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Review

Exploring the Green-Oriented Transition Process of Ship Power Systems: A Patent-Based Overview on Innovation Trends and Patterns

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Abstract: The shipping industry has accelerated the transformation of its carbon emission reduction and decarbonization, and relevant patents are rapidly increasing, but the industry still lacks consensus on the low-carbon development route of ship propulsion technology. We used the Derwent Innovation Index to collect the global patent information on ship power systems between 1965 and 2022 and proposed a new patent information mining framework. It is used for the dynamic tracking and analysis of global technology correlation characteristics, hot technology topics, and competitive situations. The findings indicate that: (1) the innovation of ship power systems is more radical and concentrated in the fuel field represented by LNG technology, whereas technical innovation in the field of pure electric propulsion is more scattered. Small tonnage ships, underwater operations, and recreation technology are among its innovation hotspots. (2) Pure electric propulsion technology is dominated by combined innovation with other propulsion methods (hybrid propulsion technology) and Chinese universities have recently begun to lead this technology. (3) Fuel cells and remote control have become innovation hotspots. Fuel cell technology, which combines electric, fuel, and hybrid power technology, is now on the cutting edge of innovation and has the potential for disruptive innovation.

Keywords: ship power systems; green-oriented transition; patent analysis; innovation trend

Citation: Sun, M.; Jia, Y.; Wei, J.; Zhu, J.X. Exploring the Green-Oriented Transition Process of Ship Power Systems: A Patent-Based Overview on Innovation Trends and Patterns. *Energies* **2023**, *16*, 2566. https://doi.org/10.3390/en16062566

Academic Editor: Maria Carmela Di Piazza

Received: 13 February 2023
Revised: 6 March 2023
Accepted: 7 March 2023
Published: 8 March 2023

1. Introduction

The International Maritime Organization's (IMO) new regulations on technical and operational measures to reduce the carbon intensity of international shipping came into effect on 1 January 2023. IMO is the specialized agency of the United Nations and is responsible for the safety of maritime navigation and the prevention of marine pollution from ships [1]. According to IMO's global greenhouse gas (GHG) study, GHG emissions from shipping activities in 2018 account for approximately 2.9% of the total global emissions in that year, generating about 1.05 billion tons of CO_2 per year [2]. This organization has been working to reduce the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2050 compared to the 2008 base year, further improving the global fleet's energy efficiency, promoting GHG emission reduction from shipping, and moving toward the ultimate goal of zero carbon emissions [2,3]. Furthermore, the IMO's new regulations reduce the current sulfur content by 85%, which will trigger significant changes never before seen in the industry. More than 70 countries, including the largest polluters—China, the United States (US) and the European Union (EU)—have set net-zero targets, covering approximately 76% of the global emissions. The shipping industry has accelerated the transition to renewable energy sources for carbon reduction and low carbonization in combination with these goals and requirements.

From the perspective of economy and politics, many scholars have focused on the construction of the decarbonization model [4–6], the improvement of energy efficiency [7,8], and the formulation of decarbonization policies for the maritime sector [9–13]. From a technological standpoint, the study of technological innovation in ship power systems is very barren, particularly when reliant on patent data analysis. Fuel cells and pure electric technology have become essential solutions for the green transformation of ship power systems, and their related patents are growing rapidly. However, an objective assessment of these technological innovation trends and a consensus on the low-carbon development path of ship power technologies are still required [14]. The research on the technological innovation in the marine sector during the last decade can be classified into two main categories. The first study area has focused on how the shipping industry can adopt new technologies and strategies to improve its competitiveness, such as innovation capabilities [15], blockchain [16], strategic alliances [17], regulatory pressure [18], and so on. The second category is mainly concerned with the bibliometric and patentometric. In terms of bibliometrics, Jimenez et al. [19] reviewed the literature on ship energy efficiency by using a hybrid review approach combining bibliometric and content analysis methods, and suggested future research directions. Moshiul et al. [20] utilized bibliometric tools to investigate alternative marine fuel research progress and future trends. Moshiul et al. [21] summarized a comprehensive bibliometric analysis to better understand the research trends in international green shipping and give recommendations for future research. Several researchers have carried out bibliometric analyses on alternative maritime fuels. While LNG has been regarded as the most frequently explored alternative shipping fuel, Ampah et al. [1] found that researchers have turned their attention to methanol, ammonia, and hydrogen fuels. Kolakowski et al. [22] found that the research on alternative marine fuels was carried out in parallel with legal research, both aimed at addressing global climate change and amplifying each other. Kolakowski et al. [23] argued that two recent bibliometric studies [1,22] on green shipping had laid the groundwork for advancing the research in this field in an innovative and meaningful way.

In-depth mining and analysis of the patent data can reveal the development trend of the target technology in time. Regarding the patentometric, Wiśnicki et al. [24] explored the critical areas of the successful adoption of technological innovation in ship technology by taking autonomous ships as an example. Utilizing the patent data withdrawn from the European Patent Organization's (EPO's) database, Chlomoudis et al. [25] investigated the innovative level of incumbent market actors in liner shipping. Ya et al. [26] conducted a comparative study of China, Japan, and Korea from the patent portfolio in a comparative study of the technological innovation capabilities in the shipbuilding industry. They found that Japan will pay more attention to R and D efficiency, South Korea more to the scale of R and D, and China more to the speed of R and D. In the study of Cardoso et al. [27], the evolution and development prospect of an electric propulsion system of large marine vessels, it is mentioned that the AC electric propulsion system is the most widely used at present, replacing the obsolete DC motors, and proposed several technical solutions to improve the ship electric propulsion system. Zhao et al. [28] found that the regional diffusion pattern of patents related to integrated power systems for ships was as follows: from the Atlantic coast, as the center, it has gradually spread to East Asia, with Japan and Korea displaying high development momentum.

With the digitization of patent information, there is an increasing variety of patent application information that can be analyzed [29]. These include: patent application country information; patent family information; time of application information; technical subject matter information; patent owner information; technical classification information; patent citation information, and so on. Furthermore, the patent application number can be used to follow the license and assignment information indirectly. Patent data mining and analysis techniques have also advanced quickly in recent years, spanning co-occurrence networks, grouping algorithms, topic models, dynamic networks, multimodal networks, and so on. These make it possible for this study to evaluate the low-carbon development path of ship power technologies objectively. In this study, we analyze the innovation trends of global ship power technologies, adopt the visualization means of social network analysis to mine the technology association features, and analyze the evolution of hot technology topics and competition situations. This work mainly reveals the trend and pattern of the green transformation of the global ship power systems by answering the following four questions: What are the main technical fields of the global ship power system? What are the technological trends in these technology areas? What are the core enterprises and core patents in these technical fields? What are the characteristics of these technological fields in terms of innovation evolution? The analysis results of this study can provide an important reference for decision-makers in formulating technology development strategy and valuable insights for the technology R and D of innovation subjects in the field of ship power systems.

2. Data and Methodology

2.1. Data Collection

Marine propulsion equipment is the shipping industry's main and most important equipment. It consists of the ship's main engine, transmission system, and thruster. It provides various kinds of energy for the vessel to ensure normal navigation, the normal life of personnel, and various operations. The ship power systems are related to the speed and smoothness of the ship, and it is an important direction of technological innovation and development in the shipping industry. The related literature has focused more on the integrated power system of ships, which includes the technical branches of AC electric propulsion, DC electric propulsion [30], superconducting electric propulsion, fuel cell propulsion [31], LNG propulsion [32,33], all-electric propulsion [34,35], heavy oil-methanol/ethanol hybrid fuel propulsion [36,37] and diesel engine-fuel cell-battery hybrid power propulsion [38].

In the process of searching and collecting the patent data, the International Patent Classification (IPC) is a search option that is usually used. The IPC category is the most commonly used classification of patent documents, to the extent that every patent document will indicate the IPC category to which it belongs. The IPC category divides all technologies into eight sections, denoted by the letters A to H. Each section is subdivided into classes, sub-classes, groups, and sub-groups. The ship propulsion power equipment or device technology corresponds to the group-level IPC classification number "B63H21". The subgroup-level IPC classification numbers under its classification represent smaller branches of technology, for example "B63H-021/17" for ship propulsion power equipment or devices with electric motors. Therefore, we used the group-level information of IPC for the data retrieval and analysis in this study.

