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From grey to green and from west to east: The geography and innovation trajectories of hydrogen fuel technologies

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ABSTRACT

Despite the potential of hydrogen as a sustainable energy carrier, existing studies analysing the recent evolution of this technology are scattered, typically focusing on a specific type of hydrogen technology within a single country or region. In this paper, we adopt a broader perspective, providing an overview of the evolution of knowledge generation across different types of hydrogen fuel, and the leading countries in developing new technologies in this field. Using data from the European Patent Office, we map knowledge generation on hydrogen fuel technologies, exploring its geographic distribution and its link with environmental sustainability. While the United States leads the generation of new knowledge, other Asian and European countries show greater dynamism in growth and specialisation. Our study shows that although hydrogen fuel is considered environmentally friendly, most recent technological developments are still related to fossil energy sources. However, a faster growth rate is observed in the knowledge of hydrogen fuel from renewable sources, pointing to a promising path towards sustainability. Moreover, our analysis of the knowledge interconnection between different hydrogen types suggests that those technologies developed for hydrogen based on fossil energy sources have enabled novel applications based on renewable energies.

1. Introduction

The development of different sources and means of transmitting energy has been a key element in the evolution of humankind for centuries [1]. In the last decades, the focus has been shifted towards renewable energies to reduce our dependency on fossil fuels and address the risks associated with climate change. Such sustainable energy transition pathways are highly complex and uncertain, requiring the development of cleaner energy technologies and complementary institutional and social transformations [2–4]. Geopolitical forces also influence the deep transformations of energy systems and the choice of alternative technological trajectories [5,6].

Among the different technologies available to drive sustainable energy transitions, this paper focuses on the case of hydrogen-driven fuel, which has become one of the most promising developments in recent years [7,8]. Accordingly, many private firms and national governments are investing heavily in developing the multiple potential applications of hydrogen technologies. This leads to increased competition among countries to acquire the knowledge required to become key players in the emerging energy geopolitics of the low-carbon future [8]. For example, after being left behind in recent technological breakthroughs in strategic fields such as artificial intelligence or electric cars, the European Union aims to become a world leader in developing and implementing hydrogen-driven fuel [9]. Furthermore, Rifkin [10] emphasised that the advent of the hydrogen economy will lead to a redistribution of power on Earth. These geopolitical implications of hydrogen technological trajectories are to be interpreted in light of the rise of techno-nationalism over the last decade [11], which has intensified following the Covid-19 pandemic [12,13].

To contribute to better understanding the technological trajectories and the emerging geopolitics of hydrogen fuel, this paper provides a first mapping of the leading countries in the development of new technologies in this field and of the evolution of knowledge generation across different types of hydrogen.[1] The analysis, based on patents, offers new

Abbreviations: PAF, Patent Application Families; EPO, European Patent Office; RPP, Relative Patent Position; RGR, Relative Growth Rate; LRTA, Linear Revealed Technological Advantages.

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[1] We use the words country and economy interchangeably, although some jurisdictions do not have country status.

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insights regarding the countries that are driving the development of such technologies, distinguishing between different types of hydrogen and exploring the technological interconnections between countries and hydrogen types. Before proceeding with the description of the methods and the presentation and discussion of results, the following section summarises the basic features of hydrogen as an energy carrier.

2. Hydrogen fuel: a brief overview

Hydrogen is currently considered as the fuel with the highest energy per mass, although its contribution to sustainable energy transition depends on the energy source used for its production [14–17]. The energy transmitted through hydrogen's molecular form (H_2) is usually classified accompanying the word with a colour representing the contamination level of the energy generation source involved in its separation and the alternative hydrogen division methods. This includes grey hydrogen, obtained from natural gas [18] or other fossil sources such as oil and coal [19–21] (although the latter is sometimes referred to as black hydrogen or brown hydrogen, depending on the colour of the carbon used as an energy source [22–25]); blue hydrogen, if obtained in the same way as grey hydrogen, but capturing the carbon emitted during the hydrogen separation process; pink hydrogen (also known as purple hydrogen), from nuclear energy and through electrolysis; turquoise hydrogen, from natural gas, through the pyrolysis process (without CO_2 emission); and green hydrogen, obtained by electrolysis and from renewable sources, such as solar, wind, sustainable hydroelectric energy, geothermal energy, and wave energy, among others [17,26–29]. Moreover, hydrogen can be obtained from biogenic sources (related to biomass) by fermentation, gasification, reforming, pyrolysis, and bio-photolysis [25].

Some authors have made a relationship between hydrogen colour and greenhouse gas footprint, specifying that grey hydrogen and turquoise hydrogen have a medium footprint, blue hydrogen has a low footprint, and pink hydrogen and green hydrogen have a minimal footprint [24,30].

Green hydrogen is the preferred option in the long term, given its impact on reducing the greenhouse effect behind climate change. However, there are two cheaper alternatives in the short to medium term [31]. Blue hydrogen is one of them because it has a lower CO_2 intensity in hydrogen generation than grey hydrogen, allowing up to 90 % of the carbon emitted in hydrogen production to be captured and stored [25,32]. The other alternative is biomass hydrogen, which is less efficient than blue hydrogen but relies on renewable sources. Its production costs are similar to grey, turquoise, and blue hydrogen [31]. Pink hydrogen is generally considered less appealing given the risks of nuclear accidents, which have dire environmental and economic consequences [33]. This is consistent with the trend towards a reduction in the number of nuclear reactors in the world [34].

