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Hydrogen innovation: An exploration of its determinants across Europe

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ABSTRACT

Hydrogen technology has advanced significantly in recent years, making it a promising future energy source. It is, in fact, a clean, safe, and valuable fuel, offering a solution to renewable energy intermittency and redirecting energy for various applications. Since hydrogen technologies can potentially represent the energy of the future, understanding the determinants facilitating innovation is of paramount relevance. This study aims at understanding the determinants of hydrogen technology innovation across EU member states. Three sets of determinants are considered: human capital (Stock of graduates), institutional quality (Size of Government, Legal System and Property Rights, Sound Money, Freedom to Trade Internationally, Regulation), and sustainability endorsement (Hydrogen public R&D, Sustainable competiveness index). From a methodological perspective, a panel model comprising 27 EU member states is used. The final dataset consists of 540 observations from 1998 to 2019. Of the three sets of determinants, our results show that investment in human capital, the legal system, property rights protection, and investment in R&D activities could support the development of hydrogen technologies.

1. Introduction

Over the past two decades, significant advancements have been made in hydrogen technologies, positioning it as the energy source of the future (Gupta et al., 2023; Zhu et al., 2023; Seck et al., 2022; Mona et al., 2020), leading some authors to speak about a future "hydrogen economy" (see, for example, Ball and Weeda, 2015; Tseng et al., 2005). Hydrogen technologies, in fact, have several promising advantages. First, in some of its forms, it represents a valuable, clean, and safe high-quality fuel (Becker, 2015). Second, hydrogen production emerges as a highly promising solution to address the issue of intermittency in renewable energy generation (Pinto, 2023; Jain, 2009). Third, hydrogen technologies help mitigate impacts associated with energy conversion (Chen et al., 2011). Fourth, hydrogen technology has the potential to replace fossil fuels in sectors traditionally reliant on them, thus supporting the shift towards more sustainable energy sources (Sarkar et al., 2019). Fifth, hydrogen technology involves the widespread utilization of hydrogen across various sectors, favoring an increase in energy supply, reducing energy costs, and serving as a versatile energy medium (Bockris, 2013). Lastly, it encompasses various components, including hydrogen production, storage, transportation, and applications like hydrogen refueling stations and fuel cell vehicles (Sinigaglia et al., 2019).

Therefore, research in the field of hydrogen technology is encouraged by several governments and sovra-national organizations, especially concerning the development, application and use of such innovations (Ashari et al., 2024; Ampah et al., 2023; Seck et al., 2022; Hacking et al., 2019). At the national and regional level, research on the determinants of development, adoption and use of innovation, especially the green ones, is not new (see, for example, Li et al., 2021; Santoalha and Boschma, 2021; Barbieri et al., 2020; Montresor and Quatraro, 2020), but hydrogen technologies, despite their immense potential, have been largely overlooked (Madsen and Andersen, 2010; Walker, 2024; Ampah et al., 2023). Given the future potential of hydrogen technology, identifying the determinants that contribute to its development has emerged as a significant research area, particularly to support the development of place-based and evidence-based hydrogen policies (Walker, 2024; Ampah et al., 2023).

Given these premises, this paper aims at analyzing the determinants of hydrogen technology innovation across European countries, where the European Commission recognizes hydrogen technology as the key driver for the Green Deal (Wolf and Zander, 2021). The relevance of hydrogen in Europe has been recently demonstrated by the EU hydrogen strategy published in 2020, *i.e.,* "Hydrogen strategy for a climate-neutral

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Europe", which sets out targets and three phases of hydrogen development and adoption[1] (Wolf and Zander, 2021) and which recognizes the fundamental role of hydrogen innovation (Vivanco-Martín and Iranzo, 2023). However, for an efficient transition to the so-called hydrogen economy, national governments need to develop their national hydrogen strategies, considering their peculiar economic and technological developments (Wolf and Zander, 2021). Moreover, the relevance of hydrogen technologies has also been recalled by REPowerEU announced in 2022 and by the 2023 Joint Declaration of Joint Declaration on Hydrogen Valleys by Hydrogen Europe, Hydrogen Europe Research, S3 H2 Valleys Platform and the European Commission. In this context, understanding the determinants of hydrogen technology at the country level is extremely important, not only because European countries are still entering the second phase highlighted by the EU hydrogen strategy but also because in the last one (2030–2050), hydrogen technologies are expected to reach maturity and to be used on a large scale (Pinto, 2023).

To achieve the stated research objective, this study adopts a systemic approach (Ott and Rondé, 2019; Buesa et al., 2010; Edquist, 1999) and it considers three country level factors to study hydrogen technology development: human capital (Stock of graduates), institutional quality (Size of Government, Legal System and Property Rights, Sound Money, Freedom to Trade Internationally, Regulation), and sustainability endorsement (Hydrogen public R&D, Sustainable competiveness index).

In investigating the determinants at country level for hydrogen technology development, Europe represents a fruitful case due to the existence of a EU hydrogen 2020 strategy for innovation and energy transition and for the availability of harmonized data that facilitates comparative analysis across countries. From a methodological point of view, two analyses are performed. First, a temporal evolution of hydrogen technologies is described by identifying which countries drive the patenting process in hydrogen technologies. Second, an econometric model is estimated to identify the determinants of hydrogen technologies at the country level. Specifically, we conduct this analysis at the 27 EU countries level, considering the number of patents in hydrogen technologies, using a panel of 540 observations from 1998 to 2019.

Results show that human capital positively affects hydrogen technology; similarly, specific R&D investments and protection of intellectual property rights positively support innovation in the hydrogen domain. These results contribute to the empirical literature on the geography of hydrogen technologies, confirming the need to adopt a system approach to study innovation, particularly green ones. Moreover, although the endorsement and support are at the European level, it is necessary to define, at the country level, specific policies and tools that facilitate this transition. Since the adoption of hydrogen technologies varies across European countries, place-based policies need to be defined at the national and regional level, taking into account the determinants of such technologies, as well as the pre-conditions and the specific territorial characteristics and innovation potential of the countries or regions. Supporting the development of hydrogen technologies through place-based country level policies will in turn facilitate the creation of cross-national collaboration and the so-called "hydrogen valley" across Europe (Bampaou and Panopoulos, 2025).

This paper proceeds as follows. Section 2 reviews the extant literature, section 3 presents the analytical framework. Section 4 presents data, variables and methods. Section describes the results and section 6 concludes.

[1] Phase 1 (2020–2024) is aimed at decarbonizing existing hydrogen production; in phase 2 (2024–2030) hydrogen is expected to become a fundamental part of the energy system; in phase 3 (20,230-2050) hydrogen technologies are expected to reach maturity and to be used on a large scale.

2. Determinants of innovation at national and regional levels: a synthesis of the extant literature

Technological innovation is crucial for economic development, playing a vital role in developing a sustainable society and mitigating climate change (Häggmark and Elofsson, 2022; Buesa et al., 2010), a topic of particular relevance to the agenda of policy makers in recent years (Gans, 2012; Steward, 2012).

The economics of innovation literature demonstrates that space matters in the development of innovation (Lengyel et al., 2020; Scott et al., 2003) and that innovation is not an isolated phenomenon but that national and regional contextual factors may strongly affect the innovation capabilities of a region or country (Edquist, 1997, 1999). This aspect is at the heart of the National or Regional Innovation System perspective (NIS or RIS) (Cooke et al., 1997), according to which innovations result from complex and interactive dynamics among different actors in a specific institutional framework, setting the rules of the game (Ortega and Serna, 2020; Edquist, 1997) in a specific geographical area with its specific features (Camagni and Capello, 2005).

When looking at the determinants of innovation, Buesa et al. (2010), according to a systemic view of innovation, considers several independent variables: i) regional innovation environment, referring to size of the region (comprising variables such as GDP, GVA, number of people employed), gross fixed capital formation, wages) and human resources; ii) university (i.e., university staff in R&D about total number employed, R&D expenditure about GDP and 3rd cycle students about population; iii) public administration (i.e., staff in R&D about total number employed; about GDP); iv) national environment (i.e., investment capital about GDP, penetration of ICTs); v) innovatory firms, (*i.e.,* firm's staff in R&D about total employees and firm's expenditure in R&D compared to GDP). These authors, by using a knowledge production function approach, find out that only regional environment, innovatory firms, and national environment have a positive effect on innovation. Rodríguez-Pose and Villareal Peralta (2015), in their study based on Mexico, use the following variables: annual growth of regional GDP per capita, level of GDP per capita, R&D expenditure, social filter (i.e., a composite index for social regional variables) and spillovers and they demonstrate that R&D investment and social filtering influence innovation activities. In their French study aimed at understanding the process of innovation generation, Ott and Rondé (2019) specifically focus on the role of knowledge and human capital. They proxy innovation using patents, and they consider i) regional firms competences, measured through a specific survey that distinguishes between "technical competences" and "organizational competences", and ii) the regional knowledge base, specifically proxied using R&D and education. Recently, Olejnik and Żółtaszek (2020), use the following variables: employment in high-tech and knowledge intensive sector, a proxy for skilled human capital; patent application; R&D investment, a proxy for the stock of knowledge used to produce new knowledge and Gross Domestic Product, as a measure for economic performance. Their analysis confirms both the relevance of space (also in terms of proximity) and that of social and human capital.