In this study, the Derwent Innovations Index (DII) was chosen as the data search source to collect the worldwide patent application and citation data for ship power systems. In terms of data collection, we do not differentiate between ship types while collecting information on ship power systems, and all patents relevant to ship power systems are gathered globally. We identified the patent search formula used for shipboard propulsion power equipment or devices as IPC = "B63H-021*" with a search date of 1 April 2022. The search yielded 16,780 patent families with a total of 45,380 units of patent application information. The patent family is a collection of applications for a single patent in different countries, which avoids duplicate counting when the same invention is carried out in different countries and regions. The number of patents indicates the richness of these countries' technological bases and reserves in this field. The top five countries in the world in terms of the number of patent applications were China (8002), the United States (7398), Korea (6568), Japan (6415), and Germany (1857). Furthermore, the IPC information and citation information of patents were extracted and cleaned to obtain 61,579 "Patent-IPC" information and 19,810 patent citations, which supplemented the data source of this study. In order to analyze the hot topics and competition situation of ship power technologies in phases, as shown in Figure 1, the life cycle of this technology field was divided into the following three-time windows: 1965–2009 (T1 phase), with a total of 5,827 patent family applications. In the T1 phase, the patents were distributed in the United States (4482), Japan (3606), EPO (1750), Germany (1501), Canada (1058), Korea (987), China (971), WIPO (851), and England (706); 2010–2016 (T2 phase), with a total of 5,126 patent family applications. In the T2 phase, the patents were distributed in Korea (3739), China (2887), the United States (2142), Japan (2061), EPO (1582), WIPO (900), Australia (345), Canada (292), and Russia (289); 2017–2022 (T3 phase), with a total of 5,326 patent family applications. In the T3 phase, the patents were distributed in China (4137), Korea (1842), the United States (766), Japan (748), WIPO (504), EPO (478), Germany (125), Australia (111), and France (81).

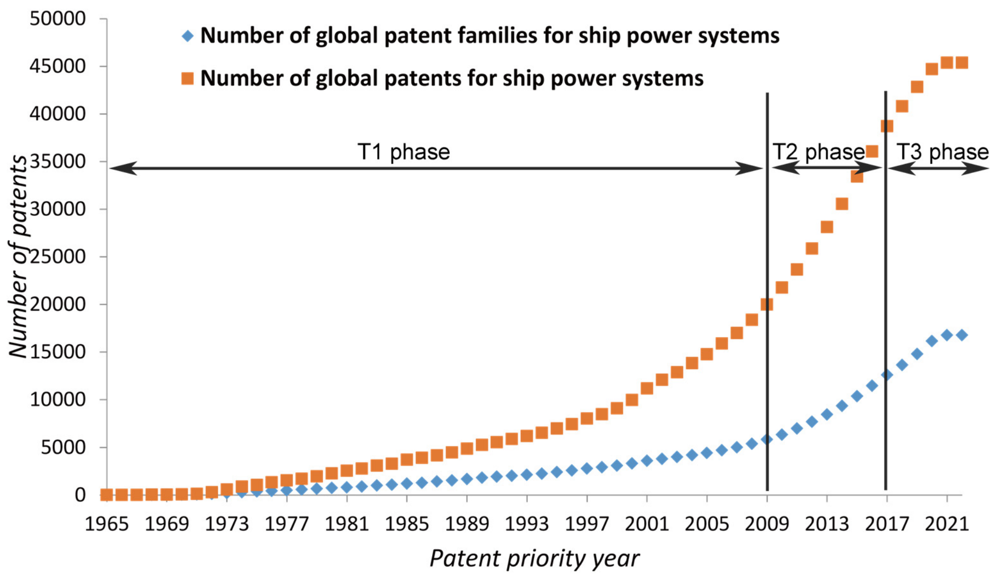

Figure 1. Global patent application trends in the field of ship power systems.

2.2. Analytical Framework

As shown in Figure 2, the analysis process of this study is divided into four steps. Step 1: Collecting the patent data of ship power systems, extracting and cleaning the key information, such as the IPC and citation. In this step, we can obtain two types of relationship information, namely "IPC-Patent" affiliation information and "Inter-Patent" citation information. "IPC-Patent" affiliation information is a many-many relationship, for example a patent may belong to several IPC categories. An IPC may also have several patents. "Inter-Patent" citation information is also a many-many relationship, such that a patent family may be cited by several other patent families, and this patent family may also cite several patent families. Step 2: Using all the "IPC-Patent" affiliation information, we can construct a matrix of co-occurrence between IPC categories. We can then transform this co-occurrence matrix into a co-occurrence network that can be easily clustered and visualized by using social network analysis software. The similarity between IPC categories in the field of ship power technologies was calculated through the IPC category co-occurrence network, which provides a numerical reference for the construction and optimization of the citation network in the next step. Step 3: Based on the information collected in Step 1, we map the "IPC-Patent" information to the "Inter-Patent" citation information to obtain the "Inter-IPC" citation information. After that, the "Inter-IPC" citation network can then be constructed. We identify the main Technology Groups of ship power systems by clustering the IPC category co-occurrence network and then mapping the cluster results into the "Inter-IPC" citation network. Step 4: The technology development trend of ship power systems is analyzed using indicators such as the scale of the technology subgroup network, the number of contained nodes, and the network density. Simultaneously, we visualize the technical topics using word division, word shape reduction, and weighted word cloud network construction and analyze the competition situation of the ship power systems by constructing a complex correlation network of "Patent Number—Patentee—Technology Group" based on the citation weighted index.

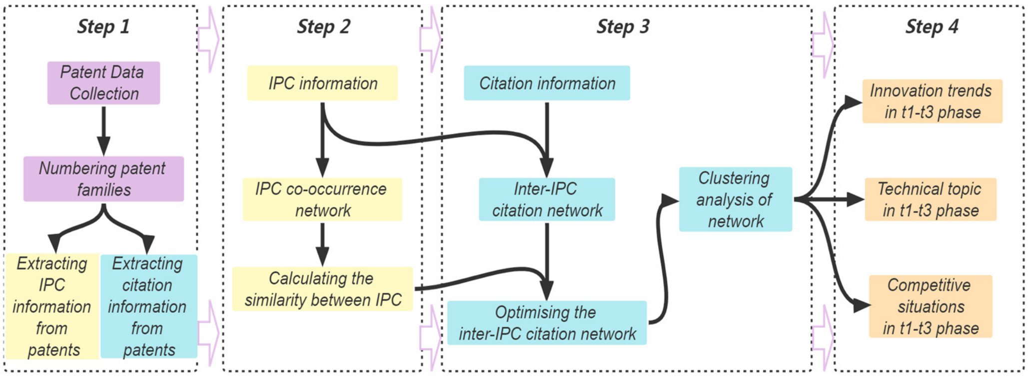

Figure 2. Analytical framework for the global innovation trend of Ship Power Systems.

2.3. Research Methods and Tools

The research tools we utilized in this study were all open-source software, such as Open Refine, R-studio, Python platform, Pajek, Gephi, and the Azure platform, which are mentioned in the description of the data processing that follows. In Step 1, we cleaned the key information, such as the IPC categories and citations, using the Open Refine Software. Step 2 involves creating an IPC category co-occurrence matrix of size 5390 × 5390 based on the dataset's 61,579 "Patent-IPC" information, which is a huge sparse matrix with most IPC categories occurring just once or twice. As a result, the core section of this co-occurrence matrix is extracted using the H-index (90 in this matrix), and a 90 × 90 IPC category co-occurrence matrix is generated. As any IPC category can obtain a 90-dimensional vector representation in this co-occurrence matrix, we use the cosine similarity formula in the R-studio platform to calculate the similarity among these 90 core IPC categories and to select a reasonable threshold to simplify the network. In Step 3, we use the Pajek and Gephi software to find different Technology Groups in the "Inter-IPC" citation network, and to dynamically measure and visualize the simplified similarity network.

We mainly used the following metrics in the trend analysis in Step 4, measuring the size of the citation network in terms of the number of connections between nodes, the number of nodes contained in the IPC subgroups in the network, and the citation network density expressed as the ratio of the number of edges to the number of nodes. The larger the network size of a technology group, the greater the number of patent applications contained in that technology group, and that technology group is the major technology field in the period. The higher the number of network nodes of a Technology Group, the more diversified the technology branches included in that Technology Group, and the technology nodes with a higher citation breadth are defined as the key basic technologies in the field. The greater the network density of the technology group, the more efficient the knowledge transfer among the technology branches in the technology group and the deeper the technology integration. Furthermore, we also performed the identification operation of the patent subject phrases in the Azure cloud computing service platform and Python platform for natural language word division and word form reduction.