Different mechanisms are also linked to energy sources to produce hydrogen [16,17]. Microbial electrolysis cell, dark fermentation, photo fermentation, bio photolysis (also called bio photodissociation, bio photodecomposition), and pyrolysis are related to the biomass; gasification (without biomass), cracking and reforming to fossil fuels (coal, oil, and natural gas); thermochemical division of water is related to nuclear energy (although more recently and increasingly to renewable and biomass energy); and electrolysis is related to different energy sources such as renewable energy, fossil fuels, and nuclear energy. For clarification, Table 1 provides definitions of some of these terms, which were used to conduct the patent queries described in Section 3.

Regarding logistics and delivery, it is worth noting that hydrogen transport can be carried out in its liquid or gaseous state through pipelines used to transport hydrogen, tanker trucks, ships, or even by injecting it into the routes used for natural gas [27]. Given the wide array of alternative technologies, institutional frameworks and infrastructures underpinning the expansion of hydrogen fuel, competitive tensions between different stakeholders and countries over which routes to follow are intensifying [6,38]. For example, within the context of the negotiations over a new regulatory framework regarding renewable energy in the European Union, a coalition of countries led by France is advocating for treating nuclear-based hydrogen in the same terms as green hydrogen. Still, Germany and other member states strongly oppose it.

Table 1
Definition of key concepts related to hydrogen-based energy.

Concept	Definition	Source
Electrolysis	Process of inducing water molecules to split using a direct electric current, producing both hydrogen and oxygen Water electrolysis operates at temperatures of around 80 °C to 120 °C Steam electrolysis operates at temperatures of around 700 °C to 950 °C	Fisher [35]
Thermolysis	Chemical decomposition by heating	Kobayashi [36]
Pyrolysis	Thermolysis carried out when organic compounds are decomposed at high temperatures	Kobayashi [36]
Cracking	Thermolysis of petroleum	Kobayashi [36]
Photolysis	Chemical process by which chemical bonds are broken as the result of the transfer of light energy (direct photolysis) or radiant energy (indirect photolysis) to these bonds	Speight [37]

(*Source*: Authors' elaboration.)

3. Data and methods

As discussed in the introduction, this paper aims to map the development of hydrogen fuel technologies, analyse the geography of knowledge generation, distinguish between different types of hydrogen, and explore the technological interconnections (co-occurrence) both between different leading countries and between technological trajectories.

3.1. Data

Following one of the classic lines of knowledge generation studies [39], this study's primary information source is patent applications. The methodology proposed has been used in earlier research analysing the case of other types of energy generation technologies, such as solar energy [40] or lithium batteries [41–44].

The first step was to collect data through content analysis of titles and abstracts in English of Patent Application Families (PAF) for the European Patent Office (EPO). This search was conducted through the Global Patent Index platform [45], with over 130 million patent documents.

PAF is an adaptation of the simple families that are a collection of patents that claim the same priority, but whose dates are considered from the oldest document of the application of that family [42]. With simple families we can identify patents related to individual inventions, see a document that involves all the inventions, see documents in several languages, etc. Therefore, the quality of the analysis is high. [46].

The PAFs point out the most relevant new knowledge, since only if the applicants perceive a high value of the invention will they incur the cost of patenting.

For this research, the queries to the database were held from June 14 to July 15, 2021, using different keywords to capture knowledge generation related to types of hydrogen (the detailed search criteria used is available in Appendix A).

The trajectory of knowledge generation of hydrogen fuel from 1890 to 2019 has been exponential. As shown in Fig. 1, this evolution can be divided into three stages: an initial latency phase, in which knowledge generation is incipient; a second take-off phase; and, finally, a phase of accelerated growth. Annual data (see Appendix B) shows that the accelerated growth phase began in 2005.

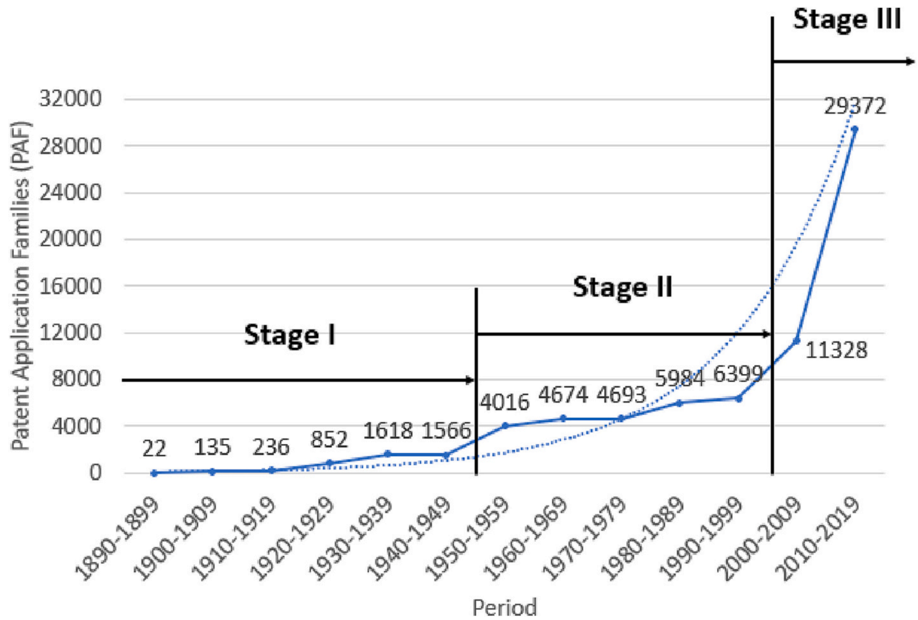


Fig. 1. Evolution of knowledge generation on hydrogen fuel.
(*Source*: Authors' elaboration based on European Patent Office [45].)

Since our paper aims to analyse the recent development of hydrogen fuel technology, the study concentrates on the period 2005–2018. To avoid bias in the sample, the years 2019 and 2020 were ruled out due to the EPO's lag in updating recent data.

