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Technological Innovation and the Development of the Fuel Cell Electric Vehicle Industry Based on Patent Value Analysis

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Abstract: *Currently, major economies are competing on the technological and industrial development of fuel cell electric vehicles (FCEVs). This paper discusses the relationship between the patent value of FCEVs and the commercialisation of this technology. First, the patent data of FCEVs are analysed, focusing on data of China, Germany, Japan, the Republic of Korea, and the United States. Then, the paper constructs the FCEV patent value index framework based on the technological value and economic value of patents. Finally, this paper conducts an empirical study to analyse the influence of patent value on the development of the FCEV industry. It is found that, under the current situation, individual patent value can significantly promote the development of the FCEV industry, whilst the gross patent value of a certain country even has a negative impact. In addition, the increase of hydrogen infrastructure, research and development expenditure, and market demand will significantly promote the development of the FCEV industry. The development level of related industries such as the battery electric vehicle industry and the reduction of environmental pollution are also significant drivers of the development of FCEVs.*

Keywords: FCEV, patent value, industry development

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1. Introduction

At present, all countries are carrying out energy transformation, increasing the scale of the development and utilisation of renewable energy, promoting the transformation of energy consumption structure to clean and low carbon, and reducing the negative effects of fossil fuels such as air pollution, noise, and global warming (Qin et al., 2020). Energy transition in the transport sector is particularly critical. Transport is responsible for about 24% of global carbon dioxide (CO_2) emissions, and as urban populations grow and e-commerce drives global trade, transport systems play a more critical role in global development than ever before. Low or zero carbon vehicles and intelligent transport systems, new fuels, electricity and digital infrastructure could potentially mitigate harmful consequences to a certain extent. Fuel cell electric vehicles (FCEVs) release heat energy and water only in addition to electric kinetic energy (Shen, Lim, and Shi, 2020). Compared with traditional vehicles, FCEVs not only help maintain a clean environment, but also make full use of fuel and reduce economic losses (Zeng et al., 2018). Current research on FCEVs mainly involves power system structure in fuel cell vehicle systems (Das, Tan, and Yatim, 2017), energy management methods (Teng et al., 2020; Yue et al., 2019), quantitative analysis of energy consumption, greenhouse gas emissions in the whole life cycle (Ashim, Sharma, and Baral, 2022; Sheng et al., 2021; Choi et al., 2020), and technology development analysis and prediction (Sheng et al., 2021). Amongst them, the research on FCEV patent technology is based on comparative analysis of bibliometric methods and patent data (Sinigaglia, Martins, and Siluk, 2022; Li and Yuan, 2021), so as to summarise the current technology development trends and predict the future technology development direction. However, at present, there is little research on the value of FCEV patents. Moreover, the influence of patent value on the development of the FCEV industry also needs to be studied.

This paper mainly contributes an FCEV patent value index framework based on FCEV patent data from three aspects: technological value, market value, and value of legal rights. We analyse the FCEV patent value of China, Germany, Japan, the Republic of Korea, and the United States from two perspectives: gross patent value and individual patent value. Finally, the influence of gross patent value and individual patent value on the development of the FCEV industry is explored under the consideration of multiple control variables, and relevant policy recommendations are put forward based on the research conclusions of this paper. This paper not only analyses FCEV patent data, but also further analyses the patent value, which supplements the gap in the research of FCEV patent value. At the same time, this paper's empirical research on FCEV technology and industrial development is also a great innovation, enriching the literature research on FCEV industry development, and specifically summarising the factors that affect the development of the FCEV industry.

The organisation structure of this paper is as follows. Section 2 reviews the literature on FCEV industry development and FCEV patent research. Section 3 introduces the methods, data, and models, and Section 4 discusses the results, patent value analysis, regression model, robustness testing, and endogeneity analysis. Section 5 discusses the result. Section 6 concludes the paper and discusses policy implications.

2. Literature Review

2.1. FCEV Industry Development

With the increasing threat of climate change and rising expectations for hydrogen energy, the world's leading automakers have increased their investment in FCEV development (Bian et al., 2017). Many governments have issued relevant policies promoting the rapid development of their FCEV industry (Yang et al., 2021). Policy subsidies are mainly concentrated in the consumption link, benefiting consumers by means of purchase tax exemptions or purchase subsidies (Song et al., 2020; Ogungbemi et al., 2021). At the same time, vehicle production, vehicle demand, and institutions all affect local FCEV deployment (Trencher and Wesseling, 2022). In addition, the popularisation of FCEVs also needs sufficient hydrogen refuelling stations to support. The construction cost estimation and location selection of hydrogen refuelling stations are equally important for the long-term development of FCEVs (Xu et al., 2023; Han, Kim, and Yoo, 2002). Government incentives for hydrogen refuelling stations, as well as research and development (R&D) and the production of vehicles are expected to accelerate the growth of the FCEV market, whilst the high price of FCEVs and the high cost per kilogramme of hydrogen will limit the market demand for FCEVs (İnci et al., 2021). Morrison, Stevens, and Joseck (2018) found that achieving a reduction in hydrogen fuel costs is critical to the overall success of FCEVs in the marketplace. Yan and Zhao (2022) also conducted an empirical study on consumers' propensity to purchase commercial FCEVs, and found that purchase price, fuel cost, and environmental awareness are important influencing factors.

2.2. FCEV Patent Research

Patents provide an exclusive source of detailed information on inventive activity (OECD, 2009) and increase the use and commercialisation of technology through market transactions (Noda, 2009) facilitating the spread of knowledge and innovation. The analysis of FCEV patents helps us grasp the technological profile of FCEVs and summarise the deficiencies, so as to promote better development of the technology. The increase in total patent numbers starting in 1998 is driven mainly by car manufacturers: they have held the majority of FCEV patents every year since 2000 (Borgstedt, Neyer, and Schewe, 2017). Alvarez-Meaza et al. (2020) found Toyota, Honda, and Hyundai were the top three applicants, and the United States, Germany, and Japan dominated patent applicants, based on patent applications from 1999 to 2019. Yuan and Cai (2021) predicted the development trends of FCEV technology using a modified technology prediction method based on FCEV patent data. In addition, the analysis of the patentees' cooperation network is one of the key points of FCEV patent analysis. In FCEV technology, the patent thickets are weakening and many famous vehicle manufacturers hold the dominant positions in patent thickets, such as Toyota, Honda, General Motors, and Mercedes-Benz (Yuan and Li, 2020). The determination of core technologies of FCEVs through patent portfolio analysis can facilitate the decision-making process of enterprises, including identifying competitors, analysing competitiveness, and developing patent portfolio strategies (Ha et al., 2015).

We found many studies on the development of the FCEV industry and on the analysis of FCEV patents. Few studies revealed the relationship between the two. Most studies on FCEV patents analyse the patent data of the world or a country and summarise the patent development trends, without in-depth discussion of patent value (Yuan and Yuan, 2023; Aaldering, Leker, and. Song, 2019; Yang et al., 2022), let alone cross-country comparative analysis of patent value. Meanwhile, empirical studies on the development of the FCEV industry are limited to several influencing factors such as supply (stimulation of vehicle production), infrastructure (construction of refuelling stations and hydrogen production), demand (stimulation of vehicle adoption), and institutional (cross-cutting measures to facilitate collaboration, innovation and cost reduction) (Trencher, 2020). The consideration of the role of technology, such as measured by FCEV patent value, in the development of the FCEV industry, has been missing in this stream of literature.

