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A Bibliometric Research on Next-Generation Vehicles Using CiteSpace

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Abstract: Next-generation vehicles (NGVs), which mainly refers to hybrid vehicles (HVs), plug-in hybrid vehicles (PHVs), electric vehicles (EVs), fuel-cell vehicles (FCVs), and clean diesel vehicles (CDVs), are becoming more and more popular as the potential answer to decreasing fossil fuel consumption and CO_2 emission from traffic sectors. Although the research on NGVs started in the 1990s, a systematic observation or summarization of the research on NGVs has not been performed yet. Thus, the current status, characteristics, latest trends, and issues of the research on NGVs have not been clarified yet. This research analyzed the research on NGVs recorded in the Web of Science published between 1990 to 2020 using CiteSpace, from a macro perspective. The results show that HVs and EVs are the crucial research objects in comparison with FCVs and CDVs. The research on NGVs was mainly performed by countries that own large vehicle makers or markets. However, it is noticeable that many developing countries have also started to study NGVs, which proves that NGVs have become popular globally. On the other hand, the research topics and categories of NGV study have always had a strong bias in favor of their function and technology development. Since NGVs have been sold for years in many countries already, there will be a considerable number of waste NGVs generated in the future, and so, future research should focus on recycling policies and/or recycling technology for NGVs to guarantee their sustainable development.

Keywords: bibliometric analyzation; CiteSpace; next-generation vehicle; research situation; research weakness; recycling

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1. Introduction

As motorization has developed rapidly worldwide, CO_2 emissions from the traffic sector have occupied a 25% share of global CO_2 emissions [1]. Moreover, according to the International Energy Agency (IEA), fossil fuel consumption in the traffic sector will grow to at least 106.3 million barrels per day in 2040 [2].

Under such circumstances, since the 1990s many advanced countries have started to develop next-generation vehicles (NGVs) to reduce the CO_2 emission and fuel consumption of the traffic sector. Furthermore, after the year 2008, not only advanced countries but also developing countries started to put effort into developing NGVs [3,4]. Although the definition of NGVs varies from country to country, generally speaking, a NGV refers to hybrid vehicles (HVs), plug-in hybrid vehicles (PHVs), electric vehicles (EVs), and clean diesel vehicles (CDVs) in most of the countries [5,6].

The research and development of NGVs started in the 1990s, and thus, there has been a tremendous number of studies on NGVs. However, these previous studies have not yet been systematically and quantitively summarized. Therefore, it is hard to clarify the current status, characteristics, latest trends, and issues of the research on NGVs.

Bibliometric analysis, which is a research method developed by Pritchard in 1969, has been proposed as a solution to such a problem. Bibliometric analysis can reveal the impact, current situation, and historical transition of a specific academic field by surveying published books or research papers using mathematics or statistics methods [7].

This research will perform a bibliometric analysis of the research on HVs, PHVs, EVs, FCVs, and CDVs published in the last 30 years. We aim at revealing the current situation, the countries leading in studying NGVs, the most focused academic categories, knowledge base, popular research topics, the historical transition of research hotspots, and the deficiencies of current research on NGVs, and will propose the direction of improvement for the future.

2. Materials and Methods

2.1. Data Source and Data Selection Standard

The research related to NGVs was collected from the Web of Science (WoS). Since the WoS includes multiple databases, only research recorded in the "Web of Science Core Collection" was collected. The document type of research was limited to "article" only. The timespan of the collected research (when the research papers were published) was set to be between 1990 to 2020. All these data were obtained on 20 May 2020 [8].

Furthermore, during the data collection process, the search equation (including file tags, boolean operators, parentheses, and query sets) should be customized to achieve a more accurate research result. The search equations used in this research are: "TS = (hybrid NEAR/2 vehicle OR hybrid NEAR/2 car)" for HVs and PHVs; "TS = (electric NEAR/2 vehicle NOT hybrid NOT hydrogen NOT plug in) OR (electric NEAR/2 car NOT hybrid NOT hydrogen NOT plug in)" for EVs; "TS = (hydrogen NEAR/2 vehicle OR hydrogen NEAR/2 car)" as well as "TS = (fuel-cell NEAR/2 vehicle OR fuel-cell NEAR/2 car)" for FCVs; and "TS = (diesel NEAR/2 vehicle OR diesel NEAR/2 car)" for CDVs. Collected papers will be checked by CiteSpace (Ver. 5.6.R5) to remove research papers that do not meet our standard (such as duplicates or papers without precise publication dates). The number of research papers on HVs (including PHVs), EVs, FCVs, and CDVs was 6341, 11,429, 2745, and 2518, respectively.

2.2. Analysis Tool, Settings, and Research Flow

CiteSpace (Ver. 5.6.R5) is the software used in this study to analyze and generate the scientific landscape of the research on NGVs. CiteSpace is a software developed by Professor ChaoMei Chen and has been widely used by various researchers to visualize the roadmap and trends of a specific academic field [9–14].

The settings of CiteSpace should be specified first to achieve a significant research result. In this research, the time-slicing of CiteSpace was set to between 1990 to 2020, which equals to the timespan of collected research. The "#Years Per Slice" was set to be 1, which means that CiteSpace will analyze the collected research on a 1-year basis. Additionally, to show a more intuitive and comprehensive network of the research on NGVs, the network was pruned by the "Pathfinder; Pruning sliced networks; Pruning the merged network" method [15].

As for the flow of this study, in order to see the current status of research on NGVs a quantitative analysis will be performed to clarify which type of NGV is the most popular research subject. We will also explain how the prevalent NGV became popular and why others did not. Next, in order to see which country is playing the central role in studying NGVs, we will identify the number of research studies on NGVs from each country and the cooperative relationship among countries. Then, to clarify the characteristics of the current research on NGVs, focusing on the most popular type of NGVs, we will analysis of their academic category, knowledge base, and popular research subject. Last, to show the historical transition of NGVs' research hotspots, this research will investigate the keywords in the collected research. Furthermore, this research will also discuss the flaws of the current research on NGVs and the expected future direction.

3. Results

3.1. Quantitative Analysis on Research Related to NGVs

Figure 1 shows the number of research studies on each type of NGVs from 1990 to 2020. It is plain to see that there are several crucial time points in the development history of NGVs.

