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Evolutionary Patterns of Renewable Energy Technology Development in East Asia (1990–2010)

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Abstract: This study investigates the evolutionary patterns of renewable energy technology in East Asian countries—Japan, Korea, and China—as an emerging technology where the catch-up strategy is actively taking place. To reflect the quality of technology development activities, we assess each country's research and development (R&D) activities using patent citation analysis. The goal of this study is to overcome the limitations of prior research that uses quantitative information, such as R&D expenditures and number of patents. This study observes the process of technological catch-up and leapfrogging in the East Asian renewable energy sector. Furthermore, we find that each nation's technology development portfolio differs depending on the composition share of technologies. Policymakers in emerging economies can use the findings to shape R&D strategies to develop the renewable energy sector and provide an alternative method of evaluating the qualitative development of technology.

Keywords: renewable energy; patent citation analysis; network analysis; technological catching-up

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1. Introduction

Global warming and environmental concerns such as air pollution and acid precipitation are two of the most critical issues in today's society [1–3]. Growing global concerns about environmental issues have increased the attention paid to renewable energy technology, which may play a key role in reducing carbon emissions and provide conditions for a sustainable growth. In addition, renewable energy technology can create new economic opportunities and its influence may change the current industrial structures entirely. Many researchers have pointed out that the development of renewable energy technology can solve environmental problems and agreed that developing renewable energy technologies is no longer a question of choice but a question of how [1,3–8].

Many developed countries have increased their investment in and support of R&D projects to develop renewable energy technology over the past two decades. The United States, Japan, and Germany are the leading nations in the renewable energy industry [9–11], and many countries wish to catch up by increasing their efforts to develop renewable energy technology. Altenburg [12] points out that the general technological solution for "shifting to a low-carbon economy" in Asian and European countries depends on the catch-up process. As argued in previous studies on low-carbon energy technology catch-up in East Asian economies [13], East Asian countries are expected to catch up and leapfrog other regions in the development of renewable energy technology. For example, China, the country with the world's largest greenhouse gas (GHG) emissions (9.0 giga-tons of CO_2, and approximately 28% of the total GHG emission on the planet in 2013), has also boosted R&D investment ($2.4 billion in 2014) in renewable energy [14]. South Korea (hereafter, Korea) also spent over $0.68 billion in 2014 to develop clean and renewable energy [15]. Both Korea and China made efforts to catch up to Japan, which is one of the leading nations in renewable energy technology.

Numerous studies have identified the catch-up tendency in renewable energy sector. However, as far as the authors are aware, most of those observations deal only with specific technologies, such as photovoltaic or wind turbine technology [16–18]. However, not only does the technological characteristics of each renewable energy source vary, but also there is no consensus on which will be the predominant future energy technology. Thus, a comprehensive understanding of the entire renewable technology industry is important.

The main purpose of this paper is to identify the patterns of technological development using a comparative analysis of Japan, Korea, and China in the renewable energy sector. We identify the patent network of the technological innovation system and illustrate the evolutionary patterns of technology during innovation activities. A network analysis is used to visualize the structure of technology network and understand its patterns of evolution. This study also examines the industrial characteristics and the effect of government-driven innovation policies. The analysis confirms the catch-up and leapfrogging patterns in the renewable technology development in all three countries, where each prominently uses the catch-up strategy. The findings could help in shaping the policy portfolios of technology development activities and advantages of industrial development.

The remainder of this paper consists of four sections. Section 2 reviews the previous research. Section 3 provides the data and methodology. Section 4 describes the empirical results. Section 5 briefly concludes the study.

2. Literature Review

2.1. Catching up and Leapfrogging

Catch-up is a process of reducing the gap in productivity and income relative to the leading country [19]. The technology-oriented catch-up view focuses on explaining how developing countries have tried to catch up to developed countries by imitating and adapting mature technologies since these technologies are considered the standard modern technologies and are thus easy to copy [20]. In this view, catching up is a process that follows a fixed track [20]. The catch-up strategy has prevailed since the beginning of the Industrial Revolution. Many European countries, especially Germany, tried to imitate the industrialization process of the United Kingdom and succeeded [19]. During the mid- to late 20th century, East Asian countries such as Japan, Korea, and China also experienced considerable economic growth using the catch-up strategy [19–23].

However, several studies suggested that developing countries do not simply follow the path taken by advanced countries. Perez and Soete [24] introduce the concept of "windows of opportunity" induced by techno-economic paradigm change, during which the follower can leapfrog the leader via anticipatory R&D investment in emerging technologies. They also show that latecomers can overcome developed countries through the catch-up strategy despite minimal fixed investment, scientific and technological knowledge, and relevant skills and experiences if developing countries can seize (identify) this window of opportunity correctly and invest wisely. Lee and Lim [20] introduce three types of catch-up strategies: path-following catch up, stage-skipping catch-up, and path-creating catch-up.

Among those three catch-up strategies, stage-skipping and path-creating catch-up is closest to leapfrogging. The term leapfrogging denotes a non-continuous development mode [25]. Several developing countries that adopt a leapfrogging strategy tend to skip several development steps [25,26]. The leapfrogging-strategy-oriented latecomers tend to skip some paths the first mover developed or create novel paths in technological development. Similarly, Bhagavan [26] notes three steps in leapfrogging: importing and absorbing; replicating, producing, and improving; and innovating. In summary, a successful developing country is likely to leapfrog the current position to seize the advantage from some developed countries.

Sohn, Chang, and Song [27] observed catch-up patterns in the Asian shipbuilding industry and conclude that a balance between imitation and innovation is important for successful technological catch-up. Lee, Lim, and Song [28] illustrated the success of Korean electronics firms in catching and leapfrogging Japanese firms, despite the technological gap in analog TV. The Korean firms were latecomers to the industry; however, they took the opportunity to leapfrog in the era of technical regime change from analog to digital. They also highlight the important role that government played in the leapfrogging. In addition, Mathews [29] showed the catch-up and leapfrog pattern in Korean cellular technology. Sauter and Watson [30] reviewed several successful leapfrogging cases, such as the Korean steel and automobile industry, and the Chinese and Indian wind industry. Although other factors driving the growth in these industries in these countries, such as strong governmental support, firms' commitment, and a large supply push, catch-up and leapfrog are evidently powerful and successful strategies for developing countries to grow.

These prior studies demonstrated that Japan, Korea, and China have succeeded in building industries in fast-moving sectors such as electronics, semi-conductors, and solar photovoltaics by using fast-follower industrial dynamics, which emphasize the role of innovation in the process [16]. Though these countries attempted to become the frontrunner in some industries, there is still a technological gap compared to developed nations in many industry sectors. Few studies focused on the different catch-up and leapfrogging patterns between East Asian countries [31], and there is not enough literature covering technological catch-up and leapfrogging in the renewable energy sector. Therefore, this study explores the current status of renewable energy industry in Japan, Korea, and China and verifies whether catching-up and leapfrogging patterns prevail in the renewable energy sector as well.

2.2. Indicator of Innovation Activities

Analyzing the effect of technology catch-up and leapfrogging requires a measurement of the performance of innovation activity. Since the 1950s, studies have used R&D expenditures to measure the inputs for innovation, with the number of patents as an innovation output [32]. Besides the electricity sector, R&D expenditures are a common indicator of innovation in various research fields. Many studies of the electricity market empirically analyzed innovation activities with intensive focus on the input-oriented innovation activities [33–37]. Using R&D expenditures to measure innovation is an advantage in that governments or international organizations, such as OECD (Organization of Economic Cooperation and Development), regularly collect the data, providing researchers with internationally comparable data since 1965 [38]. Moreover, most of the data is open to the public and easily accessible online [39]. Due to these advantages, R&D expenditure is a very popular measure of inputs in innovation activities [32].

Despite its popularity, using expenditure data as an indicator for innovation activities has several drawbacks. First, the expenditure cannot fully reflect all innovation activities. As mentioned above, R&D expenditure is one input element that explains innovation activities, so it does not follow the economic meaning of the results of innovation activities [40]. Second, as Keller [38] noted, R&D expenditure contains some noise in observing technology improvements and the returns on expenditures can be biased. Third, expenditures cannot depict technology-level innovation because it is not distinguishable. The expenditure data is reported at the firm, sector, or national level, not the technology level.

