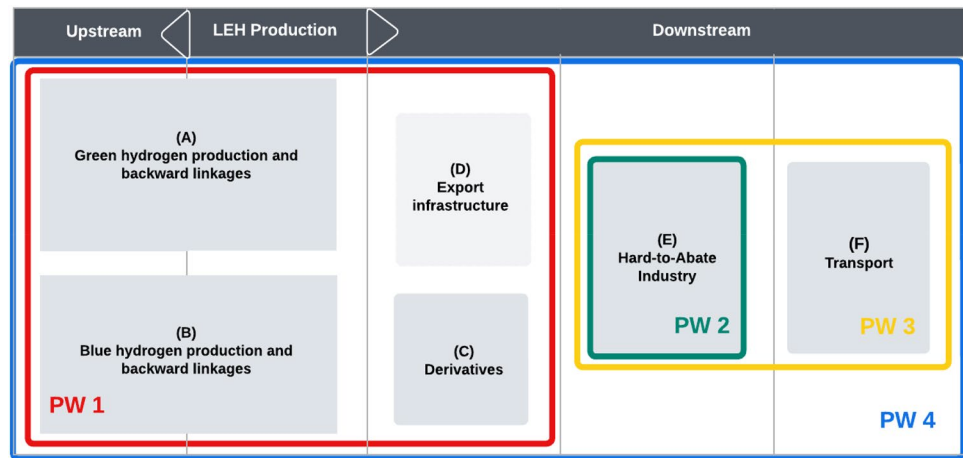
- A. Green hydrogen production and backward linkages.** For the production of green hydrogen, large solar and wind installations are needed (unless the national electricity grid is already fully decarbonized). Other renewable energy sources such as geothermal plants play a minor role. As many of the latecomer countries with favorable renewable energy endowments are water-constrained, green hydrogen projects often require seawater desalination. Projects tend to be capital-intensive and large-scale and require upstream supply, such as solar PV cells and modules, wind turbines, blades and towers as well as parts for electrolyzer and seawater desalination plants.
- B. Blue hydrogen production and backward linkages.** Blue hydrogen production requires investment in gas extraction and CCUS. Gas is extracted by drilling in pure natural gas fields or as a by-product of oil exploitation. The technologies, including drilling, steam and water shift reactors, pipes and compressors, are mature and well established in many latecomer countries, considering that long-term gas production enabled the formation of big national corporations. Industrial-scale CO₂ storage has been proven viable at numerous sites (Pettersen et al., 2022) but still lacks the experience of long-term performance and security.
- C. Derivatives.** In gaseous form, hydrogen has a low volumetric energy density. Liquefying or converting it to

derivatives like ammonia and methanol makes it easier to store and transport. This will be especially relevant for export countries in Latin America and Southern Africa that are beyond pipeline distance (about 3000 km) from major import hubs in Europe and Asia. Low-emission hydrogen can be further used to produce synthetic fuels, such as e-gasoline or sustainable aviation fuel (SAF).

- D. Infrastructure.** The infrastructure required for both domestic transport (such as pipelines and tanks) and export (pipelines, ports, and vessels) creates further industrial linkages from LEH production: natural gas pipelines need to be repurposed, new hydrogen pipelines built, ports need to be equipped with hydrogen tanks and synthesis plants, while specially equipped vessels are necessary to ship ammonia, methanol and liquid hydrogen (IRENA, 2024). Each aspect comes with its own challenges, such as limited blending potential in natural gas pipelines and embrittlement (UNIDO et al., 2023). Furthermore, cryogenic liquid, high-pressure and geological storage solutions are necessary for long-term distribution of hydrogen and balancing supply and demand (Kayikci et al., 2025).
- E. LEH use in hard-to-abate industry.** Today, conventional hydrogen – produced with fossil energy – is mainly used as a feedstock for ammonia synthesis (55% of H₂ demand, primarily for fertilizer production), in refineries (25%), and for methanol production (10%) (Riemer et al., 2022). LEH enables not only the decarbonization of these emission-intensive activities but also opens up new application opportunities, e.g., for generating high-temperature heat in the steel, aluminium and cement industry, or as a reactant in new production processes, such as the direct reduction of iron ore (Griffiths et al., 2021).
- F. LEH use in transport.** While electrification will become the dominant design in the decarbonization of the car industry, LEH technology is more efficient for long-

⁵ Note that, for the sake of simplicity, this paper does not address the use of hydrogen in the energy sector, such as for electricity generation or heating buildings. Although this is mentioned in several hydrogen strategies of latecomer countries, our discussion is confined to end uses in industry and transport.

Fig. 3 Industrial development pathways in the low emission hydrogen GVC Source: Own elaboration



distance rail and for heavy freight. Hydrogen-powered internal combustion engines and fuel cells establish forward linkages to the automotive industry. While fuel cells also hold potential in the maritime and aviation sectors, synthetic fuels are currently considered the preferred option for long-distance transport. In maritime shipping, ammonia competes with methanol as a viable alternative fuel (Weichenhain, 2021).

Industrial development pathways of latecomers: exploiting opportunities in LEH value chains

Due to its complexity, combining different sectors and value chains, the LEH ecosystem also offers multiple upgrading opportunities for latecomer countries with abundant clean energy endowments. Drawing from the analysis of 20 national hydrogen strategies, four industrial development pathways are in the following identified along the entire hydrogen value chain: Each pathway not only emphasizes different purposes and initial conditions but also involves different industrial activities (or sector components), ultimately leading to different value chain configurations.⁶ These are presented below in the first four sub-sections, “Export”, the targeted industrial activities are illustrated in Fig. 3 and their main characteristics summarized in Table 1. As shown in the subsequent “How pathways are combined and sequenced” sub-section, the pathways are often combined in practice, and most country strategies integrate

several of them, albeit with different priorities and timelines (Table A.1 in the Annex). In the final sub-section, we provide a comparative assessment of the pathways, in terms of upgrading opportunities, the role of firms, and GVC entry barriers.

Export-revenue pathway

Furthermore, most countries want to combine LEH production with (5) targets to increase local content in the required energy technologies. Only a few countries specify the part of the value chain (such as Namibia, aiming to produce wind towers and blades locally).

Strategy

This route focuses on supporting large-scale projects aimed at exporting hydrogen, either in molecular form or as derivatives such as ammonia, methanol, and synthetic fuels, thus encompassing industrial activities related to A–C in Fig. 3.

Purpose

Countries state different purposes for embarking on this pathway: (1) access to new international markets (e.g., Uruguay and Namibia); (2) replacing fossil fuel export revenues (especially coal) with sustainable energy (e.g., Colombia, South Africa); and (3) bridging the initial lack of domestic demand (Ecuador), or (4) capitalizing on excess production of low-carbon hydrogen mainly dedicated to the national market (e.g., Egypt, Indonesia).

Favorable initial conditions

Countries often highlight their competitive endowments with natural resources: renewable energy and/or natural gas for producing LEH as well as availability of land for energy

⁶ Another typology has been proposed by Weichenhain et al. (2021), distinguishing between three “Hydrogen Valley Archetypes”. These are derived from an analysis of geographically confined hydrogen investment projects in industrialized countries. The “Archetypes” correspond roughly with our export-revenue and domestic decarbonization pathways, but do not capture the other two pathways.

Table 1 Industrial development pathways along the LEH value chain

	Export-revenue pathway	Hydrogen pull pathway	Domestic decarbonization pathway	Niche technology pathway
Strategy	Leverage energy resource endowments to increase export revenues attracting FDI in LEH & derivatives	Leverage regional differences in the marginal cost of LEH to attract energy-intensive downstream industries	Decarbonize existing hard-to-abate industry and/or transport sectors	Design & develop LEH-related technologies
Focused sector components	Hydrogen production (incl. derivatives, upstream & infrastructure activities)	Hydrogen production and downstream industry	Hydrogen production and downstream industry	Any stage of LEH value chains
Main purpose	Access to new international markets, replacement of fossil fuel export revenues, local content mfr.	Economic diversification, reducing import dependency, broader green industrialization	Retain competitiveness, meet national mitigation and decarbonization targets	Targeted at local use in LEH supply chains or new competitive exports
Favorable initial conditions	Resource availability, location, attractive business ecosystem	Low energy costs, market access, attractive business ecosystem	Decarbonization incentives, large market, export-oriented star firms	Good national RDI system, skilled workforce
Focal firms	Foreign companies/MNEs, project developers, local firms as suppliers	Foreign companies/MNEs, project developers, local firms as suppliers	Domestic star firms/SOEs and locally invested MNE subsidiaries	Domestic star firms/ SOEs and tech companies

Source: Own elaboration

generation, electricity grids, pipelines, and ports. Several countries also state water availability as a comparative advantage (e.g., Brazil, Uruguay). Some countries mention geostrategic advantages (e.g., proximity to shipping corridors), special capabilities (e.g., Fischer-Tropsch skills for the production of synthetic fuels in South Africa), existing transport infrastructure (e.g., ports, pipelines and storage, as mentioned by Algeria, Egypt, and the United Arab Emirates), and decarbonized electricity grids (Brazil, Costa Rica). Furthermore, while some strategies highlight the role of national energy companies (e.g., the United Arab Emirates) for the export-revenue pathway, most of them explicitly target FDI. For this, a business-friendly investment climate matters. Several countries emphasize in this regard their political and macroeconomic stability and solid regulatory frameworks (Costa Rica and Uruguay), as well as experience in developing energy projects (e.g., Algeria, Uruguay and the United Arab Emirates).