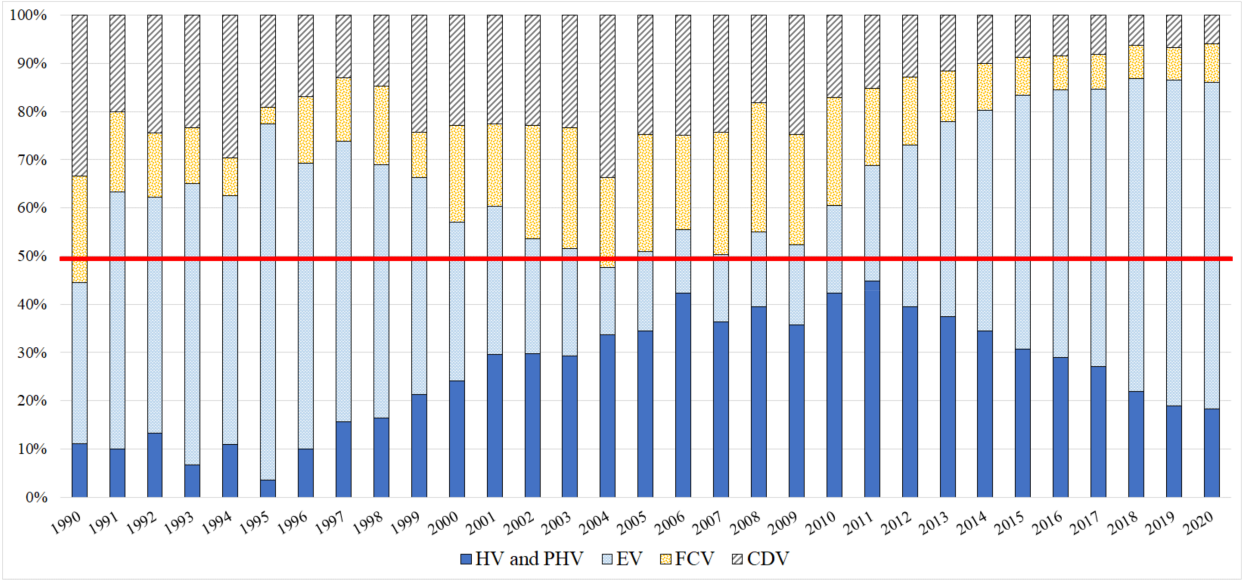

Figure 1. Number transition of research studies on each type of NGV.

3.1.1. The Early 1990s to the Mid-1990s

At the early stage of the 1990s, most research papers were about EVs instead of other types of NGVs. This indicates that EVs were the most attractive research subject back then.

Such a circumstance was effected by the "Zero Emission Vehicle (ZEV)" regulation, which was published in California, US. In 1990, California installed the first ZEV regulation to improve the air pollution due to motorization. According to the ZEV regulation, vehicle makers who sold over 35,000 vehicles per year in California (namely GM, Ford, Daimler Chrysler, Toyota, Nissan, Honda, and Mazda) were to be responsible for selling a certain percentage of EVs or FCVs, from 1998 [16]. Since America has the largest vehicle import market (Figure 2) [17], vehicle makers worldwide started to develop EVs and FCVs.

However, in the 1990s, high-capacity lithium-ion batteries (LiBs) were not commercialized yet, which lead to a relatively short running range of EVs on a single charge. Additionally, hydrogen procurement and storage technology were immature. Thus, research on EVs and FCVs started to decline after the middle of the 1990s.

3.1.2. Late 1990s to 2009

On the other hand, in the late 1990s, although the ZEV regulation was revised and delayed, major vehicle manufacturers had accumulated technology to decrease the CO_2 emissions of vehicles through the installation of driving batteries or exhaust gas treatment systems. In 1997, Toyota commercialized HVs in Japan, and soon after that CDVs were developed in European countries [18]. Compared to traditional gasoline and diesel vehicles, HVs and CDVs emit less CO_2 during the driving process without facing the problem of short running range. Consequently, HVs and CDVs became famous worldwide, and accordingly, research on HVs and CDVs began to increase.

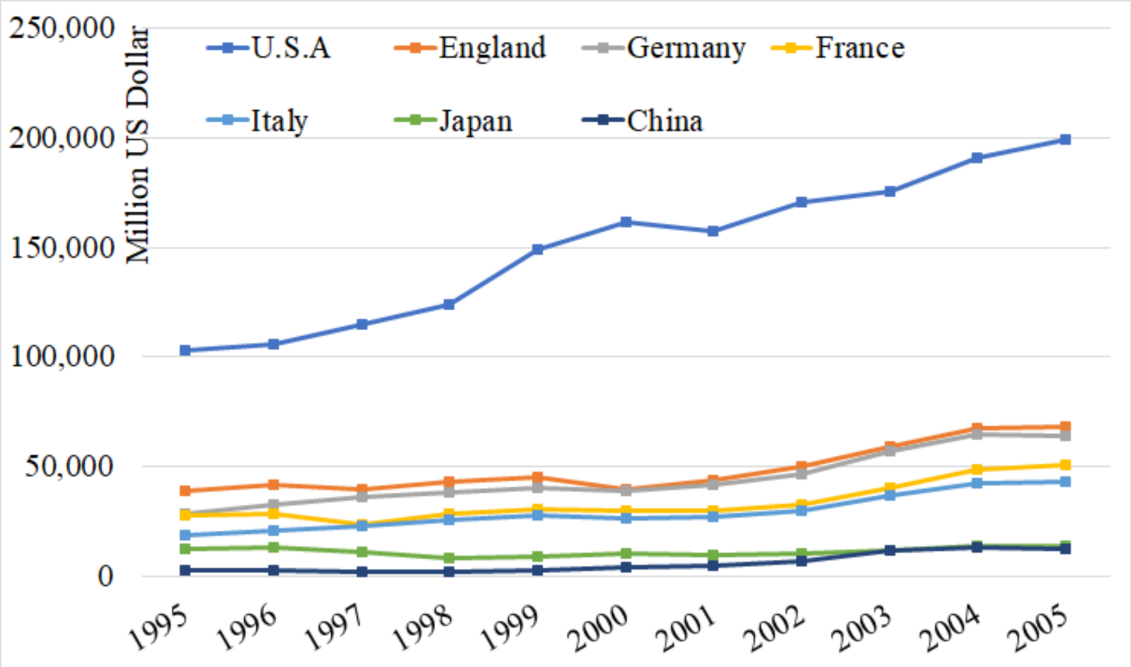

Figure 2. Vehicle import value of each country from 1995 to 2005 [17].

