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The making of H2-scapes in the Global South: Political geography perspectives on an emergent field of research

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A B S T R A C T

Clean hydrogen is touted as a cornerstone of the global energy transition. It can help to decarbonize hard-to-electrify sectors, ship renewable power over great distances, and boost energy security. Clean hydrogen's appeal is increasingly felt in the Global South, where countries seek to benefit from production, export, and consumption opportunities, new infrastructures, and technological innovations. These geographies are, however, in the process of taking shape, and their associated power configurations, spatialities, and socio-ecological consequences are yet to be more thoroughly understood and examined. Drawing on political geography perspectives, this article proposes the concept of "hydrogen landscape" – or, in short, H2-scape – to theorize and explore hydrogen transitions as space-making processes imbued with power relations, institutional orders, and social meanings. In this endeavor, it outlines a conceptual framework for understanding the making of H2-scapes and offers three concrete directions for advancing empirical research on hydrogen transitions in the Global South: (1) H2-scapes as resource frontiers; (2) H2-scapes as port-centered arrangements; and (3) H2-scapes as failure. As hydrogen booms in finances, projects, and visibility, the article illuminates conceptual tools and perspectives to think about and facilitate further research on the emergent political geographies of hydrogen transitions, particularly in more uneven, unequal, and vulnerable Global South landscapes.

1. Introduction

The advent of new hydrogen sectors is generating considerable excitement and enthusiasm. Called the "fuel of the future" or the "Swiss Army Knife of decarbonization", clean hydrogen solutions produced from renewable or low-carbon sources can help to decarbonize hard-to-electrify sectors (e.g., heavy industries, aviation, maritime shipping), offer storage and transportation options for renewable power, and boost energy security. As a versatile energy carrier with limited or zero greenhouse gas emissions, clean hydrogen is widely touted as a critical pillar of the global energy transition (IEA, 2024a).

This appeal is increasingly felt in the Global South. Due to strategic and geographic advantages that include comparatively cheaper, more abundant, and untapped renewables, Africa, Latin America, South(east) Asia, and the Middle East hold about 70% of the world's technical potential for low-cost clean hydrogen production (IRENA, 2022). Across these areas, countries are increasingly positioning themselves (or being positioned) as key producers, exporters, and consumers of clean hydrogen and its derivatives (Lindner, 2023). They hope to attract investments, build key infrastructures, and enable sustainable development in a market that can generate up to USD 6.8 trillion in global spend and contribute to about 12% of the world's final energy demand by 2050 (DNV, 2022; IRENA, 2022). Major industrialized economies like the European Union (EU) and Japan are in turn anticipating large-scale imports to meet climate targets, reduce the cost of energy transitions, enhance energy security, and alleviate pressures on local resources (European Commission, 2023).

Consequently, hydrogen project announcements have seen a marked surge in recent years. As of October 2024, approximately 2,400 clean hydrogen production projects were at concept, demonstration, feasibility studies, or early development stages globally (IEA, 2024b). About 650 of these projects are planned for the Global South, where players like Brazil, Chile, China, India, Namibia, South Africa, along with North African and Middle Eastern countries, have set forth ambitious plans and strategies. Such numbers are likely to grow further. Today, hardly a week goes by without the announcement of a major project, partnership, or funding scheme for clean hydrogen, highlighting the unprecedented momentum enjoyed by the sector.

Embedded in prevailing global production networks and power structures, the dawn of clean hydrogen is set to unleash and intensify transnational circulations of capital, technology, and commodities, and to (re-)shape the geopolitics of energy (Van de Graaf et al., 2020). At the

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same time, hydrogen necessarily relies on particular spaces for production, storage, and transportation, introducing new governance puzzles, leading to territorial disturbances, and affecting socio-spatial dynamics (Brannstrom & Gorayeb, 2022). Yet, the bulk of hydrogen research remains largely focused on the technical, financial, and acceptability hurdles of building hydrogen economies, often looking at Global North experiences and interests (Hanusch & Schad, 2021).

Against this backdrop, this article proposes the concept of "hydrogen landscape" (or, in short, "H2-scape") to theorize and explore the socio-spatial realities and associated power structures of clean hydrogen's nascent deployment, particularly across more uneven and vulnerable Global South geographies. We build on an incipient strand of social science hydrogen studies and a thriving critical human geography literature on the making of energy landscapes, especially on accounts of clean energy. In this vein, we describe H2-scapes as the new energy spaces created by the material expressions of hydrogen-based energy systems and the various social, political, cultural, and environmental regimes and practices attached to them. We posit that political geography offers suitable traditions and tools for thinking about the advent of H2-scapes, as the subdiscipline is closely attuned to how energy transitions are space-making processes imbued with power relations, normative orders, and social meanings (Becker et al., 2016). In exchange, we advance these conversations in new and hitherto little explored empirical arenas for political geographers and social scientists more generally.

In this endeavor, the article outlines a conceptual framework for understanding the making of H2-scapes and offers three concrete directions for advancing empirical research on hydrogen transitions in the Global South: (1) H2-scapes as resource frontiers; (2) H2-scapes as port-centered arrangements; and (3) H2-scapes as failure. These research directions account for key trends, empirical sites, and plausible scenarios linked to clean hydrogen's nascent deployment and illuminate how the framework can be applied to concretely think and guide further research about the nexus between power and space in Global South H2-scapes.

We engage with the notion of the "Global South" to refer to the world's less socio-economically advantaged areas, namely the regions of Latin America, Africa, South(east) Asia, and the Middle East, which are roughly located south of the old colonial centers of powers. We recognize, however, that the Global South is a flawed, ambivalent, and incomplete concept, not least considering the enormous (and growing) heterogeneity within and across "Southern" realities (see Haug et al., 2021). Notwithstanding, we follow Tunn et al.'s (2024) lead and hold that the global hydrogen rush is set to repeat and reinforce marginalizations, inequalities, and injustices that have historically been and continue to be molded along a North–South divide (e.g., unequal resource exchanges, technological dependencies, coloniality of knowledge). Focusing on the "Global South" is, therefore, analytically valuable and crucial for making sense of how patterns of global uneven development characterize and become reproduced in new energy systems. Empirically, centering on the Global South is further justified by the fact that hydrogen transitions remain novel developments that are still under-explored outside of Northern contexts. Still, while this article is Global South-focused, our conceptual and empirical propositions are useful to investigate clean hydrogen's development, power entanglements, and spatial patterns more broadly.

The article proceeds as follows. The next section reviews the state-of-the-art in hydrogen social science research, particularly on the Global South. Subsequently, we consider how (political) geographers have approached the landscape-energy relationship and account for political geography's distinctive conceptual and analytical capacities to reflect on the nexus between power and space in hydrogen transitions. We then introduce the notion of H2-scape and outline a conceptual framework for grasping and analyzing it. This is followed by our three proposed research directions, demonstrating how the framework can be empirically applied to study hydrogen transitions in the Global South and guide further research on the topic. We conclude by stimulating scholars to build on, fine tune, and expand understandings of H2-scapes – in the Global South and beyond.