Hydrogen pull pathway

Strategy

This pathway⁷ leverages regional differences in the marginal cost of LEH to attract energy-intensive *downstream* industries (segment E in Fig. 3), mainly via relocation from abroad. Costa Rica, for example, highlights the potential of green hydrogen to attract the development of industries such as fertilizers and ammonia, iron and steel, and glass.

Purpose

By focusing on the downstream integration of LEH production, three objectives are stated in national strategies: (1) increasing economic diversification, (2) reducing import dependency, especially regarding fertilizers; (3) stimulating job creation, and (3) broader green industrialization. South Africa also emphasizes the role of inward investment for improving the balance of payments.

Favorable initial conditions

The main competitive advantage for hydrogen pull lies in low hydrogen costs, supplemented by land availability, geographic proximity, and preferential access to green lead markets. As the pathway is mainly FDI-driven, a stable business ecosystem, good governance, and sound environmental and social safeguards are relevant as well.

⁷ The name of this pathway was chosen to align with the “renewables pull” concept introduced by Samadi et al. (2023), who define it “as the pull factor for industrial production triggered by exceptional renewable energy conditions in certain regions of the world” (p. 1). However, our analysis encompasses not only hydrogen produced from renewable energy sources but also hydrogen derived from fossil fuels in combination with CCUS. Therefore, we introduce the term “hydrogen pull” to capture the broader industrial production and relocation incentive associated with access to low-emission hydrogen, irrespective of the specific production pathway.

Domestic decarbonization pathway

Strategy

This pathway prioritizes hydrogen production for domestic decarbonization. It thus raises industrial development opportunities in all the basic hydrogen industries (value chain segments A–C in Fig. 3) as well as in local offtake industries (D and E in Fig. 3).

Purpose

The main motivation behind this pathway includes (1) meeting national mitigation and decarbonization targets, (2) reducing local air pollution, as well as (3) enabling domestic carbon-intensive industries to compete in green lead markets and export without facing carbon-border taxes.

In the transport sector, the decarbonization pathway focuses on heavy-freight and public bus transport (e.g., Costa Rica, Colombia) and logistics at ports (e.g., Sri Lanka and Panama) or in mining (Chile, South Africa). A special case of domestic decarbonization refers to fuels offered for maritime shipping along major shipping routes (Panama, Egypt) or air traffic hubs (United Arab Emirates).

Favorable starting conditions

Forging this pathway requires green fiscal policy: clear national decarbonization targets, backed up by sector-specific regulations such as fuel blending requirements, subsidies for national champions to retrofit plants (see, e.g., South Africa, United Arab Emirates), and carbon pricing (see, e.g., Brazil). Especially in internationally traded hard-to-abate industries, such as steel and fertilizers, big manufacturers in latecomer countries anticipate stricter international carbon standards and carbon border taxes, and therefore undertake substantive investments in LEH and derivatives.⁸

Technological niche upgrading pathway

Strategy

The main objective here is to accumulate capabilities in specific new hydrogen-related technologies or services. The innovation can thereby contribute to any of the value chain segments (A–F).

⁸ For example, between 2023 and 2027, Morocco's phosphate giant OCP plans to invest \$13 billion in five GW of renewable energy and a green ammonia plant for one million tonnes annual capacity, to substitute fossil fuel-based “grey” ammonia imports for its fertilizer manufacturing operations, see <https://ammoniaenergy.org/organization/ocp/>.

Purpose

Technological niche upgrading can either aim at new local uses in hydrogen supply chains or, more ambitiously, at developing new competitive export products. Some are related to LEH *production*, such as the design of small-scale electrolyzers (Argentina), membrane design (South Africa), CCUS technologies such as direct air capture, blockchain (the United Arab Emirates), and new hydrogen storage solutions (Türkiye); others are pursued in LEH *applications*, mostly in mobility solutions, such as hydrogen-enriched CNG buses (India) and fuel cell-powered mine-haul trucks (South Africa, Chile).

Among the countries with ambitious technology export targets, Türkiye and India aim to become global suppliers of electrolyzer and fuel cell technologies through indigenizing large parts of the supply chain. In this regard, India highlights the advantage of the fuel cell supply chain, which – unlike battery-electric vehicles – does not rely on critical minerals, thereby reducing import dependency.

Favorable initial conditions

Favorable starting conditions mentioned in the NHS include the strength of the *research* system (e.g., Argentina, Türkiye, India); existing technological capabilities (with the United Arab Emirates mentioning their experience with CCUS technology in oil recovery and Brazil ethanol-powered fuel cells); institutional knowledge of how to create industries from the scratch (e.g., Costa Rica), and complementary natural resources (like platinum metals in the case of membrane development in South Africa or Türkiye's boron endowments for hydrogen storage).

How pathways are combined and sequenced

The NHS analysis demonstrates that all latecomer countries pursue combinations of these four industrial development pathways (see Table A.1). In particular, all 20 countries state export revenues and domestic decarbonization (either for industry or transport or both) as relevant strategies. Two-thirds of the sample assign some relevance to developing LEH-related niche technologies. Here again, the highest ambitions are associated with relatively high economic complexity. Hydrogen pull is only envisaged in three country strategies (and not as a priority), suggesting that this pathway is regarded a distant option rather than a short-term opportunity.

Pursuing several pathways in parallel or in sequence may create synergies. For instance, any additional hydrogen investment, regardless of the pathway, helps to get the market started and contribute to lower unit costs. Major export-oriented projects (Pathway 1) may help to test and showcase new business models. This, in turn, may encourage

local emission-intensive industries to also use hydrogen and derivatives (Pathway 3) or incentivize foreign companies to relocate (Pathway 2). Yet, trade-offs between pathways may also arise, as investments may compete for scarce production factors such as land and skilled labor.

Several country strategies suggest country-specific sequences of pathways and hydrogen activities, either starting with domestic decarbonization and entering export markets later, or using exports to ramp up the market and complement this with domestic uses and niche technologies once costs have come down.

Comparing pathways: upgrading opportunities and entry barriers

The following section assesses the potential of latecomer countries to tap into, and upgrade in, the global LEH economy. For each industrial development pathway, we describe the industrial activities involved and the specific upgrading opportunities. Drawing on the relevant industrial policy literature, the main entry barriers are examined through the lens of three policy challenges addressed in the “*Conceptual framework*” section: (1) generic market failures, (2) the latecomer status of firms and countries, (3) and the specific barriers and demands of transitioning to a green economy.

Export-revenue

The export-revenue pathway involves large-scale deployment of solar, wind, or geothermal plants and electrolyzers for green hydrogen, and natural gas exploitation, steam methane reforming and CCUS for blue hydrogen (Griffiths et al., 2021). Upstream operations include clean technology manufacturing and project-related services; with some activities benefiting from proximity to the market (Stamm et al., 2023). The conversion to derivatives such as ammonia and methanol, along with domestic transport (such as pipelines and tanks) and export (pipelines, ports, and vessels) infrastructure offers further upgrading opportunities in construction and equipment production (Altenburg & Kantel, 2024).

Entry barriers are substantial. *On the generic level*, the hydrogen export sector is highly capital-intensive and dependent on economies of scale, particularly in electrolysis, a costly and nascent technology. Integrating multiple technologies – some mature, some emerging – further increases operational and financial complexity (Griffiths et al., 2021; Sharma et al., 2023). Inconsistent regulations and high technical standards in importing countries create a fragmented market and compliance risks (Valentini, 2021), while the lack of long-term offtake agreements and global competition increase market uncertainty (Odenweller et al., 2022).

Latecomer-specific barriers further limit upgrading prospects. While capital intensity and high upfront costs are a

generic feature of many LEH-related technologies, country-risk premiums significantly increase financing costs in latecomer economies (IEA, 2022b). Many latecomers lack the technological and institutional capabilities to drive the hydrogen sector independently. Private project developers, often MNEs, from advanced economies therefore shape the clean energy investments in most latecomer economies (Patala et al., 2021; Steffen et al., 2018), reducing the policy space for domestic indigenization efforts. The manufacturing of key technologies (solar PV, wind turbines) is dominated by MNEs holding patents and know-how (IEA, 2022a; Nahm, 2017). Even diversified emerging economies and legacy energy exporters struggle to produce critical components in wind, solar, and hydrogen (Bazilian et al., 2020; Müller & Eichhammer, 2023). Localization of activities tends to be limited to simple standardized products (solar panel frames), bulky commodities requiring proximity to the market (wind towers: Larsen & Hansen, 2022); and high value- services like siting for solar and wind farms (Davy et al., 2024; Hansen et al., 2022).