3. Results and Analysis

3.1. Analysis of Technical Trends in Ship Power Systems

In this section, we use ship power technologies as an example and construct a knowledge map of the cross-references between IPC categories to explore the innovation trends and patterns of ship power systems based on the processing of multiple large-scale data. The threshold of the cosine similarity between IPC categories is set to 0.4 to construct an "Inter-Patent" citation network for the ship's power system. Using the Modularity Class algorithm in the open-source software Gephi, we can categorize this "Inter-IPC" citation network into several main IPC Technology Groups. We needed to assess and compare the results of each division in order to ensure that the division of the technical clusters was appropriate. As indicated in Figures 3 and 4, these five main Technology Groups were finally obtained. Then, we construct a time-varying citation network between 1989 and 2021 for these five Technology Groups. As shown in Figures 5–7, we use indicators such as the number of network nodes, the citation network size, and the citation network density to further explore the technology development trends in the sub-technical field of ship power systems.

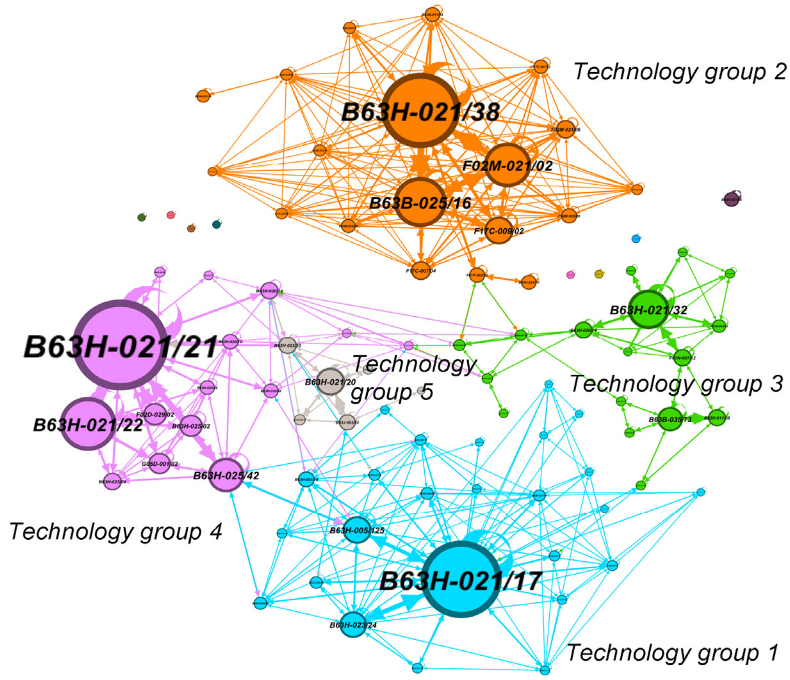

Figure 3. Inter-IPC citation network grouping results for ship power systems.

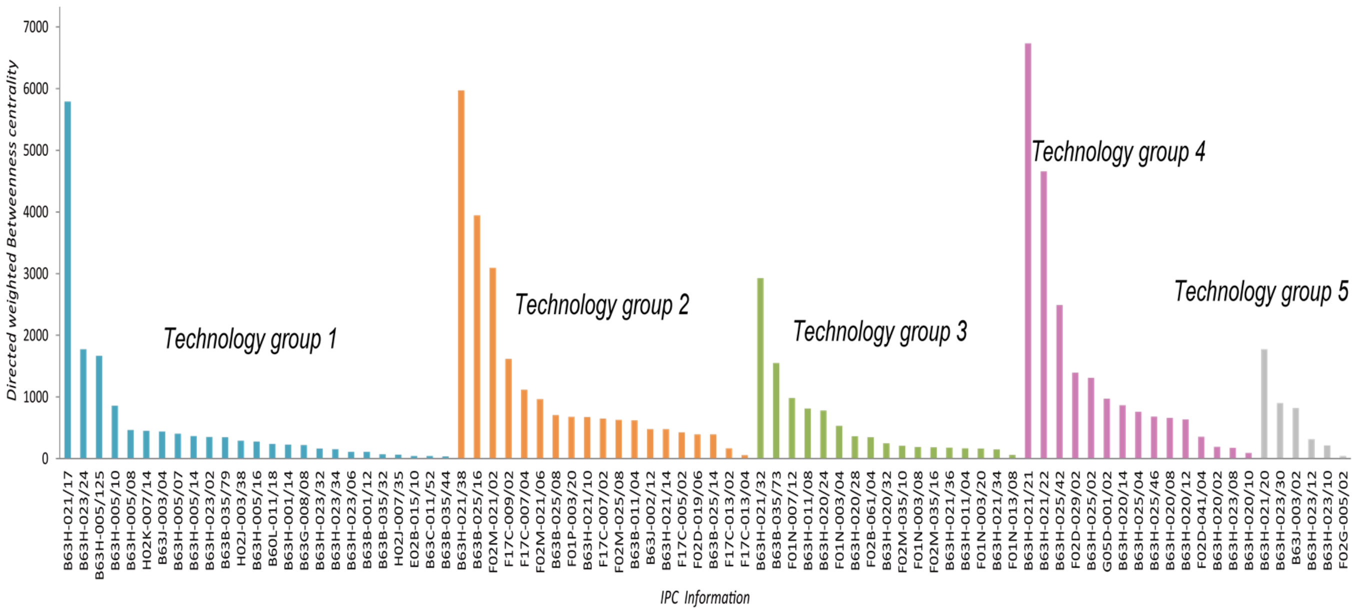

Figure 4. Descriptive Statistics of IPC Grouping Results for Ship Power Systems.

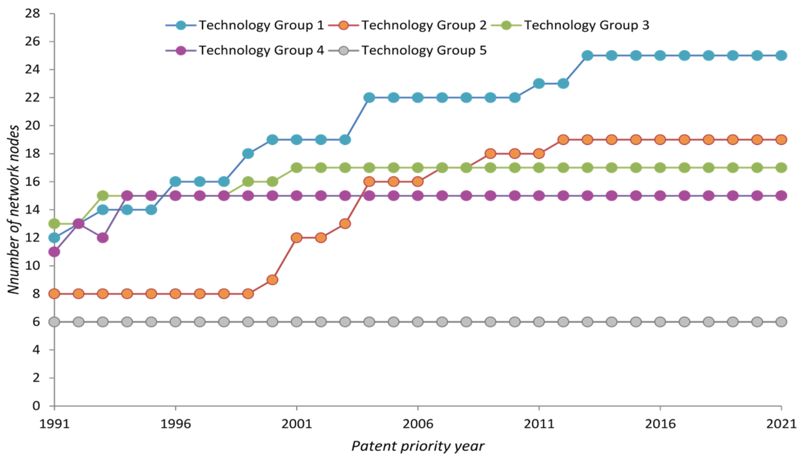

Figure 5. Trends in number of IPC nodes by different groups.

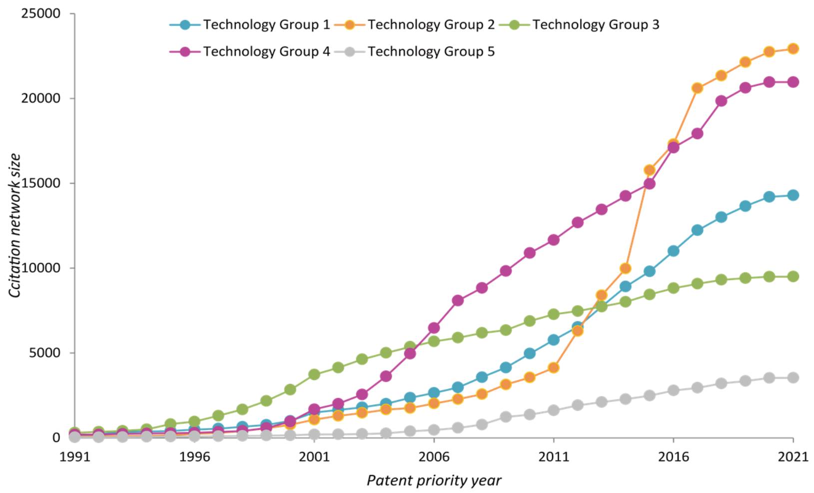

Figure 6. Trends in citation network size by different groups.

