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Analysis of Russia's biofuel knowledge base: A comparison with Germany and China

Jin-Su Kang*, Tetyana Kholod, Stephen Downing

Institute of Business and Management, National Chiao Tung University, 4F, 114, Section 1, Chung-Hsiao W. Rd., Taipei City 100, Taiwan

HIGHLIGHTS

- Biofuel knowledge base (KB) of Russia is compared to those of Germany and China.
- Citations network analysis measures KB size, growth, cumulativeness, and interdependence.
- Russian KB lacks the increasing technological specialization of German KB.
- Russia KB lacks the accelerated growth rate of Chinese KB.
- Russia KB evolution reflects the poor institutional framework.

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ABSTRACT

This study assesses the evolutionary trajectory of the knowledge base of Russian biofuel technology compared to that of Germany, one of the successful leaders in adopting renewable energy, and China, an aggressive latecomer at promoting renewable energy. A total of 1797 patents filed in Russia, 8282 in Germany and 20,549 in China were retrieved from the European Patent Office database through 2012. We identify four collectively representative measures of a knowledge base (size, growth, cumulativeness, and interdependence), which are observable from biofuel patent citations. Furthermore, we define the exploratory–exploitative index, which enables us to identify the nature of learning embedded in the knowledge base structure. Our citation network analysis of the biofuel knowledge base trajectory by country, in conjunction with policy milestones, shows that Russia's biofuel knowledge base lacks both the increasing technological specialization of that in Germany and the accelerated growth rate of that in China. The German biofuel citation network shows a well-established knowledge base with increasing connectivity, while China's has grown exceptionally fast but with a sparseness of citations reflecting limited connections to preceding, foundational technologies. We conclude by addressing policy implications as well as limitations of the study and potential topics to explore in future research.

1. Introduction

The trade-off between exploratory and exploitative learning (March, 1991) creates tension from the differential outcomes of the radical versus incremental innovation processes (Freeman and Perez, 1988; Sorensen and Stuart, 2000). Both are essential, since exploration leads to vastly new discoveries while exploitation allows for efficiency improvements (Henderson, 1993). However, both learning types are not essential at the same time, which presents a window for long-run policy to affect innovation outcomes. In the case of environmental innovations, the effect of externalities accumulate over time, potentially locking in unsustainable technologies (Ayres, 1991; Kemp and Soete, 1992). This is the situation facing global learning and innovation processes for renewable energy technologies in response to carbon lock-in (Unruh, 2000), and this has hindered the exploration and development of niche technologies in the formative stage of biofuel development in many countries, namely Russia in this study, delaying the transition to the market expansion stage (Jacobsson and Bergek, 2004).

As environmental innovation has become a must, not an option, Russia, one of the main fossil fuel exporters, also recognized the needs to develop renewable energy, particularly biofuels, which were assessed as having a huge commercial potential with devoted agriculture production, abundant timber resources, and considerable knowledge competencies (Martinot, 1998, 1999; REA,

* Corresponding author.
E-mail addresses: jinsu.kang@g2.nctu.edu.tw (J.-S. Kang), kholod.tetyana@gmail.com (T. Kholod), sdowning.bm02g@nctu.edu.tw (S. Downing).

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2012). However, due to abundant fossil fuel resources[1], developing renewable technologies such as biofuels had not been a part of the economic and political priorities in Russia during the 1990s. While the recent initiatives (e.g. Energy Strategy for 2030 (MERF, 2009)) point to a need for investment in renewable energy as a mechanism for achieving the priority of increasing energy efficiency and diversifying energy sources, a formidable gap still exists between actual progress and proposed development (Kolchinskij, 2008; Martinot, 1998; Pristupa et al., 2010; REA, 2012). During 2006–2007, there were about twenty large biofuel production facilities planned in Russia, including bioethanol, biodiesel, and pellets production (Lykova, 2010). However, only pellets plants were built and operated successfully, leaving other forms of production frozen or uninitiated due to various reasons, among which were the lack of financial investments, institutional support and uncertain demand for biofuels (Lykova, 2010). Even the existing pellet plants are mainly for exports, concentrated in the Northwestern Federal District near the border, where the main customers include Belgium, Denmark, the Netherlands, Germany and Sweden (Lykova, 2010), and the Khabarovsk region, which serves South Korea as its largest customer (INFOBIO, 2013).

While existing studies address the inefficiencies of the Russian government's policies and poor implementation in detail (Martinot, 1998, 1999; Pristupa et al., 2010; Zhang et al., 2011), there has been little quantitative analysis of the influence that policy has on the evolutionary path of Russia's knowledge base and collective abilities to utilize the available resources for commercialization. Without understanding the status quo of its development, policy conclusions or further implications may be misinformed by inadequate misunderstanding of the status quo (Lall, 1992, 2010). Thus, this paper aims to diagnose Russia's biofuel knowledge base, one of the outcomes in the formative stage of renewable energy system which is predominantly influenced by government policies. We particularly analyze the position of Russia's biofuel knowledge relative to Germany, one of successful leaders in adopting renewable energy, and China, an aggressive latecomer at promoting renewable energy. For this purpose, the present study explores relationships between said policies and their consequences upon the evolution of biofuel knowledge base network. The aim is to provide a diagnostic tool for policy makers to direct policy that helps to transition a country from the formative stage of technological system evolution to the market expansion stage for the new technology. Such policy requires accurate assessment of not only the objective but also the current state of affairs informed by quantitative analyses.

This study aligns with the call for literature related to quantitative empirical support of knowledge and social networks research (Breschi and Lissoni, 2005), which, despite the importance of collaborative and knowledge networks for technological innovation, is only sparsely addressed in the literature. In particular, patent citations have been employed as knowledge "flow" indicators (Hu and Jaffe, 2003; Jaffe and Trajtenberg, 1999). A network perspective is important in analyzing this patent citation data because invention is a cumulative and social process, and closer social proximity between inventors has been found to correlate positively with citations between them (Balconi et al., 2004). While both the networks of inventors and patent citations play important roles for technological innovation, quantitative research into the application of network analyses on these relational datasets is still in its infancy (Breschi and Lissoni, 2005). Besides the commonly used network properties of size and growth, we incorporate cumulativeness and interdependence, and we propose the "exploratory–exploitative index," (called EE index herein) which can enable us to understand the type of learning (on a spectrum between wholly exploratory and completely exploitative) observed from the structure of the patent citations network.

This paper proceeds as follows: Section 2 describes the sources of our data as well as methods adopted to achieve the goals of the study. Section 3 shows where Russia stands compared with a potential benchmark, Germany, and a competitive peer, China, based on the results from various analyses. Section 4 discusses the results in more detail which reveal possible challenges that Russia may confront in the future as well as limitations of the current research connected to suggestions for future work. Finally, we conclude the paper with implications for legislators and practitioners.

2. Methods

2.1. Data

We use biofuel related patents filed within Russia, Germany, and China. We applied a two-stage interactive approach to retrieve patents from the most recent available version of the European Patent Office database with worldwide coverage (EPO, 2013). We retrieved the patents that applied for protection of intellectual property in each of the three countries. We used a Porter stemmer in the SQL query for 90 keywords and 95 International Patent Classification (IPC) groups developed by Hu and Phillips[2] (Hu and Phillips, 2011) for identifying biofuel related patents. To trace the timing of knowledge creation closer to the actual time of invention (Hall et al., 2001), we used patent applications rather than granted patents. As a result, the number of patent applications (called "patents" hereafter) retrieved was 1797 for Russia, 8282 for Germany and 20,549 for China covering the published patent applications until the end of 2012. In this dataset, the earliest patent application happened in 1936 for Russia, 1911 for Germany, and 1953 in China. For citations network analysis we retrieved the information about patents that were cited by biofuel patent applications (outward citations) and information about patents that cited the biofuel patent applications (incoming citations). Not all patents had citations (either outward or incoming), especially in China or Russia, which might be due to the specific patenting procedures in these countries. In total, the citation network analysis included 460 patent citations for Russia, 5017 for Germany and 1831 for China.