In addition, there are significant *green-specific barriers* imposed by export markets in the Global North through strict and fragmented environmental standards, certification schemes, and supply chain monitoring requirements, posing high compliance costs and regulatory risks (see Strohmaier et al., 2024; Kayikci et al., 2025).

Hydrogen pull

In contrast to the export-revenue pathway, hydrogen pull is not yet mentioned in many strategies as a primary driver of GVC upgrading, it is expected to gain importance as decarbonization pressure intensifies and LEH costs decline (see Egerer et al., 2024; Samadi et al., 2023; Verpoort et al., 2024). This dynamic could promote new value-chain partnerships between industrialized and latecomer countries, especially in the trade of intermediate inputs such as directly-reduced iron, urea, and ethylene (Agora Industry & Wuppertal Institute, 2023; Verpoort et al., 2024). Lead firms may retain high-value downstream activities while offshoring energy-intensive stages, offering local firms opportunities through supplier linkages, spillovers and agglomeration effects (Qiang et al., 2021). Hydrogen pull may also catalyse secondary development in downstream industries, particularly the automotive sector.⁹

However, entry barriers remain. *On the generic level*, such industries often rely on local inter-firm relations to exploit industrial symbiosis and build a sector-specific skill base, making switching supplier networks costly (Ado

⁹ For example, Morocco’s automotive cluster stands to benefit from access to renewable electricity and green steel (Amachraa, 2023).

et al., 2025). The relocation of production in industries like steel – central to national and economic security – faces political resistance in the established steel-making countries, hence policymakers tend to retain them through subsidies and import tariffs.

For *latecomers*, lack of competitive local firms and shortage of skilled labor constrain the possibility to replicate the network effects enjoyed by energy-intensive industries in advanced economies. Also, industries relocating “South” for the purpose of decarbonization have stringent requirements in terms of environmental standards, e.g., lifecycle emissions monitoring. The corresponding costs of compliance (Ponte, 2020) create additional *green entry barriers* limiting participation in new hydrogen-based value chains, especially where regulatory and technical capacities are weak.

Domestic decarbonization

Under the domestic decarbonization pathway, opportunities arise across all “hydrogen basic industries” as well as in offtake industries. Avenues for domestic value creation, not only through environmental upgrading via climate-friendly processes such as DRI in steel production; but also functional upgrading through downstream fabrication (e.g., hot-briquetted iron) and inter-sectoral upgrading, as illustrated by India’s move from battery-electric to fuel-cell electric vehicles. It may also enable countries to leapfrog, as they may become competitive in the latest green technologies (e.g., green fertilizer manufacturing) without having a record in the fossil-fuel-based predecessor industry (Oyan, 2024). In transport, the use of hydrogen requires a whole new infrastructure, e.g., refueling stations and storage tanks, creating spillovers into the machinery and construction sectors (Stamm et al., 2024).

Generic entry barriers remain high due to capital and scale-intensity of most hydrogen applications. Retrofitting plants and infrastructures demands substantial investment that increases the cost of final products (Muslemeni et al., 2021). In *latecomer* contexts, the key actors for this pathway are large incumbent industries, often state-owned enterprises, parastatals or locally embedded MNE subsidiaries, in export-oriented natural resource-based industries. Those industries typically face decarbonization pressure from their international customers (Benito & Meyer, 2024), whereas their domestic customers may not be willing to pay for the increased cost of decarbonized production. Hence, transformation also hinges upon home country governments’ willingness to support the transformation of production

processes and adopt incentives to decarbonize production for the domestic market as well (Altenburg & Rodrik, 2017).

Technology niche upgrading

This pathway focuses on building capabilities and/or developing new competitive advantages across the entire LEH value chain. Promising areas include upstream hydrogen production and downstream hydrogen-use technologies, for example developing membranes for electrolyzers, building small-scale fuel cells (Stamm et al., 2023) or retrofitting diesel engines (Stamm et al., 2024). As technological niche upgrading fosters innovational capabilities in domestically owned firms, it can spur technological spillovers with other domestic firms (Matusik et al., 2018).

As with local content manufacturing, key entry barriers stem again from the design-intensive nature of clean tech, requiring substantive learning-by-doing effects (Global CCS Institute, 2021), and robust innovation systems (Schmidt & Huenteler, 2016). The clean energy technology market is dominated by a few MNEs and frontrunner countries (IEA, 2022b; Nahm, 2017; Steffen et al., 2018), particularly China (GWEC, 2022; IEA, 2022a), with strong patent protection. Weak innovation capacities and strong international market concentration pose significant challenges for latecomers to enter the GVC. Large competitive firms are best positioned to invest in such technology developments. They can hedge the risk involved in R&D against a broad product portfolio. In many latecomer countries, state oil & gas enterprises develop and manufacture technologies for the local market.¹⁰ However, without clear environmental regulations or market signals, firms may delay investment in green technology upgrading.

In summary, across all four pathways, the potential for domestic firms in latecomer economies to upgrade within the LEH value chain remains limited without strong state intervention and strategic foreign investor engagement. Especially in the export-revenue pathway, hydrogen investments risk evolving into FDI-led technological enclaves, where domestic participation is confined to low-value services or temporary construction work. National benefits are then limited to rent capture – via export taxes, land leases, and joint venture shares (Aboushady & Jaroudi, 2024; Altenburg & Kantel, 2024). Efforts to localize value creation can make host countries less attractive to investors, while public de-risking measures (e.g., export credit guarantees) may expose governments to disproportionate risk, particularly due to the transnational character of the LEH ecosystem in the context of information asymmetry and weak institutional capacity. Close collaboration with legacy high-carbon industries is often necessary but also entails risks of political capture, regulatory leniency, and the reinforcement of oligopolistic structures (Stamm et al., 2023). Ultimately,

¹⁰ Examples of companies engaged in major hydrogen-related R&D programs include YPF (Argentina), ADNOC (the United Arab Emirates), Electrobras (Brazil) and OCP (Morocco).

whether latecomer firms can use the LEH transition for GVC upgrading depends on how effectively states manage the tensions between foreign investor interests and domestic value appropriation – balancing competitiveness, industrial policy, and green transformation.

Pathway-specific industrial policies compared

Reaping the benefits of the emerging LEH economy is not straightforward given the multitude of potential industrial linkages and pathways and the cumulative market (or systems) failures of an immature, policy-induced, and politically contested industry. As we have seen in “[Industrial development pathways of latecomers: exploiting opportunities in LEH value chains](#)”, countries chose different combinations of these stylized pathways based on their natural endowments, pre-existing industrial structure and technological competencies.

In this section, we proceed to our second research question: How can industrial policies contribute to shaping these pathways and exploiting the potential development benefits they offer? We do so by identifying the industrial policies mentioned in the 20 NHS and assigning them to five categories: generic (6.1), and specific to the four pathways (6.2–6.5). These sections are mainly descriptive, essentially summarising the information contained in the 20 national strategies. In 6.6, we compare and assess the respective policy mixes against their upgrading ambitions, drawing on our conceptual framework, the identification of pathway specificities and entry barriers in “[Comparing pathways: upgrading opportunities and entry barriers](#)” section as well as additional industrial policy literature and country case studies. While the typology of industrial development pathways in “[Industrial development pathways of latecomers: exploiting opportunities in LEH value chains](#)” section identifies pathway characteristics, our following discussion of industrial policies adds a normative perspective: How development gains can be maximized. Hence, we discuss upgrading opportunities, distributional effects and how risks of enclave formation and political capture can be minimized.

Industrial policies employed across all pathways

Some industrial policies are “basics” required to prepare for the emerging hydrogen economy, regardless of the choice of pathways. For example, the national strategies mention provision of incentives and services that are not pathway-specific, such as general subsidy and soft loan schemes, de-risking of investments, infrastructure investments (e.g., to redesign and expand the electricity grid and pipeline networks) and the development of hydrogen-related skills. All

these measures are classified among the basics as long as they are not specified in path-way-specific ways.

Several countries invest in market and technology foresight to gain a better understanding of the involving LEH-related opportunities. This may include analyzing relative costs of competing energy carriers and how those change over time; how international carbon pricing and trade policies affect hydrogen markets; and where technological bottlenecks may decelerate the market ramp-up. Moreover, the national hydrogen strategies mention the creation of coordinating and deliberation agencies, often a national hydrogen council, ensuring interagency cooperation and stakeholder involvement (e.g., Ecuador, Kenya). All countries address regulatory issues, as these are indispensable for interoperability, safety, and to meet international standards regarding CO₂ emissions. Many countries also invest in mapping of national resources, such as a national atlas of solar irradiation (Colombia), or surveys for identifying national geological structures for carbon storage (the United Arab Emirates).

It should be noted that many of the barriers for an unfolding hydrogen economy originate on the demand side. Political contestation of carbon pricing, decarbonization subsidies and sector-specific decarbonization roadmaps in import countries increases uncertainty for LEH investments and translates into project delays and cancellations (IEA, 2024a). Latecomers interested in tapping into these markets have only very limited influence on the demand side. However, many countries proactively seek to establish bilateral hydrogen partnerships and to sign long-term agreements with importing countries (IRENA, 2022). Chile and Namibia, for example, specifically address the need for a hydrogen diplomacy in their national strategies.