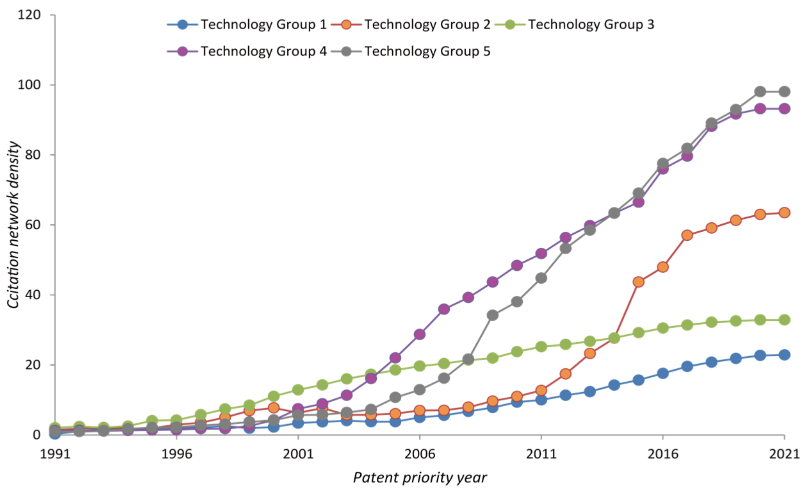

Figure 7. Trends in Citation Network Density by different groups.

We assess the technical influence of the nodes in Figure 3 by measuring the degree of the Weighted Betweenness Centrality (WBC). The formula for the calculation of the WBC is shown below:

$$C_B = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{1}$$

$\sigma_{st}(v)$ denotes the number of shortest paths $s \rightarrow t$, σ_{st} denotes the number of shortest paths $s \rightarrow t$. The statistics of the number of shortest paths for weighted networks and non-weighted networks are different, and the difference lies in the different methods used to find the shortest paths. For non-weighted networks, the breath-first traversal (BFS) is used to find the shortest paths, and for weighted networks, Dijkstra's algorithm is used to find the shortest paths. As the citation network belongs to the weighted directional network, the calculation of the WBC requires the use of Dijkstra's method for solving the shortest path, and the calculation results are shown in Figure 4.

With the advent of the fourth industrial revolution, a considerable tendency towards technical convergence within the field of ship power systems can be significantly observed. The specific definitions of IPC categories shown in Figures 3 and 4 can be found on the website [39] belonging to the World Intellectual Property Organization (WIPO). As shown in Figures 3 and 4, Technology Group 1 points to the electric propulsion and transmission system of the ship, mainly involving electric motor-driven ship power equipment (B63H-021/17) with a WBC value of 4604; power transmission of electric propulsion components (B63H-023/24) with a WBC value of 1775; acting directly on the water, the propulsion elements are movably mounted relative to the hull (B63H-005/125,) with a WBC value of 1668; arrangements on vessels with more than one propulsion elements directly acting on water (B63H-005/08) with a WBC value of 466. Technology Group 2 is for power fuel systems of ships, with a focus on ships powered by liquid fuel oil or liquefied gas fuel, mainly involving apparatus or methods specially adapted for handling power plant or unit liquids, e.g., lubricants, coolants, fuels, etc. (B63H-021/38) with a WBC value of 5972; heat-insulated load-accommodating arrangements (B63B-025/16) with a WBC value of 3945; apparatus for supplying engines with gaseous fuels, e.g., gaseous fuels stored in liquid form (F02M-021/02) with a WBC value of 3094; methods or apparatus for discharging liquefied or solidified gases from vessels not under pressure (F17C-009/02) with a WBC value of 1618; methods or apparatus for discharging liquefied gases from pressure vessels (F17C-007/04) with a WBC value of 1117.

Technology Group 3 is concerned with the exhaust of ship power systems and ships used for recreation or sports, mainly involving arrangements of propulsion power-unit exhaust uptakes (B63H-021/32) with a WBC value of 2927; other ships used for recreation or sports or similar floating structures (B63B-035/73) with a WBC value of 1551; submerged exhaust or silencing apparatus characterized by constructional features (F01N-007/12) with a WBC value of 982; ship propulsion by water jets (B63H-011/08) with a WBC value of 813; exhaust gas outlets of outboard propulsion units (B63H-020/24) with a WBC value of 780. Technology Group 4 refers to the control mechanism of the ship's power plant, mainly involving the control system of the engines or transmissions specially adapted for use in ships at sea (B63H-021/21) with a WBC value of 6725; propulsion power equipment controlled from outside the cabin (B63H-021/22) with a WBC value of 4658; steering or dynamic anchoring with propulsion components (B63H-025/42) with a WBC value of 2493; initiating means for steering (B63H-025/02) with a WBC value of 1310; control of position or course in two dimensions (G05D-001/02) with a WBC value of 974.

Technology Group 5 refers to hybrid power units for ships, mainly involving such technology branches as the combination of different types of propulsion devices to provide power (B63H-021/20) with a WBC value of 1774; transmission of power from a propulsion power plant to a propulsion element using a clutch as a feature (B63H-023/30) with a WBC value of 902; driving of auxiliaries from propulsion power plant (B63J-003/02) with a WBC value of 822; transmission of power to propulsion elements using a combined propulsion power unit (B63H-023/12) with a WBC value of 318; transmitting drive from more than one propulsion power unit (B63H-023/10) with a WBC value of 215. In addition to the five Technology Groups mentioned above, the following technology categories are involved in ship power technologies, based on the WBC value: support for propulsion equipment or devices (B63H-021/30) with a WBC value of 629; engine driven ships (B63H-021/12) with a WBC value of 97; ships powered by land vehicles loaded on board (B63H-021/175) with a WBC value of 49; ships driven by a hydraulic oil motor (B63H-021/165) with a WBC value of 27; ships powered by nuclear energy (B63H-021/18) with a WBC value of 25; and ships propelled by gas turbines (B63H-021/16) with a WBC value of 23.

Figure 5 shows that there is a clear trend difference in the number of citation network nodes for different Technology Groups. From the macro level, the number of Technology Group 1 nodes in the network has been the largest since 1996 until now, and the nodes of Technology Groups 1 and 2 have increased more. This indicates that the ship's electric propulsion, transmission system, and power fuel system technologies involve a wide range of sub-technology branches, and the technological innovation activities in the ship's electric propulsion and transmission are the most active. The number of network nodes in Technology Groups 3 and 4 is relatively stable, indicating that the technology maturity in the fields of exhaust devices and control systems of the ship's power system is higher. Since 1991, Technology Group 5 has only involved six IPC sub-categories, which indicates that the technology of a ship's hybrid power unit is still in the budding development stage and requires further R and D breakthrough.

From the micro level, the newly added nodes in Technology Group 1 mainly include devices powered by photosensitive battery to load (H02J-007/35) and tools suitable for underwater operation (B63C-011/52), indicating that a photosensitive battery and underwater electric drive technology are emerging technologies in the field of ship electric propulsion system. The newly added nodes in Technology Group 2 are engines working with multiple fuels (F02D-019/06) and valve configuration and installation (F17C-013/04). At present, a multi-fuel power supply device is the core equipment used by LNG ships to meet the requirements of the new international maritime environmental protection regulations. Under the global dual carbon target, multi-fuel power supply technology and the related configuration valve assembly technology are important research directions in the field of ship power. The newly added nodes in Technical Group 3 are mainly purified, non-toxic or other harmless exhaust treatment devices (F01N-003/08), and other devices or adapters for exhaust pipes (F01N-013/08), indicating that the field of exhaust devices for ship power systems is developing in the direction of energy saving and low carbon emission reduction.

The size of the sub-technology citation network for ship power systems is increasing, as seen in Figure 6, and the network size of each Technology Group is growing year after year, which indicates that global ship power technologies are developing rapidly. During the period 1991–2015, the network size of Technology Group 4 gradually overtook Group 3, indicating that the most dominant sub-technology area of ship power systems has changed from exhaust devices to control devices. Since 2011, the network size of Technology Group 2 has expanded rapidly, and from 2016 to the present, power fuel for ships has become the most important technology source of patent applications in the field of global ship power systems. However, the network size of Technology Group 5 started to grow later, and the hybrid propulsion technology is a promising and forward-looking technology development direction in the field of ship power in the future.

