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Multilateral governance in a global hydrogen economy: An overview of main actors and institutions, key challenges and future pathways

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ABSTRACT

This paper explores the current scope and direction of the emerging global governance of hydrogen within the broader context of the energy transition, where technological innovation and institutional change intersect. Hydrogen, as a critical yet complex energy vector, requires coordinated governance efforts to navigate its development effectively. To this end, we critically engage with key challenges facing the hydrogen sector and examine how institutional frameworks are addressing these issues. Departing from the broader scholarship on global energy governance, we conceptually leverage the socio-technical transition and innovation system literature to understand the complexities underpinning the development of the global hydrogen economy. We identify three overarching issue areas pertaining to the nature and role of hydrogen in the global energy system: end-use sector development, infrastructure and trade, and environmental and socio-economic sustainability. Each of these areas presents distinct challenges to hydrogen's global governance, from stimulating supply and demand to managing geo-economic challenges and establishing comprehensive certification and standards. Through mapping multilateral institutions at the global and regional levels and their main objectives, we offer insights into the emerging institutional architecture related to hydrogen and identify potential gaps in current governance. Our findings suggest that while newer, hydrogen-specific institutions complement the broader agenda of the main established international organizations, the overall global hydrogen structure remains a patchwork of diverse actors and frameworks, each addressing hydrogen-related challenges to varying degrees. Our research contributes to a nuanced understanding of global governance in the hydrogen sector and advances scholarly discussions on how institutional and actor dynamics shape the emergence and development of new technologies.

1. Introduction

Hydrogen as a climate-friendly energy carrier has become central to discussions on the future trajectory of the international energy system [1,2]. Calls for developing a hydrogen-based energy economy stem from the belief that hydrogen - particularly 'green' hydrogen generated from renewable electricity - serves as a cornerstone in developing a carbon-neutral energy systems at a global scale. Tellingly deemed the 'Swiss army knife of decarbonization' [3], it offers a viable path to decarbonize parts of industry and transport that are challenging to electrify, thereby aiding global efforts to combat climate change. The idea of a global hydrogen economy itself is not new; Rifkin [4] already presented a vision where hydrogen replaces fossil fuels, reshaping global economies and geopolitics. Yet technological and economic barriers historically impeded its large-scale adoption and integration into international policy frameworks [5,6]. The formulation of carbon-neutrality targets has rekindled interest in hydrogen, and countries across the globe have started to implement national roadmaps and hydrogen strategies [7].

These country-level efforts are also translating into emerging institutional structures and mechanisms to advance hydrogen [8]. The governance of hydrogen is still in its nascent stages and poses a complex challenge due to its multi-sector nature, comprising various interrelated technological, ecological, (geo)political and social dimensions [9,10]. Given the need for governance to effectively navigate these dynamics, it is crucial to understand which global institutional structures are

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currently in place to deal with the complexities facing the hydrogen sector. While a growing body of research has engaged with the global governance of energy and climate change, such mapping efforts have thus far focused on oil, gas or renewables, as well as the broader climate-energy nexus [11–13]. Meanwhile, the emerging scholarship on hydrogen governance has primarily engaged with national contexts [14–16]; research has yet to comprehensively delineate its international dimensions.

Attempting to fill this gap, the objective of this study is to provide an overview of the emerging global governance of hydrogen, linking insights from global governance and transition studies. Specifically, we adopt the lens of the innovation system scholarship to shed light on the network of institutions and actors that contribute to hydrogen technology development [17,18]. While confronted with many similar challenges as wind and solar energy, we identify three new challenges that are unique to the hydrogen sector and that require a global governance response: end-use sector development, infrastructure and trade, and environmental and socio-economic sustainability. By mapping main hydrogen-engaged institutions and actors at the global and regional level, we offer insights into the extent to which this institutional architecture is currently addressing these interrelated challenges, and which governance gaps need to be filled. Our findings contribute to a nuanced understanding of governance challenges in the hydrogen sector and advance the broader research agenda on the interplay of institutions and actors underpinning the emergence of new technologies.

Section 2 reviews the literature on global (renewable) energy governance, outlining its origins, manifestations and challenges for multilateral efforts. Section 3 then develops the analytical framework for global hydrogen governance through the lens of innovation systems, which provides the basis for delineating key challenges the hydrogen sector is facing in Section 4. Section 5 comprises the methodology for the data collection and analysis. Section 6 presents and discusses the findings in line with the questions and concepts guiding this research. The final section concludes with the contributions and limitations of this study as well as avenues for future research.

2. Global (renewable) energy governance – A review

The scholarship on global energy governance started to emerge in the early 2000s following the 2002 World Summit on Sustainable Development and the 2005 G8 Gleneagles Summit, where issues at the intersection of energy efficiency, climate change and sustainable development were formally recognized as a global governance challenge requiring multilateral cooperation [19,20]. Mapping attempts since then have identified a plethora of institutions, ranging from six to over fifty in number, as van de Graaf & Colgan [21] have observed. The following institutional structures have been deemed the most important drivers of global energy governance: intergovernmental organizations (IGOs), including the Organization of Petroleum-Exporting Countries (OPEC), the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA), UN Energy or the International Renewable Energy Agency (IRENA); summit processes, most notably the G7/8 and G20; global financial institutions and development banks such as the World Bank and regional development banks; non-governmental institutions (NGOs); and hybrid partnerships comprising public and private sector stakeholders, such as the Renewable Energy Policy Network for the 21st Century (REN21) and the Renewable Energy and Energy Efficiency Partnership (REEEP) [12,22,23].

Despite the significant role of actors from civil society and industry, the scholarship largely agrees that states remain the most powerful drivers of global energy governance [13,24,25]. The IEA, established in 1974 in response to the 1970s oil shocks, continues to be among the most prominent multilateral institutions in this space, followed by the International Energy Forum (IEF), the Energy Charter Treaty (IEF) and IRENA [26]. Due to its importance for the field of energy transition, IRENA has garnered particular attention in the scholarship, deemed a 'miracle' creation due to extensive efforts from a coalition of states aiming to integrate renewables into the global institutional architecture [27,28]. Moreover, Downie [25] finds that the G20 has significantly contributed to setting the agenda and building political consensus around renewable energy in the past two decades by contracting formal IGOs like the IEA and IRENA.