Furthermore, besides HVs and CDVs, advanced countries (such as Japan, the EU, and the US) were also making efforts in developing FCVs [19,20]. Consequently, the number of research on FCVs and CDVs continued to increase, occupying half of the number of research studies on NGVs in 2004 and maintaining such a level until 2009.

3.1.3. 2009 to Present

Since 2009, the number of research on FCVs and CDVs has started to decline.

There are two reasons for the decline of research on CDVs. One is that CDV technologies have matured and so do not need large-scale scientific exploration anymore. Another reason is that, affected by CDVs' emission cheating scandal [21], the EU, which is the largest market for CDVs globally, announced the development of EVs instead of CDVs in the future. Therefore, researchers stopped focusing on CDVs. On the other hand, although the number of research studies on FCVs is continuing to increase, FCVs are still the minority type of NGV in the research field. This could be because the technologies related to FCVs are relatively advanced and sophisticated and so it is hard for the researchers to make significant scientific progress.

In comparison, along with the development of battery technologies and the urgent necessity to stimulate consumption after the Lehman shock [22,23], from 2009 global sales of HVs and EVs started to explode. Consequently, the research on HVs and EVs started to increase and occupies over 80% of the research papers on NGVs right now. Moreover, in 2013, the number of research studies on EVs surpassed HVs, which indicates that EVs are the most attractive research subject now.

Based on the above facts, we can conclude that the most attractive research subject in the NGV field has continuously changed in recent years, but it is clear that the EVs and HVs are currently the most attractive research topic.

3.2. Country Distribution of Research on NGVs

Figure 3 shows the number of research studies on NGVs from each country. In Figure 3, every node represents a country. The node's size reflects the number of researches on a specific type of NGV from a country. The fuchsia ring outside each node reveals the centrality of each country. Typically, a higher centrality (indicated by the thickness of the

fuchsia ring) means more cooperation between a specific country with other countries and more impact in the academic field [15].

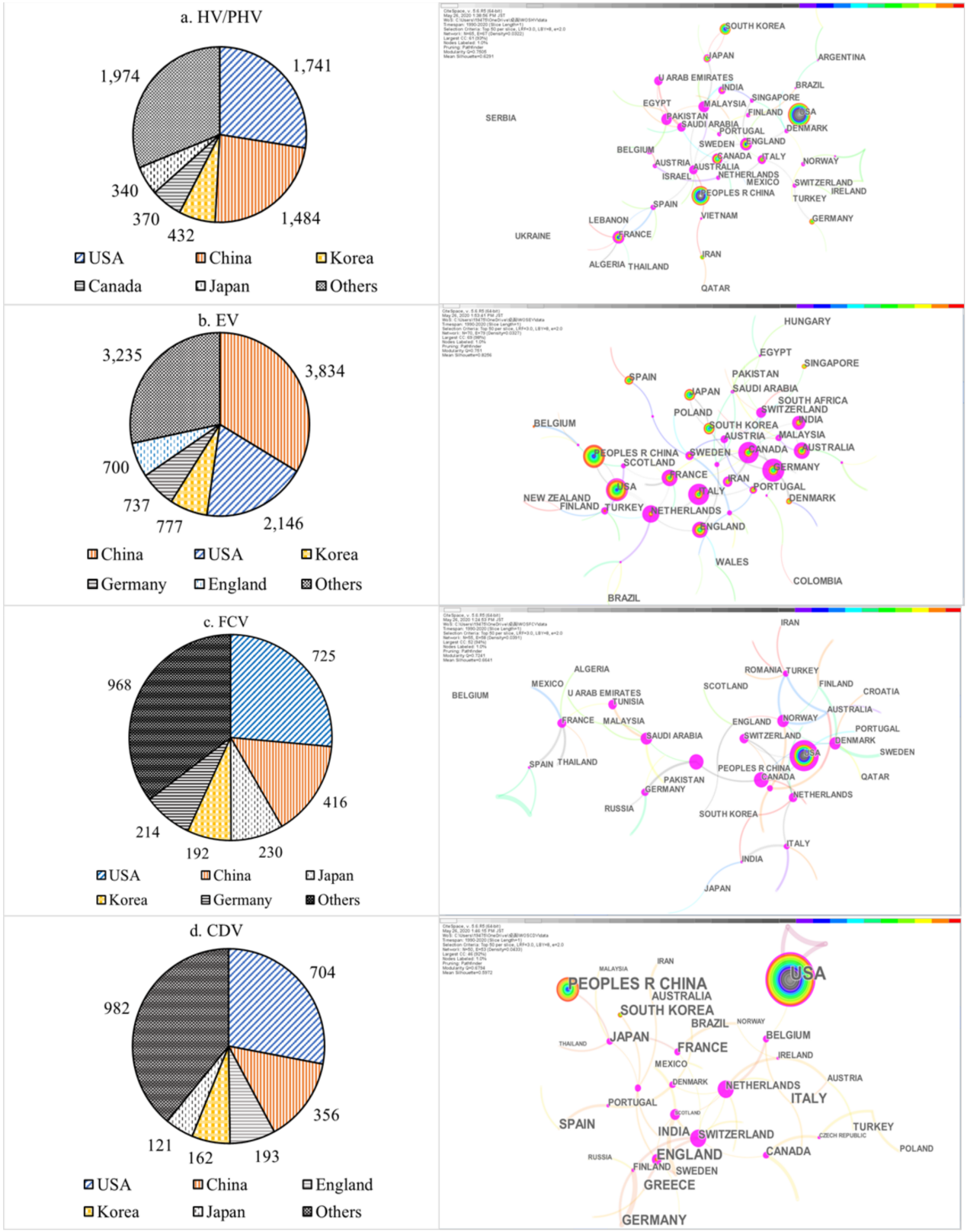

Figure 3. Country distribution of NGV research.

As shown in Figure 3, most of the research on HVs, FCVs, and CDVs were from the US, while most of the research papers on EVs were from China, which is also the largest EV market in the world. It is quite surprising that Japan, the largest HV market globally, did not take the leading role in publishing papers about HVs. This could because most of the scientific research results related to HVs were published as patents in Japan instead of research papers. To prove this conjecture, we collected the patents of HVs from the China National Knowledge Infrastructure (CNKI). The patents of HVs were collected on 30 March 2020 [24]. As shown in Figure 4, most of the patents related to HVs were applied from Japan. That is to say, in Japan, the research results of HVs were mainly published as patents as opposed to research papers.