Another traditional measure of innovation is patent activity [32]. Patents are an output-based indicator of innovation activities. Malerba and Orsenigo [41], Abraham and Moitra [42], and Abbas et al. [43] agreed that using patent information can help to identify the patterns of innovation activities at the national level. Gassler et al. [44] applied patent data as invention activities to verify the relationship between industry sector and technology sector in Austria. Godoe and Nygaard [45] also noted that patent data is plausible to use as a suitable and quantifiable indicator to measure technological creativity and innovation activities. They suggest that researchers can apply patent data to analyze the size and scope of innovation activities and demonstrated the examples of fuel cells and hydrogen technologies in Norway using patent data.

The main reason for the widespread use of patent data is that the database is open-source and provides a wide range of information validated by a third party, the patent examiner [46]. Firms are usually unwilling to report their R&D expenditures accurately, though for patents, inventors are committed to providing appropriate information to gain exclusive rights. Thus, patents provide higher quality information in terms of accuracy and value than information on expenditures. One of the greatest advantages of a patent analysis is that patent data provide bibliometric information, which contains information about the patent number, type of document, name and address of the inventor and the assignee, publishing country, date of application, cited information, international patent classification, and so on. Using bibliometric information, Narin [47] analyzed the co-citation relationship, called the patent bibliometric. Patent citation analysis can show relationships between patents and assess the quality of patent in terms of relative importance [48].

Many other studies deal with patent activities for innovation [49–51]. However, most of these studies are limited in that they only report the number of patents or claims and do not provide information about their application. As Pakes and Griliches [52] point out, not all innovations are measured as patents and each patent has heterogeneous economic value; therefore, the number of patents does not reflect true economic value [52,53]. Thus, the present study applies the network centrality index to overcome the drawbacks of counting the number of patents. OECD [54] and Alcácer and Gittelman [55] emphasize patent citation analysis as indicators of innovation and knowledge diffusion. Patent citation analysis illustrates backward and forward citation relationships between patents. It helps to identify the influence of inventions both on technology sectors and the entire economy. The number of citations reflects technological and commercial importance and enables to overcome some drawbacks pointed out by Pakes and Griliches [52]. Jaffe and Trajtenberg [56] also highlight the usage of patents and their citation data as a powerful tool to analyze the economics of innovations. The centrality index is an indicator used in network analysis that measures the direct or indirect relationships between nodes. In patent citation analysis, the centrality index can distinguish the relative importance of each patent and identify patents with higher centrality impacts that are more important in the network. The following section describes network centrality analysis.

3. Methodology

3.1. Data

We use patent applications data from the EPO Worldwide Patent Statistical Database (PATSTAT) provided by the European Patent Office (EPO). The PATSTAT database contains more than 20 bibliographic data for patent applications, such as the title, abstract, and information about the applicants and inventors, including their names, address, technological classifications, and citation information, among other things, from various countries and patent offices. The PATSTAT database consists of several databases (Figure 1), each connected with a key. These databases can be analyzed using SQL (Structured Query Language).

This study uses the PATSTAT October 2013 edition by extracting the data from 1990 to 2010. Japan initiated a renewable energy policy from the early 1970s and Korea and China followed from 1985 and the 1990s, respectively [57]. This energy policy was a response to the oil crisis of the 1970s; during this period, the main concern was self-sufficiency with respect to energy sources [58]. By the 1990s, a new phase in the development of alternative energies that can also be defined as renewable energies was led by the changes of major concerns on environmental issues; this synchronized with an increasing pattern in the number of patent applications in developing renewable energies [58]. Due to this pattern, use of the data from 1990 helps to analyze development patterns of renewable energies in East Asia. Since patent applications are generally published 18 months after the earliest priority date of the application, the study period is 1990–2010.

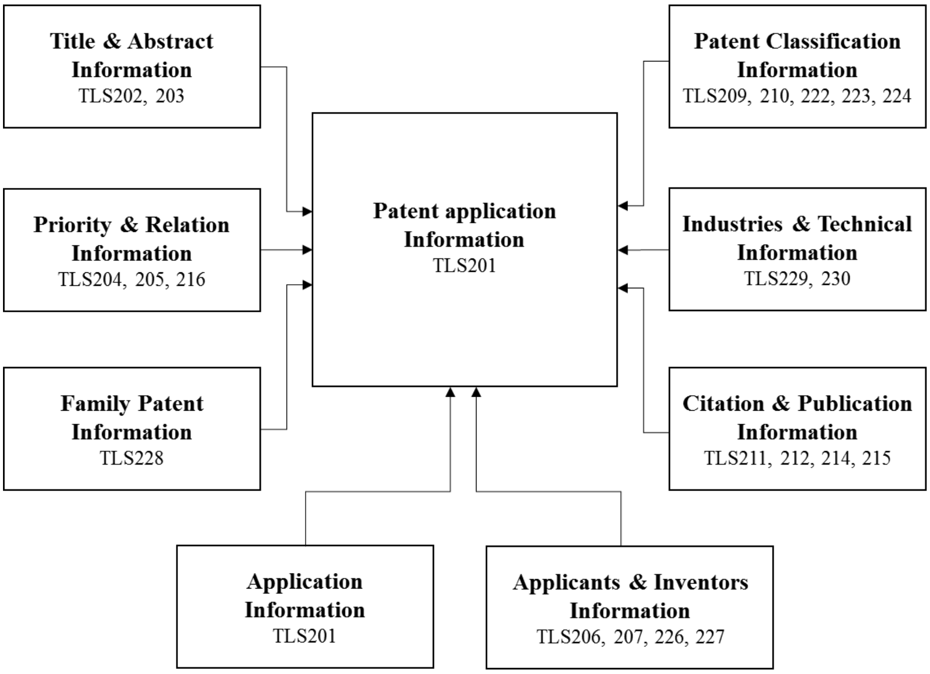


Figure 1. PATSTAT Logical model diagram.

Patents are classified by technology category using an internationally standardized framework called IPC (International Patent Classification) codes from the WIPO (World Intellectual Property Organization). The WIPO has administered IPC codes since October 1975, five years after the signing of the Strasbourg Agreement, which set the standard for international patent classification. The IPC code is a unique international patent classification that applies in each country to unify the global intellectual property system. IPC codes have four hierarchies: Section, Class, Subclass, and Group, as well as a lower-level hierarchy with more detailed technological information. The patent examiner assigns IPC to each patent, and one patent can have several codes [59].

For this study, we extracted patent applications related to renewable energy using IPC codes. Unlike prior research, we use the information in patent applications as an indicator of innovation activity since we focus on innovation activity rather than outcomes. Lanzi et al. [60] selected fossil fuel electricity generation technology by IPC code and Johnstone et al. [61] presented IPC classes related to various types of renewable energy such as wind, solar, geothermal, ocean, and biomass and waste. Noailly and Smeets [62] also used IPC codes to distinguish patents for renewable energy and fossil fuel energy. We created our selection criteria for renewable energy electricity generation using specific IPC codes building on these works. In this study, we included both solar–thermal and solar–photovoltaic as solar energy sources, as in Johnstone et al. [61] and excluded hydropower energy. Even though hydropower is considered as a sort of renewable energies, the technology was not covered in this research due to the following two reasons. First, among the three countries focused on in this research, Japan was the one that actively developed hydropower technologies before 1990 [58]. Despite the gradual increase in patent applications for this technology in those countries, it is not meaningful to compare the growth pattern of the technology since the pattern has remained relatively constant [58]. Second, hydropower generation capacity has been largely and widely installed. Hydropower capacity represented approximately two-thirds of all renewable power generation capacity in 2013 [63]. Before 1990, the main concern in the development of renewable energies was the rise of self-sufficiency for energy sources. It led to the development of hydropower and thus hydropower became a world-wide mature technology [64]. Hence, renewable energy in this research is defined on a narrow level since it is obvious that every country develops hydropower technology regardless of catch-up and leapfrogging strategies. Appendix A reports the IPC codes we used for the extraction to consider the definition of renewable energy in this research. We use the first four digits of the IPC code at subclass level in our analysis, since this is the most common in analyses of technology sectors [65–67]. However, since using the IPC four-digit classification can create a duplication of codes, we attempted to identify and eliminate these duplicates.

3.2. Network Analysis

Network analysis is based on the network and graph theories and is a powerful methodology to distinguish social structures; it consists of actors (nodes in network theory) and interactions among the actors (edges in network theory). It is widely used in various fields, such as artificial intelligence, geography, economics, and informatics [68]. Social network analysis can intuitively demonstrate the evolutionary pattern of the performance and relationships that traditional social science failed to capture [69]. Therefore, network analysis is growing in popularity as an alternate methodology to analyze interdisciplinary fields.