The spatial dimension of innovation also attracted scholars' attention when green innovation is concerned (see, for example, Hansmeier and Kroll, 2024; Grillitsch and Hansen, 2019; Boschma et al., 2018). Literature on green innovation agrees on the relevance of space and geographical features: green innovations depend on specific supply and demand characteristics, as well as on institutional context and regulatory framework (Barbieri et al., 2020; Horbach et al., 2014). Galliano et al. (2023), using the French Community Innovation Survey (CIS), focus on the externalities (measured as Location Quotient, Related Variety and Unrelated Variety) having a positive impact on green innovation, taking into account also the spatial localization of the company. They found that spatial externalities have a positive impact on firms' green innovation and, specifically, this impact varies according to firms' location. Moreover, the positive effect of spatial externalities is much more relevant for firms located in rural areas. In contrast, no effect was found about green innovation development for urban forms (Galliano et al., 2023). The relevance of spatial factors and regional and national characteristics is also stressed by Losacker et al. (2023a,b) in their systematic review of the determinants of green innovation. In their review, they highlight three main groups of regional determinants, named i) supply-side determinants, referring to technological capabilities and competitive advantages; ii) demand-side determinants, related to expected market demand and environmental awareness and, iii) institutional and political demand, i.e., environmental policies and regulations. Very recently, Hansmeier and Kroll (2024), focusing on the geography of eco-innovation and sustainability transition, identify three key driving factors: actors, institutions, and technological elements. Actors and human capital are, in fact, fundamental in generating and sharing new knowledge, which is necessary to develop innovation. Moreover, actors are a powerful tool for the creation of knowledge networks, which, in turn, facilitate the diffusion of knowledge and technologies across space. The institutional context, by setting the rules of the game, can influence both the behavior of actors as well as facilitate the adoption and diffusion of innovation through specific regulations and incentives (Hansmeier and Kroll, 2024). Lastly, technological elements refer to both technology itself and also to all the tacit knowledge connected with technological innovation, provided by actors and human capital (Hansmeier and Kroll, 2024).

Specifically focusing on the country or regional determinants of hydrogen technology, the literature is still scant, with the majority of studies focusing on factors affecting the creation of a hydrogen economy (Ashari et al., 2024; Safronova and Barisa, 2023; Kar et al., 2023; Cader et al., 2021), hydrogen R&D, hydrogen trade (Ashari and Blind, 2024) and societal acceptance of hydrogen technologies (Scovell, 2022; Emodi et al., 2021). However, in this limited literature, some previous studies confirm that space matters also when hydrogen technology is concerned. The pioneering work of Madsen and Andersen (2010), focusing on hydrogen fuel cells (H2FC) in 16 European regions, highlights that innovation and policy preconditions affect the development of hydrogen and fuel cell technologies. Specifically, they find that the presence of innovative clusters and being an innovative region have a positive impact on the H2FC innovation system. More recently, Ampah et al. (2023), in their analysis based on patent data across different countries worldwide, highlight a different level of hydrogen technology development maturity, with Japan as the leading country, followed by US and China and that the presence of a clear and effective policy strategy could support the development of hydrogen technology, as was the case of both Japan and Germany (Ampah et al., 2023). Other two studies are worth mentioning, and they are both focused on the case of Germany. Bolz et al. (2024) investigate the adoption barriers that can hinder the development of hydrogen technologies in the Bremen region. Using a qualitative approach based on different focus groups, they identified five different barriers, namely regulation (*i.e.,* subsidies, funding policy, approval procedure and legal framework), technology (*i.e.,* life cycle assessment and suitability), costs (categorized as energy carrier, investment and operating), availability (*i.e.,* energy carrier, distribution infrastructure, technical components, service and maintenance, and network), and, lastly, acceptance (operationalized as customers, personnel development, visibility, willingness to pay, public fears) (Bolz et al., 2024). In the same year, Walker (2024) studies the allocation of R&D funding in Germany and the related effect of hydrogen technology in light of the mission-oriented innovative system and mission-oriented innovation policy. He finds that allocating R&D funding considering spatial and geographical characteristics leads to different outcomes, such as creating clusters for research activities and local specialization (Walker, 2024).

The extant literature clearly highlights that space (*i.e.,* regions or countries) and their characteristics may influence innovation, especially when the green one is concerned. However, although this stream of research is increasing, more contributions are needed, especially in the field of hydrogen technology, which has been largely overlooked despite the potential of being the energy of the future. Starting from the extant literature, a conceptual framework has been developed (and presented in section 3) to investigate the regional determinants of hydrogen innovation.

3. Analytical framework

Following the previous review of the literature, an analytical framework has been developed. Three main sets of variables are identified, each of which have an impact on the hydrogen technologies at the country level (Fig. 1).

The first key factor is the **stock of skilled human capital**. The role of human capital has been widely recognized in literature on innovation and green innovation in particular (Pinate et al., 2024; Losacker et al., 2023a,b; Wen et al., 2022a,b; Barbieri et al., 2020). The relationship between human capital and innovation finds its theoretical justification in what was termed “conversion” by Bourdieu (1986), according to which country-level human capital works as input resources that can be transformed into output. In line with the human capital theory (Becker, 1964), in fact, highly educated individuals can foster productivity growth since they act as a key determinant for technological innovation (Zhang and Li, 2023; Benhabib and Spiegel, 2005; Cannon, 2000; Romer, 1990). In particular, concerning green innovation, Consoli et al. (2016) show how green innovation requires a high level of cognitive skills and a high level of education. The relevance of skilled human capital to foster innovation, and especially the green one, is highlighted by the European Commission (2022, 2021). A country with a high capital-labor ratio generally has a higher level of education and a greater number of skilled workers, and then it may have more prospects for innovation and the ability to generate new ideas and successfully bring them to market (Aron and Molina, 2020; Cascio and Boudreau, 2016). This can be particularly true in a highly innovative field, such as that of hydrogen (Lenihan et al., 2019).

The second key factor is **institutional quality** (Zanello et al., 2016; Rodríguez-Pose and Di Cataldo, 2015; Tebaldi and Elmslie, 2013; Rodríguez-Pose, 2013). Scholars have underscored the favorable influence of institutional factors on innovation, drawing upon the theoretical underpinnings of the Porter Hypothesis (Zhang and Li, 2023; Li and Shao, 2021). This hypothesis posits that strong institutional frameworks can catalyze individuals’ enthusiasm for innovation and enhance operational efficiency (Li and Shao, 2021). Several scholars, by using the Economic Freedom of the World Index (see, for example, Boudreaux, 2017; Young and Sheehan, 2014), assess institutional quality using five categories: i) size of government; ii) legal system and property rights; iii) regulations; iv) sound money; and v) free international trade (Cascio and Boudreau, 2016). Size of government is said to enhance public service functions, offering society beneficial externalities through the provision of public services and products (e.g., transportation, energy, communication, and infrastructure); successfully address market failures and, lastly, generate positive externalities by restricting or eradicating monopolies and promoting the growth of businesses (Havercroft, 2021). Favorable legal systems and property rights, such as tax incentives for research and development or strong intellectual property protection, can encourage companies to invest in new ideas and technologies (Butenko and Larouche, 2015). Conversely, uncertain or restrictive regulations can act as barriers to innovation (Hueske et al., 2015), due to the “crowding out” effect (Kemp and Pontoglio, 2011). By way of example, considering the innovation in renewable energy, Li and Shao (2021) find a significant negative impact of the legal system and regulation on renewable patents. In OECD countries, there is a negative link between innovation and the levels of the national legal system, property rights, restrictions in the credit market, labor and business. Regulation is related to governmental law and policies that can hinder or support the freedom of exchange in credit, labor, and product markets. The extant

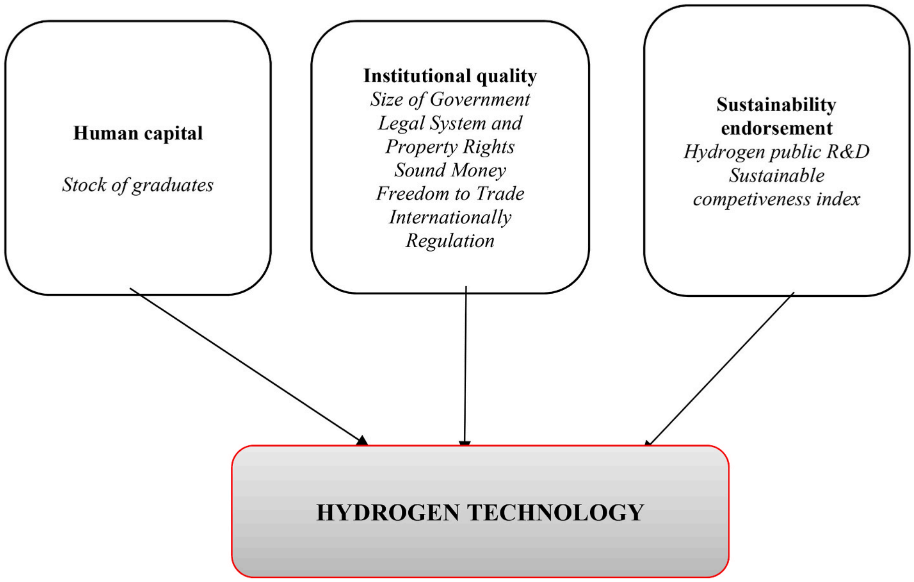

Fig. 1. Determinants of hydrogen innovation. Authors' elaboration.

literature generally distinguishes between three types of regulation, namely "market-incentive regulation" (mainly focused on pricing or cost mechanism), "command and control", *i.e.,* mandatory measures for companies, and "public participation-based regulation", with the active involvement of the civic society (Ni et al., 2023). Although there is a broad investigation on the effect of regulation on innovation, results are mixed, particularly when green innovation is concerned. Some authors, in fact, highlight that environmental regulations can promote green innovation, mainly thanks to the "innovation compensation" mechanism (Zhang and Li, 2023; Feichtinger et al., 2005). On the contrary, other scholars provide evidence that strict environmental regulation often acts as a barrier to innovation, mainly due to high investment costs to achieve the government's stated standards and measures (Zhang and Li, 2023). Sound economic institutions are crucial in fostering innovation, while inadequate economic institutions will divert the efficient distribution of resources towards unproductive avenues (Cascio and Boudreau, 2016). The role of governments is fundamental in developing innovations because they can develop policies to create incentive systems to strengthen inventions (Niroumand et al., 2021). They can also attract foreign investment to the country that promotes this type of innovation (Niroumand et al., 2021). Countries or regions with high trade barriers hinder the growth of international trade due to their limited import and export volumes. Consequently, they have fewer opportunities to access advanced technological knowledge through trade channels (Niroumand et al., 2021). The absence of technical international interaction and communication will inevitably result in a lower capacity for technological innovation.