Industrial policies for the export-revenue pathway

The main objective here is to attract hydrogen-exporting FDI as a new source of revenue. This requires an investment climate that leaves the investor freedom to repatriate revenues and infrastructure, does not tax investments too heavily and streamlines procedures – e.g., one-stop-shop for investors are mentioned in Kenya and Namibia. Chile, in addition, created a task force to accompany developers through all the requirements to get project permissions and establish permitting and piloting processes. A wide range of financial instruments are considered in the strategies to compete for foreign investments, including exemption from payment of customs duties and VAT, accelerated depreciation, income tax deduction, soft loans and direct public financing for demonstration projects (e.g., Ecuador). Several countries, including Morocco and South Africa, created special economic zones offering exemptions from business and trade laws in the rest of the country. Such zones also help to avoid disputes over land rights.

Given the above-average financing costs in latecomer countries, public de-risking instruments are particularly important. Both policy de-risking (such as a feed-in-tariff for the roll-out of renewables) and financial de-risking of specific investments are widely addressed, the latter including loan and export credit guarantees as well as insurance against political risks (Namibia).

Various countries, including Argentina, Ecuador, Panama, and the United Arab Emirates, are supporting demonstration projects as a means to attract additional FDI. Established projects help to better calculate the real costs of low-emissions hydrogen production with different technologies and at different locations and may signal commercial viability to potential investors.

Another frequently mentioned element are investments in dedicated export infrastructure, such as ports, pipelines and storage tanks. Also, a range of export-specific regulations are mentioned, such as a hydrogen certification scheme guaranteeing emission standards and the origin of hydrogen (e.g., Colombia).

Some countries have specific local content targets for LEH-related technologies. For example, Namibia wants to localize solar and wind energy parts; Türkiye aims to manufacture the necessary components for the production of pipes suitable for the transmission and distribution of hydrogen as well as sub-components such as valves, sensors, and detectors.

Finally, some governments stipulate measures to ensure reasonable national revenues from exports and to share development gains more widely. Oman specifies public incomes from land lease, royalties, corporate taxes and public equity stakes to secure decent public incomes. Some countries specify how such export revenues shall be used, e.g., to fund regional development initiatives. The United Arab Emirates has developed Social Impact Contracting guidelines to ensure increasing social and economic outcomes for a variety of net-zero industry investments. Ecuador plans to use export royalties compensate carbon pricing for the consumption of fossil fuels. In Namibia, the government included mandatory oversizing of desalination plants in its project tender, to ensure desalination serves not only export-oriented electrolyzers but also local communities.

Industrial policies for the hydrogen pull pathway

Industrial policies for this pathway are similar to the ones aimed at export revenues. The emphasis is on attracting foreign investors, yet with a different rationale and a focus on different industries. While the export-revenue pathway aims at renewable energy, electrolyses, and transportable derivatives, hydrogen-pull aims at energy- and emissions-intensive industries downstream industries, e.g., in the chemical and auto parts industries. As those industries tend to involve complex cross-border

trade relations, frictionless trade matters, calling for deep trade agreements with partner countries as well as harmonization of specific green industry regulations. Also, compared to the production of hydrogen and derivatives, such industries may depend more on local inter-firm relations to exploit industrial symbiosis or build sector-specific pools of skilled labor. This calls for policies supporting industrial clusters.

As this pathway is mainly considered as a medium- to long-term opportunity once sufficient supply of renewables and low-emission hydrogen has been developed, the national strategies place less emphasis on specifying the respective policies. Yet, Morocco's industrial policy clearly combines these elements: Morocco has a range of free trade agreements to provide good access to Europe and position the country as a link between Europe and Africa; and clusters and industrial ecosystems feature prominently in its hydrogen strategy, in combination with a particularly proactive and targeted investment promotion (Hahn & Vidican-Auktor, 2017). Similarly, the United Arab Emirates envisages the formation of "hydrogen oases" to co-locate production and end-use applications in clean energy clusters.

Industrial policies for the domestic decarbonization pathway

Domestic decarbonization is a particularly prominent stated objective in national strategies, especially in countries with a considerable stock of fossil fuel-based industries (the United Arab Emirates, South Africa, and India), including mining (Chile, South Africa, Indonesia) and/or traffic-related urban air pollution (India, Egypt, Indonesia). Here, two industrial policy elements are particularly relevant: to tilt incentive systems from pro-polluting to pro-green alternatives; and support for specific decarbonization projects with big emission-intensive industries, including pilot implementations.

With regard to the first, many countries in the sample are developing carbon pricing systems, either a cap-and-trade system (the United Arab Emirates) or carbon taxes, or a combination of both (Colombia). Phasing out fossil fuel subsidies is a widely used complement. Several countries also mandate progressive emission reduction requirements for industry, transport, and buildings (Brazil) or plan to create hydrogen demand through mandatory use quotas (Ecuador). Demand can also be induced via issuance of green bonds (Argentina, Colombia) by national companies or via public procurement of hydrogen-based products, including by state-owned enterprises, as shown by the United Arab Emirates' national oil company ADNOC. The United Arab Emirates also considers hydrogen purchase agreements between green hydrogen producers and end users, specifying the sale price for an amount of hydrogen used over an agreed timeframe.

With regard to directly supporting specific decarbonization projects, the South Africa Hydrogen Valley project

supporting a range of pilot applications has been co-designed by industry and government (Engie Impact, 2021). In several countries, subsidies for individual firms using low-emission hydrogen are mentioned, including soft loans and carbon contracts for difference (Ecuador), helping firms to cope with costly process adjustments and bridging the cost gap between low-carbon hydrogen and high-emission fuels.

Industrial policies for the technological niche upgrading pathway

Two main types of policies can be distinguished for technological niche upgrading. When the aim is to build domestic capabilities in mature technologies, policies focus on improving absorptive capacities, e.g., via skills development. Where countries aspire for own innovations in new technologies, research and development and a range of innovation policies move to the forefront.

Many strategy papers announce localization objectives without specifying the underlying industrial policies. Some countries, especially those with higher levels of economic complexity, pursue typical innovation policies such as

dedicated R&D programs, university-enterprise linkages and support for technology start-ups. Several countries mention pilot facilities, e.g., Türkiye plans those for new fuel cell and module designs including the promotion of prototypes and setup of testing infrastructure. Argentina creates regulatory sandboxes where innovative technologies can be tried in real-world conditions to improve their performance and to develop the appropriate regulatory environment in parallel. The United Arab Emirates bets on its established network of technology incubators for the development of new hydrogen technologies but also considers the acquisition of foreign firms.

LEH industrial policies: a comparative assessment

The previous sections have shown how latecomer countries pursue different hydrogen industrial development strategies and that those translate into very specific industrial policy mixes. Finalizing, we compare and assess these policy mixes with a view to (a) understanding the relevance of *generic*, *latecomer-specific* and *green-specific* industrial policies in the pursuit of specific pathways; and (b) assessing how likely it is that the sets of industrial policies extracted from the

Table 2 Industrial policies employed for LEH pathways

Type of industrial policy	Export-revenue pathway	Hydrogen pull pathway	Domestic decarbonization pathway	Technological niche upgrading pathway
Generic	Soft loans, de-risking of investments and subsidies; technology foresight; mapping of resources; promotion of generic infrastructure; regulatory compliance			R&D, pilot projects and university–industry cooperation, support for technology start-ups, regulatory sandboxes
Latecomer-specific	FDI attraction: Tax concessions, SEZ, one-stop-shops; demonstration projects; local content requirements hydrogen diplomacy to ensure long-term cooperation with importing countries	FDI attraction; deep trade agreements; support for industrial clusters around FDI		
Greening-specific	Using export royalties to compensate for carbon pricing	Carbon taxes as a means to avoid carbon border adjustments being imposed by importers	Carbon pricing via cap-and-trade or taxes; fossil fuel subsidy reform; industry-specific emission reduction requirements; mandatory hydrogen use quotas, auctions, soft loans, and carbon contracts for difference for decarbonization investments; support of pilot applications of low-carbon technologies	

Source: Own elaboration

national strategies enable countries to achieve the upgrading objectives related to each pathway and where the limitations are, linking back to the analysis of barriers in the “[Comparing pathways: upgrading opportunities and entry barriers](#)” section. We also draw from literature on industrial policy effectiveness and country case studies on hydrogen upgrading.

Table 2 shows how the policies employed for our four pathways reflect generic, latecomer-specific and green-specific industrial policies in different ways. The export-revenue and hydrogen-pull pathways display many of the characteristics described in our “[Conceptual framework](#)” as latecomer-specific industrial policies (to attract FDI in combination with some incentives for technology transfer). Both also make use of some green industrial policies. The domestic-decarbonization pathway emphasizes green industrial policies, such as policies to internalize environmental costs, green bonds and subsidies for the transformation of industrial processes. Finally, the technological niche upgrading pathway is characterized by policies that correspond with the industrial policies of advanced economies, where new frontier technologies are targeted, supporting R&D, pilot projects and university–industry cooperation.