A total of 32,872 relevant patent application families were identified for the period 2005–2018. 28,544 of them include a reference to grey hydrogen; 3269 cited biomass hydrogen; 1980 green hydrogen; 232 turquoise hydrogen; 76 blue hydrogen; and 31 pink hydrogen. Given these figures, some parts of our analysis focus on the three main technologies. This comparison is interesting from an environmental point of view, since biomass and green technologies come from renewable sources, in contrast to the grey technology (and the rest).

The different types of knowledge on hydrogen fuel technologies (grey, biomass, etc.) have not evolved in isolation. In this sense, a critical issue is the "connection" between the different types of knowledge studied. To measure this connection, we capture the number of patent application families (PAF) in which two or more types of hydrogen appear simultaneously.

To simplify the analysis, the geography of knowledge generation focuses on the leading countries participating in it. As we will analyse in detail below, these leading countries are United States, China, South Korea, Russia, Japan, Germany, France, Netherlands, United Kingdom, and Canada. To this end, we have set the threshold in those countries with more than 50 patent application families for each type of hydrogen fuel technology. As shown in Table 2, the top 10 leading countries accounted for at least four-fifths of the total patent application families for each type of hydrogen in 2005–2018.

Table 2
Concentration of knowledge generation of hydrogen fuel (% of total PAF).

Type of technology	% PAF of the TOP-10 countries (2005–2018)
All technologies	88
Grey hydrogen	90
Biomass hydrogen	84
Green hydrogen	84
Turquoise hydrogen	93
Blue hydrogen	100
Pink hydrogen	100

(*Source*: Authors' elaboration based on European Patent Office [45].)

3.2. Methods

To achieve the objectives of this research, we introduce different measures of the development of hydrogen fuel technologies. In a first stage, we use the number of patent application families to measure the volume of knowledge generation by type of hydrogen, as well as the intersections between them (i.e., the number of related-PAF) through the number of patent application families linked to more than one type of hydrogen. We also analyse the evolution of this knowledge generation using an index taking the volume in 2005 as the baseline year (i.e., 2005 = 100). With these data, the geography of knowledge generation is studied through the number of patent application families according to the country of residence of the organisation where the invention is made and the interconnection between them, based on the number of patent application families that involve more than one country in the invention. This analysis is run for the whole sample and by type of technology.

In the second stage of analysis, we construct three different indexes to measure the positioning of countries in hydrogen fuel knowledge generation. First, the Relative Patent Position (RPP) to measure the "share or presence" of a country in the knowledge generation associated to a specific technology, taking the leading country as reference [40, 42, 47]:

$$RPP_{ij} = \frac{P_{ij}}{\max_i P_{ij}} \tag{1}$$

where the RPP_{ij} is the relative patent application family presence for the technology j of the economy i; P_{ij} is the number of patent application families of the technology j of the economy i; and consequently, $\max_i P_{ij}$ is the maximum number of patent application families of the leading economy of technology j. This index can be interpreted as a proportion, and its value ranges from zero to one.

The second index is the Relative Growth Rate (RGR), measuring the "attractiveness" or "dynamism" of an economy in relation to the world [40,48]:

$$RGR_{ij} = \frac{G_{ij}}{G_w} \tag{2}$$

where RGR_{ij} is the relative growth rate of patent application families of technology j in the economy i; G_{ij} is the average growth rate of patent application families of technology j in the economy i; and G_w is the average growth rate of patent application families of all technologies in the world. Since $G_w$is strictly positive in the period analysed, the values above the unit imply a catching-up process, while the values below the unit (including negative values) imply retreating.

Finally, the Linear Revealed Technological Advantages (LRTA) index —based on Soete [49], Hoen and Oosterhaven [50], and Moreno-Brieva [44,51]—measures the degree of technological specialisation of an economy in relation to the world, considering the weight of this economy at a global level:

$$LRTA_{ij} = P_{ij}/P_i - P_j/P_w \tag{3}$$

where $LRTA_{ij}$ is the linear revealed technological advantage; P_i is the number of all patent application families of the economy i; P_j is the number of all patent application families of the technology j; and P_w is the number of patent application families of all technologies in the world. The first term of the left side of the equation shows the relative level of knowledge generation of technology j in country i, in relation to all knowledge generation in that country. The second term expresses the relative knowledge generation of technology j globally, in relation to all knowledge generation at a global level. In this sense, values equal to or greater than zero imply that the country i is specialised in the knowledge generation related to technology j.

4. Results

Fig. 2 shows that knowledge generation from 2005 to 2018 is led by grey hydrogen with 28,544 patent application families (representing 86.8 % of the world total), followed by biomass hydrogen and green hydrogen, with 3269 and 1980 patent application families, respectively (representing 9.9 % and 6.0 % of the total). Regarding the interconnection among technologies (i.e., PAF related to more than one hydrogen colour), grey hydrogen is the most connected technology, highlighting the link with biomass hydrogen in 1334 patent application families (representing 4.7 % of the knowledge generation of the former and 40.8 % of the latter). In turn, the links of grey with turquoise hydrogen and green hydrogen are also substantial. Notably, the three types of hydrogen with the most patent applications are the only ones connected with all the other types of hydrogen.

A particular situation arises in the connection of blue with grey hydrogen, since it must be assumed that for the first type to exist there must be an emission of carbon. This leads to a causal relationship indicating that all blue hydrogen is a consequence of grey hydrogen. Consequently, the knowledge generation between these types of hydrogen is 76 patent application families.

Knowledge generation by type of hydrogen, shown in Fig. 3, evolved linearly from 2005 to 2018. Grey hydrogen, biomass hydrogen, and green hydrogen increased their importance, albeit the last two—both based on renewable sources—at a higher speed. On the other hand, knowledge generation of other types of hydrogen (turquoise, blue, and pink) experienced a much lower growth.