The third key factor is the **sustainability endorsement**. According to a systemic perspective (Camagni and Capello, 2005; Edquist, 1997), the external institutional context plays a central role in supporting innovations through different policies and investments. First, technology-push policy instruments, such as government-sponsored R&D initiatives, can promote technological advances from the innovators' perspective (Sagar and van der Zwaan, 2006). Publicly funded R&D, in fact, is said to overcome the problem of firms' R&D, which shows the classical problem of public goods being non-rivalrous and non-completely excludable (Becker, 2015). Specifically, R&D perfect competition is not able to maximize the social welfare function since positive externalities generated by the innovative activities are characterized by non-appropriability, non divisibility and a high level of uncertainty, preventing firms from internalizing the return generated by initial investment in innovation (Bronzini and Piselli, 2016; Becker, 2015). To overcome this problem, in most countries, the government has defined different policies to support R&D activities through devoted public funds (e.g., through subsidies or tax incentives) in order to support an optimal allocation of innovation resources. Public R&D funds can help companies in taking riskier innovation activities due to reduced private investment in innovation input (Xu et al., 2021), especially when exploratory innovation is concerned (Gao et al., 2021). Competitiveness encompasses not only the economic performance of a nation but also its environmental and social performance. The World Economic Forum (2013) defines sustainable competitiveness as the combination of institutions, policies, and elements that enable a country to maintain productivity in the long run while also ensuring social and environmental sustainability. Innovation in the hydrogen sector is not only a question of technological advancement but also of how these innovations are integrated in a context that enhances environmental and social sustainability. Countries with high sustainable competitiveness tend to create the institutional and political conditions necessary to support technological innovations in harmony with long-term sustainability goals.

4. Data and sources

The variables used in this study were sourced from four primary data providers: OECD REGPAT, EUROSTAT, EFotW (Economic Freedom of the World), The Global Sustainability Index, and International Energy Agency (IEA) (see Table 2). OECD REGPAT database provides information on patents registered with the European Patent Office (EPO) and the Patent Cooperation Treaty (PCT). This data source allowed us to identify patents in hydrogen technologies. EUROSTAT provides information on persons with a university degree, the economically active population, the unemployment rate, GDP and the risk of poverty. The EFotW dataset measures the degree to which countries' policies and institutions support economic freedom. The Global Sustainable Competitiveness, published by SolAbility, measures competitiveness and sustainability together at the country level. The IEA is an international intergovernmental organization funded in 1974 by the Organization for Economic Cooperation and Development (OECD) following the oil shock of the previous year. The variable related to public hydrogen investment was obtained from IEA. Based on the IEA's scope, public R&D spending includes funding from central or federal government units and, when significant, provincial and state government units. Local and municipal government units are excluded.

Table 1
Patent families considered in the study. Source: author's elaboration.

Family	Description
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation
Y02E 60/30	Hydrogen technology
Y02E 60/32	Hydrogen storage
Y02E 60/34	Hydrogen distribution
Y02E 60/36	Hydrogen production from non-carbon containing sources, e.g. by water electrolysis
Y02E 60/50	Fuel cells
Y02P 20/00	**Technologies relating to chemical industry**
Y02P 20/129	Energy recovery, e.g. by cogeneration, H2 recovery or pressure recovery turbines
C01B 3/00	**Hydrogen; Gaseous mixtures containing hydrogen; Separation of hydrogen from mixtures containing it (separation of gases by physical means B01D); Purification of hydrogen (production of water gas or synthesis gas from solid carbonaceous material C10J; purifying or modifying the chemical compositions of combustible technical gases containing carbon monoxide C10K)**
C25B 1/00	**Electrolytic production of inorganic compounds or non-metals**
C01B 2203/00	**Integrated processes for the production of hydrogen or synthetis gas**

Table 2
Variables used in the study. Source: author's elaboration.

Variables	Description	Data source
Dependent		
Hydrogen patents	Number of patents in hydrogen technologies.	OECD REGPAT
Independent		
Human capital		
Graduate population	Percentage of graduates in tertiary education.	Eurostat
Institutional quality		
Size of Government	Indicators of the extent to which countries rely on the political process to allocate resources, goods and services.	EFotW
Legal System and Property Rights	Indicators of the effectiveness with which the protective functions of government are carried out.	EFotW
Sound Money	Measure the consistency of monetary policy (or institutions) with long-term price stability and the ease with which other currencies can be used through domestic and foreign bank accounts.	EFotW
Freedom to Trade Internationally	Measure a wide variety of restrictions that affect international trade.	EFotW
Regulation	Measures regulatory constraints that limit the freedom of exchange in credit, labor and product markets.	EFotW
Sustainable endorsement		
Hydrogen public R&D	R&D public expenditure in the field of hydrogen technologies in billions of €.	IEA
Sustainable competitiveness index	Global Sustainable Competitiveness Index.	SolAbility
Control variable		
Economically active population	Thousands of economically active people.	Eurostat
Unemployment rate	Percentage of unemployed persons.	Eurostat
GDP	Gross domestic product in billions of €.	Eurostat
Risk of poverty	Percentage of people at risk of poverty.	Eurostat

4.1. Dependent variable

The dependent variable is represented by *hydrogen technologies*, proxied by using patents. Specifically, to construct our dependent variable, we follow Maurat et al. (2008) and we use fractional patent counts based on the applicant's address, a method that allows to allocate a share of each patent to the countries of applicants, when co-applicants are involved. Patents demonstrate the extent of environmental technological advancement and innovation within companies and the inventiveness of such corporations. As to the OECD (2009), patent data offer various advantages over other innovation metrics, including their commensurability, quantitative nature, and accessibility.

Patent applications contain a substantial amount of information regarding the characteristics of the invention and can be broken down into specialized technological areas (Johnstone et al., 2010). Remarkably, scant instances of commercially substantial innovations have not been patented (Johnstone et al., 2010).

We searched the European Patent Office for all families of patents covering technologies used in the extraction, generation, distribution, and storage of hydrogen, whether based on chemical, electrolytic, or other processes. The results led to the identification of patent families reported in Table 1. Following Li and Shao (2021) and Milindi and Inglesi-Lotz (2022), the OECD REGPAT database in the available version of August 2023 was used.

4.2. Independent variable

Human capital. *Graduate population* represents the percentage of graduates in tertiary education and reflects the educational level of the population and the availability of a skilled workforce, providing an indication of the intellectual potential and skills present in society (Delaney and Yu, 2013).

Institutional quality. To represent the political and legal process, we use indices developed by Economic Freedom of the World that analyze different aspects of institutions (Agboola and Alola, 2023; Nwani et al., 2023; Sun et al., 2019). *Size of Government*[2] reflects the extent to which countries rely on the political process to allocate resources, goods, and services, potentially indicating the government's role in economic activities. When public spending increases relative to spending by individuals, households, and businesses, government decision-making replaces personal choice, reducing economic freedom. *Legal System and Property Rights*[3] indicates the effectiveness of the government in protecting property rights, enforcing legal systems and assessing the rule of law in a country. A coherent legal system aligned with economic freedom emphasizes the rule of law, security of property rights, an independent and impartial judiciary, and the impartial and effective application of the law. *Sound Money*[4] measures the consistency of monetary policy with long-term price stability and the ease of using other currencies through domestic and foreign bank accounts, relating to monetary stability. *Freedom to Trade Internationally*[5] measures various restrictions affecting international trade, reflecting the ease of engaging in international commerce. The components in this area are designed to measure various restrictions that affect international trade, including tariffs, quotas, hidden administrative restrictions, and controls on exchange rates and the movement of capital and people. To achieve a high

[2] It is divided into five components: government consumption, transfers and subsidies, public enterprises and investments, the top marginal tax rate, and state ownership of assets.

[3] It is divided into nine components: legal independence, impartial courts, protection of property rights, military interference in the rule of law and politics, integrity of the legal system, legal enforcement of contracts, regulatory costs of property transfer, police reliability, business costs of crime, and Gender disparity adjustment.

[4] It is divided into four components: money growth, standard deviation of inflation, recent inflation, and freedom to own foreign bank accounts. The first three components are designed to measure the consistency of monetary policy (or institutions) with long-term price stability. The fourth component is designed to measure the ease with which other currencies can be used through domestic and foreign bank accounts.

[5] It is divided into four components: tariffs, regulatory trade barriers, black market exchange rates, and controls on capital and people movement.

rating in this area, a country must have low tariffs, smooth and efficient customs procedures, freely convertible currency, and few controls on physical and human capital movement.

Regulation[6] assesses the extent to which restrictions that limit market entrance and obstruct voluntary trading diminish economic freedom. It measures regulatory constraints limiting the freedom of exchange in credit, labor, and product markets, assessing the extent of regulatory barriers. Governments employ many instruments to restrict the freedom to engage in foreign exchange and may also impose burdensome laws, both domestically and on international trade, that curtail the right to trade, obtain credit, employ or work for any desired individual, or conduct one's business freely. As these restrictions proliferate, economic freedom diminishes.

Sustainability endorsement. *Hydrogen public R&D* represents public spending on R&D in hydrogen technologies, expressed in billions of euros. It indicates the specific public investment in the research and development of hydrogen-related technologies, which may include fuel cells, hydrogen production and storage, and other applications related to this energy source (Hassan et al., 2024). The *Global Sustainable Competitiveness Index*[7] (*GSCI*) measures a country's global sustainable competitiveness, giving the evaluation of businesses' sustainability performance a more comprehensive framework (Rajnoha and Lesnikova, 2022). It considers 190 indicators, organized into 6 sub-indices: natural capital, resource efficiency & intensity, social cohesion, intellectual capital, economic sustainability, and governance efficiency. The higher the global sustainable competitiveness index corresponds, the higher the level of sustainable competitiveness.

4.3. Control variables

Economically active population represents the number of economically active people in a specific geographical area, expressed in thousands (de Souza, C.B.D. et al., 2023). It provides information on the available labour supply and productive potential of a region. *Unemployment rate* represents the proportion of unemployed persons in a given geographical area (Lambert et al., 2017). The unemployment rate is a key indicator of labour market conditions, economic health and social stability of a society, highlighting the ability of an economy to provide employment opportunities to its citizens. *Gross Domestic Product* (GDP) expressed in billions of euros, measures the value of all goods and services produced within a country's borders during a given period of time, and is widely used as an indicator of economic well-being and the size of a country's economy. *Risk of poverty* represents the proportion of people at risk of poverty in a given geographic area (Hellwig and Marinova, 2023). It indicates the proportion of individuals living in conditions of low income or economic deprivation relative to the total population, offering an indication of the level of economic and social inequality in a society.