As all the strategies have been released only after October 2020, they cannot yet be subjected to an impact evaluation. Following, we highlight some critical policy challenges that may hamper industrial upgrading, drawing on gaps between what the industrial policy literature suggests as success factors and the priorities set in the strategies.

With regard to the export-revenue (and the few cases of hydrogen pull) industrial policies, strategies reveal a bias towards open-door policies for FDI with only limited emphasis on efforts for technological learning and embedding FDI in domestic enterprise networks. Where they are highlighted, they are not (yet) underpinned by concrete incentives and operational specificity, rendering them more aspirational than actionable. Namibia’s strategy aims to indigenize production of wind tower and blade as well as solar cell and module manufacturing, projecting up to US\$11 billion in direct GDP impact by 2035–40 (MME, 2022, p. 32). It is not clear how such an industry can emerge in a country with very small market size and without a competitive industrial base, and given the competition from scale-intensive producers like China, especially as even larger economies such as South Africa, India, Brazil have struggled in this domain (Altenburg & Kantel, 2024; Bazilian et al., 2020). Similarly, Türkiye’s goal of building a competitive electrolyser industry faces headwinds from China’s global dominance and EU subsidies (IEA, 2024b). Other than local content requirements, national strategies mention few mechanisms to forge technology transfer from FDI to domestic businesses. Neither joint venture requirements nor proactive supplier development programs feature prominently in the strategies. As literature on knowledge spillovers from

FDI suggests (“[Conceptual framework](#)” section), the one-sided FDI approach neglecting transfer and linkages may lead to the formation of foreign-owned technological enclaves, at best with some follow-sourcing (Butollo et al., 2024) from abroad.

Notably, some countries recognized the downsides of enclave formation and implemented distributive policies to spread development gains more widely in their societies via Social Impact Contracting guidelines, cross-subsidization of regional development funds and other measures.

Even if hydrogen investment leads to enclave formation, it may still contribute to generating foreign exchange and tax revenues. However, public expenditure and tax concessions must be taken into account when assessing the size of such benefits. The strategy documents suggest the use of a wide range of subsidies and tax exemptions. In several pathways, state guarantees are used to de-risk private investments. Likewise, when big hydrogen investment projects are supported with state investments in project-related public infrastructure (roads, ports, grids), investment risks are shifted to the public sector, whereas profits are captured by private investors with generous tax exemptions. While de-risking may be necessary to get investment off the ground, it may structurally weaken (the state’s) ability to discipline private capital (Gabor & Sylla, 2023, pp. 1169), especially in the presence of information asymmetries between transnational investors and local administrations. Political capture is also a major risk in the domestic decarbonization pathway, where the beneficiaries of state support are either large state-owned enterprises, parastatals, or subsidiaries of MNEs. Capture can take the form of oversizing subsidies, granting unnecessary tax exemptions and further strengthening oligopolistic power.

While it is too early for any cost-benefit analysis of hydrogen industrial policies, governments may consider giving more weight to precautionary measures to avoid such risks, especially

- Greater emphasis on incentives for technology transfer and strengthening of domestic absorptive capacity to avoid enclave formation;
- Strengthening transparency and accountability, such as as public disclosure of investment deals and state-private revenue flows,
- Revenue-sharing policies such as mandatory community shares, public ownership or transferring export revenues directly to citizens.

Conclusions and research outlook

The emerging global LEH market is set to grow significantly and offer manifold new opportunities for international business. Investors have announced projects for annual production of 49 Mt LEH by 2030 (IEA, 2024a). Tapping into,

and upgrading within, newly emerging LEH value chains is now a strategic priority for firms and governments in many latecomer economies.

Our paper addresses a dual knowledge gap related to the potential societal benefits of the emerging LEH economy for latecomers. Based on an analysis of all available national hydrogen strategies in this country group, we first, identify four different pathways along which these countries can try to upgrade in hydrogen GVCs as well as the entry barriers that may hamper such efforts, focusing on internal barriers that those governments can influence. Second, we explore, classify, and assess their industrial policies in support of the envisaged upgrading pathways.

We find that country strategies focus on different upgrading pathways, combining elements of the four stylized pathways in different ways, reflecting differences in their initial conditions. These different constellations are reflected in different policy mixes, employing specific combinations of generic, latecomer-specific and greening-specific industrial policies. Finally, we offer a preliminary assessment of whether the upgrading objectives are realistic and the chosen policy-mixes suitable for achieving them, highlighting some critical policy risks.

Our work raises three major questions for future research by scholars of international business, GVCs and industrial policy. First, more research is needed to fully understand the contours of emerging LEH value chain configurations. While some studies explore socio-economic effects of LEH ecosystems (e.g., Kayikci et al., 2025; Sharma et al., 2023), many of the related industrial development opportunities are severely under-investigated, especially with respect to technology choice, entry barriers, upgrading, and leapfrogging opportunities. This applies, among others, to electrolyser manufacturing; sustainable shipping and aviation fuels; fuel cells technologies; and new developments related to CCUS.

Second, the effectiveness of the policy mixes included in the national strategies has not yet been evaluated. At the same time, our preliminary assessments points to potential

risks related to enclave formation, political capture and rising inequality. More research is needed to test the relevance of these risks and explore how this can be counteracted.

Third, our analysis has highlighted that the transition to hydrogen is essentially policy-driven and politically contested, as national interests do not easily align with the requirements of global decarbonization. This results in fragmented markets and high uncertainty for investors, affecting the formation of GVCs and the scope for firm upgrading within them. This paper has explored *country-level* industrial policy responses to cope with the specific challenges of the policy-induced hydrogen market ramp-up. More research is needed to understand *firm-level* strategies. As we have shown, most LEH-related investments are large-scale, involving MNEs and their subsidiaries in latecomer economies as well as big national, often state-owned corporations. These firms tend to be lead firms in hydrogen GVC, gatekeepers to international markets and main drivers of technological innovation. At the same time, they often operate in oligopolistic markets settings and may therefore distort markets and capture policy rents, especially given the policy-induced character of green industry transformation. The role of MNEs and their headquarter-subsidiary relations as well, as the role of national star firms and SOEs (Meissner et al. 2019) have long been at the center of international business research. Future research may explore their specific role in policy-induced green industries, and how policy can shape cross-border business transactions in a way that navigates the conflicting global (decarbonization) and national (competitiveness) interests.

Appendix

See Table 3.

Table 3 Industrial development pathways selected and prioritized in national hydrogen strategies

Economic complexity (ECI trade 2019) ³	Country	H2 production route	Export-revenue	Domestic decarbonisation		Technological niche upgrading	Renewable energy & hydrogen pull
				Ind- ustry	Trans- port		
			(I)	(IIa)	(IIb)	(IIIa)	(IV)
moderate	Türkiye		○	●	○	●	□
	India		○	●	●	●	□
	Brazil ¹		○	●	○	●	□
modest	Costa Rica		○	○	●	○	○
	United Arab Emirates		●	●	○	●	□
	South Africa		○	●	○	○	□
	Colombia		●	○	○	○	□
	Argentina ²		●	○	○	○	□
	Panama		●	○	○	□	□
	Uruguay		●	○	○	○	□
low	Indonesia*		○	●	○	□	□
	Egypt*		●	○	○	□	□
	Chile		●	○	○	○	□
	Oman		●	○	○	○	□
	Sri Lanka		○	○	○	○	□
	Kenya		○	●	○	□	○
very low	Morocco		●	●	○	○	○
	Namibia		●	□	○	○	○
	Ecuador		○	○	○	□	□
	Algeria		●	○	□	□	□

: green (incl. biomass and geothermal), : blue (incl. coal+CCUS), : other (e.g., nuclear, natural, pyrolysis)

●: highly relevant, ○: relevant, –: not relevant/not mentioned

*National hydrogen strategy launched, but document not publically available

¹Assessment based on national hydrogen program (not strategy)

²National hydrogen strategy no longer pursued under the current government

³: The following thresholds apply for the ECI: moderate: ≥ 0.45 , modest: > 0 , low: > -0.5 , very low: ≤ -0.5

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Data Availability The National Hydrogen Strategies analysed in the paper and the Economic Complexity Indicator data are publicly available through the respective publishers and data repositories. Access to the interview data is restricted to protect participant confidentiality;

however, aggregate and anonymized information is available in the cited country studies. A breakdown of interviews by country is contained in the "Supplementary Information" document. It also contains a list of the National Hydrogen Strategies covered including links.