At the same time, the scholarship has highlighted several institutional challenges in the role of IGOs [29]. For example, the G20 has failed to play a more proactive role in global governance due to a lack of leadership by the technologically advanced economies and largest carbon emitters, such as US and China [26]. Moreover, despite increasing interlinkages between institutions, tensions result from overlapping as well as conflicting governance agendas. A case in point is the complex interplay of the IEA and IRENA, whose objectives - even though the IEA broadened its fossil-centered portfolio to include renewables following IRENA's creation in 2009 - often diverge [30,31]. Similarly, while the IEA is considered closest to a global focal point in energy governance, the fact that its membership is limited to OECD countries is further contributing to perceptions of ineffectiveness [32,33]. Finally, though IRENA covers different key areas of renewable energy governance most comprehensively and its membership is universal, its de facto impact remains unclear, especially when it comes to infrastructure development and finance for the integration of renewables [34,35].

The global energy transition and its governance are thus characterized by complexity [36,37]. As Belyi [38] notes, one challenge intrinsic to multilateralism is the absence of a common understanding about what constitutes key governance issues. Previous mappings of global energy governance have largely revolved around three key issue areas – energy security, energy access and environmental sustainability -, finding that the energy security realm has traditionally been dominated by states and governmental actors, while public international organizations, private actors and hybrid initiatives have focused on questions of energy access and environmental sustainability [35,36]. Notably, IRENA has been identified as rather unique in addressing and integrating all three issue areas [35]. Moreover, precisely due to governments' traditionally security-centered views on energy, a plethora of bilateral relations exist alongside multilateral initiatives that further contribute to the complexity of global energy governance [23].

Hence, diverse actors and institutions selectively and unevenly cluster around various objectives, leading to a global governance landscape often described as fragmented [24,39,40]. This fragmentation reflects the (persistent) incompleteness and duplication of governance frameworks due to the nature of the global energy landscape, comprising diverse energy sources and markets, and a plurality of states as well as non-state actors [13,41]. Recent studies also emphasize the growing influence of new (regional) actors, driven by the shift towards low-carbon technologies and changing geopolitical dynamics surrounding the rise of renewables [42,43]. The literature further suggests that the incohesive architecture of global energy governance is symptomatic of the ad-hoc development of institutions in response to crises [12,44,45].

This complex landscape of global energy governance forms an important basis for the developing institutional landscape around hydrogen. As Westphal et al. [8] observe, the "problem is not so much that there is an organizational void but that so far coherence and direction have been lacking" (p. 6) in hydrogen governance. To further advance our understanding of how the institutional architecture is evolving to address hydrogen-related challenges, the following section discusses existing conceptualizations of the interplay between global governance and changing energy systems.

3. Governing the energy system transformation: A socio-technical perspective

An important perspective that has gained traction in the energy transition scholarship is the integration of insights from transition

studies and international political economy [46,47]. A central premise on which this perspective builds is that the energy transformation constitutes a 'tectonic shift' comprising not one but multiple energy transitions [48,49]. It is a multi-level process in which the phase-out of fossil fuels coincides with the emergence of renewable energy sources and clean technologies, leading to a cumulation of several transitions into the structural reconfiguration of the energy system [50,51]. This integrated approach is essential for understanding how technological change and institutional restructuring are influenced by vested interests and lock-in effects, as well as for identifying the diverse transition pathways that countries and regions take [47,52].

Conceptualizing global decarbonization as a 'socio-technical transition' provides a useful lens that pays attention to these dynamics [46,53]. The energy transition is socio-technical in that it fundamentally changes societies' use of energy sources; alters the technological landscape; and reconfigures industries across national and global economies [18]. While fragmentation remains a defining feature of this changing global energy landscape, it presents both challenges and opportunities. Scholars suggest that the way forward is not to eliminate fragmentation but to navigate it effectively by making use of the advantages decentralized systems can offer [13,54]. As such, 'polycentric' governance structures characterized by strong interlinkages between - rather than integration of - various institutional arrangements can enhance the capacity for flexibility, innovation and adaptation of governance outcomes, leaving space for a diverse range of non-state actors and industries, particularly in the diffusion of technology and knowledge [55,56].

As Meckling [57] observes, new institutional arrangements emerge because of policy feedback cycles between coalitions of firms and policymakers; that is, in response to market opportunities that are either enabling or constraining innovation. These new structures often reflect more open and 'softer' forms of governance focusing on specific aspects along the innovation chain in renewable energy [58]. As case in point is the rise of hybrid organizations that bypass traditional intergovernmental mechanisms, highlighting the increasing decentralization of energy governance [59]. These networks benefit from greater organization flexibility and decision-making space as they operate through markets rather than formal hierarchies, allowing them to enter innovation and policy 'niches' that can effectively complement the governance of IGOs [59,60].

At the same time, these 'niches' need to be embedded in the long-term commitment and 'hard' leadership of established institutional structures and overarching regulatory frameworks [51,60]. Over a decade ago, Fouquet [61] made the compelling argument that this is particularly crucial in the transition to a climate-friendly energy system: contrary to previous energy transitions where the private economic advantages of adopting a new technology like electricity were high, and a relatively large minority was thus willing to pay more for the better services associated with electricity, the benefits of climate-friendly energy sources and technologies are primarily collective (i.e. climate protection) rather than individual. As most consumers will be unlikely to pay more for 'niche' energy sources and technologies like hydrogen, its governance requires a delicate balancing-act between 'exploiting' strong regulatory frameworks for its protection and societal acceptance on the one hand, and creating space for flexible 'exploration' and innovation on the other [48,54].

4. Key challenges for the global hydrogen sector

To further delineate key challenges in the ramp-up of the hydrogen economy, the 'innovation system' framework serves as a useful heuristic [53,62]. As governance is embedded in wider civil society and market systems, multiple (state- and non-state) actors and institutions are involved and fulfill various so-called "system functions" to allow the sector to progress and grow [63,64]. These include 'entrepreneurial' functions that advance business opportunities around a new technology; knowledge development and diffusion that underpin technology development and adoption; guiding the visibility and direction of a technology's benefit and use; market formation for wide-spread technology adoption; resource mobilization, both financial and human to enable scaling-up; and legitimation to ensure public acceptance [64].

Global governance structures can contribute to these functions in various ways [65,66]: for example, knowledge development and diffusion can be supported by advancing international initiatives for collaborative research and development (R&D) or capacity-building to facilitate access to existing knowledge. Similarly, agenda-setting and lobbying efforts can influence the direction and visibility as well as legitimacy of the new technology. Moreover, resource mobilization is supported through leveraging public and private capital, as well as technical and political expertise for large-scale rollouts. In addition, public pressure, sharing best-practices and creating favorable regulatory environments contributes to a technology's rapid commercialization. Finally, governance can stimulate and shape market formation around innovations through public procurement and fiscal frameworks.

