Article

Not peer-reviewed version

Trend and Priority Change of Global Automotive Engine Innovation

Zheng Zhang and Hidemichi Fujii *

Posted Date: 3 October 2024

doi: 10.20944/preprints202410.0140.v1

Keywords: automotive engine technology; green R&D; international comparative studies; patent data; decomposition analysis; structural break

Article

Trend and Priority Change of Global Automotive Engine Innovation

Zheng Zhang [1] and Hidemichi Fujii [2,*]

[1] Business School, Soochow University, China; zhengzhang@suda.edu.cn
[2] Faculty of Economics, Kyushu University, Japan
* Correspondence: hidemichifujii@econ.kyushu-u.ac.jp

Abstract: The purpose of this study is to examine how sales restrictions on gasoline-powered vehicles influence patent application behavior in automobile engine technology. This is achieved through a factorial analysis targeting structural changes in patent applications. We examine patterns in patent data from 1985 to 2019 using index decomposition based on the logarithmic mean Divisia index. The analysis utilizes patent data and focuses on one non-green (internal combustion engine vehicles) and three green automobile engine technologies (battery electric vehicle, hybrid electric vehicle, and full cell vehicle). Furthermore, the study focuses on four significant patent offices (China, Japan, the United States, and Germany) to examine global disparities. The analytical results reveal that a country's green investment pattern changes depending on its growth stage. Intellectual property protection policies and encouragement of R&D will extend the scope of R&D activities in emerging nations where intellectual property markets are not well developed. Furthermore, different countries have distinct product development strategies when it comes to various forms of green automotive engine technologies. Green patents are likely to rise in industrialized nations for incentives such as tax breaks or subsidies for R&D spending on specific technological advancements and the extension of intellectual property protection.

Keywords: automotive engine technology; green R&D; international comparative studies; patent data; decomposition analysis; structural break

---

1. Introduction

Concerns about climate change have produced a dynamic environment in the automobile industry focused on the development of more sustainable technologies (Avadikyan and Llerena 2010). In response to the tough restrictions on gasoline-powered car sales all over the world, automobile companies' research and development (R&D) strategies are changing rapidly. R&D is a long-term plan, thus, there is a continuous debate among practitioners and scholars on which types of sustainable energy should be prioritized (Ibanez-Fores et al. 2014, Fujii and Managi 2019).

In the automobile industry, some firms, for example, invest in electric-based green technology, while others invest in hydrogen-based green technologies. Major debates on the development of green automotive engine technology (green AET or GAET), specifically which types (such as hybrid vehicles) may continue to be competitive and beneficial in the future. Not only do entrepreneurs compete for market share, but regulators often pass legislation to encourage innovation (Yuan and Cai 2021). Consequently, it is crucial to utilize accurate measurements to demonstrate the growth of GAET and give us direction.

In the global markets, China currently accounts for almost 60% of total EV sales. C China is at the forefront of the electric vehicle (EV) market, surpassing traditional automotive giants such as Germany and Japan. In 2022, new EV sales in China surged by 82%, representing over 60% of global EV purchases. (Lin 2024). We can see that the trends of sales can be reflected by the AETs patent applications as time goes on in Figure 1. For example, in Figure 1(a), we can observe general rising tendencies. From 2000 to 2004, China has the least number of applications in all the AET subtypes.

But it has grown fastest and finally surpass Japan and the USA during 2015-2019. Specifically, the overall number of AET patent applications in China increased dramatically, from 8,186 in 2000-2004 to 460,610 in 2015-2019. Figure 1(b) indicates that the number of patents from all countries is increasing. China had the fewest patents in 1985 but has grown to be the largest after 2010.

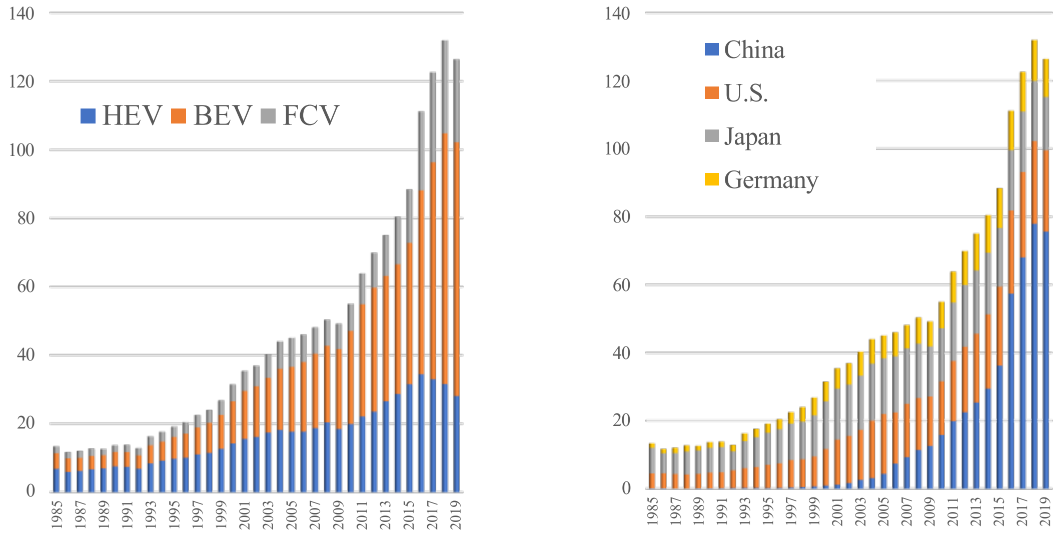

Figure 1. The trend of the number of patent publications (thousand patents).

Indeed, all relevant development may be deduced from patent data. Over time, patent data can be seen as an important source of strategic insight for effective and successful technology management (Pilkington and Dyerson 2006; Bayer et al. 2013; Fukugawa 2022; Hu et al. 2024; Niu et al. 2024). Existing studies already explore the tendencies of AET development using patent data. For instance, Chen et al. (2011) trace the technological S curves for fuel cell and hydrogen technologies using the logistic growth curve model. Yuan and Cai (2021) predict future trends in the development of transmission systems for battery-electric, hybrid electric, and fuel-cell electric vehicles. Sinigaglia et al. (2022) employ patent data to map the sub-technologies (e.g., alternative fuels, direct injection) of internal combustion engine evaluation. It is important to note that different companies have varied incentives to investigate GAET ideas, depending on the sort of technology under study. To develop effective strategies for promoting research and development (R&D), it is important to conduct a determinant analysis of inventions, including identifying priority changes, that focuses on the specific features of each type of green automotive engine technology (GAET).

Applying the decomposition method to patenting trends in technical inventions can highlight the primary factors driving innovation, such as the importance placed on specific technological inventions or the scale effects of R&D activities (Yamashita and Fujii 2022).

While existing studies on patenting trends in the automobile industry provide valuable insights into technological advancements by examining the total number of patents, there appears to be a lack of research focused on analyzing Generalized Accelerated Expiration Time (GAET) patterns. Specifically, no studies have employed a decomposition methodology to explore GAET patterns in relation to changes in priority and green development.