As different generations of biofuels convey different meaning about the evolution of the knowledge base, this study further classified patents by generation.[3] We applied a text-mining procedure[4] to a sample[5] of the abstracts of the patents retrieved from the EPO

[1] Russia is the world's second largest oil exporter and the top exporter of natural gas (IEA, 2011).

[2] The full list of keywords and IPC codes can be find in Appendix B-1 and B-2 of Hu and Phillips (2011).

[3] While there can be 3rd and 4th generation, its classification has not reached consensus yet (OECD/IEA, 2011). So far, only 1st generation technologies have achieved commercial scale, thus this study considered up to 2nd generation for which the criterion is based on the type of feedstock.

[4] We developed the training sample for each country separately based on its own patents to control for regional differences, and this training set was manually classified by subject experts. We used a Support Vector Machine (SVM), which is one of the highest accuracy algorithms for automated text categorization (Sebastiani, 2002), implemented in RapidMiner 5.0 (Rapid-I GmbH, 2014) to classify the remaining patents as 1st or 2nd generation biofuels according to the title and abstract texts. Model training set accuracy was 82.11%, which was deemed satisfactory.

[5] The sample for developing of classification was: 220 patents for Russia, 290 patents for Germany, and 300 patents for China. We used 80% as training sample and 20% as validating sample for each dataset and tested it on 8 algorithms showing the range of accuracy from 79.10% to 82.11%, of which SVM was highest.

database. While the relative simplicity of 1st generation technology, together with the active promotion of renewable energy sources, has brought successful commercialization of this technology subset worldwide, both academia and practitioners have become skeptical about its benefit due to the direct conflict with food supply (Naik et al., 2010) as well as disputable benefit of greenhouse gas reduction (Sims et al., 2008). This motivated the continued search for alternative ways to produce biofuels, so-called 2nd generation biofuel technologies, which are produced from non-food biomass including byproducts, wastes, and dedicated feedstock. While 2nd generation methods are gaining popularity, their growth is hampered by the complicated and costly technological procedure involved in processing the feedstock (Naik et al., 2010) currently without dominant technology.

2.2. Methodology

We identify four attributes that capture the knowledge base construct as a network measurable through patent citation data to offer a comparative assessment framework for the evolution of a technological knowledge base. First, the most basic measure addresses the property of network *size*, as measured by the number of patents, n, and citations, m. Second, the related property of network *growth* is observed through the rate of change in network size. The knowledge base can then be subdivided by the affiliation of the applicant groups and latent variables such as the concept of a "generation" of the emerging technology to which the patent belongs. These measures are used in the descriptive statistics of the knowledge base in Section 3.2 for each country as several scholars (Dosi, 1988; Pavitt, 2000) argue that institutions play an important role in building the knowledge base for science-based innovations (e.g. biotechnology and chemical engineering).

The third network attribute represents the extent of technological knowledge accumulation in the innovation process, termed *cumulativeness* herein, and reflects the extent of exploratory versus exploitative learning in the knowledge base. This incorporates condensation of the network's largest connected component, "reach" of knowledge through the network, and the ratio of reach to average citation degree. Drawing from percolation theory (Broadbent and Hammersley, 1957), the condensation of network components may be expected when a network develops at least one connection per member (average degree $k = 1$)[6] (Erdős and Rényi, 1959; Solomonoff and Rapoport, 1951). Although patent citation networks do not develop randomly, such a model of network phase transition offers a baseline expectation from which we may identify noteworthy deviations meriting further consideration. Additionally, the reach of knowledge disseminated by an average network member is indicative of the potential for knowledge flow throughout the knowledge base. Since we are not limiting the biofuel knowledge network to the largest connected component[7], we consider the sum of inverse distances, of the knowledge from a patent to all the patents that cite it, and all future patents that cite them, etc. Schilling and Phelps (2007) apply a measure of distance-weighted reach (R)[8] to capture the extent of the expected diffusion of knowledge throughout the network. When comparison between networks is the objective, as in this study, normalizing by the average citation degree offers a single measure of the ratio of exploitative learning (reach) to rate of overall knowledge flow (average citation degree), which is then comparable between networks of different size. We introduce this ratio (R/k) herein as the exploratory–exploitative index (EE index), whose values vary between 1.0 and an upper bound, which is a function of only the number of patents. The EE index serves as a summary statistic of the type of innovation in the knowledge base, capturing the information encoded in the structure of the citation network that is not readily apparent through non-network measures of size alone. It represents the amount of exploitative learning that would occur if each patent cited only one other patent. Values of the EE index approaching the minimum (1.0 in a non-contracted network) indicate more exploratory research or radical innovation (with shorter citation chains), and higher index values indicate more exploitative research supporting incremental innovation (with longer citation chains).

The fourth attribute of the knowledge base modeled as a network in this study is the *interdependence* of network members (patents) since the connections between subgroups within the network may have important implications for externalities of the network growth process. Since the magnitude of spillover is greater for firms conducting research in the same technological areas (Jaffe, 1986), this study investigates citation interrelatedness between applicants, over time in order to uncover the potential for spillovers between highly connected applicants that might affect the rate of the formation of market for new technology that could be expected from Russia in comparison with a technological leader (Germany) and a latecomer (China). We denote k_{Aff} to be the average citation degree of the graph contracted by affiliations, meaning each patent with the same affiliation category combined to form a shrunken network with edges weighted by the number of citations between patents within the aggregated category vertex. Similarly, R_{Aff} represents the reach of the contracted network with affiliations as vertices. Thus these contracted graph measures actually show the average citations and average reach between inventions of different affiliation groups.

In summary, this study employs the following framework for assessing the structure and evolution of the knowledge base of biofuel technology:

1. *Size*: number of patents, n, and citations, m.
2. *Growth*: new patents and citations per period, as well as the change in the rate of new patenting activity (i.e., the speeding up or slowing down of the knowledge base growth).
3. *Cumulativeness*: proportion of patents in the largest connected component, average distance-weighted reach of the citation network (R), and the exploratory–exploitative index (EE index) magnitude.
4. *Interdependence*: average degree and reach within a contracted network of patents between affiliations of the patent applicants (k_{Aff}, R_{Aff}).

Through this framework we examine the comparative capabilities of biofuel technologies implied by patent citations of Russia relative to those in Germany and China. This study's network analysis and network plotting were conducted using the igraph package version 0.7.1 (Csardi and Nepusz, 2006) for the R statistical computing language (Core Team, 2014).

3. Results

3.1. Biofuel policy milestones of Russia, Germany and China

Successful introduction of renewable energy implies the transformation of the established energy system, a transformation

[6] $k = \frac{1}{n}\sum_{i=1}^{n} d(v_i)$, where $d(v_i)$ is a function that returns the degree, or incident edges, to the vertex v_i, and this is averaged over all n vertices.

[7] The common measure of average shortest path length would encounter the infinite path length problem of unconnected networks (Watts, 1999) and is thus unsuitable for this study's focus on the whole citation network, not just the largest connected component.

[8] $R = \frac{1}{n}\sum_{i=1}^{n} \sum_{j \in V_i; j \neq i} \frac{1}{\sigma(g_{ij})}$ where σ is a function that returns the number of "hops" (citations) from origin patent i to destination patent j along the geodesic (shortest path) g, and V_i is the subset of vertices that are connected by any direct or indirect path to i.

which significantly depends on a range of policies taken at the present day and during the course of the preceding decades (Cimoli and Dosi, 1995). In the formative stage of a new technology system, government policy acts as a major inducement mechanism to generate a market for new technology by supporting the creation of new knowledge, supplying resources, and guiding the search of various actors of the new technology (Jacobsson and Bergek, 2004). Importantly, government instruments stimulate the formation of the market and the creation of knowledge application, including investment subsidies, pilot programs, and legislative changes.

