



The effects of hydrogen research and innovation on international hydrogen trade

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ABSTRACT

Climate change and the pressure to decarbonize, as well as energy security concerns, have drawn the attention of policymakers and the industry to hydrogen energy. To advance the hydrogen economy at a global scale, research and innovation progress is of significant importance, among others. However, previous studies have provided only limited quantitative evidence of the effects of research and innovation on the formation of a global hydrogen market. Instead, they postulate rather than empirically support this relationship. Therefore, this study analyzes the effects of research and innovation measured by scientific publications, patents, and standards on bilateral hydrogen trade flows for 32 countries between 1995 and 2019 in a gravity model of trade, using regression analyses and Poisson Pseudo Maximum Likelihood (PPML) estimation. The main results of the PPML estimation show that research and innovation progress is indeed associated with increased trade, especially with patenting and (international) standardization enhancing hydrogen export volumes. As policy implications, we derive that increased public R&D funding can help increase the competitiveness of hydrogen energy and boost market growth, along with infrastructure support and harmonized standards and regulations.

1. Introduction

Given its versatility and applicability across sectors, hydrogen energy has gained significant importance for decarbonizing the energy system and enhancing energy security in recent years. This has particularly brought hydrogen into the political spotlight following the natural gas supply shock caused by Russia's invasion of Ukraine in 2022. The dependence of Western countries, in particular, on fossil fuels has led them to explore new energy alternatives, including hydrogen energy, to stabilize the energy supply while mitigating dependencies (Asna Ashari et al., 2024; Mbah and Wasum, 2022). Hydrogen can be produced from various feedstocks, including renewable energy, natural gas,¹ or nuclear energy. This versatility enables greater diversification of imported feedstocks and trading partners, thus reducing dependence on energy imports from individual countries (Asna Ashari et al., 2024; Yukesh Kannah et al., 2021).

Due to the benefits associated with the transition to a hydrogen-based economy, a growing number of countries have adopted national

hydrogen strategies and policies. These outline national approaches to the hydrogen economy, including target sectors, sustainability goals, research and innovation areas, funding schemes, and projections for future market penetration (Albrecht et al., 2020; IEA, 2021, 2022). Hydrogen technologies have long been subject to substantial R&D funding and activities before the adoption of national hydrogen strategies. Examples include the *National R&D Program* in South Korea (Yoo and Park, 2023) or the *National Innovation Program Hydrogen and Fuel Cell Technology* in Germany (Projektträger Jülich, 2023). R&D progress and the growing importance of hydrogen technologies are further reflected in hydrogen-relevant publishing, patenting, and standardization activities (Asna Ashari et al., 2023a).

Previous studies have highlighted the significance of research and innovation progress in hydrogen technologies for advancing the hydrogen economy. R&D advances, including standardization, can improve the availability of green hydrogen and the adoption of hydrogen technologies (Bach et al., 2020; Cammeraat et al., 2022; Cervantes et al., 2023; Dincer and Acar, 2017). However, despite their

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¹ Including hydrogen produced from natural gas with carbon capture, utilization, and storage (CCUS).

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postulated importance, these studies provide only limited quantitative evidence of the actual effects of research and innovation on market formation. Instead, various studies in the area of renewable energy (RE) (Costantini and Crespi, 2008, 2013; Groba, 2014; Kim and Kim, 2015) and studies with a more generic technology scope (Blind and Jungmittag, 2005; Blind et al., 2018a; Haruna et al., 2010; Wakelin, 1997, 1998) have investigated the relationship between R&D, innovation, and bilateral trade. Therefore, this study contributes to previous research by expanding the analysis of the trade effects of research and innovation to the hydrogen area. To the best of our knowledge, this study presents the first attempt to investigate this relationship for bilateral hydrogen trade. Specifically, the quantitative approach deployed in this study enhances our understanding of whether hydrogen research and innovation exert export-enhancing ‘push’ effects and import-enhancing ‘pull’ effects on hydrogen trade. Furthermore, we differentiate whether research and innovation are positively associated with absorptive capacity or export competitiveness generated from hydrogen trade.

To this end, we analyze the effects of publications, patents, and standards (PPS) as established research and innovation indicators (Blind et al., 2022a; Dziallas and Blind, 2019; Watts and Porter, 1997) on bilateral hydrogen trade as an indicator of global market dynamics (Coe and Helpman, 1995; Grossman and Helpman, 1991). Although the bilateral trade of hydrogen presents only one part of the hydrogen value chain, the safe production, storage, transport, and utilization require a high level of research and innovation progress (Faye et al., 2022; Sgarbossa et al., 2023). Therefore, the explorative design of this study aims to analyze whether higher levels of research and innovation, and thus expertise, in hydrogen technologies exhibit a greater capacity to trade hydrogen internationally. To do so, this study relies on a gravity model of trade covering 32 countries responsible for around 90 % of worldwide hydrogen exports and imports between 1995 and 2019. Thereupon, we formulate policy implications to assist future science, technology, and innovation (STI) policies in promoting the hydrogen market ramp-up, i.e., the research and innovation outcomes that most effectively predict the emergence of an international hydrogen market.

To specify these research objectives, we rely on the following research questions.

RQ1. Do publications, patents, and standards (PPS) as quantitative research and innovation indicators effectively correlate with international hydrogen trade?

RQ2. How do PPS differ in terms of their export-enhancing ‘push’ effects (competitiveness) and import-enhancing ‘pull’ effects (absorptive capacity) on hydrogen trade?

The remainder of this paper is structured as follows: Section 2 covers the conceptual background, including an in-depth review of the relevant literature and theoretical foundations. Section 3 presents the gravity model of trade as our methodological approach and the underlying data. Section 4 is a joint results and discussion section, which discusses our results against the backdrop of our conceptual background and the broader research context. The final Section briefly summarizes the results and formulates policy implications, limitations, and prospects for future research.

2. Conceptual background

2.1. Literature review and research gaps

Interdisciplinary approaches, including those from the social sciences, are finding increasing consideration alongside purely technical approaches in hydrogen research. As a result, we observe a growing number of studies on hydrogen markets and trade in global value chains.

Van der Zwaan et al. (2021) analyzed the economic benefits associated with green hydrogen trade, deploying the cost optimization energy system model TIAM-ECN to project the potential of five North

African countries to export green hydrogen to Europe. The findings reveal that the analyzed North African countries have a comparative advantage in green hydrogen production compared to Europe, which could benefit a potential future hydrogen partnership and foster economic growth for hydrogen-exporting African countries. Simultaneously, such a partnership bears the risk of new geopolitical dependencies for Europe due to the asymmetric distribution of comparative advantage. Similarly, Van de Graaf et al. (2020) qualitatively analyzed the geopolitics and international governance of hydrogen. The authors find that, due to the globally uneven distribution of cost-effective hydrogen production, new geopolitical dependencies may arise from future global hydrogen trade patterns.

Using a mixed-methods design, Eicke and De Blasio (2022) analyzed various countries worldwide regarding their potential to establish a green hydrogen value chain in ammonia, methanol, and steel industrial applications. These countries are classified into five clusters: front-runners, upgraders, green hydrogen exporters, green hydrogen importers, and bystanders. To do so, the authors rely on three assessment criteria: resource endowment, size of industrial production, i.e., existing hydrogen markets, and economic relatedness, which describes already existing economic activities that could be related to green hydrogen production, such as ammonia and methanol production. The results reveal an uneven worldwide distribution of hydrogen production and usage capabilities, leading to new markets and value chains but also potential dependencies.

Müller and Eichhammer (2023) investigated nine MENA region countries in terms of their industrial preconditions for green hydrogen production, excluding renewable energy capacity. To do so, the authors analyzed the economic complexity of 36 products required for green hydrogen production according to the *Harmonized System* (HS) of traded commodities for 1995–2019. The results indicate that fossil fuel-exporting MENA countries with higher natural resource rents, in particular, scored lower in the economic complexity of green hydrogen products due to a lack of export product diversification. In their techno-economic analysis, Okunlola et al. (2022) calculated the delivery costs for exporting gaseous hydrogen from Western Canada to different destinations in North America, the Asia-Pacific region, and Europe toward a future hydrogen value chain. The calculation considers energy demand, material components, and the costs associated with each stage of the export value chain as components. The results show that exports to other North American destinations involve the lowest delivery costs, followed by the Asia-Pacific region and Europe. Thus, the results support the gravity model assumption, stating that longer geographical distance is, on average, associated with less trade (De Benedictis and Taglioni, 2011; Tinbergen, 1962), given the higher costs for longer-distance hydrogen delivery (Okunlola et al., 2022).