Furthermore, when we examine car innovation globally over the past 30 years, we can see that the shocks from various factors, such as environmental regulation, marketing structure, and economic circumstances, have a substantial impact on the developments of GAET technologies (Dijk and Yarime 2010; Hashmi and Biesebroeck 2016; Bhatia and Jakhar 2021; Ruoso and Ribeiroc2022). These several factors combined mean that the advancement of AET technologies at any one time may not follow a typical curve like the S in some locations. There is, however, little literature that proposes assessing more comprehensive structural breaks in each engine. As remarked by Voana (2012) and Dogan and Ozturk (2017), without considering structural break might result in estimating mistakes

 doi:10.20944/preprints202410.0140.v1

since countries most likely encounter unexpected shocks (i.e, structural change) in energy markets, the natural environment, and macroeconomic factors.

To summarize, this paper aims to address existing gaps by employing a patent analysis decomposition methodology. Specifically, we will decompose relevant patent categories into four contributing factors that influence the patent filing hierarchy, as outlined by Fujii et al. (2016) and illustrated in Figure 2. Specifically, we collect the data from the PATSTAT database which includes more than 138 million patents in the world. We focus on 3 GAET types based on the WIPO (2022): (1) Battery electric vehicle (BEV), (2) Hybrid electric vehicle (HEV), and (3) Fuel cell vehicle (FCV). Meanwhile, we compile the patents for ICEVs (internal combustion engine vehicles) as non-green AETs for comparison with GAETs. Our results show the trends of adopting different types of green (instead of non-green) investment patterns for each country based on its growth stage. We also find that policies on intellectual property (IP) protection and support to encourage R&D can be expected to extend the scope of R&D operations in emerging and developing nations where IP markets are not well developed.

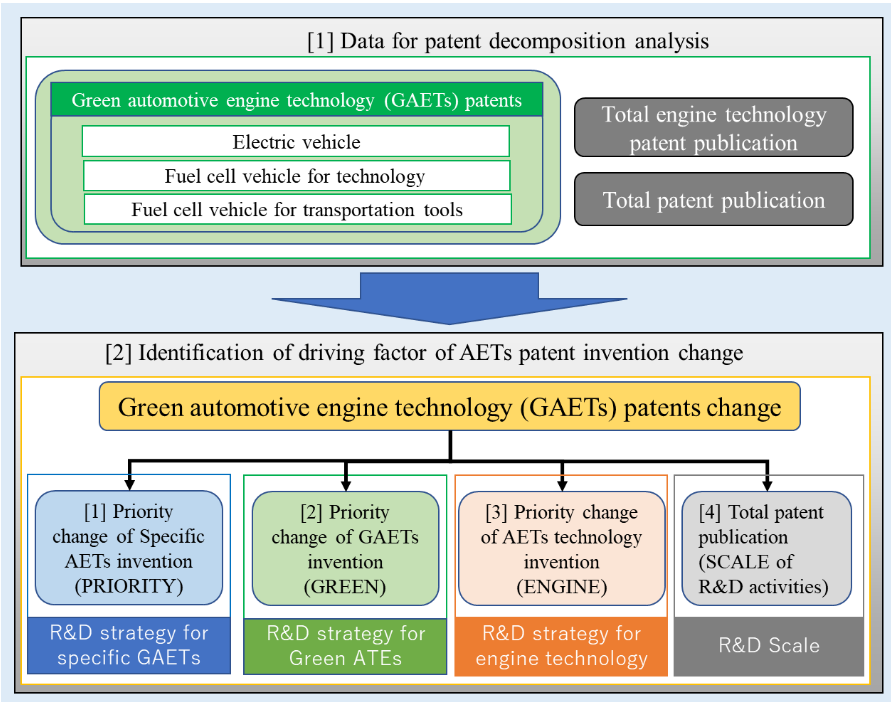

Figure 2. The research framework.

The novelty of this study is the application of structural break identification to patent decomposition analysis, which makes it possible to quantitatively identify the main causes of major changes in R&D activities. This analytical framework has not been used in previous studies and is considered unique to this study.

The remainder of the paper is organized as follows. In Section 2, we review the relevant literature. Section 3 details the methodology employed in the study. We introduce the data collected in Section 4. We present the results and findings in Section 5 and conclude the paper with discussions on conclusions and policy implications in Section 6.

2. Materials and Methods

2.1. Government Regulations and Green Automobile Technology R&D

Climate change, a critical issue impacting humanity, underscores the need for rapid and effective technological adoption across various industries. In recent decades, the focus on altering production and consumption patterns has increasingly extended to sectors like transportation, which relies heavily on fossil fuels (De Stefano et al. 2016).

Governmental action using policy is what spurs technological innovation (Fischer and Newell, 2008; Zhao et al. 2020; Burke et al. 2023). Non-financial policies that give enterprises the freedom to select their technologies often lead to the adoption of cheaper options. In contrast, financial policies that guarantee market prices tend to encourage the adoption of more expensive technologies (Kim 2014). For instance, Fujii and Managi (2019) demonstrate that priority adjustments in green technology inventions varied across China's five-year plans. These variations in environmentally friendly technology are useful in assessing national and global market demands and selecting specific technologies. They also aid in formulating strategies for green growth within China.

The car industry, being particularly sensitive to environmental regulations, is adjusting its research and development (R&D) processes in response to increasingly stringent sales limits on gasoline-powered vehicles worldwide. R&D is a long-term strategy; thus, it is critical to decide which forms of sustainable energy should be given priority (Gauto et al. 2023). There are two techniques for addressing vehicle emission issues (Welberforce et al. 2017). The first way is to switch to a different fuel type (e.g., electronic, hybrid, etc.), which can be accomplished by either improving the quality of conventional fuel or utilizing alternative fuel systems. For example, Van den Hoed (2007) examines the factors influencing private investment in the automotive industry's shift from combustion engine technology to fuel cell technology. The second option incorporates engine technology and the decrease of in-use vehicle emissions as well as new vehicle emissions requirements (e.g., efficiency improvement). Due to the diversity of technological qualities, it is difficult to determine which type of technology has the best technical performance (Chan 2007). For example, electric cars face challenges such as limited driving range and lengthy charging times, while hybrid vehicles encounter difficulties integrating energy storage devices into their power systems.

As a result, determining unique AETs using external indicators in accordance with government laws is difficult yet critical. This research intends to capture green automobile technology R&D at various levels of regulatory legislation.

2.2. Technological Changes and Temporal Patent Data

Patents are significant outcomes of R&D. As a result, they are one of the best tools for tracking technological advancements through time. Moreover, it offers data on the geographic distribution of certain patents, forecast insights, R&D plans, and other things (Cho 2013). They have been recognized as a valuable information resource for technology management research, as well as for the study of innovation and technological advancement.

Research on patent analysis frequently concentrates on two main areas: evaluating a nation's technical competitiveness and the economic impacts of technological innovation (Choi and Park 2009). The patent data can assist practitioners in determining R&D priorities (Hirschey and Richardson 2004), creating a patent map to identify technology gaps (Lee et al. 2015), analyzing technological trends and opportunities (Yoon and Park 2005), investigating the consequences of technological change on company performance (Levitas et al. 2006), and Emphasizing the importance of patents in the innovation of maritime transportation and help to stop patent infringement (Nerheim 2023).