The mapping of knowledge generation related to hydrogen as fuel (Fig. 4), considering all countries over the period 2005–2018, shows that the Northern hemisphere is more inventive than the Southern. Asia has the highest number of patent application families, followed by Europe and North America. At the other extreme is Africa, where the scarce knowledge generation is concentrated in South Africa, Morocco, Madagascar, Tunisia, and Egypt. In the Middle East, the leading country is Saudi Arabia, while countries that have conflicted with terrorist groups, such as Iraq, Syria, and Yemen, did not generate knowledge linked to hydrogen as fuel.

China, South Korea, and Japan stand out in Asia, with 1970, 1179, and 921 patent application families, respectively. Russia, Germany, France, the Netherlands, and the United Kingdom are the leading European countries, with 1069, 805, 474, 344, and 315 patent application families, respectively. Finally, the United States and Canada stand out in North America, with 2336 and 231 patent application families, respectively.

The highest number of knowledge generation carried out jointly by two leading economies was between the United States and the Netherlands, with 175 patent application families, followed by the United States with France and the United States with the United Kingdom.

Knowledge generation by type of hydrogen in the top 10 economies

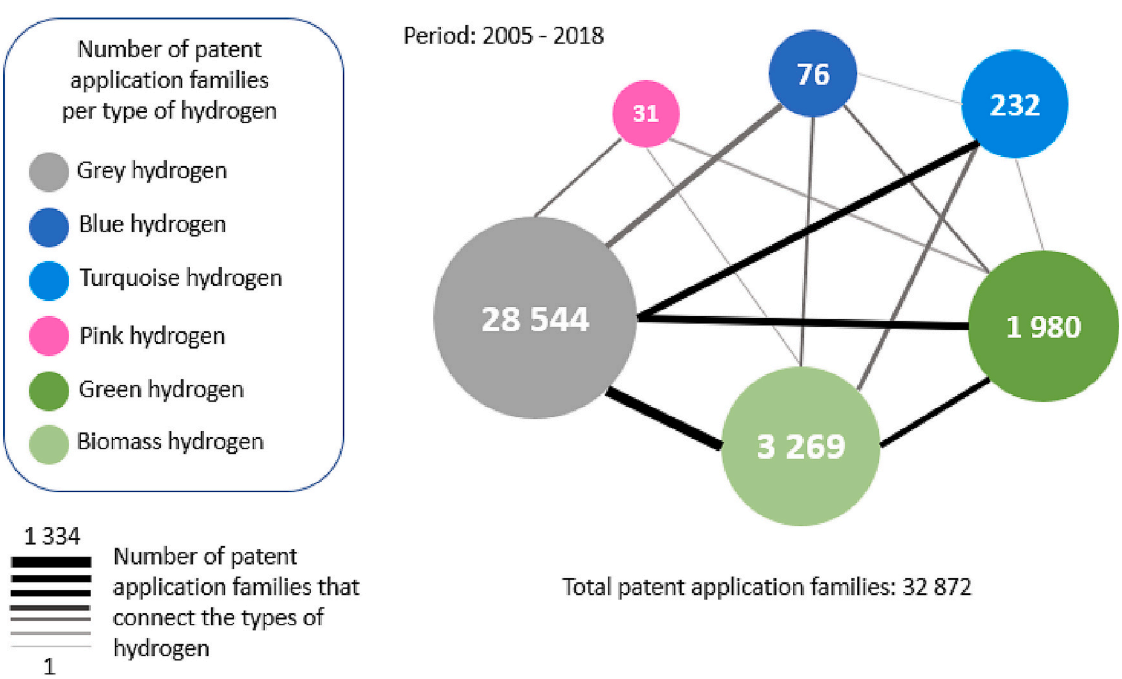


Fig. 2. Knowledge generation by type of hydrogen.
(*Source*: Authors' elaboration based on European Patent Office [45].)

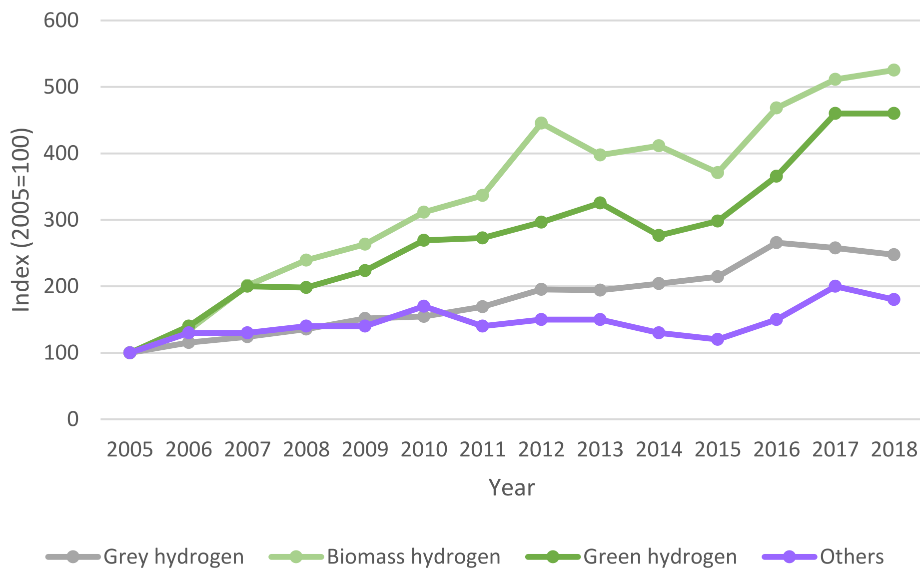


Fig. 3. Evolution of the knowledge generation by type of hydrogen (Number of PAF; Index, 2005 = 100). (Source: Authors' elaboration based on European Patent Office [45].)

