sustainability

MDPI

Review

An Investigation of the Underlying Evolution of Shale Gas Research's Domain Based on the Co-Word Network

Wen Li, Yuxi Liu, Siqi Xiao, Yu Zhang and Lihe Chai *

School of Environmental Science and Engineering, Tianjin University, Tianjin 300354, China; 13920536037@163.com (W.L.); 3014214076@tju.edu.cn (Y.L.); 18222070557@163.com (S.X.); 18622148076@163.com (Y.Z.)

* Correspondence: lhchai@tju.edu.cn; Tel.: +86-22-8789-1368

Received: 22 November 2017; Accepted: 9 January 2018; Published: 13 January 2018

Abstract: With the increasing shortage energy, the exploration and utilization of shale gas (SG) have greatly changed the world's natural gas supply pattern. In this study, based on a bibliometric review of the publications related to SG, by analyzing the co-word networks during the past years, we provide comprehensive analyses on the underlying domain evolution of shale gas research (SGR). Firstly, we visualize the topical development of SGR. We not only identify the key topics at each stage but also reveal their underlying dependence and evolutionary trends. The directions of SGR in the future are implied. Secondly, we find the co-word network has small-world and scale-free characteristics, which are the important mechanisms of driving the evolution of SGR's domain. Thirdly, we analyze China's SGR. We find the co-word network in China's SGR has not yet emerged obvious differentiation. Nevertheless, it has a similar self-organized evolution process with the co-word network of international SGR. Our above results can provide references for the future SGR of scholars, optimization or control of the domain and the strategy/policy of countries or globalization.

Keywords: shale gas (SG); shale gas research (SGR); bibliometrics; co-word network; data mining

1. Introduction

Based on the recent estimation from the U.S. EIA, there are 35,782 Trillion cubic feet (Tcf) risked shale gas in-place for 41 countries, of which 7299 Tcf shale gas is considered technically recoverable [1,2]. The effective exploitation of SG for solving human energy shortage problems has a great significance [3]. In 1970s, America began to rigorously pay attention to SG and did much related research and achieved commercial exploitation in the late 1990s [4–6]. With the situation that American natural gas production declined, the rapidly rising SG production promoted, in 2012, the U.S. has surpassed Russia in natural gas production for the first time since 1982 [7]. North American SG exploration greatly changed the North American and even the world's natural gas supply pattern [8]. Canada has also achieved a commercial development of SG and a number of countries and regions carried on the prospecting or developing work and related pilot test of SG [9–12]. Other countries, such as Poland [13,14], Australia [15,16], England [17–19], South Africa [20,21], Brazil [22], India [23], pay much attention to the search of SG.

SG has become the new darling energy in both global and regional scales. SG has complex characteristics such as large reserves, long production cycle, somewhat expensive exploration costs compared with other unconventional types of gas reservoirs and so on. The complexity of SG brings that the fields of SGR during the past years are diverse, which include theoretical SGR of analyzing the foundation of SG exploration [1,2,10,24–26], model investigation in SG [24,27–33], technical and economic research of considering the potential application of SG [7,25,33–36], the environmental impact assessment in SG exploitation [21,37–48] and many others. Anyway, with the evolution from initial exploitation to the more and more complicated development of SG, the diverse research of SG can be found in available literature during past decades. To help the researchers, government policy-makers and managers to comprehensively and critically grasp this rapidly developing knowledge domain, it is very necessary for us to carry out a bibliometric research based on the analysis of a large scale of literature related to SGR, going to reveal the key topical development, evolutionary codes and underlying dynamic law hidden in SGR. Based on our analysis of the main research fields of all the papers, the research fields of SG are mainly concerned with two aspects: First, the physical properties of shale reservoirs, including porosity, adsorption and desorption of SG; The second is the technology of reservoir exploitation, the dominating part of which is hydraulic fracturing, which reflects that the international research community pays more attention to some basic researches that are closely related to the development of SG. However, the words such as groundwater and carbon dioxide also appear at top 50 keywords. The keywords list reflects that environmental issues related to the development of SG have also received the attention of researchers. Compared with the international level, China has conducted many studies on the physical properties of SG reservoirs. The future development of shale gas in China will focus on the improvement of mining technology. Once China can overcome the pressure of high-cost mining, obtain sufficient water supply and make breakthroughs in key mining technologies. Given the huge SGR and rising domestic demand, the SG market in China will have a promising future.