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References

- Aboushady, N., & Jaroudi, S. (2024). *Towards a green H2 economy: Algeria country report*. (HYPAT-Working Paper 11/2024). https://hyapat.de/hypat-wAssets/docs/new/publications/HyPAT_Country-Report_Algerien_FV.pdf
- Ado, A., Osabutey, E. L. C., Sinha, P., & Adeola, O. (2025). Africa's international trade paradox, technology transfer, and value chain upgrade. *Technological Forecasting & Social Change*, 213, 124014. <https://doi.org/10.1016/j.techfore.2025.124014>
- Agora Industry. (2024). *A vision for international trade in CO2-intensive materials*. Agora Industry.
- Agora Industry, & Wuppertal Institute. (2023). *15 insights on the global steel transformation*. <https://www.agora-industry.org/publications/15-insights-on-the-global-steel-transformation>
- Altenburg, T. (2000). *Linkages and spill-overs between transnational corporations and small and medium-sized enterprises in developing countries – opportunities and policies*. DIE Reports and Working Papers 5/2000. https://www.idos-research.de/fileadmin/migratedNewsAssets/Files/BuG_5_2000_EN.pdf
- Altenburg, T., & Kantel, A. (2024). *Green hydrogen in Namibia: Opportunities and risks*. (IDOS Discussion Paper 6/2024). German Institute of Development and Sustainability (IDOS). <https://doi.org/10.23661/idp6.2024>
- Altenburg, T., & Lütkenhorst, W. (2015). *Industrial policy in developing countries: Failing, markets, weak states*. Edward Elgar Publishing.
- Altenburg, T., & Rodrik, D. (2017). *Green industrial policy: Accelerating structural change towards wealthy green economies*. https://drodrik.scholar.harvard.edu/files/dani-rodrik/files/altenburg_rodrik_green_industrial_policy_webversion.pdf
- Amachraa, A. (2023). *Driving the dream: Morocco's rise in the global automotive industry*. https://www.policycenter.ma/sites/default/files/2023-05/PP_09-23_AMACHRAA.pdf
- Anderson, P., & Tushman, M. L. (1990). Technological discontinuities and dominant designs: A cyclical model of technological change. *Administrative Science Quarterly*, 35(4), 604–633. <https://doi.org/10.2307/2393511>
- Awate, S., Larsen, M. M., & Mudambi, R. (2015). Accessing vs sourcing knowledge: A comparative study of R&D internationalization between emerging and advanced economy firms. *Journal of International Business Studies*, 46(1), 63–86. <https://doi.org/10.1057/jibs.2014.46>
- Baglieri, D. (2024). Turning green hydrogen into firms' decarbonization strategies: Opportunities, challenges, and implications for China. *Asian Business and Management*, 23, 660–682. <https://doi.org/10.1057/s41291-024-00285-2>
- Bakhuis, J., Manon Kamp, L., Barbour, N., & Chappin, E. J. L. (2024). Frameworks for multi-system innovation analysis from a socio-technical perspective: A systematic literature review. *Technological Forecasting & Social Change*, 201, 123266. <https://doi.org/10.1016/j.techfore.2024.123266>
- Bazilian, M., Cuming, V., & Kenyon, T. (2020). Local-content rules for renewables projects don't always work. *Energy Strategy Reviews*, 32, 100569. <https://doi.org/10.1016/j.esr.2020.100569>
- Bell, M., & Pavitt, K. (1993). Technological accumulation and industrial growth: Contrasts between developed and developing countries. *Industrial and Corporate Change*, 2(2), 157–210. <https://doi.org/10.1093/icc/2.2.157>
- Benito, G. R. G., & Meyer, K. E. (2024). Industrial policy, green challenges, and international business. *Journal of International Business Studies*, 55, 1093–1107. <https://doi.org/10.1057/s41267-024-00722-6>
- Berry, H. (2017). Managing valuable knowledge in weak IP protection countries. *Journal of International Business Studies*, 48, 787–807. <https://doi.org/10.1057/s41267-017-0072-1>
- Bleda, M., & del Río, P. (2013). The market failure and the systemic failure rationales in technological innovation systems. *Research Policy*, 42(5), 1039–1052. <https://doi.org/10.1016/j.respol.2013.02.008>
- Boschma, R., Coenen, L., Frenken, K., & Truffer, B. (2017). Towards a theory of regional diversification: Combining insights from evolutionary economic geography and transition studies. *Regional Studies*, 51(1), 31–45. <https://doi.org/10.1080/00343404.2016.1258460>
- Buckley, P. J., & Ghauri, P. N. (2004). Globalisation, economic geography and the strategy of multinational enterprises. *Journal of International Business Studies*, 35, 81–98. <https://doi.org/10.1057/palgrave.jibs.8400076>
- Butollo, F., Staritz, C., Maile, F., & Wuttke, T. (2024). The end of globalized production? Supply-chain resilience, technological sovereignty, and enduring global interdependencies in the post-pandemic era. *Critical Sociology*. <https://doi.org/10.1177/08969205241239872>
- Chang, H.-J. (1994). *The political economy of industrial policy*. Palgrave Macmillan.
- Chen, Y., & Sun, S. L. (2023). Leapfrogging and partial recapitulation as latecomer strategies. *Journal of Open Innovation: Technology, Market, and Complexity*, 9(3), 100099. <https://doi.org/10.1016/j.joitmc.2023.100099>
- Cimoli, M., Dosi, G., & Stiglitz, J. E. (Eds.). (2009). *Industrial policy and development: The political economy of capabilities accumulation*. Oxford University Press.
- Contractor, F. J. (2019). Can a firm find the balance between openness and secrecy? Towards a theory of an optimum level of disclosure. *Journal of International Business Studies*, 50(2), 261–274. <https://doi.org/10.1057/s41267-018-0204-2>
- Čučuk, A. (2024). *Westwood Insight – Over a fifth of all European hydrogen projects stalled or cancelled*. <https://www.westwoodenergy.com/news/westwood-insight/westwood-insight-over-a-fifth-of-all-european-hydrogen-projects-stalled-or-cancelled>
- Davy, E., Hansen, U. E., & Nygaard, I. (2024). Localizing the solar value chain in Kenya? *Innovation and Development*, 14(1), 217–240. <https://doi.org/10.1080/2157930X.2022.2121306>
- De Marchi, V., & Alford, M. (2022). State policies and upgrading in global value chains: A systematic literature review. *Journal of International Business Policy*, 5, 88–111. <https://doi.org/10.1057/s42214-021-00107-8>
- Egerer, J., Farhang-Damghani, N., Grimm, V., & Runge, P. (2024). The industry transformation from fossil fuels to hydrogen will reorganize value chains: Big picture and case studies for Germany. *Applied Energy*, 358, 122485. <https://doi.org/10.1016/j.apenergy.2023.122485>
- Eicke, L., & De Blasio, N. (2022). The future of green hydrogen value chains: Geopolitical and market implications in the industrial sector. *Energy Research & Social Science*, 93, 102847. <https://doi.org/10.1016/j.erss.2022.102847>
- Engie Impact. (2021). *South Africa Hydrogen Valley final report*. https://www.dsti.gov.za/images/2021/Hydrogen_Valley_Feasibility_Study_Report_Final_Version.pdf
- Gabor, D., & Sylla, N. S. (2023). Derisking developmentalism: A tale of green hydrogen. *Development & Change*, 54(5), 1169–1196. <https://doi.org/10.1111/dech.12779>
- Gambhir, A., Gross, R., & Green, R. (2014). The impact of policy on technology innovation and cost reduction: A case study on crystalline silicon solar PV modules. *Imperial College London Working Paper*, November 2014. <https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publicatio>