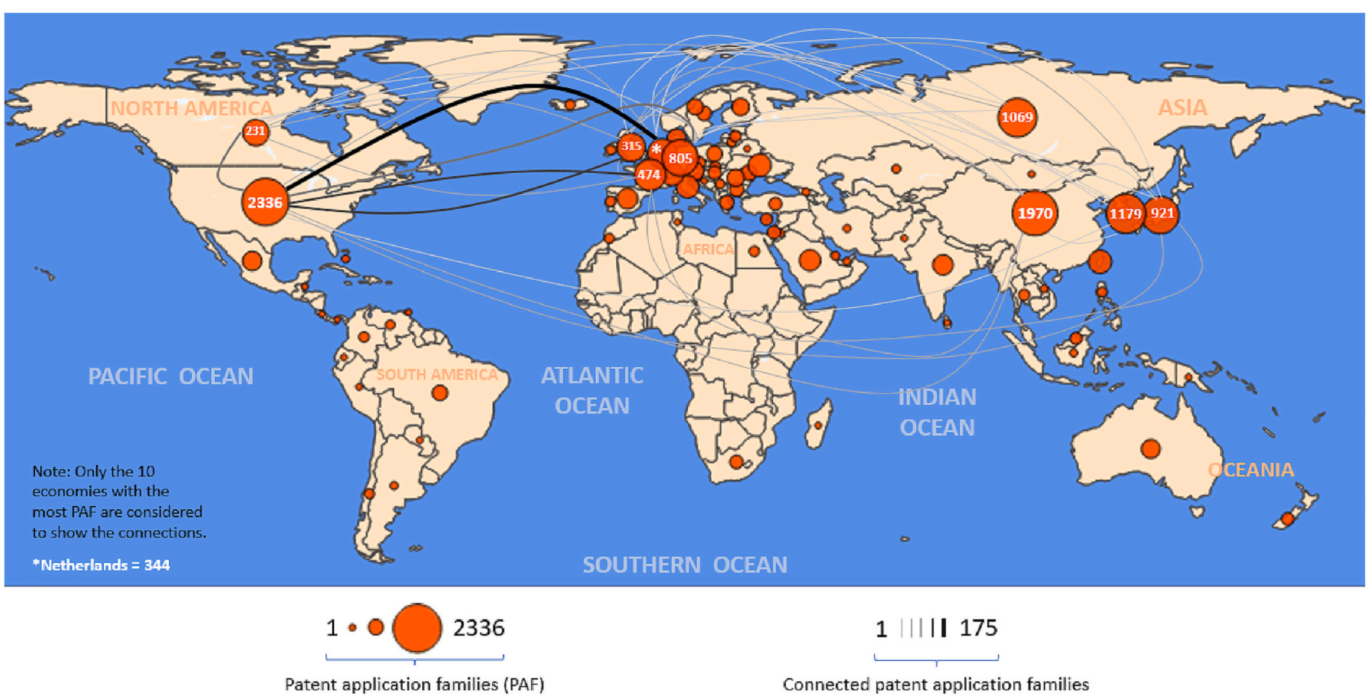


Fig. 4. Knowledge generation on hydrogen fuel (2005–2018).
Note: Connectivity shown is only between the leading economies. The detail of the number of PAF per economy is in Appendix C, in a column called Overall. (*Source*: Authors' elaboration based on European Patent Office [45].)

reveal interesting patterns (Fig. 5). The United States leads knowledge production in the field of grey hydrogen, biomass hydrogen, blue hydrogen, and pink hydrogen; and ranks second in terms of turquoise hydrogen and green hydrogen. China leads knowledge generation of green hydrogen; ranks second in grey hydrogen; and third in turquoise and biomass hydrogen. Russia leads in turquoise hydrogen; ranks third in pink hydrogen and grey hydrogen. South Korea ranks second in biomass and pink hydrogen; third in green, blue and turquoise hydrogen. The rest of countries occupy less relevant positions.

Fig. 5 also shows the links between the leading economies in generating knowledge across different types of hydrogen. Grey hydrogen has the highest number of connected economies of the top 10, followed by biomass hydrogen. The connection between the United States and the Netherlands is the highest in grey hydrogen, biomass hydrogen and turquoise hydrogen. In the case of green hydrogen, the most relevant connections are those between the United States and South Korea. Connections between countries are only incipient in the rest of technologies. The leading country in connectivity is the United States because it leads the connections in all types of hydrogens and because, if we consider all the types of hydrogen jointly, it is the economy most connected to other countries with 28 links.

Fig. 6 shows the positioning of the eleven selected countries in the knowledge generation of any type of hydrogen fuel and by type of technology, focusing on the three main technologies: grey, biomass and

