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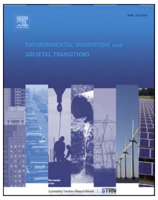

How "clean" is the hydrogen economy? Tracing the connections between hydrogen and fossil fuels

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ABSTRACT

Hydrogen is experiencing a resurgence in energy transition debates. Before representing a solution, however, the existing hydrogen economy is still a climate change headache: over 99 % of production depends on fossil fuels, oil refining accounts for 42 % of demand, and its transportation is intertwined with fossil infrastructure, like natural gas pipelines. This article investigates the path-dependent dynamics shaping the hydrogen economy and its interconnections with the oil and gas industry. It draws on the global production networks (GPN) approach and political economy research to provide a comprehensive review of current and prospective end-uses of hydrogen, modes of transport, networks of industrial actors and state strategies, along the major production facilities and holders of intellectual property rights. The results presented in this article suggest that the superimposition of private agendas may jeopardise the viability of future energy systems and requires counterbalancing forces to override the negative consequences of path-dependent energy transitions.

1. Introduction

Hydrogen is the talk of the town. In the aftermath of the Paris Agreement, governments and corporations have heightened their commitments to achieve net-zero emissions by 2050, sparking a surge of interest and optimism surrounding hydrogen. Projections suggest that global demand for hydrogen will increase fivefold by 2050, accounting for approximately 22 % of final energy demand (IRENA, 2022a) and potentially supplying up to 18 % of the energy sector (Oliveira et al., 2021). Hydrogen is also often presented as the "Swiss army knife" of low-carbon transitions, given its potential for a wide range of industrial and civil applications. However, the majority of hydrogen production currently relies on steam methane reforming (SMR)[1], a process that consumes 6 % of the world's natural gas annually (IEA, 2019). Moreover, hydrogen production is an energy-intensive process, accounting for over 275 Mtoe per year, which is roughly equivalent to Japan's annual final energy consumption. Together with end-uses, this contributes to over 2 % of global CO_2 emissions annually (900 $MtCO_2$) (IEA, 2023). Its climate change impact is potentially even higher when considering methane emissions throughout the supply chain (Bertagni et al., 2022; Howarth and Jacobson, 2021), as well as the indirect global warming potential (GWP) of hydrogen itself (Ocko and Hamburg, 2022). Despite its prominent role in energy transition discussions, as of 2022, almost 100 % of hydrogen is produced using fossil fuels – and the petrochemical industry is also its largest consumer (IEA, 2023). These interrelations with the oil and gas industry cast several doubts about the transformative potential of hydrogen.

This article investigates the path-dependent dynamics that are shaping the hydrogen economy in relation to the existing economic

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[1] The hydrogen that is produced by SMR is commonly referred to as "grey hydrogen".

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regimes, industrial conglomerates, and global networks of energy production. It begins with the premise that history matters. New hydrogen technologies do not spread in a vacuum but build upon existing infrastructure, material flows, trade routes, and economic agendas. Past structures and networks of actors shape the present conditions for future economic development. This does not imply that change is impossible or predetermined, but that it rather advances under the pressure of present constraints. Equally, new modes of production compete with established business-as-usual practices. On the one hand, this Schumpeterian development of the technological frontier kick-starts new economic cycles of capital formation whilst, on the other hand, it poses a threat to the continuity of present economic activities, including one of the most lucrative and capitalized businesses in world history: the oil and gas industry. Therefore, how does the hydrogen economy relate to the still prevalent modes of energy production, namely the fossil fuels complex it seeks to replace?

To address this question, this article examines the economic processes and political interests cutting across global networks of clean hydrogen.[2] It draws upon research on global production networks (GPN) and the political economy of energy transformations to position hydrogen within ongoing developments in energy markets and fossil-based industries. While electrification can leverage existing infrastructure, the scaling up of hydrogen production is often described as a chicken-and-egg problem (Schlund et al., 2022); namely a three-sided challenge encompassing demand, supply, and modes of transport and storage. These need to be created almost from scratch to accelerate an otherwise too slow evolutionary transition (Spek et al., 2022). However, who and whose interests determine which options should be prioritised? Despite a few notable exceptions (e.g. Geels, 2014; Johnstone and Newell, 2018; Kuzemko et al., 2016; Vezzoni, 2023), sustainability transition research has only recently begun to interrogate the ideological and political pressures that shape priorities in capitalist economies (Newell, 2020). This requires framing capitalism as a non-homogenous form of socio-economic organisation, constituted by historically site-specific arrangements (Feola, 2020, p. 242). Therefore, conflicts over alternative climate change mitigation scenarios emerge from the intersection of political ideas, social interests, economic practices, and the material requirements of the energy sector.

These tensions have been observed also in the case of hydrogen industrial developments (Ohlendorf et al., 2023). Potentially conflicting strategies can influence the trajectory of energy transitions. As a case in point, the entrenched influence of fossil fuel actors has been actively obstructing the legislative process and, consequently, it has also been a key source of delayed climate action (Carton et al., 2023; Lamb et al., 2020). However, the challenge extends beyond the mere postponement of energy transition pathways by incumbents. Studies on the history of “energy additions” (Stoddard et al., 2021; York, 2012), have highlighted the risk of adding low-carbon energy sources on top of fossil fuel consumption, instead of substituting for it. In fact, some energy infrastructures may paradoxically be reconfigured for the valorisation of fossil capital or other extractive industries (Vezzoni, 2023). The political economy of energy transitions suggests that changes in the structures and modes of energy production are conducive to shifts in social power configurations (Newell, 2021, p. 65). Yet, conversely, can hydrogen transform energy systems and, above all, their material bases of accumulation, if social relations and power configurations remain unaltered?

Currently, hydrogen is mostly produced in a few industrialised countries but, unlike fossil fuel reserves, green hydrogen is promoted as “a technology available to any country with a natural endowment of renewable energy” (GH2, 2021, p. 3). The availability of wind and especially solar energy in peripheral economies may hold the potential for a decentralized global energy production system (IRENA, 2022a). Nevertheless, the Global South also provides the world market economy with lower wages and loser environmental regulation, raising concerns about value appropriation by core countries through global trade and ecological unequal exchange (Dorninger et al., 2021; Hickel et al., 2022). These reservations extend to prospective hydrogen trade, as recent commercial partnerships between European and African countries betray a displacement of environmental and social costs that is reminiscent of colonial times (Barnard, 2022; Eberhardt, 2023; Müller et al., 2022). The advent of potentially cheaper or more decentralized energy systems, combined with increasingly stringent climate policies, poses a threat to the viability of the fossil fuel industry, thus prompting adaptive responses from oil and gas majors. The widespread adoption of clean hydrogen is presented as a win-win solution for repurposing existing fossil infrastructure, trade routes, and energy markets to align with the decarbonisation targets of the Paris Agreement. A too good to be true scenario, and indeed one which warrants closer examination.

In the next section, this article illustrates major sources of path dependency in energy systems and the relevance of framing the temporal dimension of energy transitions. It is followed by Section 3 on research methods and data, which highlights the significance of a GPN approach to the study of corporate strategies and social power relations shaping the hydrogen economy. Section 4 delves into the key relationships between hydrogen and other industries (notably, oil and gas players), including end-uses, infrastructural investments in capture, utilization, and storage (CCUS) and pipeline networks, as well as the main actors, projects, and patent holders from other GPNs. Section 5 discusses the findings while advancing policy recommendations, and Section 6 concludes with avenues for further research. Overall, this article contributes to the ongoing debate over hydrogen deployment and broader sustainability transitions, showing that a relational and processual account can shed light on the political-economic forces shaping the development of alternative energy systems.

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[2] To clarify, this article uses the standard definition of “clean hydrogen”, which commonly includes not only hydrogen produced from low-carbon sources (like solar and wind), but also from fossil fuels with carbon capture, utilisation and storage (CCUS) technologies (European Clean Hydrogen Alliance, 2020; IRENA, 2022a). In the common nomenclature of “hydrogen colours”, green hydrogen refers to hydrogen produced via electrolysis using low-carbon energy sources (e.g., wind and solar) while blue hydrogen refers to hydrogen produced via SMR with CCUS.