5. Method

To analyze factors that can influence a nation's propensity to patent in hydrogen technology within European Union member states, we develop a linear panel model where the 27 member states were considered from 1998 to 2019. Applying a one- or two-year lag between the explanatory variables and the dependent variable, the final dataset consists of 540 observations. We decided not to consider 2020 and 2021 because they are affected by the COVID pandemic and because patents are subject to truncation bias (e.g., patent applications not yet granted). Since processing a patent application usually takes several years, truncation bias impacts the data on patent applications. The presence of truncation bias is widely recognized and has been extensively examined (Hall et al., 2001). The EPO publicly discloses information on patent applications soon after the grant date. Moreover, there is a considerable (median of 3 years) and unpredictable interval between a company's patent application and the eventual grant of the patent (if successful). Consequently, patent data have a truncation error, as it can take several years to ascertain the total number of patents applied for in a given time period (Dass et al., 2017; Lerner and Seru, 2022). Because they haven't been issued yet, a significant percentage of patent applications that are close to a database's expiration date may be missing (Fig. 2) (Macher et al., 2024).

We decided to use a panel model to consider both the sample's diversity and the temporal evolution of the phenomenon. Since a patent may be shared by several companies located in different states, the variable should not be treated as a simple discrete count, and it represents a continuous variable, as it reflects the degree of co-ownership distributed among multiple entities (Wooldridge, 2010). In particular, given the nature of the dependent variable, a panel model using linear regression was chosen (Wooldridge, 2010). For all the independent variables, a lag of two years has been considered in line with accounting for a potential endogeneity issue (Ashwin et al., 2015; Liang et al., 2013). The model with fixed effect was chosen, in line with the Hausman test performed.[8]

The model is:

Model 1. *Hydrogen patents = f(Graduate population + Size of Government + Legal System and Property Rights + Sound Money + Freedom to Trade Internationally + Regulation + Hydrogen public R&D + Sustainable competiveness index + Control variables)*

As a robustness tests, we use a different time lag of one year, a different dependent variable (*i.e.,* the number of firms that patent in the hydrogen field), and the random effect model.

6. Results

Fig. 2 shows the total number of patents in hydrogen technologies in the European Union, by application year, showing, overall, an increasing trend, except for 2020 and 2021, probably due to COVID-19 pandemic and truncation bias (e.g., patent applications not yet granted).

Concerning the spatial distribution of hydrogen technologies between 1998 and 2021 (Fig. 3), Germany clearly stands out as the leader in hydrogen technologies, with an impressive number of 3768,2 patents in the period considered. Germany, in fact, began promoting hydrogen as part of its energy strategy as early as the 1990s and early 2000s, well before the National Hydrogen Strategy was formalised in 2020 (Bolz et al., 2024; Walker, 2024). One example is the National Innovation Programme for Hydrogen and Fuel Cell Technology, with a duration from 2008 to 2016.

France follows at a considerable distance with 1608.5 patents and Italy with 409.2 patents. These two countries clearly represent the main players in hydrogen-related technologies in Europe. On the contrary, countries like Greece, Estonia, Lithuania, Latvia, Malta, Croatia, and Slovakia had the lowest number of hydrogen patent applications during the period considered.

Table 3 shows the descriptive statistics. Multicollinearity has been estimated through the Variance Inflation Factors (VIF). Table 3 shows the descriptive statistics for the selected variables, reporting a VIF value of 4.61 (Shrestha et al., 2020). The correlation matrix is in Appendix A.

[6] It is divided into three components: credit market discipline, labor market regulation, and business regulation.

[7] www.solability.com/the-global-sustainable-competitiveness-index/the-index.

[8] The Hausman test yields a p-value of 0.0322, which is below the 0.05 threshold. This leads us to reject the null hypothesis that the differences between the fixed effects and random effects estimators are not systematic. In other words, the differences are systematic, supporting the use of the fixed effects model over the random effects model.

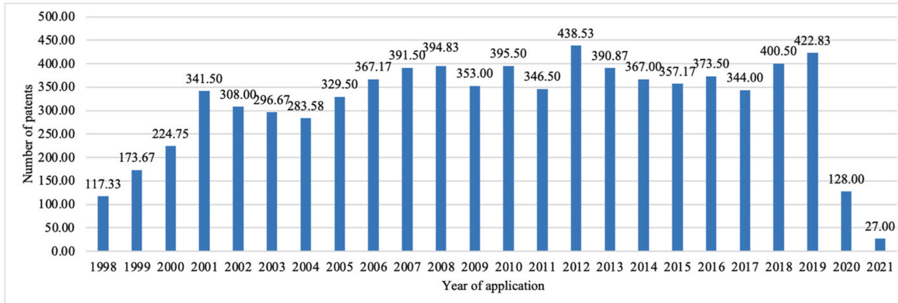

Fig. 2. Number of patents in hydrogen technologies over time. Source: author's elaboration.

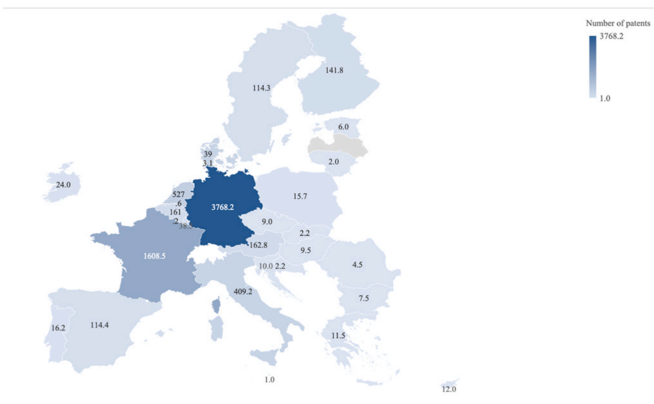

Fig. 3. Number of patents in hydrogen technologies in EU countries 1998–2021. Source: author's elaboration.

Table 3
Descriptive statistics. Source: author's elaboration.

Variable	Obs	Mean	Std. Dev.	Min	Max
Dependent variables					
Hydrogen patents t+2	540	13.198	36.182	0	244
Hydrogen patents t+1	540	12.737	35.315	0	244
Firm that patent t+2	540	15.074	41.319	0	269
Firm that patent t+1	540	14.515	40.152	0	269
Independent variables					
Human capital					
Graduate population	540	30.904	11.172	8.671	57
Quality of governments					
Size of Government	540	5.984	0.86	4.217	7.832
Legal System and Property Rights	540	7.025	0.99	4.644	8.998
Sound Money	540	9.19	0.828	2	9.897
Freedom to Trade Internationally	540	8.308	0.59	6.017	9.684
Regulation	540	7.411	0.619	5.433	8.645
Sustainability endorsement					
Hydrogen public R&D	540	0.005	0.017	0	0.149
Sustainable competiveness index	540	51.086	4.206	40.758	62.965
Control variables					
Economically active population	540	7571.393	9930.919	133.087	43,111
Unemployment rate	540	9.056	4.381	1.8	27.5
Risk of poverty	540	24.998	8.528	12.2	61.3
GDP	540	459.149	727.039	7.295	3605.24

6.1. Empirical results

Table 4 shows the results of linear regression with a fixed effect of factors influencing innovation in hydrogen technologies.

Human capital. *Graduate population* is positive and significant, implying that a higher percentage of educated individuals contribute to hydrogen technology ($b = 0.147$, $p < 0.01$). A high level of education could provide a larger pool of talent that can contribute specialized skills and advanced knowledge in the hydrogen field, thus facilitating innovation. Our results thus confirm previous findings of the literature on human capital and innovation, according to which the former is a valuable input for innovation and competitiveness (Dakhli and De Clercq, 2004; Maskell and Malmberg, 1999). Moreover, this finding also aligns with the specific literature on green innovation. As demonstrated by Pinate et al. (2024), Yun et al. (2020), Consoli et al. (2016), for green innovation to occur, high levels of cognitive skills and highly educated individuals are fundamental, as well as a high level of education.

Institutional quality. *Government size* is not statistically significant, suggesting that the extent to which a country relies on the political process to allocate resources, goods and services does not have a significant impact on the number of patents in the hydrogen sector. *Legal System and Property Rights* is significant and positive indicating that an effective legal system and property rights protection are associated with an increase in the number of hydrogen patents ($b = 3.430$, $p < 0.05$). A stable legal environment and property rights protection can encourage investment and innovation in the sector, confirming results of the extant

Table 4
Econometrics results. Source: author's elaboration.

	Model 1	
Variables	Hydrogen patents t+2 (FE)	
	Coeff	Standard error
Human capital		
Graduate population	0.147**	(0.0698)
Institutional quality		
Size of Government	1.099	(1.256)
Legal System and Property Rights	3.430**	(1.445)
Sound Money	−0.609	(0.712)
Freedom to Trade Internationally	1.130	(1.044)
Regulation	−3.922***	(1.081)
Sustainability endorsement		
Hydrogen public R&D	188.5***	(34.75)
Sustainable competitiveness index	0.273*	(0.140)
Control variable		
Economically active population	0.00215***	(0.000637)
Unemployment rate	0.0680	(0.136)
Risk of poverty	−0.0764	(0.147)
GDP	−0.0129**	(0.00545)
Constant	−20.67	(17.60)
Observations	540	
R-squared	0.6227	
Number of states	27	

Standard errors in parentheses,*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

literature (see, for example, Clò et al., 2020; Butenko and Larouche, 2015; Rodríguez-Pose and Storper, 2006), according to which a stable legal environment and proper intellectual property rights encourage companies to invest in new ideas and technologies. *Sound Money* is not statistically significant. The consistency of monetary policy with long-term price stability has no impact on the number of patents in the hydrogen sector. *Freedom to Trade Internationally* is not significant suggesting that restrictions on international trade may not affect innovation in the hydrogen sector. *Regulation* is also significant and negative (b = -3.922, $p < 0.01$), suggesting that regulatory restrictions hinder hydrogen innovation. These results confirm previous studies on the relevance of the institutional context (see, for example, Santoalha and Boschma, 2021; D'Ingiullo and Evangelista, 2020; Sun et al., 2019).