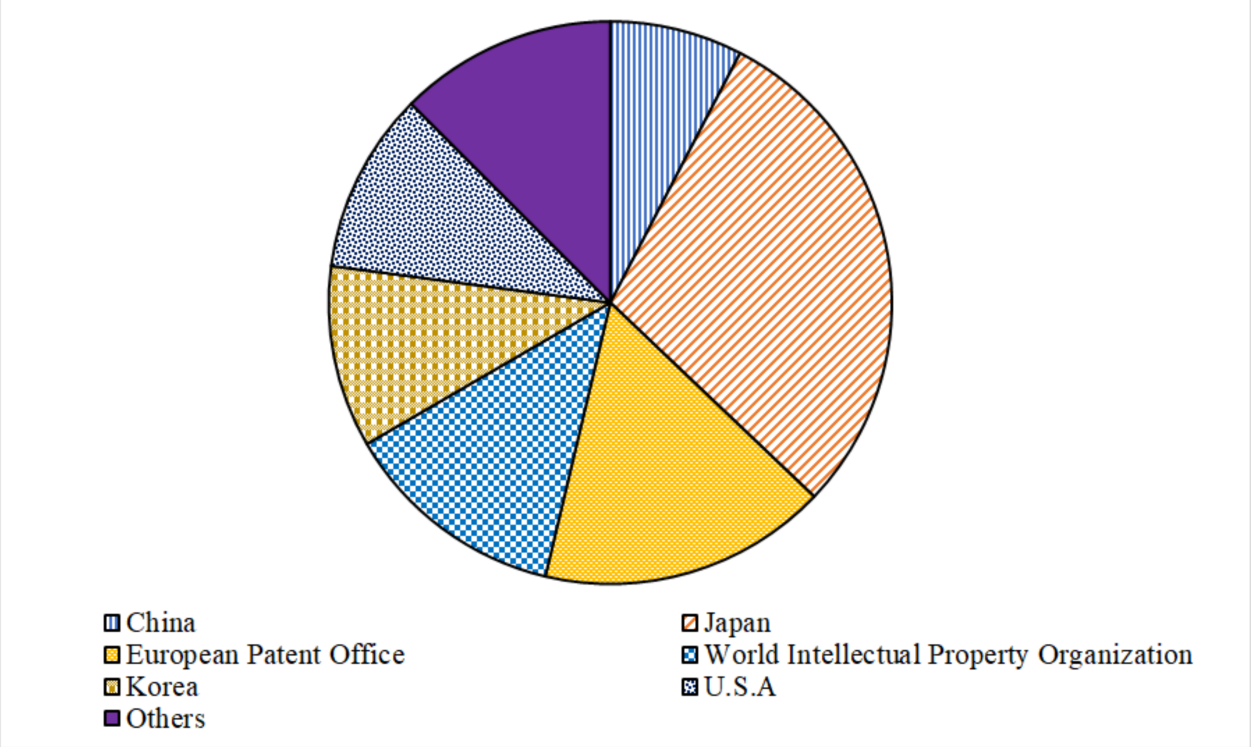

Figure 4. Patents of HVs from each country and association.

As for each country's centrality, it is surprising that although China publishes the most research papers on EVs, the centrality of China is relatively low compared to other countries. As mentioned previously, this normally means that the international cooperation between the researchers in China and other countries is comparatively little, and their academic impact may be small.

However, if looking from a social perspective, a higher centrality does not guarantee a higher research impact every time. An obscure reason for high centrality could be due to similar NGV policy among a particular group of countries. For instance, the top five countries with the highest centralities in the research on CDVs are the "Netherlands", "Switzerland", "Scotland", "Belgium", and "Bangladesh". Among these five countries, the former four countries/districts are all in/near the European Union, where there is heightened enthusiasm for developing CDVs [25].

One more point worth noticing is that there is also a sudden increase in the research on NGVs in developing countries such as Pakistan, Tunisia, and Iran, which indicates that developing countries have also noticed the importance of NGVs and are putting efforts into installing NGVs. Such a trend proves that research on NGVs has become a global concern.

3.3. Category Distribution of the Research on NGVs

Figures 5 and 6 show the category distribution of research on HVs and EVs, respectively.

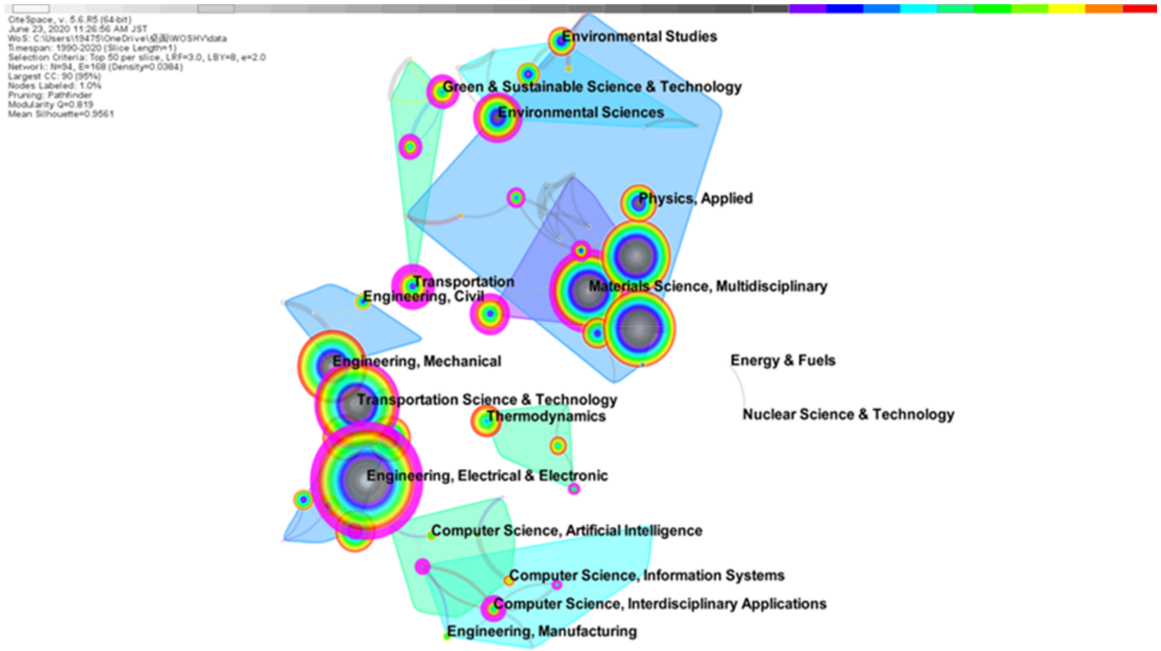

Figure 5. Main research categories of HVs and PHVs.