Compared to Germany and China, the institutional framework in Russia has been ineffective at creating a sustainable biofuel market. The policy deficiency in Russia was due to (i) slow formalization of standards, (ii) weak incentives, (iii) poor policy coordination, and (iv) failure to attract various interest organizations. These institutional shortcomings are reflected in the summary of biofuel policy milestones presented in Fig. 1. Firstly, during the formative stage, the creation of standards influences the formation of a market by creating a legal base to allow the use of particular technologies. The pace for standardization in Russia was slower than that of Germany, which had established standards for biodiesel in 1994 (Prankl et al., 2004) and China for bioethanol in 2001 (Sorda et al., 2010). Standardization in Russia first appeared in 2002 for 5% blends of bioethanol (National Standard GOST R 51866-52002, 2002) and later extended to 5–10% blends (National Standard GOST R 52201-2004, 2004). In 2007, a standard was developed for energetics from bio waste, which gave definitions for such energy (National Standard GOST R 52808-2007, 2007). However, until now, pellets producers, the most active biofuel industry in Russia, use European standards (e.g. German DIN & DIN Plus, Swedish SS 18 71 21 and Swiss SN 166000) not only for final products but also for production processes (Boyaryntseva and Popov, 2014).

Secondly, providing appropriate financial incentives to investors stimulates the formation of early markets for new technology, aiming to guide the direction of search for firms towards the new field (Martinot et al., 2002). While Russia has had several investment initiatives regarding biofuels, these have been scattered, undertaken by different government organizations and failing to guide the direction of search for firms towards new technology. Those incentives include biogas station investment for local use under the federal program for energy-efficient economy (Russian Government, 2001), pellets investment as a part of wood processing projects under the forest development program (Russian Government, 2007), biodiesel production through rapeseed cultivation projects in 2008 (Ministry of Agriculture in Russia, 2008), etc. In comparison, China has intensively promoted biofuels through investments in pilot projects since 2002. The straightforward, direct investments in these pilot projects have succeeded to attract firms, which facilitated improving the overall price-performance ratio and achieving social agreements while progressing from 1st to 2nd generation (Sorda et al., 2010).

Thirdly, during the formative stage, policy coordination under a 'roof program' is important between ministries and agencies responsible for different parts of the incumbent and emerging systems (Jacobsson and Bergek, 2004). In this perspective, Russia's biofuel policy has been developed without its comprehensive, dedicated policy. Before BIO 2020 (2012), the development plan of Russian biotechnology, Russia had not had specific targets for biofuels, although it had tried to pass biofuel-related law since 2007 (Pristupa et al., 2010). According BIO 2020 (2012), Russia aims to reach 10% of bioenergy in thermal power, 10% of biofuels in motor fuels, and utilize 30% of solid household wastes and 90% of

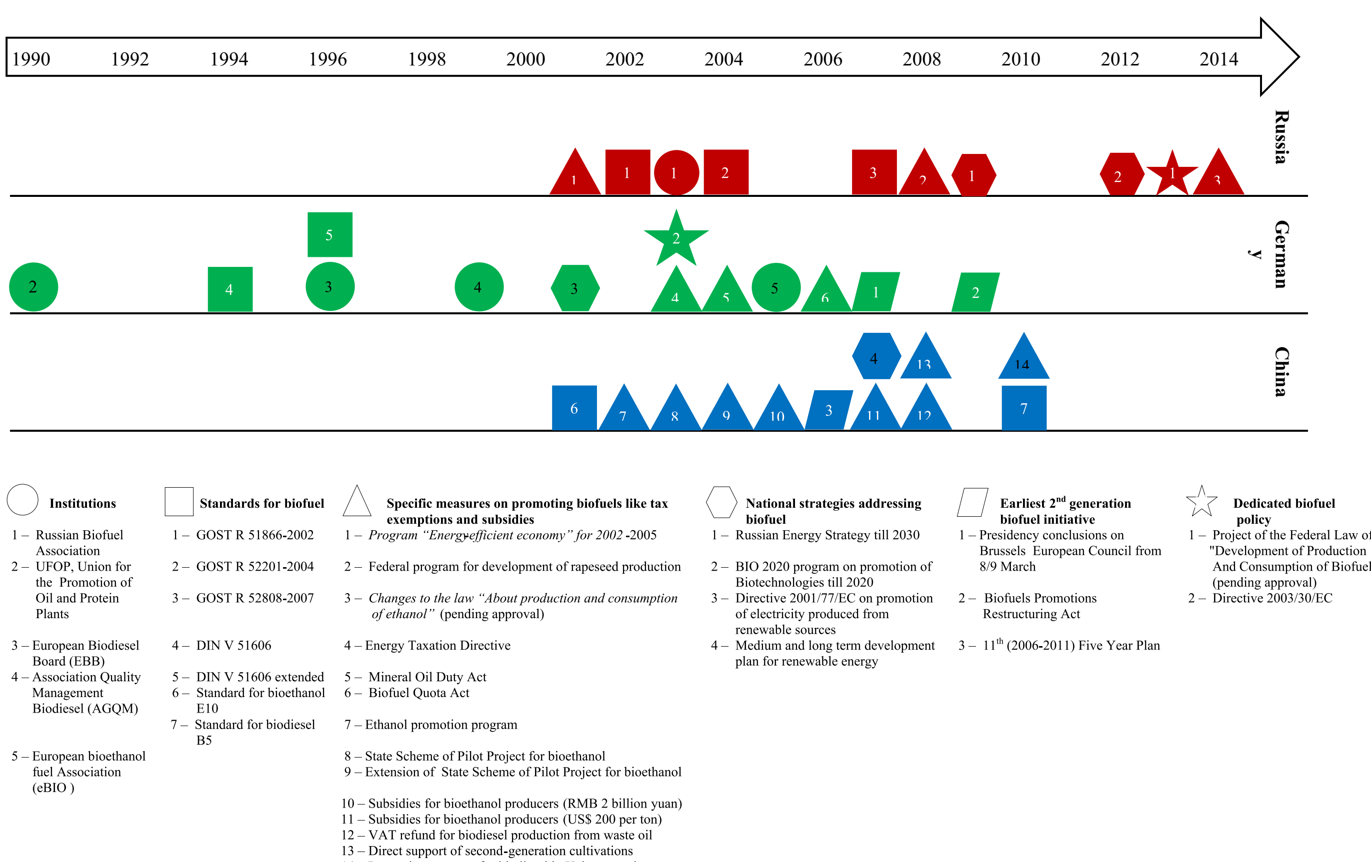

Fig. 1. Biofuel policy milestones of Russia, Germany, and China.

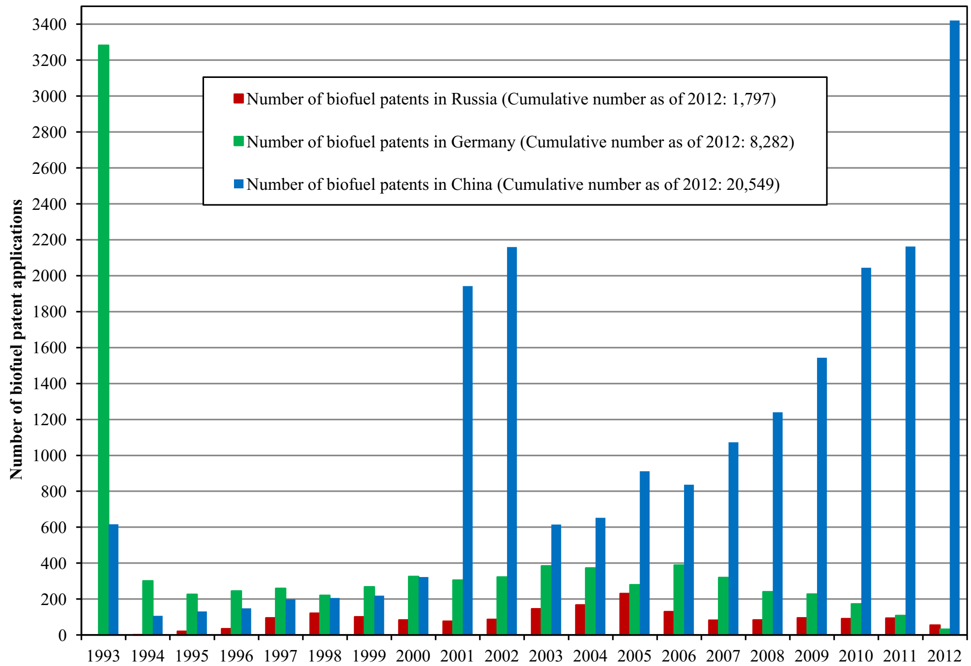

Fig. 2. Statistics of patent applications by year in Russia, Germany, and China (Source: EPO (2013), compiled by authors).