2. Hydrogen social science research and the Global South

Hydrogen production is not a new phenomenon and hydrogen has long been deployed as an industrial feedstock, with main applications today being in oil refineries, fertilizer production, and steelmaking. Yet, virtually all of this hydrogen is of a fossil nature, obtained from natural gas or coal without carbon capture (known as "grey" or "black" hydrogen[1]), and responsible for about 2.3% of global emissions (Kakoulaki et al., 2021). In recent years, declines in the cost of renewables and advancements in carbon capture and storage (CCS) technologies have strengthened the case for clean hydrogen. Obtained from renewable or low-carbon sources, clean hydrogen offers an attractive proposition for energy transitions, introducing a low-carbon or emission-free solution from production to end-use, as hydrogen only emits water vapor as a by-product when burnt. It can play an important role in sectors with no or limited decarbonization options via direct electrification (i.e., hard-to-electrify), such as heavy industries (e.g., steel, cement, fertilizer), aviation, and long-haul transportation (trucks, maritime shipping).

Clean hydrogen includes different variants but most existing policy and market initiatives revolve around two main types, namely "green" and "blue" hydrogen (IEA, 2023). Green hydrogen is produced by using renewable electricity (e.g., from wind, solar, hydropower or nuclear sources) to split hydrogen from water via a chemical process called electrolysis. Blue hydrogen is manufactured in a similar way to fossil hydrogen, based on the steam reforming of natural gas, but distinguished by the use of CCS technologies to limit carbon emissions. Yet, classifications for considering hydrogen clean (e.g., emission thresholds) significantly vary across countries and international organizations. The same applies to its labelling: hydrogen derived from nuclear-based electricity is sometimes referred through its own category (pink hydrogen) and entities like the EU prefer the term "renewable hydrogen" to designate green hydrogen solutions (European Commission, 2023).

For parsimony and to simplify otherwise complex technicalities and nomenclatures, this article follows the International Energy Agency (2023) and adopts the notion of "clean hydrogen" to generically refer to zero-emission or low-carbon pathways for hydrogen production. It pays particular attention to green and blue hydrogen. The former is the most sustainable option, with least or no emissions, and is hailed in policy and corporate circles as the most effective hydrogen solution for achieving net-zero targets (IRENA, 2022; IEA, 2023; European Commission, 2023). The latter is envisioned as a transitional, less costly alternative that can help to scale-up low-carbon hydrogen adoption and pave the way toward a full green hydrogen economy.

Particularly from the early 2020s, amid greater policy commitments to decarbonization and geopolitical disruptions like the Russian invasion of Ukraine, clean hydrogen has been gaining momentum, with estimates projecting a widespread, cross-sectoral adoption and a five- to six-fold increase in hydrogen consumption by 2050 (IRENA, 2022). Research and development initiatives have, as a result, surged across academia, businesses, and industries to support the maturation of hydrogen technologies, tackle scale-up hurdles, devise cost-effective models for project implementation, and stimulate market acceptance and adoption (Griffiths et al., 2021).

Yet, observing a tendency to put "technology first, society second" (Hanusch & Schad, 2021) and the sidelining of political, societal, and spatial questions (Vallejos-Romero et al., 2022), social science scholars

[1] While hydrogen is a colorless gas, it is conventionally classified through color codes, depending on production source.

have critiqued the prevalence of overly technical and financial considerations in mainstream hydrogen research. To craft more holistic and inclusive assessments, they began to call for different, critically oriented, and qualitative lines of scientific inquiry into hydrogen transitions. In this vein, researchers have encouraged considerations of issues of coloniality, gender, socio-ecological costs, and path dependencies (Brannstrom & Gorayeb, 2022; Hanusch & Schad, 2021; Hine et al., 2024; Kalt & Tunn, 2022), flagged and analyzed hydrogen-related justice concerns (Müller et al., 2022; Tunn et al., 2024; Virens, 2024), explored public perceptions of and discourses around hydrogen's deployment (Belova et al., 2023; Scott & Powells, 2020), and assessed emerging geopolitical and energy security ramifications of hydrogen trade (Dejonghe et al., 2023; Quitzow & Zabanova, 2024; Van de Graaf et al., 2020).

But hydrogen knowledge, including in the social sciences, remains primarily generated by epistemic communities in the Global North, with most research to date concentrated on hydrogen transitions in North America, Europe, Japan, Oceania, and, exceptionally, a few selected major Southern powers like China (see Gavaert et al., 2023). Such countries and regions are leading the way in technological, policy, and project development and, consequently, have drawn most of the attention. Moreover, the prohibitive costs of clean hydrogen today imply that it can only be afforded at a high cost and is only viable if propped up by subsidies and incentives in wealthier nations (Hunt & Tilsted, 2024). Therefore, new hydrogen sectors in the Global South remain largely coupled to and studied in relation to developments in and the interests of Northern (import) markets, with many studies being designed to support policy and market strategies for building hydrogen export economies (see Chantre et al., 2022). Some critical works have tentatively outlined broader (geo)political, macro-financial, socio-spatial, and energy justice challenges linked to the rollout of clean hydrogen in the Global South more specifically but have been limited to exploratory literature reviews of project documents and policy strategies (Gavaert et al., 2023; Fladvad, 2023; Tunn et al., 2024; Galan & Lindner, 2024; Scholvin et al., 2025) or to the mapping and content analysis of prospective North–South hydrogen partnerships (Lindner, 2023).

More recently, as Southern countries have begun to release governance strategies, draft legislations, and implement initial projects, the first empirical and field-based studies into clean hydrogen systems in the Global South have started to emerge, displaying efforts at addressing some of these insufficiencies. This literature draws on country- or region-specific case studies and engages with selected conceptual perspectives (e.g., environmental justice, green extractivism, technopolitics, socio-technical imaginary) to offer initial assessments of the power-laden character and spatialities of hydrogen transitions in the Global South.

For example, focusing on the Maghreb region, Hamouchene (2023) problematizes green hydrogen, along with the associated expansion of massive solar and wind parks, as a new hype that constitutes neocolonial schemes of plunder and dispossession. Zumbraegel (2025) approaches the technopolitics of hydrogen in the Arab Gulf states, suggesting that the emergence of green and blue hydrogen partnerships is reinforcing authoritarian structures in the region. Gabor and Sylla (2023) draw on the case of Namibia to argue that the deployment of green hydrogen – buoyed by German interests, finances, and technologies[2] – is set to aggravate structural dependencies and weaken domestic control over new strategic sectors (see also Monteith & Bäumer Escobar, 2025 in this special issue) . Looking at South Africa, Kalt et al. (2023) offer a nuanced account of various competing visions and political projects around clean hydrogen, identifying the prevalence of "green extractivist" initiatives which prioritize export-oriented models and reproduce patterns of neocolonialism. Similarly, Caiafa et al. (2024) and Combariza Diaz (2024) uncover a range of risks from international green hydrogen investments in Brazil and Colombia, respectively, which include increased external economic dependencies, limited linkages with host societies, and the perpetuation of extractive imperatives. Elsewhere in Latin America, Dorn (2024) explores the role of sociotechnical imaginaries linked to the production of low-emission hydrogen in peripheral regions of Argentina, arguing that current power constellations have resulted in hydrogen path decisions that prioritize fossil interests.