3. Data and Methodology

3.1. Patent Retrieval and Data Collection

We adopt Thomson Reuters' Derwent Innovations Index to retrieve the related patents. The index is a famous comprehensive database that has collected a large volume of patent documents worldwide since 1963, with weekly updates of about 25,000 patent documents published by more than 40 patent offices and 45,000 patent citation documents from six major patent offices (Wan and Zhu, 2008). In this study, we used a combination of keyword and patent technology classification to collect patent data. The specific keywords in the title and abstract of patent documents provide a high number of patents that are closely related to FCEV technology, whilst International Patent Classification classes are used to differentiate distinct technologies and further exclude irrelevant patents (Luan et al., 2013). Following the technique proposed by Aghion et al. (2016) in the FCEV search strategy, this paper proposes a more refined and accurate FCEV patent search formula as follows:

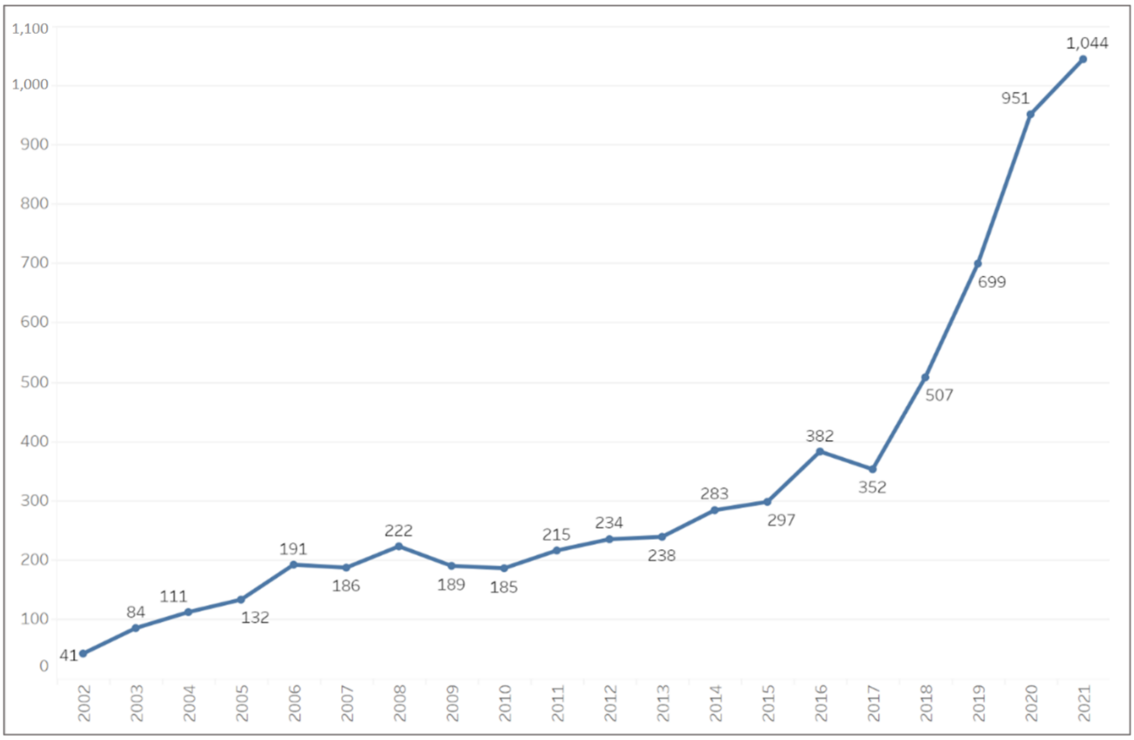
TAB=(hydrogen AND (fuel NEAR cell) AND (vehic* OR automobile OR car OR bus OR truck OR trailer)) AND IC=(H01m* OR B60l* OR B60k* OR C01b* OR F17c*) NOT IC=(A61*) AND AD>=(20020101) AND AD<=(20220531).

A total of 12,996 patent families were obtained, amongst which 6,631 were alive, 5,134 were dead, and 1,231 were indeterminate. In order to ensure the validity of data, 6,631 alive patent families were verified and data were randomly selected to verify whether their patent contents were related to FCEV technology. The main criteria for determining whether a patent family is valid are (i) the theme of the title, (ii) the relevance of content of the abstract, and (iii) the uses of the patented technology. Amongst the 669 randomly selected data, 27 data were not related to FCEV technology, with a correlation rate of 96%, and 6,596 patent family data were obtained after deleting the irrelevant data.

3.2. Patent Data Analysis

Figure 1 presents a review of global trends in FCEV patents from 2002 to 2021. From 2002 to 2008, the number of FCEV patent applications showed a gradual rising trend, and reached a peak in 2008, and an exponential growth from 2017. Overall, there has been a gradual increase in the number of FCEV patent applications globally over the past 20 years, which also demonstrates the increasing level of technological innovation in FCEVs.

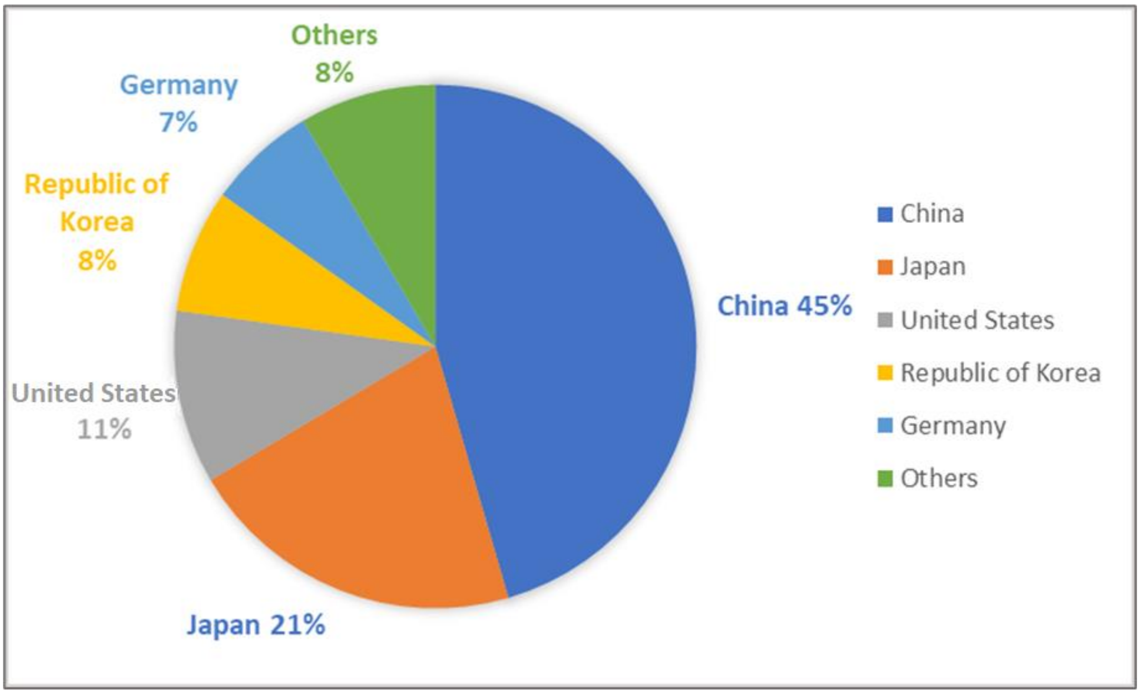
Figure 1: Patent Application Trends, 2002–2021



Source: Summarised by authors based on Derwent Innovation Index.

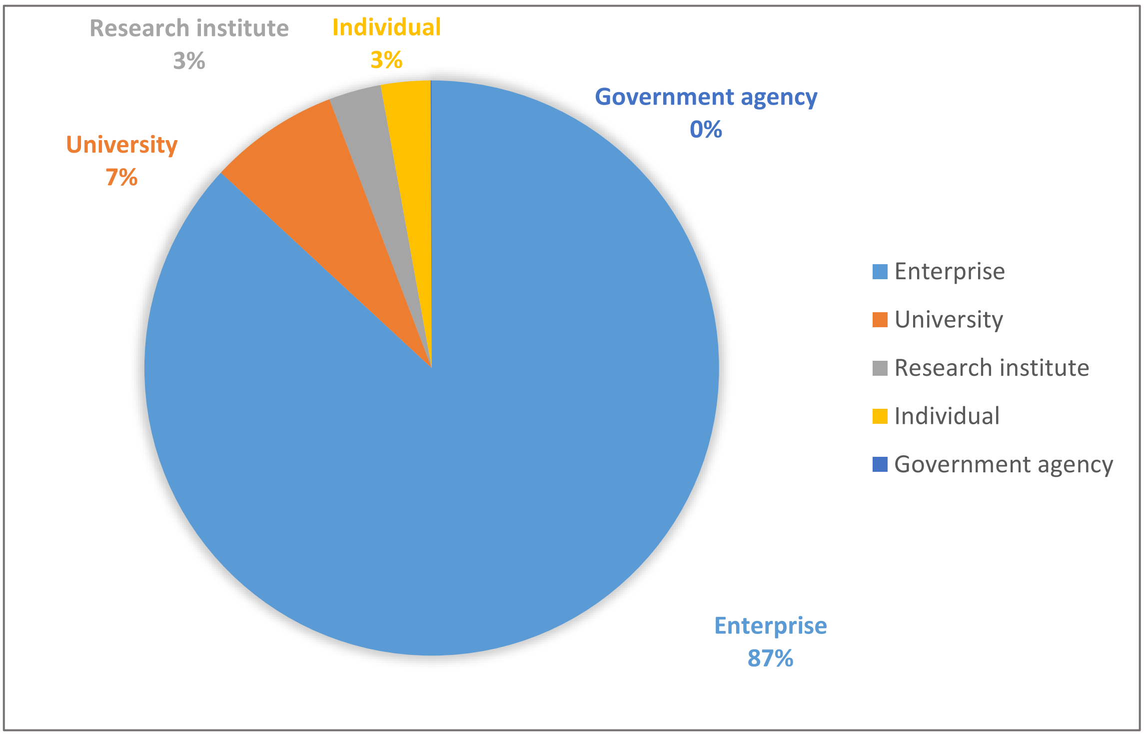
Amongst the filing countries, China filed the most patents, accounting for 45% of the total, followed by Japan with 21%, and the United States with 11%. The Republic of Korea and Germany followed with 8% and 7% of total filings, respectively (Figure 2). As shown in Figure 3, we found that enterprises account for 87% of the total number of patentees, which is the largest group of patentees. The next largest group is universities, which account for 7% of all patentees. At the same time, research institutes and individuals account for 3% of the total number of patentees, and government departments account for the least. These results show that in FCEV patent applications, enterprises dominate, followed by universities. According to the different types of patentee, the patentee partnership can be divided into 10 types: enterprise and enterprise (E–E), enterprise and university (E–U), enterprise and research institute (E–R), enterprise and individual (E–I), university and research institute (U–R), individual and individual (I–I), research institute and research institute (R–R), enterprise, university, and research institute (E–U–R), enterprise, university, and individual (E–U–I), and government agency and government agency (G–G) (Figure 4). The most cooperative relationship type is E–E, followed by E–U, and the number of E–R partnerships is also relatively large.