2. Path-dependent energy transitions

The transformation of energy provisioning systems rarely occurs as an abrupt change with clear before-and-after partitions, particularly on a planetary scale (Fouquet, 2016; Smil, 2016) (cf Sovacool, 2016). The larger and more complex an energy system, the slower the transition process (Grubler, 2012). Synchronous industrial development is uncommon, as temporary and contextual adjustments are possible and often favoured by incumbent production networks. Köhler et al., 3) argue that these actors "are likely to protect their vested interests and contest the need for and speed of transitions". The oil and gas industry, for example, operates via capital-intensive processes whose rate of profitability depends on leveraging finance to actualize future cash flows. These are then capitalised upon to fund long-term infrastructural investments in the extraction, refining, and distribution of fossil-based commodities. Consequently, fossil fuel companies are resistant to rapid change but can also effectively establish new energy markets (Newell and Paterson, 2010). Energy transitions, therefore, occur across multiple and intersecting fronts, where potentially viable but contested economic pathways are reconciled by coalitions of actors seeking to either defer conflicts over resource ownership and use, or to resolve them in their favour (Roberts et al., 2018; Stoddard et al., 2021).

Simply put, path dependency refers to the selective narrowing of options due to decisions taken at an earlier point in time. The historical trajectory resulting from the concatenation of path-dependent choices bends the course of history, making certain outcomes more likely than others (Vadén et al., 2019). Drawing on the Post-Keynesian economics tradition, this implies that there is no such thing as a long-term "natural" equilibrium, for the final outcome of a socio-economic system is irreversibly influenced by previous states, as encapsulated in the notion of hysteresis (Kronenberg, 2010, p. 1491). For instance, Husu (2022) applies Bourdieu's "hysteresis effect" to energy transitions to describe the mismatch between opportunities for change and the incapacity to seize them while clinging onto outdated dispositions. Similarly, Patomäki (2022, p. 121) refers to this as "the presence of the past in the embodied persons and social actors". Transformative social change involves temporarily overlapping tendencies that may at times exert opposing forces, as in the case of new commercial technologies clashing against established practices, even within the same industry. The result of these competing dynamics – in terms of policy outcomes, economic paradigms, investment strategies, and so on – determines which future energy provisioning systems will be economically and materially viable. The hydrogen economy is developing according to path-dependent arrangements, and this article explores when, who, how, where, and what is determining them.

2.1. When? today's inaction is tomorrow's cost

Temporality poses real constraints on future events, while these are also contingent on conscious decisions made by social actors in the present (Patomäki, 2022, chap. 8). Climate policy debate is a case in point. While climate change scepticism and outright denial of anthropogenic impact are losing ground, they have been replaced by "climate delay" discourses (Lamb et al., 2020). These discursive tactics aim to undermine actions, misrepresent solutions, or support policies "that maintain existing political and economic power relations" (Painter et al., 2023, p. 2). Paradoxically, the intentional use (or waste) of time responds to the reproductive strategies of incumbent actors, whereas the costs and liabilities of delay fall squarely on future generations. Thus, time is of the essence, not only due to the looming collapse of planetary ecosystems, but also because the hysteresis in social-ecological systems limits future possibilities to the timely enactment of consistent choices in the present. However, the self-reinforcing inertia of social systems is wired in capital-intensive sectors of the economy, such as fossil-fuel-based industrial complexes (Unruh, 2000), and it is further bolstered by alliances between policy and corporate interests (Geels, 2014). This relates to a second source of path dependency in energy transitions, namely the social power of incumbent actors, and the permanence of their networks.

2.2. Who, how, and where? the geographies of incumbent networks

The strategic capture of novel energy systems represents the agents' drive to survive in the evolving technological landscape. By co-opting, containing, or endorsing new ideas, actors can re-position themselves in the market to redirect expected capital flows under their control (Sovacool, 2016, p. 205). Therefore, it is key to identify "*who* the agents are in this process and *how* [they] bring about or resist transitions" (Newell, 2021, p. 30) (emphasis in original). The fossil fuel industry is currently re-positioning itself as a key player in the energy transition. However, mounting evidence suggests that low-carbon technologies are often purposed to preserve, rather than replace, fossil physical infrastructure and economic rents (Dunlap and Marin, 2022; Vezzoni, 2023). This pattern has also been observed in the case of hydrogen (Balanyá et al., 2020; Szabo, 2022; Tilsted et al., 2022; Tvedten and Bauer, 2022). Furthermore, taking stock of the historical reliance of Western countries on unequal ecological exchange (Hickel et al., 2022), it is relevant to question also the geographical location, i.e. the *where*, of these key agents. While multinational firms often transcend the strategic influence of state power (Newell, 2021), the spatial distribution of added value and price differentials in international trade betrays a world economy that still relies on post-colonial core-periphery relations (Dorninger et al., 2021). This net appropriation implies that most productive investments are located in the Global North, and so is most capital stock.

2.3. What? infrastructural lock-in

Investments in physical capital come with infrastructural lock-in effects. Physical stocks create path dependence on material and energy consumption for their maintenance, as well as on the carbon intensity of production (Krausmann et al., 2017). Since new developments cannot disregard the interrelations between modes of production and existing infrastructure, particularly in capital-intensive industries (Grubler, 2012), dominant technologies increase the likelihood of related modes of production prevailing in the future (Vadén et al., 2019). In other words, the stock of existing infrastructure can influence the historical trajectory of energy systems. Additionally, the sunk costs of capital investments may result in stranded assets if these get prematurely devalued due to environmental policy or market shifts. Large capital expenditures (CapEx)[3] typically extend over long payback periods, hence encouraging calls for adaptation, transition, and retrofit of existing energy systems. In light of climate policy, stranded assets pose an increasingly serious issue for the oil and gas industry (Hansen, 2022; Seto et al., 2016). Under a 1.5 °C global warming scenario, fossil fuel reserves may lose up to 13–17 trillion US$ over the next two decades, that is, up to half of their current valuation (Hansen, 2022).

Much like discourses of "climate delay", strategies to avoid stranded assets by fossil fuel majors are what Carton (2019, p. 750) caustically labels the "political economy of delay in devaluing carbon-intensive accumulation". A 2022 report by the International Energy Agency (IRENA, 2022a, p. 107), for instance, acknowledges that the adoption of hydrogen may well hinder climate targets if it is deployed as a means to sustain fossil fuel extraction. Similarly, several scholars (Howarth and Jacobson, 2022; Tvedten and Bauer, 2022; van Renssen, 2020) have pointed out that support for hydrogen production with CCUS may be "the answer incumbents have proposed" to keep on selling natural gas (Szabo, 2022, p. 7). The remainder of this article explores how these sources of systemic path dependence are shaping the nascent hydrogen economy.

3. Research design

3.1. Methodological approach: global production networks (GPNs) of hydrogen

Most scientific and grey literature on the hydrogen economy focus on the notion 0f value chains, by looking at the "research and development, production, distribution, applications, and retail of products to end users" (Eicke and De Blasio, 2022, p. 2). While this perspective is undoubtedly valuable, it also comes with limitations. It may uncover the hurdles and promises within the hydrogen industry, although it remains blind to the strategic actions and organisational features of the networks shaping the hydrogen economy from the outside. As argued by Kalt and Tunn (2022, p. 73), most studies fall short of identifying emerging alliances and power struggles between state, corporate, and civil society in the appropriation of new energy sources. Additionally, Bridge and Bradshaw (2017, p. 224) contend that by seeking to reassure the industry over future prospects, studies that are overtly focused on supply chain issues tend to be rather uncritical. Some scholars have attempted to bridge this gap by incorporating critical social science perspectives into hydrogen systems research (e.g., Dillman and Heinonen, 2022; Müller et al., 2022), yet their analyses often remain confined within the perimeters of the hydrogen value chain itself.