By overcoming narrow techno-financial readings of hydrogen transitions, these works have made great strides in establishing a critical social scientific research agenda on what hydrogen transitions mean for Southern polities and contexts, offering pertinent questions, initial theorizations, and empirical observations. This article builds on such an emerging body of hydrogen social science research, elaborating on key themes and tendencies to offer a thinking framework to inform and expand critical interpretations. Specifically, by proposing the concept of H2-scape, we seek to more effectively "ground" the emergence of clean hydrogen in the socio-material settings in which they occur. We do so while identifying and speaking to common trends, trajectories, and power differentials that underwrite hydrogen transitions more broadly. In this endeavor, political geography offers productive theoretical frameworks and tools.

3. Energy landscapes and the case for a political geography of hydrogen

The making of energy landscapes for low-carbon energy systems has been the subject of growing scholarly interest (Nadaï & van Der Horst, 2010; Calvert, 2016; Bridge & Gailing, 2020; Tornel, 2023). While the concept of "energy landscape" has long been applied in energy geography to describe the material artefacts of energy systems over given spaces (see Zimmerer, 2011), relational and critical strands in geography have emphasized how such landscapes, more than material artefacts, are constructed through social, political, cultural and economic relationships (Bridge et al., 2013). In recent years, shifting patterns in energy generation and consumption have extended the focus of analyses from traditional "carbonscapes" (Haarstad & Wanvik, 2017) – such as "petroleumscapes" (Hein, 2018) or "coal landscapes" (Pasqualetti & Frantál, 2022) – to the new landscape functions, expressions, and implications arising from the expansion of low-carbon and renewable forms of energy. Depending on the specific energy resource or technology, such landscapes have been conceived in the literature under various possibilities: "windscapes" (Mauro, 2019), "hydropower landscapes" (Ferrario & Castiglioni, 2017), "biofuel scapes" (Mol, 2007), "minescapes" for critical minerals (Pusceddu & Zerilli, 2024), among others.

In common, these "(land)scapes" reflect socio-material arrangements that are spatially constituted and constitute space through systems, infrastructures, and technologies of low-carbon or clean energy production, distribution, and consumption (Bridge & Gailing, 2020). They also denote broader assemblages that englobe and cross-cut different places (sites of energy production and consumption), networks (value-chains, distribution systems), scales (local, national, global), functions (e.g., livelihoods, decarbonization), and symbolic aspects (e.g., discursive, cultural) (Nadaï & van Der Horst, 2010; Tornel, 2023). They evidence how energy transitions are space-making processes that combine and entangle material spatializations (via forms of, e.g., infrastructuring and resource-making) with various socio-symbolic dimensions related to spatial identities, geographical imaginaries, and land politics. As interactive, contingent, and evolving assemblages, these novel energy landscapes are thus constantly in the "making" (Ferrario & Castiglioni, 2017).

Political geographers have directed particular attention to understanding how power is inscribed into the making of these new energy landscapes and lead to complex, differentiated, and uneven socio-spatial outcomes. For example, drawing on influential conceptualizations such

[2] For a detailed account of Germany's interests and involvement in Namibia's green hydrogen industry, see Kalvelage & Walker (2024).

as "material politics" (Barry, 2013), "technopolitics" (Hecht, 2011), and "energopolitics" (Boyer, 2019), scholars have discussed the ways in which elements of authority, dominance, and power hierarchies define governance strategies and become spatially projected and exercised (i.e., territorialized) with the proliferation of renewable energy materialities and technologies (Chandrashekeran, 2022; McEwan, 2017; Power et al., 2016; Stripple & Bulkeley, 2019). Others have engaged with notions such as "energy futures" (Burke & Stephens, 2018) and "socio-technical imaginaries" (Jasanoff & Simmet, 2021) to illuminate the visions, desires, and expectations determining which choices and paths are taken in emergent clean energy landscapes, along with how existing power relations act to promote and stabilize certain (dominant) futures and imaginaries over others (Chateau et al., 2021; Sareen & Shokrgozar, 2022). Concerted efforts have also been made to highlight energy transition landscapes as sites of contentious politics (Tornel, 2023) and how social movements, affected communities, and marginalized groups have acted to challenge dynamics of "oppressive energopolitics" (Allan, Lemaadel, & Lakhal, 2022), demand "energy democracy" (Van Veelen & van der Horst, 2018), and propose alternative energy futures (Envall & Rohracher, 2024).

On the Global South more specifically, a prominent line of investigation in political geography has highlighted how the making of new energy landscapes – whether in the form of large farms for biofuels, the mining of critical minerals, or the expansion of solar and wind energy – is intrinsically connected to the making of new resource frontiers (Almeida et al., 2023; McEwan, 2017; Thaler et al., 2019). "New resources–new spaces", as put by Rasmussen and Lund (2018, p. 391), result in "new enclosures, territorializations, and property regimes", facilitating the expansion and (re-)allocation of global capital through new patterns of extraction and commodification. Building on such understandings, a popular conceptual framing for problematizing the political geographies and ecologies of energy transition landscapes has been through vocabularies of "green extractivism" and "energy colonialism" (Alkhalili et al., 2023; Andreucci et al., 2023; Bruna, 2022; Dunlap & Laratte, 2022). Here, the (re-)appropriation of land, mineral, and energy resources linked to or justified by the green economy (i.e., green extractivism) is seen as a major driver of neocolonial patterns in the global energy transition, with resources transferred to industrial centers in the Global North and socio-ecological costs and risks externalized to "green sacrifice zones" in the Global South. These analyses also centrally stress the (in)justice dimensions of energy transitions, which can cause or reinforce inequalities, exclusions, and undue burdens within and across countries, particularly for already vulnerable groups such as minorities, indigenous populations, and the urban poor (Barnes, 2022).

Conversely, other scholars have challenged the supposed "newness" of such dynamics. They point at how "old" and "new" energy landscapes cannot be neatly distinguished due to their inherent entanglements and continuities (see Bridge & Gailing, 2020; Verweijen & Dunlap, 2021). This is evidenced by the fact that the main driving forces of the "energy transition" and the "green economy" are often traditional fossil fuel and mining companies (see Chatterjee et al., 2023). Verweijen and Dunlap (2021) propose, instead, that these developments are better captured through alternative labels such as "total extractivism" or "fossil fuel+". New energy landscapes may arguably act as new resource frontiers in the sense that they expand energy or mineral extraction to areas where these have not been practiced before, or in the sense that they are given new purpose and objectives (e.g., decarbonization). Yet, as noted, these processes often support and rely on old and established circuits of capital and finance, global trading systems, and conventional business practices.

Taken together, these literatures lend appropriate thinking tools and approaches for conceptualizing unfolding hydrogen transitions in their complex, multi-scalar, and contentious characteristics, particularly in more uneven and unequal Global South settings. By proposing the vocabulary of "H2-scape", rather than merely adding another "scape" into the mix, we seek to further political geography's intellectual purchase in new and hitherto little explored empirical arenas. While embedded within other renewable energy landscapes (e.g., solar, wind) and carbonscapes (e.g., natural gas), hydrogen's distinct production methods and materialities, strong multi-scalar properties, and far-reaching applications can benefit, we suggest, from a specific conceptual framework and dedicated "scape".