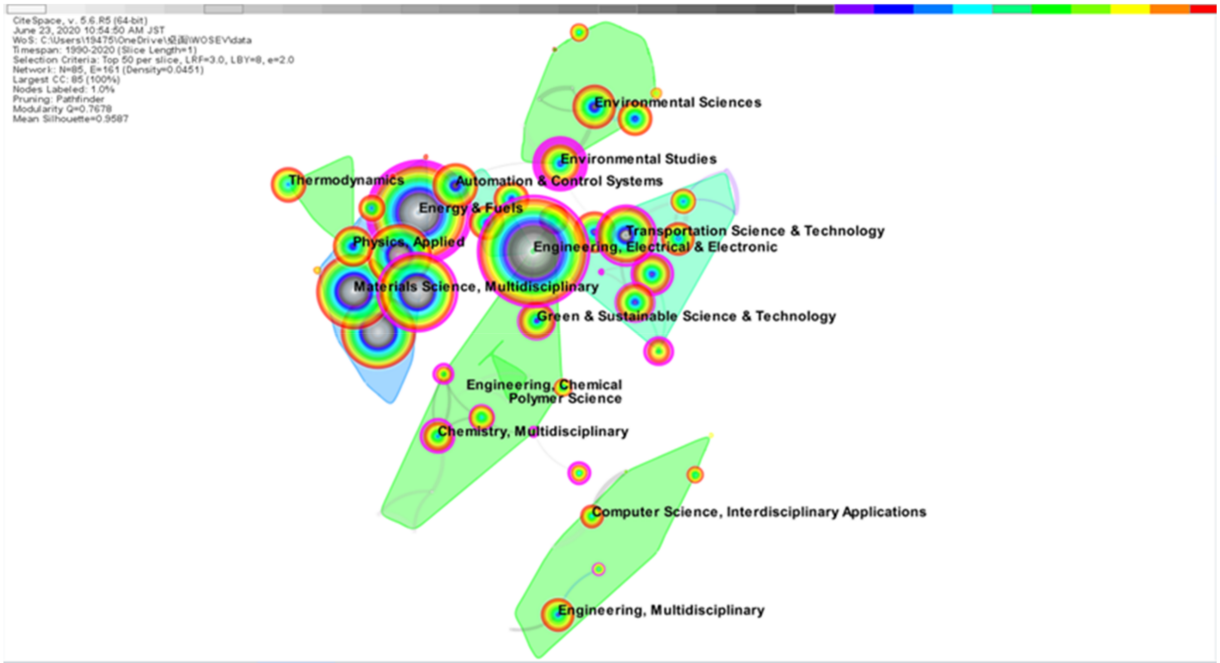

Figure 6. Main research categories of EVs.

For HVs and EVs, most of the research belongs to the "Engineering, Electrical, and Electronic" category, with the following most popular categories being "Energy and Fuels" and "Transportation Science and Technology", indicating that manufacturing technology, as well as battery technology, is most researchers' primary focus. However, as the latest trend, the category "Computer Science, Information Systems" has started to attract attention.

The CASE (Connected; Autonomous; Shared; Electric) trend in the vehicle industry could explain this phenomenon [26].

From the results above, it is plain to see that most of the research on NGVs belongs to the "Engineering, Electrical, and Electronics" category, which indicates that most researchers are still focusing on improving the running or environmental functions of an NGV. In comparison, only a tiny group of research belongs to the "Environmental Sciences and Ecology" category. In other words, topics such as the proper treatment or recycling of end-of-life NGVs have not attracted enough attention yet. This phenomenon could be because most of the researchers believe that NGVs, especially EVs, have just become fashionable, and thus it is too early to consider the recycling of NGVs at this point.

Moreover, "Computer Science" has become a new popular research area for both HVs and EVs. This new trend could be caused by the increasing electrification of vehicles and high-capacity battery equipment.

3.4. Knowledge Base of Study on NGVs

This section focuses on the "Engineering, Electrical, and Electronic" category and will survey the content of the top ten most cited research studies in this category to see their knowledge base (Tables 1 and 2).

Table 1. Frequently cited research on EVs in Engineering, Electrical, and Electronics fields.

Ranking	Number of Citations	Year of Publication	Reference Number
1	818	2005	[28]
2	639	2011	[33]
3	588	2004	[27]
4	587	2015	[29]
5	516	2011	[34]
6	512	2001	[36]
7	493	2013	[30]
8	457	2011	[32]
9	453	2013	[31]
10	429	2013	[35]

Table 2. Frequently cited research on HVs and PHVs in Engineering, Electrical, and Electronics fields.

Ranking	Number of Citations	Year of Publication	Reference Number
1	1315	2010	[37]
2	981	2013	[38]
3	847	2007	[46]
4	834	2009	[39]
5	758	1999	[42]
6	700	2003	[45]
7	682	2008	[43]
8	631	2008	[44]
9	565	2011	[40]
10	551	2010	[41]

Over half of the research on EVs in this category focused on wireless charging technology (basic theory, design of related components, improvement of charging efficiency, and the technical requirements of power transmission systems) [27–32]. This demonstrates that installing efficient charging facilities is necessary for the popularization of EVs, and EVs are, indeed, becoming more and more popular.

On the other hand, part of the research tries to develop the models that can quantitatively specialize the impact of EVs' popularization on power distribution systems or discuss the optimization of EVs' charging pattern [33–35].

Also, the research papers related to energy storage facilities and the related technological development status were frequently cited as well. Thus, it is fair to presume that most researchers focused on driving batteries and energy supplement systems (Tables 1 and 2) [36].

As for HVs, most of the research being frequently cited was talking about the impact on the power distribution system due to the installation of PHVs [37–41].

Besides that, research studies focusing on HVs and PHVs' driving batteries, converters, motors, control systems, and power electronic component technologies were cited frequently as well [39,42–45].

In other words, the research related to HVs is mainly focusing on their technology development as well.