Innovation thus takes place through the 'co-evolution of both technology and institutions' that are linked by the system functions [67]. In the hydrogen sector, this process is complicated by three important issues pertaining to its nature and role in the energy system: End-use sector development, infrastructure and trade, and environmental and socio-economic sustainability.

Firstly, market formation for hydrogen as an energy carrier is linked to a whole range of potential yet so far undeveloped end-uses. It is a multi-sector issue where separate end-use sectors and therefore market domains need to be developed and integrated [53]. Moreover, the nascent stage of hydrogen applications creates additional insecurities for investors and governments; previous research on hydrogen market stakeholders underlines the urgency of reducing political and regulatory uncertainty to foster effective market design [68]. Governments also need to address risks associated with hydrogen and incentivize large-scale investments through fiscal frameworks and public procurement efforts [69]. Hence, contrary to well-established demand structures for wind and solar power, stimulating not only sufficient supply but *demand* through end-use sector development presents a key governance challenge [70]. This also feeds into broader questions on value distribution in the hydrogen economy to incentivize developing countries' participation in its market ramp-up. Effectively addressing both the opportunities (e.g., job creation and industrialization) and potential risks (e.g., for the environment) of hydrogen is crucial to foster sustainable growth in emerging markets [71].

Secondly, contrary to wind and solar power which are locally harnessed energy sources, hydrogen is a tradable energy carrier. Put differently: not just the technology but the molecule itself can be traded. It requires massive infrastructure development for distribution, transport and storage (including pipelines and ships specifically designed for hydrogen and its derivatives) as well as its application, with each step in the value chain necessitating international guidelines [14]. This also requires negotiating frameworks for trading standards and protocols that give due consideration to the geo-economic and -political implications of emerging hydrogen markets [2,42]. The hydrogen economy is likely to be characterized by new centers of supply and demand, with some countries becoming more dependent on imports than others due to geographically limited renewable resource endowment, which fundamentally alters political and economic relations [72]. Similarly, strategic advantages of powers like the US or China, who possess abundant renewable energy potential and large technological and manufacturing capacities, will further spur competition over industrial and trade policy in the emerging hydrogen economy [73].

Thirdly, the environmental implications of hydrogen production and its various methods are more complex compared to that of solar panels and wind turbines, which have mainly revolved around questions of disposal [74]. Hydrogen still lacks universally accepted standards, especially when it comes to purity and carbon intensity of production;

even if hydrogen derived from natural gas through steam methane reforming ('grey' hydrogen) is combined with carbon capture and storage (CCS) ('blue' hydrogen), its environmental benefits are limited since emissions are not reduced or eliminated but merely stored [75]. Yet generating renewable ('green') hydrogen through water electrolysis is still several times more expensive than its fossil-derived counterparts; apart from encouraging scientific cooperation and R&D, governance thus needs to target the rapid cost-reduction of green hydrogen [76]. Moreover, harmonized standards are deemed pivotal to ensuring that hydrogen contributes effectively to global decarbonization, and to scaling-up public and private investments in a global hydrogen market [77]. At the same time, the proliferation of various hydrogen certification labels presents difficulties in terms of comparison, undermining their usefulness for cross-border hydrogen trade [78]. Finally, the governance challenge that the sustainability of hydrogen presents not only requires harmonized definitions for hydrogen and its emissions intensity, but also giving due consideration to broader societal concerns, including socioeconomic security, energy access and local community involvement (Müller et al., 2022; [79]).

Against this backdrop, the remainder of this study maps global multilateral institutions currently engaged with hydrogen, examines how these governance structures are dealing with the main challenges identified, and discusses the broader scope and direction global hydrogen governance is taking.

5. Data selection and analysis

The data selected in this study entails principal multilateral institutions (that is, comprising parties from three or more different countries) engaged in hydrogen governance at the global and regional level. The data was collected based on information and resources available in English and has been validated by experts from Europe and Asia to ensure representativeness.

Institutions that were included in the dataset were (i) hydrogen-related taskforces or programs that have been added to the broader agenda of institutions, as well as (ii) (new) initiatives, organizations and platforms dealing exclusively with hydrogen. The data was retrieved and collected through extensive desktop-research and includes the name of the institution; year of founding; region; overall mission/goal; and membership (see *Appendix*). The institutions were subsequently analyzed as to which main governance objectives they aim to carry out, and how these anticipated activities contribute to dealing with the main governance challenges identified above. Mapping the institutional landscape against this backdrop therefore not only shed light on the general direction and scope the global governance of hydrogen is taking, but further allowed for an assessment of the extent to which the system functions critical for the transition towards a hydrogen-based economy are being supported by current global governance, and of potential gaps needing to be addressed.

It is important to note that it was beyond the scope of this study to make any claims about the actual performance and effectiveness of multilateral governance on hydrogen-related matters. As such, the research aim was not to assess whether, and how, the objectives and governance functions of individual institutions are de facto implemented and carried out, but to provide an overview of activities by these institutions and how they address the main governance challenges in the hydrogen sector. The following sections present and discuss the findings.

6. Results and discussion

This study identified a total of 52 multilateral bodies currently engaged in the governance of hydrogen at the global and regional level, as of October 2023 (see *Appendix*). The largest global economies and highly industrialized countries currently seeking leadership in the global hydrogen market-ramp up (e.g., Australia, Canada, China, France, Germany, Italy, Norway, US and UK) are those participating in most global institutions and initiatives (Fig. 1). They are closely followed by emerging economies like Saudi Arabia, Chile, and India who aspire to adjust their conventional energy industries or utilize their favorable geographical conditions and renewable resource endowment to become important 'hydrogen hubs' [80]. This aligns with previous research findings that most hydrogen strategies are being pushed by advanced and emerging economies [81]. Our mapping of multilateral institutions and their membership (see *Appendix)* further revealed that the African continent is least represented, while the EU appears to be the currently most proactive multilateral actor in the global hydrogen ramp-up, driving several regional and global initiatives.

The findings also highlight the active participation of stakeholders from the corporate sector and industry in multilateral hydrogen governance, which is in line with previous analyses of actors and institutions governing the climate-energy nexus (Fig. 2) [13,58]. While most (28) institutions and forums at the global and regional level are fully government/state-driven, there are several initiatives that reflect public-private partnerships and hybrid alliances between governments, civil society and/or businesses (16), or fully industry-driven initiatives (8). It is notable that the involvement of civil society organizations such as NGOs is comparably small.