For instance, unlike energy transition resources such as lithium, cobalt, and rare earth minerals, hydrogen is mainly manufactured through an industrial process. It reflects dynamics of energy extractivism, but it is not an extractable resource as such.[3] Different from renewables such as solar and wind, which can allow for small-scale, decentralized ownership and management, hydrogen frequently requires highly centralized, capital-intensive energy systems, distinctively affecting governance structures and power relations. Moreover, as an invisible gas, hydrogen has specific material properties that pose significant technical, logistical, and safety hurdles (see Hine et al., 2024). When it comes to seaborne trade, shipping hydrogen in its natural, gaseous state is unpractical. Thus, hydrogen needs to be liquefied or converted into carriers such as ammonia, which entail significant energy losses and involve technically complex and costly procedures. Hydrogen is also extremely hazardous for the landscapes in which it is situated, as well as for the populations and workers exposed to it (highly explosive, invisibility of flame).

Green hydrogen economies, more specifically, extend the typically terrestrial spatialities of renewable energy systems into water and marine ecosystems. Green hydrogen is also reliant on freshwater for production, centrally depends on seaport infrastructures for storage and distribution, and intensifies the development of infrastructures at sea such as offshore facilities for renewable power generation. Furthermore, as a way of "bottling renewables", green hydrogen expands the reach and multi-scalar character of otherwise local and regional renewable energy systems by converting electrons into molecules that can be distributed and applied globally. Blue hydrogen demonstrates, in turn, various entanglements and continuities with fossil fuel sectors and economies.

Against this backdrop, we approach clean hydrogen through the lens of landscape to push understandings of the political geographies of energy transitions farther and in new empirical domains. H2-scapes, as we proceed to conceptualize next, foreground hydrogen as a space-making process, enacted through socio-material co-constitutions and the workings of power.

4. The making of H2-scapes: A conceptual framework

We propose the term "hydrogen landscape" – or, in short, "H2-scape" – to describe the new energy spaces created by hydrogen-based energy systems and the various social, political, cultural, and environmental regimes and practices attached to them. H2-scapes aggregate several material artefacts associated with hydrogen production, distribution, and consumption: wind-, solar-, hydro-power generation infrastructures; natural gas extraction platforms; electrolyzers; carbon capture and storage facilities; production plants for derivatives such as ammonia; hydrogen storage facilities; ports; pipelines, transmission lines; desalination systems; refueling stations to support hydrogen-powered road, rail, and air transport; and many others. Yet, H2-scapes are more than the material, physical, and technical expressions of hydrogen-based energy systems over given spaces. They also describe the constellation of social, political, cultural, and environmental relations that are enacted through and within such landscapes (Nadaï & van Der Horst, 2010). In this sense, H2-scapes are political geographies constituted through and shaping interactions between society and

[3] Except on rare occasions where hydrogen is found naturally, known as "white" hydrogen.

hydrogen systems, where "hydrogen power" is also about power structures, relations, and struggles.

For capturing and understanding the making of H2-scapes, we delineate a conceptual framework based on three key dimensions that highlight the plural, contingent, and contested character linked to the socio-material constitution of hydrogen across space: (1) territoriality; (2) articulation of old and new; and (3) cross-spatiality and multi-scalarity.

4.1. Territoriality

As place-specific arrangements requiring different modes of infrastructuring and resource-making, the establishment of H2-scapes reflects various forms of "territoriality" – that is, "geographical strategies of partition and integration employed by economic and political actors (states, firms)" to implement and operationalize energy systems over a given space (Bridge et al., 2018, p. 336). The territoriality of H2-scapes underscores how hydrogen is associated with numerous implications for land uses and tenure. These include the appropriation and enclosure of land for investments and infrastructure building, processes of dispossession and displacement, and associated shifts in livelihoods, mobility patterns, and cultural practices. Such implications extend to water resources, as the production of green hydrogen more specifically demands access to and use of freshwater, and to marine ecosystems, which are impacted through seaport infrastructures, desalination systems, submarine cables, and offshore facilities for renewable power generation and natural gas extraction (see also Tunn et al., 2024).

Thus, a focus on the ways through which H2-scapes are "territorialized" evidences not only the uneven effects and impacts of their spatial constitution but also the exercise of political and commercial power in providing legal backing and legitimacy to hydrogen developments. This perspective illuminates the material and technical configurations of hydrogen systems as foundations on and through which politics take place (i.e., material/technopolitics) and can shed light on how emergent governance frameworks for clean hydrogen are (unevenly) devised; whose interests, imaginaries, and energy futures go into determining these; and the resultant exercise of authority and commercial power in and across hydrogen spaces.

The territorialization of H2-scapes may also reveal commonalities or differences with other renewable energy landscapes (e.g., solar, wind) and carbonscapes (e.g., natural gas). Considering hydrogen's centralizing characteristics as an energy system that is highly capital-, technology-, and infrastructure-intensive, hydrogen economies are prone to authoritarian, top-down modes of governance, mirroring other forms of large-scale energy and resource extractivism premised on monopolization and capital accumulation (e.g., fossil fuels, biofuels, large-scale mining) (Zumbraegel, 2025). Yet, the territorialization of H2-scapes may also exceptionally reflect possibilities for more decentralized management and community participation. Similarly to community-owned renewable energy initiatives like small-scale solar parks (Joshi & Yenneti, 2020), prospective applications such as clean hydrogen-powered cooking devices and low-carbon fertilizers (which can be synthetized from green ammonia, a derivative of green hydrogen) may lead to more socially empowering and inclusive H2-scapes, reducing emissions while increasing food security and economic opportunities.

Finally, H2-scapes can be de-territorialized, "when the forces holding them together are weakened, diverted or undermined" (Haarstad & Wanvik, 2017, p. 441). The early deployment of clean hydrogen is already entangled with various forms of contentious politics. Affected societies, grassroots movements, and transnational publics are exposing and opposing the range of risks, injustices, and forms of oppression associated with the territorialization of hydrogen (see Corporate Europe Observatory, 2024; Tunn et al., 2024). Such dynamics reveal challenges to hegemonic, homogenized imaginaries of hydrogen futures and seek to re-signify relationships between humans, energy, and space in H2-scapes (e.g., through calls for energy justice), demonstrating H2-scapes as inherently unstable and contingent arrangements – prone to movement and change.

4.2. Articulation of old and new

To draw on Bridge and Gailing (2020), novel energy landscapes arise from a combination of new energy systems and remnants of the old. This ambivalence is also present in the making of H2-scapes. Hydrogen requires the deployment of cutting-edge technologies and technical apparatuses linked to, for example, electrolysis plants and CCS technologies. At the same time, H2-scapes are (re-)produced over remnants of "old" energy systems, particularly fossil fuel production technologies and infrastructures. This is more straightforwardly seen in the case of blue hydrogen, which is based on conventional fossil production pathways. But more generally, it is also evidenced in the repurposing of natural gas pipelines and networks to distribute clean hydrogen, in the use of fossil-derived finances and accumulation structures to drive and implement hydrogen agendas (as in the case of the Arab Gulf states), or in the installation of electrolyzers on existing or decommissioned oil and gas platforms for offshore hydrogen production.