In this research, we use network analysis to verify the evolutionary patterns of technological innovation activities. Nodes indicate IPC codes and edges are the interconnection between two IPC codes. This method shows the convergence of technologies since the IPC codes also indicate technological categories. For example, solar energy technologies represented by H01L31/04 cites B09B03/00, one renewable energy technology. Thus, renewable energy technologies affected solar energy technologies in their technology development process and therefore a newly developed solar energy technology can be considered as a convergence technology between those two types of technologies. These patterns of technology convergence can show patterns of technological innovation at the national level. To draw the patterns, we first draw the network structure for the countries during the study period and analyze the network topology to understand the overall network structure and properties of the network. Second, we identify the quantitative information of the importance of each individual node through centrality analysis.

3.2.1. Network Structure Analysis

Network visualization is a basic method to explain the general structure and allows us to interpret the distributions and evolution of the network structure easily. Visualization is based on graph theory, and there are numerous visualization tools, such as NetMiner, UCINet, NodeXL, Pajek, and Gephi. Network visualization can be a useful means to determine the general intuition of networks such as the dynamics of complexity in network. However, it is difficult to identify the characteristics of the network, nodes, and edges only through network visualization. To provide more clarity, we analyze various statistical indices suggested by Albert and Barabási [70], such as the number of nodes and edges, network density, average degree and path length, network diameter, clustering coefficient, and centralization index, which are common in research to discover the properties of network structures [71].

The number of nodes and link edges represent the size of the network. In a patent citation network, if the number of nodes increases, then various IPC codes exist in the network and the network becomes diversified. As the number of edges increases, two IPC codes have active interactions. Graph density is an indicator that shows the effectiveness and efficiency of a network. The density of a network is the ratio of the actual number of edges to all possible edges of the entire network [72]:

$$density = \frac{2 \times (number\ of\ edges)}{(number\ of\ nodes) \times \{(number\ of\ nodes) - 1\}} \quad (1)$$

The higher the density of a network, the more effective and highly connected the network is.

The average degree is the average number of edges connected to it, and the average path length is the average of the shortest path, and the geodesic path that between every pair of nodes [73], defined as follows:

$$average\ path\ length = \frac{\sum_{i \neq j} d(n_i, n_j)}{(number\ of\ nodes) \times \{(number\ of\ nodes) - 1\}}, \quad (2)$$

where $d(n_i, n_j)$ is the distance between nodes n_i and n_j.

The average path length can be used to estimate the speed of information diffusion in the network. Technology and information can spread easily in a network with a low average path length. The network diameter is the largest geodesic path length in a network. The clustering coefficient of a node is the ratio between the number of actual edges among its neighbors and the maximum possible edges between those neighbors, defined as follows:

$$clustering\ coefficient = \frac{3 \times (number\ of\ triangles)}{number\ of\ connected\ triplets\ of\ nodes} \quad (3)$$

3.2.2. Network Centrality Analysis

To observe the importance of nodes, we apply network centrality analysis. The centrality index is one of the most widely used quantitative measures of indicators in network analysis [74]. Moreover, Freeman's [75] three concepts of centrality are also popular: degree centrality, closeness centrality, and betweenness centrality.

Degree centrality indicates the number of direct edges incident upon a node. In the case of a directed network, however, each edge has a direction between the nodes. Thus, degree centrality can be either in-degree centrality or out-degree centrality. In-degree centrality represents the number of directed edges to the node and the out-degree centrality represents the number of edges that the node directs to other nodes. In-degree and out-degree centrality are meaningful indices that can identify the tendency of patents in a patent citation network. The standardized degree centrality of node *i* (C_d^i) can be defined as follows:

$$C_d^i = \frac{C_d^i}{C_d^{\max}} = \frac{C_d^i}{(number\ of\ nodes) - 1}, \quad (4)$$

where $C_d^{\max}$ is the maximum of degree centrality observed in the network. A node with a higher degree centrality has more relationships than those with a lower degree centrality, and they can transfer more information. However, since degree centrality indices consider only direct edges to the nodes, they may overlook the effect of indirect and intermediary relationships.

4. Results and Analysis

4.1. Evolution of Technology Network in Renewable Energy

To illustrate the evolution of a technology network, we identified the patent citation network in each country by analyzing patents with a weighted out-degree of more than 10 (Appendixs B and C). Since our main focus is on renewable energy technology, we do not include fossil fuel technologies. Japan developed renewable energy technology earlier than the other two countries, so Korea and China have no significant technology development activity before 1998 and 2005, respectively (see Figures B2 and B3). During the 1990s and early 2000s, renewable energy technology development in Japan concentrated on biomass and waste energy technology such as F23G5/00 (incineration), F09B3/00 (destroying or transforming solid waste), and C10L10/00 (liquid carbonaceous fuels). Starting from the mid-2000s, however, technology development in solar energy such as H01L31/04 (semiconductor devices sensitive to infra-red radiation, light-adapted as conversion devices) and wind energy field such as F03D9/00 (adaptations of wind motors for special use) and F03D11/00 (details, components parts, or accessories) increased, while development in biomass and waste energy technology gradually decreased. This was due to the increased global demand for solar and wind energy technology. In other words, biomass and waste energy technology development may stagnate without a significant technological breakthrough. Korea's renewable energy technology development follows Japan's trend. Korea has been developing renewable energy technology since 2000. In the early 2000s, most research was in biomass and waste energy technology (C10L1/00 and C10L1/22). Starting from the mid-2000s, Korea also began actively developing wind and solar energy technology such as F03D3 (wind motors with axis), F03D11/00, and H01L042 (semiconductor devices sensitive to infra-red radiation, light-adapted as conversion devices). China gradually started developing renewable energy technology from the early 2000s. Unlike Japan, China focused on wind and solar energy technology from the start, and supported this development with policies. From the mid-2000s, China mainly focused on developing wind energy technology such as F03D3, F03D9/00, and F03D11/00.

To understand the properties of network structures, we analyze the network topology of each country (Tables 1–3). We can define the growth pattern by considering the characteristics of the network topology. The number of nodes in Tables 1–3 indicates the degree of variety of renewable energy technology groups. The higher the number for a particular country, the more varied the technology the country developed. The number of edges refers to the degree of technology convergence. Since the maximum number of nodes is constrained because it corresponds to the number of IPC codes in the renewable energy group, the graph will be denser when the number of edges increases. Once the degree of density in a network increases, the path length between two nodes will be shorter. Thus, the average path length will also decrease. Similarly, a higher clustering coefficient for the network indicates a higher level of technology developed in the network. Thus, in a country with highly developed and convergent technology, the number of nodes and edges, graph density, average degree, and clustering coefficient tend to be higher, but the average path length is shorter.

Comparing the results of the three countries, Japan had already developed many types of renewable energy technologies and thus the number of nodes rarely changed. However, the number of edges and average degree in Japan decreased from 2007 to 2010. This is because the development of biomass and waste energy technology declined and the country depended on technology transfer from overseas. Due to this trend, even though Japan developed solar and wind energy technology vigorously, it seems that development of renewable energy technology in Japan reduced during this period.

Korea and China developed more types of technologies gradually. In 2010, the three countries had almost the same number of technology groups. Japan recombined more than 1000 technologies from the early 1990s, whereas the number of technology developments by recombination activities in the other two countries was less than 1000. Thus, Japan retained higher technology competence than the others.

Table 1. Network topology of Japan (1990–2010).

Year	Number of Nodes	Number of Edges	Graph Density	Average Degree	Average Path Length	Diameter	Clustering Coefficient
1990	43	4493	2.49	208.98	2.12	5	0.54
1991	43	3940	2.18	183.26	2.16	5	0.54
1992	42	3639	2.11	173.29	2.13	5	0.58
1993	41	2766	1.69	134.93	2.33	6	0.58
1994	41	2056	1.25	100.29	2.27	6	0.50
1995	37	1452	1.09	78.49	2.41	6	0.56
1996	35	817	0.69	46.69	2.21	6	0.57
1997	35	920	0.77	52.57	2.04	5	0.53
1998	36	1424	1.13	79.11	2.21	6	0.53
1999	41	2428	1.48	118.44	2.19	5	0.54
2000	43	7309	4.05	339.95	2.09	5	0.61
2001	44	12,059	6.37	548.14	1.86	4	0.65
2002	42	2585	1.50	123.10	2.20	6	0.65
2003	41	5774	3.52	281.66	2.26	6	0.68
2004	43	14,884	8.24	692.28	1.84	4	0.70
2005	43	24,896	13.79	1157.95	1.75	4	0.71
2006	42	26,988	15.67	1285.14	1.76	4	0.71
2007	43	27,520	15.24	1280.00	1.78	5	0.70
2008	43	20,380	11.28	947.91	1.87	5	0.67
2009	42	12,583	7.31	599.19	1.93	5	0.64
2010	44	9166	4.84	416.64	2.00	5	0.63

Table 2. Network topology of Korea (1990–2010).