Figure 2: Patent Application Countries, 2002–2022



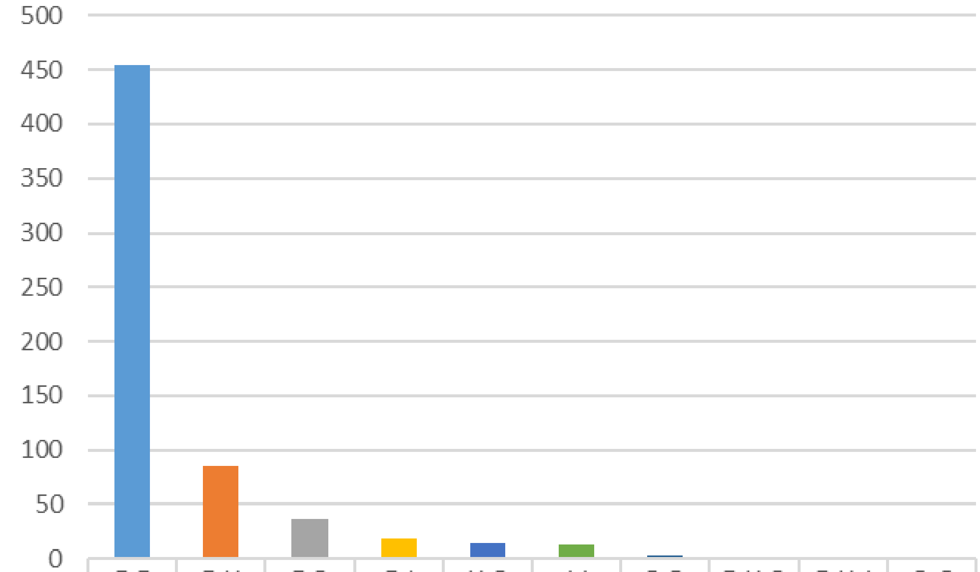
Source: Summarised by authors based on Derwent Innovation Index.

Figure 3: Patentee Types, 2002–2022



Source: Summarised by authors based on Derwent Innovation.

Figure 4. Cooperation Between Patentees



	E-E	E-U	E-R	E-I	U-R	I-I	R-R	E-U-R	E-U-I	G-G
Number	455	85	36	19	14	13	3	2	2	1

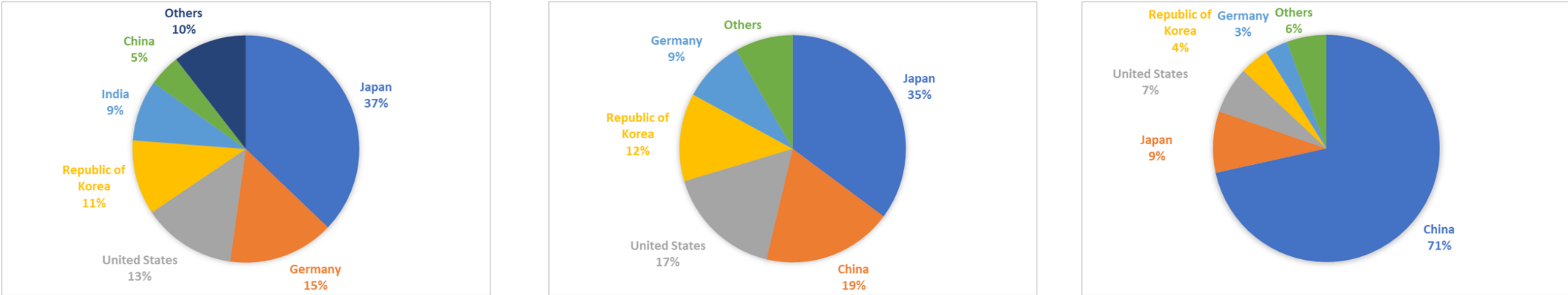
E = enterprise, I = individual, R = research institute, U = university, G = government agency.
Source: Summarised by authors based on Derwent Innovation Index.

According to the trends of FCEV patent applications, 2002–2022 is divided into three development stages: inception stage (2002–2008), growth stage (2009–2016), and acceleration stage (2017–2022). In the inception stage, the number of patent applications is relatively small, with 967 patent families, and the cooperation between patentees is relatively limited with only 88 projects. The number of patent applications in the growth stage increased significantly to 2,023 patent families, and there were 253 projects of cooperation between patentees. In the acceleration stage, the number of patent applications reached 3,606 patent families, and the cooperation between patentees reached 289.

The number of patent applications in each country in the three stages is shown in Figure 5. FCEV patent applications in China increased gradually, from sixth place in the inception stage to first place in the acceleration stage, and the corresponding proportion also increased from 5% to 71%. Whilst Japan's patent application volume is in the top two in the three stages, the corresponding proportion is decreasing. The number of patent applications in the United States also remain in the top three in all stages, with its proportion fluctuating. The Republic of Korea's share of patent filings is stable at No. 4. Germany has fallen from second place to fifth, and its share has fallen from 15% to 3%.

The types of patentees at each stage are shown in Figure 6. Enterprises occupy a dominant position in the three stages, accounting for more than 80%, and the share of universities keeps increasing. The cooperation between the patentees in the three stages is shown in Figure 7. Enterprise–enterprise cooperation is the most common type of patent cooperation, especially between leading enterprises, such as Hyundai and Kia, and JTEKT and Toyota.

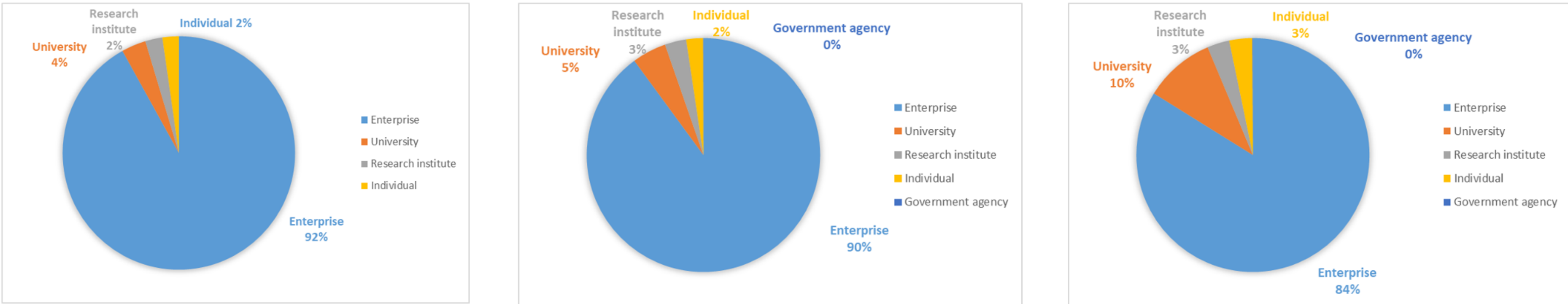
Figure 5: Patent Applications in Each Country in the Three Stages



Inception stage: 2002-2008　　Growth stage: 2009-2016　　Acceleration stage: 2017-2022

Source: Summarised by authors based on Derwent Innovation Index.