In their review article, Hjej et al. (2022) assessed ten natural gas-exporting countries regarding their potential to transition to a hydrogen economy in terms of hydrogen production, storage, transport, and applications. Using assessment criteria such as resource availability, political status, economic potential, knowledge, and adaptability, the authors ranked the competitiveness of these countries to become hydrogen exporters. Upon analyzing the countries regarding these criteria, the results show that the USA and Canada are the most competitive countries across the hydrogen value chain. Another set of studies links research and innovation progress in hydrogen technologies to market formation and trade.

The scenario analysis by Antweiler and Schlund (2023) studies various determinants of international hydrogen trade for 48 countries, including hydrogen demand and supply, policies, transportation costs, subsidies, and innovation speed. The authors identify innovation, along with transportation costs, as the primary driver of future international hydrogen trade patterns. However, they do not refine innovation by the phases of research and innovation, e.g., with scientific publications as outcomes in early phases followed by patents and standards in the more advanced phases (Blind and Fenton, 2022; Blind and Gauch, 2009).

The comprehensive OECD policy analyses by Cammeraat et al. (2022) and Cervantes et al. (2023) highlight the essential role of innovation and standards for hydrogen market formation, among other factors. Both studies demonstrate the need for innovation in hydrogen production technologies to reduce costs and enhance the competitiveness of green hydrogen, driven by coherent policy mixes. Furthermore, the authors emphasize the importance of international hydrogen standards to facilitate the harmonization of requirements toward establishing a global hydrogen value chain.

Velazquez Abad and Dodds (2020) conducted a review of hydrogen characterization initiatives, including green hydrogen definitions, guarantees of origin, and regulations. The authors elaborate that regulations, standards, and certification schemes are necessary requirements for the emergence of an international hydrogen market, as the harmonization of requirements facilitates trade among countries. Dincer and Acar (2017) critically evaluated various innovative methods in hydrogen production using the 18 S concept, with S representing the first letter of each driver of innovation and market formation. The authors underline, among others, the vital role of standards in facilitating trade and market formation through “compatibility, safety, quality, consistency, reliability, and commercial viability” across countries.

Moreover, studies in the area of *Technological Innovation Systems* (TIS) link research and innovation progress to market formation. Bach et al. (2020) qualitatively analyzed the TIS for hydrogen solutions vs. battery-electric solutions in maritime transport in Norway based on 72 semi-structured expert interviews. The results suggest that R&D advances in hydrogen technologies and their market formation are closely linked through the interrelatedness of TIS functions. Likewise, Hacking et al. (2019) illustrated in their event history analysis of the UK hydrogen TIS for the 1954–2012 period, complemented by semi-structured expert interviews, that the TIS function ‘market formation’ is interconnected to other TIS functions in the UK TIS, including R&D advances. Asna Ashari et al. (2024) analyzed the hydrogen TISs of Germany and South Korea based on the qualitative analysis of 24 semi-structured expert interviews. The authors identified, among others, the barriers to the market formation of hydrogen technologies. These barriers include the high unit manufacturing costs, regulatory gaps, a lack of infrastructure, and matters of safety and social acceptance. With that, translating research and innovation advances into market formation poses a complex challenge.

The quantitative time-series analysis by Asna Ashari et al. (2023b) provides an R&D-focused analysis of the TIS for fuel-cell vehicles (FCVs) in relation to electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) as context structures. In doing so, the authors investigated the mutual causal effects between FCVs and EVs and FCVs and ICEVs based on publications and patents for the 1980–2019 period and standards for the 2000–2019 period. Thereupon, the authors derive implications for the commercialization of FCVs arising from the R&D linkages to EVs and ICEVs.

While previous research links research and innovation to hydrogen market and value chain formation, no study, to the best of our knowledge, investigates their quantitative effects on trade in the commodity hydrogen. Therefore, we refer to previous studies linking R&D to natural resource trade and reductions in CO₂ emissions. In their econometric gravity model analysis of global oil trade patterns in 2011 for a sample of 18 oil-exporting countries, Zhang et al. (2015) deployed R&D as one of the explanatory variables in the group of technological factors, along with other variables grouped into economic, supply and demand, political, alternative energy, and interactive factors. The results provide evidence that R&D investments and innovation on the part of oil-importing countries are associated with reduced demand for oil imports. In the area of sustainability transitions, Petrović and Lobanov (2020) investigated the effects of R&D expenditure on CO₂ emissions in 16 OECD countries in 1981–2014, relying on regression analysis. The effects of R&D on CO₂ emissions are mixed, including positive, negative, or insignificant effects. However, the authors do not differentiate the

type of R&D investment, such as R&D allocated to green innovation.

In contrast, studies in other geographical contexts find positive effects of R&D on reductions in CO₂ emissions, including for 15 EU countries, China, and the USA (Fernández et al., 2018), France (Shahbaz et al., 2018), and China (Zhang et al., 2017). As a research gap from this literature review, we identify the lack of analyses of the actual correlations between research and innovation progress in hydrogen technologies and market formation. Although previous research hypothesizes this relationship, we find no supportive quantitative evidence for the hydrogen area. Therefore, this study synthesizes three previous research areas: 1.) Analyses of the global hydrogen market and value chains; 2.) Studies linking R&D, innovation, and clean energy (technology) trade (see Section 2.2); 3.) the trade effects of R&D on raw material trade.

2.2. Trade effects of research and innovation

To measure research and innovation progress in hydrogen technologies, we rely on publications, patents, and standards (PPS) as established R&D indicators. PPS represent knowledge and technology transfer channels that disseminate knowledge about technology. At the same time, they act as inputs and outputs of research and technology development (Asna Ashari et al., 2023a; Blind and Fenton, 2022; Blind and Gauch, 2009; Blind et al., 2018b; Dziallas and Blind, 2019; OECD & Eurostat, 2018). Following previous research, this study refers to publications as an indicator of research and patents and standards as indicators of innovation (Asna Ashari et al., 2023a; Blind and Gauch, 2009; Dziallas and Blind, 2019; OECD & Eurostat, 2018). To measure the effects of PPS on hydrogen market formation, we refer specifically to the bilateral trade volumes of hydrogen as a commodity under the *Harmonized System* code HS 280410 (United Nations, 2023).

To better classify the direction of influence of PPS, we refer to their ‘push’ and ‘pull’ effects on trade. In our approach, a push effect on trade signifies that higher levels of domestic research and innovation in hydrogen technologies drive hydrogen exports (Clougherty and Grajek, 2008) because the handling of hydrogen requires minimum technological know-how. In contrast, the pull effect refers to domestic research and innovation attracting hydrogen imports based on the absorptive capacity to effectively use the imported hydrogen (Clougherty and Grajek, 2008; Duchek, 2013).

Previous studies using PPS as indicators provide evidence of the push and pull effects of research and innovation on trade. Research activities (Costantini and Crespi, 2008), patenting (Blind, 2004; Blind and Jungmittag, 2005; Haruna et al., 2010), standards (Blind et al., 2018a; Swann, 2010; Swann et al., 1996), and standard-essential patents (SEPs), which combine elements of patents and standards (von Laer et al., 2022), have been found to exert trade-enhancing effects. However, to the best of our knowledge, no previous study has quantitatively investigated the push and pull effects of research and innovation on hydrogen trade. Therefore, this remaining sub-section draws upon additional conceptual and empirical studies on the trade effects of research and innovation, forming the basis for analyzing the hydrogen area. The focus is particularly on renewable energy (RE) as a comparable emerging technology field. Additionally, Table 1 gives an overview of the most relevant studies in the RE area linking R&D, innovation, and trade as a reference for the hydrogen area.

In their gravity model analysis of 20 countries exporting RE technologies in the 1996–2005 period, Costantini and Crespi (2008) investigated, among others, the effect of innovation (using patenting and R&D expenditure as indicators) on RE technology exports. The findings show that technological innovation induced by more stringent environmental regulation following the Porter and van der Linde (1995) Hypothesis significantly enhances the export performance of RE technology-exporting countries.