Sustainability endorsement. Focusing on the specific public investment in hydrogen, *Hydrogen public R&D* is significant and positive (b = 188.5, $p < 0.01$). This suggests that greater public investment in hydrogen technology R%D is associated with an increase in the number of patents in the field, highlighting the role of public investment in promoting innovation in strategic sectors such as hydrogen. This result, therefore, confirms the relevance of public support in innovative technologies, especially the more riskier ones, as the extant literature previously demonstrated (see, for example, Bronzini and Piselli, 2016; Moretti and Wilson, 2014; Branstetter and Sakakibara, 2002) . *Sustainable competitiveness index* is significant and positive, indicating that greater global sustainable competitiveness is associated with an increase in the number of patents in the hydrogen sector ($b = 0.273$, $p < 0.1$). Sustainable competitiveness could foster an environment conducive to innovation in the hydrogen sector, promoting the development of sustainable and competitive solutions in the global market.

Control variable. *Economically active population* is positive and significant, indicating that a larger working population contributes positively to hydrogen technologies ($b = 0.00215$, $p < 0.01$), maily facilitating the generation and circulation of new ideas, which, in turn, support innovation. *Unemployment rate* and *Risk of poverty* are not significant, suggesting that they do not have a significant direct effect on hydrogen innovation. *GDP* is negative and significant, suggesting that higher GDP is associated with less innovation in the hydrogen sector (b = -0.0129, $p < 0.05$). This may be because in countries with a high GDP, economies tend to be more mature and diversified. This means that, rather than focusing exclusively on emerging technologies such as hydrogen, they may be more inclined to invest in a wide range of technological and innovative sectors.

6.2. Robustness test

As a robustness test, we use a different time lag of one year and a different dependent variable (*i.e.,* the number of firms patenting in the hydrogen field) and the random effect model. The results are in line with previous ones, as shown in Table 5.

Table 5
Robustness test. Source: author's elaboration.

	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Variables	Hydrogen patents t+2 (RE)	Hydrogen patents t+1 (FE)	Hydrogen patents t+1 (RE)	Firm that patent t+2 (FE)	Firm that patent t+2 (RE)	Firm that patent t+1 (FE)	Firm that patent t+1 (RE)
Human capital							
Graduate population	0.123*	0.153**	0.138*	0.0362***	0.0316***	0.0426***	0.0396***
	(0.0689)	(0.0756)	(0.0742)	(0.00420)	(0.00394)	(0.00435)	(0.00402)
Institutional quality							
Size of Government	0.704	−0.183	−0.414	−0.111	−0.149**	−0.337***	−0.364***
	(1.198)	(1.361)	(1.280)	(0.0684)	(0.0656)	(0.0696)	(0.0655)
Legal System and Property Rights	4.314***	3.462**	4.172***	0.562***	0.573***	0.668***	0.668***
	(1.359)	(1.566)	(1.449)	(0.0871)	(0.0812)	(0.0886)	(0.0806)
Sound Money	−0.674	−0.405	−0.494	−0.127	−0.0856	−0.0830	−0.0551
	(0.719)	(0.772)	(0.775)	(0.0786)	(0.0791)	(0.0802)	(0.0804)
Freedom to Trade Internationally	1.423	1.107	1.150	0.112**	0.154***	0.110**	0.133***
	(1.038)	(1.131)	(1.120)	(0.0468)	(0.0448)	(0.0480)	(0.0455)
Regulation	−3.865***	−3.908***	−3.750***	−0.159***	−0.178***	−0.304***	−0.319***
	(1.085)	(1.172)	(1.169)	(0.0427)	(0.0417)	(0.0437)	(0.0424)
Sustainability endorsement							
Hydrogen public R&D	172.1***	222.3***	215.6***	1.110*	1.166*	1.641**	1.706**
	(33.71)	(37.66)	(36.32)	(0.663)	(0.661)	(0.683)	(0.678)
Sustainable competiveness index	0.295**	0.277*	0.298**	0.0347***	0.0338***	0.0395***	0.0380***
	(0.140)	(0.152)	(0.151)	(0.00693)	(0.00686)	(0.00706)	(0.00697)
Control variable							
Economically active population	0.00272***	0.00285***	0.00278***	5.98e-05***	0.000107***	0.000103***	0.000132***
	(0.000399)	(0.000690)	(0.000417)	(2.08e-05)	(1.47e-05)	(2.18e-05)	(1.41e-05)
Unemployment rate	0.0630	−0.0902	−0.0887	−0.00342	−0.00514	−0.0309***	−0.0331***
	(0.137)	(0.148)	(0.148)	(0.00830)	(0.00825)	(0.00858)	(0.00850)
Risk of poverty	−0.118	−0.00175	−0.0395	−0.0564***	−0.0502***	−0.0357**	−0.0260**
	(0.143)	(0.160)	(0.153)	(0.0149)	(0.0131)	(0.0151)	(0.0130)
GDP	−0.00326	−0.0113*	−0.00351	−0.000186**	−0.000203***	−0.000185**	−0.000197***
	(0.00479)	(0.00590)	(0.00512)	(7.55e-05)	(7.34e-05)	(7.62e-05)	(7.35e-05)
Constant	−34.74**	−22.56	−29.59*		−3.489**		−3.126**
	(16.54)	(19.08)	(17.67)		(1.366)		(1.353)
lnalpha					−0.0750		−0.362
					(0.304)		(0.305)
Observations	540	540	540	520	540	520	540
R-squared	0.7000	0.6572	0.6989				
Number of states	27	27	27	27	27	27	27

Standard errors in parentheses ***p < 0.01, **p < 0.05, *p < 0.1.

7. Discussion and conclusion

Governments across the world, and especially in Europe, are devoting particular attention to the search for new sources of energy, especially to mitigate the climate change effect (Sun et al., 2019). Among the potential new forms of energy, that of hydrogen seems to be particularly promising for the future, thanks to its features, e.g. it is a safe and clean high quality fuel (Becker, 2015), its production may address issues of intermittency in renewable energy generation (Sun et al., 2019), it can replace fossil fuels, facilitating the use of more sustainable sources of energy (Sarkar et al., 2019).

The relevance of hydrogen innovation, as well as the transition to a hydrogen economy, has been at the heart of policy initiatives at the European level. For these policies to be effective, national governments have to develop their own national strategies, taking into account their national and regional characteristics as well as innovative capacity. As the traditional literature on economics of innovation and green innovation has shown, countries and regions have different innovative potential, different socio-economic development and are lastly characterized by a different institutional setting (Ortega and Serna, 2020; Camagni and Capello, 2005; Edquist, 1997). According to the National Innovation System or the Regional Innovation System perspective, innovation is the result of a complex set of interactions among different actors, playing in a specific context with a different institutional framework. In this context, understanding which are the factors supporting the development of hydrogen technologies becomes crucial for the design of an efficient place-based hydrogen innovation policy, for the development of a hydrogen economy, and lastly, to support the future development of the hydrogen valley.

This paper aims at addressing this gap by analyzing which are the determinants of hydrogen innovation in European countries. To this end, patent data from 1998 to 2019 has been used as a hydrogen innovation proxy. Following the extant literature, determinants have been grouped in human capital, sustainability endorsement and institutional quality.

Our results confirm previous findings of the literature on the determinants of innovation and, especially, the green and sustainable one (Fig. 4).

First, the relevant role of skilled human capital turns out to have a positive impact on hydrogen technologies. In fact, as previously highlighted by the literature, human capital, especially the highly skilled one, plays a fundamental role in fostering innovation through knowledge creation, knowledge sharing and new idea development (Baycan et al., 2017; Dahkli and De Clerq, 2004). Human capital, particularly the skilled one, in fact, is a key input resource that can be converted into innovative output (Bourdieu, 1986) enhancing, in turn, country and regional economic growth and competitiveness (Dakhli and De Clercq, 2004; Cannon, 2000; Maskell and Malmberg, 1999). The role of skilled human capital becomes particularly relevant when green innovation is concerned (Pinate et al., 2024; European Commission, 2021, 2022; Consoli et al., 2016). As such, in order to support the development of hydrogen technologies and the transition to hydrogen technology, investment in human capital is fundamental at the regional and country level, especially to support the development of specific courses at the higher education level, support continuous training and education, and, eventually, support university-industry collaboration.

Second, the relevance of institutional quality in supporting hydrogen innovation is confirmed, especially with respect on the one hand to the legal system and property and, on the other hand, regulation. According to the literature on innovation, institutions are not only players, but they set the rules of the game (North, 1990) and, acting as a kind of "social filters" (Crescenzi and Rodriguez-Pose, 2009), they can support the translation of innovative input generated by human capital into innovative output (D'Ingiullo and Evangelista, 2020). A sound legal system and intellectual property rights can foster hydrogen innovation, pushing companies to invest in innovative ideas, processes and technologies (Clò et al., 2020; Butenko and Larouche, 2015; Rodríguez-Pose and Storper, 2006). This perspective aligns with the idea that a stable legal framework and intellectual property rights can indeed encourage innovation in emerging technologies like hydrogen. These results are aligned with the more recent studies on institutional quality and green innovation. For example, Chen et al. (2024), Amin et al. (2023), and Dam et al. (2023) argue that robust institutions protecting intellectual property rights encourage investment in green innovations. Conversely, we find that stringent government regulation has the effect of hindering hydrogen innovation, limiting investment from the private sector side, confirming previous results showing the "crowding out" effect of regulation.