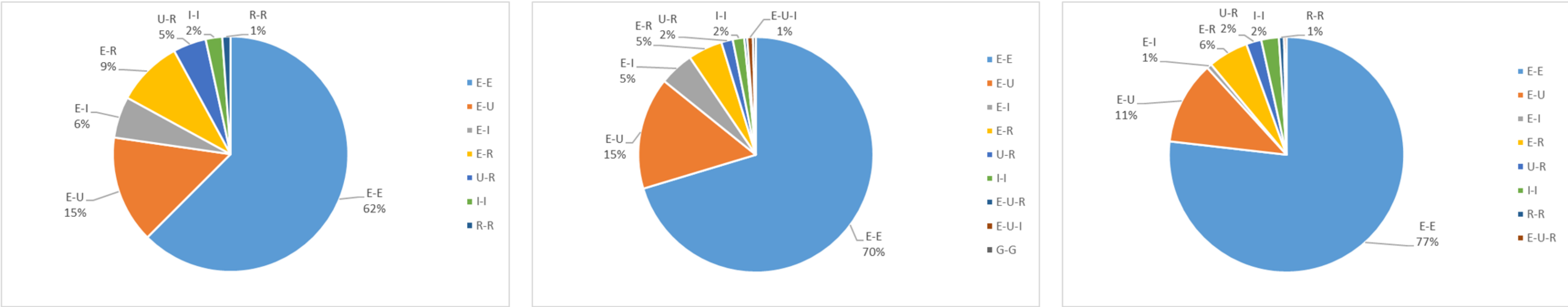
Figure 6. Patentee Types in the Three Stages



Inception stage: 2002-2008　　Growth stage: 2009-2016　　Acceleration stage: 2017-2022

Source: Summarised by authors based on Derwent Innovation Index.

Figure 7: Cooperation Between Patentees



Inception stage： 2002-2008 | Growth stage： 2009-2016 | Acceleration stage： 2017-2022

E = enterprise, I = individual, R = research institute, U = university, G = government agency.
Source: Summarised by authors based on Derwent Innovation Index.

3.3. The Construction of FCEV Patent Value Evaluation Framework and Measurement

This paper mainly analyses the patent value of FCEV from three factors: technical value, market value, and value of legal rights (Borgstedt, Neyer, and Schewe, 2017). Technical value refers to the value brought by the performance of the patented technology itself. In this paper, technology application range, correlation degree, protection degree, extension, and concentration are selected to represent the technical value. Market value is the expected benefit brought by the patented technology in the process of commercialisation, industrialisation, and marketisation. Market activity, domain influence, and corporate strategic influence of patents are used to measure market value. The value of legal rights is the value generated by the exclusive rights endowed by the law to the rights holder. The transfer and legal status of patent rights are used to evaluate the value of rights. The FCEV patent value index framework falls into four basic parts: object level, system level, factor level, and indicator level. Table 1 shows the framework of the country's gross patent value, and Table 2 shows the framework of individual patent value.

Table 1: FCEV Gross Patent Value of the Country

Object level	System level	Factor level	Indicator level
Gross patent value of the country	Technical value (S1)	Technical application scope (F1)	IPC classes (I1)
		Technical relevance (F2)	Citing patents (I2) Cited patents (I3)
		Technical protection (F3)	Claims (I4)
		Technical malleability (F4)	Patent family (I5)
		Technology concentration (F5)	Published patents in the country that year/total publication patents (I6)
	Market value (S2)	Market activity (F6)	Remaining validity period (I7)
		Domain influence (F7)	The importance of patent to their field of technology (I8)
		Strategic importance (F8)	The importance of patent to the company to which it belongs (I9)
	Value of legal rights (S3)	Transfer of patent rights (F9)	Patent assignment (I10)
		Firmness of legal standing (F10)	Litigation cases (I11)

FCEV = fuel cell electric vehicle, IPC = International Patent Classification.
Source: Summarised by authors.

Table 2: FCEV Individual Patent Value

Object level	System level	Factor level	Indicator level
Individual patent value	Technological value (S1)	Technical application scope (F1)	Average number of IPC categories (I1)
		Technical relevance (F2)	Average of citing patents (I2) Average of cited patents (I3)
		Technical protection (F3)	Average of claims (I4)
		Technical malleability (F4)	Average of patent family (I5)
		Technology concentration (F5)	Average of published patents in the country that year/Total publication patents (I6)
	Market value (S2)	Market activity (F6)	Average of remaining validity period (I7)
		Domain influence (F7)	Average of the importance of patent to their field of technology (I8)
		Strategic importance (F8)	Average of the importance of patent to the company to which it belongs (I9)
	Value of legal rights (S3)	Transfer of patent rights (F9)	Average of patent assignment (10)
		Firmness of legal standing (F10)	Average of litigation cases (I11)

FCEV = fuel cell electric vehicle, IPC = International Patent Classification.
Source: Summarised by authors.

We apply the entropy method to estimate the weights of patent value indicators, as such the score of each dimension of patent value could be calculated. In the following, the steps to calculate the score of S1 are illustrated as an example:

Step 1: Sampling. Select indicators m (m=6), with a total of n (n=6596) observations. Let X_{ij} be the value of the jth indicator of the ith observation. (i=1, 2, 3...6596; j=I1, I2, I3...I6)

Step 2: Standardisation. As the units of measurement and direction of the indicators are not uniform, there is a need to standardise the data. For positive indicators, the processing is as follows:

$$X' = \frac{X_{ij} - Min(X_{ij})}{Max(X_{ij}) - Min(X_{ij})} \qquad (1)$$

For the negative indicators, the processing is as follows:

$$X' = \frac{Max(X_{ij}) - X_{ij}}{Max(X_{ij}) - Min(X_{ij})} \tag{2}$$

Step 3: Calculating the proportion of the X_{ij} :

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \tag{3}$$

Step 4: Calculating the entropy of the *j*th indicator:

$$e_j = -K * \sum_{i=1}^{n} (P_{ij} * \ln(P_{ij})) \tag{4}$$

$K = \frac{1}{\ln(n)}$, Where n is 6596.

Step 5: Calculating the difference coefficient of the *j*th indicator.

$$d_j = 1 - e_j \tag{5}$$

Step 6: Calculating the weight of difference coefficient. The weight of the *j*th indicator:

$$w_j = \frac{d_j}{\sum_{j=I1}^{m} d_j} \tag{6}$$

Step 7: The composite score of each sample was calculated.

$$z_i = \sum_{j=I1}^{m} w_j x_{ij} \tag{7}$$

Z_i is the final score of S1. In the same way, we can follow the same steps to get the scores of S2 (i=1, 2, 3...6596; j=I7, I8, I9) and S3 (i=1, 2, 3...6596; j=I9, I10). At this time, the calculated scores of S1, S2 and S3 will be selected, with a total of n samples (n=6596). Then, we can calculate the weight (w_j, j=S1, S2, S3) of the three, and then calculate the patent value (*gpv* and *ipv*) of each sample, as shown:

$$gpv_i / ipv_i = \sum_{j}^{m} w_j x_{ij}, m = 3, j = S1, S2, S3, i = 1, 2, 3...6596 \tag{8}$$

3.4. Regression Model and Variable Description

Research on the factors affecting the development of the FCEV industry should consider more microscopic factors. There are large gaps in infrastructure construction (Soete, 1985), R&D investment (Gao, 2004), market demand (Branstetter et al. 2011), and hydrogen supply potential (Zao and Chen, 2018). At the same time, the development of the industry is also inseparable from the support of related industries. Environmental policies also play a guiding role in the development of the FCEV industry. The development level of the entire FCEV industry chain is also a factor that cannot be ignored. Therefore, the development level of related industries, environmental impact, and supply chain level impact on the development of the FCEV industry are also taken into consideration. This paper sets the following model to examine the influence of FCEV technology level on the development of FCEV industry:

$$Y_{it} = \beta_0 + \beta_1 X_{it} + \alpha_n Control_{it} + \mu_i + \varepsilon_{it} \tag{9}$$

Amongst them, Y_{it} is the dependent variable FCEV industrial development level ($industry_{it}$), which is measured by the FCEV stock of the country. X_{it} is a set of explanatory variables representing FCEV technological development level (gpv_{it}, ipv_{it}), which is measured by the patent value obtained by the above indicator system through the entropy method. $Control_{it}$ is a set of control variables, including the following as shown in formulae (9) and (10): $infra_{it}$ is the level of infrastructure construction, measured by the number of hydrogen refuelling stations that have been built and put into use in each country (Hwang et al., 2021); rd_{it} is the level of research and development, measured as the percentage of the country's R&D expenditure to gross domestic product (GDP) (Cader, Koneczna, and Olczak, 2021); demand_{it} is the market demand, measured by the number of cars in a country (Ko and Shin, 2023). $Hydrogen_{it}$ is hydrogen energy supply potential, measured by hydrogen production of each country (Li and Kimura, 2021); $related_{it}$ refers to related industries, measured by sales volume of electric vehicles (Li and Taghizadeh-Hesary, 2022); $environment_{it}$ is each country's per capita CO_2 emissions (Balali and Stegen, 2021), and $supply_{it}$ is automobile output, measured as a percentage of global vehicle production by that country (Yang et al., 2021). μ_i represents the individual fixed effect and ε_{it} is the error term. The regression model is shown in formulae (10) and (11). To sum up, the introduction of specific variables is shown in Table 3.