Accordingly, H2-scapes, though re-configuring spaces under "transition" mottos, hardly represent a fundamental departure away from the material and power levers of carbonscapes. Instead, they contribute to "re-territorialize" them, conferring renewed purpose and legitimacy to the structures of "fossil capitalism" (Huber, 2013). H2-scapes are thus prone to forms of value and regulatory capture by the fossil industry (see Dorn, 2024; Hunt & Tilsted, 2024). Approximately half of all hydrogen consumed globally today goes into petroleum refining, with most hydrogen production happening on-site at refinery compounds. Against this backdrop, the fossil industry not only holds vital technical expertise but also owns and operates (and is expected to build more) key infrastructures in hydrogen value-chains. It is not surprising, therefore, that the composition of the Hydrogen Council, the main corporate initiative for (clean) hydrogen, highlights the unequivocal presence of the world's major oil companies: Shell, Total, BP, Aramco, Equinor, Sinopec, among others (see Hydrogen Council, 2021).

The promotion of a clean hydrogen economy – specifically through its "blue", fossil-derived variant –paradoxically contributes to carbon lock-ins and prolongs the fossil phase-out, while conferring a fundamental role to traditional fossil players in the energy transition. H2-scapes reflect, in this regard, ambivalent juxtapositions between old fossilist structures and new, supposedly green initiatives. These re-alignments preserve and expand fossil fuel assets, materialities, and agencies that have long been entangled with socio-environmental disruptions, disasters, and violence across energy landscapes, justifying readings of hydrogen transitions as "fossil fuel+" or "total extractivism" configurations (Verweijen & Dunlap, 2021).

4.3. Cross-spatiality and multi-scalarity

Lastly, the envisioned scaling-up of clean hydrogen is set to consolidate H2-scapes as "cross-spatial" and "multi-scalar" realities. Virtually all hydrogen consumed today never leaves the compound where it is produced, let alone crosses an international border. With estimates projecting a widespread adoption of clean hydrogen and a massive growth in global hydrogen trade (IRENA, 2022), H2-scapes will increasingly traverse diverse spatial localities (e.g., the household, energy generation sites, industrial centers, ports) and geographical scales (local, regional, international), along with varied political structures and forms of economic organization (see Caiafa et al., 2024; Hine et al., 2024). These sites and scales can comprehend, for example, local applications at specific industries or the household, regional projects in the form of "hydrogen valleys" (i.e., a broader geographical area aggregating different parts of hydrogen value-chains), and global trade routes served by inter-continental maritime corridors. Such dynamics also bring together various actors, agencies, and interactions: international diplomacies and multinationals seeking to create opportunities for investment, national and local governments shaping broader policy agendas, frontline communities and grassroots groups opposing and navigating impacts on the ground, and many others.

Thus, a focus on the cross-spatial and multi-scalar properties of H2-scapes can reveal how hydrogen acquires different relational qualities of physical presence (e.g., as an industrial plant, transnational pipeline, or major port), the specific socio-spatial meanings related to the manners or modes in which it is deployed (whether as a form of energy storage for grid balancing, an exportable commodity, or as a source of heating and cooking at the household), and where the boundaries of political and corporate responsibility lie in each of these cases. A cross-spatial and multi-scalar approach is also useful in highlighting how H2-scapes tie together different sites, actors, and scales. That is, how these landscapes cohere and function as an integrated assemblage of social, technical, and ideational features across a broad space, connecting spaces of energy extraction to spaces of consumption (e.g., as hydrogen valleys or, more broadly, as global production networks).

5. The making of H2-scapes in the Global South: Three directions for empirical research

In what follows, we identify and elaborate on three relevant directions to illuminate how the concept of H2-scape can be applied to think and facilitate further empirical research about the political geographies of hydrogen transitions: (1) H2-scapes as resource frontiers; (2) H2-scapes as port-centered arrangements; and (3) H2-scapes as failure. These directions are well-suited for critically analyzing the character and geographical implications of H2-scapes in the Global South, highlighting dynamics of global uneven development, marginalization, and coloniality but also new types of socio-material interactions, spatial hybridizations, and investment hype.

5.1. H2-scapes as resource frontiers

A common critical reading sees clean hydrogen as a new global commodity that is set to (re-)produce new resource frontiers in the Global South (De Leeuw & Vogl, 2024; Hamouchene, 2023; Kalt et al., 2023). H2-scapes, in this sense, territorialize new patterns of resource exploration, enclosures, and accumulation, opening up new spaces of extraction under supposedly green prerogatives and discourses. For example, Hamouchene (2023) describes the hydrogen frontier in North Africa as a means for Europeans to tap into cheap energy and undervalued labor to support hydrogen production and circulation, while consolidating “fortress Europe” and “border imperialism” that violently repress human flows. De Leeuw and Vogl (2024) contend that, while clean hydrogen offers appealing green industrialization prospects to resource peripheries (e.g., green steelmaking) (see also Eicke & De Blasio, 2022), it still taps into and revives old resource frontiers by increasing mineral extraction and appropriating land for industrial expansion. By the same token, Kalt et al. (2023) show that the hydrogen rush in South Africa opens new resource frontiers by inducing new forms of “green extractivism”, both via direct demands for wind, solar, hydrological, and hydrocarbon resources to produce hydrogen but also indirectly, as hydrogen’s technological and material apparatuses (e.g., electrolyzers) require critical minerals such as platinum, palladium, and iridium (see IEA, 2022). Developing countries are set to import, in return, higher value-added equipment, technologies, and services to implement hydrogen systems (Tunn et al., 2024).

We do not disagree with these perspectives. But to complement and nuance such interpretations, we add that H2-scapes should not be reduced into mere, inert resource frontiers that only operate as extractive zones. We propose that these frontiers, while extractive at their core, are also premised on (1) distinctive forms of space-making and (2) diverse contact structures.

Firstly, most clean hydrogen projects in the Global South are expected to be territorialized through distinctive forms of spatial development, predicated on the establishment of spaces of exception such as special economic zones and industrial clusters (see IEA, 2023). This can also occur through the combination of several fragmented territories representing different parts of hydrogen value-chains, such as in plans for “hydrogen valleys” – an EU project conception that appears in funding and subsidy schemes for clean hydrogen and has been diffused to hydrogen frameworks in the Global South (e.g., South Africa, whose strategy is premised on the establishment of three hydrogen valleys) (see Clean Hydrogen Partnership, n.d.). From this vantage point, H2-scapes fundamentally operate as “zones of distinction”: exceptionalized, enclaved spaces contemplated by distinctive governance, security, and temporal logics. Typically imposed by outside actors, these logics produce distinctive meanings and sets of relations across space (see Easterling, 2014).

Here, the frontier describes areas where economic projects are pushed forward and where neoliberal commercial and political governmentalities and rationalities are tailored to and inserted into demarcated localities to favor differentiated treatment for global market forces – in a dynamic conceptualized by Ong (2000) as “graduated sovereignty”. Mirroring long-held patterns in large-scale extractive investments in the Global South, these frontiers emerge as new spaces of seamless economic productivity and connectivity for flows of capital and commodities but are frequently closed off from and have few productive links with local societies (Ferguson, 2005). In exploring these “distinct” frontier dynamics, timely research directions include detailing the specific ways in which H2-scapes – and hydrogen’s own specific materialities – contribute to exceptional(ized) political geographies, create life-worlds of their own, and enable particular forms of graduated sovereignty, as well as how this compares to other forms of resource extractivism.