Year	Number of Nodes	Number of Edges	Graph Density	Average Degree	Average Path Length	Diameter	Clustering Coefficient
1990	1	2		4.00			
1991	1	3		6.00			
1992	6	9	0.30	3.00	1.00	1	0.00
1993	5	19	0.95	7.60	1.00	1	0.60
1994	9	28	0.39	6.22	1.48	3	0.48
1995	4	8	0.67	4.00	1.00	1	
1996	19	53	0.15	5.58	1.00	1	0.38
1997	13	45	0.29	6.92	1.24	2	0.69
1998	16	42	0.18	5.25	1.13	2	0.45
1999	14	38	0.21	5.43	1.31	2	0.55
2000	23	97	0.19	8.43	1.30	2	0.32
2001	25	184	0.31	14.72	2.68	6	0.34
2002	32	362	0.36	22.63	2.35	6	0.38
2003	31	399	0.43	25.74	2.26	5	0.47
2004	33	351	0.33	21.27	2.10	5	0.53
2005	36	532	0.42	29.56	2.49	6	0.43
2006	39	1860	1.26	95.38	2.35	6	0.47
2007	41	2124	1.30	103.61	2.23	6	0.60
2008	38	1498	1.07	78.84	2.47	7	0.45
2009	40	2122	1.36	106.10	2.52	6	0.48
2010	42	2965	1.72	141.19	2.36	5	0.54

Table 3. Network topology of China (1990–2010).

Year	Number of Nodes	Number of Edges	Graph Density	Average Degree	Average Path Length	Diameter	Clustering Coefficient
1990							
1991							
1992							
1993							
1994	5	9	0.45	3.60	1.00	1	0.00
1995	4	13	1.08	6.50	1.00	1	
1996	5	21	1.05	8.40	1.00	1	
1997	11	31	0.28	5.64	1.00	1	0.60
1998	19	53	0.15	5.58	1.00	1	0.00
1999	11	36	0.33	6.55	1.00	1	0.00
2000	15	69	0.33	9.20	1.64	3	0.47
2001	18	93	0.30	10.33	1.36	2	0.43
2002	18	106	0.35	11.78	1.58	3	0.26
2003	20	110	0.29	11.00	1.45	3	0.00
2004	22	140	0.30	12.73	1.57	3	0.50
2005	26	248	0.38	19.08	1.93	4	0.29
2006	26	364	0.56	28.00	1.96	4	0.44
2007	38	870	0.62	45.79	3.07	9	0.50
2008	34	822	0.73	48.35	2.34	5	0.51
2009	36	1173	0.93	65.17	3.05	7	0.44
2010	42	2222	1.29	105.81	2.64	7	0.43

4.2. Technology Level Catch-Up and Leapfrogging

In this section, we verify the technology catch-up and leapfrogging aspects by analyzing the impact of each type of renewable energy technology and the structure of the technology portfolios in Japan, Korea, and China.

We illustrate the core technologies of each energy as the top 10 technologies based on IPC codes. By analyzing the technologies with the highest impact on other technologies using weighted out-degree centrality, we can derive each country's technology development strategies. The weighted out-degree helps to clarify the real impact of the technologies by summing the duplicate citations between nodes. Figure 2 shows the share of the different types of renewable energy technology within the top 10 renewable energy technologies in (A) Japan, (B) Korea, and (C) China.

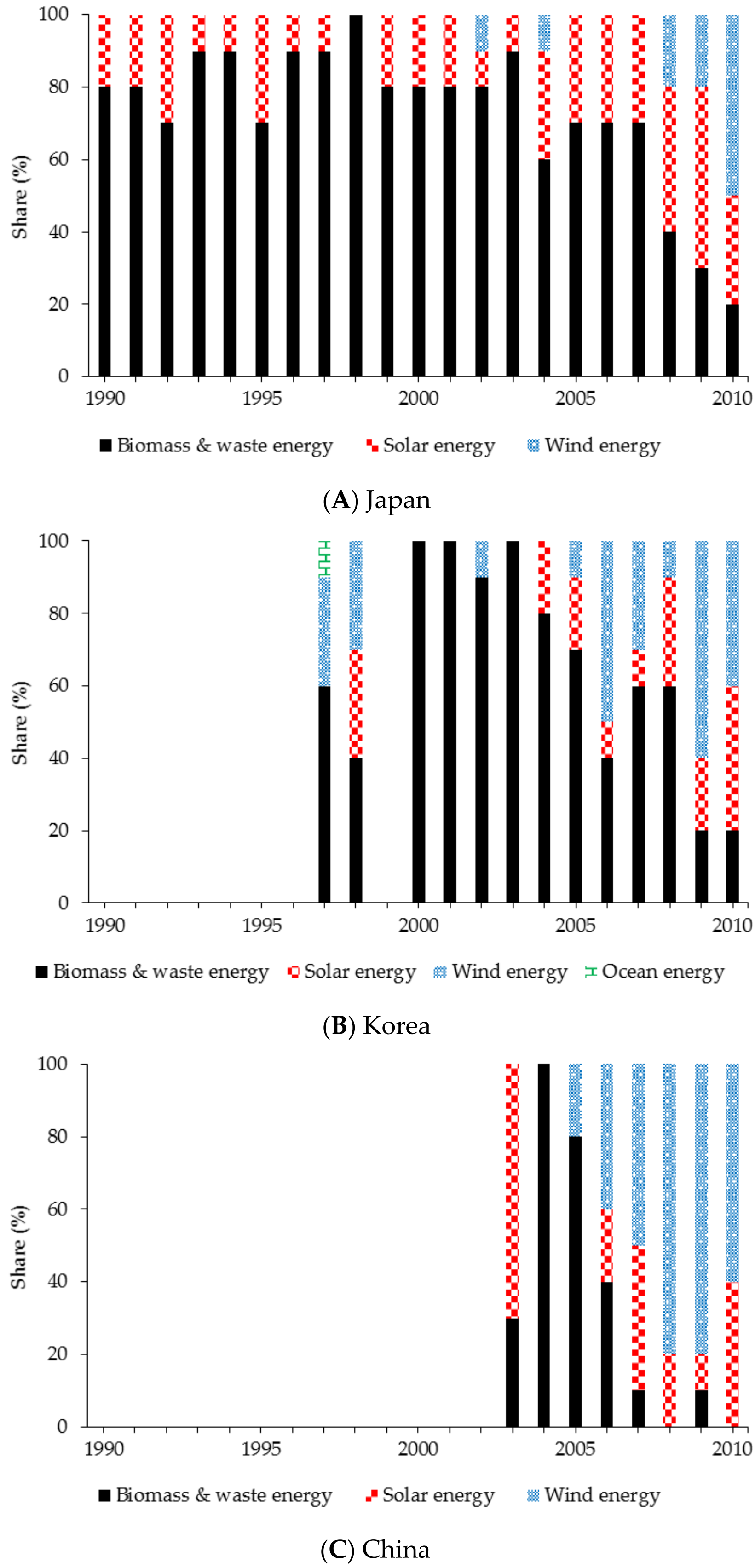


Figure 2. Top 10 ranked renewable energy technologies in the East Asian countries. Note: We only consider technologies that have weighted out-degree of 10 or above. In Korea, none of technologies developed in 1999 has weighted out-degree more than 10.

Comparing renewable energy technology development patterns in each country, we can derive the patterns of catching-up and leapfrogging for two latecomers, Korea and China. Since Japan focused on biomass and waste energy technology from the early 1990s to the early 2000s, Korea also concentrated on the development of biomass and waste energy technology. Then, both countries shifted to developing solar and wind energy technologies during the mid-2000s. This pattern indicates that as a latecomer in renewable energy technology development, Korea established a development strategy of imitating Japan. China also adopted a catch-up strategy, but different from that of Korea. China tried to overcome the limitations of the catch-up strategy and established a leapfrogging strategy by focusing on wind and solar energy technology. This indicates that China spotted the paradigm shift in the renewable energy industry, and intensively focused on developing the new niche technologies.