wastes from poultry production. Also ambitious targets were set for exports, including 20% market share of solid biofuels (pellets) in European market; and 5% share of the world market of motor biofuel and components (BIO 2020, 2012). However, these programs have been introduced by different departments without consistency. It was not until 2013 that the corresponding federal law was actually developed, though as of March 2015, it has been still pending government approval (Ministry of Agriculture in Russia, 2013). In contrast, Germany has set up goals and a roadmap in its policy dedicated to promotion and use of biofuels in 2003 alongside European Union (EU) policies (Directive 2003/30/EC, 2003). Furthermore, the Council of the EU has decided that in addition to ensuring biofuels accounts for 10% of all transportation fuel consumption, 2nd generation biofuels should become commercially available by 2020 (Council of the European Union, 2007). China is a special case whose biofuel market has developed without its own dedicated policy, but by gaining experiences and insights from successful pilot programs across the regions and technologies.

Lastly, the creation of various interest organizations in addition to firms can facilitate promoting new technology as they form technology-specific advocacy coalition influencing policy designs (Unruh, 2000). In the case of Germany, dedicated policies successfully attracted participants to form public organization who actively contributed to promoting and diffusing biofuels, starting from as early as 1990 with the Union for the Promotion of Oil and Protein Plants. Others include the members of European Biodiesel Board (EBB) established in 1997 and the Association Quality Management Biodiesel (AGQM) founded in 1999. Both organizations positively influenced the success of the German biodiesel industry by developing ideas for more efficient production processes and promoting biofuel consumption while producing 80% of all EU biodiesel (EBB) and assuring the quality of biodiesel (AGQM) (Bolter et al., 2007). More recently, the European Bioethanol Fuel Association (eBIO) was established to represent the interests of bioethanol producers (Bolter et al., 2007). However, in Russia, the organization that united biofuel producers appeared only in 2003 (Russian Biofuel Association) and it has had only minimal impact on policy. This limits the capacity to achieve a political network, which is often crucial for the development of commercial prospects for new technology.

Once the legitimacy of new technology is established in the formative stage, the policy should be focused on creating positive feedback from the market, further leading to market expansion while assuring institutional alignment (Jacobsson and Bergek, 2004). One of the ways to diagnose the status of the formative stage can be done through examining its knowledge network over time, which reflects how actors in the network have created and diffused knowledge enough to form a sustainable market. In the following section, we show how the institutional framework of Russia influences the evolution of its biofuel knowledge network, compared to the impact of those frameworks in Germany and China on their respective knowledge networks.

3.2. Descriptive analysis

The number of biofuel related patent applications has been declining recently in both Germany and Russia, while China stands as an exception from this trend showing an aggressive increase in biofuel patent applications (Fig. 2). In Russia, the peak of patent applications falls between 2003 and 2005 when European countries have actively searched for biofuel sources to satisfy the first target of biofuel market penetration (e.g. 5.7% by 2010 with variation by country set by the EU directive (Sorda et al., 2010)). This reflects the focus on exports in biofuel development in Russia. On the other hand, China shows a rapid growth of patenting activity during 2001–2002, aligned with introducing the standards for bioethanol for automobiles in 2001 as well as the Ethanol Promotion Program in 2002 (Sorda et al., 2010).

This study further investigates the applicants of biofuel patents in these countries by four group classifications[9] (company, government non-profit, individuals, and university) as well as their origin of country (Fig. 3). First, the distribution of applicants'

[9] While PATSTAT database divides applicants by affiliation to more than four groups (e.g. Company Government in Russia, Hospital in China), they do not appear in this study due to their inconsistency among countries and minor contribution. However, more detailed descriptive statistics are available upon request.

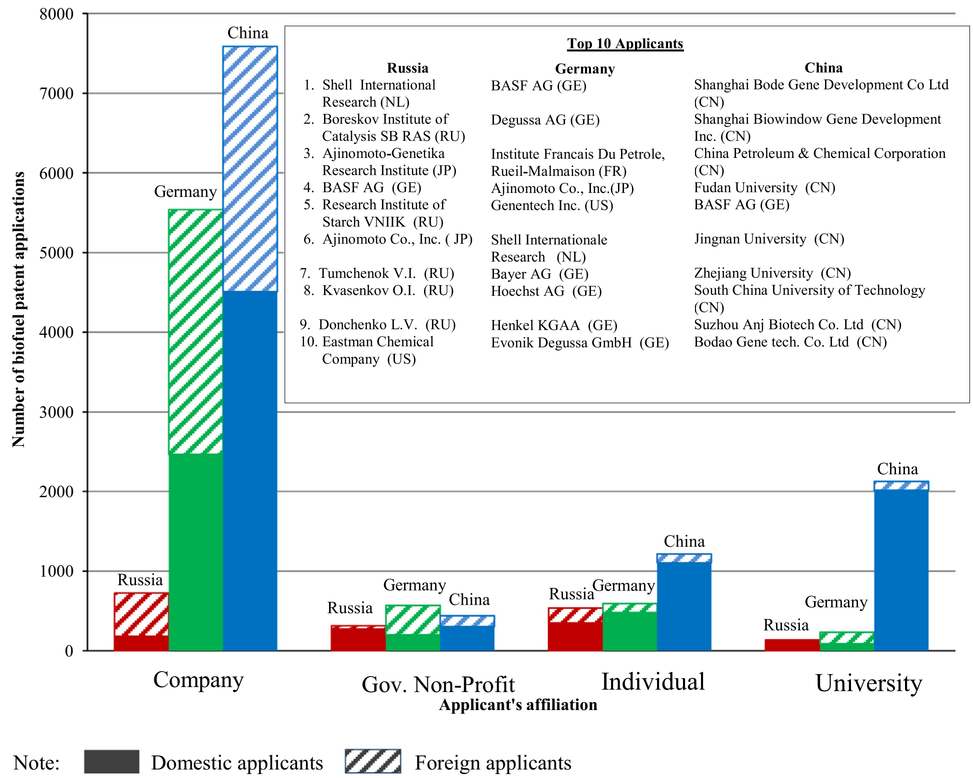

Fig. 3. Statistics of biofuel patents applications classified by affiliation and country of origin (Source: EPO (2013), compiled by authors).

affiliation in Russia delivers a plausible explanation for the deficiency of domestic biofuel market because the largest group among Russian applicants is individuals, who are less equipped than companies with the capital and motivation necessary to build sustainable market infrastructure (Rakitova and Ovsyanko, 2009). This is a stark contrast to Germany and China whose largest group is companies. Since it is predominantly companies and institutions that turn inventions to innovations (Dosi, 1988), the limited corporate presence among domestic applicants in Russia may indicate a lack of capacity to develop the biofuel industry in the future. The second largest group in Russia is the Russian government, which had not prioritized the development of renewables prior to their recent energy policy in 2008 (Pristupa et al., 2010). These government research institutes have less interest in commercialization than private companies, while even private companies appear to be indifferent to biofuels in Russia (Fig. 3). Additionally, the considerable presence of foreign company applicants indicates that they have played a disproportionate role in the development of biofuels in Russia compared to either Germany or China.

Analysis of the trends of the 1st and 2nd generation technologies by origin of applicants offers further support for the argument that biofuel technology development was led by foreigners in Russia (Fig. 4). During 2003–2007, foreign applicants were more active than domestic applicants for both generations (Fig. 4a). Interestingly, this happened right after the directive for promotion of biofuels in the EU (Directive 2003/30/EC, 2003), but the shift in proportion of applicant origin coincided with waning support for the initiative, which was replaced instead by growing skepticism towards biofuels in Europe (Sorda et al., 2010). In contrast to declining trend of 2nd generation applications, the patenting activity of domestic applicants for 1st generation started to increase after 2009. This implies a growing interest in a biofuel market among domestic applicants targeting easy-to-commercialize 1st generation technologies.