6.1. Programs and taskforces within existing multilateral institutions and forums

The majority (31) of identified governance bodies reflects hydrogen-related programs, initiatives and taskforces set up within the framework of established multilateral institutions and forums governing the energy-climate nexus. Hydrogen has largely been 'added' to these institutions' agendas alongside broader governance challenges such as fossil and renewable energy (Fig. 3). These initiatives generally focus on knowledge production and diffusion, and on enhancing the political and economic visibility of hydrogen as a technology through R&D, agenda-setting and capacity-building. Here, most institutions are dealing with various types of hydrogen technologies, as well as with both green (renewable-based) and blue (natural gas-based) hydrogen; they are dominantly those institutions that have added hydrogen to their broader agendas. By contrast, the share of institutions exclusively dealing with hydrogen is largest among those engaging with green hydrogen only (Fig. 4). These findings reflect the present state of hydrogen development, where - even though renewable-based hydrogen is widely considered the preferred and environmentally most sustainable path – alternatives are being explored due to high costs associated with green hydrogen production in the short-to mid-term [76].

Institutions' main tasks and objectives shed light on the extent to which global hydrogen governance currently address the challenges outlined in Section 4, For example. the IEA's Hydrogen TCP functions as a global data and information hub, carrying out research on sustainability and safety aspects in the production, storage and transport of hydrogen, as well as on potential market barriers to the commercialization of renewable hydrogen [82]. While the IEA's research collaboration focuses on various hydrogen technologies, including fossil, renewable and nuclear hydrogen, IRENA exclusively deals with green hydrogen across a range of areas such as transportation, certification and end-use application, as well as societal acceptance and its relevance for smaller markets [83]. The IAEA, on the other hand, advances research on the economic costs and emissions-intensity of nuclear energy-based production technologies [84]. These findings are in line with previous observations on how the principal IGOs in global energy governance largely 'defend' their traditional fuels and associated technologies, while at the same time duplication and overlap -result from institutions having broadened their agendas in light of functional pressures [25,31]. Moreover, IRENA's engagement across multiple issue areas and focus on green hydrogen feeds into previous arguments regarding its comparably comprehensive approach and 'special' status in the global renewable energy space [27,35].

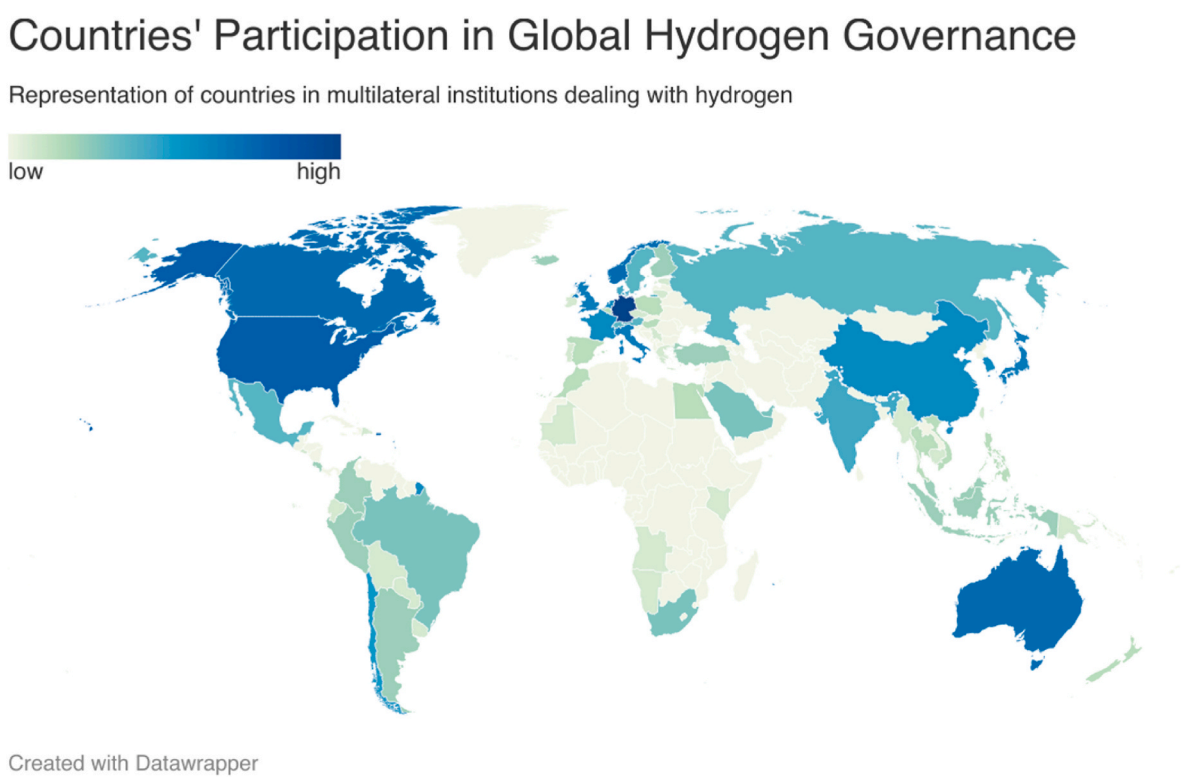

Fig. 1. Countries' representation in global hydrogen governance (authors' own visualization).