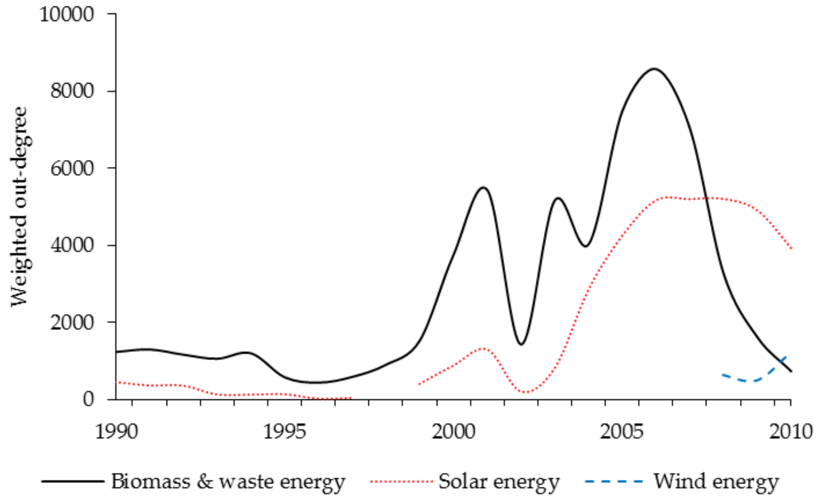
Figure 3 illustrates the influence of each type of energy technology, with Japan, Korea, and China represented in panels (A), (B), and (C), respectively. Before the mid-2000s, biomass and waste energy technologies were the core renewable energy technology developed in Japan (Figure 3A). Thus, many energy technologies were related to biomass and waste energy technologies. After 2007, however, the influence of solar energy technology increased, and the influence of biomass and waste energy over other technologies decayed. Therefore, both the capital and labor resources required to develop biomass and waste energy were re-distributed to develop other renewable energy technologies, such as solar and wind.

The influence of each renewable energy technology in Korea follows a similar pattern to that of Japan. From 2000 to 2006, the influence of biomass and waste increased. Starting from 2007, however, the influence of biomass and waste energy technology diminished due to the increase in the influence of solar and wind energy technologies. After 2008, the influence of solar energy technology exceeded that of biomass and waste energy technology, and showed a steadily increasing trend. Korea focused on developing solar energy technology more than wind energy technology, which diverges from Japan's strategy of developing both technologies simultaneously. This is because Korea concentrated on the photovoltaic industry, which has many similarities to the display and semiconductor industries [76], and the Korean government implemented a feed-in tariff from 2002 to 2011 to encourage photovoltaic technology development [77]. Thus, as Japan was one of the leading countries in solar photovoltaic technology [78], it seemed that the renewable energy technology development strategy in Korea imitated the Japanese strategy until 2007.

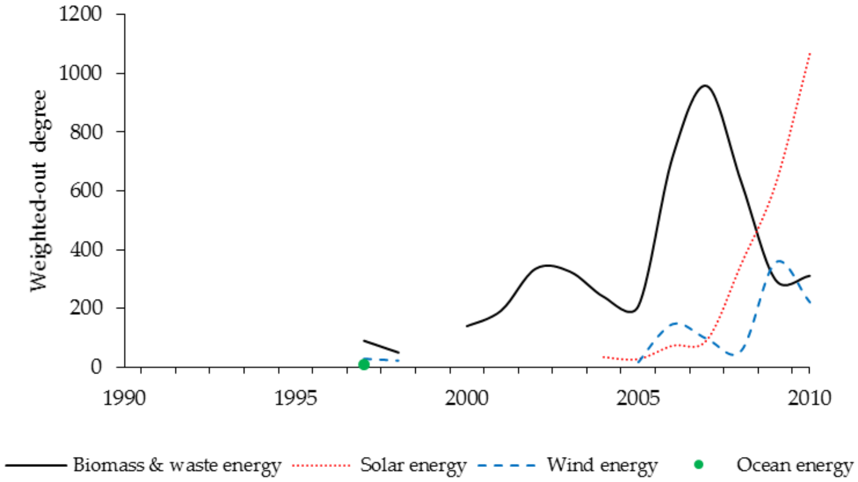
China set up a totally different strategy by concentrating on wind energy technology development. Even though China mainly developed biomass and waste energy technology in the early 2000s, the Chinese government initiated a set of policies to encourage wind energy technology development and thus made significant progress in wind energy technology. This means that China tried to catch up to Japan and Korea for some time, then shifted to a leapfrogging strategy.

The results show that the renewable energy technology development strategies for Japan, Korea, and China are different. Japan conducted solar and wind energy technology development activities simultaneously in the mid-2000s, which is in line with the international trend. However, by the mid-2000s, Japan had been developing biomass and waste energy technology for almost a decade, which made it difficult for Japan to shift their focus to solar and wind swiftly.

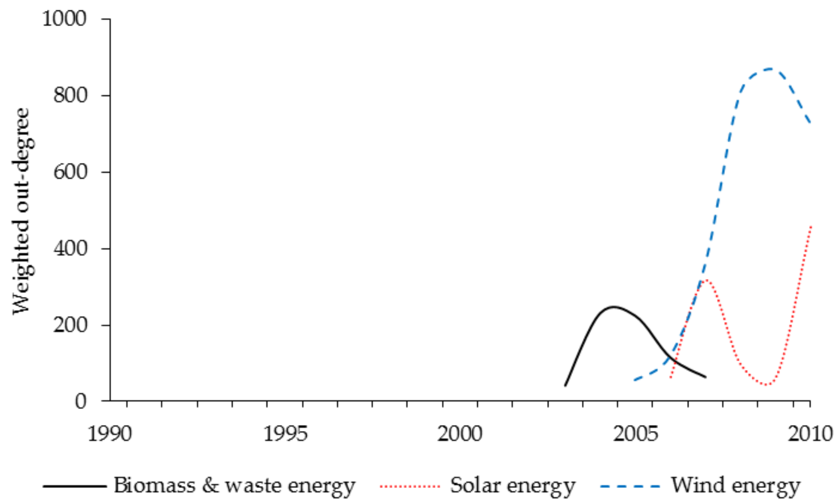
Korea and China set a renewable energy technology development strategy based on Japan's case. Though both Korea and China started with a similar catch-up strategy, they implemented different leapfrogging strategies. Korea appeared to have established a similar strategy for renewable energy technology development as Japan. Although Korea first imitated Japan's strategy to develop biomass and waste energy, it quickly shifted focus to solar and wind energy, since development in these two areas became a global issue. This shift shows Korea's sensitivity to globally emerging issues. However, China's catch-up strategy was based on the government's powerful influence. Since passing the Renewable Energy Law, wind energy technology had more influence than other renewable technologies. Considering this fact, China has maintained a post-catch-up strategy of leapfrogging.



(**A**) Japan



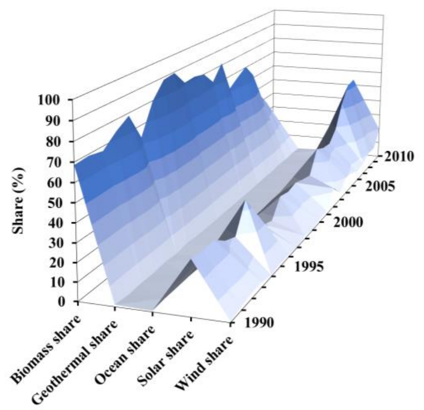
(**B**) Korea



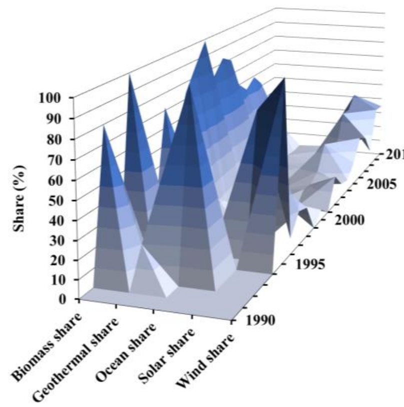
(**C**) China

Figure 3. Influence of each type of technology on technology development. Note: We only consider technologies that have weighted out-degree of 10 or above. In Korea, none of technologies developed in 1999 has weighted out-degree more than 10.