In a later study, Costantini and Crespi (2013) analyzed, among others, the effects of R&D investments in RE and the broader energy

Table 1
Overview of selected studies linking R&D, innovation, and trade in the area of RE technologies.

Authors & year	Study period	Relevant data (source)	Sample	Methodology	Dependent variables (DVs) and independent variables (IVs)	Major findings regarding R&D, innovation, and trade
Costantini and Crespi (2008)	1996–2005	UN COMTRADE database	20 exporting OECD countries and 148 importing countries	Gravity model regression analysis, including fixed and random effects	DV: Bilateral exports of RE and energy-saving technologies IVs: GDP, geographical distance, various environmental regulation variables, innovation (indicated by patenting and R&D expenditures), and other control variables	Positive and significant association of innovation induced by more stringent environmental regulation on RE technology exports.
Costantini and Crespi (2013)	1996–2006	UN COMTRADE database	20 exporting countries and 148 importing countries	Gravity model regression analysis, including fixed and random effects Instrumental variables	DVs: RE technologies, energy-saving technologies, the sum of RE and energy-saving technologies IVs: GDP, geographical distance, population size, country size, colonial ties, geographical contiguity, various environmental regulation variables, public support for biofuels, R&D expenditure on RE and energy-saving technologies	R&D expenditure is positively and significantly associated with export performance.
Groba (2014)	1999–2008	UN COMTRADE database	21 exporting OECD countries and 129 importing countries	Gravity model Poisson Pseudo Maximum Likelihood (PPML) estimation	DV: Bilateral exports of solar energy technologies IVs: GDP, geographical distance, population size, common language, various environmental regulation variables, R&D budget for solar energy technologies, and other control variables	Positive and significant association of R&D budget for solar energy with solar technology exports.
Kim and Kim (2015)	1991–2008	UN COMTRADE database OECD iLibrary database (for patents)	16 OECD countries exporting solar PV technologies 14 OECD countries exporting wind power technologies	Fixed effects regression analysis	DVs: Solar PV technologies, wind power technologies IVs: proportion of patent applications for RE technologies to total patent applications, domestic and foreign knowledge stock, public R&D budget, population size, and other control variables	Patents, knowledge stock, and public R&D expenditure are positively and significantly associated with exports and imports of solar PV and wind power technologies.

sector on bilateral exports of RE and energy-saving technologies for 20 exporting OECD countries from 1996 to 2006. The results provide evidence of various R&D expenditure variables being positively associated with export performance.

Similarly, Groba (2014) explores the effects of public R&D budgets for solar energy on the exports of solar technology components for 21 exporting OECD countries from 1999 to 2007, using Poisson Pseudo Maximum Likelihood (PPML) estimation as a method. The author finds that a higher R&D budget for solar energy is positively and significantly associated with solar technology exports, thereby enhancing export competitiveness.

Kim and Kim (2015) investigated the relationship between domestic R&D and international trade in solar PV and wind power technologies for a sample of 16 countries from 1991 to 2008, conducting fixed-effects regression analysis. The findings reveal that R&D, including patents, knowledge stock, and public R&D expenditure, is positively and significantly associated with exports and imports of solar PV and wind power technologies. Thus, the authors conclude that R&D enhances both absorptive capacity and global competitiveness in RE technologies. Furthermore, we identified other studies at the intersection of R&D, innovation, and trade in the RE area. However, these deploy dependent variables that are less relevant to this study. For instance, Liu et al. (2022) analyzed the impact of renewable energy and eco-innovation, mediated through international trade, on environmental performance in China between 1981 and 2018 using a quantile-based autoregressive distributed lag model. While the study does not explicitly assess the impact of renewable energy (RE) and eco-innovation on trade in RE technologies, the results reveal that trade openness facilitates the diffusion of RE innovation, thereby contributing to enhanced environmental performance, as proxied by carbon emissions.

Khan et al. (2020) analyzed the effects of renewable energy, carbon emissions, environmental management, and regulatory pressure on

trade openness in a sample of five Northern European countries between 2001 and 2018, using the dynamic common correlated effect method. The results show, among others, that renewable energy is positively associated with trade openness as a measure of countries' financial health. However, trade in the accordant RE technologies is not deployed as the dependent variable.

Finally, an extensive body of research has explored the reverse relationship between innovation and trade, finding positive effects of trade on innovation, R&D, and R&D spillovers. This also applies specifically to the RE area (Herman and Xiang, 2022; Khezri et al., 2021; Lumenga-Neso et al., 2005; Melitz and Redding, 2021; Wen et al., 2022). However, this reverse effect of trade on innovation is out of the scope of this study and thus not considered any further. Instead, the empirical design of this study combines previous, rather technology-generic studies on the trade effects of PPS with those that have explored the relationship between R&D, innovation, and trade for RE. In doing so, this study expands this previous realm of research to the hydrogen area.

2.3. Proprietary vs. non-proprietary disclosure of knowledge

Publications, patents, and standards (PPS) disclose knowledge about technology either in a proprietary or non-proprietary way. Thus, we aim to explore whether these characteristics show different effects on trade. Publications and standards released by standards development organizations usually have the character of a classic public good by disclosing knowledge in a publicly available, non-rivalry manner to potential technology adopters (Blind et al., 2022a, 2022b; Blind and Thumm, 2004; von Laer et al., 2022; Zi and Blind, 2015). For standards and, in some cases, publications, only a small fee may be charged (Blind, 2001; Blind et al., 2022a). However, no party can be excluded from using the disclosed knowledge, thereby eliminating competition in its use.

Scientific publications and standards are also enablers of absorptive

capacity (Blind et al., 2012; Duchek, 2013; Gambardella, 1992). Absorptive capacity describes the “ability of a firm to recognize the value of new external information, assimilate it, and apply it to commercial ends” (Cohen and Levinthal, 1990). Due to their public-good character, potential users hardly face barriers to applying knowledge from publications and standards. This way, knowledge acquisition contributes to more absorptive capacity, enabling the capacity to handle technologies or raw materials effectively (Blind and Mangelsdorf, 2013; Cohen and Levinthal, 1990).

In contrast, a patent is defined as “an exclusive right granted for an invention, which is a product or a process that provides, in general, a new way of doing something, or offers a new technical solution to a problem” (World Intellectual Property Organization, 2022). Despite making knowledge about technology publicly available, patents disclose it in a proprietary, rival way (Blind et al., 2022b). Unlike publications and standards, adopting knowledge and technology protected by patents from other patent holders is not possible at all or requires payment of licensing fees (Blind et al., 2022a; Pohlmann et al., 2016), thereby creating high barriers to knowledge utilization. The temporary monopoly on patented technology gives patent holders a competitive advantage, which can exert an export-enhancing push effect (Blind, 2004; Blind and Jungmittag, 2005; von Laer et al., 2022).

3. Methodology and data

3.1. Methodological approach

This study uses a gravity model of trade to operationalize the relationship between research and innovation and bilateral hydrogen trade. Gravity models of trade postulate that the trade volume between two trading countries is positively influenced by both countries’ size of the economy, as proxied by their GDP, and negatively by their geographical distance (De Benedictis and Taglioni, 2011; Tinbergen, 1962). Several studies on the trade effects of research and innovation have deployed gravity models, including Blind et al. (2018a) for analyzing the trade effects of ISO 9000 certifications, Swann (2010) for the trade effects of international standards, Kunze (2016) for R&D expenditure and patenting impacts on trade, or Dussaux et al. (2022) for the intellectual property (IP) rights effect on trade in low-carbon technologies. Gravity models have also been applied to analyze trade in raw materials, e.g., by Barnes and Bosworth (2015) for trade in natural gas or Babri et al. (2017) for trade in coal, iron ore, and crude oil.