Lastly, concerning sustainability endorsement, two factors have a positive impact on hydrogen innovation. First, the results show the importance of investing in R&D activities to promote innovation. Our study highlights that specific government investment in hydrogen technologies has a positive impact on innovation in the sector. This result suggests that targeted government funding for research and

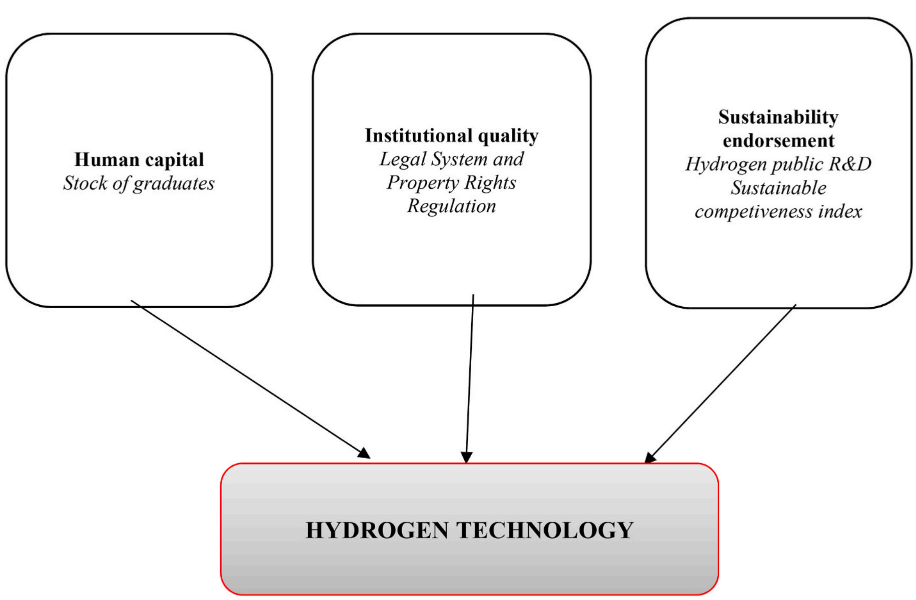

Fig. 4. Determinants of hydrogen innovation. Authors' elaboration.

development of hydrogen technologies can foster innovation and technological advancement in this crucial sector. In line with the previous literature, public support for explorative innovation (Gao et al., 2021), which generally requires a high level of initial investment and is characterized by a high level of uncertainty, turns out to support innovation in hydrogen technologies. In this context, public incentives to R&D may support companies in undertaking riskier innovation activities and also in being involved in more challenging technological projects (Bronzini and Piselli, 2016). Lastly, due to the national and European endorsement in supporting hydrogen innovation and the development of a hydrogen economy, supply support becomes fundamental, not only in providing financial supports but also in developing technology, innovation and R&D policies in accordance with the national and supranational priority (Gao et al., 2021). The sustainable competitiveness index plays a significant role in promoting innovation in the hydrogen technology sector. This index, focused on assessing a country's sustainability and competitiveness, provides a useful framework for identifying areas where nations excel or need to improve in terms of sustainability.

In conclusion, this research underscores the importance of a holistic approach to hydrogen innovation. In fact, totally in line with the National and Regional Innovation System Perspective, hydrogen innovation is the result of complex dynamics involving different actors acting in a specific institutional framework and in a specific geographical area, with its own specific features (Ortega and Serna, 2020; Camagni and Capello, 2005; Edquist, 1997).

7.1. Policy implications and limitations of the study

Our results lead to the identification of different policy implications, which we highlight following the three dimensions of our framework of analysis.

First, investment in human capital turns out to be a fundamental driver for the development of hydrogen technologies. On the one hand, we claim that country level policies are necessary to support the development of specific university courses that, at the highest level of education, provide the necessary skills and competencies to support the transition to a hydrogen economy. Second, continuous training, by way of example through government-sponsored programs at different levels of education and work experience, has proven to be an important driver for individuals to continuously upgrade their skills, not only at the university level (World Development Report, 2008). A third policy alternative we suggest is strengthening university-industry collaboration, which can be a valuable source of innovation (Tian et al., 2022; Shi et al., 2020; Freitas et al., 2013), for example with the 'industrial doctorate' and specific government-funded projects or Public Private Partnership.

Second, national and European institutions do play a relevant role in fostering the development of hydrogen technology. Regulation, in particular, may be treated with caution: if, on the one hand, it can support innovation, it turns out to be a hindering factor. It is therefore necessary to design a common regulatory framework effectively able to support hydrogen innovation through the definition of measures and standards to be achieved but that, at the same time, do not discourage companies' investment in hydrogen technology. In other words, national and European institutions should work together to define a coherent set of policy tools, by way of example, a mix of "market regulation" and "command and control regulation" that effectively supports hydrogen technology adoption and the transition to a hydrogen economy.

Moreover, it is important, from the perspective of sustainability endorsement, to support R&D activities through devoted resources and incentives focused on the development of hydrogen-related technologies and create funding programs for research institutes, universities and businesses. Second, designing and implementing specific incentives for companies that invest in hydrogen research and development, thereby encouraging innovation. These policy tools are fundamental drivers for companies to promote the transition to a hydrogen economy, not only because they support companies in engaging in exploratory innovation but also to align innovative activities at the firm level with the technological strategic areas at the country and European levels. Moreover, in order to facilitate the future creation of the hydrogen valleys, cross-country collaboration should also be supported, facilitating the sharing of knowledge, resources and technologies.

Lastly, despite the endorsement and support at the European level, it is crucial to establish specific policies and tools at the national level to facilitate the transition to a hydrogen economy. Since the adoption of hydrogen technologies varies across European countries, tailored, place-based policies must be developed at both national and regional levels. These policies should consider the key factors influencing these technologies, along with the unique territorial characteristics, preconditions, and innovation potential of each country or region.

This study is not devoid of limitations. Not all inventions are patented, so the number of patents in a state may not be fully representative of the total level of innovation. Studying the European context, some of our results may not be applicable to other countries or regions. While qualitative analysis can elucidate *why*, quantitative analysis clarifies *what*. Regarding this study, we look at the characteristics that influence innovation in hydrogen technology but are unable to explain why these things are important for innovation.

CRediT authorship contribution statement

Chiara Leggerini: Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Mariasole Bannò:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision. **Martina Dal Molin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision.

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

Table S1
table of correlation matrix. Authors' elaboration

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Hydrogen patents t+2	1															
2	Hydrogen patents t+1	0.973	1														
3	Firm that patent t+2	0.997	0.97	1													
4	Firm that patent t+1	0.972	0.997	0.973	1												
5	Graduate population	0.003	0.004	0.01	0.012	1											
6	Size of Government	−0.088	−0.088	−0.087	−0.087	−0.15	1										
7	Legal System and Property Rights	0.313	0.311	0.304	0.301	0.416	−0.421	1									
8	Sound Money	0.162	0.16	0.162	0.16	0.329	−0.196	0.494	1								
9	Freedom to Trade Internationally	0.162	0.156	0.156	0.15	0.255	−0.137	0.574	0.713	1							
10	Regulation	−0.089	−0.087	−0.085	−0.085	0.508	−0.161	0.444	0.331	0.323	1						
11	Hydrogen public R&D	0.522	0.525	0.557	0.562	0.149	−0.149	0.185	0.136	0.063	0.042	1					
12	Sustainable competiveness index	0.143	0.142	0.139	0.139	0.152	−0.414	0.517	0.25	0.224	0.324	0.112	1				
13	Economically active population	0.793	0.789	0.801	0.797	−0.08	−0.031	0.116	0.096	0.049	−0.201	0.523	−0.024	1			
14	Unemployment rate	−0.092	−0.095	−0.088	−0.09	−0.004	0.081	−0.381	−0.175	−0.303	−0.258	−0.044	−0.113	0.091	1		
15	Risk of poverty	−0.229	−0.225	−0.226	−0.223	−0.237	0.518	−0.644	−0.457	−0.391	−0.264	−0.186	−0.395	−0.069	0.419	1	
16	GDP	0.869	0.864	0.876	0.87	−0.006	−0.117	0.275	0.215	0.193	−0.112	0.59	0.075	0.951	−0.012	−0.219	1

Data availability

The authors do not have permission to share data.