Second, we add that the H2-scape frontier produces and is produced through what Pratt (1992) has termed “contact zones”. By embedding global capital investments within specific localities, H2-scapes forge (or impose) new encounters and interactions between disparate elements, cultures, practices, and jurisdictions. These can take on forms of converging, mutually reinforcing contact structures, such as those resulting from coalitions between state and business actors, or between fossil and clean energy industries (“old” and “new”), to facilitate the creation and smooth running of the hydrogen frontier. But as meanings and practices are imposed on the landscape by outsiders through particular forms of power, project models, and knowledge, these contact zones can also evidence spaces of friction and oppression. For example, Fladvad (2023) and Combariza Diaz (2024) assert how hydrogen export-oriented plans in La Guajira, Colombia, systematically threaten indigenous rights and sovereignty and exclude indigenous knowledges, perpetuating colonial dynamics of land appropriation and increased militarization. On this account, a pertinent research angle consists in interrogating how colonial and Eurocentric knowledges collide with the cosmologies and lived experiences of marginalized sectors of society in H2-scapes, whether and to which extent principles of energy democracy and inclusive governance contemplate their needs, and what kinds of hydrogen counter-knowledges and alternative energy futures are furthered to “decolonize” hydrogen (see also Tornel, 2023). Besides indigenous populations, analyses can extend to other (marginalized) social groups present in H2-scapes such as peasant communities, racial minorities, women, and low-ranked caste populations.

Another relevant angle for comprehending H2-scapes as contact zones is in the realm of capital-labor encounters and workplace relations, which can shed important light into emerging labor geographies of “green jobs”. Green jobs – employment opportunities linked to the low-carbon economy – are promoted by public and private sectors as a core vector for prosperity, social security, and skills transfers in the Global South (see ILO, n.d.; see also Namaganda, 2023). As H2-scapes are established, new frontiers of work – involving business owners, managers, technicians, and workers – are formed and (re-)articulate capital-labor encounters. Still, we are yet to learn more about these processes, which operate across multi-scalar structures of global finance, domestic legislations (e.g., on local content), community life, and foreign and local labor cultures and range from highly qualified roles (e.g., chemical engineers at electrolysis plants) to low-paid, fixed-term infrastructure construction jobs. Here, considering H2-scapes' multi-scalar and cross-spatial dimensions, scholars can elucidate how these labor geographies are socially and spatially organized across different parts of the value-chain and influenced by factors such as nationality, hierarchy, race, type of technology, and whether they give rise to new (transnational) geographies of labor struggles.

5.2. H2-scapes as port-centered arrangements

As defined by Starosielski (2015, p. 97), ports are "gateways, nodes that function as a region's entry or exit point, house a range of technologies, and comply with standards that knit together heterogeneous communities of practice". In H2-scapes, ports represent strategic nodes for importing or exporting hydrogen, either via seaborne trade (e.g., in the form of green ammonia and liquid hydrogen), or via pipelines that start or end in the port area. Yet, well beyond only serving as import and export hubs, their relevance extends to the entire hydrogen value-chain (Notteboom & Haralambides, 2023). Accordingly, many wind or solar farms for green hydrogen generation are projected for lands, breakwaters, shorelines, and offshore spaces close to ports. In a demonstration of how old and new articulate, existing port infrastructures for the handling of fossil fuels (e.g., underground wells, pipeline networks, power plants) can also be turned into CCS facilities for blue hydrogen production or repurposed for overall hydrogen storage and hinterland distribution. Additionally, supported by the availability of multi-modal logistics infrastructures and special economic zones, many port areas are home to large industrial ecosystems. The presence of industries using hydrogen as energy or feedstock (e.g., refineries, steelmaking, fertilizer) provides, in turn, the prospect of a relevant customer base. Ports are also set to host desalination plants intended to supply fresh water for green hydrogen production and are crucial for the decarbonization of the shipping sector itself, as manufacturers and consumers of clean hydrogen-based fuels for vessel fleets. Therefore, across several geographies, ports act as crucial nodes and enablers of H2-scapes.

Not surprisingly, most clean hydrogen projects in the Global South are planned along coastal areas, typically in and around port complexes (IEA, 2024a). Many of these are envisioned as port-based hydrogen hubs or clusters. Such investments are usually backed up by Northern port authorities and capital and predicated on the establishment of "hydrogen corridors" that connect producing areas in the Global South with Northern import destinations. Playing a prominent role within these dynamics is Europe's largest seaport, the Port of Rotterdam, which is spearheading a series of hydrogen agreements and partnerships with port authorities and governments in the Global South (see SOMO, 2020; Monteith & Bäumer Escobar, 2025). A key example includes the Port of Rotterdam's co-ownership of the Pecém Industrial Port Complex in the northeastern Brazilian state of Ceará, home to a hydrogen export hub that is expected to supply 25% of all green hydrogen imported by Rotterdam in 2030 (Port of Rotterdam, 2022; see also Caiafa et al., 2024). The Port of Rotterdam also sponsors the annual World Hydrogen Summit, which is attended by decision-makers, CEOs, and has become the main global springboard for hydrogen deals, knowledge dissemination, and business networking (Port of Rotterdam, 2024).

On this account, we argue that ports are pertinent empirical windows through which to learn more about the new political geographies of H2-scapes in the Global South. Ports shape spaces where different resources, physical environments, bodies of knowledge, actors, and infrastructures (old and new alike) interact in hydrogen transitions. Furthermore, as place-specific infrastructures situated at the crosshairs of land and water that have global reach and connect different parts of hydrogen value-chains, ports adequately epitomize the cross-spatial and multi-scalar character of H2-scapes. In this sense, for two fruitful analytical directions, we propose reading port-centered H2-scapes as (1) terraqueous spaces and (2) power-geometries.

First, ports reflect the "terraqueous" dimension of H2-scapes, producing spaces at the intersection of the terrestrial and the aquatic (Monteith & Bäumer Escobar, 2025; see also Campling & Colás, 2018). This draws attention to the many ways in which both land and water environments are (re-)combined to territorialize H2-scapes, illuminating how prevailing modes of "green" and "blue" grabbing intertwine in the appropriation of both land and water resources for realizing hydrogen transitions and crafting new resource frontiers. Yet, besides conflating land and water, ports also evidence the collision of industrial, logistic, touristic, and livelihood functions in ecologically rich and sensitive landscapes. In this vein, scholars can look at how land struggles, water justice movements, and other types of activisms (e.g., fishing communities) interact to oppose and de-territorialize H2-scapes. Another key perspective lies in comparing such terraqueous spaces across distinct geographies to account for contextual nuances and variations in the territorialization of H2-scapes (legislative, operational, spatial, social) (e.g., between sea and inland ports).

Second, to draw on Massey (2005), but also echoing the literatures on material-, techno-, and energo-politics (Barry, 2013; Boyer, 2019; Hecht, 2011), port-centered H2-scapes constitute "power-geometries" under which interactions between humans and spaces – including materials, technologies, and energy – are central to the conduct of politics and reproduce power differentials (see also Hine et al., 2024). Political geographers have traditionally described ports in the Global South as a typical feature of postcolonial geographies, reflecting power-geometries that structure space through ambivalent mixtures of connection and disconnection (Cowen, 2014; Hönke & Cuesta-Fernandez, 2017; Wilmsmeier & Monios, 2015). In this sense, ports produce globally connected spaces that enable the efficient, standardized workings of global capitalism but at the same time act as zones of distinction driving the enclosure of lands and waters through (foreign) investment and configuring spaces of exception and graduated sovereignty through specific arrangements of public-private authority.