Therefore, as Bridge and Faigen (2022) argue in their analysis of lithium-ion battery production networks, there is a risk of overlooking the organizational structure of global production and the strategic interactions among different industrial networks. To address this gap, this article draws on the global production network (GPN) approach to identify the political economic logics cutting across the vertical relationships of hydrogen production. Developed in the early 2000s and departing from the cognate global value chain (GVC) research, the GPN framework advances a time- and space-sensitive heuristic to capture the "inter-relationships shaping and reshaping the global economy" (Coe et al., 2008, p. 272). In energy industry studies, it has been used as a cross-sectoral analytical framework to complement existing value chain research with a view of the "competing agendas and asymmetric power relations through which" global networks of energy production emerge (Bridge and Bradshaw, 2017, p. 222) (see also, Bridge, 2008; Dodge, 2020; Guo et al., 2021; Galan, 2022; Bridge and Faigen, 2022, 2023). Accordingly, in this article, we do not frame hydrogen as inherently disruptive or oppositional to existing industrial conglomerates; on the contrary, the "clean" hydrogen economy is emerging from the material and ideational possibilities within existing relationships in the global market economy.

The multi-scalar articulation of transnational energy actors, chiefly oil and gas companies, and their intersections with other industries – like mining, automotive, and renewables – transcends and yet determines the value chain of hydrogen. These GPNs are not static and coherent, but can harbour conflicting dynamics and tensions, such as the conflict between the valorisation of capital invested in fossil fuel infrastructure and the need to replace it with low-carbon energy sources. Likewise, companies within the oil and gas industry may temporarily pursue divergent tactics (Levy and Kolk, 2002), occasionally resorting to discursive strategies that do not align with their business practices.[4] Energy transition scholars are increasingly aware of the contradictions-with-continuity that characterise incumbent strategies within energy systems and across geographies (Köhler et al., 2019; Newell, 2020), and have been calling for research to "do justice to hydrogen futures […] expected to determine socio-ecological path dependencies for decades to come" (Hanusch and Schad, 2021, p. 84). Along these lines, this article operationalises the conceptual repertoire developed in GPN research to identify, reconstruct, and make sense of the organisational strategies, industrial relations, and economic trends shaping the developments of the allegedly up-and-coming "clean" hydrogen economy.

3.2. Methods and data collection

The data for this study has been collected and refined through three phases. First, we conducted a literature survey in December

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[3] The CapEx measures the financial capital spent by a company in physical capital, such as the funding requirements of new energy projects and infrastructural investments.

[4] For example, Green and colleagues (2022) find that having disclosed pro-climate behaviour since the Paris Agreement in 2015, BP has lagged behind competitors like Equinor, Shell, and Total in terms of upstream investments in traditional business operations and renewable investments.

2022 and June 2023, resulting in 127 research items.[5] Second, this was complemented by 18 in-depth interviews conducted between April and July 2023. The interviewees were hydrogen world experts from industrial partnerships, project developers, leading intergovernmental agencies and, civil society organisations working on the energy transition, and academia. The interviews have been integrated with email correspondence with corporate actors and public authorities, as well as participant observation in four industry events on hydrogen and energy transitions. Third, the information gathered was triangulated with publicly available market analytics and data, as well as corporate document and media analyses. Detailed information on the comparison and juxtaposition of different data sources is provided in the appendix.

The primary materials collected in this study were used to refine regional and national datasets of hydrogen projects, actors, investments, and industrial patents, such as the European Clean Hydrogen Alliance (ECHA) membership list, the IEA Hydrogen Projects Database, the S&P Global Hydrogen Atlas, and the European Patent Office (EPO) global trend analysis. This desk-based research provided insights into the composition of the ECHA (1638 entries) memberships as a snapshot of the main actors (Section 4.3.1), the world's largest hydrogen projects (section 4.3.2), and the distribution of hydrogen technologies ownership (section 4.3.3).

4. Results

4.1. End-uses

Fig. 1 provides an overview of the prevalent modes of hydrogen production, sources of demand, and related volumes. Advocates project that in the coming decades hydrogen will play a significant role in powering vehicles like cars, trains, ships, and planes (Hydrogen Council, 2021), as well as in storing excess energy from renewables (Yue et al., 2021). However, these end-uses are currently negligeable. As of 2022, hydrogen is predominantly employed in refining crude oil (43.2 %) and to manufacturing nitrogen-based fertilizers (33.5 %) (IEA, 2023). China alone accounts for nearly one-third of the global demand for hydrogen (largely produced from coal), with the rest mainly consumed in the US, India, the Middle East, and Europe.

Due to the superior exergy content of electricity, anything that can be electrified should be electrified (Oliveira et al., 2021). Nevertheless, hydrogen can represent a viable alternative whenever competing decarbonisation options, like energy savings and electrification, are not economically or technically feasible (IRENA, 2022b, p. 24). For instance, hydrogen could replace fossil fuels in aviation and intercontinental transport (Yue et al., 2021), or serve as an industrial feedstock to reduce CO2 emissions, like in direct reduced iron (DRI) plants (Schneider, 2022). These five end-uses – i.e., refining, fertilizers, chemicals, steel, and long-distance transport – already constitute over 99 % of hydrogen consumption. It is crucial to prioritise the decarbonisation of current industrial demand, since over 99 % of hydrogen production still relies on the consumption of fossil fuels. Despite considerable enthusiasm surrounding hydrogen, recent industry figures suggest that low-carbon hydrogen adoption will only cover 12–17 % of projected demand in 2030 (IEA, 2023), with a substantial portion still dependent on natural gas and coal.

Surprisingly, while new hydrogen applications such as domestic heating and blending in existing natural gas networks have received significant media coverage and policy attention, mounting evidence indicates that "H_2 is the worst energy carrier for building heating with a view to efficiency and infrastructure requirements" (Gerhardt et al., 2020, p. 13) (Rosenow, 2022; Weidner and Guillén-Gosálbez, 2023). This issue has been reiterated also by the scientific experts and civil society organisations interviewed (e.g., ORG_2; ORG_5; SCI_1; SCI_4) .[6] Conversely, industry groups with policy influence in the UK (ENA, 2023), Europe (ENTSOG and ENTSO-E, 2022) and globally (Hydrogen Council, 2021) staunchly advocate for the advancement of new end-uses. These include the utilization of hydrogen for residential building, heating, and transportation. The risk of stranded assets provides a compelling reason for transmission system operators (TSOs) to tailor nascent hydrogen markets to their infrastructural needs. To assure the continuity of their business, fossil energy companies, and particularly those operating in natural gas markets, may have found a viable strategy in producing hydrogen with CCUS technologies and then transporting it via refurbished gas pipelines.

4.2. Investing in infrastructural lock-in

4.2.1. Carbon capture utilisation and storage (CCUS)

The oil and gas industry has historically ostracised hydrogen deployment (e.g., in Norway see Klitkou et al., 2015). Yet the adoption of CCUS technologies is making its infrastructural requirements more compatible with those of fossil fuel infrastructures. Blue hydrogen (i.e., SMR with CCUS) is often presented as a transitional fuel to meet temporary hydrogen demand (Bertagni et al., 2022). Van de Graaf et al. (2020, p. 5), for instance, suggest that "paradoxically, blue hydrogen currently has a lower carbon footprint than electrolytic hydrogen in most regions – because of their current electricity mixes". However, concerns about blue hydrogen's lifecycle climate impact have challenged the legitimacy of these claims (Howarth and Jacobson, 2021). Particularly due to fugitive methane (CH_4), the equivalent carbon footprint of blue hydrogen may be even higher than simply burning fossil fuels for electricity production. Likewise, in their worst-case scenario (leak rates CH_4 3 %, H_2 10 %), Ocko and Hamburg (2022, p. 9359) conclude that blue hydrogen "could initially be worse for the climate than the CO_2 emissions from the corresponding fossil fuel technologies". Romano and co-authors (2022) dispute these concerns, claiming that the leakage rates used in these studies (i.e., CH_4 1.5–3.5 %) are "at the high end of the estimated emissions from current NG production" (Romano et al., 2022, p. 1950). Notably, this claim would disprove the

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[5] See the appendix for more details.