References

Agboola, M.O., Alola, A.A., 2023. The energy mix-environmental aspects of income and economic freedom in Hong Kong: cointegration and frequency domain causality evidence. J. Environ. Econ. Policy 12 (1), 63–78.
Amin, N., Shabbir, M.S., Song, H., Farrukh, M.U., Iqbal, S., Abbass, K., 2023. A step towards environmental mitigation: do green technological innovation and institutional quality make a difference? Technol. Forecast. Soc. Change 190, 122413.
Ampah, J.D., Jin, C., Fattah, I.M.R., Appiah-Otoo, I., Afrane, S., Geng, Z., Yusuf, A.A., Li, T., Mahlia, T.I., Liu, H., 2023. Investigating the evolutionary trends and key enablers of hydrogen production technologies: a patent-life cycle and econometric analysis. Int. J. Hydrogen Energy 48 (96), 37674–37707.
Aron, A.S., Molina, O., 2020. Green innovation in natural resource industries: the case of local suppliers in the Peruvian mining industry. Extr. Ind. Soc. 7 (2), 353–365.
Ashari, P.A., Blind, K., 2024. The effects of hydrogen research and innovation on international hydrogen trade. Energy Policy 186, 113974.
Ashari, P.A., Oh, H., Koch, C., 2024. Pathways to the hydrogen economy: a multidimensional analysis of the technological innovation systems of Germany and South Korea. Int. J. Hydrogen Energy 49, 405–421.
Ashwin, A.S., Krishnan, R.T., George, R., 2015. Family firms in India: family involvement, innovation and agency and stewardship behaviors. Asia Pac. J. Manag. 32, 869–900.
Ball, M., Weeda, M., 2015. The hydrogen economy–vision or reality? Int. J. Hydrogen Energy 40 (25), 7903–7919.
Bampaou, M., Panopoulos, K.D., 2025. An overview of hydrogen valleys: current status, challenges and their role in increased renewable energy penetration. Renew. Sustain. Energy Rev. 207, 114923.
Barbieri, N., Perruchas, F., Consoli, D., 2020. Specialization, diversification, and environmental technology life cycle. Econ. Geogr. 96 (2), 161–186.
Baycan, T., Nijkamp, P., Stough, R., 2017. Spatial spillovers revisited: innovation, human capital and local dynamics. Int. J. Urban Reg. Res. 41 (6), 962–975.
Becker, G., 1964. Human Capital. The University of Chicago Press, Chicago.
Becker, B., 2015. Public R&D policies and private R&D investment: a survey of the empirical evidence. J. Econ. Surv. 29 (5), 917–942.
Benhabib, J., Spiegel, M.M., 2005. Human capital and technology diffusion. Handb. Econ. Growth 1, 935–966.
Bockris, J.O.M., 2013. The hydrogen economy: its history. Int. J. Hydrogen Energy 38 (6), 2579–2588.
Bolz, S., Thiele, J., Wendler, T., 2024. Regional capabilities and hydrogen adoption barriers. Energy Policy 185, 113934.
Boschma, R., Coenen, L., Frenken, K., Truffer, B., 2018. Towards a theory of regional diversification: combining insights from evolutionary economic geography and transition studies. In: Transitions in Regional Economic Development. Routledge, pp. 55–81.
Boudreaux, C.J., 2017. Institutional quality and innovation: some cross-country evidence. J. Entrepren. Public Policy 6 (1), 26–40.
Bourdieu, D., 1986. The forms of capital. In: Richardson, J. (Ed.), Handbook of Theory and Research for the Sociology of Education. Greenwood, New York, pp. 241–258.
Branstetter, L.G., Sakakibara, M., 2002. When do research consortia work well and why? Evidence from Japanese panel data. Am. Econ. Rev. 92 (1), 143–159.
Bronzini, R., Piselli, P., 2016. The impact of R&D subsidies on firm innovation. Res. Pol. 45 (2), 442–457.
Buesa, M., Heijs, J., Baumert, T., 2010. The determinants of regional innovation in Europe: a combined factorial and regression knowledge production function approach. Res. Pol. 39 (6), 722–735.
Butenko, A., Larouche, P., 2015. Regulation for innovativeness or regulation of innovation? Law Innov. Technol. 7 (1), 52–82.
Cader, J., Koneczna, R., Olczak, P., 2021. The impact of economic, energy, and environmental factors on the development of the hydrogen economy. Energies 14 (16), 4811.
Camagni, R., Capello, R., 2005. ICTs and territorial competitiveness in the era of internet. Ann. Reg. Sci. 39, 421–438.
Cannon, E., 2000. Human capital: level versus growth effects. Oxf. Econ. Pap. 52 (4), 670–676.
Cascio, W.F., Boudreau, J.W., 2016. The search for global competence: from international HR to talent management. J. World Bus. 51 (1), 103–114.
Chen, Y.H., Chen, C.Y., Lee, S.C., 2011. Technology forecasting and patent strategy of hydrogen energy and fuel cell technologies. Int. J. Hydrogen Energy 36 (12), 6957–6969.
Chen, C., Pinar, M., Román-Collado, R., 2024. Green innovation and energy efficiency: moderating effect of institutional quality based on the threshold model. Environ. Resour. Econ. 1–32.
Clò, S., Florio, M., Rentocchini, F., 2020. Firm ownership, quality of government and innovation: evidence from patenting in the telecommunication industry. Res. Pol. 49 (5), 103960.
Consoli, D., Marin, G., Marzucchi, A., Vona, F., 2016. Do green jobs differ from non-green jobs in terms of skills and human capital? Res. Pol. 45 (5), 1046–1060.
Cooke, P., Uranga, M.G., Etxebarria, G., 1997. Regional innovation systems: institutional and organisational dimensions. Res. Pol. 26 (4–5), 475–491.
Crescenzi, R., Rodríguez-Pose, A., 2009. Systems of innovation and regional growth in the EU: endogenous vs. external innovative activities and socio-economic conditions. In: Growth and Innovation of Competitive Regions: the Role of Internal and External Connections. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 167–191.
Dakhli, M., De Clercq, D., 2004. Human capital, social capital, and innovation: a multi-country study. Entrepren. Reg. Dev. 16 (2), 107–128.
Dam, M.M., Işık, C., Ongan, S., 2023. The impacts of renewable energy and institutional quality in environmental sustainability in the context of the sustainable development goals: a novel approach with the inverted load capacity factor. Environ. Sci. Pollut. Control Ser. 30 (42), 95394–95409.
Dass, N., Nanda, V., Xiao, S.C., 2017. Truncation bias corrections in patent data: implications for recent research on innovation. J. Corp. Finance 44, 353–374.
Delaney, J.A., Yu, P., 2013. Policy innovation and tertiary education graduation rates: a cross-country analysis. Compare 43 (3), 387–409.
D'Ingiullo, D., Evangelista, V., 2020. Institutional quality and innovation performance: evidence from Italy. Reg. Stud. 54 (12), 1724–1736.
Edquist, C., 1997. Introduction. In: Systems of Innovation Technologies, Institutions and Organisations. Routledge, London, pp. 1–5.
Edquist, C., 1999. Innovation Policy: a Systemic Approach. Tema, Univ, p. 19.