$$\begin{aligned} industry_{it} = {} & \beta_0 + \beta_1 gpv_{it} + \alpha_1 infra_{it} + \alpha_2 rd_{it} + \alpha_3 demand_{it} + \alpha_4 hydrogen_{it} + \alpha_5 related_{it} \\ & + \alpha_6 environment_{it} + \alpha_7 supply_{it} + \mu_i + \varepsilon_{it} \end{aligned} \tag{10}$$

$$\begin{aligned} industry_{it} = {} & \beta_0 + \beta_1 ipv_{it} + \alpha_1 infra_{it} + \alpha_2 rd_{it} + \alpha_3 demand_{it} + \alpha_4 hydrogen_{it} + \alpha_5 related_{it} \\ & + \alpha_6 environment_{it} + \alpha_7 supply_{it} + \mu_i + \varepsilon_{it} \end{aligned} \tag{11}$$

Table 3: Variable Description

	Variable Name	Definition	Measure
Dependent variable	industry	FCEV industrial development	FCEV holdings of various countries
Explanatory variable	gpv	FCEV technical level	FCEV gross patent value
	ipv		FCEV individual patent value
Control variable	infra	Infrastructure construction	Hydrogen refuelling stations
	rd	Research and development	Percentage of the country's R&D expenditure to GDP
	demand	market demand	Car ownership
	hydrogen	hydrogen energy supply potential	Hydrogen production
	related	related industry	Sales volume of battery electric vehicles (BEVs)
	environment	Environmental impact	Per capita CO_2 emissions
	supply	supply chain capacity	Global market share of vehicle production

FCEV = fuel cell electric vehicle, GDP = gross domestic product, R&D = research and development.
Source: Summarised by authors.

This paper selects panel data from China, Germany, Japan, the Republic of Korea, and the United States from 2012 to 2021. The above data are from official websites of national statistics bureaus, the World Bank database, the International Energy Agency database (IEA, 2021), research reports (IEA, 2022a; IEA, 2015; Weeda and Elgowainy, 2015), and related literature (Ling et al, 2019; Liu, 2019; Xu, 2022; Wang et al., 2022; Popov and Baldynov, 2018; Alazemi and Andrews, 2015; Ball and Weeda, 2015; Caponi et al., 2022). Descriptive statistics of variables are shown in Table 4.

Table 4: Descriptive Statistics

Variables	(1) Obs	(2) mean	(3) Sd	(4) min	(5) max
industry	50	2,898	4,507	6	19,608
gpv	50	0.188	0.157	0.0538	0.775
ipv	50	0.182	0.0677	0.0830	0.484
infra	50	51.06	43.00	3	167
rd	50	3.136	0.743	1.912	5.025
demand	50	125.0	100.4	18.87	302
hydrogen	50	776.1599	998.5361	4.8	3300
related	50	200.2	463.4	0.512	2,870
environment	50	10.46	2.880	7.046	16.11
supply	50	10.87	7.830	0.300	29.02

Source: Summarised by authors.

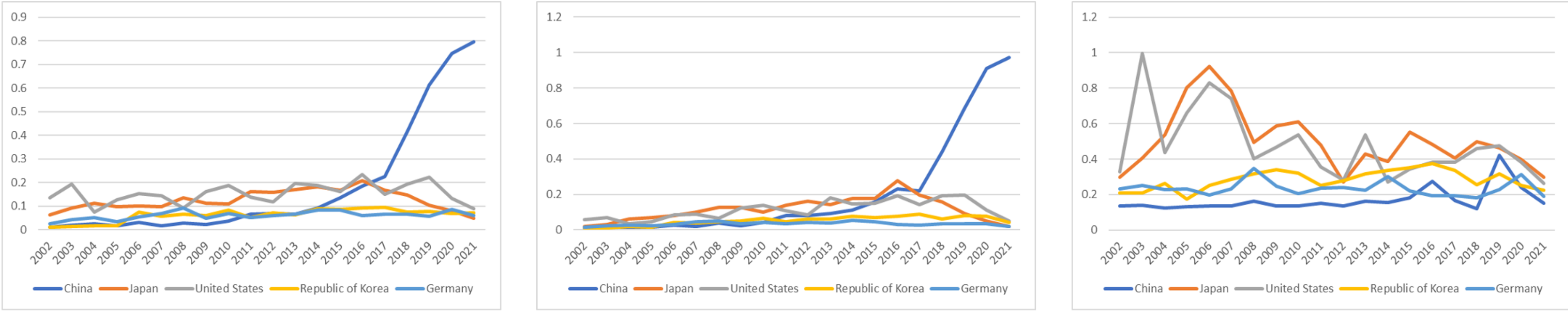
4. Results

4.1. Patent Value Analysis

The technology value, market value, and legal rights value of gross patent value are shown in Figure 8. Technology value and market value in China have increased significantly, but the value of legal rights has not changed much, indicating that the number of FCEV patents in China is relatively large, but the transfer of patent rights and patent protection are not prominent. In the United States and Japan, the technology value and market value fluctuate within a certain range, whilst the value of legal rights fluctuates greatly. This indicates the steady development of FCEV patent technology in the United States and Japan, whilst focusing on patent protection. However, the technology value and market value of the Republic of Korea and Germany are lower, mainly because of the small number of patents.

The technical value, market value, and legal rights value of individual patents are shown in Figure 9. The technical value of Japan's individual patent is in the leading position, but the trend is declining. The technology value of individual patents in the United States was high in the early stage, whilst in China, the Republic of Korea, and Germany it was low. The market value of individual patents in all five countries showed an upwards trend, indicating that the influence of individual patents in each country was increasing and the overall level was rising. However, the value level of individual patent rights varies greatly in different countries, and the transfer of single patent rights is not much and the level of patent protection is not high.

Figure 8: Technology Value, Market Value, and Legal Rights Value of Gross Patents



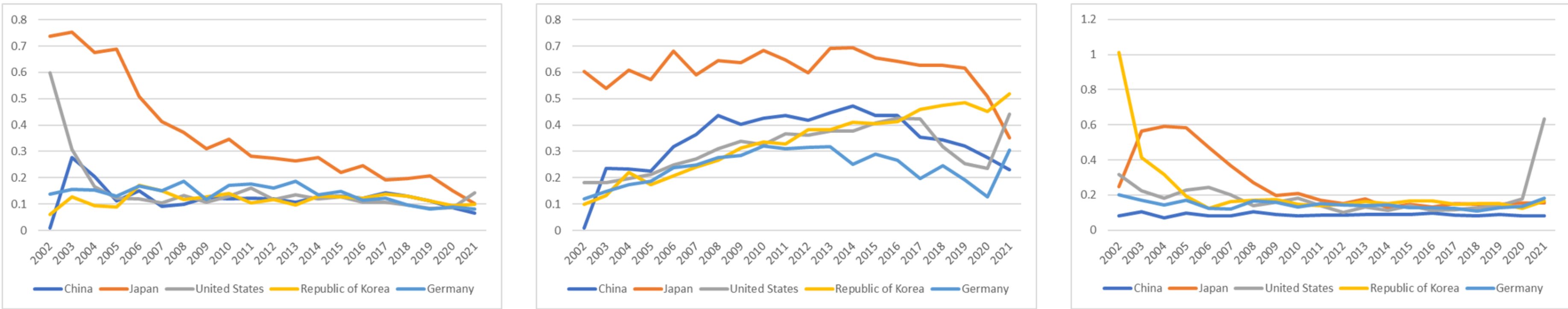
Technological value

Market value

Value of legal rights

Source: Summarised by authors.