For the automobile industry, previous researchers have attempted to examine GAET systems using patent data. For example, Oltra and Jean (2009) study the rivalry among several low-emission vehicle technologies, as well as automobile manufacturers' inventive strategies. Bonilla et al. (2014) showed that pollution control legislation enacted in the US, EU, and Japan positively impacted the tendency to develop emissions control systems, but not the expansion of the automobile market. Aaldering et al. (2019) provided an in-depth examination of how engine systems competed and evolved with one another. Phirouzabadi et al. (2020) explore dynamic inter-powertrain connections with a focus on information diffusion. Lin et al. (2023) find that green technology diversification affects energy intensity indirectly through vertical spillovers along the supply chain overtime.

However, most studies focus solely on the number of patents, providing no insight into the fundamental drivers of innovation, such as the priority given to specific technological breakthroughs or the scale effect of R&D. This limitation can be overcome using patent decomposition analysis (Fujii et al. 2016).

In brief, considering the research gaps in previous studies, we have the following objectives: (1) identify the trends of adopting green (instead of non-green) investment patterns for each country based on its growth stage. (2) identify which types of green automotive engine technologies for each country to research and development during their green transformation.

3. Methodology

3.1. Patent Decomposition Analysis

Although previous studies (e.g., Wesseling et al. 2014, Ha et al. 2015, and Yuan and Cai 2021) of GAET patents filed for a specific subtype of vehicles (such as electric or other low-emission vehicles) have produced promising results about technological trends, a more thorough examination of the patenting applications is required to determine what drives innovation in various subtypes of the automotive industry. To this end, we utilize a patent analysis decomposition methodology that breaks down relevant patent categories into three factors contributing to the hierarchy of filed patents, as described by Fujii et al. (2016). This method calculates coefficients representing changes in patent applications for each factor by comparing two different time points and using the natural logarithm of their ratio, following the Logarithmic Mean Divisia Index method (Ang et al., 1998). This approach has been extensively applied in various fields, including climate change mitigation (Yamashita and Fujii, 2022), artificial intelligence (Fujii and Managi, 2018), and environmental protection (Fujii and Managi, 2016).

When applied to advanced technologies, the decomposition method can identify key factors driving innovation, such as the prioritization of specific technological inventions or the scale effect of R&D activities (Chen and Lin, 2020). By accounting for the scale effect, patent decomposition approach (Fujii et al., 2016) provides a more accurate measure of the relationship between patent data and actual innovations. To decompose GAET-related patents regarding green technology, we define four indicators: $PRIORITY_k$ (where k=1 and 2), GREEN, ENGINE, and SCALE.

(1) $PRIORITY_k$, the number of GAET-related patent applications in each subtype[1] divided by the total number of engine patent applications. This indicator rises if the targeted subtype has more patents than the other four ones. That is, as $PRIORITY_k$ increases, innovators prioritize the development of the k-th subtype of GAET-related patents over other subtypes.

(2) GREEN, the total number of patent applications in the development of green automotive engines divided by the total number of patent applications in that of automotive engines, indicating the proportion of all GAET-related patents among all the AET patents. ENGINE increases when the growth rate of GAET-related patent applications exceeds the growth rate of all patent applications, indicating that scientists are concentrating their efforts on green automobile engines.

(3) ENGINE, the total number of patent applications in the development of automotive engines divided by the total number of patent applications, indicating the share of all AET-related patents among all the patents. ENGINE goes up when the number of AET-related patent applications increases faster than those of all patent applications, demonstrating that researchers are focusing their efforts on automotive engines.

(4) SCALE, the total number of patent applications to describe the scale of research and development (R&D) activities. As the overall number of patent applications rises, SCALE also increases. Since active R&D efforts usually encourage the development of new technologies, the number of AET-related patent applications increases as the SCALE expands proportionally to the expansion of all R&D activities.

[1] Specifically, we have the *PRIORITY* for battery electric vehicles when k=BEV and hybrid electric vehicles when k=HEV. For more details, see Table 1.

The number of each GAET patent application ($GAET_k$) can be decomposed relative to the number of patent applications for two subtypes of GAET and the total number of patent applications (TOTAL) as shown in Equation (1).

$$GAET_k = \frac{GAET_k}{\sum_k GAET_k} \times \frac{\sum_k GAET_k}{AET} \times \frac{AET}{TOTAL} \times TOTAL$$
$$= PRIORITY_k \times GREEN \times ENGINE \times TOTAL \quad (1)$$

Now consider the change of each GAET-related patent from year t (i.e., $GAET_k^t$) to t+1 (i.e., $GAET_k^{t+1}$). Following Equation (1), we can represent the change in $GAET_k$ patents by Equation (2).

$$\frac{GAET_k^{t+1}}{GAET_k^t} = \frac{PRIORITY_k^{t+1}}{PRIORITY_k^t} \times \frac{GREEN^{t+1}}{GREEN^t} \times \frac{ENGINE^{t+1}}{ENGINE^t} \times \frac{SCALE^{t+1}}{SCALE^t} \quad (2)$$

Then, we can transform Equation (2) into Equation (3) by applying a natural logarithm operator.

$$\ln(GAET_k^{t+1}) - \ln(GAET_k^t) = \ln\left(\frac{PRIORITY_k^{t+1}}{PRIORITY_k^t}\right) + \ln\left(\frac{GREEN^{t+1}}{GREEN^t}\right)$$
$$+ ln\left(\frac{ENGINE^{t+1}}{ENGINE^t}\right) + ln\left(\frac{SCALE^{t+1}}{SCALE^t}\right) \quad (3)$$

For both the left and right hands of Equation (3), we can multiply them by $\omega_k^{t,t+1} = \frac{GAET_k^{t+1} - GAET_k^t}{ln\,(GAET_k^{t+1}) - ln\,(GAET_k^t)}$ to obtain Equation (4).

$$GAET_k^{t+1} - GAET_k^t = \Delta GAET_k^{t,t+1} = \omega_k^{t,t+1} \ln\left(\frac{PRIORITY_k^{t+1}}{PRIORITY_k^t}\right) + \omega_k^{t,t+1} \ln\left(\frac{GREEN^{t+1}}{GREEN^t}\right)$$
$$+\omega_k^{t,t+1} \ln\left(\frac{ENGINE^{t+1}}{ENGINE^t}\right) + \omega_k^{t,t+1} \ln\left(\frac{SCALE^{t+1}}{SCALE^t}\right) \quad (4)$$

Consequently, changes in the number of GAET patents for each subtype overtime are decomposed based on changes into four terms shown in previous equations: (1) $PRIORITY_k$, (2) GREEN, (3) ENGING (the third term), and (4) SCALE. We use an additive weight $\omega_k^{t,t+1}$ to estimate how many published patents there are for each GAET subtype.