In our empirical strategy, we refer to the gravity model approaches by Blind et al. (2018a), Yotov et al. (2016), Shepherd (2013), and Böhmecke-Schwafert and Blind (2023). Our analysis comprises regression analyses and a Poisson Pseudo Maximum Likelihood (PPML) estimation using STATA 16 (StataCorp, 2019). To analyze our panel data, we estimated various regression models, including a pooled ordinary least squares (OLS) regression model, a regression model with exporter and importer country-pair fixed effects, and a fixed effects regression model² with exporter- and importer-time country pairs to account for unobserved heterogeneity in the form of exporter- and importer-specific, as well as year-specific effects on hydrogen trade. Following Anderson and van Wincoop (2003) and Olivero and Yotov (2012), we address general equilibrium effects in gravity model estimations, controlling for multilateral resistance terms, by including exporter- and importer-time fixed effects. Additionally, we included clustered robust standard errors with country-pair clusters to control for heteroskedasticity and autocorrelation.

The PPML estimation, following Silva and Tenreyro (2006), provides

² The decision to use fixed effects instead of random effects was supported by the highly significant results of the Hausman test ($p = 0.00$), indicating a systematic difference in the coefficients, which calls for the inclusion of fixed effects.

more robust estimates in the presence of heteroskedasticity and zero trade flows between country pairs, while the regression analysis excludes zero trade flows due to log linearization (Böhmecke-Schwafert and Blind, 2023). Especially due to the presence of many zero trade flows in our data, the PPML estimation complements the results of the regression analysis and more reliably estimates the effects of research and innovation on hydrogen trade. With that, we reduce bias arising from zero trade flows and heteroskedasticity and use PPML as an established method in previous gravity model analyses (Böhmecke-Schwafert and Blind, 2023; Groba, 2014; Yotov et al., 2016). Our baseline model is the standard gravity regression model with exporter- and importer-time fixed effects:

$$\begin{aligned} \ln(X_{i,j,t}) \equiv & \pi_{i,t} + \chi_{j,t} + \beta_1 \ln DIST_{i,j} + \beta_2 \ln PUB_{i,t-1} + \beta_3 \ln PUB_{j,t-1} \\ & + \beta_4 \ln PAT_{i,t-1} + \beta_5 \ln PAT_{j,t-1} + \beta_6 INTSTD_{i,t-1} + \beta_7 INTSTD_{j,t-1} \\ & + \beta_8 NATSTD_{i,t-1} + \beta_9 NATSTD_{j,t-1} + \beta_{10} HIA_{i,t-1} + \beta_{11} HIA_{j,t-1} \\ & + \beta_{12} RCA_{i,t-1} + \beta_{13} RCA_{j,t-1} + \beta_{14} \ln GDP_{i,t-1} + \beta_{15} \ln GDP_{j,t-1} \\ & + \varepsilon_{i,j,t}; \end{aligned} \quad (\text{Eq. 1})$$

where our variables denote:

$\ln(X_{i,t})$ = Logarithm of hydrogen exports (HS code 280410) from country i to country j at t ;

$\pi_{i,t}$ = Exporter-time fixed effects

$\chi_{j,t}$ = Importer-time fixed effects

$\ln DIST_{i,j}$ = Logarithm of geographical distance between country j and country i (distance between the capital cities, in km).

$\ln PUB_{i,t-1}$ = Logarithm of hydrogen-related scientific publications per country i at $t - 1$;

$\ln PUB_{j,t-1}$ = Logarithm of hydrogen-related scientific publications per country j at $t - 1$;

$\ln PAT_{i,t-1}$ = Logarithm of hydrogen-related patent applications per country i at $t - 1$;

$\ln PAT_{j,t-1}$ = Logarithm of hydrogen-related patent applications per country j at $t - 1$;

$INTSTD_{i,t-1}$ = International ISO and IEC hydrogen and fuel cell standards adopted by country i at $t - 1$;

$INTSTD_{j,t-1}$ = International ISO and IEC hydrogen and fuel cell standards adopted by country j at $t - 1$;

$NATSTD_{i,t-1}$ = National hydrogen and fuel cell standards in the ICS classified groups published by country i at $t - 1$;

$NATSTD_{j,t-1}$ = National hydrogen and fuel cell standards in the ICS classified groups published by country j at $t - 1$;

$HIA_{i,t-1}$ = Hydrogen-related incidents and accidents in country i at $t - 1$;

$HIA_{j,t-1}$ = Hydrogen-related incidents and accidents in country j at $t - 1$;

$RCA_{i,t-1}$ = Revealed comparative advantage (Balassa Index) in hydrogen exports in country i at $t - 1$;

$RCA_{j,t-1}$ = Revealed comparative advantage (Balassa Index) in hydrogen exports in country j at $t - 1$;

$\ln GDP_{i,t-1}$ = Logarithm of GDP (current US\$) in country i at $t - 1$;

$\ln GDP_{j,t-1}$ = Logarithm of GDP (current US\$) in country j at $t - 1$;

$\varepsilon_{i,j,t}$ = Idiosyncratic error term.

Each independent variable is depicted twice in the model specification, corresponding to the exporting and importing countries, and lagged by one year to reduce endogeneity from a simultaneity bias of trade with the independent variables (Blind et al., 2018c). Endogeneity is further reduced by using country-pair and time-fixed effects (Yotov et al., 2016).

In addition to our set of research and innovation indicators, i.e., scientific publications, patent applications, and national and interna-

tional standards, we deploy additional control variables. Since hydrogen safety is considered one of the main drivers of acceptance and market ramp-up (Markert et al., 2007), we include the number of hydrogen incidents and accidents (European Commission, 2022; Cristina Galassi et al., 2012) as a proxy for hydrogen safety. Furthermore, our model operationalizes the Ricardian Theory of Comparative Advantage, which postulates that countries export goods that are comparatively cheaper to produce and import goods that are comparatively more costly to produce domestically from countries that have a comparative advantage in producing those goods (Dornbusch et al., 1977; Van de Graaf et al., 2020). In line with the Ricardian Theory, the Revealed Comparative Advantage (RCA) or Balassa Index empirically operationalizes a country’s comparative advantage in producing a specific commodity and has proven applicable as an explanatory variable in previous trade research (Bahar et al., 2014; Batra and Khan, 2005; Haruna et al., 2010; Scheifele et al., 2022). Bahar et al. (2014) define the RCA as “the ratio between the share of total exports that the product represents in the country’s export basket and the product’s share of global trade.” Thereupon, we calculated the RCA for hydrogen exports as an explanatory variable:

$$RCA_{i,hydrogen} = \frac{X_{i,hydrogen} / X_{w,hydrogen}}{X_{i,total} / X_{w,total}}; \tag{Eq. 2}$$

where the RCA in hydrogen exports is the ratio of hydrogen exports from country *i* and world hydrogen exports divided by the ratio of total exports from country *i* and total world exports. An $RCA \geq 1$ indicates a comparative advantage in exporting hydrogen.

Lastly, we included the GDP variable in our model to grasp the basic gravity model assumption, which posits that bilateral trade is determined by the size of the trading economies, as represented by their GDP, and their geographical distance (De Benedictis and Taglioni, 2011; Tinbergen, 1962). As we base our analysis on fixed effects regression models, we excluded further time-invariant variables used in more recent gravity models, such as common language, shared borders, or former colonial ties due to multicollinearity issues with the fixed effects. Thus, we included the distance variable only in the OLS and PPML estimations (Blind et al., 2018a). We also did not include population size as a variable since we cannot assume a systematic link to hydrogen research, innovation, and trade based on previous findings (Asna Ashari et al., 2023a).

3.2. Data

Our dataset encompasses 32 countries³ over the period 1995–2019. Through data cleansing, we only selected countries with reasonable hydrogen trade volumes, publications, patents, and adopted international and national standards. We collected data on our dependent variable, bilateral hydrogen trade, from the United Nations International Trade Statistics Database Comtrade (United Nations, 2023) referring to the 6-digit Harmonized System (HS) code ‘HS 280410 – Hydrogen’. Comtrade displays bilateral trade data based on countries’ self-reported exports and imports to other trading partners, starting from 1995. To avoid bias from a potential shock induced by the COVID-19 pandemic in 2020 and incomplete data for more recent years in the database, we truncated the period to 1995–2019. We specifically refer to the reported exports from country *i* to country *j* at time *t*, which form a country pair. Moreover, we collected publication data using Clarivate Analytics’s Web of Science (Clarivate Analytics, 2022) and annual patent application data from assignees in our sample countries using the European Patent Office’s (EPO) Espacenet database (EPO, 2023) (Appendix A).