[6] The details of each interview are provided in Table 6 of the appendix.

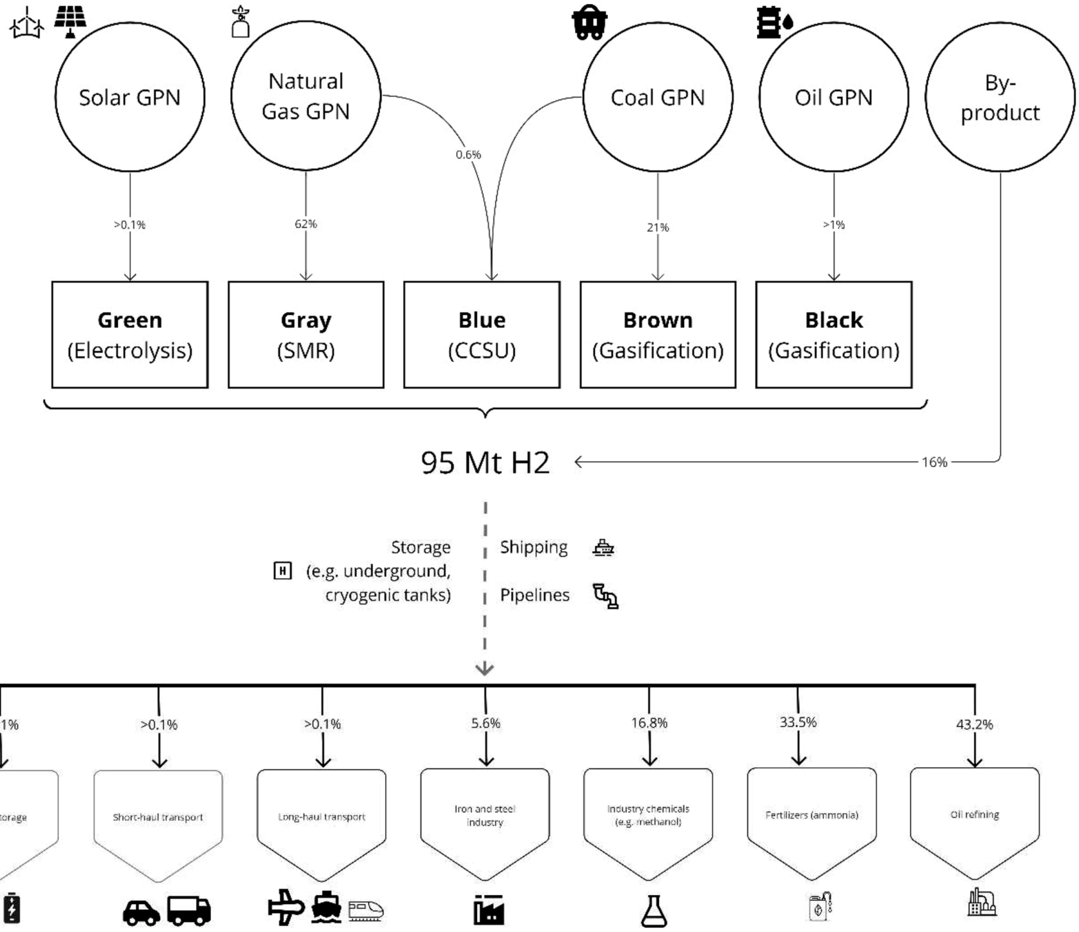

Fig. 1. Overview of the hydrogen economy in 2022. Production and end-use percentages are approximations of the prevalent technologies and applications. Own elaboration from (Dillman and Heinonen, 2022; IEA, 2023; IRENA, 2022a).

evidence provided in a previous paper co-authored by five of the scholars in Romano et al. (2022), since in Bauer et al. (2021) the authors caution that methane emissions have been widely underestimated and exhibit significant variability across extraction sites, being anything from 0.9 to over 9 % in the US, and "significantly higher than 2 %" for most exporting countries (Bauer et al., 2021, p. 71) .[7]

Fugitive CH_4 emissions amounting to 9.4 % of gross production[8] in the Permian Basin further underscore these concerns (Chen et al., 2022). The climate impact of CH_4, combined with the still under-investigated indirect effect of higher H_2 ppm in the atmosphere (Ocko and Hamburg, 2022; Warwick et al., 2022), should cast serious doubts over the prospects of blue hydrogen. According to Hauglustaine et al.,2022), over a 20-years period, "the climate benefit is lost if the blue hydrogen fraction is >30 % and if the leakage rate exceeds 3 %". Accordingly, in a reply to the comment, Howarth and Jacobson (2022, p. 1956) expose the weak science behind "Romano et al.'s estimates" which "are based on two out-of-date, non-peer-reviewed reports and a cartoon on a web page from the oil and gas industry". This corporate bias remains an unresolved issue (Carton et al., 2023), for the lowest CH_4 emissions figures most often rely on voluntary disclosure by gas companies. Assuming near-100 % CCUS capturing rates (a process which anyway comes with its own energy requirements) and CH_4 leakage rates <1 % demands a significant leap of faith (Bertagni et al., 2022, p. 5), in the absence of which, a fossil fuel economy would paradoxically be more climate-friendly than one based on blue hydrogen.

Nevertheless, oil and gas majors remain committed to developing blue hydrogen industrial applications (van Renssen, 2020), also influencing government strategies (interviews IND_3; GOV_5; SCI_4) and diverting substantial public funding (Balanyá et al., 2020; Tvedten and Bauer, 2022). The risk of corporate capture and commodification of climate gases has raised scepticism about the real

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[7] Likewise, the US Environmental Protection Agency (EPA) suggests that 2-3% of natural gas gets lost across the North American supply chain. Bauer et al. (2021) also argue that leak rates <1% have been observed in Northern Europe and should be taken as a standard for modernising gas infrastructure around the globe. Whether this is an economically (and technically) feasible proposition to be accomplished in the next two decades remains uncharted territory.

[8] Therefore, this figure excludes losses occurring during transmission, distribution, and consumption.

potential of CCUS since its early days (Ford and Newell, 2021). Between 2007 and 2017, CCUS projects attracted $28 billion of public funding, of which 85 % ultimately failed (GH2, 2021, p. 10). Governments, however, persist in investing substantial funds, with nearly $18 billion allocated in 2021 alone (IEA, 2022b). Investments in blue hydrogen risk locking-in capital in oil and gas infrastructures (Rosenow and Lowes, 2021) and potential stranded assets (Dillman and Heinonen, 2022). Unlike electrolysers, which are modular, blue hydrogen becomes cost-effective only at large volumes (Spek et al., 2022), and only as long as it remains cost competitive against hydrogen from solar and wind energy (interview SCI_3). The attractiveness of blue hydrogen seems to lie more in its political marketability rather than its techno-economic viability.

As Szabo (2022, p. 7) notes, blue hydrogen “allows for the extension of the status quo”, allowing producers to continue exploiting fossil fuel reserves, gas operators to maintain their infrastructure, and policymakers to appease the public with illusory promises of net-zero technological innovations. Oil and gas majors are seeking a place in a low-carbon energy system, and hydrogen produced with CCUS “carries the potential to perpetuate current capital accumulation practices that rely on the exploitation of our natural resources in an unsustainable manner” (Szabo, 2021, p. 105). The leeway granted to blue hydrogen seems scientifically unjustified, but the absence of international standards and methodological guidelines for measuring cradle-to-grave greenhouse gas emissions has been harnessed by oil and gas lobbies to carve out a favourable space in energy transition agendas and government budgets, including efforts to repurpose gas pipeline networks.

4.2.2. *Transport, or not*

Hydrogen transportation networks currently play a minor role, with 70–80 % of hydrogen used on-site in applications such as steel production and refineries (Fan et al., 2022; Hydrogen Europe, 2022; IEA, 2023). Dedicated pipelines (<5000 km, mostly in the EU and the US) are a fraction of the 3 million km natural gas grid (Griffiths et al., 2021, p. 45). However, if the expected sharp increases in hydrogen demand will materialise, this will lead to significant infrastructure growth (Spek et al., 2022). This is likely to be supported by public funding due to the widespread emphasis on export-led value chains and international trade in government policy (IRENA, 2022a, 2022b).