In this study, taking "shale gas" as the topic word, we will obtain a large scale of literature related to SGR from database and then tend to reveal the key topics, evolutionary dependence and evolutionary trends and underlying dynamic law of SGR by keyword analysis and co-word network method. After the introduction section, in next section, we give our research method. In third section, we elaborate our results and discussions. In last section, we give our summary.

2. Methods

The samples used in this study are searched from Web of Science's core database with the topic word "shale gas" as the retrieval term. The first literature searching of SG in Web of Science was in 1998. The retrieval time is from 1998 to 2016 and we get 2528 publications, from which 1665 publication samples are then obtained by keyword screening. The time distribution of these publications is shown in Figure 1.

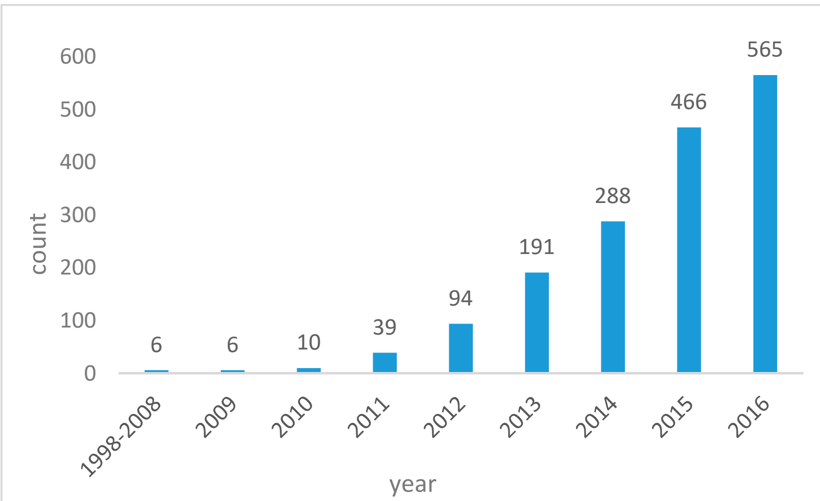

Figure 1. The time distribution of the publications of SGR.

The keyword analysis and co-word network method are here adopted. First of all, from the selected publications, we obtain a total number of 5462 keywords. Some pretreatments are necessary. For example, we combine the keywords "shale" and "shales" into one keyword "shale"; "fracture", "fractures", "fracking", "hydraulic fracturing" and "hydraulic fracture" into one keyword "hydraulic fracture"; "sedimentary basin" and "sedimentary basins" into the keyword "sedimentary basin" and "resources", "resource" into the keyword "resource"; and so on. The specific operation process is shown in Figure 2.

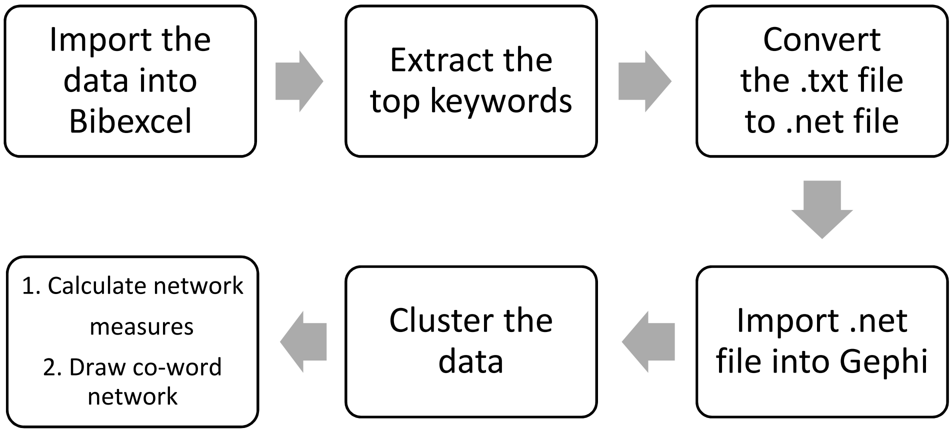

Figure 2. The specific operation process.

Taking the shale gas as the topical word, the keyword analysis and co-word network method can cluster the large scale of information from big data. By showing the morphological characteristics between the keywords at each stage, the qualitative results are transformed into quantitative analysis, revealing the status, development trends and evolutionary code of SGR.