³ Australia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Denmark, Estonia, Finland, France, Germany, India, Italy, Japan, South Korea Republic, Lithuania, Malaysia, Netherlands, Norway, Poland, Portugal, Russia, Singapore, Slovakia, Spain, Sweden, Switzerland, Thailand, Turkey, UK, USA.

We collected data on international and national hydrogen standards from the PERINORM database, which covers all international ISO (International Organization for Standardization), IEC (International Electrotechnical Commission), and many national standards. We identified relevant ISO and IEC hydrogen standards published as harmonized national standards based on the list of Hydrogen/Fuel Cell Codes & Standards of the Hydrogen Tools Portal (Hydrogen Tools, 2023) and the analysis of international hydrogen standards by Asna Ashari et al. (2023a). For national hydrogen standards, we referred to standards published under three selected hydrogen-related ICS (International Classification of Standards) codes.⁴ To avoid overlaps between international and national standards, we subtracted international standards that have been harmonized as national standards from purely national ones.

Hydrogen incident and accident data were retrieved from the European Commission’s Hydrogen Incident and Accident Database (HIAD) (European Commission, 2022), which covers safety-related events in the European Union (EU) and non-EU countries. For calculating the RCA in hydrogen exports, we used hydrogen trade data from Comtrade and total national and global export data from the World Bank’s World Development Indicators (World Bank, 2023). We also used the World Development Indicators (World Bank, 2023) to collect GDP data. Table 2 gives an

Table 2
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Hydrogen exports (HS280140), in millions of US\$	3309	0.92	5.26	1	82.07
Distance between exporting and importing country, based on capitals (in km)	24,800	5696.84	4524.95	59.62	18069.91
Publications by exporting country	25,600	175.62	401.79	0	5474
Publications by importing country	25,600	175.62	401.79	0	5474
Patent applications by exporting country	25,600	153.23	404.88	0	3014
Patent applications by importing country	25,600	153.23	404.88	0	3014
Intl. Hydrogen standards adopted by exporting country	25,600	.29	1.13	0	16
Intl. Hydrogen standards adopted by importing country	25,600	.29	1.13	0	16
National standards by exporting country	25,600	.72	1.90	0	27
National standards by importing country	25,600	.72	1.90	0	27
Hydrogen incidents and accidents in exporting country	25,600	.396	1.27	0	12
Hydrogen incidents and accidents in importing country	25,600	.396	1.27	0	12
RCA in hydrogen exports by exporting country	25,600	1.07	2.95	0	18.28
RCA in hydrogen exports by importing country	25,600	1.07	2.95	0	18.28
GDP exporting country, in billions of US\$	25,536	14,300	2704	4.50	20,530
GDP importing country, in billions of US\$	25,536	14,300	2704	4.50	20,530

⁴ ICS codes 27.070: Fuel Cells, 27.075: Hydrogen technologies, 71.100.20: Gases for industrial applications including compressed air and hydrogen.

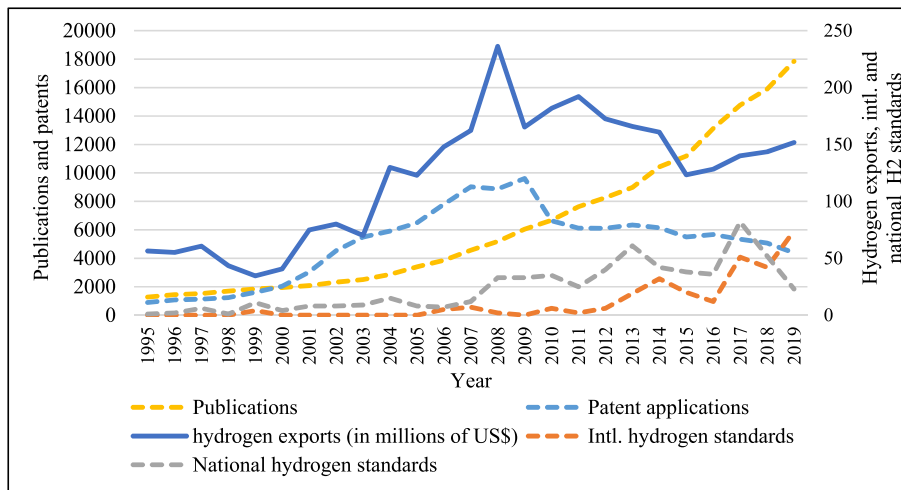


Fig. 1. Hydrogen exports and research and innovations indicators over time (1995–2019).

overview of the descriptive statistics of all model variables. The correlation matrix (Appendix B) shows the correlations among all model variables.

4. Empirical results

4.1. Descriptive results

Fig. 1 gives an overview of the total hydrogen exports and our research and innovation variables between 1995 and 2019. Since our bilateral trade data are based on the self-reports of the exporting countries, the export and import statistics are identical. Therefore, Fig. 1 only includes export data, while Tables 3 and 4 give a more differentiated overview of the countries with the highest exports and imports. The

Netherlands and Canada accounted for about 61% of global hydrogen exports from 1995 to 2019 (Table 3). The high exports from the Netherlands, especially to Belgium and France (Observatory of Economic Complexity, 2023), can be attributed to the 900 km hydrogen pipeline network connecting Rotterdam (the Netherlands), Antwerp (Belgium), and Dunkirk (France) (Van de Graaf et al., 2020). Currently, longer-distance hydrogen transport involves a considerably higher cost per kilogram than transport via pipelines (Okunlola et al., 2022). Therefore, geographical proximity largely explains bilateral hydrogen trade (see also Section 4.2).

Accordingly, the USA and Belgium accounted for about 50 % of global hydrogen imports between 1995 and 2019 (Table 4), mainly from Canada and the Netherlands (Observatory of Economic Complexity, 2023). Although most of the highest-exporting countries also appear in

Table 3
Highest-exporting countries (1995–2019).

Rank	Country	Total exports (in millions of US\$)	Share of world exports (%)
1	Netherlands	1121.67	33.34
2	Canada	942.52	28.02
3	Belgium	454.77	13.52
4	USA	146.18	4.35
5	Germany	142.17	4.23
6	France	109.74	3.26
7	Slovakia	21.90	0.65
8	Czech Republic	20.07	0.60
9	UK	19.09	0.57
10	Spain	15.53	0.46
	Total	3364.20	100.00

Table 4
Highest-importing countries (1995–2019).

Rank	Country	Total imports (in millions of US\$)	Share of world exports (%)
1	USA	949.62	27.92
2	Belgium	754.63	22.19
3	Netherlands	483.44	14.21
4	France	317.34	9.33
5	Germany	152.04	4.47
6	Canada	124.42	3.66
7	UK	35.54	1.04
8	Italy	35.12	1.03
9	Denmark	34.44	1.01
10	Austria	30.82	0.91
	Total	3401.36	100.00

the import ranking, we find no evidence of balanced exports and imports. Instead, we observe differences in countries' world shares of exports and imports.

4.2. Results and discussion of the empirical models

Table 5 gives an overview of the results of our estimations. Models 1–3 represent the regression models, i.e., the OLS, exporter and importer fixed effects, and exporter- and importer-time fixed effects models, with the logarithm of hydrogen exports from country *i* to country *j* as the dependent variable. Model 4 represents the Poisson Pseudo Maximum Likelihood (PPML) estimation with integer values for hydrogen exports. Given the greater statistical power of PPML in the presence of zero bilateral trade flows, we mainly refer to Model 4 in the discussion of our results. However, we also discuss the results of Models 1–3 and the robustness checks (Models C.1–C.7, Appendix C) to validate our findings. The robustness checks include exporter- and importer-time fixed effects models, additionally divided into two sub-periods to account for the financial crisis shock observed in Fig. 1 (Models C.1 and C.2). Furthermore, we analyze the isolated effects of individual PPS variables on trade (Models C.3–C.6) and conduct an estimation without control variables (Model C.7).

Consistent with the basic assumption of gravity models (Blind et al.,

2018a; Böhmecke-Schwafert and Blind, 2023; De Benedictis and Taglioni, 2011), geographical distance between trading partners is associated with significantly less bilateral trade at the 1% significance level in Models 1 and 4, holding all other variables constant.