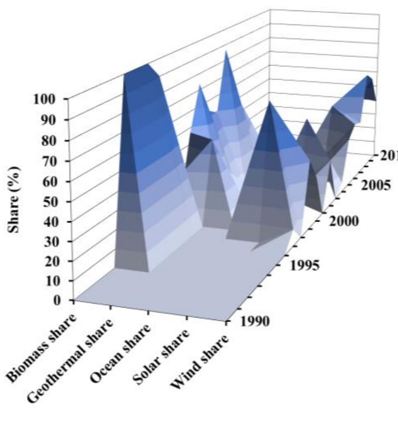
Figure 4 illustrates the differences in the portfolios of technology development activity among the three countries. Japan has consistently developed biomass and waste energy technology since 1990. Unlike Japan, Korea and China seem not to have a specific direction for a technology development portfolio. Though the latter two countries seem to share similar patterns, China started concentrating on wind energy technology in 2004, whereas Korea did not decide to develop a specific type of technology. This difference in setting the direction for a technology portfolio between these two countries led to China's success and Korea's failure in the renewable energy sector in terms of technology level. Thus, China might be considered a successful follower that leapfrogged, whereas Korea failed to overcome its position as a follower.



(**A**) Japan



(**B**) Korea



(**C**) China

Figure 4. Change of technology development portfolio (1990–2010).

5. Conclusions

Growing concerns about global warming and other environmental issues have focused our attention on the future role of renewable energy technology. Consequently, R&D activities in the renewable energy sector have rapidly increased in recent decades. Many researchers have investigated these technological changes and new trends in the energy sector. However, most studies analyze quantitative information such as the amount of R&D expenditures and number of patents. The present study analyzes the technological evolution trends and its influence using a qualitative patent citation analysis and applies a network analysis to the R&D activities of renewable energy-related technologies in Japan, Korea, and China.

The study yields two main empirical findings. First, the results show the trend of research activities among the three countries and indicate the technology catch-up and leapfrogging patterns between them. Korea used a catch-up R&D strategy of imitating Japan. On the other hand, China initially adopted a catch-up strategy, but eventually attempted to overcome the limitations of this strategy by creating its own path. China thus adopted a leapfrogging strategy by focusing on wind and solar energy instead of concentrating on biomass and waste energy. Second, we analyzed the consistency of each country's R&D portfolio. Japan established a technology portfolio mainly concentrated in biomass and waste energy technology, whereas China created a wind-energy-oriented technology portfolio. Unlike the technology portfolios in Japan and China, which show relatively consistent patterns, Korea's technology development portfolio shows unpredictable annual changes, showing its lack of consistent renewable energy technology development activity. Thus we argue that, due to this inconsistency, it will be difficult for Korea to leapfrog and become a leading nation in renewable energy technology.

This study makes the following contributions. First, from a methodological perspective, this research suggests a qualitative assessment framework to evaluate R&D activities using patent citation analysis. Unlike previous studies that use quantitative data such as the number of patents, weighted out-degree centrality was used to measure innovation activity performance. Second, we examined the trend of R&D activities related to renewable energy in East Asia. The results show differences in the renewable energy research strategies and portfolios of technology development activities among the countries, especially in terms of the technological catch-up and leapfrogging patterns in Korea and China. We expect that a multi-national analysis based on qualitative information about technology will help researchers provide meaningful policy implications.

Despite these contributions, this study has some limitations. First, the main focus is on East Asian countries, so the patterns observed here may not apply globally. Second, although we adopted patent citations to provide a qualitative evaluation of R&D activities, the impact of policy factors in R&D activities in each country were not considered. Hence, future studies are required to reflect the political elements to shape more suitable policies and strategies for developing countries to choose between catching-up and leapfrogging. Despite these problems, this study could help policymakers understand the evolutionary patterns of the technological network and trends in East Asian countries from a technological quality perspective.

Author Contributions: All three authors contributed to the completion of the research. Yoonhwan Oh contributed to the concept and design of the paper, and data analysis. Jungsub Yoon contributed to result analysis and modified the draft. Jeong-Dong Lee provided comments and review suggestions. All authors read and approved the final manuscript.

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

Appendix A. IPC Codes for Generation Technologies

Table A1. IPC codes for traditional fossil fuels (TFF).

Description	IPC Code
Fossil fuel technologies in general	
Production of fuel gases by carburetting air or other gases without pyrolysis	C10J
Steam engine plants; steam accumulators; engine plants not otherwise provided for; engines using special working fluids or cycles	F01K
Gas-turbine plants; air intakes for jet-propulsion plants; controlling fuel supply in air-breathing jet-propulsion plants	F02C
Hot-gas or combustion-product positive-displacement engine; use of waste heat of combustion engines, not otherwise provided for	F02G
Steam generation	F22
Combustion apparatus; combustion processes	F23
Furnaces; kilns; ovens; retorts	F27

Note: We follow the IPC codes for traditional fossil fuels from Lanzi et al. [60].

Table A2. IPC codes for efficiency-improving fossil fuels (EFF).

Description	IPC Code
Coal gasification	
Production of combustible gases containing carbon monoxide from solid carbonaceous fuels	C10J3
Improved burners	
Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent	F23C1
Combustion apparatus characterized by the arrangement or mounting of burners; disposition of burners to obtain a loop flame	F23C5/24
Combustion apparatus characterized by the combination of two or more combustion chambers	F23C6
Combustion apparatus characterized by the combination of two or more combustion chambers	F23B10
Combustion apparatus with driven means for agitating the burning fuel; combustion apparatus with driven means for advancing the burning fuel through the combustion chamber	F23B30
Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber	F23B70
Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel	F23B80
Burners for combustion of pulverulent fuel	F23D1
Burners in which drops of liquid fuel impinge on a surface	F23D7
Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel	F23D17
Fluidized bed combustion	
Chemical or physical processes in general, conducted in the presence of fluids and solid particles; apparatus for such processes; with liquid as a fluidizing medium	B01J8/20-22
Chemical or physical processes in general, conducted in the presence of fluids and solid particles; apparatus for such processes; according to "fluidized-bed" technique	B01J8/24-30
Fluidized bed furnaces; Other furnaces using or treating finely divided materials in dispersion	F27B15
Apparatus in which combustion takes place in a fluidized bed of fuel or other particles	F23C10
Improved boilers for steam generation	
Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; Arrangements or dispositions of combustion apparatus	F22B31
Steam generation plants, e.g., comprising steam boilers of different types in mutual association; combinations of low- and high-pressure boilers	F22B33/14-16
Improved steam engines	
Plants characterized by the use of steam or heat accumulators, or intermediate steam heaters, therein	F01K3
Plants characterized by use of means for storing steam in an alkali to increase steam pressure, e.g., of Honigmann or Koenemann type	F01K5
Plants characterized by more than one engine delivering power external to the plant, the engines being driven by different fluids	F01K23
Super-heaters	
Steam superheating characterized by heating method	F22G
Improved gas turbines	
Features, component parts, details or accessories; heating air supply before combustion, e.g., by exhaust gases	F02C7/08-105
Features, component parts, details or accessories; cooling of plants	F02C7/12-143
Features, component parts, details or accessories; preventing corrosion in gas-swept spaces	F02C7/30

Table A2. *Cont.*

Description	IPC Code
Combined cycles	
Plants characterized by more than one engine delivering power external to the plant, the engines being driven by different fluids; the engine cycles being thermally coupled	F01K23/02-10
Gas turbine plants characterized by the use of combustion products as the working fluid; using special fuel, oxidant or dilution fluid to generate the combustion products	F02C3/20-36
Plural gas-turbine plants; combinations of gas-turbine plants with other apparatus; supplying working fluid to a user, e.g., a chemical process, which returns working fluid to a turbine of the plant	F02C6/10-12
Improved compressed-ignition engines	
Engines characterized by fuel-air mixture compression; with compression ignition	F02B1/12-14
Engines characterized by air compression and subsequent fuel addition; with compression ignition	F02B3/06-10
Engines characterized by the fuel-air charge being ignited by compression ignition of an additional fuel	F02B7
Engines characterized by both fuel-air mixture compression and air compression, or characterized by both positive ignition and compression ignition, e.g., in different cylinders	F02B11
Engines characterized by the introduction of liquid fuel into cylinders by use of auxiliary fluid; compression ignition engines using air or gas for blowing fuel into compressed air in cylinder	F02B13/02-04
Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the engine's intake	F02B49
Co-generation	
Use of steam or condensate extracted or exhausted from steam engine plant; returning energy of steam, in exchanged form, to process, e.g., use of exhaust steam for drying solid fuel of plant	F01K17/06
Plants for converting heat or fluid energy into mechanical energy	F01K27
Plural gas-turbine plants; combinations of gas-turbine plants with other apparatus; using the waste heat of gas-turbine plants outside the plants themselves, e.g., gas-turbine power heat plants	F02C6/18
Profiting from waste heat of combustion engines	F02G5
Machines, plant, or systems, using particular sources of energy; using waste heat, e.g., from internal-combustion engines	F25B27/02

Note: We follow the IPC codes for traditional fossil fuels from Lanzi et al. [60].