3.5. Popular Topics of Research on NGVs

Figures 7 and 8 show the popular topics of research on HVs and EVs.

As shown in Figure 7, the 13 most mentioned topics were "induction motor drives"; "distribution networks"; "lithium-ion battery"; "biofuel"; "lead/acid batteries"; "demand response"; "cathode"; "wind power"; "motors"; "segment magnet wire"; "state of charge"; "fuel cell"; and "digital control". Although "electric vehicle" is also listed as a topic in Figure 7, since we are analyzing EV articles already, "electric vehicle" should be excluded as an interference.

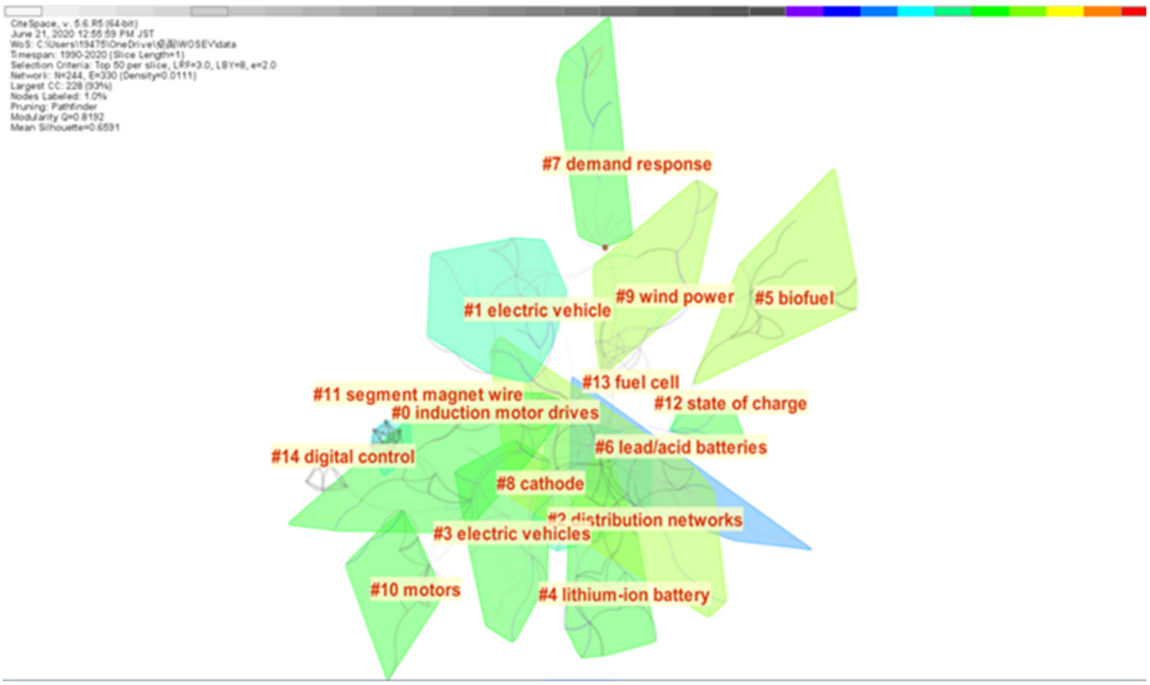

Figure 7. Popular topics of research on EVs.

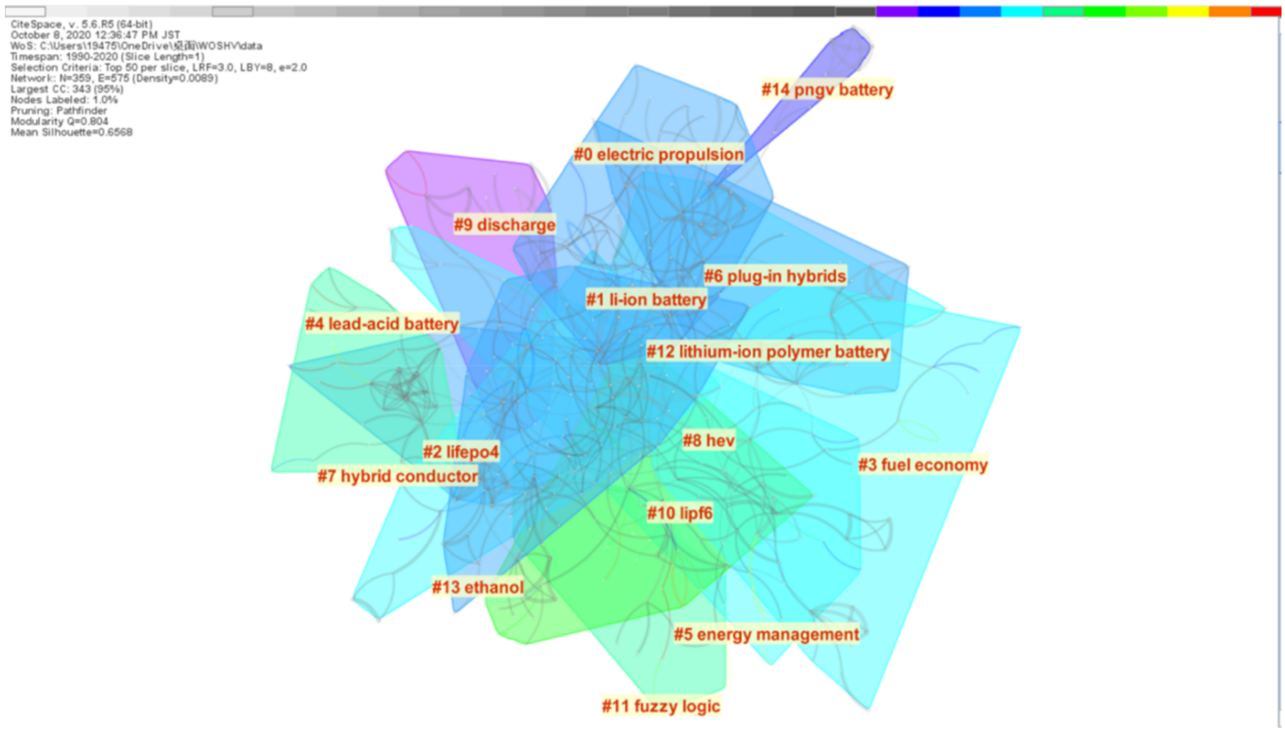

Figure 8. Popular topics of research on HVs and PHVs.