Hydrogen transportation costs, however, could triple production due to its low volumetric energy density and high energy costs for storage, especially if shifting from on-site to decentralised consumption (IEA, 2019). Notably, hydrogen is not an extraction business, as it does not provide net energy outputs, but serves as an energy carrier and storage (IRENA, 2022a). This poses a conundrum: to expand the hydrogen economy, hydrogen costs must be low, hence leading to increased competition. Moreover, whereas large volumes of hydrogen are required in industrial processes, the profit margins lie in its transport and related applications (van Renssen, 2020). Compared to fossil fuels, therefore, capturing economic rents along the hydrogen value chain is more challenging, unless an economic case can be made to lock in the industry in capital-intensive modes of production and transportation (thus securing the position of key incumbent actors).

This seems to be exactly the scenario favoured by some industry groups, tilting the industrial policy playfield in their favour (e.g., interviews IND_1; IND_4). While gas TSOs advocate for the converting gas grids to accommodate hydrogen (EHB, 2022; ENA, 2023), independent studies, have raised concerns about the technical challenges and economic obstacles of repurposing natural gas infrastructure (Barnard, 2022; Ogden et al., 2018). These include increase costs for consumers associated with blending hydrogen into the gas grid (up to 20 % volume) (Bard et al., 2022; Rosenow, 2022), the climate impact of hydrogen and methane leaks in long-distance pipeline transport (Bauer et al., 2021; Ocko and Hamburg, 2022), as well as the economic and environmental implications of global bulk shipping of hydrogen, e.g., in the form of ammonia (NH_3) (Wolfram et al., 2022). Consequently, refurbishing existing infrastructure seems highly context-dependent, and its viability should be assessed based on broader considerations than avoiding stranded assets. Accordingly, IRENA (2022a, p. 73) suggests that every “new investment decision is long-lived, so fixed pipeline infrastructure should be assessed with a future-proof logic. For instance, any gas pipeline infrastructure built today should be amenable to “repurposing” to carry clean gases such as hydrogen and biomethane”. However reasonable, this proposition is often exploited by incumbent actors to promote new gas infrastructure, as seen in the case of new LNG terminals in Germany post-2020 (Brauers et al., 2021). Even the now infamous Nord Stream 2 gas pipeline, sabotaged in September 2022, had been once considered a possible means of transporting hydrogen from Russia to Europe (Rosenow and Lowes, 2021).

4.3. *Hydrogen at a crossroad: the oil & gas, mining, and automotive global production networks (GPNs)*

4.3.1. *The actors: a focus on Europe*

In 2017, Japan alone had a national hydrogen strategy. Fast forward six years, and over forty states had advanced official hydrogen strategies (IEA, 2023), half of which are European countries. Beyond governmental strategies, numerous organisations and initiatives have been crowding the hydrogen policy space. Globally, the International Energy Agency (IEA) has coordinated the Hydrogen Initiative since 2019, providing a collaborative forum for policies, programs, and hydrogen deployment projects (interviews GOV_1; GOV_2). The Initiative’s partners include the World Economic Forum (WEF) and, most notably, the Hydrogen Council – formed at the Davos WEF in 2017, by the French multinational chemical company Air Liquide and CEOs of thirteen transnational corporations (TNCs) like Shell, Toyota, and Anglo American.[9] The Hydrogen Council has grown to be an influential partnerships worldwide, counting among its Steering Members TNCs from the oil and gas (e.g., ADNOC, Aramco, BP, Chevron, EcoPetrol, Eneos, Equinor,

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[9] More information on the founding process is available on the Hydrogen Council webpage: https://hydrogencouncil.com/en/founding-story/.

Indian Oil Corporation, KoGas, PETRONAS, Shell, SINOPEC, Snam, Total), automotive (e.g., BMW Group, Daimler Truck, Faurecia, General Motors, GWM, Honda, Hyundai, Toyota, Weichai) and mining industry (e.g., Anglo American, CHN Energy, Fortescue Metals). Its headquarters are in Brussels, Belgium, reflecting Europe's status as a prominent region for hydrogen (Yue et al., 2021), particularly in terms of public outreach and networks of actors. In Europe, as significant actor is Hydrogen Europe, a public-private partnership (PPP) with over 400 members and providing position papers, public events, consulting, and reports covering the European hydrogen value chain. Hydrogen Europe is part of the European Clean Hydrogen Alliance (ECHA), the broadest hydrogen network in the world (also operating on the procurement logic of PPP). Established in July 2020 as part of the New Industrial Strategy of the European Union, the ECHA aims to develop low-carbon hydrogen "as a viable and competitive energy carrier in Europe", and to provide a forum coordinating the actions of "all stakeholders in the hydrogen value chain" (ECHA, 2020, p. 1).

However, despite the emphasis on diversity of actors, a screening of the 1638 members registered as of March 2023, shown in Table 1, indicates that over 80 % are corporations or PPPs, including port authorities, development agencies, and city councils partnering with businesses to promote investments in the region, under the increasingly fashionable notion of hydrogen valleys or hubs. Both Hydrogen Europe and the Hydrogen Council, along with their represented TNCs,[10] are members of the ECHA. In addition to the Steering Members of the Hydrogen Council, all the other major integrated oil and natural gas companies with headquarters in Europe are part of the ECHA, together with lobby groups like the International Association of Oil & Gas Producers (IOGP). This includes the four biggest companies behind Europe's gas transport network, as shown in the right half of Table 1. Civil society represents less than 2 % of memberships, including the questionable labelling as "civil society organisations" of entities registered as companies (e.g., Nordseeheilbad Borkum GmbH), or of organisations with no proven track record of activities (e.g., Dbay, Europe Energy Transition Foundation, Experts Platform on implementing the European Green Deal of Sofia, Regional Innovation Fund-Vidin 2020).

Notably, oil and gas TNCs play a significant role in setting-up, funding, and operating hydrogen partnerships. Another exemplary case is the European Hydrogen Backbone (EHB) initiative, a consortium of 32 TSOs, mostly gas companies. These gas TSOs control over 75 % of European natural gas consumption.[11] Since 2020, the EHB has published industry outlooks on hydrogen infrastructural developments, with a particular focus on repurposing the existing natural gas grid (interview IND_1), as detailed in Section 4.2.2. These actors exert preferential influence on policymakers, especially when accompanied by multi-billionaire investments, as explored in the next sub-section.

4.3.2. *Largest hydrogen projects*

Currently, the largest hydrogen plants rely on unabated fossil fuels, mainly located next to refineries in coastal areas of oil-producing countries (Table 2). These facilities are usually owned by IOGs for on-site upgrading of oil and its derivatives.

A key challenge in addressing advancements in clean hydrogen production is the lack of international traceability for major project developments. Despite this, in early 2021, the largest clean hydrogen plant was reported to be owned and operated by Air Liquid[12] in Quebec, Canada (Edwardes-Evans, 2021), equipped with a 20 MW proton exchange membrane (PEM) electrolyser producing up to 3 kt of hydrogen per year – about two orders of magnitude lower than the production volumes of the largest grey hydrogen facilities. However, this record was quickly surpassed later in the same year by the 30 MW electrolyser installed by the Chinese coal company Baofeng Energy. The following year, in 2022, Baofeng Energy again made headlines by doubling the global electrolysers capacity overnight with the installation of a new 150 MW plant in central China (IEF, 2022). Interestingly, in the same year, Shell claimed to own and operate about one-tenth of global electrolysers installed capacity (Shell plc, 2022). Nevertheless, it was yet another Chinese company, the state-owned enterprise Sinopec, which made waves in early 2023 when announcing a record-breaking 260 MW electrolyser plant in Xinjiang, northwest China. Whereas most of the announced investments in clean hydrogen come from the Global North, largely from Europe (US$ 117 bn, or 35 % of global investment, according to the Hydrogen Council, 2023), it is noteworthy that China's oil and gas industry is at the forefront of developing the largest operational facilities.