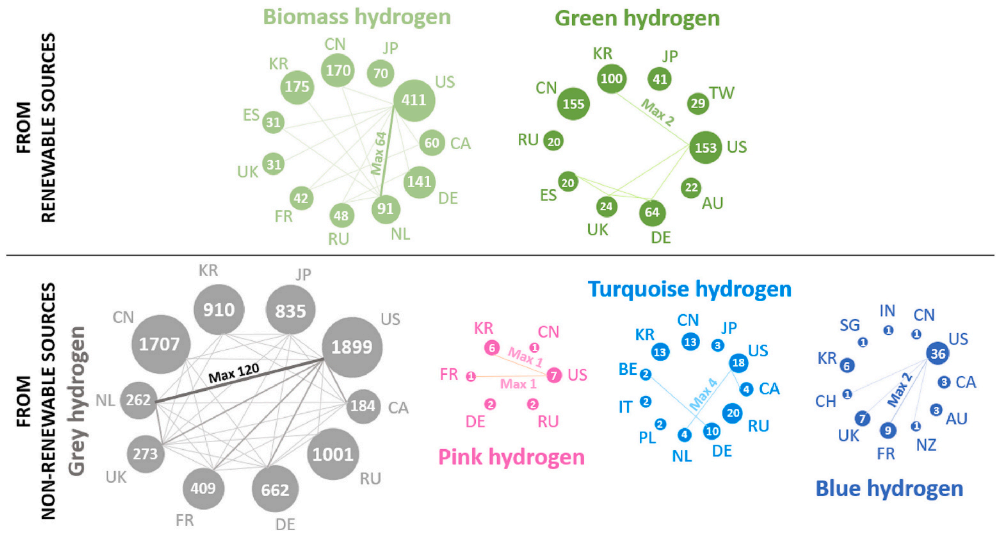


Fig. 5. Knowledge generation by type of hydrogen in leading economies (2005–2018).
Note: Details of the rest of the economies and their PAF number are found in Appendix C. Country codes according to ISO3166-2.
(*Source*: Authors' elaboration based on European Patent Office [45].)

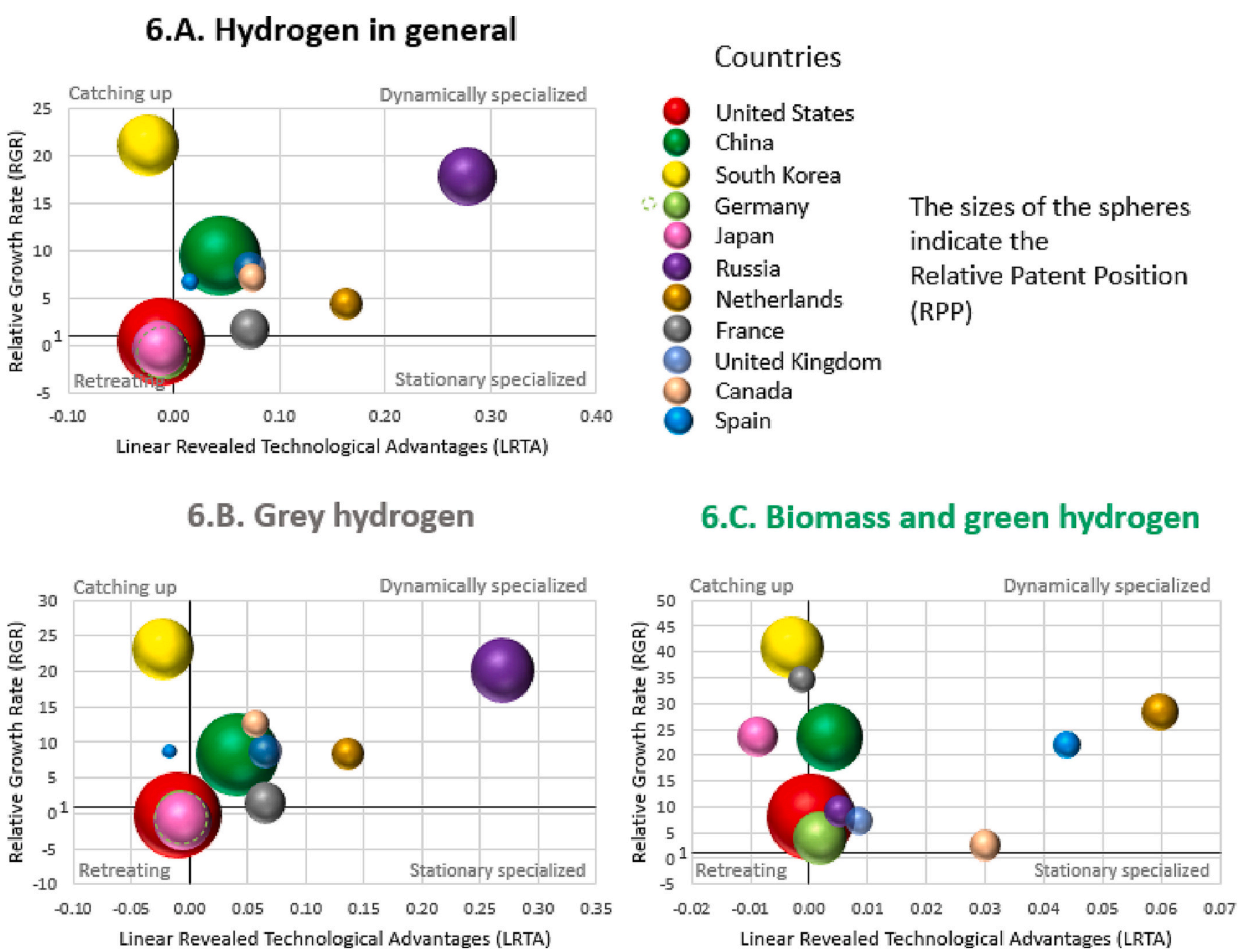


Fig. 6. Positioning indexes on knowledge generation by type of hydrogen (2005–2018).
(Source: Authors' elaboration based on European Patent Office [45].)

green hydrogen. The last two technologies are studied jointly to compare technologies from renewable and non-renewable sources.

The Relative Growth Rate (RGR) index shows that, except for the United States, Germany and Japan, the knowledge generation on hydrogen fuel (considering all types) has grown above the world's average level for all technologies. This is also the case for grey hydrogen. However, all eleven countries analysed grew at a higher rate in the case of biomass and green hydrogen, showing more dynamism in developing technologies from renewable sources.