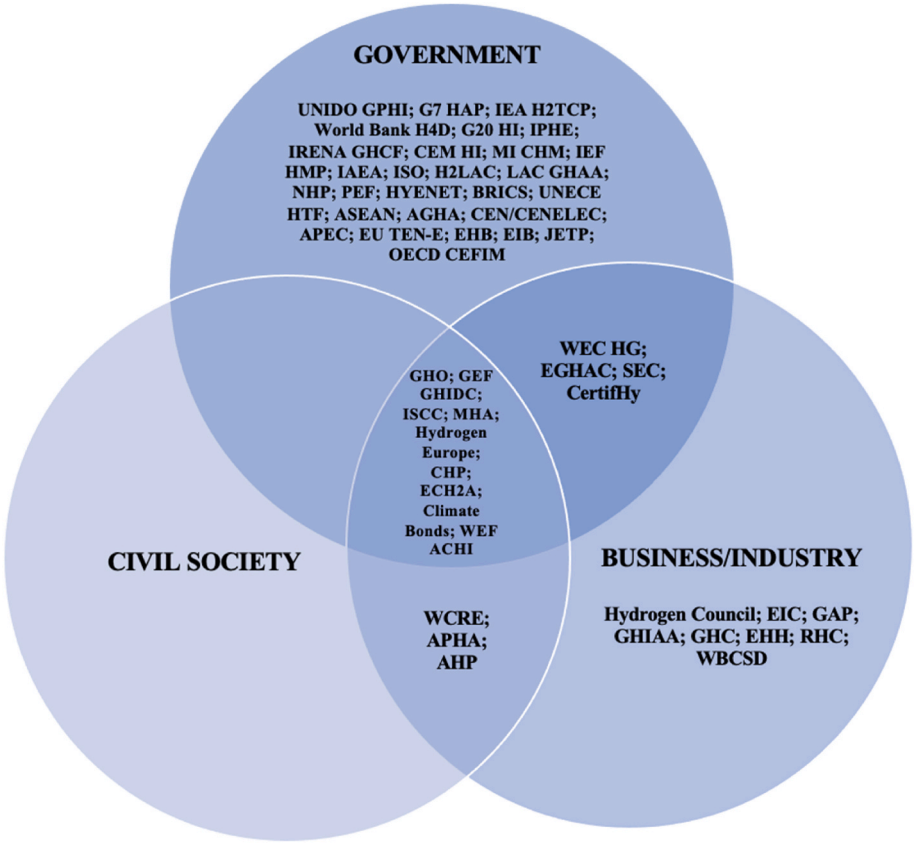

Fig. 2. Types of actors in global hydrogen governance ('Governance Triangle' based on [13,20], authors' own data).

Multilateral institutions and initiatives that have added hydrogen to their agenda

- UNIDO Global Program of Hydrogen in Industry (UNIDO GPHI)
- G7 Hydrogen Action Pact (G7 HAP)
- IEA Hydrogen Technology Collaboration Program (IEA H2TCP)
- World Bank H4D
- Just Energy Transition Partnership (JETP)
- G20 Hydrogen Initiative (G20 HI)
- IRENA Collaborative Framework on Green Hydrogen (IRENA GHCF)
- Clean Energy Ministerial Hydrogen Initiative (CEM HI)
- Energy Industries Council (EIC)
- OECD Clean Hydrogen Finance and Investment Mobilization (OECD CEFIM)
- Global Alliance Powerfuels (GAP)
- Mission Innovation Clean Hydrogen Mission (MI CHM)
- World Economic Forum Accelerating Clean Hydrogen (WEF ACHI)
- International Energy Forum Hydrogen Market Pathways (IEF HMP)
- Sustainable Energy Council Hydrogen Summits (SEC)
- World Council for Renewable Energy (WCRE)
- World Energy Council Hydrogen Global (WEC HG)
- World Business Council for Sustainable Development (WBCSD)
- International Atomic Energy Agency (IAEA)
- Global Environment Facility Green Hydrogen in Developing Economies (GEF GHIDC)
- International Organization for Standardization (ISO)
- International Sustainability and Carbon Certification (ISCC)
- Climate Bonds
- Pentalateral Energy Forum (PEF) (Regional)
- European Investment Bank (EIB) (Regional)
- BRICS Hydrogen Summit (Regional)
- EU Trans-European Networks for Energy (EU TEN-E) (Regional)
- United Nations Economic Commission for Europe Hydrogen Taskforce (UNECE HT) (Regional)
- ASEAN Hydrogen Summit (Regional)
- CEN/CENELEC (Regional)
- APEC Low Carbon Hydrogen International Standard (Regional)

Multilateral institutions and initiatives exclusively dealing with hydrogen

- International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
- Hydrogen Council (HC)
- Global Hydrogen Industrial Association Alliance (GHIAA)
- Green Hydrogen Organization (GHO)
- Green Hydrogen Catapult (GHC)
- H2LAC (Regional)
- LAC Green Hydrogen Action Alliance (LAC GHAA) (Regional)
- Nordic Hydrogen Partnership (NHP) (Regional)
- MENA Hydrogen Alliance (MHA) (Regional)
- Hydrogen Europe (Regional)
- European Hydrogen Highway/Backbone (EHH) (Regional)
- European Green Hydrogen Acceleration Center (EGHAC) (Regional)
- Clean Hydrogen Partnership (CHP) (Regional)
- Hydrogen Energy Network (HyENet) (Regional)
- European Clean Hydrogen Alliance (ECH2A) (Regional)
- Renewable Hydrogen Coalition (RHC) (Regional)
- European Hydrogen Bank (EHB) (Regional)
- Asia-Pacific Hydrogen Association (APHA) (Regional)
- Africa Green Hydrogen Alliance (AGHA) (Regional)
- African Hydrogen Partnership (AHP) (Regional)
- CertifHy (Regional)

Fig. 3. Hydrogen-exclusive vs. -non-exclusive institutions and frameworks.

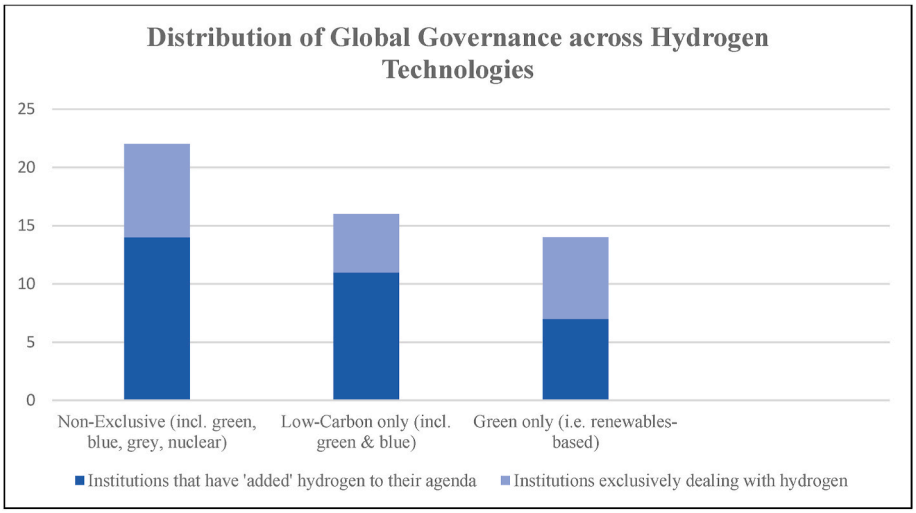

Fig. 4. Distribution of multilateral institutions across different hydrogen production technologies.

Fig. 4 Types of actors in global hydrogen governance (figure based on Abbott & Snidal [20], see Annex I for list of abbreviations).