Our independent variables of interest show varying effects and significances across the models. While *publications* are positively and significantly associated with hydrogen exports at the 10% significance level in Model 3, the PPML estimation indicates a negatively significant effect on imports at the 1% significance level, ceteris paribus. This result suggests that publications predict hydrogen trade only to a limited extent. This result is supported by our robustness checks, providing mixed evidence on the direction of effects of publications on trade, including differences with respect to their push and pull effects on trade. However, except for the significant isolated pull effect of publications in Model C.3, the other models show significant push effects (Models 3, C.1, and C.2), negative push effects (C.7), or insignificant effects. Although publications disclose knowledge in a non-proprietary way, thus posing only little barriers to knowledge utilization (Blind et al., 2022a, 2022b), our results provide no statistical evidence of an import pull and absorptive capacity effect. We conclude that publications can only weakly explain trade in hydrogen. Nevertheless, in line with previous research, we acknowledge the significance of hydrogen-related research in advancing knowledge and technology transfer, thereby

Table 5
Overview of results.

Variables	(1)Pooled OLS 1995–2019	(2)Exporter, importer FE 1995–2019	(3)Exporter-time, importer-time FE, 1995–2019	(4) PPML 1995–2019
Distance	–1.157*** (0.138)			–2.242*** (0.209)
Publications exporting country	–0.0196 (0.214)	–0.229 (0.183)	1.985* (1.029)	0.206 (0.316)
Publications importing country	0.0103 (0.184)	–0.0302 (0.148)	0.177 (0.660)	–0.782*** (0.302)
Patents exporting country	0.132 (0.107)	–0.0743 (0.0819)	–0.113 (0.670)	0.437*** (0.135)
Patents importing country	0.123 (0.0824)	0.0327 (0.0772)	–0.160 (0.307)	0.0845 (0.134)
Intl. standards exporting country	–0.0750* (0.0430)	–0.0749*** (0.0254)	0.0855 (0.0953)	0.0749*** (0.0259)
Intl. standards importing country	–0.0635 (0.0658)	0.0141 (0.0355)	–0.131 (0.128)	–0.156 (0.118)
Nat. standards exporting country	–0.0685* (0.0388)	–0.00812 (0.0320)	–0.230* (0.130)	–0.0683 (0.0695)
Nat. standards importing country	0.0346 (0.0405)	0.0625** (0.0250)	–0.0974 (0.0693)	–0.0862** (0.0405)
Hydrogen incidents & accidents exporting country	0.188*** (0.0549)	0.0393 (0.0278)	–0.180 (0.213)	–0.0540 (0.0720)
Hydrogen incidents & accidents importing country	0.0943 (0.0902)	0.0865** (0.0440)	0.492* (0.250)	0.0257 (0.0498)
RCA exporting country	0.193*** (0.0433)	–0.0297 (0.0294)	0.259*** (0.0930)	0.193*** (0.0202)
RCA importing country	–0.00443 (0.0491)	–0.0866** (0.0347)	0.463*** (0.0340)	0.126*** (0.0384)
GDP exporting country	0.490* (0.260)	1.000** (0.394)	–0.946 (0.768)	0.303 (0.328)
GDP importing country	0.277 (0.236)	–0.000241 (0.285)	0.686 (0.756)	1.777*** (0.383)
Constant	–4.500 (6.871)	–18.19* (9.908)	6.403 (23.50)	–30.74*** (9.803)
Observations	2872	2872	2872	17,560
R-squared	0.304	0.322	0.518	0.630

***p < 0.01, **p < 0.05, *p < 0.1; robust standard errors in parentheses.

facilitating innovation and market growth (Asna Ashari et al., 2023a; Blind and Gauch, 2009). Furthermore, previous studies investigating the reverse relationship have found that trade can create knowledge and technology spillovers (Eaton and Kortum, 2006; March and Schieferdecker, 2023), resulting in more research and publications.

For *patents*, the regression models (1–3) do not provide evidence of significant effects on trade. However, the PPML estimation (Model 4) indicates that hydrogen-related patenting activities are, on average, positively and significantly associated with more exports at the 5% significance level, *ceteris paribus*. Several additional robustness checks (Models C.2, C.4, C.7) confirm the positive and significant effect of patenting on exports, with only Model C.2 indicating a weakly significant, negative import effect. The export-enhancing push effect of patenting suggests that increased innovation activity contributes to improved competitiveness in exporting hydrogen and effectively predicts more significant exports. This finding aligns with previous research on the export-enhancing push effect of patents (Blind, 2004; Blind and Jungmittag, 2005; von Laer et al., 2022; Wakelin, 1998). By disclosing technological knowledge in a proprietary way, patents primarily enhance exporting countries' competitiveness rather than increasing importers' absorptive capacity. While innovation in hydrogen technologies is pivotal for hydrogen production, storage, and delivery, it cannot solely explain hydrogen exports. Factors such as industrial demand and resource endowment, including feedstocks for hydrogen production, are other drivers of hydrogen trade (Eicke and De Blasio, 2022). However, our results indicate that innovation is a complementary factor in explaining hydrogen trade. This finding aligns with the hypothesized link between hydrogen innovation and market formation from previous research (Cammeraat et al., 2022; Cervantes et al., 2023). Particularly, innovation can help further optimize the safety in handling and transporting hydrogen, an essential factor for market formation, with increased technological know-how facilitating safety assurance (Dincer and Acar, 2017). Therefore, patenting indicates whether more innovative countries can successfully translate their leadership in hydrogen technology development into more significant hydrogen exports in the infant global hydrogen market. Yet, we acknowledge that technological spillovers beyond geographical boundaries, such as the export of patented technology for hydrogen production, can also drive hydrogen trade.

The effects of *international hydrogen standards* on trade are mixed: International standards implemented as national standards by the exporting country are negatively and significantly associated with hydrogen exports at the 10% and 1% significance levels in Models 1 and 2, respectively. In contrast, including the exporter- and importer-time fixed effects (Model 3) provides no evidence of significant trade effects. However, the PPML estimation (Model 4) and Model C.7 show that these standards have a positive and significant effect on exports. Moreover, Model C.5 shows a positively significant effect on imports. Despite the negative association of international hydrogen standards with trade in several models, the more robust PPML estimation and the additional robustness checks reveal significant push effects (Models 4 and C.7) and pull effects (Model C.5) on hydrogen trade. These results are consistent with previous studies that have found trade-enhancing effects of international standards (Blind and Jungmittag, 2005; Blind et al., 2018c; Swann, 2010; Swann et al., 1996). Herewith, we also provide empirical support for earlier studies' assertion that (international) standardization in hydrogen technologies has a positive effect on market and value chain formation (Cammeraat et al., 2022; Cervantes

et al., 2023; Dincer and Acar, 2017; Velazquez Abad, 2020). However, instead of an absorptive capacity effect resulting from the non-proprietary disclosure of knowledge through standards, they show an export-pushing effect rather than an import-enhancing pull effect. Standards define the requirements to which a product, process, or service must conform, with safety as one of their central objectives (Blind, 2004; OECD & Eurostat, 2018). Therefore, international standards adopted by exporting countries can have a signaling effect on the importing country, enhancing the trust in hydrogen (Blind et al., 2018a; Swann, 2010). In doing so, the exporting country can demonstrate its compliance with internationally agreed requirements on hydrogen properties and the technologies necessary for its production, storage, transport, and use.

In contrast, purely *national standards* show no push effects across all models and robustness checks. Instead, they even exhibit negatively significant effects on exports (Models 1, 3, C.2, C.6), significant import-enhancing pull effects (Models 2 and C.6), or negative and significant effects on imports (Model 4). While our findings align with those from previous research on the mixed trade effects of national standards (Blind and Jungmittag, 2005; Blind et al., 2018c; Swann et al., 1996), they are not clearly associated with hydrogen trade, as our models only provide mixed evidence regarding the direction of effects. This result underscores that adopting international standards is even more critical in advancing the global hydrogen market, as indicated by their significant push effect (Models 4 and C.7). The harmonization of requirements provides common grounds for cross-border trade, thereby reducing the trade barriers imposed by national standards (Blind and Jungmittag, 2005; Cammeraat et al., 2022).