Emodi, N.V., Lovell, H., Levitt, C., Franklin, E., 2021. A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies. Int. J. Hydrogen Energy 46 (60), 30669–30697.
European Commission, 2021. Towards a Zero Pollution for Air Water and Soil available at: EUR-Lex - 52021DC0400 - EN - EUR-Lex (europa.eu).
European Commission, 2022. Flash Eurobarometer 456: Smes, Resource Efficiency and Green Market, Available At: Smes, Green Markets and Resource Efficiency - Publications Office of the EU (Europa.Eu).
Feichtinger, G., Hartl, R.F., Kort, P.M., Veliov, V.M., 2005. Environmental policy, the porter hypothesis and the composition of capital: effects of learning and technological progress. J. Environ. Econ. Manag. 50 (2), 434–446.
Freitas, I.M.B., Marques, R.A., e Silva, E.M.D.P., 2013. University–industry collaboration and innovation in emergent and mature industries in new industrialized countries. Res. Pol. 42 (2), 443–453.
Galliano, D., Nadel, S., Triboulet, P., 2023. The geography of environmental innovation: a rural/urban comparison. Ann. Reg. Sci. 71 (1), 27–59.
Gans, J.S., 2012. Innovation and climate change policy. Am. Econ. J. Econ. Pol. 4 (4), 125–145.
Gao, Y., Hu, Y., Liu, X., Zhang, H., 2021. Can public R&D subsidy facilitate firms' exploratory innovation? The heterogeneous effects between central and local subsidy programs. Res. Pol. 50 (4), 104221.
Grillitsch, M., Hansen, T., 2019. Green industry development in different types of regions. Eur. Plan. Stud. 27 (11), 2163–2183.
Gupta, R., Guibentif, T.M., Friedl, M., Parra, D., Patel, M.K., 2023. Macroeconomic analysis of a new green hydrogen industry using input-output analysis: the case of Switzerland. Energy Policy 183, 113768.
Hacking, N., Pearson, P., Eames, M., 2019. Mapping innovation and diffusion of hydrogen fuel cell technologies: evidence from the UK's hydrogen fuel cell technological innovation system, 1954–2012. Int. J. Hydrogen Energy 44 (57), 29805–29848.
Häggmark, T., Elofsson, K., 2022. The drivers of private and public eco-innovations in six large countries. J. Clean. Prod. 364, 132628.
Hall, B.H., Jaffe, A.B., Trajtenberg, M., 2001. The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools.
Hansmeier, H., Kroll, H., 2024. The geography of eco-innovations and sustainability transitions: a systematic comparison. ZFW–Adv. Econ. Geograph. (0).
Hassan, Q., Algburi, S., Sameen, A.Z., Salman, H.M., Jaszczur, M., 2024. Green hydrogen: a pathway to a sustainable energy future. Int. J. Hydrogen Energy 50, 310–333.
Havercroft, J., 2021. The British academy brian barry prize essay why is there No just riot theory? Br. J. Polit. Sci. 51 (3), 909–923.
Hellwig, T., Marinova, D.M., 2023. Evaluating the unequal economy: poverty risk, economic indicators, and the perception gap. Polit. Res. Q. 76 (1), 253–266.
Horbach, J., Chen, Q., Rennings, K., Vögele, S., 2014. Do lead markets for clean coal technology follow market demand? A case study for China, Germany, Japan and the US. Environ. Innov. Soc. Transit. 10, 42–58.
Hueske, A.K., Endrikat, J., Guenther, E., 2015. External environment, the innovating organization, and its individuals: a multilevel model for identifying innovation barriers accounting for social uncertainties. J. Eng. Technol. Manag. 35, 45–70.
Jain, I.P., 2009. Hydrogen the fuel for 21st century. Int. J. Hydrogen Energy 34 (17), 7368–7378.
Johnstone, N., Haščič, I., Popp, D., 2010. Renewable energy policies and technological innovation: evidence based on patent counts. Environ. Resour. Econ. 45, 133–155.
Kar, S.K., Sinha, A.S.K., Bansal, R., Shabani, B., Harichandan, S., 2023. Overview of hydrogen economy in Australia. Wiley Interdiscip. Rev.: Energy Environ. 12 (1), e457.
Kemp, R., Pontoglio, S., 2011. The innovation effects of environmental policy instruments—A typical case of the blind men and the elephant? Ecol. Econ. 72, 28–36.
Lambert, T.E., Mattson, G.A., Dorriere, K., 2017. The impact of growth and innovation clusters on unemployment in US metro regions. Reg. Sci. Policy Pract. 9 (1), 25–38.
Lengyel, B., Bokányi, E., Di Clemente, R., Kertész, J., González, M.C., 2020. The role of geography in the complex diffusion of innovations. Sci. Rep. 10 (1), 15065.
Lenihan, H., McGuirk, H., Murphy, K.R., 2019. Driving innovation: public policy and human capital. Res. Pol. 48 (9), 103791.
Lerner, J., Seru, A., 2022. The use and misuse of patent data: issues for finance and beyond. Rev. Financ. Stud. 35 (6), 2667–2704.
Li, S., Shao, Q., 2021. Exploring the determinants of renewable energy innovation considering the institutional factors: a negative binomial analysis. Technol. Soc. 67, 101680.
Li, D., Heimeriks, G., Alkemade, F., 2021. Recombinant invention in solar photovoltaic technology: can geographical proximity bridge technological distance? Reg. Stud. 55 (4), 605–616.
Liang, Q., Li, X., Yang, X., Lin, D., Zheng, D., 2013. How does family involvement affect innovation in China? Asia Pac. J. Manag. 30, 677–695.
Losacker, S., Horbach, J., Liefner, I., 2023a. Geography and the speed of green technology diffusion. Ind. Innovat. 30 (5), 531–555.
Losacker, S., Hansmeier, H., Horbach, J., Liefner, I., 2023b. The geography of environmental innovation: a critical review and agenda for future research. Rev. Reg. Res. 43 (2), 291–316.
Macher, J.T., Rutzer, C., Weder, R., 2024. Is there a secular decline in disruptive patents? Correcting for measurement bias. Res. Pol. 53 (5), 104992.
Madsen, A.N., Andersen, P.D., 2010. Innovative regions and industrial clusters in hydrogen and fuel cell technology. Energy Policy 38 (10), 5372–5381.
Maskell, P., Malmberg, A., 1999. Localised learning and industrial competitiveness. Camb. J. Econ. 23 (2), 167–185.
Milindi, C.B., Inglesi-Lotz, R., 2022. The role of green technology on carbon emissions: does it differ across countries' income levels? Appl. Econ. 54 (29), 3309–3339.
Mona, S., Kumar, S.S., Kumar, V., Parveen, K., Saini, N., Deepak, B., Pugazhendhi, A., 2020. Green technology for sustainable biohydrogen production (waste to energy): a review. Sci. Total Environ. 728, 138481.
Montresor, S., Quatraro, F., 2020. Green technologies and smart specialisation strategies: a European patent-based analysis of the intertwining of technological relatedness and key enabling technologies. Reg. Stud. 54 (10), 1354–1365.
Moretti, E., Wilson, D.J., 2014. State incentives for innovation, star scientists and jobs: evidence from biotech. J. Urban Econ. 79, 20–38.
Ni, L., Ahmad, S.F., Alshammari, T.O., Liang, H., Alsanie, G., Irshad, M., Alyafi-AlZahri, R., BinSaeed, R.H., Al-Abyadh, M.H.A., Bakir, S.M.D.M.A., Ayassrah, A.Y.B. A., 2023. The role of environmental regulation and green human capital towards sustainable development: the mediating role of green innovation and industry upgradation. J. Clean. Prod. 421, 138497.
Niroumand, M., Shahin, A., Naghsh, A., Peikari, H.R., 2021. Frugal innovation enablers, critical success factors and barriers: a systematic review. Creativ. Innovat. Manag. 30 (2), 348–367.
North, D.C., 1990. Institutions, Institutional Change and Economic Performance. Cambridge university press.
Nwani, C., Bekun, F.V., Agboola, P.O., Omoke, P.C., Effiong, E.L., 2023. Industrial output, services and carbon emissions: the role of information and communication technologies and economic freedom in Africa. Environ. Dev. Sustain. 25 (4), 3299–3322.
OECD, 2009. OECD Patent Statistics Manual. OECD. https://doi.org/10.1787/9789264056442-en.
Olejnik, A., Żółtaszek, A., 2020. Tracing the spatial patterns of innovation determinants in regional economic performance. Comp. Econ. Res. 23 (4), 87–108.
Ortega, A.M., Serna, M., 2020. Determinants of innovation performance of organizations in a regional innovation system from a developing country. Int. J. Innovat. Sci. 12 (3), 345–362.
Ott, H., Rondé, P., 2019. Inside the regional innovation system Black box: evidence from French data. Pap. Reg. Sci. 98 (5), 1993–2027.
Pinate, A., Cattani, L., Dal Molin, M., Faggian, A., 2024. Get back to where you once belonged? Effects of skilled internal migration on Italian regional green growth. Pap. Reg. Sci. 103 (4), 100036.
Pinto, J., 2023. The key tenets of a hydrogen strategy: an analysis and comparison of the hydrogen strategies of the EU, Germany and Spain. Global Energy Law Sustain. 4 (1–2), 72–95.
Rajnoha, R., Lesnikova, P., 2022. Sustainable competitiveness: how does global competitiveness index relate to economic performance accompanied by the sustainable development? J. Compet. 14 (1), 136–154.
Rodríguez-Pose, A., 2013. Do institutions matter for regional development? Reg. Stud. 47 (7), 1034–1047.
Rodríguez-Pose, A., Di Cataldo, M., 2015. Quality of government and innovative performance in the regions of Europe. J. Econ. Geogr. 15 (4), 673–706.
Rodríguez-Pose, A., Storper, M., 2006. Better rules or stronger communities? On the social foundations of institutional change and its economic effects. Econ. Geogr. 82 (1), 1–25.
Rodríguez-Pose, A., Villarreal Peralta, E.M., 2015. Innovation and regional growth in M exico: 2000–2010. Growth Change 46 (2), 172–195.
Romer, P.M., 1990. Endogenous technological change. J. Polit. Econ. 98 (5), S71–S102.
Safronova, A., Barisa, A., 2023. Realizing a green hydrogen economy: an examination of influencing factors. Environ. Clim. Technol. 27 (1), 928–949.
Sagar, A.D., Van der Zwaan, B., 2006. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. Energy Policy 34 (17), 2601–2608.
Santoalha, A., Boschma, R., 2021. Diversifying in green technologies in European regions: does political support matter? Reg. Stud. 55 (2), 182–195.
Sarkar, M.S.K., Al-Amin, A.Q., Filho, W.L., 2019. Revisiting the social cost of carbon after INDC implementation in Malaysia: 2050. Environ. Sci. Pollut. Control Ser. 26, 6000–6013.
Scott, A.J., Storper, M., Regions, G., 2003. Development. Reg. Stud. 37 (6&7), 579–593.
Scovell, M.D., 2022. Explaining hydrogen energy technology acceptance: a critical review. Int. J. Hydrogen Energy 47 (19), 10441–10459.
Seck, G.S., Hache, E., Sabathier, J., Guedes, F., Reigstad, G.A., Straus, J., Wolfgang, O., Ouassou, J.A., Askeland, M., Hjorth, I., Skjelbred, H.I., 2022. Hydrogen and the decarbonization of the energy system in Europe in 2050: a detailed model-based analysis. Renew. Sustain. Energy Rev. 167, 112779.
Shi, X., Wu, Y., Fu, D., 2020. Does university-industry collaboration improve innovation efficiency? Evidence from Chinese firms. Econ. Modell. 86, 39–53.
Sinigaglia, T., Freitag, T.E., Kreimeier, F., Martins, M.E.S., 2019. Use of patents as a tool to map the technological development involving the hydrogen economy. World Pat. Inf. 56, 1–8.
Steward, F., 2012. Transformative innovation policy to meet the challenge of climate change: sociotechnical networks aligned with consumption and end-use as new transition arenas for a low-carbon society or green economy. Technol. Anal. Strat. Manag. 24 (4), 331–343.
Sun, H., Edziah, B.K., Sun, C., Kporsu, A.K., 2019. Institutional quality, green innovation and energy efficiency. Energy Policy 135, 111002.
Tebaldi, E., Elmslie, B., 2013. Does institutional quality impact innovation? Evidence from cross-country patent grant data. Appl. Econ. 45 (7), 887–900.
Tian, M., Su, Y., Yang, Z., 2022. University–industry collaboration and firm innovation: an empirical study of the biopharmaceutical industry. J. Technol. Tran. 47 (5), 1488–1505.
Tseng, P., Lee, J., Friley, P., 2005. A hydrogen economy: opportunities and challenges. Energy 30 (14), 2703–2720.

Vivanco-Martín, B., Iranzo, A., 2023. Analysis of the European strategy for hydrogen: a comprehensive review. Energies 16 (9), 3866.

Walker, B., 2024. Place-based allocation of R&D funding: directing the German innovation system for hydrogen technologies in space. Environ. Innov. Soc. Transit. 52, 100878.

Wen, J., Li, L., Zhao, X., Jiao, C., Li, W., 2022a. How government size expansion can affect green innovation—An empirical analysis of data on cross-country green patent filings. Int. J. Environ. Res. Publ. Health 19 (12), 7328.

Wen, J., Okolo, C.V., Ugwuoke, I.C., Kolani, K., 2022b. Research on influencing factors of renewable energy, energy efficiency, on technological innovation. Does trade, investment and human capital development matter? Energy Policy 160, 112718.

Wolf, A., Zander, N., 2021. Green hydrogen in Europe: do strategies meet expectations? available at: https://www.h2knowledgecentre.com/content/journal4467.

Wooldridge, J.M., 2010. Econometric Analysis of Cross Section and Panel Data. MIT press.

World Development Report, 2008. Agriculture for Development. The International Bank for Reconstruction and Development/World Bank, Washington DC.

Xu, J., Wang, X., Liu, F., 2021. Government subsidies, R&D investment and innovation performance: analysis from pharmaceutical sector in China. Technol. Anal. Strat. Manag. 33 (5), 535–553.

Young, A.T., Sheehan, K.M., 2014. Foreign aid, institutional quality, and growth. Eur. J. Polit. Econ. 36, 195–208.

Zanello, G., Fu, X., Mohnen, P., Ventresca, M., 2016. The creation and diffusion of innovation in developing countries: a systematic literature review. J. Econ. Surv. 30 (5), 884–912.

Zhang, J., Li, S., 2023. The impact of human capital on green technology Innovation—Moderating role of environmental regulations. Int. J. Environ. Res. Publ. Health 20 (6), 4803.

Zhu, M., Dong, P., Ju, Y., Li, J., Ran, L., 2023. Effects of government subsidies on heavy-duty hydrogen fuel cell truck penetration: a scenario-based system dynamics model. Energy Policy 183, 113809.

World Economic forum, 2013. The Global Competitiveness Report 2013–2014. available at:. https://www3.weforum.org/docs/WEF_GlobalCompetitivenessReport_2013-14.pdf.