Furthermore, we can calculate some network measures (e.g., degree, degree distribution, density, modularity, clustering coefficient, average path length and so on) related to the co-word network, uncovering the underlying dynamic law (e.g., small-world effect, scale-free nature) in the evolving knowledge domain.

In summary, the keyword analysis and co-word network technique provide a novel approach of analyzing the large amount of information from the big data of SGR publications. Through the method, we can visually identify the development of SGR in each period. By the underlying analysis founding upon quantitative calculations of some important measures, the key topical development, evolutionary code and the underlying dynamic law of SGR can be well revealed.

3. Research Results and Discussions

3.1. The Evolution of SGR's Hotspots at Each Stage

Based on the quantity of literature (Figure 1), we broke the study period into four parts. We take the top keywords with high frequency at each stage to make the keyword analysis and construct the co-word network for the hotspot identification and evolutionary trend analysis.

3.1.1. Research Hotspot Analysis during 1998–2010

After ascertaining all keywords with high frequency in 1998–2010, we select the top 25 of those the frequency, degree, betweenness centrality and the associated ranks of which are listed in Table 1. The text continues here.

Besides giving hot keywords directly from frequency, degree and so on as in Table 1, we use Gephi to draw the co-word network pattern (including the top 50 keywords) (Figure 3), further showing the underlying relationship between these keywords with high frequency.

Table 1. Statistical analysis of the top 25 keywords of SGR during 1998–2010.

Number	Keyword	Degree (Rank)	Frequency (Rank)	Betweenness Centrality (Rank)
1	shale gas	21(1)	10(1)	246.500(1)
2	organic carbon	12(2)	3(2)	44.500(4)
3	kerogen	10(3)	3(3)	4.499(8)
4	vitrinite reflectance	9(4)	2(4)	0.499(9)
5	maceral	9(5)	2(5)	0.499(10)
6	black shale	9(6)	2(6)	0.499(11)
7	methane	8(7)	2(8)	5.000(7)
8	petroleum	8(8)	2(7)	0.000(12)
9	Permian	8(9)	1(12)	0.000(13)
10	migration	8(10)	1(13)	0.000(14)
11	maturity	8(11)	1(14)	120.000(2)
12	sedimentary basin	7(12)	2(9)	78.000(3)
13	gas	5(13)	2(11)	13.500(5)
14	shale	5(14)	2(10)	13.500(6)
15	pipelines	4(15)	1(15)	0.000(15)
16	producers	4(16)	1(16)	0.000(16)
17	supply demand	4(17)	1(17)	0.000(17)
18	reserves	4(18)	1(18)	0.000(18)
19	resource	4(19)	1(19)	0.000(19)
20	resource potential	4(20)	1(20)	0.000(20)
21	source rock and reservoir	4(21)	1(21)	0.000(21)
22	thickness	4(22)	1(22)	0.000(22)
23	Pleistocene glaciation	3(23)	1(23)	0.000(23)
24	salinity	3(24)	1(24)	0.000(24)
25	porosity	3(25)	1(25)	0.000(25)