4. Data

This study utilized patent application data from the European Patent Office's PATSTAT Online database. The Orbis Intellectual Property database contains information on over 100 million patents in the world. Patent application data was collected on 20th April 2023 from the PATSTAT database. The collection period covers from 1985 to 2019. Following the scopes adopted by Phirouzabadi et al. (2020), this study focuses on 3 AET types in WIPO (2022): (1) battery electric vehicle (BEV), (2) hybrid electric vehicle (HEV), and (3) internal combustion engine vehicle (ICEV). Aghion et al. (2016) identify the BEV and HEV as clean (green) technology and ICEV as dirty (non-green) technology.

The patent classification code is International Patent Classification (IPC), founded by the World Intellectual Property Organization (WIPO). For the details of each IPC code, see Table A1 in the Appendix.

Table 1. Definition of AET subtypes.

Technology Group	Tag	Description (Search strategy)
(Green AET) AET related to battery electric vehicles	BEV	Technologies for electric propulsion, devices, among others relating to vehicles. Keywords: "electric vehicle"; "electric automobile"; "electric car" IPC codes: H02k; H01M; B60L011; B60L003; B60L015; B60K00101; B60W001008; B60W001024; B60W001026
(Green AET)	HEV	Technologies for plural diverse prime-movers for

AET related to hybrid electric vehicles		mutual propulsion relating to vehicles. Keywords: "hybrid propulsion"; "hybrid electric vehicle"; "hybrid vehicle"; "hybrid automobile"; "hybrid electric car"; "hybrid car" IPC codes: F02; F16H; B60K006; B60W020; B60L00071; B60L000720
(Green AET) AET related to fuel cell vehicles	FCV	Technologies for control and power supply from hydrogen fuel cells relating to vehicles. Keywords: "hydrogen" IPC codes: B60Y2200/10; B62; G01R 31/006; G05D2201/0213%; Y02T 10; B60W2510/28; B60W2710/28; Y02T 90/14; Y02T 90/34
(Non-green AET) AET related to internal combustion engine vehicles	ICEV	Technologies for internal combustion engines and their accessories relating to vehicles. Keywords: "internal combustion engine"; "diesel engine"; "IC engine" IPC codes: F01; B60; F02B; F02D; F02F; F02M; F02N; F02P

The alternative approach entails investigating patent application data (Dubarić et al., 2013; Fu et al., 2014), thereby offering valuable perspectives into the R&D efforts of innovators. The requirement of an application fee suggests that inventors generally assume their ideas will succeed in the test, even though some applications may not pass the inspection procedure, highlighting potential concerns with the invention's quality. Therefore, compared to awarded patent data, patent application data are thought to more precisely reflect inventors' research and development efforts and plans. Consequently, we represented inventors' R&D strategies for automotive engine technologies using data from patent applications[2]. To avoid double-counting, we constructed our patent dataset using the principal IPC code and the primary applicant's name, as Fujii (2016) suggested.

Besides, Chinese patent application law was revised in 2001 and 2009, according to Dang and Motohashi (2015), making it easier for local businesses to file patent applications. Furthermore, in 2011 the State Council of China published the Energy Saving and New Energy Vehicle Development Plan (SC 2011), which said that the plan will use national scientific and technology programs along with targeted initiatives to support the development of new electric vehicles. Hu et al. (2017) further pointed out that these legal changes and the implementation of a new subsidy system, rather than internal elements like human resources or shifts in R&D priorities, were the main causes of the spike in patent applications at the State Intellectual Property Office of the People's Republic of China (SIPO). As a result, more AET patent applications have been filed as a result of the new subsidy structure and updated patent application laws, which have enabled increased R&D activities, including patent inventions.

5. Results and Discussion

5.1. Decomposition Analysis

The findings of the decomposition investigation per year in the four nations from various AET categories are displayed in Figures 3 through 6. The bars (in blue, green, grey, and orange) indicate the change of priority, green engine, engine, and scale. According to these figures, all four countries reflect rising trends in all AET subtypes. However, the change of decompositions (i.e., priority, green, engine, and scale) for each varies. For China, the increase in total numbers after the Paris Agreement was mainly due to the scale. But in the other three countries, the key driving factor is priority, and it was shifted from HEV to BEV and FCV.

[2] Applying scientific papers to examine R&D tactics and endeavors is another method. Nevertheless, the lack of a thorough classification of automotive engine technologies in scientific publications makes it challenging to use scientific publishing data for this study. To retrieve the data, a keyword search approach must be used. Scientific journals that are not specifically relevant to AETs may be found using a keyword search technique. It is so challenging to get data on scientific publication counts that accurately reflect the R&D strategies of inventors.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 October 2024 doi:10.20944/preprints202410.0140.v1

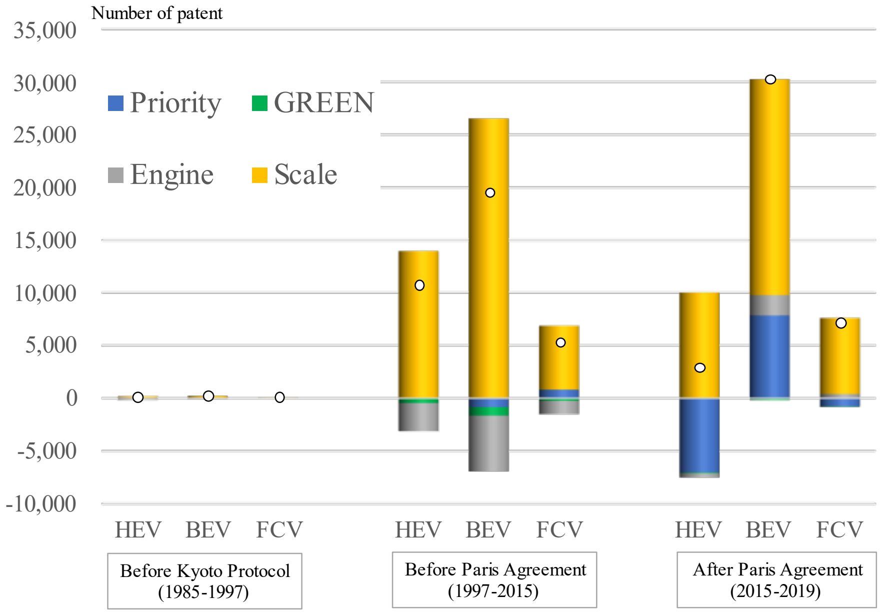

Figure 3. Patent decomposition analysis results for HEV, BEV, and FCV in China. Note: The y-axis is standardized by setting the number of changes in the patents in 1985 to zero.