Table A3. IPC codes for renewable energy technologies (REN).

Description	IPC Code
Wind	
Wind motors with rotation axis substantially in wind direction	F03D1
Wind motors with rotation axis substantially at right angle to wind direction	F03D3
Wind motors with rotation axis substantially at right angle to wind direction	F03D5
Controlling wind motors	F03D7
Adaptations of wind motors for special use	F03D9
Details, component parts, or accessories not provided for in, or of interest apart from, the other groups of this subclass	F03D11
Solar	
Devices for producing mechanical power from solar energy	F03G6
Use of solar heat, e.g., solar heat collectors	F24J2
Devices consisting of a plurality of semiconductor components sensitive to infra-red radiation, light-specially adapted for the conversion of the energy of such radiation into electrical energy	H01L27/142
Semiconductor devices sensitive to infra-red radiation, light-adapted as conversion devices	H01L31/04-78
Generators in which light radiation is directly converted into electrical energy	H02N6
Aspects of roofing for energy collecting devices—e.g., incl. solar panels	E04D13/18
Geothermal	
Production or use of heat, not derived from combustion-using natural or geothermal heat	F24J3
Devices for producing mechanical power from geothermal energy	F03G4
Mechanical-power-producing mechanisms-using pressure differences or thermal differences occurring in nature	F03G7/04
Ocean	
Tide or wave power plants	E02B9/08
Submerged units incorporating electric generators or motors characterized by using wave or tide energy	F03B13/10-26
Mechanical-power producing mechanisms-ocean thermal energy conversion	F03G7/05

Table A3. *Cont.*

Description	IPC Code
Biomass and waste	
Solid fuels essentially based on materials of non-mineral origin-animal or vegetable substances; sewage, town, or house refuse; industrial residues or waste materials	C10L5/40-48
Engines or plants operating on gaseous fuel generated from solid fuel, e.g., wood	F02B43/08
Liquid carbonaceous fuels	C10L1
Gaseous fuels	C10L3
Solid fuels	C10L5
Dumping solid waste	B09B1
Destroying solid waste or transforming solid waste into something useful or harmless	B09B3
Incineration of waste; Incinerator constructions	F23G5
Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels, e.g., chemicals	F23G7
Plants for converting heat or fluid energy into mechanical energy; use of waste heat;	F01K27
Profiting from waste heat of combustion engines	F02G5
Machines, plant, or systems, using particular sources of energy-using waste heat, e.g., from internal-combustion engines	F25B27/02
Plants or engines characterized by use of industrial or other waste gases	F01K25/14
Incineration of waste-recuperation of heat	F23G5/46

Note: We follow the IPC codes for traditional fossil fuels from Johnstone et al. [61].

Appendix B. Evolution of Technology Network in Renewable Energy

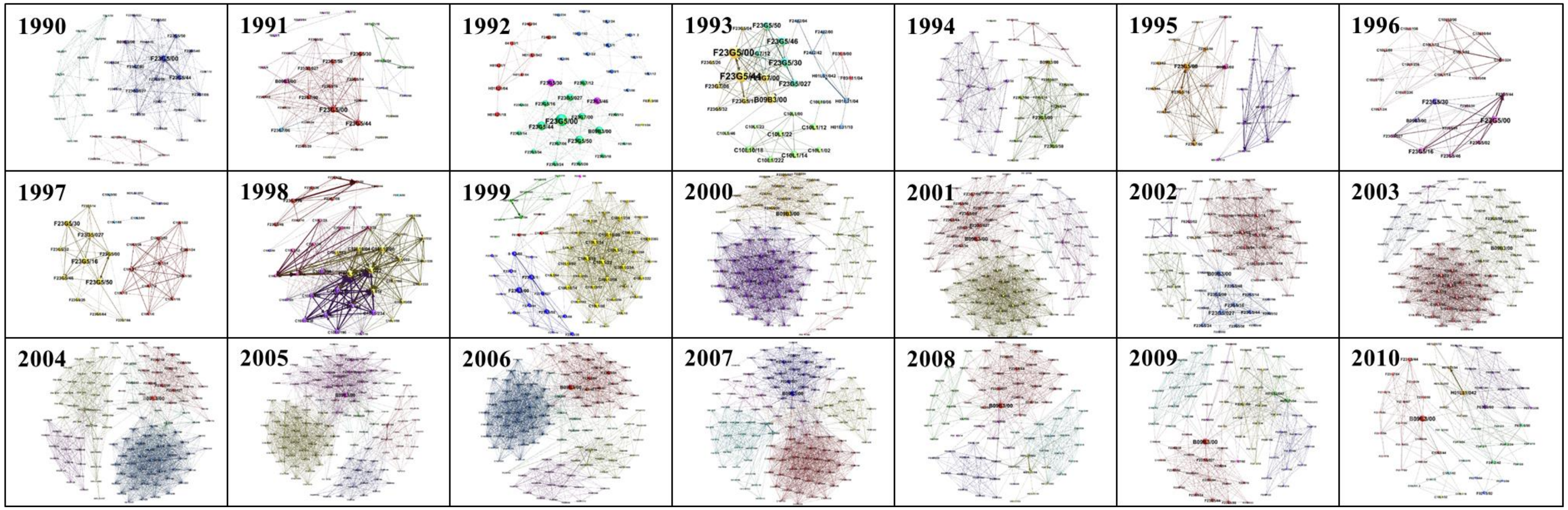


Figure B1. Technology network of Japan (1990–2010).

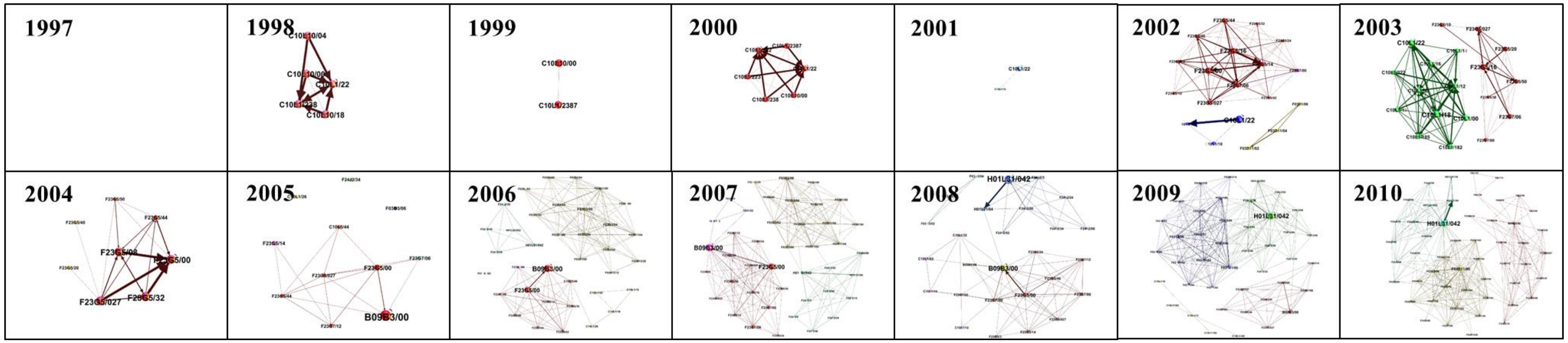


Figure B2. Technology network of Korea (1990–2010).

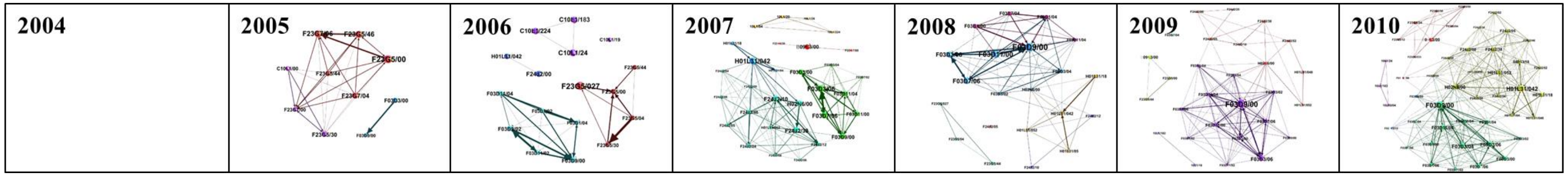


Figure B3. Technology network of China (1990–2010).