Combined with the analysis of Figures 6 and 7, Technology Group 1 involves the most IPC subcategories, but the lowest network density, which indicates that the degree of integration among the sub-technologies of the ship's electric propulsion and transmission technology is low and the technology association is more fragmented. Its innovation has the potential for continuous growth. Technology groups 4 and 5 have the highest network density and involve fewer IPC subcategories, indicating a very close knowledge flow and strong integration between subtechnologies in the areas of ship power control systems, hybrid power units of ships, and waste heat utilization of exhaust. Technology Group 2 involves more IPC subcategories, and the network density has increased rapidly in recent years, since 2011, which indicates that there is a clear innovation direction in the field of power fuel systems, i.e., liquefied natural gas (LNG) technology is rapidly integrating with other technologies and developing rapidly in concert with its network scale development trend.

3.2. Analysis of Technical Topics and Competitive Situation in Ship Power Systems

We first extracted the technical topic phrases from the patents and then assigned the citation frequencies of the patents to the co-occurrence relationships between the topic phrases. We finally obtained the subject word association network of ship power systems by calculating the co-occurrence relationship values of the subject phrases and using the H-index (100, 45, 10, respectively) as the threshold for truncating the network edges in different periods, as shown in Figures 8–10. At the same time, we construct a three-mode network of "Technical Field—Innovation Subject—Hotspot Patent" based on the association information of the different types of patent nodes, and weight the association (edges of the network) by the citation frequency of the patents, and finally truncate the edges of the network with the line values of 30, 10, and 4 as the threshold values after repeated experiments. The final results are shown in Figures 11–13. In these three figures, we have used different colored and shaped graphics, together with node labels, to convey as much information as possible while maintaining the visual effect. The green triangles represent the technology groups, and the numerical labels represent the name of the technology group, e.g., the number 1 represents Technology Group 1. The yellow squares represent patents, and the numerical labels represent the serial number of the patent in this dataset, by which the corresponding specific patent number can be found. The red diamond in the diagram represents the innovation subject, and the text label represents the abbreviation of the name of that innovation subject, also known as the Derwent Standard Patentee Code, which can be used to find the complete name of the specific patentee. In Table A1 of Appendix A, we can find supplemental details of the labels relating to the patents and patentees in Figures 11–13.

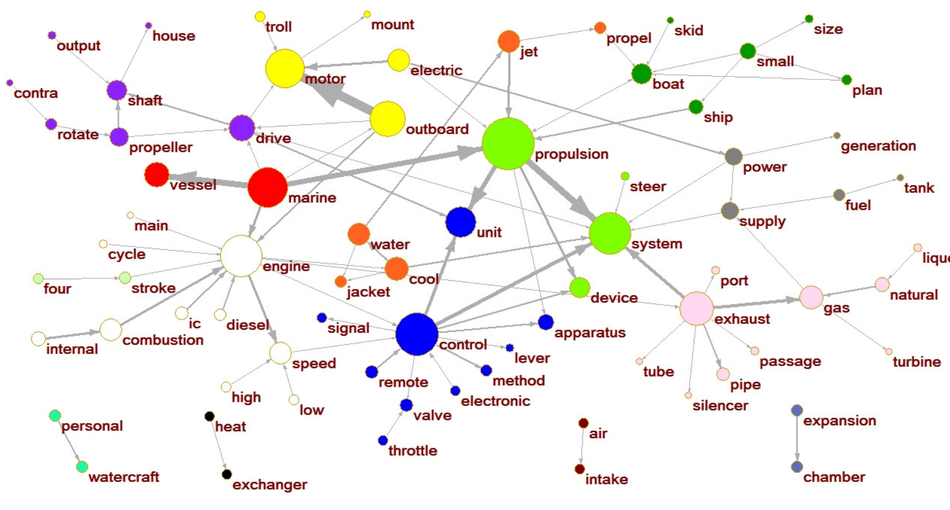

Figure 8. Hotspot technical topic network of ship power systems in T1.

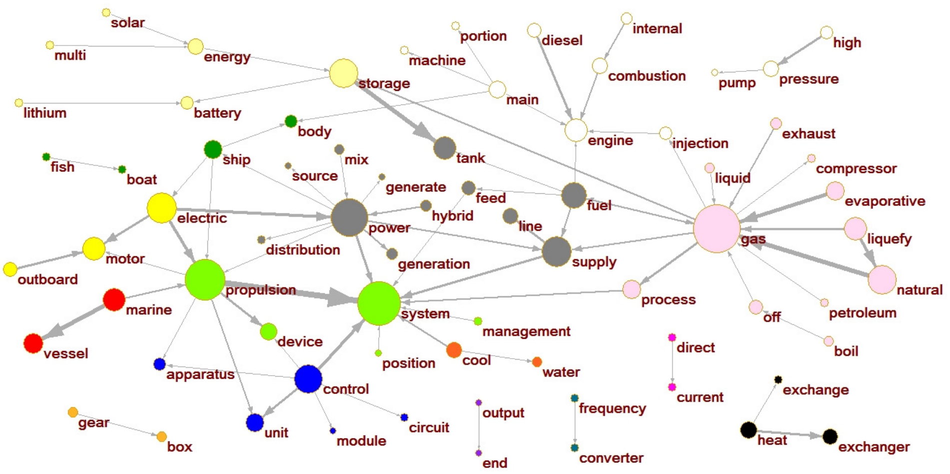

Figure 9. Hotspot technical topic network of ship power systems in T2.

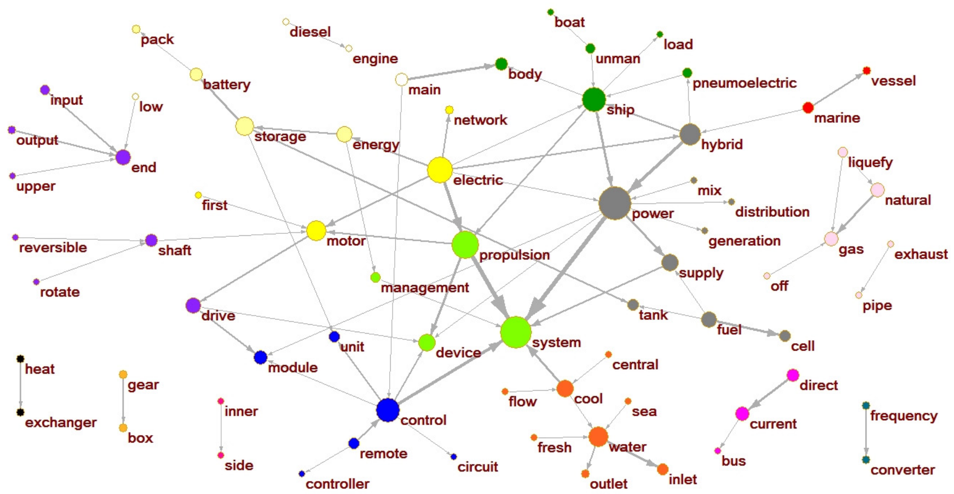

Figure 10. Hotspot technical topic network of ship power systems in T3.

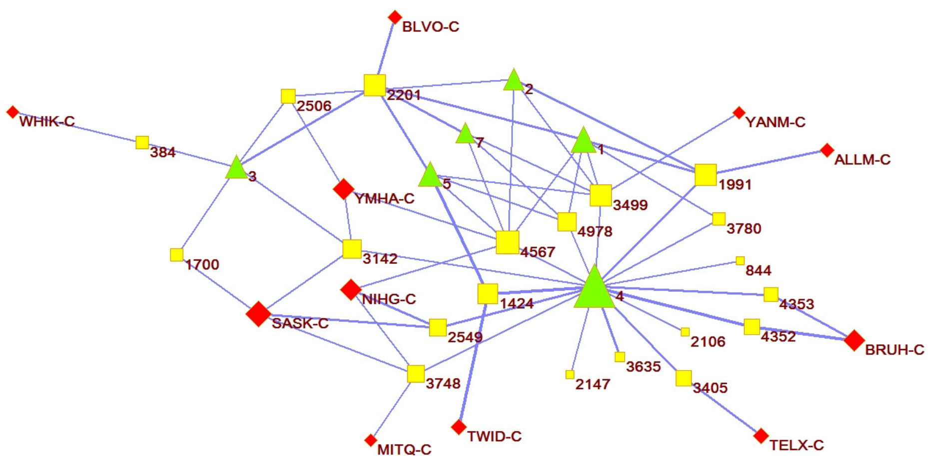

Figure 11. "Technical Field—Innovation Subject—Hotspot Patent" Three-Mode Network in T1.