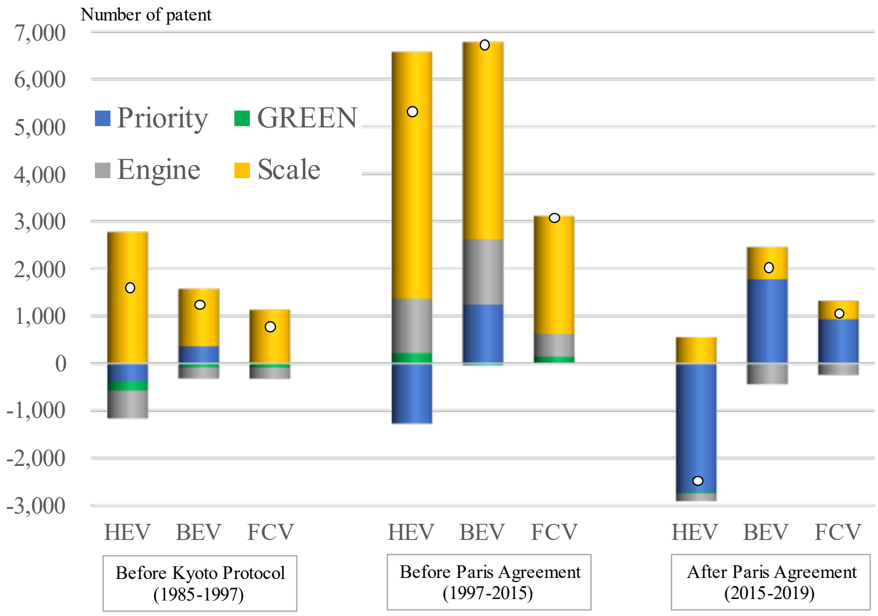

Figure 4. Patent decomposition analysis results for HEV, BEV, and FCV in the U.S. Note: The y-axis is standardized by setting the number of changes in the patents in 1985 to zero.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 October 2024 doi:10.20944/preprints202410.0140.v1

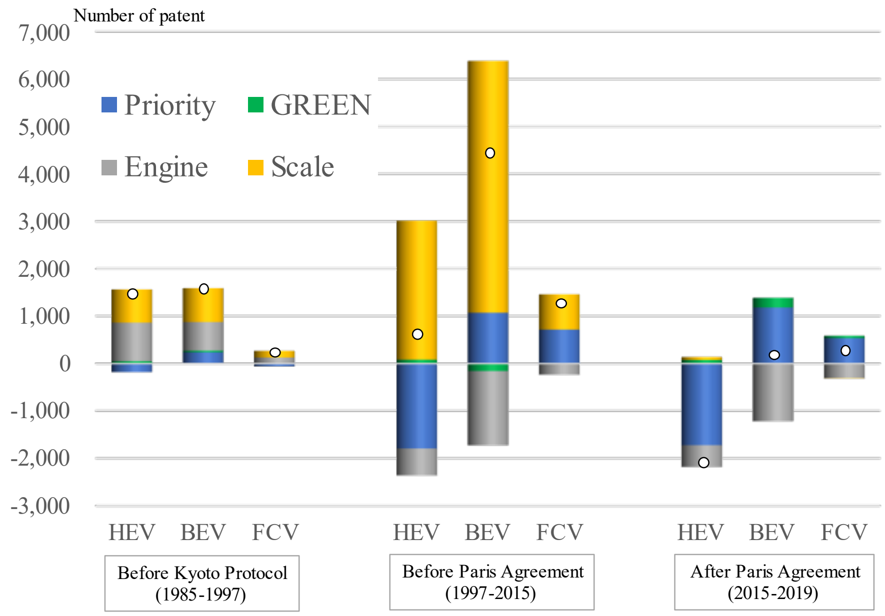

Figure 5. Patent decomposition analysis results for HEV, BEV, and FCV in Japan. Note: The y-axis is standardized by setting the number of changes in the patents in 1985 to zero.

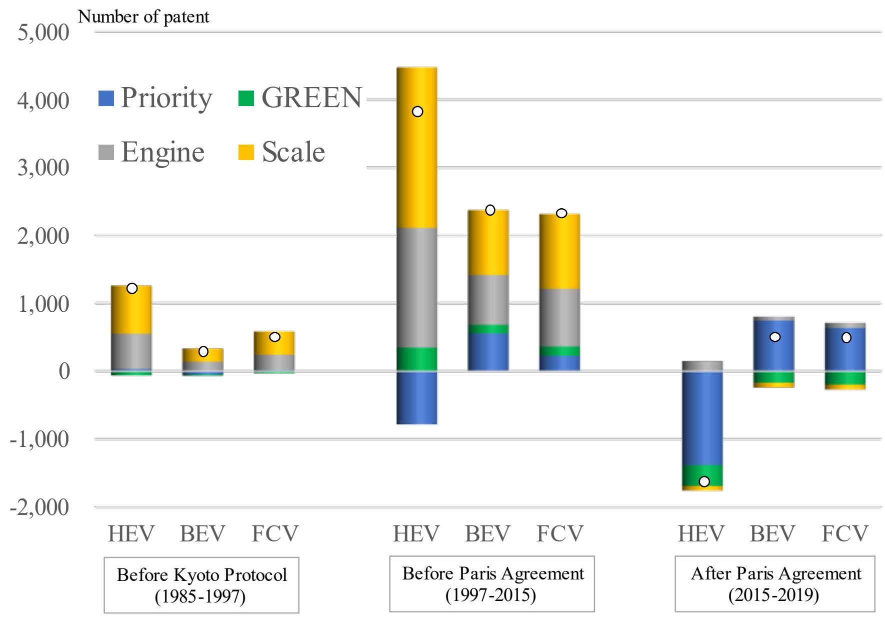

Figure 6. Patent decomposition analysis results for HEV, BEV, and FCV in Germany. Note: The y-axis is standardized by setting the number of changes in the patents in 1985 to zero.

It is not surprising that as time goes on (since 2005), there are more AET-related patents for novel energy sources in China. We consider the following reasons for these breaks. According to Fong et al. (2018), "China's National Medium- and Long-Term Science and Technology Development Planning (2006-2020)" remarkably enhanced Chinese university technology transfer. Especially for vehicle development, it indicates low energy consumption and new energy vehicles as priority themes together with fuel cell technology as cutting-edge technologies (SC 2006). In 2009, China's Patent Law was amended to make applying for patents for domestic businesses that receive government subsidies simpler (Feng 2009). Besides, China made the Auto Industry Adjustment and Revitalization Plan, focusing on the combination of transforming traditional products and promoting new energy vehicles (SC 2009). Furthermore, the Chinese government released 25 items in 6 categories in 2014

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 October 2024 doi:10.20944/preprints202410.0140.v1

with the goal of promoting and implementing new fuel cell vehicles more quickly. These items included building charging stations and enhancing product quality control and technical innovation (SC 2014).

5.2. Structure Break Analysis

Table 2 shows the findings of an investigation of structural changes in the number of patents issued and decomposition factors for HEVs, BEVs, and FCVs across the four nations. The four-digit number represents the number of years in which the structural change has occurred and is shown in two ways: upper structural break (U), which is the structural change associated with an increase, and lower structural break (L), which is the structural change associated with a decrease.

Table 2. Structural breakpoints of patent and decomposed factors in four countries.