Figure 9: Technology Value, Market Value, and Legal Rights Value of Individual Patents



Individual patent technological value

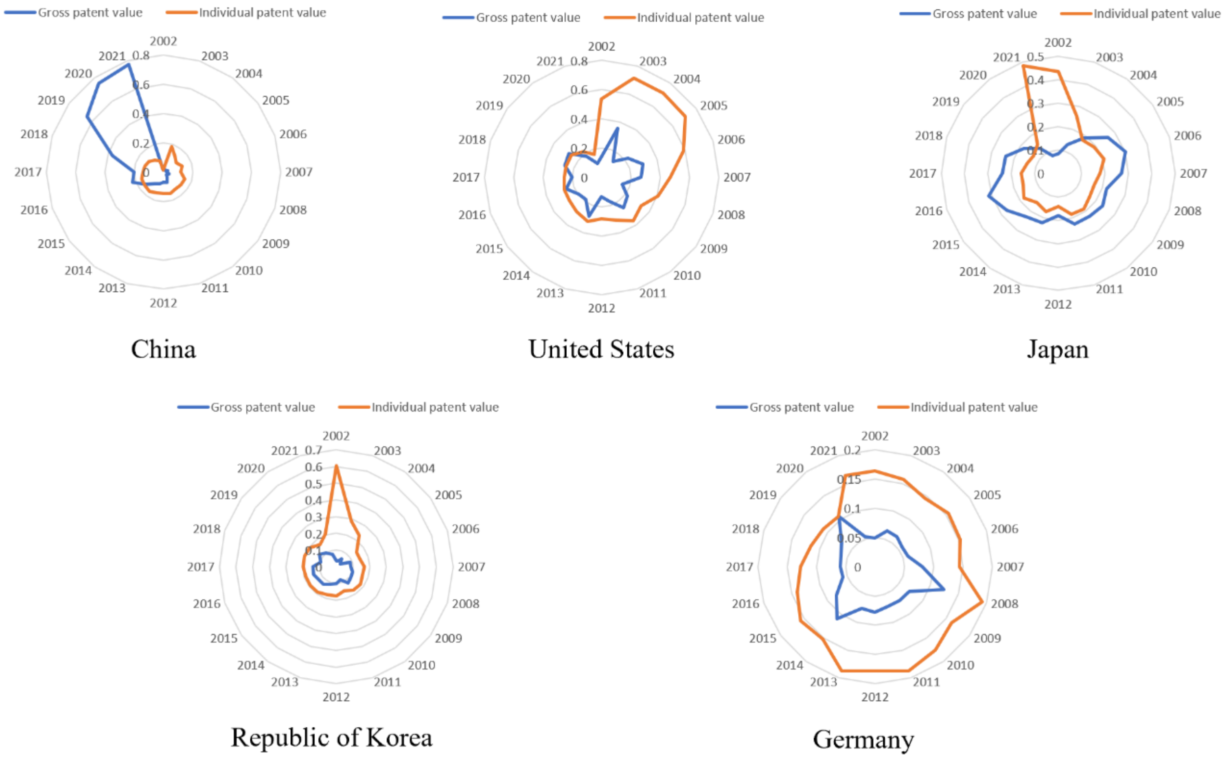
Individual patent market value

Individual patent value of legal rights

Source: Summarised by authors.

This subsection mainly analyses the patent value of China, Germany, Japan, the Republic of Korea, and the United States. After calculation, the patent value of the five countries is shown in Figure 10. The gross value of patents in China began to increase rapidly from 2017 and maintained an accelerating trend until 2021, but the individual patent value remained stable and basically did not change greatly. This situation shows that in China, the number of patentees participating in FCEV patent application is relatively large and complex, and the direction of technological innovation is not concentrated, and there is no representative patentee. The individual patent value of the United States is the highest amongst the five countries, indicating that the United States occupies a dominant position in the field of FCEV technological innovation. However, the declining trend of the individual patent value may be the manifestation of the patentee's new technological innovation. The gross patent value of Japan did not change much, whilst the value of individual patents was high in the early stage and gradually stabilised, reaching a new high in 2021, indicating that Japan had a high level of FCEV technology in the early stage and was in a leading position in 2021 after development. In 2021, the individual patent value in Japan reached a new high, mainly due to the transfer of licensing rights and the increase in the remaining term of the patent families during the year. This may also be due to the fact that Japan's Ministry of Economy, Trade and Industry increased its budget for fuel cell technology in 2019. The gross patent value in the Republic of Korea and Germany was not high and changed little, but the individual patent value in the Republic of Korea was higher in the early stage, indicating that the development direction of FCEV technology was concentrated and the decline of the individual patent value may be related to the diversification of the development direction. In the early stage in the Republic of Korea, there were fewer FCEV patent families, so the average value used in calculation was higher. Therefore, the value of individual patents in the Republic of Korea was higher in 2002. With the development of technology, the number of Korean patent families gradually stabilised, and the level of patent value also developed steadily. The low level of individual patent value in Germany may be due to the small number of FCEV patents in Germany.

Figure 10: Gross Patent Value and Individual Patent Value in Countries



Source: Summarised by authors.

4.2. Regression Analysis

When the ordinary least squares (OLS) method is used to estimate the panel data model, the fixed effect model or the random effect model should be determined first. Tables A1 and A2 in the Appendix show the results of the Hausman test, where the original hypothesis of random effects is rejected, so the fixed effects panel model is used. Subsequently, annual dummy variables are added to examine whether there is an individual time effect. Tables A3 and A4 in the Appendix show the test of the joint significance of all annual dummy variables after considering the time effect. The results show that the P value is greater than 0.10, so the original hypothesis of 'no time effect' is strongly accepted and it is believed that there is no time effect in the model. Therefore, the individual fixed effect model is selected and the cluster robust standard error is used to eliminate the influence of heteroscedasticity on the model.

Table 5 reports the regression results of mixed regression model (OLS) and individual fixed effect (FE) model. In Model (2), the coefficient of the core explanatory variable gross patent value (gpv) was negative and the results were not significant, whilst some individual variables were significant at the 1% level. It shows that the enhancement of the gross patent value of FCEVs does not effectively promote the development of the FCEV industry. In addition, the improvement of infrastructure construction level, research and development level, and the development level of related industries has a significant positive impact on the development of FCEV industry.

In Model (4), the coefficient of the core explanatory variable, single patent value (ipv), is positive and significant at the level of 10%, indicating that the improvement of single patent value of FCEVs can significantly promote the development of the FCEV industry. In addition, the improvement of infrastructure construction will significantly promote the development of the FCEV industry, the improvement of research and development level will significantly promote the development of the FCEV industry, and the development of related and supporting industries will also significantly promote the development of the FCEV industry. In addition, the greater the market demand, the more conducive to the development of the FCEV industry, and higher CO_2 emission leads to lower FCEV adoption, implying that environmental policies driving CO_2 reduction play significant role in promoting FCEVs, and the effect is significant.

Table 5: Regression Analysis of Driving Factors of Industrial Development

Variables	(1) OLS	(2) FE	(3) OLS	(4) FE
Lngpv	–0.242	–0.298		
	(–0.78)	(–0.84)		
Lnipv			1.357**	1.119*
			(2.40)	(2.02)
lninfra	0.744***	0.591***	0.689***	0.563***
	(4.69)	(2.93)	(4.75)	(3.14)
lnrd	3.448***	8.171**	3.796***	10.746***
	(2.85)	(2.68)	(3.42)	(3.55)
lndemand	–0.146	0.011	–0.118	0.014
	(–0.55)	(0.05)	(–0.47)	(0.06)
lnenvironment	–0.117	–2.800	–1.501*	–4.221**
	(–0.20)	(–1.08)	(–1.94)	(–2.06)
lnsupply	0.560	–0.159	0.438	–0.114
	(1.49)	(–0.43)	(1.56)	(–0.35)
lnhydrogen	–0.009	–0.030	–0.004	–0.012
	(–0.10)	(–0.36)	(–0.04)	(–0.15)
lnrelated	0.712***	0.481***	0.746***	0.400**
	(7.27)	(2.85)	(8.05)	(2.63)
Constant	–3.262	2.033	2.561	5.914
	(–1.18)	(0.33)	(0.99)	(1.33)
Observations	50	50	50	50
R-squared	0.828	0.886	0.847	0.895

FE = fixed effect, OLS = ordinary least squares.

Note: ***, **, and * indicate that the regression results are significant at 1%, 5%, and 10%, respectively.

Source: Summarised by authors.

4.3. Robustness Test

In order to verify the reliability of the conclusion and avoid the accidental phenomenon of empirical results due to the selection of specific variables, this paper chooses to use the method of replacing explanatory variables for robustness testing. Instead of individual patent value (ipv), we choose individual patent market value (imv), individual patent technology value (itv), and individual patent-owned legal patent value (ilr), respectively. The robustness test regression results are shown in Table 6. The regression results of the robustness test show that the market value of individual FCEV patents has a significant promoting effect on the development of the FCEV industry. In addition, the influence of control variables on the development of the FCEV industry is basically consistent with the above analysis, except for the difference between the strength of the effect. The results of the robustness test are basically consistent with the above analysis results. Therefore, it can be considered that the analysis of the influence of FCEV patent value on the development of the FCEV industry has strong robustness, and the conclusions drawn from this are reliable.