The figures of Germany (Fig. 4b) and China (Fig. 4c) reflect that both countries have recognized the conflicts of 1st generation biofuels with food supply and started to prioritize 2nd generation in their policies during last decade (Sims et al., 2010; Sorda et al., 2010). China's case again confirms the relationship between the aforementioned policies and biofuel knowledge base: motivated by the Ethanol Promotion Program in 2002, the number of 1st generation biofuel patents (Fig. 4c) even outnumbered 2nd generation in 2001–2002. This strong growth of 1st generation during 2001–2002 explains why some previous study found a strong correlation between biofuel industry and food-related industries (Hu and Phillips, 2011).

3.3. Network analysis

3.3.1. Size and growth

The scale and growth rate of the biofuel patent citations network in Russia convey a vastly different pattern of biofuel knowledge base development than those witnessed in Germany or China. Fig. 5 contrasts these three biofuel patent citation networks with snapshots of each network colored by biofuel generation from 1990, 2000, and the most recent year of complete data, 2012. In panel (a), Russia's biofuel knowledge base began to develop later than Germany's (b) and the latest to develop was the network in China (c). As of 2012, the Russian network remains not only sparse but small too, roughly one-seventh the number of patents in the German network and only one-quarter the number in the Chinese network with average citation degree per patent of 0.93. In comparison, the biofuel citation network in Germany (Fig. 5b) began to develop as early as the first quarter of the 20th-century when the biofuel-related patents in that country have outgoing citations to technologies patented. By 2012, the biofuel knowledge base within Germany dwarfed those in China and Russia in terms of patent count ($n = 3936$), citations ($m = 5017$), and average citation degree ($k = 1.28$). While not at the level of Germany yet, the

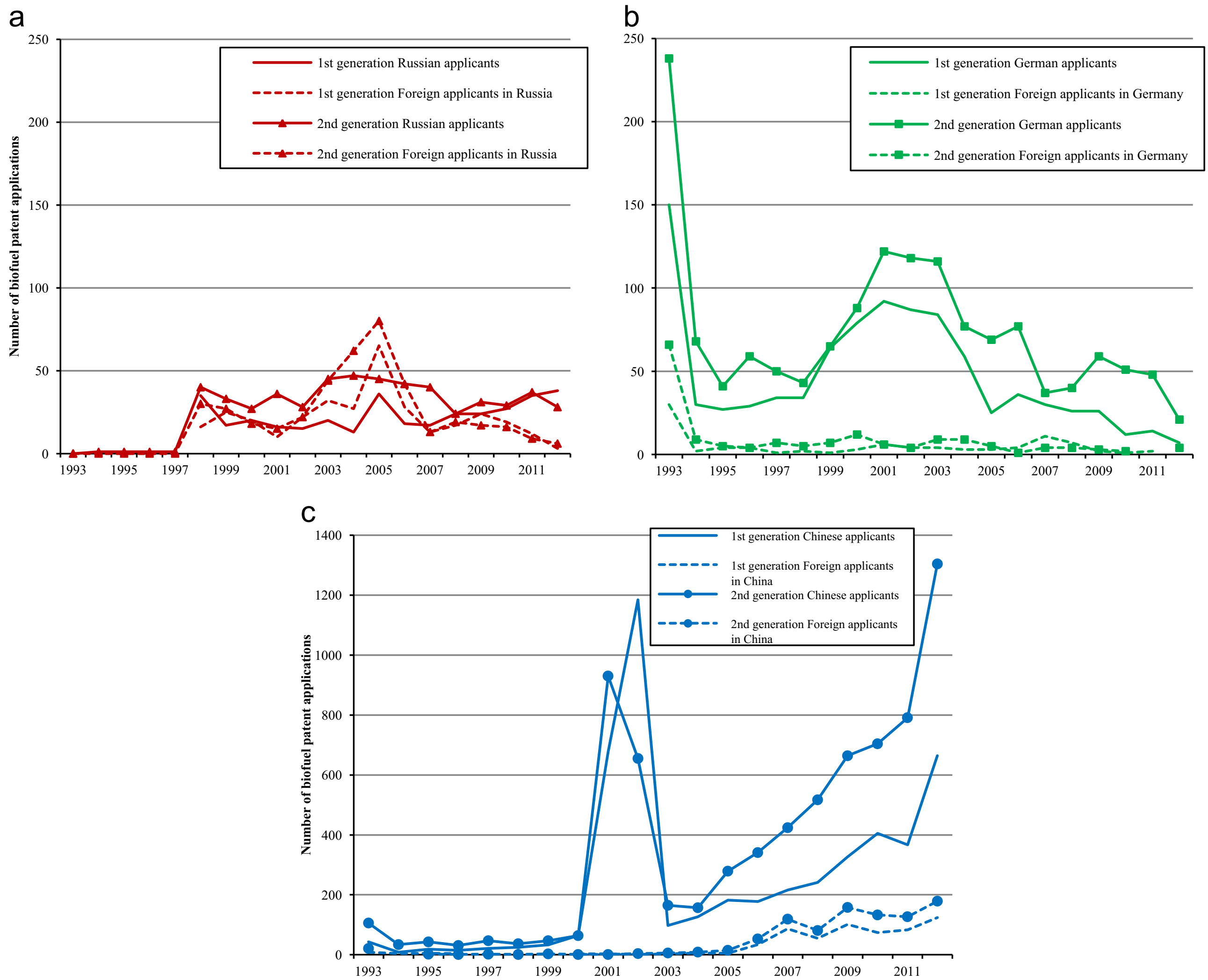

Fig. 4. Patent applications per year by generation: (a) Russia; (b) Germany; and (c) China (Source: EPO (2013), compiled by authors).

biofuel knowledge base within China has actually grown at a very fast rate within the last decade, more than tripling the number of patents ($n = 2264$) and increasing the citation count by over 80 times that of 2000 ($m = 1831$).

3.3.2. *Cumulativeness*

After addressing network size and growth, the next important consideration is the potential for knowledge flow throughout the network and what that entails for exploratory versus exploitative learning and the cumulativeness versus originality of technological innovation. We quantify the expected reach of the knowledge contained in the patents of a network and the structure of their connections using Schilling and Phelps (2007)'s average distance-weighted reach value, R. Fig. 5 presents that the reach of a patent in the Russian ($R = 0.93$) and Chinese ($R = 0.89$) networks in 2012 were even much less than the reach of the German network over a decade earlier in 2000 ($R = 1.40$). The rate of increase in the Russian citation network reach implies that the biofuel knowledge diffusion in Russia is slowly catching up to Germany; however, this is mitigated by the anemic growth of the network size in terms of new patents and citations. The reach of the biofuel citation network in Germany indicates increased expected distance of knowledge flow through the network such that, by 2012, the technology of the average patent reached almost two other patented inventions, from 0.53 as of 1990 to 1.94 by the end of 2012. From this we infer that the German biofuel patent network exhibits an increasingly interconnected and distributive quality that facilities greater knowledge flow, impacting the work of more researchers. This is important since higher reach of network members has been shown to impact their network's innovative output (Schilling and Phelps, 2007). Interestingly, the Chinese citation network, despite the fastest growth among the three countries, suffers from an isolated structure that causes minimal expected reach within the network.