Country	Variables	HEV	BEV	FCV
China	Patent	2009(U), *2015(L)*	2005(U), 2010(U), 2015(U)	2008(U), 2015(U)
	Priority	*2015(L)*	2015(U)	-
	Green	-	-	-
	Engine	-	-	-
	Scale	2013(U)	2013(U)	2013(U)
United States	Patent	1995(U), 2000(U), 2012(U)	1995(U), 2001(U), 2010(U), 2015(U)	1995(U), 2001(U), 2015(U)
	Priority	*2015(L)*	1991(U), 1997(U), 2003(U), 2009(U), 2015(U)	2001(U), *2006(L)*, 2013(U)
	Green	*2011(L)*	1995(U), 2001(U), 2006(U), 2011(U)	*2011(L)*
	Engine	-	2001(U), 2006(U), *2015(L)*	-
	Scale	2001(U), *2006(L)*	*1993(L)*, *2006(L)*, 2011(U), 2016(U)	2001(U), *2006(L)*, 2011(U)
Japan	Patent	1994(U), 2000(U), *2015(L)*	1995(U), 2000(U), 2005(U), 2011(U)	1995(U), 2000(U), 2013(U)
	Priority	-	-	-
	Green	-	-	-
	Engine	*2004(L)*	*2012(L)*	*2012(L)*
	Scale	-	-	-
Germany	Patent	1994(U), 1999(U), 2008(U), *2013(L)*	1999(U), 2011(U)	1993(U), 1998(U), 2003(U), 2012(U)
	Priority	*2015(L)*	-	2001(U), *2005(L)*, 2009(U)
	Green	2001(L), 2005(U), *2012(L)*	*2013(L)*	*2013(L)*
	Engine	-	-	-
	Scale	-	-	-

Note: (U) represents "upper structural break", which means structural changes due to the rapid increase. (L) represents "lower structural break", which means structural changes due to the rapid decrease.

We see a lower break in HEV patents and an upper break in BEV patents in China in 2014-2015. As a result, we determine a lower/upper limit for their priority in that year. As a result, we believe that China's priority in new energy development has shifted from hybrid to battery. Since 2014, China has begun to accelerate the building of charging facilities, establish and implement charging facility development plans, and include charging facility construction into overall urban planning (SC 2014). Consequently, more companies were motivated to develop more battery and electricity technologies.

In the United States, there are higher breaks in both 1994-1995 and 2000-2001, brought about by the change to green technologies. In the United States, the upper split in 2000 is caused by both priority and scale. The green trends before and after 2000 are easily identifiable. This guideline is consistent with the stricter environmental regulations. For example, at the beginning of 2000, the United States Environmental Protection Agency (EPA) enforced a rule regulating automobile air pollution (EPA 2000). In the U.S., the 2014-2015 priority index shows different trends by technology, with HEV technology showing a lower break, while BEV technology shows an upper break, similar to the results for China. One of the reasons for these results is California's zero-emission vehicle (ZEV) program, according to The California Air Resources Board. Under this program, automobile manufacturers are obligated to sell a specific proportion of zero-emission vehicles (ZEVs), including fuel cell and electric vehicles, to consumers in the state of California. The tightening of regulations in California in 2011, as well as the introduction of ZEV regulations by the Chinese government in 2012 and the EU in 2016, suggest that R&D priorities have shifted from HEVs to BEVs and FCVs.

We discovered that most patents' higher structural breaks occurred before 2000 in Japan. These breaks, however, cannot be explained by priority, green, engine, or scale. There are no significant structural changes in Japan as they develop each type of technology (e.g., Electric and Hydrogen) unevenly.

In Germany, we can notice a lower break about 2013. It could be due to a slowing of green technology development. One reason is that in Germany, priority was given to research and development of diesel engines. Since patents related to gasoline and diesel vehicles are included in the non-green AET in this analysis, the GREEN indicator is related to a decrease in the GREEN indicator if the development of diesel engines proceeds at a faster rate than the GAET. In fact, the number of patents related to diesel vehicles in Germany increased significantly from 2001 to 2013. The expansion of subsidies for high-performance diesel vehicles in Germany may have pushed German automakers to accelerate the development of diesel vehicles, resulting in a quick decrease in the GREEN index. Besides, Germany closed its nuclear facilities in March 2011 in response to the Fukushima nuclear accident in Japan, which saw the participation of over 200,000 demonstrators against nuclear power in four major German towns. As a result, Germany burned more coal between 2011 and 2014, resulting in an additional 9.5 million tonnes of oil equivalent (BP 2015).

To summarize, due to environmental regulations, China and the United States are shifting their investment from HEV to BEV. Japan develops all technologies, both green and non-green, in an unequal manner. In recent decades, Germany has not invested more in green technologies caused by internal and external shocks.

 doi:10.20944/preprints202410.0140.v1

6. Conclusion and Policy Implication

This study examines the key driving factors behind patent inventions in green automotive engine technology across four countries (China, the United States, Japan, and Germany) from 1985 to 2019. We developed a decomposition framework with a structural break approach to evaluate research and development efforts. This framework explicitly considers the prioritization of GAET technologies as dictated by prevailing research and development policies for sustainable development.

Considering the research gaps in previous studies, we have the following objectives: (1) identify the trends of adopting green (instead of non-green) investment patterns for each country based on its growth stage. (2) identify which types of green automotive engine technologies for each country to research and development during their green transformation. The key findings are summarized below.

We choose the Kyoto Protocol and the Paris Agreement as two cutoff milestones to create three periods for the patterns of green investment uptake. We can see that all four nations (China, the United States, Japan, and Germany) exhibit rising patterns across all AET subtypes over time. However, the decompositions (i.e., priority, green, engine, and scale) alter for each. For China, the increase in overall population following the Paris Agreement is primarily attributable to scale. However, in the other three countries, the attention has changed from green technologies.

In regard to the types of green transformation, China and the United States are switching their investments from HEV to BEV for environmental restrictions. Japan develops all technologies unevenly, regardless of whether they are green or not, and whether they are electric-related or hydrogen-related. Furthermore, Germany has not made significant investments in green technologies in recent years.

This study has several key implications for developed and emerging countries. Based on our research findings, we gain deep insights into the research priority of GAET technological invention. The main elements encouraging private enterprises to support new technological discoveries are shifts in research objectives. To be more specific, governments in emerging countries should develop supporting policies to encourage private companies to prioritize GAET as well as develop relevant patents to gain the scale effect of R&D activities. Such governmental support on IP protection and R&D is especially important for less developed intellectual property markets. Particularly in emerging and developing countries where intellectual property markets are not well developed, policies on IP protection and support to encourage R&D can be expected to increase the scale of R&D activities.

On the other hand, developed countries that have already invested a large amount of budget in R&D can be expected to accelerate patent invention by shifting the allocation of money to GAET development. According to the study's findings, PRIORITY and GREEN are significant factors in the rise of GAET patents in Germany and the US. Additionally, in developed countries, incentives such as tax breaks or subsidies for R&D expenditures for certain technological developments, as well as extended terms of intellectual property protection, can be expected to have the effect of increasing GAET patents.