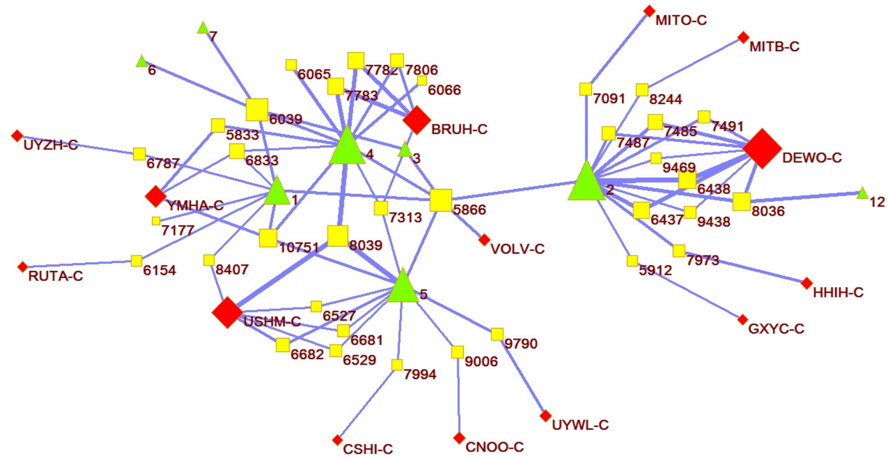

Figure 12. "Technical Field—Innovation Subject—Hotspot Patent" Three-Mode Network in T2.

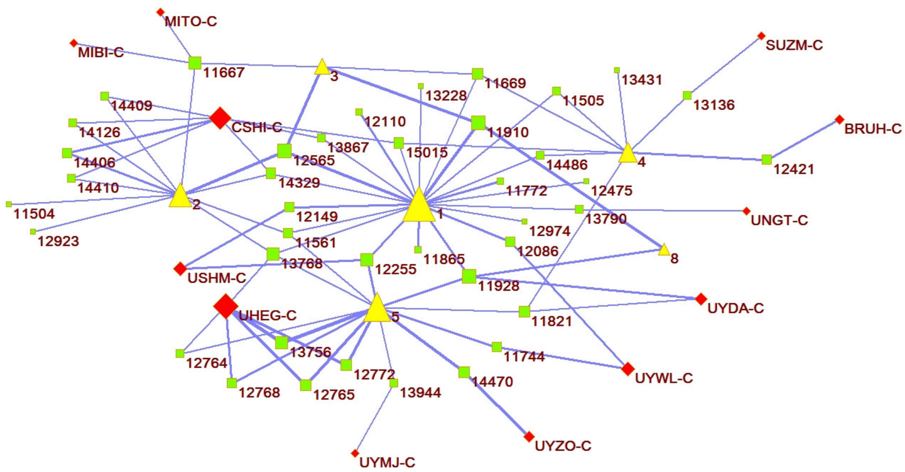

Figure 13. "Technical Field—Innovation Subject—Hotspot Patent" Three-Mode Network in T3.

3.2.1. Technical Topics and Competitive Situation in T1 Phase (1965–2009)

As can be seen in Figure 8, the hot topics of technical innovation in the T1 phase (1965–2009) of the ship power systems are mainly: control technology, internal combustion engine, outboard motor, private vessel, exhaust system, fuel tank, and fuel supply. As shown in Figure 11, Technology Group 4, which represents ship drive control technology, was at the center of the network during this period. Technical innovations in this area include the control application US4836809-A (1424) for ship propulsion by Twin Disc Inc (TWID-C); the electronic control system for ship throttle WO200299455-A3 (3405) by Teleflex Corporation (TELX-C); as the world's largest leisure yacht company, Brunswick Corp's (BRUH-C) EP1775212-A3 (4352) and EP1775211-A3 (4353) for controlling the magnitude and direction of thrust of marine propulsion units; ABB Corporation's (ALLM-C) propulsion unit for large ships or high-power ships US5403216-A (1991); Yanmar Co Ltd.'s (YANM-C) electric propulsion equipment located between the internal combustion engine and the transmission unitEP1426287-A4 (3499). In addition, the marine diesel engine of Blohm and Voss Gmbh (BLVO-C) enhances the main engine drive power through auxiliary motor drive technology US5616056-A (2201) and the marine dehumidification system technology of Whittaker Corp (WHIK-C) US4019456-A (384). The Japanese Sanshin Kogyo Kk (SASK-C), Yamaha Motor Co Ltd. (YMHA-C), and Mitsubishi Electric Corp (MITQ-C) also have strong technical competence in control technology to improve the speed of marine engines.

3.2.2. Technical Topics and Competitive Situation in T2 Phase (2010–2016)

As seen in Figure 9, the emergence of new technologies, such as liquefied natural gas, fuel supply, high-pressure pumps, energy storage, hybrid energy, electrical energy, electric motors, and remote control, make up the hot topics in the T2 phase (2010–2016), and are distinctly different from those in the T1 phase. The T2 phase network structure has distinctive features, as illustrated in Figure 12, with Technology Groups 2, 4, and 5 forming the core position. At the same time, Technology Group 2 is in a relatively independent position. In Technology Group 2, Korea Daewoo Shipbuilding and Marine Corporation (DEWO-C) has made a large number of patent layouts for LNG dual-fuel vessels, such as the ME-GI type engine fuel supply and re-liquefaction system WO2012128448-A1, WO2012128449-A1, KR1511214-B1 (6437, 6438, 9438), and marine liquefied gas handling system WO2014065619-A1, WO2014065621-A1, WO2014092369-A1, WO2014209029-A1, WO2016195231-A1 (7485, 7487, 7491, 8036, 9469). These patents are widely laid out to the World Intellectual Property Organization, the European Patent Office, the United States, Japan, China, Korea, Russia, Singapore, Vietnam, the Philippines, Indonesia, and other countries or regions of intellectual property organizations. In addition, the liquefied gas handling system US10767921-B2 (7973) of Hyundai Heavy Industries, Korea (HHIH-C), the liquefied fuel gas supply pressure regulating valve WO2013146314-A1 (7091) of Mitsubishi Heavy Industries, Japan (MITO-C), and the gas supply system for liquefied gas carriers of Mitsui Engineering and Shipbuilding Co. (MITB-C) WO2015053126-A1 (8244) also have some technical competitive advantages.

In Technology Group 5, Shanghai Maritime University (USHM-C) has carried out many patents in the fields of hybrid electric propulsion systems for ship energy management and control, such as the hybrid electric propulsion system for marine diesel generator and battery power CN202147836-U, CN103332284-B, CN102211657-A, CN202156534-U, and CN102358412-B (6527, 6529, 6681, 8039, and 6682). The marine diesel-motor hybrid power system CN103287563-B (7994) of the 703rd Research Institute of China Shipbuilding Ind (CSHI-C) and the energy management method of the diesel-electric hybrid power ship propulsion system CN104859828-B (9790) of Wuhan University of Technology (UYWL-C) also have specific technical competitive advantages. In Technology Group 4, ship control technology, the Brunswick Corp (BRUH-C) in system US9248898-B1 and US9039468-B1 (7782, 7783) for controlling the ship speed and system US8924054-B1 (7806) for ship orientation, Yamaha Motor Co Ltd. (YMHA-C) in the ship propulsion control device US8700238-B2 (5833), and the ship propulsion device with electric motor US8956195-B2, US10150550-B2 (6833, 10751) continue the high-quality patent layout.

3.2.3. Technical Topics and Competitive Situation in T3 Phase (2017–2022)

As can be seen in Figure 10, the drive module, remote control, electrified propulsion system, DC bus, battery storage of energy, hybrid energy drive system (including LNG, fuel cell, diesel, electricity), unmanned ship, and cooling system became the innovation hot words in the T3 Phase (2017–2022). In contrast, the innovation hot words of LNG and other related technologies started to decrease. As shown in Figure 13, Technology Group 1 and Group 5 together form the core of the T3 phase network structure. Many high-impact patents appear in Technology Group 1, such as Energy Self-Supporting Marine Monitoring Ship WO2019235842-A1 (12974), which utilizes solar energy to electrolyze water to generate hydrogen for fuel cell power supply to the ship. In addition, energy vessels with a hybrid power battery system CN109733583-A (13790); underwater stable and fast self-moving intelligent life-saving device CN107826225-A (12475); the propeller control system for submarine WO2018133413-A1 (11505); propulsion for autonomous underwater vehicle/underwater glider WO2018201890-A1 (11772); electric hydrofoil US10836457-B2 (11910); marine tractor US10377459-B2 (11669); shaftless electric propulsion device CN108974308-A (13228); external electric propulsion device for ships WO2021073378-A1 (14486); marine DC grid distribution system WO2021185056-A1 (15015); pure electric ship power integration system CN107697256-A (12110); ship direct grid power propulsion system CN109927872-B (13867); modular electric ship WO2019129687-A1 (12565). However, there are few high-impact innovation subjects in this field, such as the fast-moving remote-controlled lifeboat CN206841680-U (11865) from the Dalian University of Technology (UYWL-C), the unmanned underwater vehicle propulsion and power generation integrated device CN107499487-B (12086) from Wuhan University of Technology (UYWL-C), and the standardized battery energy storage system based on the container ship system CN110481748-A (14329) from the 702th Research Institute of China Shipbuilding Ind (CSHI-C).