Table 6: Robustness Test Regression Results

Variables	(1) OLS	(2) FE	(3) OLS	(4) FE	(5) OLS	(6) FE
lnimv	1.803***	1.706**				
	(3.56)	(2.68)				
lnitv			0.183	1.257		
			(0.23)	(1.58)		
lnilr					0.619	0.497
					(1.15)	(1.01)
lninfra	0.874***	0.700***	0.718***	0.635***	0.641***	0.491**
	(6.12)	(3.80)	(4.59)	(3.26)	(3.88)	(2.59)
lnrd	3.422***	11.101***	3.351**	11.930***	3.117***	8.926***
	(3.39)	(3.84)	(2.26)	(3.36)	(2.75)	(3.00)
lndemand	–0.149	–0.035	–0.164	–0.016	–0.118	0.032
	(–0.64)	(–0.16)	(–0.61)	(–0.07)	(–0.44)	(0.14)
lnenvironment	–2.224***	–5.852***	–0.406	–5.902**	–0.352	–3.541
	(–2.90)	(–2.80)	(–0.36)	(–2.46)	(–0.59)	(–1.62)
lnsupply	0.239	0.038	0.393	–0.216	0.425	–0.264
	(0.91)	(0.12)	(1.29)	(–0.66)	(1.43)	(–0.80)
lnhydrogen	–0.002	–0.000	0.000	–0.003	–0.008	–0.022
	(–0.02)	(–0.00)	(0.00)	(–0.04)	(–0.08)	(–0.26)
lnrelated	0.660***	0.345**	0.700***	0.338**	0.739***	0.450***
	(7.77)	(2.31)	(7.12)	(2.05)	(7.23)	(2.84)
Constant	4.236*	7.968*	–1.126	9.437*	–0.224	5.253
	(1.75)	(1.82)	(–0.34)	(1.81)	(–0.09)	(1.14)
Observations	50	50	50	50	50	50
R-squared	0.867	0.903	0.826	0.891	0.831	0.887

FE = fixed effect, OLS = ordinary least squares.
Note: ***, **, and * indicate that the regression results are significant at 1%, 5%, and 10%, respectively.
Source: Summarised by authors.

4.4. The Issue of Endogeneity

The issue of endogeneity refers to the problem in which one or more explanatory variables in the model interact with the perturbation term. Common endogeneity problems are mainly divided into three aspects: explanatory variable omitted, measurement error, and reverse causality. We adopt the instrumental variable method, select the lag of one stage of the explanatory variable of the development index of digital economy as the instrumental variable, and use the two-stage least square method to test the model. In the selection of instrumental variables, due to the lag period of the technical level of the explanatory variable FCEV is selected as the instrumental variable, there is an obvious correlation between the instrumental variable and the explained variable, so there is no weak instrumental variable and the constraint conditions of correlation are satisfied. In addition, the lag period of the FCEV technical level was selected as the instrumental variable, and the current disturbance term could not affect the result of the lag period of FCEV technical level, so the constraint condition of exogenesis was satisfied.

Table 7: Endogeneity Test Regression Results

Variables	**(1) FE lnindustry**	**(2) 2SLS lnindustry**	**(3) FE lnindustry**	**(4) 2SLS lnindustry**
L.lngpv	–0.298	–0.014		
	(–0.84)	(–0.04)		
L.lnipv			1.119*	4.387***
			(2.02)	(2.73)
lninfrastructure	0.591***	0.715***	0.563***	0.637***
	(2.93)	(4.84)	(3.14)	(3.67)
Lnrd	8.171**	3.155***	10.746***	5.266***
	(2.68)	(2.76)	(3.55)	(3.53)
lndemand	0.011	–0.157	0.014	–0.030
	(0.05)	(–0.64)	(0.06)	(–0.10)
lnenvironment	–2.800	–0.179	–4.221**	–4.443***
	(–1.08)	(–0.33)	(–2.06)	(–2.63)
lnsupply	–0.159	0.388	–0.114	0.573*
	(–0.43)	(1.00)	(–0.35)	(1.70)
lnhydrogen	–0.030	–0.002	–0.012	–0.007
	(–0.36)	(–0.03)	(–0.15)	(–0.07)
lnrelated	0.481***	0.696***	0.400**	0.859***
	(2.85)	(7.68)	(2.63)	(7.03)
Constant	2.033	–1.820	5.914	12.153**
	(0.33)	(–0.62)	(1.33)	(2.19)
Observations	50	50	50	50
R-squared	0.886	0.826	0.895	0.740

FE = fixed effect, OLS = ordinary least squares.
Note: ***, **, and * indicate that the regression results are significant at 1%, 5%, and 10%, respectively.
Source: Summarised by authors.

As can be seen from Table 7, after using the time lag of patent value index as an instrumental variable to control the endogenous problem, the results show that the gross patent value index has a negative impact on the FCEV industry development, but its effect is not significant, whilst the individual patent value index is significantly positive at the significance level of 1%. The significance is relatively enhanced and the positive and negative signs of the coefficients do not change. Therefore, after the possible endogeneity problem is controlled, the promotion effect of the FCEV individual patent value on industrial development is still obvious, indicating that the research results are robust.

5. Discussions

Based on FCEV patent data, this paper analyses FCEV patent application trends, types of patentees, and types of patent cooperation, focusing on FCEV patents in China, Germany, Japan, the Republic of Korea, and the United States. At the same time, this paper constructs an index framework to measure the value of FCEV patents from the perspectives of gross patent value and individual patent value, and analyses the value of FCEV patents in the five countries studied. Finally, the panel data is used to specifically analyse the effects of gross patent value and single patent value on the development of FCEV industry, and analyse other related factors affecting the development of the FCEV industry.

Our research results show that the improvement of the gross patent value has a negative effect on the development of the FCEV industry, whilst the improvement of the individual patent value can significantly promote the development of the FCEV industry. This result indicates that in the process of technological innovation of FCEVs, more attention should be paid to the improvement of average technical level than the improvement of total technical level. The likely reason for this situation is that the core FCEV patents are in the hands of a few companies, and although there are many participants involved in patent development, there are far fewer patents of truly high value compared to those that have been published. It is found that the strengthening of supply chain capacity cannot promote the development of the FCEV industry, mainly because the current FCEV supply chain is not perfect and has not formed a mature commercial system. We also found that the increase of hydrogen production cannot effectively promote the development of the FCEV industry, because the hydrogen required by FCEVs is pure hydrogen, and hydrogen is currently mostly produced by fossil fuels (IEA, 2022b), with low purity and impurities, which need further processing before it can be used in FCEVs.

The regression analysis results of the five countries are shown in Table A5 in the Appendix. We found that the individual patent value has different effects on the development of the FCEV industry in different countries, indicating that the development modes of the FCEV industry in different countries are different. First, China's infrastructure construction level, market demand, environmental pollution level, hydrogen production, and the development of related industries have a significant impact on the development of the FCEV industry, whilst these factors have no significant effect on the development of the FCEV industry in other countries. Second, the value of individual patents plays a different role in different countries, which may be related to the FCEV patent structure of each country. In addition to the relevant factors discussed in this paper, other factors such as policies (subsidies, taxes etc.), resource endowment, enterprise development strategy etc. will have an impact on the development of the FCEV industry in a country.

The analysis of FCEV patent data in this paper is conducive to mastering the development trends of FCEV technology and the construction of the index framework of FCEV patent value will enrich the literature on technological innovation of FCEV. In addition, the analysis of the influence of FCEV patent value on industrial development can also provide some feasible policy suggestions for the development of the FCEV industry and enrich the research on the development of the FCEV industry.

6. Conclusions and Policy Implications

This study constructed an index system reflecting the FCEV patent value, analysed the development trends and characteristics of FCEV patents, and discussed the patent value of five countries (China, Germany, Japan, the Republic of Korea, and the United States) from the perspective of gross patent value and individual patent value. The panel data of these five countries were used to build an econometric model to study the relationship between the FCEV industry development and patent value and other factors. The main conclusions of this study are:

(1) The number of different types of patentees varies markedly. Enterprises account

for 87% of patentees, which is the largest number, followed by universities, research institutions, and individuals, and the least is government agencies. In the cooperation of patentees, enterprise–enterprise accounts for the largest proportion, followed by enterprise–university, and the third is enterprise–research institute. It is not difficult to see that enterprises occupy a leading position in patent application and cooperation, universities rank second in FCEV patent research, followed by research institutions, whilst individuals and government agencies have low participation. This indicates that in the current development stage, enterprises largely drive FCEV technology development, with the participation of universities and scientific research institutions to assist in the development, whilst individuals and government agencies contribute little.