As stated before, R&D for GAETs varies among countries and across time. To the best of our knowledge, this is the first study to use decomposition analysis and structural breaks on numerical data to evaluate green automotive engine patent applications. Comparing the scale effect and research activity priorities over time provides valuable insights into the variations in patent application filings.

Author Contributions: Zheng Zhang: Investigation, Methodology, Data curation, Software, Writing- Original draft preparation. Hidemichi Fujii: Conceptualization, Visualization, Validation, Writing- Reviewing and Editing.

Funding: This research was funded by Jiangsu Education Department, grant number 2024SJYB1013".

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A Description of Patent Data.

Data were collected using the IPC code. See Table A1 for detailed information.

Table A1. Description of IPC patent classes.

IPC	Description
B60K	Arrangement or mounting of propulsion units or transmissions in vehicles; arrangement or mounting of plural diverse prime-movers in vehicles; auxiliary drives for vehicles; instrumentation or dashboards for vehicles; arrangements in connection with cooling, air intake, gas exhaust or fuel supply of propulsion units in vehicles
B60L	Propulsion of electrically-propelled vehicles
B60W	Conjoint control of vehicle sub-units of different types or different functions; control systems specially adapted for hybrid vehicles; road vehicle drive control systems for purposes not related to the control of a particular sub-unit
F02B	Internal-combustion piston engines; combustion engines in general
F02D	Controlling combustion engines
F02F	Cylinders, pistons, or casings, for combustion engines; arrangements of sealings in combustion engines
F02M	Supplying combustion engines in general with combustible mixtures or constituents
F02N	Starting of combustion engines; starting aids for such engines, not otherwise provided for
F02P	Ignition, other than compression ignition, for internal-combustion engines; testing of ignition timing in compression-ignition engines
H01M	Processes or means, e.g., batteries, for the direct conversion of chemical energy into electrical energy

Source: World Intellectual Property Organization https://www.wipo.int/classifications/ipc/en/.

References

1. Aaldering, L. J., Leker, J., & Song, C. H. (2019). Competition or collaboration? –analysis of technological knowledge ecosystem within the field of alternative powertrain systems: a patent-based approach. *Journal of Cleaner Production*, 212, 362-371.
2. Avadikyan, A., & Llerena, P. (2010). A real options reasoning approach to hybrid vehicle investments. *Technological Forecasting and Social Change*, 77(4), 649-661.
3. Ang, B. W., Zhang, F. Q., & Choi, K. H. (1998). Factorizing changes in energy and environmental indicators through decomposition. *Energy*, 23(6), 489-495.
4. Bai, J., & Perron, P. (2003). Computation and analysis of multiple structural change models. *Journal of Applied Econometrics*, 18, 1–22.
5. Bayer, P., Dolan, L., & Urpelainen, J. (2013). Global patterns of renewable energy innovation, 1990–2009. *Energy for Sustainable Development*, *17*(3), 288-295.
6. Becker, N., Rust, H. W., & Ulbrich, U. (2022). Modeling hourly weather-related road traffic variations for different vehicle types in Germany. *European Transport Research Review*, 14(1), 1-16.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 3 October 2024 doi:10.20944/preprints202410.0140.v1

7. Bhatia, M. S., & Jakhar, S. K. (2021). The effect of environmental regulations, top management commitment, and organizational learning on green product innovation: Evidence from the automobile industry. *Business Strategy and the Environment*, 30(8), 3907-3918.
8. Bonilla, D., Bishop, J. D., Axon, C. J., & Banister, D. (2014). Innovation, the diesel engine and vehicle markets: Evidence from OECD engine patents. *Transportation Research Part D: Transport and Environment*, 27, 51-58.
9. BP (2015). BP Statistical Review of World Energy 2015, http://www.bp.com/statisticalreview, accessed on 9/19/2022
10. Burke, A. F., Zhao, J., Miller, M. R., Sinha, A., & Fulton, L. M. (2023). Projections of the costs of medium- and heavy-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues. *Energy for Sustainable Development*, *77*, 101343.
11. Chan, C. C. (2007). The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*, 95(4), 704-718.
12. Chen, Y. H., Chen, C. Y., & Lee, S. C. (2011). Technology forecasting and patent strategy of hydrogen energy and fuel cell technologies. *International Journal of Hydrogen Energy*, 36(12), 6957-6969.
13. Chen, Y., & Lin, B. (2020). Decomposition analysis of patenting in renewable energy technologies: From an extended LMDI approach perspective based on three Five-Year Plan periods in China. *Journal of Cleaner Production*, 269, 122402.
14. Cho, Y. (2013). Investigating the merge of exploratory and normative technology forecasting methods. *In 2013 Proceedings of PICMET'13: Technology Management in the IT-Driven Services (PICMET)* (pp. 2083-2092). IEEE.
15. Choi, C., & Park, Y. (2009). Monitoring the organic structure of technology based on the patent development paths. *Technological Forecasting and Social Change*, 76(6), 754-768.
16. Daizadeh, I. (2021). Trademark and patent applications are structurally near-identical and cointegrated: Implications for studies in innovation. *Iberoamerican Journal of Science Measurement and Communication*, 1(2).
17. De Stefano, M. C., Montes-Sancho, M. J., & Busch, T. (2016). A natural resource-based view of climate change: Innovation challenges in the automobile industry. *Journal of Cleaner Production*, 139, 1436-1448.
18. Dijk, M., & Yarime, M. (2010). The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand. *Technological Forecasting and Social Change*, 77(8), 1371-1390.
19. Dogan, E., & Ozturk, I. (2017). The influence of renewable and non-renewable energy consumption and real income on CO2 emissions in the USA: evidence from structural break tests. *Environmental Science and Pollution Research*, 24(11), 10846-10854.
20. EPA (2000). Final Rule for Control of Air Pollution From New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements, The U.S. Environmental Protection Agency, https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-control-air-pollution-new-motor-vehicles-tier, accessed on 12/19/2022
21. Feng, X. (2009). The interaction between enhancing the capacity for independent innovation and patent protection: A perspective on the third amendment to the patent law of PR China. *Pittsburgh Journal of Technology Law & Policy*, 9, 1.
22. Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, 55(2), 142-162.
23. Fujii, H., & Managi, S. (2016). Research and development strategy for environmental technology in Japan: A comparative study of the private and public sectors. *Technological Forecasting and Social Change*, 112, 293-302.
24. Fujii, H., & Managi, S. (2018). Trends and priority shifts in artificial intelligence technology invention: A global patent analysis. *Economic Analysis and Policy*, 58, 60-69.
25. Fujii, H., & Managi, S. (2019). Decomposition analysis of sustainable green technology inventions in China. *Technological Forecasting and Social Change,* 139, 10-16.
26. Fujii, H., Yoshida, K., & Sugimura, K. (2016). Research and development strategy in biological technologies: A patent data analysis of Japanese manufacturing firms. *Sustainability*, 8(4), 351.
27. Fukugawa, N. (2022). Effects of incorporating public innovation intermediaries on technology transfer performance: evidence from patent licensing of Japan's Kohsetsushi. *Heliyon*, 8(10).
28. Gauto, M. A., Carazzolle, M. F., Rodrigues, M. E. P., de Abreu, R. S., Pereira, T. C., & Pereira, G. A. G. (2023). Hybrid vigor: Why hybrids with sustainable biofuels are better than pure electric vehicles. *Energy for Sustainable Development*, *76*, 101261.
29. Ha, S. H., Liu, W., Cho, H., & Kim, S. H. (2015). Technological advances in the fuel cell vehicle: Patent portfolio management. *Technological Forecasting and Social Change*, 100, 277-289.
30. Hashmi, A. R., & Biesebroeck, J. V. (2016). The relationship between market structure and innovation in industry equilibrium: a case study of the global automobile industry. *Review of Economics and Statistics*, 98(1), 192-208.