Appendix C. Top 10 Ranked Technologies (1990–2010)

	Rank	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Japan	1	F23G5/00	F23G5/00	F23G5/00	B09B3/00	B09B3/00	F23G5/00	F23G5/00	F23G5/30	C10L10/00	C10L10/00	B09B3/00	B09B3/00	F23G5/027	C10L1/18	B09B3/00	B09B3/00	B09B3/00	B09B3/00	H01L31/04	H01L31/04	H01L31/04
	2	H01L31/04	H01L31/04	B09B3/00	F23G5/00	F23G5/00	F23G5/16	F23G5/30	F23G5/16	C10L1/192	C10L1/22	H01L31/04	C10L1/18	B09B3/00	H01L31/04	H01L31/04	H01L31/04	H01L31/04	H01L31/04	B09B3/00	H01L31/042	H01L31/042
	3	F23G5/44	B09B3/00	H01L31/04	F23G5/44	F23G5/50	B09B3/00	F23G5/16	F23G5/50	C10L10/04	H01L31/04	C10L1/22	H01L31/04	C10L1/18	C10L1/19	H01L31/042	H01L31/042	H01L31/042	H01L31/042	H01L31/042	B09B3/00	B09B3/00
	4	B09B3/00	F23G5/44	F23G5/50	H01L31/04	F23G5/44	F23G5/50	B09B3/00	F23G5/027	C10L1/18	C10L1/14	C10L1/18	C10L1/22	H01L31/04	C10L1/22	C10L1/18	F23G5/027	C10L1/06	F23G5/027	H01L31/10	H01L31/10	H01L31/10
	5	F23G5/50	F23G5/50	F23G5/44	F23G5/30	H01L31/04	H01L31/10	F23G5/02	F23G5/00	C10L1/16	C10L1/238	C10L10/00	C10L1/14	C10L1/22	C10L1/08	C10L3/06	F23G5/00	C10L1/182	H01L31/10	F03D11/00	E04D13/18	F03D9/00
	6	H01L31/10	H01L31/10	F23G5/30	F23G5/50	F23G5/16	F23G7/00	F23G5/46	H01L31/042	C10L1/234	H01L31/042	C10L1/182	C10L10/04	F23G5/16	C10L1/14	C10L1/22	F23G5/44	C10L1/185	F23G5/44	F23G5/027	F03D11/00	F03D7/04
	7	F23G5/027	F23G5/30	F23G5/027	F23G7/00	F23G7/00	H01L31/052	F23G5/44	C10L1/08	C10L1/22	C10L1/18	C10L10/04	H01L31/042	C10L1/16	B09B3/00	F03D9/00	H01L31/10	F23G5/44	C10L1/08	F23G5/44	F03D7/04	F03D11/00
	8	F23G7/00	F23G5/027	H01L31/042	F23G5/027	F23G5/30	F23G5/02	H01L31/10	C10L1/14	C10L1/195	C10L1/08	H01L31/042	C10L10/00	C10L10/04	C10L1/182	F23G5/00	C10L3/06	H01L31/10	F23G5/00	E04D13/18	F23G5/44	F03D1/06
	9	F23G5/30	F23G5/14	F23G7/00	F23G5/46	C10L1/32	H01L31/042	C10L1/14	C10L1/16	C10L1/197	C10L10/08	C10L1/19	F23G5/027	C10L1/14	C10L10/14	H01L31/10	F23G5/16	C10L1/08	F23G5/50	C10L3/06	F23G5/027	F02G5/02
	10	F23G7/06	F23G7/00	E04D13/18	C10L10/18	C10L1/14	F23G5/027	C10L1/18	C10L1/18	C10L1/222	C10L1/2383	C10L1/198	C10L1/222	F03D9/00	C10L10/04	F23G5/027	F23G5/50	C10L1/196	C10L1/06	F03D1/06	H01L31/052	F03D3/06

Figure C1. Top 10 ranked technologies (1990–2010) in Japan. Note: We only consider technologies that have weighted out-degree of 10 or above. Gray, red, blue, and green blocks indicate biomass & waste, solar, wind, and ocean energy, respectively.

	Rank	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Korea	1								C10L1/22	C10L1/2387		C10L1/22	C10L1/22	C10L1/22	C10L1/18	F23G5/027	B09B3/00	B09B3/00	B09B3/00	H01L31/042	H01L31/042	H01L31/042
	2								C10L1/238	C10L10/00		C10L1/222	C10L1/19	F23G5/00	C10L1/22	F23G5/00	F23G5/00	F23G5/00	F23G5/00	B09B3/00	B09B3/00	F03D11/00
	3								C10L10/00	F24J2/05		C10L1/238	C10L1/20	F23G5/16	B09B3/00	F23G5/32	F23G5/14	F03D3/00	F23G7/06	F23G5/00	F03D11/00	F03D3/06
	4								C10L10/04	F24J2/10		C10L10/00	C10L1/233	F23G5/027	F23G5/16	F23G5/08	F23G7/06	F03D3/04	F03D3/06	F23G7/00	F03D3/06	B09B3/00
	5								C10L10/18	F24J2/46		C10L1/2387	C10L3/00	F23G5/44	C10L1/00	B09B3/00	F03D3/06	H01L31/042	H01L31/042	H01L31/04	F24J2/38	F03D11/02
	6								F23G7/00	C10L1/32		C10L1/223	B09B3/00	F23G7/06	F23G7/06	F23G5/44	F23G5/027	C10L5/46	F23G7/00	F23G7/06	F03D11/04	F24J2/38
	7								F03B13/10	C10L10/18		F23G5/46	F23G5/00	F23G5/14	F23G5/027	F24J2/05	E04D13/18	F03D7/06	F23G5/46	F03D3/06	F03D9/00	F23G5/46
	8								F03D7/02	F03D3/06		F23G5/16	F23G5/32	C10L1/10	F23G5/20	F24J2/14	F23G7/12	F03D1/06	F03D3/04	F23G5/46	F23G7/12	H01L31/18
	9								F03D11/04	F03D9/00		F23G5/00	C10L1/10	F23G5/46	C10L1/12	F23G5/20	H01L31/042	F23G7/00	F03D3/02	F24J2/38	F03D3/02	F03D3/04
	10								F03D1/00	F03D9/02		F23G5/04	F23G5/44	F03D11/04	C10L1/30	F23G5/40	C10L5/44	F03D3/06	F23G5/04	C10L1/02	F03D3/04	H01L31/052

Figure C2. Top 10 ranked technologies (1990–2010) in Korea. Note: We only consider technologies that have weighted out-degree of 10 or above. In Korea, none of technologies developed in 1999 has weighted out-degree more than 10. Gray, red, blue, and green blocks indicate biomass & waste, solar, wind, and ocean energy, respectively.

	Rank	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
China	1														F23G5/027	F23G5/00	F23G5/00	F03D9/02	H01L31/042	F03D9/00	F03D9/00	F03D9/00
	2														F24J2/26	F23G5/02	F23G5/46	F24J2/00	F03D3/06	F03D11/00	F03D3/06	H01L31/042
	3														F24J2/04	F23G5/26	F23G7/06	H01L31/042	F03D7/06	F03D7/06	F03D7/06	F03D3/04
	4														F23G7/06	C10L1/10	F03D3/00	F03D11/04	F24J2/10	F03D3/06	F03D11/00	F03D3/06
	5														F24J2/32	C10L3/12	F23G7/04	F23G5/04	H02N6/00	F03D1/00	F03D11/04	H02N6/00
	6														F24J2/24	C10L1/18	F23G5/44	F23G5/30	F24J2/38	F03D7/04	B09B3/00	F03D11/00
	7														H01L31/068	C10L1/12	F23G5/30	F23G5/027	F03D9/00	F03D1/04	F03D3/02	H01L31/052
	8														F24J2/05	C10L3/00	F03D9/00	F03D11/02	F03D3/00	F03D3/04	F03D3/00	F03D3/00
	9														B09B3/00	F23G7/00	C10L1/00	C10L1/24	B09B3/00	H01L31/18	H02N6/00	F03D7/06
	10														F24J2/46	F23G5/40	F23G7/00	F03D9/00	F03D11/04	H01L31/042	F03D1/06	H01L31/18

Figure C3. Top 10 ranked technologies (1990–2010) in China. Note: We only consider technologies that have weighted out-degree of 10 or above. Gray, red, blue, and green blocks indicate biomass & waste, solar, wind, and ocean energy, respectively.

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