(2) The evolution of FCEV patentee cooperation has obvious stage characteristics, which is related to the strengthening of various country policies for the development of FCEVs. From 2002 to 2008, the cooperation between patentees was in the initial stage and there were few cooperative patents. In the growth stage, the number of cooperative patent applications increased significantly. At the same time, in the acceleration development stage, the number of patentees applying for patent cooperation increased steadily. Enterprises play a leading role in patent cooperation at all stages. Universities and research institutions are also involved in the process, but their share is smaller.

(3) The development of FCEV patents varies from country to country. The number of patent applications in China is the largest and keeps rising. The proportion of patentees in universities is the highest in the five countries, but there is a large gap between the number of patent applications and the number of citations. Japan ranked second in the number of patent applications, which kept a cyclical change of 2–3 years, with enterprises taking the leading position amongst the patentees. The United States ranks third in the number of patent applications, maintaining a periodic change of 3–4 years, and its patent citation volume is much higher than the number of patent applications. Both the Republic of Korea and Germany have a cyclical change in the number of patent applications, with a longer period of 4–5 years in the Republic of Korea and a shorter period of 2–3 years in Germany. Enterprises account for the largest share of patentees in the Republic of Korea, whilst the proportion of scientific research institutions is the highest amongst the five countries, at 81% and 9%, respectively. In Germany, enterprises account for 98% of patentees, almost occupying the whole FCEV technology innovation market.

(4) The gross patent value of China, Germany, Japan, the Republic of Korea, and

the United States also varied. China's gross patent value was very low at the initial and growth stage, but began to increase significantly in 2017, surpassing other countries to become first. The value of gross patents in the United States is cyclical, leading both in the initial stage and growth stage. Although the gross patent value of Japan has increased or decreased slightly, it basically maintains a stable level, and takes the lead in the initial stage and growth stage. The gross patent value of the Republic of Korea remained stable but has increased, from lower than Germany in the initial stage to higher than Germany in the growth stage and acceleration stage. Germany's gross patent value was basically stable at about 0.1, with little change overall, but it was at the bottom of the five countries.

(5) In the analysis of the individual patent value, we found that the individual patent value in the United States was the highest, but showed a downwards trend, whilst the individual patent value in Japan showed a stable state after a short decline but increased significantly in 2021. The value of China's single patent basically stays between 0.1 and 0.2, which has room for improvement. The value of the Republic of Korea’s single patent also remained stable after a brief decline. The value of a single patent in Germany remained stable between 0.1 and 0.2. The value of a single patent in the United States, Japan, and the Republic of Korea will decrease only if the value of a single patent issued in the early period is very high, whilst the value of a single patent in China and Germany will remain stable only if the value of a single patent does not change significantly.

(6) This study found that the gross patent value of FCEVs does not significantly promote the development of the FCEV industry, and even has a negative impact, whilst the individual patent value of FCEVs has a significant promoting effect on the development of the FCEV industry. At the same time, the role of patent value in promoting the development of the FCEV industry is conditional, including the development of the electric vehicle market, environmental policies, infrastructure (hydrogen refuelling stations), and so on. Currently, hydrogen production is not a constraint.

The broader implications on policies are summarised as follows:

(1) Countries should scientifically improve the value of FCEV patents. Patentees should focus on improving the level of technology innovation, expanding the scope of technology application, enhancing the degree of technology correlation and market activity, and improving the degree of technology protection. At the same time, patentees should also pay attention to improving their influence in the field of technology,

formulate appropriate development strategies, and enhance their patent value. Patentees can also cooperate with each other to develop new technologies. When promoting patent value, a country should also focus on the individual patent value of FCEVs, because the improvement of individual patent value will be more conducive to the development of the FCEV industry.

(2) Different countries have different levels of FCEV technological innovation, and corresponding promotion policies should also be formulated according to the development of national FCEV industries. In China, attention should be paid to infrastructure construction, market demand, development level of related industries (electric vehicle industry), hydrogen production, and environmental pollution. However, Germany, Japan, the Republic of Korea, and the United States are different from China in their development mode. Technological innovation has already happened at an early stage, so they should improve their technological and industrial competitiveness and supply level.

(3) Governments can strengthen the construction of the FCEV technology innovation cooperation platform. Due to the large amount of capital, equipment, and high-tech talent required in the process of FCEV technology R&D, individual enterprises, universities, and research institutions face great challenges in technology-related R&D. According to the analysis of the cooperation types of the patentees of FCEVs, we found that there are various types of cooperation, mainly amongst enterprises, universities, and scientific research institutions. Therefore, governments can help to establish an innovation platform covering enterprises, universities, and scientific research institutions to promote the cooperation between different patentees.

(4) There is a need to increase R&D investment in technological innovation, especially in key technological areas. First, governments should strengthen the capital and talent investment of active innovation entities. Our analysis of the types of patentees shows that firms are a key link in FCEV technological innovation. Governments should guide or formulate policies to support the innovation direction of the head enterprises, promote the integration of their own internal innovation resources, rational allocation of innovation resources, and maximise the value of innovation resources. Second, governments can also increase the investment in external resources, so as to attract more enterprises, universities, and scientific research institutions to participate in the collaborative innovation process of FCEVs.

(5) Countries should stick to protecting the environment and reducing environmental pollution to provide a good ecological environment for the development of the FCEV industry. The development of the FCEV industry and the reduction of pollutant emissions are an interactive process. The reduction of environmental pollution will effectively promote the development of the FCEV industry, and the development of the FCEV industry will also reduce the emission of pollutants. Therefore, countries can scientifically plan and develop the FCEV industry, whilst protecting the environment and reducing the emission of pollutants, so as to achieve the synergistic development of the two. Countries should seek the best way to protect the ecological environment and promote the industrial development.

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Appendix

Table A1: Hausmann Test Results-tpv

Test of H0: Difference in coefficients not systematic
chi2(8) = (b-B)'[(V_b-V_B)^(-1)](b-B)
= 10.10
Prob > chi2 = 0.2581
(V_b-V_B is not positive definite)

Source: Summarised by authors.

Table A2: Hausmann Test Results-ipv

Test of H0: Difference in coefficients not systematic
chi2(8) = (b-B)'[(V_b-V_B)^(-1)](b-B)
= 15.78
Prob > chi2 = 0.0456
(V_b-V_B is not positive definite)

Source: Summarised by authors.

Table A3: Joint Significance of Annual Dummy Variables-tpv

(1) year2=0	(2) year3=0
(3) year4=0	(4) year5=0
(5) year6=0	(6) year7=0
(7) year8=0	(8) year9=0
(9) year10=0	
F (9, 32) = 1.70	Prob > F = 0.1299

Source: Summarised by authors.

Table A4: Joint Significance of Annual Dummy Variables-ipv

(1) year2=0	(2) year3=0
(3) year4=0	(4) year5=0
(5) year6=0	(6) year7=0
(7) year8=0	(8) year9=0
(9) year10=0	
F (9, 32) = 1.69	Prob > F = 0.1319

Source: Summarised by authors.

Table A5: Country Regression Analysis

Variables	(1) China	(2) Germany	(3) Japan	(4) Republic of Korea	(5) United States
lnipv	–3.283	0.131	1.489	–17.341	–0.076
	(–4.69)	(0.02)	(1.61)	(–2.53)	(–0.03)
lninfrastructure	0.684*	–0.800	0.394	0.688	–2.153
	(8.01)	(–0.12)	(0.65)	(1.31)	(–1.37)
lnrd	12.239	41.902	–1.281	21.638	4.560
	(4.17)	(1.94)	(–0.16)	(1.21)	(0.32)
lndemand	0.652**	–0.294	0.535	0.049	0.760
	(16.05)	(–0.13)	(0.63)	(0.09)	(1.29)
lnenvironment	–38.596**	–6.480	–23.887	75.807	–24.026
	(–23.37)	(–0.44)	(–2.31)	(1.87)	(–2.92)
lnsupply	–3.157	0.565	5.174	0.605	1.978
	(–4.23)	(0.06)	(0.91)	(0.78)	(0.40)
lnhydrogen	–0.198*	0.094	–0.017	–0.567	–0.090
	(–10.98)	(0.20)	(–0.10)	(–2.67)	(–0.66)
lnrelated	0.625**	–0.337	–0.752	0.255	0.930
	(24.46)	(–0.07)	(–0.44)	(0.36)	(1.19)
Constant	70.979**	–22.584	50.453	–243.577	64.655
	(37.93)	(–0.52)	(1.82)	(–1.93)	(1.74)
Observations	10	10	10	10	10
R-squared	1.000	0.976	0.993	0.999	0.996

Note: ***, **, and * indicate that the regression results are significant at 1%, 5%, and 10%, respectively.

Source: Summarised by authors.

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