To expand the global hydrogen market in the future, publications, patents, and standards (PPS) as research and innovation indicators should not be considered in isolation. The interplay between PPS can have important implications for advancing the commercialization of the technologies required to boost the global hydrogen market. As shown by previous research (Asna Ashari et al., 2023a; Sick et al., 2018), greater gaps between consecutive phases of research and innovation, e.g., patenting and standardization lagging behind publishing, indicate the need for intensified market-relevant patenting and (evidence-based) standardization. Based on intensified knowledge and technology transfer, enhanced alignment between PPS could contribute to more innovation and market growth (Asna Ashari et al., 2023a; Cammeraat et al., 2022; Cervantes et al., 2023). On the one hand, increased innovation can enhance the availability of hydrogen (technologies). On the other hand, it will likely stimulate demand for hydrogen, leading to more significant global trade volumes. However, trade patterns will substantially depend on the availability of feedstocks for hydrogen production, including renewable energy, and the distribution of comparative advantage (Eicke and De Blasio, 2022; Okunlola et al., 2022; van der Zwaan et al., 2021).

More *hydrogen incidents and accidents* are associated with increased hydrogen imports (Models 2, 3, C.1, C.2) and exports (Model 1). Although safety is considered a driver of hydrogen market growth (Hardman et al., 2017; Schulte, 2004), less safety appears to increase hydrogen exports at first glance. However, there are multiple potential reasons for this result: 1.) Only countries with reported accidents are considered in the database; 2.) More hydrogen-related activities are more likely to involve more incidents or accidents; 3.) Learning from incidents can help reduce safety issues and improve hydrogen safety in affected countries afterward (European Commission, 2022; Cooke and Rohleder, 2006; Drupsteen and Guldenmund, 2014).

A comparative advantage in hydrogen exports (RCA) is positively and significantly associated with increased hydrogen exports (Models 1, 3, 4, C.1, C.2) but also with higher imports (Models 3, 4, C.2). Lastly, GDP is associated with increased exports in Models 1 and 2 but shows negative signs when the time period is divided into two sub-periods (Models C.1., C.2). For imports, the GDP coefficient shows the expected signs and significances (Models 4 and C.2).

5. Conclusion and policy implications

This study has analyzed the effects of hydrogen research and innovation on bilateral trade for 32 countries between 1995 and 2019. Our results provide data-driven, empirical evidence relying on international hydrogen trade data. The findings show mixed evidence of the trade effects of publications, patents, and standards (PPS) as research and innovation indicators (RQ1). Essentially, the results across various model estimations suggest that patent applications appear to increase the competitiveness of countries in exporting hydrogen. Adopted international hydrogen standards show mixed effects, including positive and significant effects on hydrogen exports. Publications and purely national standards are primarily weakly to negatively associated with trade in the main models, thereby failing to effectively explain hydrogen trade (RQ2).

The quantitative approach taken in this study contributes to previous research at multiple levels: First, in contrast to previous studies in the hydrogen area that postulate a positive link between research and innovation progress and market growth (e.g., Cammeraat et al., 2022; Cervantes et al., 2023), this study provides quantitative evidence of this relationship using bilateral trade data. Herewith, we follow previous studies in the renewable energy (RE) area linking R&D and trade (Costantini and Crespi, 2008, 2013; Groba, 2014; Kim and Kim, 2015). However, these studies were primarily confined to the effects of R&D expenditures and patenting activity on trade. Furthermore, no study has previously empirically tested this relationship for the hydrogen area. Therefore, the second contribution of this study is to introduce publications, patents, and standards as indicators to assess the effects of research and innovation on trade more comprehensively. With bilateral hydrogen trade as the dependent variable, we were able to explore whether national research and innovation capacity translates into more hydrogen export supply and import demand and, thus, bilateral trade flows. Although factors other than R&D, such as feedstocks for hydrogen production, influence domestic hydrogen production capacity, our approach proxies whether, in the past, countries have been able to exploit their hydrogen trading potential in the global hydrogen market through their technological advances. Third, this study builds on previous research linking R&D advances to raw material trade by broadening the scope from trade in fossil fuels to hydrogen trade. In doing so, it synthesizes previous studies on the effects of R&D on sustainability outcomes and raw material trade (e.g., Petrović & Lobanov, 2020; Zhang et al., 2015).

From a policy perspective, our results have demonstrated that patenting activity and international standards, in particular, are associated with increased bilateral hydrogen trade. Therefore, science, technology, and innovation (STI) policies should adopt coherent policy mixes that promote patenting and standardization as R&D activities and outcomes. In line with previous research, such policy mixes would include

increased R&D expenditure on hydrogen technologies, which foster R&D activity. Simultaneously, reducing the subsidies on fossil fuels and fossil-based technologies can help reallocate public budgets to R&D in hydrogen technologies to increase their competitiveness, thereby boosting market growth (Acemoglu et al., 2016; Asna Ashari et al., 2024; Blind et al., 2018b; Cammeraat et al., 2022).

More specifically, policymakers should incentivize further patenting and standardization activities within the scope of STI policies, e.g., by making standardization efforts eligible for R&D funding and considering not only patent applications but also contributions to standardization as output or performance indicators of such programs. This will help countries enhance global export competitiveness in hydrogen, as revealed by our results, and thus contribute to the formation of the international market. Furthermore, our results have shown that international standards facilitate bilateral hydrogen trade through the harmonization of requirements and the elimination of barriers to cross-border trade. By doing so, international standards provide a 'common language' for trade (see also Blind and Jungmittag, 2005; Blind et al., 2018a; Swann, 2010). Here, we expect the commitment of policymakers to adopt hydrogen standards, driven by the adoption of hydrogen strategies and policies worldwide, to boost hydrogen trade even further (Albrecht et al., 2020; IEA, 2021, 2022, 2023). Furthermore, the link between research and standardization could be further complemented by the regulatory framework, which can influence research and innovation activities and thus have implications for trade (Blind et al., 2017). In terms of value chain parts, R&D activities in hydrogen production, given sufficient natural resource endowment, are particularly important to enhance the export supply, thus lowering the global hydrogen price and expanding the global market (Asna Ashari et al., 2024; IEA, 2023; Wappler et al., 2022).

Beyond the findings related to the trade effects of research and innovation, our results have demonstrated that geographical distance is indeed associated with significantly reduced bilateral hydrogen trade. This aligns with the basic assumption of gravity models regarding the impact of distance on trade. More importantly, this finding illustrates that hydrogen transport is still an infant component of the existing hydrogen value chain, primarily occurring between neighboring countries (see Tables 3 and 4). While this study does not deliver empirical evidence of the past means for hydrogen transport, it highlights the relevance of the current lack of transport infrastructure (IEA, 2023). In line with previous research, the lack of infrastructure requires policymakers to foster investments, especially in pipelines, which involve the lowest transportation costs out of all options (Asna Ashari et al., 2024; Okunlola et al., 2022; Van de Graaf et al., 2020). Herewith, policymakers can contribute to facilitated cross-border trade and, thus, the transition to a hydrogen economy.

This study is not without limitations. First, we proxy the international hydrogen market using bilateral trade data, thereby ignoring national and regional market dynamics. Second, the correlations in our regression models do not necessarily imply causality. Here, instrumental variables (IV) and difference-in-differences (DID) approaches, e.g., incorporating policy variables and free trade agreements, could increase the causal explanatory power of the models. However, due to the small number of total observations for these variables in the 1995–2019 period, which could have explained hydrogen trade in the past, we did not include them, so IV or DID could not be applied. Third, our data

suffer from trade-reporting bias, preventing us from distinguishing whether missing bilateral trade data results from countries' non-reporting or actual zero trade flows. Fourth, our trade data do not distinguish the hydrogen production source, causing uncertainty about the trade volumes of sustainably produced 'green' hydrogen as a share of the total amount of hydrogen traded internationally. However, more differentiated trade data could be matched more accurately with more differentiated PPS data, thereby expanding Müller and Eichhammer (2023) with PPS as explanatory variables.