- ns/working-papers/The-impact-of-policy-on-technology-innovation-and-cost-reduction-WP.pdf
- Gehrke, T. (2022). EU open strategic autonomy and the trappings of geoeconomics. *European Foreign Affairs Review*, 27, 61–78. <https://doi.org/10.54648/eerr2022012>
- Gereffi, G. (2005). The global economy: Organization, governance and development. In N. J. Smelser, & R. Redberg (Eds.), *Handbook of economic sociology* (2nd ed., pp. 160–182). Princeton University Press and Russell Sage Foundation.
- Gereffi, G. (2019). Economic upgrading in global value chains. In S. Ponte, G. Gereffi, & G. Raj-Reichert (Eds.), *Handbook on global value chains* (pp. 240–254). Edward Elgar Publishing. <https://doi.org/10.4337/9781788113779.00022>
- Gereffi, G., & Sturgeon, T. (2013). Global value chain-oriented industrial policy: The role of emerging economies. In D. K. Elms & Low.P. (Eds.), *Global value chains in a changing world* (pp. 329–360). WTO Publications. <https://www.wto-ilibrary.org/content/books/9789287042446s007-c004>
- Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy*, 12(1), 78–104. <https://doi.org/10.1080/09692290500049805>
- Gerschenkron, A. (1962). *Economic backwardness in historical perspective: A book of essays*. Belknap Press of Harvard University Press.
- Gibbon, P., & Ponte, S. (2005). *Trading down: Africa, value chains, and the global economy*. Temple University Press.
- Global CCS Institute. (2021). *Technology readiness and costs of CCS*. <https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf>
- Görg, H., & Greenaway, D. (2004). Much ado about nothing? Do domestic firms really benefit from foreign direct investment? *The World Bank Research Observer*, 19(2), 171–197. <https://doi.org/10.1093/wbro/lkh019>
- Griffiths, S., Sovacool, B. K., Kim, J., Bazilian, M., & Uratani, J. M. (2021). Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Research & Social Science*, 80, 102208. <https://doi.org/10.1016/j.erss.2021.102208>
- GWEC. (2022). *Global wind report 2022*. <https://energycentral.com/system/files/ece/nodes/539196/gwec-global-wind-report-2022.pdf>
- Hahn, T., & Vidican-Auktor, G. (2017). The effectiveness of Morocco's industrial policy in promoting a national automotive industry. *DIE Discussion Paper*, 27/2017. German Development Institute.
- Hansen, U. E., Nygaard, I., Morris, M., & Robbins, G. (2022). Servitification of manufacturing in global value chains: Upgrading of local suppliers of embedded services in the South African market for wind turbines. *The Journal of Development Studies*, 58(4), 787–808. <https://doi.org/10.1080/00220388.2021.2017892>
- Hidalgo, C. A. (2021). Economic complexity theory and applications. *Nature Reviews Physics*, 3(2), 92–113. <https://doi.org/10.1038/s42254-020-00275-1>
- Hobday, M. (1995). East Asian latecomer firms: Learning the technology of electronics. *World Development*, 23(7), 1171–1193. [https://doi.org/10.1016/0305-750X\(95\)00035-B](https://doi.org/10.1016/0305-750X(95)00035-B)
- Humphrey, J., & Schmitz, H. (2002). How does insertion in global value chains affect upgrading in industrial clusters? *Regional Studies*, 36(9), 1017–1027. <https://doi.org/10.1080/003434002000022198>
- Hydrogen Council, & McKinsey & Company. (2023). *Global hydrogen flows – 2023 update: Considerations for evolving global hydrogen trade*. <https://hydrogencouncil.com/wp-content/uploads/2023/11/Global-Hydrogen-Flows-2023-Update.pdf>
- IEA. (2022a). *Special report on solar PV global supply chains*. International Energy Agency. <https://www.iea.org/reports/solar-pv-global-supply-chains>
- IEA. (2022b). *World energy outlook 2022*. International Energy Agency. <https://www.iea.org/reports/world-energy-outlook-2022>
- IEA. (2023). *Global hydrogen review 2023*. International Energy Agency. <https://www.iea.org/reports/global-hydrogen-review-2023>
- IEA. (2024a). *Global hydrogen review 2024*. International Energy Agency. <https://www.iea.org/reports/global-hydrogen-review-2024>
- IEA. (2024b). *Electrolysers*. International Energy Agency. <https://www.iea.org/energy-system/low-emission-fuels/electrolysers>
- IRENA. (2022). *Geopolitics of the energy transformation: The hydrogen factor*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/IRENA_Geopolitics_Hydrogen_2022.pdf
- IRENA. (2023). *Geopolitics of the energy transition: Critical minerals*. International Renewable Energy Agency. <https://www.irena.org/Publications/2023/Jul/Geopolitics-of-the-Energy-Transition-Critical-Materials>
- IRENA. (2024). *Shaping sustainable international hydrogen value chains*. International Renewable Energy Agency. <https://www.irena.org/Publications/2024/Sep/Shaping-sustainable-international-hydrogen-value-chains>
- Jakob, M. (2021). Why carbon leakage matters and what can be done against it. *One Earth*, 4(5), 609–614. <https://doi.org/10.1016/j.oneear.2021.04.010>
- Kayikci, Y., Ramjan Ali, Md., Khan, S. A., & Ikpehai, A. (2025). Examining dynamics of hydrogen supply chains. *Technological Forecasting & Social Change*, 215, 124101. <https://doi.org/10.1016/j.techfore.2025.124101>
- Kaplinsky, R. (2014). Shudder: The challenges to “industrial policies” in the early 21st century in low- and middle-income economies. *International Business and Sustainable Development*, 8, 69–90. [https://doi.org/10.1108/S1745-8862\(2013\)0000008019](https://doi.org/10.1108/S1745-8862(2013)0000008019)
- Kaplinsky, R., & Morris, M. (2001). *A handbook for value chain research*. IDRC. https://www.fao.org/fileadmin/user_upload/fisheries/docs/Value_Chain_Handbook.pdf
- Kaplinsky, R., & Morris, M. (2016). Thinning and thickening: Productive sector policies in the era of global value chains. *European Journal of Development Research*, 28, 625–645. <https://doi.org/10.1057/ejdr.2015.29>
- Klein Woolthuis, R., Lankhuizen, M., & Gilsing, V. (2005). A system failure framework for innovation policy design. *Technovation*, 25(6), 609–619. <https://doi.org/10.1016/j.technovation.2003.11.002>
- Kostova, T., Marano, V., & Tallman, S. (2016). Headquarters–subsidiary relationships in MNCs: Fifty years of evolving research. *Journal of World Business*, 51(1), 176–184. <https://doi.org/10.1016/j.jwb.2015.09.003>
- Krugman, P. R. (1987). Is free trade passé? *Journal of Economic Perspectives*, 1(2), 131–144. <https://doi.org/10.1257/jep.1.2.131>
- Kümmritz, V., Taglioni, D., & Winkler, D. E. (2017). Economic upgrading through global value chain participation: Which policies increase the value added gains? *World Bank Policy Research Working Paper No. 8007*. <https://ssrn.com/abstract=3170147>
- Larsen, T. H., & Hansen, U. E. (2022). Sustainable industrialization in Africa: The localization of wind-turbine component production in South Africa. *Innovation and Development*, 12(2), 189–208. <https://doi.org/10.1080/2157930X.2020.1720937>
- Lee, K., & Malerba, F. (2017). Catch-up cycles and changes in industrial leadership: Windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research Policy*, 46(2), 338–351. <https://doi.org/10.1016/j.respol.2016.09.006>
- Lema, R., & Lema, A. (2012). Technology transfer? The rise of China and India in green technology sectors. *Innovation and Development*, 2(1), 23–44. <https://doi.org/10.1080/2157930X.2012.667206>