The clear lack of clustering in the Russian and Chinese networks, which is an important structural and functional difference between the German citation network and those of Russia and China, is also evident in Fig. 5, accentuated by the force-directed Kamada–Kawai layout algorithm (Kamada and Kawai, 1989) used to plot the networks. We monitor the growth of the densely-connected largest component within the network because of the effect that higher connectivity, and thus shorter distance, has on knowledge creation and innovative productivity (Schilling and Phelps, 2007). The proportion of the network contained in the largest component demonstrates the cumulativeness of the biofuel technology knowledge base (i.e., larger components, more cumulativeness). We identify this as a stylized fact of the knowledge base[10] that signals the extent of transition from exploratory to

[10] Other such stylized facts of networks, such as patent citation networks, include the scale-free degree distribution (Barabasi and Albert, 1999) and small-

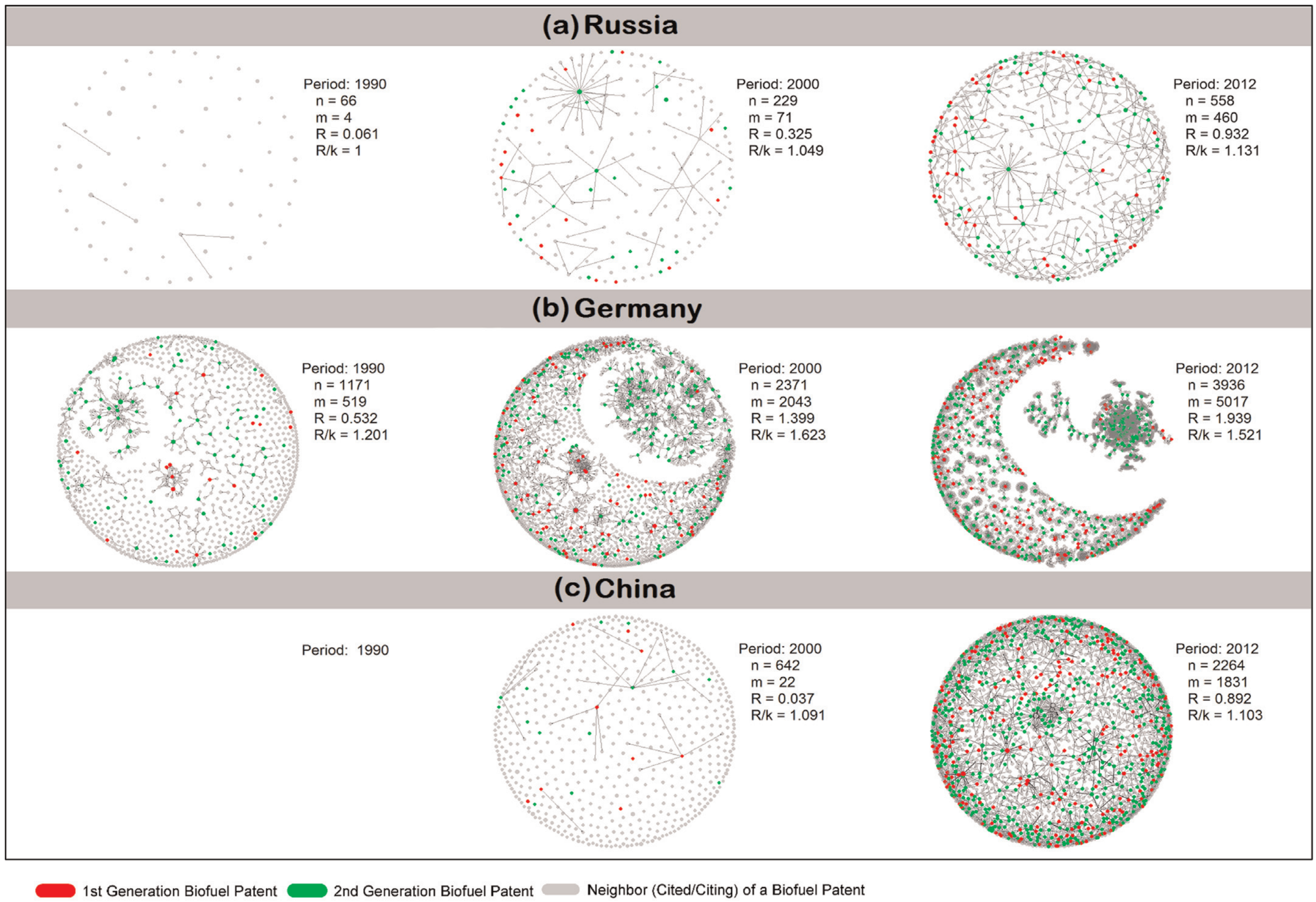

Fig. 5. Evolution of biofuel patent citations networks by country colored according to biofuel generation.

exploitative learning.

It is immediately clear that the pattern of development in the citation network structure in Russia is a stark contrast to that in Germany, while differing less substantially from that in China. Germany increasingly exhibits the impact of technological innovation building upon itself, with the largest component proportion of the network increasing through the 1990s and 2000s to just under 35% by 2012 (illustrated in Fig. 5). The Russian and Chinese networks exhibit more fragmented or scattered citation structure representing either entirely original innovation or potentially some duplication of research by scientists who were unaware of the existing research in the knowledge network. Regardless of the specific cause, this is emblematic of exploratory learning. Specifically, in China, the largest connected component emerged as a negligible portion (1.1%) of the overall network has increased only slightly (up to 2.1%) by 2012. In Russia, the largest connected component of biofuel patent citations increased from 5.1% to 10.1% of the overall network by 2000, in large part due to the increased patenting activity of foreign applicants, but then actually dropped back to 5.9% by 2012, following the decrease in foreign applications. An isolated view of only Russian-owned patents would present a picture of the growth of the largest connected component in Russia similar to that of China. The contrasting patterns of percolation within the citation networks present a biofuel industry that is much more cumulative in Germany, reflecting a greater extent of exploitative learning, and less so in China and Russia. The implications of these patterns are that (i) the knowledge base within Germany is deepening in the areas that have been determined to be promising technological specializations, and (ii) the knowledge bases in China and Russia are widening, with minimal barriers to entrants but lower expectations for successful technological contribution due to the shallower foundation upon which to build.

We address the issue of comparing knowledge flows across networks by offering the EE index (R/k), which normalizes the reach value (R) by average citation degree (k), to allow for comparison of distance-weighted reach between our three citation networks of different densities.[11] The yearly EE index values in Fig. 6 track the trajectories of each biofuel knowledge base, representing the exploratory–exploitative learning tradeoff in each country. Larger values signify more exploitative learning, while smaller values indicate more exploratory learning. The origination of a new technology's knowledge base may be expected to follow a characteristic pattern of initial exploration (EE index values beginning from 1.0) followed by exploitation (increasing EE values

(*footnote continued*)
world property of disproportionately short average path length due to localized clustering and few but important distant ties (Watts & Strogatz, 1998).

[11] The EE index is a different view of innovation and technological trajectory than the firm-specific time-between-citations probabilistic measure employed by Sorensen and Stuart (2000). This present research focuses instead on the macroscopic objective of summarizing the knowledge base of an entire industry for comparison across countries, and so we propose an innovation index that more accurately captures the exploration-exploitation learning trade-off (March, 1991) and the radical-incremental innovation distinction (Freeman and Perez, 1988), by measuring the ratio of evidence of incremental innovation (citation chains) to the overall rate of knowledge transmission (average citation degree).

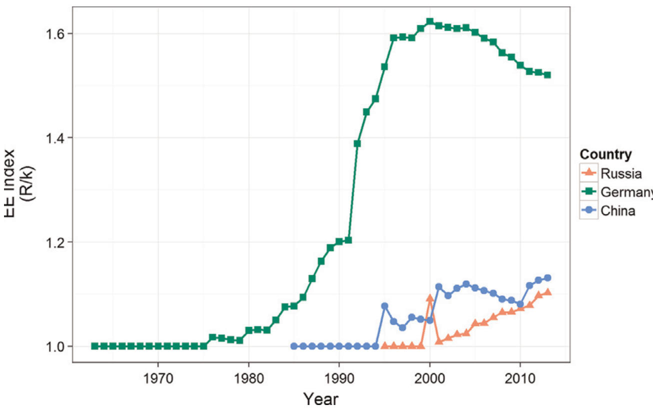

Fig. 6. Exploratory–Exploitative (EE) index for biofuel knowledge base.

above 1.0). Then in time it may shift back and forth in either exploratory (decreasing) or exploitative (increasing) directions depending upon numerous conditions, including the rate and scope of technological advancement, the market prospects for commercialization, and the systematic factors affecting the rate of transition of the new technological system. The first biofuel patents were cited in Germany in 1963, Russia in 1985, and China in 1995. It was then 10 years before Russia had its first sign of incremental innovation in biofuels (that is, a biofuel patent that cited another biofuel patent). China was much faster to begin exploiting biofuels knowledge for innovation after only 5 years, and Germany took somewhat slower at 13 years. However, after the incremental innovation began, it accelerated much faster in Germany than in either Russia or China.