Table 3 refines the IEA Hydrogen Projects Database (IEA, 2021), listing the twenty largest projects listed, eleven of which involve at least one oil and gas company as lead developer, often in partnership with public authorities (projects #1 and #9). Renewable energy developers such as Copenhagen Infrastructure Partners (CIP) and CWP Global are also prominent players, leading six of the projects in Table 3. Several projects are based in Australia, where mining corporations such as Iron Road and Fortescue Metals Group (through its subsidiary Fortescue Future Industries) play a key role, together with the automotive industry (Porsche's subsidiary, #16). It should be noted that CWP was acquired in late 2022 by the investment firm Tattarang, owned by the Forrest family, and notably Andrew Forrest, who is also the CEO of Fortescue (Murdoch et al., 2022). The mining industry thus accounts for five of the top ten announced hydrogen projects, representing 25 % of the ones listed in Table 3.

Only a few of these projects have reached the final investment decision (FID) stage, and details are bound to change as some projects get downsized or even dismissed. Notably, compared toIRENA's (2022a, p. 87) list of the world's 20 largest green hydrogen projects, Table 3 introduces five new projects (excluding the two SMR+CCS plants). While 13 projects overlap between the two lists, 8

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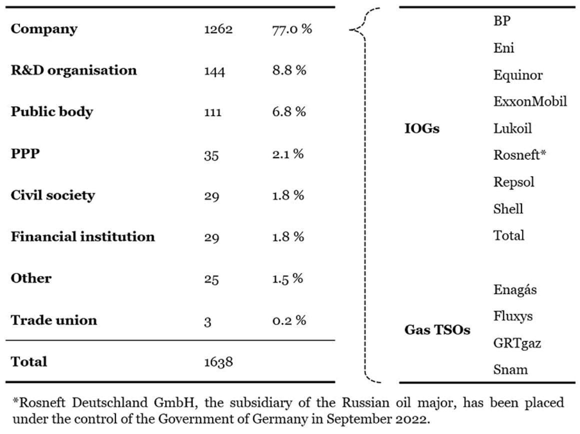
[10] According to the Criteria for Membership in the European Clean Hydrogen Alliance, only stakeholders with legal establishments in EU and neighbouring countries are allowed to apply. This for example includes regional branches of TNCs like Honda R&D Europe or Toyota Motor Europe.

[11] As a spin-off of the Gas For Climate coalition, the members include Amber Grid, Bulgartransgaz, Conexus, CREOS, DESFA, Elering, Enagás, Energinet, Eustream, FGSZ, FlusSwiss, Fluxys Belgium, Gas Connect Austria, Gasgrid Finland, Gassco, Gasunie, GASCADE, Gas Networks Ireland, GRTgaz, National Gas Transmission, NET4GAS, Nordion Energi, OGE, ONTRAS, Plinacro, Plinovodi, REN, Snam, TAG, Teréga, Transgaz and the TSO of UA.

[12] Air Liquid is also the first proponent of the Hydrogen Council, see Section 4.3.1.

Table 1
The membership structure of the European Clean Hydrogen Alliance as of March 2023. Acronyms: public-private partnership (PPP), integrated oil and natural gas companies (IOGs), transmission system operators (TSOs). Source: data publicly available on the European Commission portal.



Company	1262	77.0 %
R&D organisation	144	8.8 %
Public body	111	6.8 %
PPP	35	2.1 %
Civil society	29	1.8 %
Financial institution	29	1.8 %
Other	25	1.5 %
Trade union	3	0.2 %
Total	1638	

IOGs	BP Eni Equinor ExxonMobil Lukoil Rosneft* Repsol Shell Total
Gas TSOs	Enagás Fluxys GRTgaz Snam

*Rosneft Deutschland GmbH, the subsidiary of the Russian oil major, has been placed under the control of the Government of Germany in September 2022.

Table 2
Top nine largest grey hydrogen facilities as of 2023. The list originally showed the top 10 facilities, but no evidence could be found for the Toa Oil Company refinery in Kakuda-shi, Japan. The Japanese site has therefore been removed from the list. Source: S&P Global Commodity Insights.

Facility	Country	Owner	Industry	Capacity (Kt H2/y)
Ulsan coking Refinery	KOR	SK Energy	Oil & gas	635
Shuaiba Refinery	KWT	Kuwait National Petroleum Corp.	Oil & gas	451
Port Arthur Refinery	USA	Valero	Oil & gas	390
Sturgeon Refinery	CAN	PPP (North West Redwater Partnership)	Oil & gas	390
Vadinar Refinery	IND	Nayara Energy	Oil & gas	389
Maoming Refinery	CHN	SINOPEC	Oil & gas	376
Huizhou Refinery	CHN	China National Offshore Oil Corporation	Oil & gas	312
Esfahan Oil Refinery	IRN	National Iranian Oil Co.	Oil & gas	277
Jazan Refinery	SAU	Saudi Aramco	Oil & gas	268

of these report substantially different (and in all cases but one, smaller) installed electrolysers capacity in Table 3.[13] There is also considerable variability in the coupled installed capacity of wind and solar energy compared to the size of the electrolyser in each production plant. For those projects that disclosed information, ratios between installed low-carbon energy and electrolyser capacity range from 1:1 (#8) to 3:1 (#12). This variability, influenced by location-specific factors, raises concerns about the actual additionality of some projects. Reliance on grid power could potentially compete with alternative uses of low-carbon electricity. Similarly, production volumes also vary widely, from 18 GW of electrolysers (GWel) for every 1 ktH_2 (#1) to only 3.3 GWel/ktH_2 (#13). The inconsistency in input-to-output ratios – both in low-carbon energy to electrolysers capacity ratios and in expected production volumes per GWel – reveals that either production volumes will be much lower than announced, or the expected targets will be achieved using traditional methods, such as unabated natural gas, and by drawing electricity from the grid.

As a final note, China is conspicuously absent from Table 3. This may be due to the difficulties in sourcing information in English, diverse corporate communication cultures, or a different approach by the Chinese national hydrogen strategy. While Europe currently leads hydrogen discussions, partnerships, and announcements of future investments, China dominates the present of hydrogen production (IEA, 2023), as also noted by several interviewees familiar with large-scale project development (e.g., IND_2; IND_4; SCI_3; SCI_4).

4.3.3. Patents

An examination of intellectual property rights in hydrogen technology reveals the prominence of GPNs already encountered in Section 4.3.1, from sectors like automotive, oil and gas, and industrial chemicals. Interestingly, despite substantial investments in hydrogen projects, the mining industry is not among the top players in technology ownership. The European Patent Office (EPO) recently collaborated with IRENA and IEA to analyse innovation trends in electrolysers (EPO and IRENA, 2022) and other technological advancements across the hydrogen value chain (EPO and IEA, 2023). Based on the latter report, Table 4 outlines the leading holders of hydrogen patents in the “world’s top ten hydrogen innovation clusters” throughout the 2010s decade (EPO and IEA, 2023,

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[13] Further details are provided in Table 7 in the appendix.

Table 3

Top twenty announced low-carbon hydrogen projects by 2030 (as of June 2023). Projects are ranked per targeted production volumes. Companies from the oil and gas industry are bolded. Project 1 may include others in the list (see appendix). Projects 19 and 20 are for blue hydrogen. Countries are listed according to ISO alpha-3 codes. Acronyms: GW el. (electrolyser installed capacity), Kt H2/y (Kilo tonnes of hydrogen per year); SMR +CCS (Steam methane reforming from natural gas + carbon capture and storage), n.a. (not available or unclear), NH3 (ammonia). Source: primary materials and IEA Hydrogen Projects Database refined as explained in the appendix.