Moreover, summit processes like the G7/8 and G20 as well as the hydrogen summits and conferences held by regional alliances like BRICS and ASEAN seek to advance dialogue on the political and economic benefits and use of hydrogen. Albeit lacking clearly defined functions beyond declarations of intent, these summit processes are steering the direction of global hydrogen governance by formulating specific commitments and defining policy priotities, such as the acceleration of green hydrogen production and the development of necessary regulation. This is in line with previously mentioned observations regarding the G20's important agenda-setting role despite lacking clear leadership [25,26]. It is notable that while all these initiatives - the G7/8 Hydrogen Action Pact, the G20's Hydrogen Initiative as well as the BRICS and ASEAN hydrogen summits – aim to facilitate dialogue and promote cooperation among their members, there appear to be no comprehensive attempts to foster inter-institutional exchange between these forums and their respective agendas.

Public-private formats such as the Sustainable Energy Council (SEC) and the World Energy Council (WEC), comprising governments and global industry, support demand stimulation by advancing the business case of hydrogen through international conferences, exhibitions and trainings in various regions SEC, 2023. Fully business-led organizations like the World Council for Renewable Energy (WCRE) also focus on lobbying around the economic benefits of renewables-based hydrogen to promote global investment and international offtake [85]. Complementing such efforts, the International Energy Forum's (IEF) Hydrogen Market Pathways (HMP) research initiative assesses the requirements for price formation and market structure of the global hydrogen economy [86]. In addition to such R&D and capacity-building, initiatives like the Global Alliance Powerfuels (GAP) and Mission Innovation (MI) are implementing different hydrogen pilot projects around the world that explicitly cover the entire value chain [87,88]. The growing participation of and synergy between these diverse public and private actors suggest an increasingly dynamic, polycentric and multi-stakeholder approach to hydrogen, resembling the 'softer' forms

of governance across the broader renewable energy space [58].

Moreover, it is worth noting that Clean Energy Ministerial's (CEM) scope of objectives appear rather unique in terms of comprehensiveness regarding market formation at a global scale; under its Hydrogen Initiative, CEM promotes four projects targeting specific market-related challenges; a 'Global Ports Coalition' focused on collaboration in the integration of hydrogen into coastal industries; a Roundtable to advance collaboration in developing a regional hydrogen market in North-West Europe; the recently created 'International Hydrogen Trade Forum' that seeks to foster dialogue on creating an international hydrogen market; and the 'H2 Twin Cities' initiative that takes a subnational approach to exchange best practices and information on local hydrogen use [89].

Another initiative that stands out is UNIDO's Global Program of Hydrogen in Industry (GPHI), which is among the few intergovernmental initiatives specifically promoting market development in emerging and transition economies. Its 'Green Hydrogen Cluster' model builds on two pillars, one focused on fostering global cooperation, and one bringing together national governments and industry to provide technical assistance in designing and implementing local hydrogen projects [90]. UNIDO also collaborates closely with other IGOs and coordinates initiatives like CEM's International Hydrogen Trade Forum. Apart from this, institutionalized collaboration linking different governance agendas appears limited. Aiming to address this gap, the United Nation Economic Commission for Europe's (UNECE) Hydrogen Taskforce has set out to create linkages between various existing initiatives to reduce overlap and duplication, though dominantly focusing on the pan-European context. It also seeks to promote more inclusivity and incentivize engagement of countries currently underrepresented in multilateral hydrogen governance [91].

Intergovernmental efforts with the explicit attempt to foster equity-centered energy transitions in fossil-based developing and emerging economies of the 'Global South' are the H4D Program of World Bank or the OECD Clean Energy Finance and Investment Mobilization (CEFIM) initiative; they promote technical assistance and financial investments from both public and private sources, targeting emerging economies and future hydrogen exporters such as Chile, India, Namibia, as well as Mauritania, Tunisia, and Uzbekistan [92]. The Just Energy Transition Partnerships (JETP) framework launched by the UK, US, Japan, Germany, France, Italy, Canada, Denmark and Norway at COP26 also seeks to facilitate the fossil phase-out in coal-based developing economies, including prioritized finance for green hydrogen projects [93].

Established institutions' activities in developing global sustainability criteria and certification schemes for hydrogen are still ongoing, and dominantly focus on the greenhouse gas (GHG) emissions-intensity of hydrogen technologies. Both the European Committee for Standardization (CEN)/Electrotechnical Standardization (CENELEC) as well as the International Organization for Standardization (ISO) deal with the development of a technical standard for hydrogen technologies in production, transport, storage and use [94]. At the COP28, ISO presented a new methodology for determining GHG emissions of hydrogen production and transport, which aims to provide a framework for harmonizing hydrogen standards [95]. Moreover, the non-profit initiative Climate Bonds, the first global certification program for climate bonds aiming to stimulate market formation through sustainable investment criteria, focusses only on hydrogen production processes [96]. Finally, while the private sector-led multistakeholder initiative of International Sustainability and Carbon Certification (ISCC) aims to incorporate broader social and ecological criteria, their current hydrogen certification efforts primarily target European markets [97].

In sum, these findings show that many established global governance frameworks have added hydrogen to their broader energy and climate agendas, which indicates that hydrogen is seen as an integral part of the wider transition to a sustainable energy system. Primary activities of these institutions are knowledge development and diffusion and enhancing hydrogen's political and economic visibility. This points the foundational role of incumbent international governance frameworks and actors focused on laying the groundwork for more substantial policy and regulation. In addition, most of these institutions are dealing with various production technologies, reflecting the flexible exploration of different pathways that seek to accommodate both short-term practicalities (e.g. blue hydrogen) and long-term sustainability goals (green hydrogen).

6.2. *Multilateral institutions and organizations exclusively dealing with hydrogen*

In addition to institutions that have added hydrogen to their agendas, we identified 21 multilateral bodies *exclusively* dealing with hydrogen-related issues (Fig. 3). Except for the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Nordic Hydrogen Partnership (NHP) and Hydrogen Europe, these hydrogen-specific institutions were all created in the past five to six years, underpinning that the advance of hydrogen into global energy transition and decarbonization governance structures constitutes a relatively recent phenomenon. Moreover, most institutions exclusively dealing with hydrogen are located at the regional level, pointing to broader coordination challenges the governance of hydrogen poses at the global institutional level.

Against this backdrop, several of the newer and hydrogen-specific organizations set more targeted objectives aimed at increasing investment demand and market development alongside fostering public-private cooperation. Efforts to stimulate hydrogen demand through mitigating investment risk have only recently begun to accelerate (over the course of 2022 and early 2023) and are dominantly driven by actors from industry and business in Europe. The global industry-led Hydrogen Council seeks to advance the visibility and business case of hydrogen through public-private engagement with governments and civil society, and to accelerate significant investments for the commercialization of hydrogen and fuel cell sectors [98]. Similarly, representing the thus far largest private sector-commitment to deploy 45 GW of renewables-powered electrolyser capacity by 2026, the Green Hydrogen Catapult (GHC) targets the massive scale-up of clean hydrogen production as well as its cost-reduction to below 2 UDS/kg through business case- and investment promotion [99]. Moreover, Hydrogen Europe targets enhancing investment security through establishing certification, building infrastructure, and leveraging state aid, while the public-private European Green Hydrogen Acceleration Center (EGHAC) seeks to de-risk hydrogen projects through sector-coupling between steel, fertilizer, and hydrogen value chains [100,101].