The 1990s saw tremendous exploitation of the biofuel knowledge base within Germany, which is characteristic of accelerated incremental innovation. This then peaked in 2000 but had declined by 2012, due to the average citation rate increasing faster than the reach value within the citation network. Since the evidence of overall knowledge flow (average citation degree) was increasing faster than the exploitative learning (high reach values that signify long citation chains), this signaled a shift back toward exploratory learning with a decreasing EE index for Germany after 2000. This indicates increasing attempts at exploration of the biofuel technology space in Germany and presents evidence of the result of an intensive search that had been undertaken for different types of biofuel technologies (Directive 2003/30/EC, n.d.). Prior to that 2003 broad scope directive, however, biofuel policy in Germany had only been focused on transportation fuel, including biodiesel, through the late 1990s (Prankl et al., 2004), a period when the EE index depicted accelerated exploitative learning characteristic of increasing technological specificity.

As a benchmark for comparison with another developing nation, China has a biofuel knowledge base that started late, accelerated in a hurry, and then progressed steadily. Exploitative learning began quickly, only 5 years after the introduction of the first Chinese biofuel patent, and it then proceeded to increase rapidly. As of 2012, China had nearly closed the gap with Russia in terms of the extent of transition from explorative to exploitative learning in its biofuel knowledge base.

Russia represents a middle case as it began building its biofuel knowledge base before China, and Russia's first signs of exploitative knowledge flow occurred relatively sooner (10 years after its first biofuel patent) than in Germany. However, since then, Russia has shown inconsistency and progressed through technological specialization at a slower rate than China, which is on pace to surpass Russia's rate of exploitative learning in the near future, and at a much slower rate than Germany. Since exploitative learning as well as incremental innovation is necessary for efficiency improvements (Henderson, 1993; March, 1991), particularly given the systemic carbon lock-in (Unruh, 2000), both endeavors to develop the biofuel knowledge base are paramount for transitioning from the formative phase to the market expansion phase for commercialization of biofuel technologies (Jacobsson and Bergek, 2004). The slow and inconsistent rate of exploitative learning in Russia presents a hindrance for the commercial viability of its biofuel industry and signals a need for particular policy focus.

3.3.3. *Interdependence*

We next address the extent of interdependence among patent applicants (e.g., university, company, government, etc.). This functional distinction presents an overview of the groups that are driving the new technology's development, which has implications for the technological trajectory and commercializability based on the resources at the disposal of the leaders. Instead of presenting the commonly used degree of interdependence metric (Fung and Chow, 2003; Hu and Phillips, 2011), we examine patent applicants with a network perspective to capture the interconnectedness of the groups of actors that occupy similar positions within the network.

Citations between patent applicants of the same affiliation group allow a clearer interpretation of the knowledge flows between each functional sector (Fig. 7). Individuals play a larger role in Russia and Germany where they, along with companies and government, account for the heaviest weighted arcs in terms of total citations. Citations between individuals and companies are at the origination of biofuel research in each of the three countries, which reflects the common patterns of new technology emergence started by a small group of individual inventors, generating interest for the involvement of corporate researchers (Dosi, 1982, 1988). The networks between firms and non-profit organizations (such as public agencies, universities, etc.) enhance the technological capabilities of firms and therefore enhance the innovative process (Cimoli and Dosi, 1995). On the contrary, the lack of such networks limits the opportunities for improvement of technology. Therefore, strong links between universities, companies and government organizations in Germany suggest that its biofuel technology draws upon capabilities of all these sectors. In Russia companies have the strongest connection with individuals, weaker connection with government organizations, and a particularly weak connection with universities. This implies that a lack of collaboration between the corporate and public sectors may restrain the opportunities for the development of new technology (Cimoli and Dosi, 1995). It is clear that in China, the majority of citations occur between patents from corporate applicants and university applicants. The second highest prevalence of citations exists between government researchers and universities.

4. Discussion

The biofuel citation networks of the three countries examined in this study—Russia, Germany, and China—exhibit different growth profiles, summarized in Table 1, which portrays different markets for and patterns of biofuel technological development. The biofuel knowledge base in Russia, when evaluated in comparison with Germany and China, is apparently lacking the best of what each of its counterparts have managed to achieve toward the eventual goal of market expansion of new biofuel technology. The transformation of the energy sector technology system to incorporate biofuels requires initially extensive exploratory learning, but Russia has trailed behind the growth rate and extent of exploratory learning seen in China. After sufficient exploration, public institutions and policy makers are starting to shape the

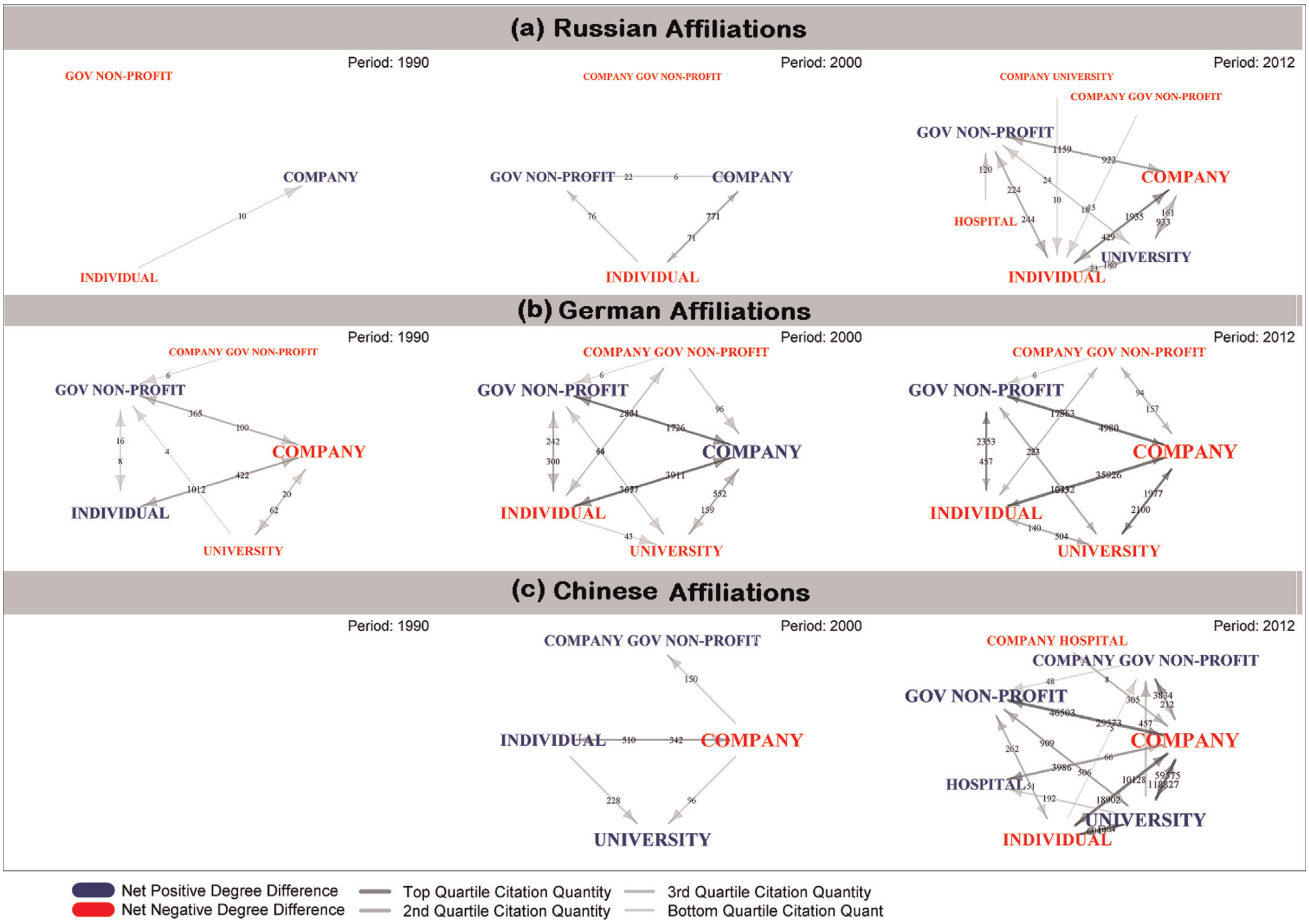

Fig. 7. Evolution of affiliation networks and strength of ties within networks.