	Project	Country	Date Online	Main players	CapEx (USD bn)	Main Purpose	Energy source	GW el.	Kt H_2/y
1	HyDeal Ambition	ESP, FRA, DEU, MAR, MRT	2025–2030	PPP (EU, Gov. of Spain (and Regional Gov.); Soladvent, DH2; FalckRenewables; Qair; Tunur; **Snam, Enagas, GRTgaz, OGE, Terega**; ArcelorMittal, **Naturgy**, BASF, **GazelEnergie**, Fertiberia)	n.a.	Integrated hydrogen chain, cost competitive	95 GW solar and wind	67	3 720
2	Western Green Energy Hub	AUS	>2027	Intercontinental Energy, CWP Global, Mirning Green Energy Limited	70	Export	50 GW solar and wind	20	3 500
3	Rio Negro	ARG	2030	Fortescue Future Industries	8.4	Export	n.a	15	2 200
4	Hyrasia One	KAZ	2027–2032	Svevind	40–50	Export to EU	40 GW solar and wind	20	2 000
5	Aman Green Hydrogen	MRT	2030	CWP Global	40	Export and domestic industries	18 GW wind and 12 GW solar	15	1 700
6	Asian Renewable Energy Hub	AUS	2028–2036	**BP** (40.5 %), CWP Global (17.8 %), Intercontinental Energy (26.4 %)	20	Export (90 %)	10 GW solar and 16 GW wind	14	1 700
7	Project Nour	MRT	2030	**Chariot, Total**	n.a.	Export to NL	Unknown solar and wind	10	1 200
8	BrintØ - Hydrogen Island	DNK	2030	CIP	n.a.	Export to EU	10 GW wind	10	1 000
9	AquaVentus	DEU	2025–2035	PPP (among which **BP, Equinor, Gascade, Gasuine, RWE**, Siemens Gamesa, **Shell, Total**, Vestas)	6	Offshore production	12 GW wind	10	1 000
10	Cape Hardy	AUS	2028	Iron Road, Amp Energy	n.a.	Steel production, export	n.a.	7.0	900
11	H2 Magallanes	CHL	2027	**Total**	Up to 20	Export	10 GW wind	8	800
12	Oman Dhofar and Duqm (3 projects)	OMN	2030	(1) CIP, BPP, Al Khadra; (3) **BP**; (3) **OQ, Shell**, ETC, ICE, GWWT	20	Export	12 GW solar	4.3	500
13	HyVal	ESP	2027–2030	**BP**	2	Refining + Export	n.a.	2	600
14	HyEnergy Zero Carbon Hydrogen	AUS	2030	Province Resources (**Total** exited 50/50 partnership in March 2023)	n.a.	Export	8 GW solar and wind	5.2	550
15	Desert Bloom	AUS	2027	Aqua Aerem, **Osaka Gas**	Up to 10.75	Export (e.g. JPN)	4000 units 2 MW of integrated solar and electrolysers	3.5	410
16	Murchison Hydrogen Renewables	AUS	2025–2030	CIP	n.a.	Export NH3 (e.g. JPN, KOR)	3.7 GW wind and 1.5 GW solar	3	348
17	Matagorda eFuels	USA	2026	HIF Global (Subsidiary Porsche)	6	E-fuels for vehicles	n.a.	1.8	300
18	NorthH2	NLD	2030	**Eneco, Equinor, RWE, Shell**	n.a.	Integrated hydrogen chain	Unspecified offshore wind	4	300
19	Baytown Refinery	USA	2027–2030	**ExxonMobil**	7	Refining	SMR + CCS		920
20	Louisiana Clean Energy Complex	USA	2026	Air Products	4.5	Export of H2 (pipeline) and NH3 (ships)	SMR + CCS		690

Table 4

Top 15 international patent holders in 2020. International Patent Families (IPFs) include patent applications published at several patent offices. Country refers to the headquarters of the company. The figures represent the lower bound of the percentage of world intellectual property families (IPFs) held by each applicant. *Source*: own elaborations from (EPO and IEA, 2023).

Applicant	Country	World's IPFs	Industry
Toyota	JPN	>2.0%	Automotive
Air Liquide	FRA	>1.0%	Industrial chemicals
Linde	DEU	>1.0%	Industrial chemicals
Panasonic	JPN	>0.9%	Conglomerate
Mitsubishi	JPN	>0.9%	Automotive, heavy industry
ExxonMobil	USA	>0.7%	Oil & Gas
Toshiba	JPN	>0.6%	Conglomerate
Air Products	USA	>0.6%	Industrial chemicals
BMW	DEU	>0.6%	Automotive
Thyssenkrupp	DEU	>0.5%	Engineering and steel
Jx Nippon Oge	JPN	>0.5%	Oil & Gas
Kawasaki	JPN	>0.4%	Automotive, heavy industry
IFPEN	FRA	>0.3%	Oil & Gas Research
SABIC	SAU	>0.3%	Industrial chemicals
Suzuki	JPN	>0.2%	Automotive

Table 5

Top 10 companies per hydrogen granted patents. *Source*: (GlobalData, 2022).

Company	Country	Granted patents	Industry
Linde	DEU	1209	Industrial chemicals
Air Products	USA	1203	Industrial chemicals
Air Liquide	FRA	1193	Industrial chemicals
BASF	DEU	1038	Industrial chemicals
Shell	GBR	924	Oil & Gas
Chevron	USA	872	Oil & Gas
Toyota	JPN	848	Automotive
Panasonic	JPN	796	Conglomerate
ExxonMobil	USA	773	Oil & Gas
Topsoe	DNK	609	Petrochemicals

tbl. 2.2). The applications listed in Table 4 represent 10.5 % of world IPFs. Except for IFPEN (French Institute of Petroleum – New Energies), all the leading patent holders are corporations, mostly from the automotive industry (4.1 % out of 10.5 %), followed by the industrial chemicals sector (3 %), and the oil and gas industry (1.5 %).

A similar dominance of the industrial chemicals, oil and gas, and automotive sectors is evident in the total number of granted hydrogen patents worldwide. Most companies listed in Table 5 also appear in Table 4, with the addition of BASF, Shell, Chevron, and Topsoe. Despite a few prominent players from the US (like ExxonMobil, AirProducts, Chevron), Europe and Japan lead the patents race, accounting for 52 % of IPFs in the period 2011–2020, and particularly after 2015 (EPO and IEA, 2023). Moreover, concerning intellectual property rights on electrolysers technologies, China lags behind individual European countries like Germany and France (EPO and IRENA, 2022).

5. Discussion

There is broad recognition that hydrogen will play a role in the transformation of energy systems – the question is which one. Currently, the hydrogen economy is responsible for emitting as much greenhouse gases as global aviation, or more than half of Africa's total emissions. The hydrogen economy, from production to consumption, is predominantly controlled by the oil and gas industry. On the supply side, other GPNs involved in downstream applications, such as the chemical industry and automotive groups, are emerging as key players. The mining industry, also a prominent market mover, plays a significant role in providing the necessary raw materials and stands to benefit from the development of low-carbon energy sources. Section 4 has highlighted that hydrogen value chains are at a crossroad, underscoring the still contested aspects of hydrogen off-take, transportation, infrastructural investments, and production processes. Other GPNs with overlapping interests – primarily the oil and gas industry, but also the mining, industrial chemicals, and automotive industry – are likely to influence the course of industrial development, which may not necessarily align with the common good.

Based on the evidence presented in Section 4 and drawing on the three drivers of path-dependency conceptualised in Sections 2.1, 2.2, and 2.3, we argue the following:

1. The boundaries of the analysis should be drawn broad enough to include the temporal and spatial arrangements required by any alternative mode of production. Effective and timely decarbonization requires lifecycle emissions and cradle-to-grave socio-

environmental impacts assessments. This includes addressing natural gas leakage used in hydrogen production (Howarth and Jacobson, 2022, 2021), the moral hazard implicit in CCUS technologies (Carton et al., 2023), but also the social issues and material requirements associated with low-carbon energy sources (Dunlap and Marin, 2022; Vezzoni, 2023). Moreover, it is crucial to align greenhouse gas emission assessments with the most relevant time scale, often set at 2050 for climate targets. Actions taken (or not taken) until then can reshape, and uncomfortably narrow down, the possibilities of altering the ongoing collapse of planetary ecosystems. This lesson should guide the assessment of alternative options, first and foremost, hydrogen production with CCUS. Public authorities investing in research and development should ripe the benefits of expanding the technological frontier, but also be held accountable for investing in detrimental ventures.