In Technology Group 5, Chinese universities are starting to lead the frontier of innovation, such as the diesel-gas-electric parallel marine hybrid power system CN108860549-A (12764) from Harbin Engineering University (UHEG-C), the gas-electric parallel power system for LNG-cooled hybrid ships US11034424-B2 (13768), the gas-electric marine parallel hybrid power system CN109941417-B (13756), fuel cell integrated two-ship hybrid power system CN108674627-B (12765), two-axis hybrid gas-electric ship propulsion system CN108438189-B (12772), Dalian University of Technology (UYWL-C) high-speed oil-electric hybrid trimaran CN107380341-B (11928), fuel cell hybrid electric propulsion system of Jimei University (UYMJ-C) CN110001908-A (13944), hybrid ship energy management system of Wuhan University of Technology (UYWL-C) CN107140168-B (11744), fuel cell hybrid propulsion system for ships of Zhejiang Ocean University (UYZO-C) CN110758708-A (14470), and CN107554741-B (12149), and CN107748498-A (12255) of the hybrid ship energy management method by Shanghai Maritime University (USHM-C). Furthermore, the 719th Research Institute of China Shipbuilding Ind (CSHI-C) also has some high-impact patent layouts in marine cooling technology, such as CN206476080-U (11504) and CN108750064-A (12923) for the central cooling water device for ships. The marine parallel self-flow cooling system CN110539869-A, CN110525624-A, CN110435865-A, CN110539870-A (14406, 14410, 14126, 14409). The Brunswick Corp (BRUH-C) started a patent layout EP3486742-B1 (12421) in the field of unmanned ships.

4. Conclusions

It is important to highlight that the research framework and methods designed and proposed in this paper achieve a better analysis effect. This not only helps us to better understand ship power systems' innovation characteristics and paradigms in the green-oriented transition process, but also to better judge future development trends. Hybrid technology with electric or fuel cell technology will be an important support for the green transformation of ship power systems. The following specific conclusions can be obtained through the in-depth analysis of the five main Technology Groups mentioned above.

Firstly, global ship power technologies are in a period of rapid development and the number of patents worldwide will continue to grow at a rapid pace. The innovation of ship power technologies is more radical in the fuel field, represented by LNG technology. The innovation in pure electric propulsion is more scattered, and its innovation hotspots are mostly concentrated in the technologies of small tonnage ships, underwater operations, and entertainment. There are few high-impact innovation subjects.

Furthermore, we found that the innovation fervor of LNG dual-fuel ship technology is decreasing, and fuel cells, remote control, etc., have become new innovation hotspots. Fuel cell technology spans multiple categories of electric technology, fuel technology, and hybrid technology, and is at the frontier of innovation at present and has the potential for disruptive innovation.

Finally, hybrid propulsion technology (characterized by the combination of pure electric propulsion technology and other propulsion methods) is a promising and forward-looking technology development direction in the field of ship power in the future. In recent years, China has started to take a leading position in this technology, but the high-impact innovation subjects are still mainly from universities.

This study has several limitations. First, the global ship power system patent data is increasing in real time, and the tracking and analysis of innovation trends in this technological sector is a long-term dynamic process. Therefore, it is critical to replace the time-consuming manual data processing approach with a standardized, process-oriented computer software application. Second, our paper's analysis is based on the global patent data. To support green innovation policy formulation and technology development plan selection at the national or regional level, an analysis procedure based on country- or region-specific patent databases still needs to be established. Third, in the present and future patent research, the examination of the novelty, practicality, and efficacy of particular patents on ship power systems to discover innovative iterations and technological progress is critical, and this is what we need to concentrate on more in the future.

Author Contributions: Conceptualization: M.S. and J.X.Z.; methodology: M.S.; patent data collection: M.S.; patent data processing and visualization: M.S.; analysis and interpretation of indicators and charts: Y.J. and J.W.; writing: M.S., Y.J. and J.X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by "the Fundamental Research Funds for the Central Universities, grant number 30922011407" and "High-tech ship research projects of Ministry of Industry and Information Technology, grant number CY03N20".

Data Availability Statement: The patent datasets analyzed in this study can be downloaded (registration required) via the website (https://www.webofscience.com/wos/diidw/basic-search, accessed on 1 January 2020).

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

Appendix A

Table A1. Details of the labels relating to patents and patentees in Figures 11–13.

Phase	Lable	Representation in the Patent Family	Distributed Countries and Regions	Patentees
T1	384	US4019456-A	CA; DE; FR; GB; IT; US	WHITTAKER CORP (WHIK-C)
T1	844	DE3222054-A	AU; BR; CA; DE; ES; GB; US; ZA	SCHOTTEL-WERFT J BE (SCHO-N)
T1	1424	US4836809-A	DE; GB; US	TWIN DISC INC (TWID-C)
T1	1700	US5234364-A	JP; US	SANSHIN KOGYO KK (SASK-C)
T1	1991	EP590867-A1	CA; DE; EP; ES; FI; JP; KR; NO; RU; SG; US	KVAERNER MASA-YARDS OY (KVAE-N); ABB OY (ALLM-C)
T1	2106	US5386368-A	US	JOHNSON FISHING INC (JOHN-N)
T1	2147	WO9528682-A1	EP; US; WO	ROBERTSON G (ROBE-I)
T1	2201	DE4432483-A1	DE; ES; FI; JP; KR; NO; SG; US	BLOHM and VOSS AG (BLVO-C)
T1	2506	JP10067390-A	JP; US	YAMAHA MOTOR CO LTD (YMHA-C)
T1	2549	JP10176560-A	JP; US	SANSHIN KOGYO KK (SASK-C); YAMAHA MARINE CO LTD (NIHG-C)
T1	3142	US2001036777-A1	JP; US	YAMAHA MOTOR CO LTD (YMHA-C); SANSHIN KOGYO KK (SASK-C)
T1	3405	WO200299455-A2	AU; EP; US; WO	TELEFLEX INC (TELX-C)
T1	3499	WO2003024784-A1	EP; JP; US; WO	YANMAR CO LTD (YANM-C)
T1	3635	US2003191562-A1	US	ROBERTSON G (ROBE-I)
T1	3748	JP2004142538-A	JP; US	SANSHIN KOGYO KK (SASK-C); MITSUBISHI ELECTRIC CORP (MITQ-C); YAMAHA MARINE KK (NIHG-C)
T1	3780	US6848382-B1	US	BEKKER J (BEKK-I)
T1	4352	EP1775212-A2	EP; US	BRUNSWICK CORP (BRUH-C)
T1	4353	EP1775211-A2	EP; US	BRUNSWICK CORP (BRUH-C)
T1	4567	EP1897801-A2	EP; JP; US	YAMAHA MARINE KK (NIHG-C); YAMAHA HATSUDOKI KK (YMHA-C)
T1	4978	WO2009076659-A1	AU; CA; CN; EP; ES; JP; KR; SG; US; WO	FOSS MARITIME CO (FOSS-N); ASPIN KEMP and ASSOC (ASPI-N); XEROPOINT ENERGY (XERO-N)
T2	5833	US2011166724-A1	EP; JP; US	YAMAHA HATSUDOKI KK (YMHA-C)
T2	5866	WO2011100641-A1	AU; CN; EP; JP; US; WO	DAVIS ENG LLC (DAVI-N); SEVEN MARINE LLC (SEVE-N); VOLVO PENTA AB (VOLV-C)
T2	5912	CN201633913-U	CN	GUANGXI YUCAI MACHINE CO LTD (GXYC-C)