Finally, our study does not consider the effects of *Quality Infrastructure* (QI) on bilateral hydrogen trade, although a QI system is vital for the safety and quality assurance of products, processes, and services, and can facilitate cross-border trade (Blind, 2024; Blind et al., 2018a; Koch et al., 2022; Mirtsch et al., 2022). In the hydrogen area, the effects of QI on trade could be measured by adopted certification schemes defining threshold values for the carbon emissions associated with the production of green hydrogen or by regulatory variables that can induce more innovation and trade in hydrogen (Costantini and Mazzanti, 2012; Groba, 2011; IEA, 2023; Porter and van der Linde, 1995).

Future research should address the shortcomings of this first quantitative gravity model analysis of the international hydrogen market. First, empirical analyses of national or regional hydrogen supply chains could more accurately assess the effects of R&D activities on market formation. For instance, including research projects, committed project funding, or government expenditures on public procurement as further variables could add to the portfolio of relevant research and innovation indicators and capture R&D activities more comprehensively (IEA, 2022, 2023).

Second, to make more sophisticated forecasts about the trade effects of research and innovation, future research should investigate, e.g., the interaction effects of publications, patents, standards, and possibly other indicators on trade once global hydrogen trade patterns are consolidated. For the 1995–2019 period, we found no supportive evidence of significant interaction effects. Third, provided sufficient data availability, future research could make more robust forecasts by analyzing more

precisely how R&D differentiated by hydrogen production technologies or feedstocks impacts trade in the accordant hydrogen colors. Finally, qualitative studies, e.g., on hydrogen transportation demonstration projects, could delve more deeply into the causal link between research and innovation progress and the transport of the hydrogen commodity.

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CRedit authorship contribution statement

Parsa Asna Ashari: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Knut Blind:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A: Search queries for publication and patent data

Table A.1 gives an overview of the search queries for publication and patent data collection. We used Clarivate Analytics's *Web of Science (WoS) Core Collection* (Clarivate Analytics, 2022) as a comprehensive and established publication database to collect publication data (Asna Ashari et al., 2023a; Birkle et al., 2020). To this end, we ran searches using the Boolean search terms (Table A1) in the 'Topic' field, comprising title, abstract, and keywords.

Patent data were collected from the open-source *Espacenet* (EPO, 2023) patent database of the European Patent Office (EPO) and filtered by the annual hydrogen-relevant patent applications of the assigning countries. Since we do not differentiate the patent data by technology applications but rather measure national innovation capacity, we refrained from using additional IPC (*International Patent Classification*) codes.

Table A.1
Search queries for publication and patent data

Variable	Boolean search terms	Additional search settings
Publications	hydrogen energy (Topic) or hydrogen technology (Topic) or fuel cell (topic) or hydrogen production (Topic) or hydrogen generation (Topic) or hydrogen storage (Topic) or hydrogen transport (Topic) or hydrogen delivery (Topic) or hydrogen fueling station (Topic)	Language: English Document types: Articles and proceeding papers
Patents	Hydrogen* (title) OR fuel cell* (title)	Document type: Patent applications Assigning office: EPO

Appendix B:. Correlation matrix

Variables	$\ln(X_{ij,t})$	$\ln DIST_{ij}$	$\ln PUB_{it-1}$	$\ln PUB_{jt-1}$	$\ln PAT_{it-1}$	$\ln PAT_{jt-1}$	$INTSTD_{it-1}$	$INTSTD_{jt-1}$	$NATSTD_{it-1}$	$NATSTD_{jt-1}$	HIA_{it-1}	HIA_{jt-1}	RCA_{it-1}	RCA_{jt-1}	$\ln GDP_{it-1}$	$\ln GDP_{jt-1}$
$\ln(X_{ij,t})$	1															
$\ln DIST_{ij}$	-0.296***	1														
$\ln PUB_{it-1}$	0.095***	0.140***	1													
$\ln PUB_{jt-1}$	0.133***	0.140***	0.267***	1												
$\ln PAT_{it-1}$	0.148***	0.076***	0.718***	0.084***	1											
$\ln PAT_{jt-1}$	0.146***	0.076***	0.084***	0.718***	0.043***	1										
$INTSTD_{it-1}$	-0.007	-0.068***	0.193***	0.154***	0.119***	0.029***	1									
$INTSTD_{jt-1}$	0.028*	-0.068***	0.154***	0.193***	0.029***	0.119***	0.169***	1								
$NATSTD_{it-1}$	-0.004	-0.003	0.345***	0.155***	0.218***	0.040***	0.171***	0.122***	1							
$NATSTD_{jt-1}$	0.036**	-0.003	0.155***	0.345***	0.040***	0.218***	0.122***	0.171***	0.120***	1						
HIA_{it-1}	0.140***	-0.009	0.260***	-0.030***	0.331***	-0.005	-0.023***	-0.020***	0.026***	-0.021***	1					
HIA_{jt-1}	0.136***	-0.009	-0.030***	0.260***	-0.005	0.331***	-0.020***	-0.023***	-0.021***	0.026***	0.016**	1				
RCA_{it-1}	0.257***	-0.041***	0.074***	0.025***	0.094***	0.010	0.114***	0.011*	-0.053***	0.015**	-0.003	-0.002	1			
RCA_{jt-1}	0.091***	-0.041***	0.025***	0.074***	0.010	0.094***	0.011*	0.114***	0.015**	-0.053***	-0.002	-0.003	0.003	1		
$\ln GDP_{it-1}$	0.120***	0.177***	0.892***	0.139***	0.758***	0.051***	0.117***	0.073***	0.279***	0.081***	0.345***	-0.014**	0.070***	0.015**	1	
$\ln GDP_{jt-1}$	0.173***	0.177***	0.139***	0.892***	0.051***	0.758***	0.073***	0.117***	0.081***	0.279***	-0.014**	0.345***	0.015**	0.070***	0.081***	1

***p < 0.01, **p < 0.05, *p < 0.1.

Appendix C. Robustness checks

Variables	(C.1)	(C.2)	(C.3)	(C.4)	(C.5)	(C.6)	(C.7)
	Exporter-time, importer-time FE, 1995–2008	Exporter-time, importer-time FE, 2009–2019	Exporter-time, importer-time FE, 1995–2019	Exporter-time, importer-time FE, 1995–2019	Exporter-time, importer-time FE, 1995–2019	Exporter-time, importer-time FE, 1995–2019	Exporter-time, importer-time FE, 1995–2019
Distance							
Publications exporting country	2.667*** (0.564)	4.269*** (1.101)	0.0433 (0.345)				-2.153** (0.900)
Publications importing country	-1.284 (0.798)	-5.858* (3.104)	0.927*** (0.295)				-0.534 (1.363)
Patents exporting country	0.407 (0.320)	1.959*** (0.654)		0.612*** (0.201)			2.011*** (0.308)
Patents importing country	0.264 (0.266)	0.194 (0.535)		-0.353*** (0.135)			-0.0919 (0.633)
Intl. standards exporting country	-1.648 (1.160)	-0.342* (0.196)			-0.0620 (0.218)		0.310** (0.146)
Intl. standards importing country	0.0282 (0.672)	0.352 (0.381)			0.758*** (0.252)		0.00368 (0.181)
Nat. standards exporting country	0.112 (0.357)	-0.290** (0.142)				-0.231* (0.132)	0.220 (0.192)
Nat. standards importing country	-0.208 (0.252)	0.526 (0.365)				0.398*** (0.140)	0.0184 (0.0938)
Hydrogen incidents & accidents exporting country	0.0666 (0.277)	-0.141 (0.191)					
Hydrogen incidents & accidents importing country	0.420* (0.222)	0.463** (0.212)					
RCA exporting country	0.302*** (0.102)	0.380*** (0.128)					
RCA importing country	-0.0739 (0.211)	0.336*** (0.0837)					
GDP exporting country	-2.210*** (0.844)	-5.828*** (1.115)					
GDP importing country	0.593 (0.899)	4.602** (2.201)					
Constant	44.37 (29.70)	40.22 (55.29)	12.63*** (2.066)	7.607*** (0.734)	2.147** (0.964)	2.147** (0.964)	13.62** (6.162)
Observations	1265	1607	3251	2872	3309	3309	2872
R-squared	0.592	0.469	0.523	0.518	0.526	0.526	0.518

***p < 0.01, **p < 0.05, *p < 0.1; robust standard errors in parentheses.

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