31. Hirschey, M., & Richardson, V. J. (2004). Are scientific indicators of patent quality useful to investors? *Journal of Empirical Finance*, 11(1), 91-107.
32. Hu, F., Wei, S., Qiu, L., Hu, H., & Zhou, H. (2024). Innovative association network of new energy vehicle charging stations in China: Structural evolution and policy implications. *Heliyon*.
33. Ibanez-Fores, V., Bovea, M. D., & Perez-Belis, V. (2014). A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective. *Journal of Cleaner Production*, 70, 259-281.
34. Kim, J. E. (2014). Energy security and climate change: How oil endowment influences alternative vehicle innovation. *Energy Policy*, 66, 400-410.
35. Lee, C., Kang, B., & Shin, J. (2015). Novelty-focused patent mapping for technology opportunity analysis. *Technological Forecasting and Social Change*, 90, 355-365.
36. Levitas, E. F., McFadyen, M. A., & Loree, D. (2006). Survival and the introduction of new technology: a patent analysis in the integrated circuit industry. *Journal of Engineering and Technology Management*, 23(3), 182-201.
37. Lin, C. (2024). 3 Drivers of China's Booming Electric Vehicle Market. Operations Strategy, https://hbr.org/2024/01/3-drivers-of-chinas-booming-electric-vehicle-market, accessed on 02/01/2024.
38. Lin, S., Long, X., Huang, J., & Gao, R. (2023). Green technology diversification, technology vertical spillovers, and energy intensity in Chinese cities. *Energy for Sustainable Development*, *76*, 101281.
39. Nerheim, A. R. (2023). Maritime LNG fuel systems for small vessels—A survey of patents. *Transportation Research Part D: Transport and Environment*, 119, 103766.
40. Niu, Z., Yan, C., & Tan, F. (2024). Green innovation and eco-efficiency: Interaction between society and environment of sustainable development demonstration belt in China. *Environmental Technology & Innovation*, *34*, 103620.
41. Oltra, V., & Saint Jean, M. (2009). Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis. *Journal of Cleaner Production*, 17(2), 201-213.
42. Phirouzabadi, A. M., Blackmore, K., Savage, D., & Juniper, J. (2020). On the coexistence of positive and negative externalities in the inter-powertrain relationships. *Journal of Cleaner Production*, 277, 124118.
43. Phirouzabadi, A. M., Savage, D., Blackmore, K., & Juniper, J. (2020). The global patents dataset on the vehicle powertrains of ICEV, HEV, and BEV. *Data in Brief*, 32, 106042.
44. Pilkington, A., & Dyerson, R. (2006). Innovation in disruptive regulatory environments: A patent study of electric vehicle technology development. *European Journal of Innovation Management*.
45. Ruoso, A. C., & Ribeiro, J. L. D. (2022). The influence of countries' socioeconomic characteristics on the adoption of electric vehicle. *Energy for Sustainable Development*, *71*, 251-262.
46. SC (2006). China's national medium and long term science and technology development planning (in Chinese), The State Council of the People's Republic of China, http://www.gov.cn/gongbao/content/2006/content_240244.htm, accessed on 9/19/2022
47. SC (2009). Auto Industry Adjustment and Revitalization Plan (in Chinese), The State Council of the People's Republic of China, http://www.gov.cn/zhengce/content/2009-03/20/content_8121.htm, accessed on 9/19/2022
48. SC (2011). The State Council on printing and distributing energy conservation and new energy automobile industry notice of development planning (2012-2020) (in Chinese), The State Council of the People's Republic of China, http://www.gov.cn/zwgk/2012-07/09/content_2179032.htm, accessed on 11/20/2022
49. SC (2014). Guiding opinions on accelerating the promotion and application of new energy vehicles (in Chinese), The State Council of the People's Republic of China, http://www.gov.cn/xinwen/2014-07/21/content_2720944.htm, accessed on 9/19/2022
50. Schwarz, G. (1978). Estimating the Dimension of a Model. *The Annals of Statistics*, 6, 461–464
51. Sinigaglia, T., Martins, M. E. S., & Siluk, J. C. M. (2022). The technological evolution of internal combustion engine vehicle: A patent data analysis. *Applied Energy*, 306, 118003.
52. Smit, R., Awadallah, M., Bagheri, S., & Surawski, N. C. (2022). Real-world emission factors for SUVs using on-board emission testing and geo-computation. *Transportation Research Part D: Transport and Environment*, 107, 103286.
53. Van den Hoed, R. (2007). Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry. *Journal of Cleaner Production*, 15(11-12), 1014-1021.
54. Vittori, D. (2021). Threat or corrective? Assessing the impact of populist parties in government on the qualities of democracy: A 19-country comparison. *Government and Opposition*, 1-21.
55. Wesseling, J. H., Faber, J., & Hekkert, M. P. (2014). How competitive forces sustain electric vehicle development. *Technological Forecasting and Social Change*, 81, 154-164.
56. WIPO (2022)., Patent landscape report—Hydrogen fuel cells in transportation. https://www.wipo.int/publications/en/details.jsp?id=4604, accessed on 4/10/2023
57. Yamashita, A. S., & Fujii, H. (2022). Trend and priority change of climate change mitigation technology in the global mining sector. *Resources Policy*, 78, 102870.

 doi:10.20944/preprints202410.0140.v1

58. Yoon, B., & Park, Y. (2005). A systematic approach for identifying technology opportunities: Keyword-based morphology analysis. *Technological Forecasting and Social Change*, 72(2), 145-160.
59. Yuan, X., & Cai, Y. (2021). Forecasting the development trend of low emission vehicle technologies: Based on patent data. *Technological Forecasting and Social Change*, 166, 120651.
60. Zeileis, A., Leisch, F., Hornik, K., & Kleiber, C. (2002). strucchange: An R package for testing for structural change in linear regression models. *Journal of Statistical Software*, 7(2), 1–38.
61. Zeileis, A., Kleiber, C., Krämer, W., & Hornik, K. (2003). Testing and dating of structural changes in practice. *Computational Statistics & Data Analysis*, 44(1–2), 109–123.
62. Zhao, J. H., Zeng, D. L., Che, L. P., Zhou, T. W., & Hu, J. Y. (2020). Research on the profit change of new energy vehicle closed-loop supply chain members based on government subsidies. *Environmental Technology & Innovation*, 19, 100937.