In the political geographies of H2-scapes, this leads us to explore how and by whom power and authority are distinctively exercised, not only in the immediate port zone, but also in the broader archipelago-like territoriality of H2-scapes (e.g., hydrogen valleys) that have ports as central nodes (e.g., South Africa's plans for a hydrogen valley around the ports of Durban and Richards Bay; Namibia's and Brazil's main hydrogen hubs around the ports of Lüderitz and Pecém, respectively). This entails asking how political authority in these spaces is co-exercised or dispersed between various state actors, multinational companies, and commercial operators to produce a seamless and managed H2-scape. All of which can similarly underscore modes of "corporate sovereignty" (Barkan, 2013) or "extraterritorial agency" (Kalvelage & Walker, 2024), illuminating the role of (transnational) port authorities in claiming or exercising sovereign acts over (parts) of the H2-scape: as landlord, security provider, community builder, or through border-making and management practices, among other functions.

Speaking to the multi-scalar nature of H2-scapes, investigations can also account for how power-geometries are at play in the transnational circulation of hydrogen. For example, the export of hydrogen through North–South, port-to-port links such as in the Rotterdam–Pecém corridor is set to be facilitated by favorable treaties, fiscal incentives, and simplified customs procedures, as envisioned by the EU-Mercosur trade agreement (European Commission, 2024). Human mobilities or commercial flows with greater empowerment effects (e.g., exports of family farming-based agricultural products) between the regions are in turn constrained by cumbersome visa and sanitary procedures. Furthermore, the territorialization of such maritime corridors – which ironically support the deployment of an invisible gas – is often premised on strategies of invisibilization. To remain on the Rotterdam–Pecém example, Brannstrom and Gorayeb (2022) note how corporate maps and outputs of the Pecém green hydrogen hub prominently highlight the area's privileged maritime connection to Rotterdam, more than 7000 km away, whilst nearby indigenous communities are never depicted in such images. To counter these representations, critical cartography and counter-mapping methodologies can help to draw more accurate representations of H2-scapes, while supporting claims for social and environmental justice.

Researchers may similarly explore how these power-geometries are not only constricted to the actual physical localities of ports and the maritime corridors they sustain but also extend to the (transnational) governance spaces that port authorities create and nurture. At the Port of Rotterdam-led World Hydrogen Summit, which acts as a major forum for agenda-setting in global hydrogen governance, attendance is only possible for a hefty USD 2700 fee (World Hydrogen Summit, 2024b). Purportedly, participants are offered "high-level networking" opportunities with ministers, government representatives, and global decision makers to "drive forward collaboration, enabling deal-making and project advancement" (World Hydrogen Summit, 2024a). The Summit's program (World Hydrogen Summit, 2024c) highlights not only the lack of civil society and grassroots representatives but also the lack of panels and sessions dedicated to addressing their concerns – in yet another revelation of how ports distinctively connect and disconnect in H2-scapes.

Another relevant empirical window for capturing the power-geometries of port-centered H2-scapes is through their geopolitical significance. The advent of clean hydrogen responds to geopolitical imperatives (e.g., Russian invasion of Ukraine, shipping disruptions in the Red Sea) pressuring ports and maritime economies to shift away from fossil fuels and embrace the production, transport, handling, and storage of low-carbon energy, including hydrogen (Quitzow & Zabanova, 2024; Van de Graaf et al., 2020). As the geopolitics of energy is redrawn and policy, diplomatic, and financial instruments gear up accordingly, investigations can assess whether and how port-centered H2-scapes in the Global South emerge as geostrategic arenas over which global powers compete for influence and control of new shipping routes and resources.

5.3. H2-scapes as failure

Undoubtedly, there is strong momentum for clean hydrogen: large-scale production, trade, and uptake have not yet materialized, but policies, plans, and investments are underway and growing. However, after a few years of unabated enthusiasm, a certain reality check is slowly kicking in. This is evidenced, among other things, by the changing discursive tone of leading energy organizations and consultancies, where overly cheerful takes on the future of hydrogen have been giving ground to more measured and cautious assessments (see IEA, 2023, 2024a).

Dulling hydrogen's shine is a host of cost, technical, and practical hurdles (Hunt & Tilsted, 2024). Central to global net-zero strategies, clean hydrogen remains more expensive than hoped. For green hydrogen, most near-term forecasts hover around USD 4.50–6.50/kg and reach, at their very best, USD 3/kg for countries where renewable electricity is cheapest (Collins, 2023). This falls significantly above the USD 1–2/kg range required to compete with fossil hydrogen and is a lot more to pay for energy than conventional alternatives like natural gas.[4] Blue hydrogen, regarded as a cheaper alternative, has been described as "clean in theory but not reality" due to the inefficiencies and unproven nature of carbon capture technologies (IEEFA, 2023). Adding transport and storage, costs for clean hydrogen can rise even further, prompting some to call it the "champagne of the energy transition" (Gilmore, 2024). In this regard, some have noted that, from a developmental and climate perspective, it is more effective to shift industrial production to areas in the Global South where clean hydrogen production is cheapest and can be tapped directly from the source (Eicke & De Blasio, 2022; Samadi et al., 2023).Yet, this remains highly unlikely in current conjunctures of heightened protectionist and deglobalization tendencies in Global North countries, fueled recently by President Donald Trump's return to power in the United States. In addition, clean hydrogen stands as a more inefficient solution for sectors where direct electrification is possible (e.g., cars, trains, buses, domestic heating). Even for applications with a sounder business case (e.g., heavy industries, aviation, and maritime shipping), advances in electrification-based technologies or the need to completely overhaul existing infrastructures, supply chains, and behavior presents further obstacles for clean hydrogen's deployment.

As such, widely circulated and replicated projections of 600–700 million tons (Mt) of clean hydrogen by 2050 (Hydrogen Council, 2021) remain a distant reality. Attaining this would not only require "cleaning" all the approximately 100 Mt of hydrogen produced annually today – 97% of which deriving from unbated fossil fuels – but also a massive 600-700-fold increase in current clean hydrogen production levels, which stand at about 1 Mt (1% of total global output) (IEA, 2024a, p. 60). These ambitious objectives have galvanized the hydrogen ecosystem, but progress has been slow. Due to regulatory uncertainties, high costs, and lack of offtakers, many projects have been delayed or shelved. By the end of 2024, only 4% of all announced clean hydrogen projects have reached final investment decision (IEA, 2024a, p. 59). Many projects have also been discontinued, as use cases for hydrogen proved tenuous (e.g., car refueling stations) (Martin, 2024).

Yet, most hydrogen studies, including critical works, still overlook the plausible scenario of hydrogen as failure, often taking for granted its (massive) scaling-up nature. We hold that it is reasonable to put hydrogen's projected magnitude into question and ask: What if hydrogen fails or turns out to play a much smaller role than what is being projected? What are the implications for Global South H2-scapes?

Drawing on Graham (2010), we understand failure as moments when technical and infrastructure systems are interrupted, disrupted, and discontinued due to a lack of success or viability, along with the political, spatial, and social processes that contribute to or are affected by these configurations. In this sense, looking at the plausible political geographies of H2-scapes as failure can make for insightful readings, in at least three ways.