- Lin, J. Y. (2016). The latecomer advantages and disadvantages. In M. Andersson, & T. Axelsson (Eds.), *Diverse development paths and structural transformation in the escape from poverty* (pp. 43–67). Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780198737407.003.0003>
- Marquardt, J., Fast, C., & Grimm, J. (2022). Non- and sub-state climate action after Paris: From a facilitative regime to a contested governance landscape. *Wires Climate Change*, 13(5), e791. <https://doi.org/10.1002/wcc.791>
- Mathews, J. A. (2002). Competitive advantages of the latecomer firm: A resource-based account of industrial catch-up strategies. *Asia Pacific Journal of Management*, 19(4), 467–488. <https://doi.org/10.1023/A:1020586223665>
- Mathews, J. A. (2006). Catch-up strategies and the latecomer effect in industrial development. *New Political Economy*, 11(3), 313–335. <https://doi.org/10.1080/13563460600840142>
- Matusik, S. F., Heeley, M. B., & Amorós. (2018). Home court advantage? *Knowledge-based FDI and spillovers in emerging economies*. Wiley. <https://doi.org/10.1002/gsj.1324>
- Mayring, P. (2008). *Qualitative Inhaltsanalyse. Grundlagen und Techniken* (10th ed.). Beltz.
- Mazzucato, M. (2016). From market fixing to market-creating: A new framework for innovation policy. *Industry and Innovation*, 23(2), 140–156. <https://doi.org/10.1080/13662716.2016.1146124>
- Meckling, J. (2021). Making industrial policy work for decarbonization. *Global Environmental Politics*, 21(4), 134–147. https://doi.org/10.1162/glep_a_00624
- Meissner, D., Sarpong, D., & Vonortas, N. S. (2019). Introduction to the special issue on “innovation in state-owned enterprises: Implications for technology management and industrial development.” *Industry and Innovation*, 26(2), 121–126. <https://doi.org/10.1080/13662716.2019.1551838>
- Meynard, J. M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., & Michon, C. (2017). Designing coupled innovations for the sustainability transition of agrifood systems. *Agricultural Systems*, 157, 330–339. <https://doi.org/10.1016/j.agsy.2016.08.002>
- MME (Ministry of Mines and Energy). (2022). *Green hydrogen and derivatives strategy*. <https://gh2namibia.com/wp-content/uploads/2022/11/Namibia-GH2-Strategy-Rev2.pdf>
- Morris, M., & Staritz, C. (2019). Industrialization paths and industrial policy for developing countries in global value chains. In S. Ponte, G. Gereffi, & G. Raj-Reichert (Eds.), *Handbook on global value chains* (pp. 506–520). Edward Elgar Publishing.
- Müller, V. P., & Eichhammer, W. (2023). Economic complexity of green hydrogen production technologies – a trade data-based analysis of country-specific industrial preconditions. *Renewable and Sustainable Energy Reviews*, 182, 113304. <https://doi.org/10.1016/j.rser.2023.113304>
- Muslemani, H., Liang, X., Kaesehage, K., Asci, F., & Wilson, J. (2021). Opportunities and challenges for decarbonizing steel production by creating markets for ‘green steel’ products. *Journal of Cleaner Production*, 315, 128127. <https://doi.org/10.1016/j.jclepro.2021.128127>
- Nahm, J. (2017). Renewable futures and industrial legacies: Wind and solar sectors in China, Germany, and the United States. *Business and Politics*, 19(1), 68–106. <https://doi.org/10.1017/bap.2016.5>
- Simoes, A. J. G., & Hidalgo, C. A. (2025). *ECI (Trade)* (2019). *The observatory of economic complexity*. MIT Media Lab. Retrieved June 7, 2025, from <https://oec.world/en/rankings/eci/hs6/hs96?tab=table>
- Odenweller, A., Ueckerdt, F., Nemet, G. F., Jensterle, M., & Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. *Nature Energy*, 7, 854–865. <https://doi.org/10.1038/s41560-022-01097-4>
- Oyan, E. (2024). *Towards a green H2 economy: Türkiye country report* (HYPAT Working Paper 10/2024). https://hypat.de/hypat-wAssets/docs/new/publications/hypat_country-report_turkey.pdf
- Oyan, E., & Kantel, A. (2025). *Towards a green H2 economy: Kenya country report*. (HYPAT Working Paper 13/2024). https://hypat.de/hypat-wAssets/docs/new/publicationen/hypat_country-report_kenya.pdf
- Patala, S., Juntunen, J. K., Lundan, S., & Ritvala, T. (2021). Multinational energy utilities in the energy transition: A configurational study of the drivers of FDI in renewables. *Journal of International Business Studies*, 52, 930–950. <https://doi.org/10.1057/s41267-020-00387-x>
- Pettersen, J., Steeneveldt, R., Grainger, D., Scott, T., Holst, L.-M., & Hamborg, E. S. (2022). Blue hydrogen must be done properly. *Energy Science & Engineering*, 10(9), 3220–3236. <https://doi.org/10.1002/ese3.1232>
- Pipkin, S., & Fuentes, A. (2017). Spurred to upgrade: A review of triggers and consequences of industrial upgrading in the global value chain literature. *World Development*, 98, 536–554. <https://doi.org/10.1016/j.worlddev.2017.05.009>
- Ponte, S. (2020). The hidden costs of environmental upgrading in global value chains. *Review of International Political Economy*, 29(3), 818–843. <https://doi.org/10.1080/09692290.2020.1816199>
- Qiang, C. Z., Liu, Y., & Steenbergen, V. (2021). *An investment perspective on global value chains. Overview*. World Bank. <https://hdl.handle.net/10986/35526>
- Rao, A., Ali, M., & Smith, J. M. (2024). Foreign direct investment and domestic innovation: Roles of absorptive capacity, quality of regulations and property rights. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0298913>
- Richstein, J., & Neuhoof, K. (2022). Carbon contracts-for-difference: How to de-risk innovative investments for a low-carbon industry? *iScience*, 25(8), 104700. <https://doi.org/10.1016/j.isci.2022.104700>
- Riemer, M., Zheng, L., Eckstein, J., Wietschel, M., Pieton, N., & Kunze, R. (2022). *Future hydrogen demand: A cross-sectoral, global meta-analysis* (HYPAT Working Paper 04/2022). <https://doi.org/10.24406/publica-339>
- Rodrik, D. (2004). Industrial policy for the twenty-first century. *CEPR Discussion Paper No. 4767*. <https://cepr.org/publications/dp4767>
- Rodrik, D. (2009). Industrial policy: Don’t ask why, ask how. *Middle East Development Journal*, 1(1): 1–29. <https://doi.org/10.1142/S1793812009000024>
- Samadi, S., Fischer, A., & Lechtenböhmer, S. (2023). The renewables pull effect: How regional differences in renewable energy costs could influence where industrial production is located in the future. *Energy Research & Social Science*, 104, 103257. <https://doi.org/10.1016/j.erss.2023.103257>
- Saviotti, P. (1998). On the dynamics of appropriability, of tacit and of codified knowledge. *Research Policy*, 26(7–8), 843–856.
- Sinkovics, N., & Sinkovics, R. R. (2019). International business and global value chains. In S. Ponte, G. Gereffi, & G. Raj-Reichert (Eds.), *Handbook on global value chains* (pp. 417–431). Edward Elgar.
- Schmidt, T. S., & Huenteler, J. (2016). Anticipating industry localization effects of clean technology deployment policies in developing countries. *Global Environmental Change*, 38, 8–20. <https://doi.org/10.1016/j.gloenvcha.2016.02.005>
- Schmitz, H., & Altenburg, T. (2016). Innovation paths in Europe and Asia: Divergence or convergence? *Science and Public Policy*, 43(4), 454–463.
- Schmitz, H., Johnson, O., & Altenburg, T. (2015). Rent management – the heart of green industrial policy. *New Political Economy*, 20(6), 812–831. <https://doi.org/10.1080/13563467.2015.1079170>
- Sharma, G. D., Verma, M., Taheri, B., Chopra, R., & Parihar, J. S. (2023). Socio-economic aspects of hydrogen energy: An integrative review. *Technological Forecasting & Social Change*, 192, 122574. <https://doi.org/10.1016/j.techfore.2023.122574>
- Stamm, A., Altenburg, T., Strohmaier, R., Oyan, E., & Thoms, K. (2023). Green hydrogen: Implications for international cooperation: With

- special reference to South Africa (IDOS Discussion Paper 9/2023). <https://doi.org/10.23661/IDP9.2023>
- Stamm, A., Kantel, A., & Sagner, L. (2024). *Towards a green H2 economy: Costa Rica country report*. HYPAT Working Paper 02/2024). https://hypat.de/hypat-wAssets/docs/new/publikationen/hypat-wp_02-2024-costa-rica-country-report_03.07.2024.pdf
- Steffen, B., Matsuo, T., Steinemann, D., & Schmidt, T. S. (2018). Opening new markets for clean energy: The role of project developers in the global diffusion of renewable energy technologies. *Business and Politics*, 20(4), 553–587. <https://doi.org/10.1017/bap.2018.17>
- Steininger, K. W., Munoz, P., Karstensen, J., Peters, G. P., Strohmaier, R., & Velázquez, E. (2018). Austria's consumption-based greenhouse gas emissions: Identifying sectoral sources and destinations. *Global Environmental Change*, 48, 226–242. <https://doi.org/10.1016/j.gloenvcha.2017.11.011>
- Steininger, D. M., Trenz, M., & Veit, D. J. et al. (2021). Taxonomy development for business research: A hands-on guideline. In H. Gimpel et al. (Eds.), *Market engineering* (pp. 93–114). Springer. https://doi.org/10.1007/978-3-030-66661-3_4
- Strohmaier, R., Wende, P., Stamm, A., Prados, P., Bambini, G., Muniz, F., Perrone, G., & Robert, V. (2024). Low-emission hydrogen in Argentina and Uruguay: policymaking under uncertainties. Paper presented at the Conference of the European Association for Evolutionary Political Economy, Bilbao, Spain.
- Strohmaier, R., Scherrer, A., Lira, F., & Quitzow, R. (2025). *Towards a green hydrogen economy: Brazil country report*. Unpublished working paper.
- Tagliapietra, S., & Veugelers, R. (Eds.). (2023). *Sparkling Europe's new industrial revolution: A policy for net zero, growth and resilience* (Bruegel Blueprint Series, Vol. 33). Bruegel. <https://www.bruegel.org/book/sparking-europes-new-industrial-revolution-policy-net-zero-growth-and-resilience>
- Taglioni, D., & Winkler, D.E. (2016). *Making global value chains work for development* (English). Trade and Development, D.C.: World Bank Group. <http://documents.worldbank.org/curated/en/450521467989506537>
- UNIDO, IRENA, IDOS. (2023). *Green hydrogen for sustainable industrial development: A policy toolkit for developing countries*. United Nations Industrial Development Organization.
- Valentini, A. (2021). *The market for green ammonia: Future potential and hurdles*. <https://www.energy.gov/sites/default/files/2021-08/6-market-for-green-ammonia.pdf>
- Verpoort, P. C., Gast, L., Hofmann, A., & Ueckerdt, F. (2024). Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains. *Nature Energy*, 9(4), 491–503. <https://doi.org/10.1038/s41560-024-01492-z>
- Weichenhain, U. (2021). *Hydrogen transportation: The key to unlocking the clean hydrogen economy*. Roland Berger.
- Weichenhain, U., Kaufmann, M., Benz, A., & Gomez, G. M. (2021). *Hydrogen valleys: Insights into the emerging hydrogen economies around the world*. Publications Office of the European Union.
- World Economic Forum. (2023). *Net-zero industry tracker: 2023 edition. Insight Report November 2023*. Geneva. https://www3.weforum.org/docs/WEF_Net_Zero_Tracker_2023_REPORT.pdf
- World Energy Council-Germany. (2024). *International hydrogen strategies*. <https://www.weltenergierrat.de/publikationen/studien/international-hydrogen-strategies/>
- Yap, X.-S., & Truffer, B. (2019). Shaping selection environments for industrial catch-up and sustainability transitions: A systemic perspective on endogenizing windows of opportunity. *Research Policy*, 48(4), 1030–1047. <https://doi.org/10.1016/j.respol.2018.10.002>

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