The index of Linear Revealed Technological Advantages (LRTA) shows that: five economies (China, Russia, the Netherlands, the United Kingdom, and Canada) are specialised in the three types of hydrogen; France and Spain are specialised in two types of hydrogen, coinciding on hydrogen in general; the United States and Germany are only specialised in biomass and green hydrogen; and South Korea and Japan are not specialised in any particular type of hydrogen. Finally, the index of Relative Patent Position (RPP) shows that the United States is the leading economy generating knowledge across all the types of hydrogen analysed; followed by China and South Korea in hydrogen in general, and in biomass and green hydrogen; and by China and Russia in grey hydrogen.

By combining the dynamism (RGR) and specialisation (LRTA) inspired by previous research, applied to industrial classifications [52–54], we observe, first, that the United States, Japan, and Germany are the only countries retreating in hydrogen in general and in grey hydrogen. Second, that the rest of countries are catching up or dynamically specialised in those types of hydrogen. Third, that all leading countries are catching up or dynamically specialised in biomass or green hydrogen. Fourth, that China, Russia, the United Kingdom, Canada, and the Netherlands are dynamically specialised in the three graphs. Fifth, that South Korea is the only country in the catching up group in the three types of hydrogen analysed. Sixth, that Spain is dynamically specialised in hydrogen in general and in biomass and green hydrogen, but it is in the catching up segment in grey hydrogen. Seventh, that France is dynamically specialised in hydrogen in general and in grey hydrogen, but it is in the catching up group in biomass and green hydrogen.

The joint analysis of all the positioning indices of the three graphs in Fig. 6 reveals a similarity in the location of the countries on the graphs related to hydrogen in general and grey hydrogen. The United States has a similar positioning to Germany on all graphs in terms of dynamism, although with a better relative position. Notwithstanding, the United States and Germany have a similar positioning to Japan in hydrogen in general and in grey hydrogen, especially Germany with almost the same results as those of Japan in all indicators.

5. Concluding remarks

Although the existing literature recognises the potential of hydrogen energy as an alternative to replace fossil fuels [10,55–57], there is a shortage of comprehensive studies analysing the recent evolution of hydrogen fuel technologies. This paper has contributed to this research agenda, offering new insights to better understand the technological trajectories of hydrogen fuel, as well as a first mapping of the leading countries in the development of new technologies in this field.

Despite the fact that hydrogen fuel is considered environmentally friendly, our study shows that most of its recent technological developments are still related to fossil energy sources. However, a faster growth rate is observed in knowledge on hydrogen fuel from renewable sources, pointing to a promising path towards a sustainable transition. Our analysis of the knowledge interconnection between different hydrogen types suggests that those technologies developed for hydrogen based on fossil energy sources have enabled novel applications based on renewable energies. This illustrates how technological change unfolds through incremental progress along a technological paradigm but shifting towards more sustainable trajectories. However, it should be noted that grey hydrogen still has a higher level of interconnectivity than green or biomass hydrogen. This could be explained by the fact that grey hydrogen-oriented knowledge generation has been going on for more decades [45].

Geographically, we find that while the United States leads the knowledge generation in hydrogen fuel technologies, other Asian and European countries show greater dynamism both in terms of growth and specialisation. In particular, it is worth to highlight the increasing importance of China and South Korea in knowledge generation for green hydrogen technologies, which holds important geopolitical implications. Our study shows that the technological development of hydrogen fuel is mainly carried out within the boundaries of each economy, as is also the case with other technologies involved in the transition to sustainability, such as lithium batteries [41]. This shortage of international collaboration may lead to duplications and other inefficiencies, calling for stronger efforts to coordinate joint research and innovation initiatives across countries. A notable exception is the case of United States and the Netherlands, which have collaborated intensively to generate knowledge across the main types of hydrogen, whether from renewable and non-renewable sources.

Among other possible agendas, future research should address knowledge generation of hydrogen fuel at the organisational level, identifying the leading research institutes and centres across different types of hydrogen technologies and countries, as well as the interconnections between them. Another relevant avenue for future research would be to consider more carefully the participation of developing countries in the development and uptake of hydrogen fuel technologies, with particular attention to those countries located in the coastal, subtropical, and tropical zones, since they hold location advantages that enhance their potential for the development of green hydrogen.

An important limitation of this research is that it analyses the interconnections between technologies based only on co-occurrence, without accounting for the relevance of patents. Nevertheless, the method employed enabled us to provide a clear picture of the basis of the knowledge flows across different types of hydrogen, in line with the stated objective of the paper. While using patent citations could contribute to enriching the results, the risk is that it could lead to biases associated with an under-representation of public research knowledge flows and an over-representation of factors not representative of knowledge flows [58]. A more promising avenue for future research would be to introduce advanced techniques based on natural language processing that would allow to classify patents and to identify links between them more effectively [59]. Another broader limitation of our study is that we focus on knowledge generation as measured by patenting activity. This could be complemented in future studies by considering also scientific publications, R&D investments, or business activity indicators. Finally, although our study has focused on the generation of new knowledge, the mainstreaming of hydrogen fuel depends on the emergence of new industrial applications (e.g. ammonia, methanol, and steel production) and the transformation of existing value chains [6,38]. Future studies should also consider these complementary dimensions that will shape the geopolitical dynamics of the transition to a hydrogen economy.

Declaration of competing interest

The authors declare that we have no conflict of interest.

Data availability

The data can be obtained from the Global Patent Index platform.