Table 1
Knowledge base profiles by attribute levels.

	Russia	Germany	China
Size (n, m)	Low	High	Medium
Growth (Δn, Δm)	Low	Medium	High
Cumulativeness (R, ρ)	Low	High	Low
Interdependence (k_{Aff}, R_{Aff})	Low	High	Low

Note: The "n" represents the number of patents, "m" the number of citations, "R" the average distance-weighted reach, "k" the average degree; "Δ" denotes one-period difference, "ρ" is the proportion of patents in the largest connected component, and "k_{Aff}" and "R_{Aff}" are the values for the contracted graph with affiliations as vertices.

directions for the most prominent technologies to develop (Dosi, 1982). This is reflected by extensive exploitative learning, such as that seen in the German citation network during the 1990s and early 2000s. It also appears that in Germany, comparatively viable options have already begun emerging since increasing proportions of new research is building upon predecessors evident in the growth of the largest connected component. However, Russia has not only lagged in overall innovation rate but also in its ability to convert existing biofuel knowledge to exploitative learning or incremental innovation. The lack of strong ties between government organizations and companies in Russia is especially unfortunate, since government organizations are the second largest domestic patent applicant in Russia.

Unexpectedly, this study also offers insights to China's biofuel knowledge base, which has grown exceptionally fast, despite a late start. Unlike the structure seen in Germany, the overwhelming majority of new patented research in biofuel-related fields is propagating around the open areas of the knowledge landscape that indicate less reliance on preceding, foundational technologies. The biofuel knowledge base in China appears to be essentially growing outward with extensive exploratory learning, not yet upward. This could prove to be a beneficial mechanism for maintaining creativity by reducing redundant lines of thinking and linear development trends in the searchable technology space; however, it could just as well be detrimental to the prospect of commercializable biofuel technology, since exploitative learning and innovation that builds upon earlier inventions incrementally and cooperatively can offer the benefits of efficiency and speed through distributed contributions.

Despite the novel results offered in this study, the picture of the biofuel knowledge base presented by patent citations is subject to numerous limitations that have been well detailed in the literature (Archibugi, 1992; Basberg, 1987; Griliches, 1990; Pavitt, 1985; Von Wartburg et al., 2005). They include the availability and correctness of citations in the patent databases at a macroscopic level, as well as the choice of each researcher, at the microscopic level, to patent his or her technology and the decisions of the patenting offices whether or not to grant the patent. Inevitably, the actual knowledge base will exceed that which is portrayed by patent citations alone; however, in the sense that knowledge transfer is more likely to have happened where citations are documented than where they are absent (Jaffe et al., 2000), then the available patent data nonetheless provides valuable insight into the biofuel knowledge base of each country as an approximate indicator of the knowledge flow, dynamically, or knowledge base, statistically.

Lastly, the present study utilized only citation network data but not the network of coauthorship or other person-to-person connections. Future research in this area might examine coauthorships for the potential impact of network structure on innovation. Examples of the impact of increased connectivity on productivity are found in myriad domains, including biological networks, where Kretzschmar and Morris (1996) found that increasing concurrency of relationships increased the extent and speed of the spread of disease, and in academic research, where Goyal (2006) found that increases in the scale of the largest connected component of the co-authorship network accompany increases in the abundance of collaborative research.

5. Conclusion and policy Implications

The importance of developing biofuels is recognized to larger or smaller degree in the biofuel policies of all three countries compared in this study. However, for successful commercialization of any new technology, besides economic inputs, there should first be created an adequate knowledge base, upon which the new technology is developed (Dosi, 1988). Filling the gap in the research on the most attended renewable energy, biofuels, in Russia, this study analyses the knowledge base and compares it with the ones of Germany and China – two countries which have been successfully developing biofuels to date as a leader and latecomer, respectively. By analyzing biofuel related patenting activity in these respective countries we assessed the evolutionary path of the knowledge base and its interlinked development with renewable energy policies through various network analyses. For the purpose, a total of 1797 patents filed in Russia, 8302 in Germany and 21890 in China were retrieved from the European Patent Office database covering all applicable patents through the end of 2012.

The citation network analysis, in conjunction with policy milestones, conveys an understanding of poor institutional framework for biofuels in Russia influencing the development trajectory of its knowledge base, which lacks both the increasing technological specialization of that in Germany and the accelerated growth rate that has been seen in China. The Russian network's size and structure as of 2012 would imply both a lack of consensus of the best technological avenues to pursue and a lack of drive from corporate R&D, evidenced by the smaller relative proportion of domestic corporate patent applicants within the Russia. The evolution of the biofuel knowledge base in Russia thus presents challenges for the diffusion of renewable energy that is not a priority for stakeholders within Russia.

Our results further inform three policy implications. First, it is important to balance exploratory–exploitive learning to transform the energy sector. Our results demonstrate that Russia's biofuel knowledge base particularly shows a slow and inconsistent rate of exploitative learning and incremental innovation, which is problematic for the commercial viability of its biofuel technology and signals a need for particular policy focus. A likely source of delayed innovative progress could be a deficiency of domestic market, which brings us to the next implication.

Second, government should support the creation of a domestic market by offering incentives to domestic industry players for producing biofuel, rather than raw materials for exports. For example, introducing a pilot program using mandatory blending of biofuels, such as in China, can provide a cornerstone to increase domestic production capacity large enough eventually to cover a whole country. In that process, it is also important to attract existing players who have accumulated abundant resources and capital to explore new technology. New technology often emerges as a result of R&D activities made by existing companies with either resources for creating this new technology or infrastructure for its commercialization (Dosi, 1988). Thus, in Germany and China, it is predominantly petroleum and pharmaceutical companies (including Shell, China Petroleum, BASF, etc.) with sufficient infrastructure for fuel supply and biotechnology research, respectively, that appear among the top ten applicants. However, these companies in Russia appear to lack sufficient incentives to prioritize the development of biofuels.

Third, government policy as an inducement mechanism should place additional emphasis on the guidance of technology search and diffusion, which aligns with the existing framework of government functions for technology system change (Jacobsson and Bergek, 2004). Government should facilitate existing industry stakeholders' connections with promising new renewable technologies. This is another role for government besides offering incentives since governments are the only entity positioned with a full understanding of both the developing technology space and the eventual downstream stakeholder groups of commercialization. Government policy therefore plays a vital role in technology commercialization matchmaking by identifying the predominant stakeholder groups and the technology with highest potential to benefit them, ideally facilitating and developing this connection between new technology and its industry stakeholders. As shown in the evolution of Germany's biofuel knowledge base, this is the process that enabled Germany to progress beyond the formative stage and move onto the market expansion stage of their renewable energy technological system (Jacobsson and Bergek, 2004). We see this technology diffusion process as applicable to Russia and other countries contingent upon the guidance of government policy.

Due in part to the increasing possibility of sanctions from the EU, Russia has started to acknowledge the importance of developing its own biofuel technologies, which most of them have been imported from abroad (Interview with Head of Ministry of Energy of Russian Federation, 2015; Interview with Russian Prime-minister, 2015). This research not only gives an explicit analysis of the state of existing biofuel technology in Russia but also suggests some important policy implications by providing the comparison with potential benchmarks, Germany and China. Russia still has a vast potential to develop its biofuels whose initial knowledge base has been evolved by foreign companies thus far. If Russia wants to promote the adoption of biofuels successfully, now is the time for the Russian government to actively pursue biofuel policies and intensifying the cooperation among domestic stakeholders of the industry to create a sustainable biofuel market.

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