Firstly, the non-territorialization or discontinuation of hydrogen systems does not mean that projects are suddenly free of impacts, disturbances, and grievances. As seen in recent studies on biofuel investment failures in the Global South, supposed "wonder-crops" like jatropha have propelled global market hypes driving large-scale land acquisitions under conjunctures of uncertainty, randomness, and unpredictability, resulting in negative environmental impacts, land alienation, food insecurity, and high investment losses (Antwi-Bediako et al., 2019). Namibia's much-vaunted Hyphen hydrogen project, worth USD 10 billion, roughly the size of the country's entire economy, provides a good example. The project's mere announcement in 2021, premised on plans to build large-scale solar and wind parks in the Namib Desert along with port expansion developments, has unleashed processes of land enclosure, displacement, and speculation, interfering with biodiversity hotspots, fishing, and tourism activities (Grobler et al., 2023). Yet, as of this writing in early 2025, the project has not yet achieved a final investment decision, and it remains unclear when the first molecule of hydrogen will be produced. The concept of "presource curse", deployed in the extractive industries' literature to refer to the upheavals created by the anticipation of future extractive revenues (Frynas & Buur, 2020; Alencastro & Cezne, 2023), can offer pertinent insights here. Particularly in the Global South, where hydrogen's hyperdrive is hasting governments and business to announce ambitious

[4] Based on price estimates for 2030, green hydrogen is projected to cost an average of USD 216/MWh. In comparison, natural gas costs USD 8/MWh in the United States and EUR 30/MWh in Europe (Palladino, 2024).

mega-projects, sometimes matching entire countries' or regions' economies, scholars can detail and explore the negative effects of a presource curse and investment hype in contexts where hydrogen production may never materialize, or long before it actually materializes.

Second, considering a recent string of suspended or scrapped projects due to high costs or hydrogen's competitive disadvantage, it is not unconceivable to think of H2-scapes as immanent spaces of "infrastructural ruination" (Anand et al., 2018). Here, the possible decay, degeneration, and de-territorialization of hydrogen infrastructures can prompt us to re-think how given energy futures and socio-technical imaginaries for the Global South (e.g., green developmentalism, green industrialization) are disrupted, forgotten, or re-signified. Such dynamics can also trigger us to question why energy futures and landscape imaginaries centering on inefficient, expensive, and technically-intensive solutions like hydrogen are made desirable, favored, and territorialized in the first place (see also Burke & Stephens, 2018; Hine et al., 2024; Virens, 2024). This can shed light on how power influences and lobbying dynamics by "old", hegemonic fossil players and interest groups drive particular types of transitions over others.

Lastly, hydrogen may also be viewed as a case of "productive failure", under which setbacks, experimentation, and creative risk-taking are deemed crucial for any innovation to succeed. While popular solutions nowadays like electric vehicles and solar panels were once dismissed as market failures, learning curves, cost declines, and technological breakthroughs have eventually enabled their scaling-up (Sierzchula et al., 2014). These are critical puzzles to monitor in hydrogen transitions. Will current setbacks, bottlenecks, and difficulties represent a bridge to hydrogen's future success? Along the way, studying hydrogen as failure thus allows us to draw productive lessons, improve policies, and ameliorate socio-spatial outcomes. Or, conversely, we might find out that considerable time and scarce resources have been used on the wrong development projects, in the wrong places, and with irreversible consequences.

6. Conclusion

The incipient deployment of clean hydrogen calls for new forms of critical and social science thought. Drawing on political geography perspectives, this article proposed the concept of "H2-scape" to explore hydrogen transitions as space-making processes imbued with power relations, institutional orders, and social meanings. We described H2-scapes as the new energy spaces created by the material expressions of hydrogen-based energy systems and the various social, political, cultural, and environmental regimes and practices attached to them. To capture and understand the making of H2-scapes, we delineated a conceptual framework based on three key dimensions: (1) territoriality – the geographical strategies aimed at implementing and operationalizing hydrogen systems over given spaces; (2) articulation of old and new – how "new" hydrogen sectors are produced over remnants of "old" energy systems, particularly fossil fuel production technologies and infrastructures; (3) cross-spatiality and multi-scalarity – hydrogen systems traverse diverse spatial localities and geographical scales.

Subsequently, we identified and elaborated on three relevant directions to illuminate how the concept of H2-scape can be applied to analyze and facilitate further empirical research on hydrogen transitions in more uneven, unequal, and vulnerable Global South landscapes: (1) H2-scapes as resource frontiers; (2) H2-scapes as port-centered arrangements; and (3) H2-scapes as failure. First, to complement emerging thought on clean hydrogen's propensity to produce new resource frontiers in the Global South, we underscored two analytical propositions for grasping the complex, differentiated, and plural nature of frontier-making dynamics in H2-scapes. Namely, by viewing these as of "zones of distinction" that create fragmented territories and spaces of exception managed by distinct governance, temporal, and economic logics; and as "contact zones" where disparate knowledges, cultures, and labor practices interact and clash. Second, we accounted for the crucial role of ports, which act as central nodes and key enablers of Global South H2-scapes. We illuminated analytical approaches for thinking about ports as "terraqueous spaces", drawing attention to how terrestrial and water spaces are (re-)combined in the territorialization of hydrogen; and as "power-geometries", whereby ports reproduce power differentials that structure space through both connection and disconnection. Third and lastly, we considered plausible scenarios of H2-scapes as failure and how to study them, distilling both problematic consequences and productive lessons that we can derive from hydrogen's possible failure to scale-up, lack of viability, and non-materialization in Global South settings.

The making of H2-scapes is also significant for policy and is, conversely, policy-dependent. Clean hydrogen's specific political geographies both integrate new dimensions and reinforce socio-spatial challenges of "old" energy systems and resource economies, with implications to landscape planning, impact assessment, and social justice. Yet, most policy-making remains chiefly guided by narrow technical and economic preoccupations. Recognizing hydrogen transitions as space-making processes, as delineated by our proposed notion of H2-scape, can thus contribute to more holistic, plural, and inclusive public policies, decision-making, and institutional frameworks. This is specifically relevant for Global South realities where prospective hydrogen investments sometimes overmatch entire economies and entail profound transformations to already uneven and vulnerable land and water geographies, though in highly uncertain and speculative conjunctures.

Notwithstanding, our propositions here are necessarily tentative and partial. They are neither definitive nor exhaust the wide and interlinked range of social, political, economic, and environmental implications that hydrogen is set to (re-)produce. On the contrary, our objective was to think through the early stages of hydrogen transitions, flag emerging tendencies, and offer points of departure for further research, particularly in still under-explored Global South geographies. As hydrogen booms (or bursts) in the years to come, future studies are welcome to fine-tune and complement conceptualizations and applications of our H2-scape framework – for instance, by extending it to Global North settings or differentiating between disparate Southern geographies and locales, or by contrasting between different types of clean hydrogen.

Finally, the development and deployment of clean hydrogen is fundamentally a multidimensional and multisectoral affair. Thus, achieving just and inclusive political geographies of hydrogen in the Global South and beyond ultimately rests on collaborative work involving different scientific disciplines, policy-makers, industry actors, and civil society. This is no doubt a challenging task, but if nothing else, we hope this article can contribute to efforts in this direction.

CRediT authorship contribution statement

Eric Cezne: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Kei Otsuki:** Writing – original draft, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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