Acknowledgements

This document is dedicated to Victoria Jarpa Velis and Juan Cueto Ortiz for the support they have always given to Fernando Moreno-

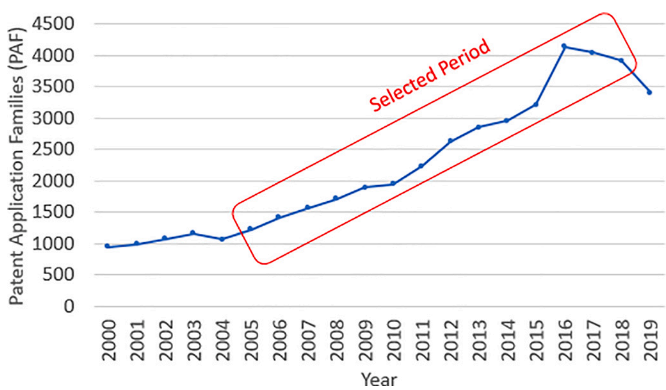
Brieva.

Appendix A. Search criteria of patent families

Type	Search criteria
Biomass hydrogen	The words "hydrogen" or "H2" were combined with keywords related to different energy sources (e.g., "biomass", "bio-oil", "biofuel", "biogas").
Blue hydrogen	First, the words "hydrogen" or "H2" were combined with keywords related to hydrocarbons and carbon capture, but without the combinations about "no carbon capture". Second, the combination "blue hydrogen" was used. Third, the words "hydrogen" or "H2" were combined with words that allude to blue energy.
Grey hydrogen (including Brown and Black)	First, the words "hydrogen" or "H2" were combined with keywords related to hydrocarbons (e.g. "fossil fuels", "gasoline", "petroleum" or "natural gas", etc.) but excluding the combination "carbon capture" and considering the combination "no carbon capture". Second, the combinations "grey hydrogen", "black hydrogen" and "brown hydrogen" were used. Third, the words "hydrogen" or "H2" were combined with words that allude to grey, black and brown energy.
Green hydrogen	First, the words "hydrogen" or "H2" were combined with keywords related to different energy sources ("solar energy", "wind energy", "hydraulic energy", "geothermal energy", "tidal energy", "wave energy") or with words referring generally to renewable energies. Second, different keywords related to green hydrogen and zero-emission hydrogen combinations were used.
Pink hydrogen (also called Purple)	First, the words "hydrogen" or "H2" were combined with keywords related to "nuclear energy" and with "electrolysis", together. Second, different keywords, such as "pink hydrogen" or "purple hydrogen" were used.
Turquoise hydrogen	First, the words "hydrogen" or "H2" were combined with keywords related to "natural gas" and pyrolysis, together. Second, the combination "turquoise hydrogen" was used. Third, the words "hydrogen" or "H2" were combined with keywords that allude to "turquoise energy".

Source: Authors' elaboration.

Appendix B. Evolution of knowledge generation from 2000 to 2018



(Source: Authors' elaboration based on data from the European Patent Office [45].)

Appendix C. Knowledge generation by type of hydrogen (2005–2018)

Total families	Overall	Grey	Biomass	Green	Biomass or green	Turquoise	Blue	Pink
US	2336	1899	411	153	548	18	36	7
CN	1970	1707	170	155	318	13	1	1
KR	1159	910	175	100	271	13	6	7
RU	1069	1001	48	20	67	20		2
JP	921	835	70	41	111	3		
DE	805	662	141	64	199	10		2
FR	474	409	42	8	49		9	1
NL	344	262	91	6	97	4		
GB	315	273	31	24	52		7	
CA	231	184	60	13	68	4	3	
TW	143	95	19	29	48			
CH	136	121	8	13	20	1	1	
UA	132	104	16	11	27			
IT	123	107	18	5	23	2		
SA	98	95	1	4	5	1		
ES	85	46	31	20	51	1		
IN	81	66	16	4	20	1	1	
MX	68	53	12	5	17	1		
DK	63	53	12	4	16			
AU	61	38	2	22	24		3	
AT	57	41	14	11	25			
FI	45	28	24		24			
RO	44	29	10	9	19	1		

(*continued on next page*)

(*continued*)

Total families	Overall	Grey	Biomass	Green	Biomass or green	Turquoise	Blue	Pink
NO	33	29	7		7			
VG	33	32						
MD	31	15	13	4	17			
PL	30	19	14	1	15	2		
BE	27	17	8	1	9	2		
BR	27	20	10		10			
LU	22	19	3		3			
SE	22	18	8		8			
BG	20	8	1	9	10			
GR	19	11	5	6	8			
SG	17	11	4	1	5		1	
HU	16	10	4	3	7			
ZA	16	14	4		4			
IL	15	7	1	4	5			
TR	13	11	1	1	2			
CZ	12	8	2		2	1		
NZ	12	8	4		4		1	
MY	11	6	4	1	5			
CY	10	9		2	2			
LV	8	3	2	3	5			
TH	8	8	1		1			
BB	7	7						
SK	7	6	4		4			
CO	6	5	1		1			
EG	6	5		1	1			
PT	6	4	1		1			
AN	5	4	1		1			
CL	5	5						
HK	5	4	2		2			
IS	5	2	2	3	4			
MA	5	1	2	3	5			
PH	5	5	1		1			
IE	4	3		2	2			
RS	4	3		1	1			
VE	4	4						
LT	4	2	1		1			
KZ	3	3		1	1			
QA	3	3						
AE	2	2						
AR	2	2						
BS	2	2						
GE	2	1						
ID	2	2						
IR	2	2						
JO	2			2	2			
SC	2	2						
SI	2	1		1	1			
VN	2	1	1		1			
BH	1	1		1	1			
BM	1	1						
BY	1	1						
BZ	1			1	1			
CR	1	1						
EC	1	1						
HR	1			1	1			
KP	1	1						
LI	1		1		1			
LK	1	1		1	1			
MC	1	1						
MG	1	1						
MN	1	1						
PA	1	1						
PE	1	1						
PG	1	1						
PK	1	1						
PY	1	1						
SH	1	1						
TN	1	1						
TT	1	1						
VC	1	1						

Source: Authors' elaboration based on data from the European Patent Office [45].

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