From all the topics collected, we noticed that the research relating to EVs so far has been focusing on the running performance of EVs ("induction motor drives", "segment magnet wire", "motors", "cathode", and "fuel cell"); battery technology and convenience ("lead/acid batteries", "lithium-ion battery", "state of charge", and "distribution networks"); the effectiveness of governments' promotion policies ("demand response"); and EVs' absolute environmental performance. Some researchers clearly have doubts about the current energy source of EVs ("biofuel", "wind power").

As for HVs, their popular research topics are "electric propulsion", "li-ion battery", "lifepo4", "fuel economy", "lead-acid battery", "energy management", "plug-in hybrids", "hybrid conductor", "discharge", "lipf6", "fuzzy logic", "lithium-ion polymer battery", "ethanol", and "pngv battery". Similarly, we excluded the topic "hev" from the collected topics, which is an abbreviation for hybrid electric vehicle.

The above topics indicate that the research relating to HVs are centered on the battery development ("li-ion battery", "lead-acid battery", "lithium-ion polymer battery", "lixfepo4", and "lipf6"); and HVs' running ability and alternative fuel ("energy management", "discharge", "hybrid conductor", "fuel economy", "ethanol", and "electric propulsion"). Moreover, PHVs also attract much attention ("plug-in hybrids", and "electric propulsion").

One interesting feature of the HVs' topic transition trend is that the time interval for the HVs' topic occurrence is much earlier than for EVs (Figures 7 and 8). This proves our previous statement that research on HVs has been declining over these years. However, this does not necessarily represent a negative phenomenon, especially when considering that HVs have been commercialized for over 20 years since 1997. Thus, their technology should be matured already.

3.6. Burst Keywords Analyzation

Figures 9 and 10 presents the burst keywords from the research on HVs and EVs. The burst keywords will show if a specific keyword has been frequently cited in a specific time range, and will represent the historical transition of the research hotspots on HVs and EVs.

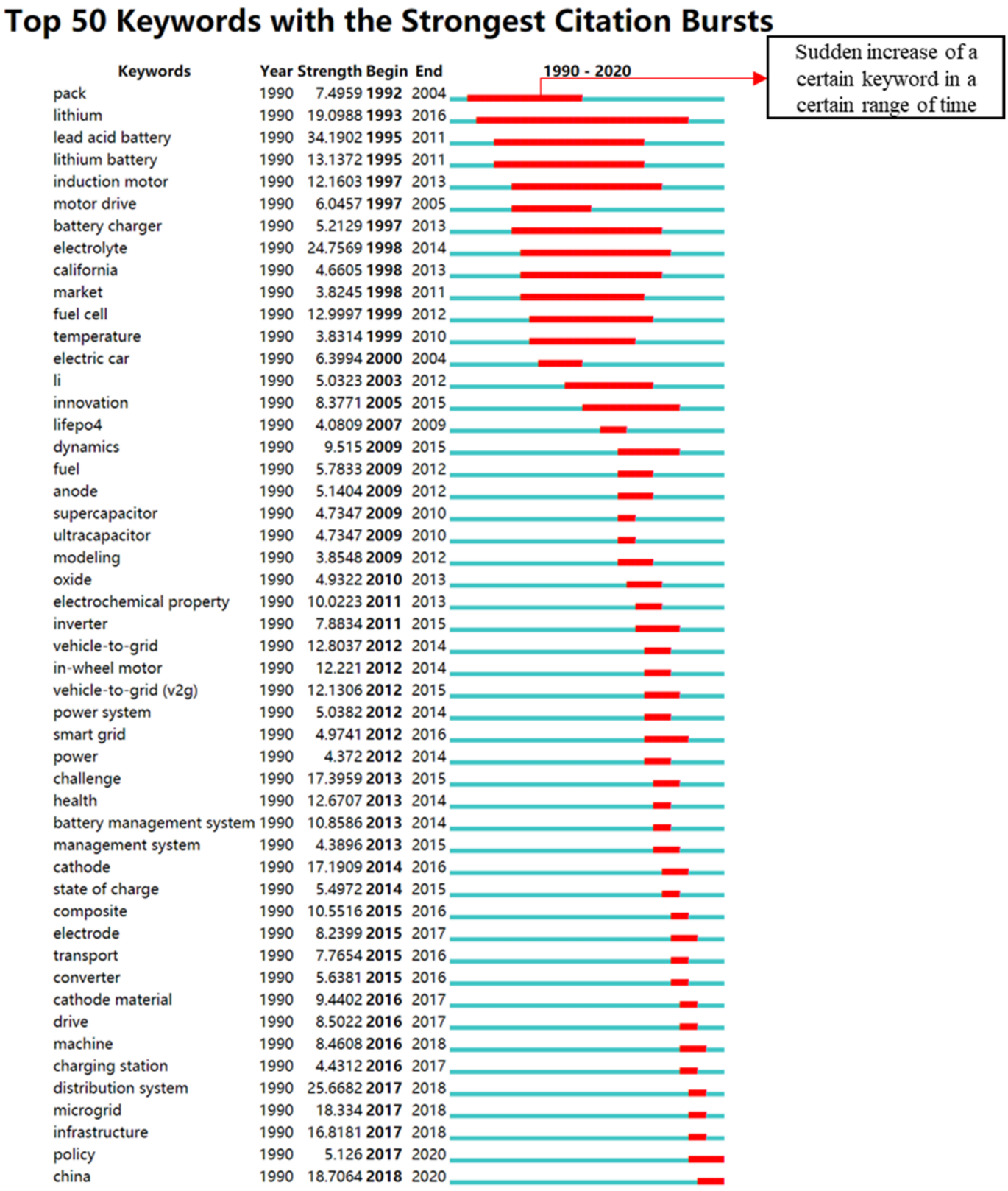

Figure 9. Keywords burst for EV research.