Notably, the recently created European Hydrogen Bank (EHB) represents the first government-driven multilateral effort towards comprehensive risk-sharing, supporting the uptake of renewable hydrogen within the EU and international imports through two new financing mechanisms that subsidize hydrogen production [102]. As such, the EHB is the first significant multilateral auction scheme leveraging the large-scale fiscal capacity needed to stimulate the formation of a global hydrogen market; thus far, similar de-risking efforts have only been institutionalized at the national level by some of the currently most proactive countries, such as the German H2Global scheme, the UK's Electrolytic Allocation Round or the US's Regional Clean Hydrogen Hubs Program [103].

Several hydrogen-specific institutions and initiatives in Europe also engage more substantively with the infrastructure and trade requirements for the regional hydrogen market ramp-up. The NHP focuses on expanding necessary infrastructure for hydrogen end-use applications in the Nordic transport industry, while the updated EU's TEN-E framework prioritizes the development of three regional hydrogen corridors by linking transport infrastructure between West, East and the Baltics [104]. Complementing such efforts, the industry-led European Hydrogen Highway/Backbone (EHH) is a proposed infrastructure pathway for the development of a pan-European hydrogen market until 2040, based on different regional supply and demand scenarios [105].

Though most regional institutions and initiatives are driven by public and private stakeholders from Europe, other regions are creating similar governance structures aimed at dealing with regional market and trade development. Regional trade and industry associations like the MENA Hydrogen Alliance and the African Hydrogen Partnership (AHP) focus on developing trade routes and infrastructure for regional hydrogen transport and on exploring export options and international offtake [106,107]. However, like the infrastructure and market development efforts of European initiatives like the EHH or NHP, MENA Hydrogen Alliance and the AHP prioritize their respective domestic and regional markets for the deployment of hydrogen. Notably, the Global Hydrogen Industrial Association Alliance (GHIAA) is the only hydrogen-specific institution at the global level that explicitly aims to foster broader inter-regional cooperation and exchange on hydrogen, comprising corporate representatives from the Asia-Pacific, Europe, North America and Latin America [108]. Apart from this, the number of global multilateral institutions representing future exporting regions and their interests, particularly from the African continent, is comparably limited, pointing to the dominant role of countries and regions with high demand for hydrogen imports, such as the EU, in current global hydrogen governance.

Finally, hydrogen-specific initiatives also appear to be leading efforts on sustainability standardization and certification of hydrogen. The IPHE published a methodology already in 2021 to determine the GHG emissions of different hydrogen production technologies, which – alongside the relatively new ISO methodology - serves as the primary basis in ongoing certification efforts [109]. One multilateral institution utilizing the IPHE methodology is the Green Hydrogen Organization (GHO), which recently introduced an industry-agreed standard for green hydrogen and its derivatives ('GH2 Standard'), the first global hydrogen standard of its kind [110]. It includes broader sustainability metrics such as protecting local livelihoods, ensuring sustainable and equitable land use, and providing local infrastructure access [111]. While the GHO focuses on green hydrogen only, other multilateral efforts to establish global certification such as the APEC Low-Carbon Hydrogen International Standard might extend to include hydrogen from non-renewable sources as well. Lastly, whereas the certification activities of the GHO specifically target the global hydrogen market, other voluntary market-schemes such as those of CertifHy only cover the EU-market for bio-based and renewable fuels [112].

In sum, a maturing network of hydrogen-specific institutions and new actors is driving the generation, diffusion and application of (green) hydrogen technology. Taking a more targeted approach to address key challenges in the sector, these new institutions and actors often focus on innovation 'niches' and particular issue areas. This trend also emphasizes the central role of cross-border public-private partnerships and hybrid institutional formats in scaling-up hydrogen technologies. Moreover, the fact that many of these institutions operate at the regional level highlights the localized nature of hydrogen infrastructure and market development but also potential fragmentation in international governance efforts. The subsequent section discusses the implications of our findings in more detail.

6.3. Scope and direction of global hydrogen governance

Our mapping of global institutions governing hydrogen reveals similar patterns and issues as those identified in broader global renewable energy governance. The emergence of a plethora of frameworks, initiatives and actors who focus on specific 'niches' in the (green) hydrogen scale-up points to the need for new structures in international governance to advance new technologies. The adoption of hydrogen is driven by a growing array of new institutions and actors who exclusively deal with (green) hydrogen, and who complement the agenda-setting efforts of incumbent international institutions, resembling dynamics in renewable energy governance [13]. While IRENA is an exception to this by addressing different challenges associated with specifically green hydrogen more comprehensively, previous research has found its overall impact within renewable energy governance to be unclear [35]. In this respect, newer institutions and actors exclusively dealing with hydrogen potentially benefit from their greater agency in successfully developing specific technology 'niches'. Fostering stronger interlinkages between incumbent and new institutional structures can thus accelerate hydrogen adoption.

Moreover, countries' representation in the principal global institutions is skewed towards highly industrialized economies associated with the 'Global North', most notably Europe. Large energy consumers and emerging economies like India or Brazil participate in a much smaller number of organizations and initiatives, and important future supply markets such as Namibia, Morocco and other African states are least represented. This suggests that hydrogen governance might risk being 'Western-centric', which is notable given that global governance along the energy-climate nexus has been deemed more diverse and inclusive compared to past (fossil-driven) energy multilateralism [13]. In addition, traditional fossil-exporters such as Qatar and UAE are primarily active in regional forums, suggesting a potential gap regarding the more comprehensive integration of fossil-based economies into the global institutional architecture around energy and climate.

Similarly, it is striking that Japan's engagement primarily concentrates on the Asia-Pacific region and less the global level, given the country's leading role in hydrogen technology development [113]. In addition, while China and the US participate in the majority of long-established bodies, our mapping shows that Europe has taken its place at the forefront of most of the newer and hydrogen-specific initiatives, making current global hydrogen governance potentially not only a Western but an arguably European one. As previously posited by Müller et al. [114], this geographical concentration of governance frameworks correlates with European countries' current focus on hydrogen production and supply (i.e., imports to Germany). Efforts like those of UNECE to increase countries' representation might thus prove particularly crucial both for the legitimacy and efficacy of global hydrogen governance in the long run.