2. Besides considering the timing (i.e., *when*), this article emphasises the importance of addressing the *who, how*, and *where* of hydrogen systems. Emerging industrial partnerships, often dominated by corporate groups, are led by major integrated oil and gas companies and gas TSOs (e.g., Table 1). Public authorities are frequently involved in these consortia, providing funding for R&D (for CCUS and hydrogen hubs in Europe), subsidising costs of production (the US IRA), or facilitating long-term agreements and Public Private Partnerships (PPPs) to de-risk investments (Weichenhain et al., 2022). However, PPPs have also faced criticism for increasing costs, systemic inertia, and ultimately for being a proliferation of private interests' in public service provision (Bayliss and Van Waeyenberge, 2018; Gabor, 2021). These PPPs respond to "de-risking strategies", "as policies that create risk buffers to render development projects 'investible'" (Gabor, 2021, p. 433). This comes at the risk of binding economic policies to the long-term export of low added value commodities instead of developing domestic industrial capacity, as in the case of hydrogen developments in Namibia (Gabor and Sylla, 2023) and Morocco (Müller et al., 2022). Alarmingly, seven of the twenty projects listed in Table 3 are in the Global South, and all of them primarily focus on hydrogen exports to high-income countries.[14] Price differentials and resource endowment can provide a source of competitive advantage, but weak labour and socio-ecological standards often result in unequal ecological exchange (Hickel et al., 2022), as evidenced by the long-term bilateral agreements currently being negotiated between European and African countries (Eberhardt, 2023; Müller et al., 2022).
3. The building of new infrastructure for intercontinental hydrogen transport is both a prerequisite and an incentive for transporting increasingly large volumes of hydrogen around the globe. Since infrastructural development entails energy and material requirements extending well beyond the building phase (Krausmann et al., 2017), careful consideration must be given to determining which infrastructures should be developed first, and which should not be built at all. This includes refurbished pipelines, serving the dual purpose of rescuing gas companies' capital assets from becoming stranded while ensuring that they will have something to sell in the future. As highlighted in Section 4.3.2, the largest forthcoming clean hydrogen plants are designed for either long-distance exports or petrochemical production processes, or both. Furthermore, it is often unclear whether these new developments will incorporate additional low-carbon energy sources or rely on the existing electricity grid (and if so, to which extent). A paradoxical scenario may arise in which, at least temporarily, "clean" hydrogen produced from fossil-based electricity is used to upgrade and enhance the quality of fossil fuels. Infrastructural lock-in, therefore, should prompt considerations over long-term uses, including traditional ones. While hydrogen manufactured through low-carbon energy can contribute to reducing the climate impact of steel manufacturing and long-haul transport, large-scale electrolysers are currently being constructed alongside oil and coal refineries, port terminals, and in the middle of the desert, thus begetting the question: *what* purpose will these facilities serve in a low-energy intensity, low-carbon future?

Today, hydrogen is a critical feedstock for industries worldwide, and meeting current global demand solely through electrolysis would require more electricity than what is currently consumed by the entire European Union (IEA, 2019, p. 43). This task is already daunting enough. Industrial development priorities should be set based on scientific and technical evidence, environmental standards, and recognition of land and labour rights. The allocation of public funding and the drafting of regulations for new end-uses should follow principles of democratic consultation and accountability. However, the key actors in the hydrogen economy are currently oil and gas TNCs, along with players from extractive sectors like mining. These GPNs represent a systemic source of inertia, requiring counterbalancing forces from the scientific community, regulatory agencies, and other public authorities to override the adverse consequences of path-dependent energy transitions.

6. Conclusions

Despite the prevalent focus on future developments, the hydrogen economy is already here, and it has been for decades. This article has demonstrated that the oil and gas industry (along with a few other sectors like mining, industrial chemicals, and automotive) wields significant influence over hydrogen development – from policymaking, ownership of production facilities, and control of patents. As we confront the challenge of scaling up hydrogen production, often likened to a "three-sided chicken and egg problem" (Schlund et al., 2022), it is crucial to understand who and on which bases is taking the initial steps, for this will determine future lock-ins, i.e., the "chickens and the eggs" to come. The emphasis on expanding hydrogen production in the name of a (still in the making) "energy transition", nevertheless, may distract from alternative solutions to reduce the energy requirements of the over-consumptive world economy.

In a hypothetical fossil-free economy, hydrogen demand would drop by over 40 Mt (simply by not using hydrogen in oil refineries).

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[14] Concerning project 1, this refers to the developments in Mauritania and Morocco.

This could liberate production volumes for more fruitful applications, as for the direct reduction of iron ore in steel manufacturing. Further discussion on alternative and competitive end-uses has been recently popularised by the “Clean Hydrogen Ladder”[15] by the founder of Bloomberg NEF, Michael Liebreich. Likewise, even within current hydrogen end-uses (as explored in Section 4.1), the possibilities for scaling down instead of expanding these applications should be further explored. For instance, can widespread retrofitting improve buildings thermal insulation, instead of increasing sources of domestic heating with hydrogen? Can urban planning and public transport, along with reduced commuting and broader changes in consumption habits, lessen the demand for private transportation and fuels, including fuel cell vehicles? Can the over 30 Mt hydrogen that every year go into manufacturing synthetic fertilizers be curbed by a progressive transition to organic or agroecological farming practices?

Besides re-purposing end-uses, moreover, the still overwhelmingly dependent on fossil fuels hydrogen production is a low-hanging fruit. Since its climate impact is equivalent to that of a G7 country, the priority should be to replace the remaining fossil-based hydrogen with additional installed capacity of low-carbon energy, such as solar or wind. Industry initiatives, government funding, and academic research should target the fast and enduring substitution of natural gas and coal with electrolysers powered by additional low-carbon energy sources. A first attempt to standardise the definition of low-carbon hydrogen (including issues of “additionality” and methodology for the calculation of greenhouse gas emissions) has been advanced by two EU Delegated Acts in February 2023. While representing a clear step forward, these standards have been the result of tight negotiations among the member states, notably the French nuclear industry (that managed to insert nuclear-based hydrogen in the legislation) and Germany (that was pushing for more exact “green hydrogen” guidelines defining specific “additional” renewable electricity requirements). More ambitious, transparent, and comprehensive standardisation is warranted, also beyond European countries.

Finally, and to reiterate the point made above, the cleanest and most just source of energy is energy savings, as emphasised by several post-growth energy transition studies (e.g., Dorninger et al., 2021; Dunlap and Marin, 2022; Vezzoni, 2023; Vezzoni and Ramcilovic-Suominen, 2023). Despite being the most sensible approach to climate change, and the broader ecological disarray undermining life-support systems, reductions in primary energy consumption are difficult to turn into a tradable commodity. In other words, vital and substantial energy savings will not be delivered by unfettered market forces. The alignment of the energy transition agenda with the public interest demands for a higher involvement of public authorities in the regulation and steering of capital investments, together with an active participation in energy production. The pervasiveness of the procurement logic of public-private partnerships in hydrogen development, however, points to a pernicious manoeuvring of policy initiatives by private corporate actors. In view of the path dependent developments reviewed in this article (e.g., delay strategies, neocolonial relations of production, natural gas infrastructural lock-ins), the burgeoning number of national hydrogen strategies should consider not only the prospects of a future low-carbon economy, but also the long-term impacts that hydrogen production already has in the present.

The superimposition of private agendas over the public interest may restrict future options to preserve corporate economic power while transitioning away from fossil fuels, thus jeopardising the viability of future energy systems and, with it, the functioning of the biosphere as we know it.

CRediT authorship contribution statement

Rubén Vezzoni: Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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Supplementary materials

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