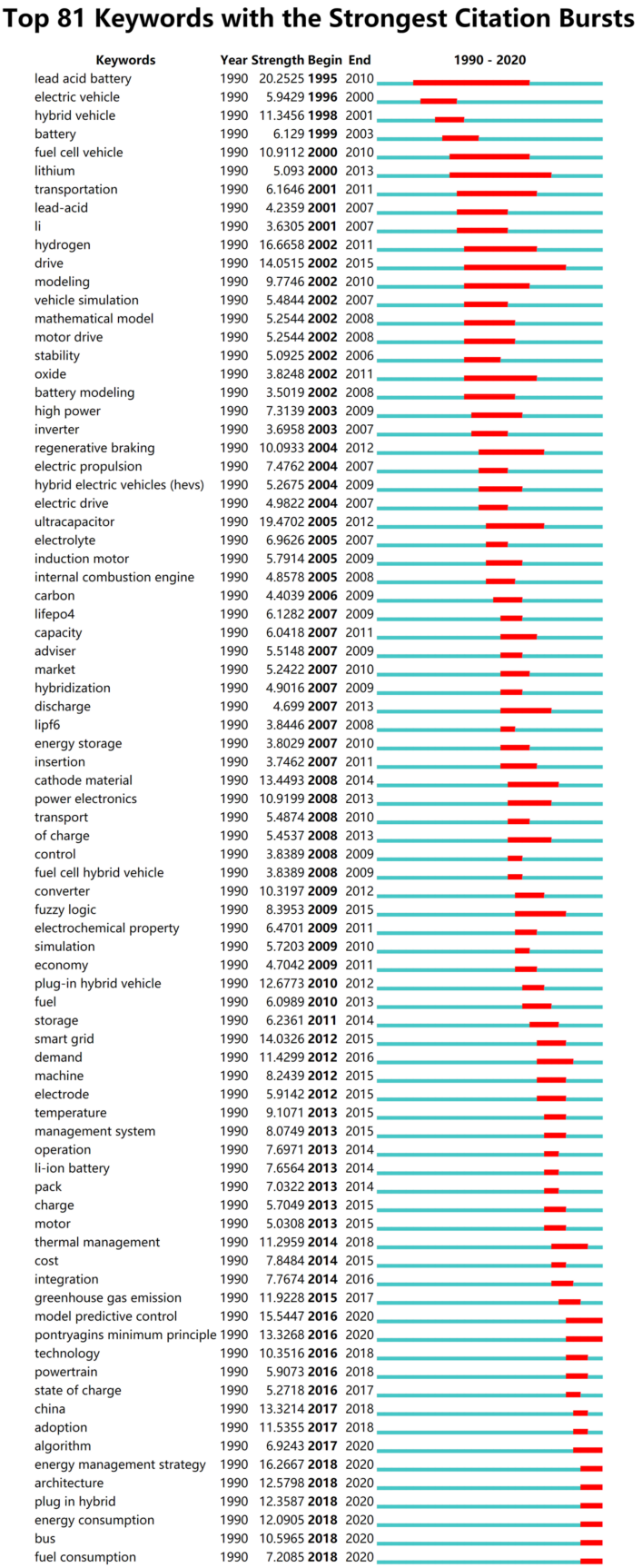

Figure 10. Keyword burst of HV researches.

We found fifty keywords with the most robust citation bursts for research on EVs. In accordance with these keywords, we can conclude that the driving battery and motor have been the enduring research hotspots for EVs. Additionally, improving the performance and the durability of these components has also been a current research hotspot. This could because these components can decide an EVs' performance. Moreover, with the popularization of EVs worldwide, research on EV charging facilities has also become a hotspot.

On the other hand, two toponyms "California" and "China" were detected as well. This means that these two places have a special meaning for the development of EVs. As mentioned previously, California is the first place that installed the "Zero-Emission Vehicle (ZEV)" regulation [16]. Affected by the "ZEV" regulation, General Motor began to lease the first mass-production EV in California in 1996 (the "EV1") [47]. This is undoubtedly a milestone in the history of EVs. Meanwhile, China has attracted the world's attention since the Chinese government began developing EVs in 2009, with China becoming the largest EV market in the world since 2015 [48,49].

Furthermore, 81 bursts of keywords were detected from the research related to HVs. Similarly, battery technology and drive systems are sustained research hotspots for HVs. Additionally, "plug-in hybrid" has been a recent research hotspot. This may suggest that traditional HVs' environmental performance and fuel economy are becoming less satisfying and so researchers/governments are taking a more aggressive strategy to solve the problem by installing PHVs, if not EVs.

4. The Issue of Current NGV Research

As mentioned previously, HVs were launched into the market in 1997, and most advanced countries have been developing NGVs since the 1990s. Moreover, both developed countries and developing countries have been installing NGVs to solve environmental problems since 2009. This means NGVs have been sold for over ten years and will be disposed of in large quantities shortly. Since various NGVs have widely applied high-capacity driving batteries and motors, waste NGVs have a higher resource content than ordinary vehicles [50]. If the discussion on the proper treatment or efficient recycling of end-of-life NGVs is insufficient, a tremendous amount of resources may be wasted, and there could be severe environmental pollution problems in the end-of-life vehicle recycling industry. In other words, there is a necessity to develop new collection/recycling policies and technologies that are suitable for end-of-life NGVs.

Nevertheless, after investigating the main research category and hotspots of NGVs, keywords such as "end-of-life", "collection", "reuse", "recycling", and "proper treatment" were not found, indicating that they have apparently not been valued enough as research topics. Although after manual selection, we found some articles that revolved around the material flow, collection, recycling policy, and recycling technology for end-of-life NGVs or ordinary vehicles [51–60]. These articles are certainly in the minority in the research field of NGVs and should be emphasized more in the future.

5. Summary

In this research we carried out a comprehensive bibliometric analysis of the research on NGVs. Moreover, since we did not limit our research to a specific type of NGV, we managed to perform a horizontal contrast on the research related to multiple types of NGVs.

Based on our research, we identified the HVs and EVs are the most attractive research objects, and normally, countries with large vehicle makers and markets play the leading role in studying NGVs, but part of the developing world has also started to show their interest in developing NGVs. Additionally, we clarified that research categories related to engineering, such as "Engineering, Electrical, and Electronic", "Energy & Fuels", and "Transportation" are the most valued. The research on NGVs has focused on their technology innovation, and "driving batteries", "motors" and "driving systems" have been the protracted research hotspots.

However, the research on NGVs is far from flawless since the proper treatment of end-of-life NGVs has not been valued enough. This kind of disadvantage should be improved since there will be a massive number of end-of-life NGVs generated worldwide shortly.

Moreover, it is plain to see that the transition of the research objects and categories of NGVs has been continuously affected by governmental policy and social events. Therefore, although from a bibliometric perspective this is already a mature academic area, in order to reveal the historical development of an academic area more comprehensively, future researchers are recommended to explain their research results from a social perspective as well.

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Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://apps.webofknowledge.com/.

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

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