The dominance of certain 'frontrunner' countries and regions in the nascent hydrogen economy must also be understood within the broader context of geopolitical and -economic tensions [2]. Industrial competition over clean technology patents and supply chains for critical materials combined with the regionalization of energy relations due to more localized infrastructure and grid development are expected to reconfigure global trade patterns [10]. As such, hydrogen trade introduces a new dimension to geo-economic rivalry among the major global powers, as the competition for technological leadership and the strategic (re) location energy-intensive industries intensifies [2]. At the same time, the pronounced role of highly industrialized countries in current hydrogen governance might be testament to the structural persistence of past geopolitical fault lines in the low-carbon transition [115].

The findings further show that current hydrogen governance varies in the extent to which it addresses the key challenges the global hydrogen economy is facing. First, regarding end-use sector development, a comparably small fraction of current global hydrogen governance comprehensively addresses the investment risks associated with hydrogen applications and their required infrastructure to stimulate demand and support global market formation. Moreover, the multilateral institutions targeting this issue area are dominantly private sector-driven and located at the regional level, with the majority of them in Europe. At a global scale, however, the question of adequate risk-sharing to incentivize internationally integrated end-sector development is yet to be determined in global hydrogen governance. Here, government-led fiscal frameworks like the EHB could serve as a blueprint for the public financing of technological innovation to take on associated investment risks and spur demand for hydrogen [116].

Second, the role of international infrastructure and trade is particularly crucial as global market formation is dependent on developing hydrogen transport routes that connect different regions. Most

initiatives targeting infrastructure and trade development currently focus on regional markets, where re-configuring existing as well as building new infrastructure – first and foremost in the form of pipelines - proves most viable. This trend towards regionalization might contribute to an initially highly fragmented hydrogen market, similar to that of LNG in its early stages [2]. Reducing such fragmentation in the long run will require more pronounced global multilateral efforts to build infrastructure for hydrogen transport over longer distances via ships. Moreover, apart from the recently created International Hydrogen Trade Forum of CEM, comprehensive attempts to spur broader multilateral dialogue and collaboration on international trade remain largely absent. Incentivizing stronger multilateral exchange on international trade policy in the context of broader geopolitical and -economic dynamics might prove particularly critical given that neither of the two technologically most advanced economies and arguably fiercest industrial competitors – the US and China – are currently involved in CEM's Forum.

Finally, public and private certification bodies currently developing regional and global hydrogen standards (e.g. the ISO and GHO) both help diffuse knowledge and further legitimize clean hydrogen as a sustainable innovation system [117]. Yet our findings underscore previous observations that most certification efforts focus on Europe, are private sector-driven and remain vague in terms of defining sustainability metrics beyond production technologies' emissions-intensity. There also exists duplication across institutions and their respective focus areas, evident in the multiplicity of institutions currently engaging in (partially contradictory) efforts around hydrogen certification and its various production technologies. As the growing number of disparate standards creates difficulties in ensuring globally consistent criteria, the regional level will likely become an important locus for more comprehensive sustainability governance of hydrogen [78,118].

7. Conclusion, limitations and future research trajectories

In sum, our findings contribute to the broader research agenda on global governance of new technologies in the energy transformation in two main ways. First, they provide a novel overview of governance structures currently dealing with hydrogen, highlighting that the generation, diffusion and application of hydrogen is driven by network of new and incumbent institutions and actors. Second, by developing a framework for analysis that links insights from global governance and innovation system approaches, we explored the extent to which this institutional architecture currently deals with three key issue areas in the hydrogen sector: end-use sector development, infrastructure and trade, and environmental and socio-economic sustainability.

Our findings reveal many parallels to the developments previously observed in the proliferation of global governance around energy transition and energy more broadly. The institutional landscape exhibits similar patterns of fragmentation, along geographic, technological and political fault lines. This may be effective when the nature of challenges corresponds to the same delineation as those exhibited by institutional structures. For instance, regional governance institutions may well be the most suitable for addressing emerging regionalized trade in hydrogen. However, it may also represent a reflection of competing interests and approaches, including those of existing multilateral organizations, within an emerging hydrogen economy, which may in turn yield a fragmented and less integrated global hydrogen market. It raises the questions whether and how rivalry between the major powers is shaping hydrogen governance and, by extension, hydrogen markets. Related to this, it points to the question whether the fragmented governance landscape reveals divisions along geopolitical fault lines or whether other factors explain the clustering of activities and stakeholders.

Disentangling how these different factors are shaping the international landscape of hydrogen governance is a central topic for further research on sustainability transitions [119]. Additional analysis should explore how different types of actors and their interests are shaping the evolution of global and regional institutional structures and assess implications for the further development of the market [120]. Moreover, given the powerful role of stakeholders from industry and business, the global governance scholarship should also explore potential risks of this significant private sector influence on hydrogen governance. The involvement of the fossil fuel industry could steer hydrogen governance in ways that prioritize incumbent energy system over more sustainable alternatives, potentially hindering an effective transition to a low-carbon economy [121].

A key question in this context revolves around how institutional arrangements designed to catalyze investments in hydrogen technologies allocate risks and rewards between public and private stakeholders [116]. Addressing this issue is essential for crafting policy that can shape an institutional architecture capable of overcoming the multiple uncertainties hampering investment in a hydrogen economy – whether political, regulatory, economic, social and technological. An important consideration is which actors are best positioned to absorb different types of risks. This pertains not only to the distribution of risks between public and private actors but also between future export- and import countries. This raises questions about 'rent management', moral hazard and policy effectiveness and points more fundamentally to concerns of global equity [79,122,123]. A burgeoning scholarship on 'just transitions' provides an important forum for this debate, including discussions on how equity and justice considerations can be integrated into the governance of hydrogen [114,124]. Among other things, our research revealed relatively low levels of civil society actors in global hydrogen governance. Future research could delve further into this and related challenges of representation in global governance.

Finally, a key limitation of this research is its focus on multilateral institutions; to gain a fuller understanding of global hydrogen governance, research will need to examine the many bilateral governance bodies dealing with hydrogen. This includes more in-depth engagement with potential drawbacks of multilateral cooperation on hydrogen and the specific outcomes it should achieve. Future research should also assess when bilateral approaches are more effective, considering factors such as economic and energy security, geopolitical dynamics and sustainable development to provide insights into how actors can best manage the global hydrogen economy.

CRediT authorship contribution statement

Hannah Lentschig: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aliaksei Patonia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Data curation. **Rainer Quitzow:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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