Table A1. *Cont.*

Phase	Lable	Representation in the Patent Family	Distributed Countries and Regions	Patentees
T2	6039	WO2012003333-A1	AU; BR; CA; CN; EP; IL; JP; MX; NZ; TW; US; WO; ZA	BOOMERBOARD LLC (BOOM-N)
T2	6065	US2012015566-A1	US	JOHNSON OUTDOORS INC (JOHN-N)
T2	6066	US2014249698-A1	US	JOHNSON OUTDOORS INC (JOHN-N)
T2	6154	RU2436708-C1	RU	RUSSIA IND TRADE MIN (RUTA-C)
T2	6437	WO2012128448-A1	CN; EP; JP; KR; US; WO	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	6438	WO2012128449-A1	CN; EP; JP; KR; US; WO	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	6527	CN202147836-U	CN	UNIV SHANGHAI MARITIME (USHM-C)
T2	6529	CN102211657-A	CN	UNIV SHANGHAI MARITIME (USHM-C)
T2	6681	CN202156534-U	CN	UNIV SHANGHAI MARITIME (USHM-C)
T2	6682	CN102358412-A	CN	UNIV SHANGHAI MARITIME (USHM-C)
T2	6787	CN102381464-A	CN	UNIV ZHEJIANG ZHOUSHAN OCEAN (UYZH-C)
T2	6833	US2013115833-A1	CN; EP; JP; US	YAMAHA HATSUDOKI KK (YMHA-C)
T2	7091	WO2013146314-A1	CN; EP; JP; KR; WO	MITSUBISHI HEAVY IND CO LTD (MITO-C)
T2	7177	CN102673763-A	CN	WUXI FUHONG TECHNOLOGY CO LTD (WUXI-N)
T2	7313	US8762022-B1	US	BRUNSWICK CORP (BRUH-C)
T2	7485	WO2014065619-A1	CN; EP; ES; ID; IN; JP; KR; PH; RU; SG; US; VN; WO	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	7487	WO2014065618-A1	CN; EP; ES; ID; KR; WO	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	7491	WO2014092369-A1	CN; EP; ID; JP; KR; PH; RU; SG; US; WO	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	7782	US9248898-B1	US	BRUNSWICK CORP (BRUH-C)
T2	7783	US9039468-B1	US	BRUNSWICK CORP (BRUH-C)
T2	7806	US8924054-B1	US	BRUNSWICK CORP (BRUH-C)
T2	7973	KR1289212-B1	CN; EP; JP; KR; US;	HYUNDAI HEAVY IND CO LTD (HHIH-C)
T2	7994	CN103287563-B	CN	HARBIN COUPLING POWER ENG (HARB-N); LIAONING ZHONGCHUAN (LIAO-N); CHINA SHIPBUILDING 703TH INST (CSHI-C)
T2	8036	WO2014209029-A1	CN; EP; ES; ID; IN; JP; KR; PH; RU; SG; US; VN; WO;	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	8039	CN103332284-B	CN	UNIV SHANGHAI MARITIME (USHM-C)
T2	8244	WO2015053126-A1	CN; JP; KR; WO	MITSUI ENG and SHIPBUILDING CO LTD (MITB-C)
T2	8407	CN103708015-B	CN	UNIV SHANGHAI MARITIME (USHM-C)
T2	9006	CN204056278-U	CN	CHINA NAT OFFSHORE OIL CORP (CNOO-C); OIL PRODN SERVICES BRANCH (OILS-N)
T2	9438	KR1511214-B1	KR	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	9469	WO2016195231-A1	CN; EP; ID; IN; JP; KR; PH; RU; SG; US; VN; WO	DAEWOO SHIPBUILDING and MARINE (DEWO-C)
T2	9790	CN104859828-B	CN	UNIV WUHAN TECHNOLOGY (UYWL-C)
T2	10751	US2017349256-A1	JP; US	YAMAHA HATSUDOKI KK (YMHA-C)
T3	11504	CN206476080-U	CN	GUANGZHOU JINHAI INTELLIGENT (GUAN-N)
T3	11505	WO2018133413-A1	CN; EP; US; WO	DONGGUAN EPROPULSION INTELLIGENT TECHNOL (DONG-N)
T3	11561	WO2018149044-A1	CN; WO	CHEN C (CHEN-I)
T3	11667	WO2018181504-A1	CN; JP; KR; SG; WO	MITSUBISHI HITACHI POWER SYSTEMS (MIBI-C); MITSUBISHI SHIPBUILDING CO LTD (MITO-C)
T3	11669	EP3381790-A1	AU; CA; EP; US	NAVICO HOLDING AS (NAVI-N)
T3	11744	CN107140168-B	CN	UNIV WUHAN TECHNOLOGY (UYWL-C)
T3	11772	WO2018201890-A1	AU; CN; EP; JP; US; WO	TIANJIN DEEPFAR OCEAN EQUIP (TIAN-N)
T3	11821	CN107161313-B	CN	UNIV DALIAN TECHNOLOGY (UYDA-C)
T3	11865	CN206841680-U	CN	MA S (MASS-I)
T3	11910	US10836457-B2	AU; DE; EP; JP; KR; US	ELLERGON ANTRIEBSTECHNIK GMBH (ELLE-N)
T3	11928	CN107380341-B	CN	UNIV DALIAN TECHNOLOGY (UYDA-C)
T3	12086	CN107499487-B	CN	UNIV WUHAN TECHNOLOGY (UYWL-C)
T3	12110	CN107697256-A	CN	GUANGZHOU FAZHAN RUIHUA (GUAN-N)
T3	12149	CN107554741-B	CN	UNIV SHANGHAI MARITIME (USHM-C)
T3	12255	CN107748498-A	CN	UNIV SHANGHAI MARITIME (USHM-C)

Table A1. *Cont.*

Phase	Lable	Representation in the Patent Family	Distributed Countries and Regions	Patentees
T3	12421	EP3486742-A1	EP; JP; US;	BRUNSWICK CORP (BRUH-C)
T3	12475	CN107826225-A	CN	OUBO INTELLIGENT TECHNOLOGY (OUBO-N)
T3	12565	WO2019129687-A1	CN; EP; US; WO	RIDE AWAKE AB (RIDE-N)
T3	12764	CN108860549-A	CN	UNIV HARBIN ENGINEERING (UHEG-C)
T3	12765	CN108674627-B	CN	UNIV HARBIN ENGINEERING (UHEG-C)
T3	12768	CN108657406-B	CN	UNIV HARBIN ENGINEERING (UHEG-C)
T3	12772	CN108438189-B	CN	UNIV HARBIN ENGINEERING (UHEG-C)
T3	12923	CN108750064-A	CN	GUANGZHOU MARITIME INST (GUAN-N)
T3	12974	WO2019235842-A1	CN; JP; KR; US; WO	KWATERCRAFT CO LTD (KWAT-N)
T3	13136	US2020043315-A1	JP; US	SUZUKI MOTOR CORP (SUZM-C)
T3	13228	CN108974308-A	CN	NINGBO JIEMAO SHIPPING (NING-N)
T3	13431	KR2020052535-A	KR	MARINE TECHNO KOREA CO LTD (MARI-N)
T3	13756	CN109941417-A	CN	UNIV HARBIN ENGINEERING (UHEG-C)
T3	13768	US11034424-B2	CN; US	UNIV HARBIN ENGINEERING (UHEG-C)
T3	13790	CN109733583-A	CN	UNIV GUANGXI NORMAL (UNGT-C)
T3	13867	CN109927872-A	CN	SHANXI FENXI HEAVY IND CO LTD (CSHI-C); WUXI SILENT ELECTRIC SYSTEM (WUXI-N)
T3	13944	CN110001908-A	CN	UNIV JIMEI (UYMJ-C)
T3	14126	CN110435865-A	CN	CHINA SHIPBUILDING 719TH RES (CSHI-C)
T3	14329	CN110481748-	CN	CHINA SHIPBUILDING 702TH INST (CSHI-C)
T3	14406	CN110539869-A	CN	CHINA SHIPBUILDING 719TH RES (CSHI-C)
T3	14409	CN110539870-A	CN	CHINA SHIPBUILDING 719TH RES (CSHI-C)
T3	14410	CN110525624-A	CN	CHINA SHIPBUILDING 719TH RES (CSHI-C)
T3	14470	CN110758708-A	CN	UNIV ZHEJIANG OCEAN (UYZO-C)
T3	14486	WO2021073378-A1	CN; WO	SUZHOU PM and T POWER CO LTD (SUZH-N)
T3	15015	WO2021185056-A1	CN; WO	WUXI SILENT ELECTRIC SYSTEM (WUXI-N); SHANXI FENXI HEAVY IND CO LTD (CSHI-C)

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