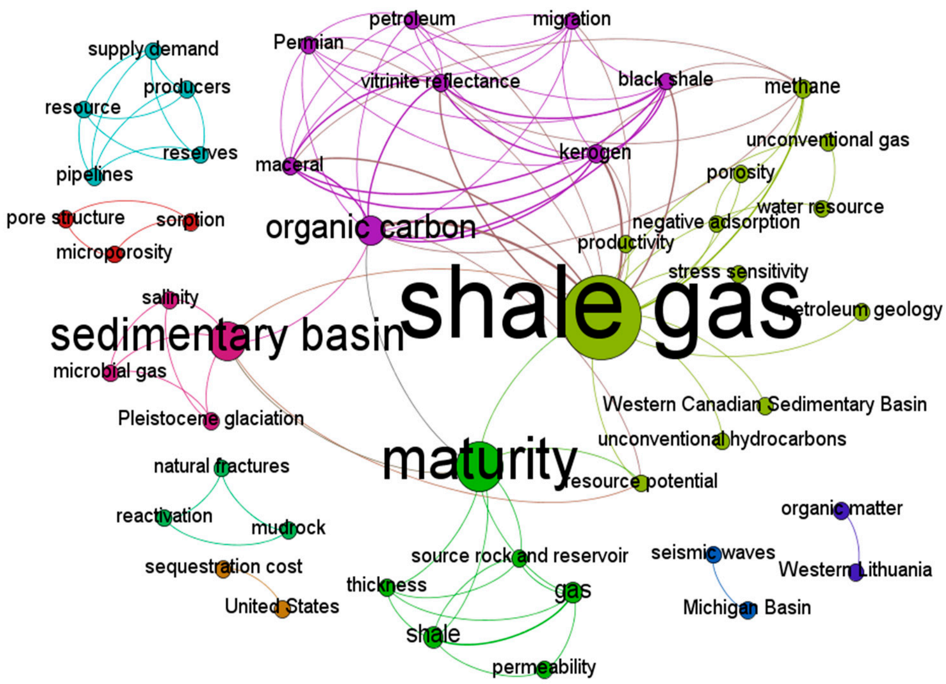

Figure 3. The co-word network during 1998–2010 (density = 0.094, network diameter = 4, average degree = 4.34, average density = 5.149, average clustering coefficient = 0.897, average path length = 2.161).

In Figure 3, we can clearly see the network pattern is divided into four modules, in which shale gas, maturity and sedimentary basin are the prominent themes.

After the first output of SG from an organic-rich Devonian shale in the Appalachian Basin in 1821 [8], more than a hundred years since then, people had no sense of urgency on oil resource depleted, paying little attention to such resources. This fact is also verified from our database that the number of the publications related to SG was almost zero before 1998. Through the analysis of the keywords in 1998–2010 as in Figure 3, the modules in the network are too diverse and scattered. Though there are four modules directly connected with the SG, the remaining six modules are not linked with each other and there is no edge between the keywords. However, these modules contain SG-related areas such as geological structure, resource distribution and gas components that were gradually emerging [49]. The keywords such as organic carbon, kerogen and vitrinite reflectance that have high degree of connection with SG indicate that the study of the mechanism, geological framework and related characteristics of SG was the focus at this time [50]. At the same time, during this period, as American SG revolution successfully developed and spread to the world, the potential of SG has gradually been confirmed [51] and enterprises have also joined the SG investment [52].

3.1.2. Research Hotspot Analysis during 2011–2012

Table 2 lists the top 25 keywords with high frequency from all the related keywords in 2011–2012, giving their frequency, degree, betweenness centrality and the associated ranks.

Table 2. Statistical analysis of the top 25 keywords of SGR during 2011–2012.

Number	Keyword	Degree (Rank)	Frequency (Rank)	Betweenness Centrality (Rank)
1	shale gas	41(1)	71(1)	765.414(1)
2	unconventional Gas	17(2)	11(4)	66.680(3)
3	natural gas	15(3)	11(3)	80.579(2)
4	hydraulic fracture	9(4)	16(2)	11.227(11)
5	shale oil	8(5)	5(6)	21.045(5)
6	energy policy	8(6)	4(11)	4.117(15)
7	shale	8(7)	7(5)	5.367(14)
8	greenhouse gases	8(8)	3(14)	19.305(6)
9	regulation	7(9)	4(10)	6.450(13)
10	tight gas	6(10)	5(7)	3.834(16)
11	pyrobitumen	6(11)	3(19)	2.000(20)
12	fugitive emissions	6(12)	2(31)	0.542(27)
13	Europe	6(13)	3(18)	2.658(19)
14	FIB	5(14)	3(22)	0.000(32)
15	desorption	5(15)	4(8)	17.357(7)
16	China	5(16)	4(12)	3.833(17)
17	kerogen	5(17)	2(35)	0.000(33)
18	TEM	5(18)	2(36)	0.000(34)
19	STXM	5(19)	2(37)	0.000(35)
20	global warming potential	5(20)	2(38)	0.000(36)
21	source rock	5(21)	3(17)	2.833(18)
22	Q410	5(22)	2(30)	1.000(25)
23	Coalbed methane	5(23)	2(27)	1.667(21)
24	mathematical model	4(24)	3(15)	13.321(8)
25	diffusion	4(25)	4(9)	13.321(9)

In order to further show the relationship between the hot topics, using the top 50 high frequency keywords, we obtain the co-word network pattern during 2011–2012 as in Figure 4.

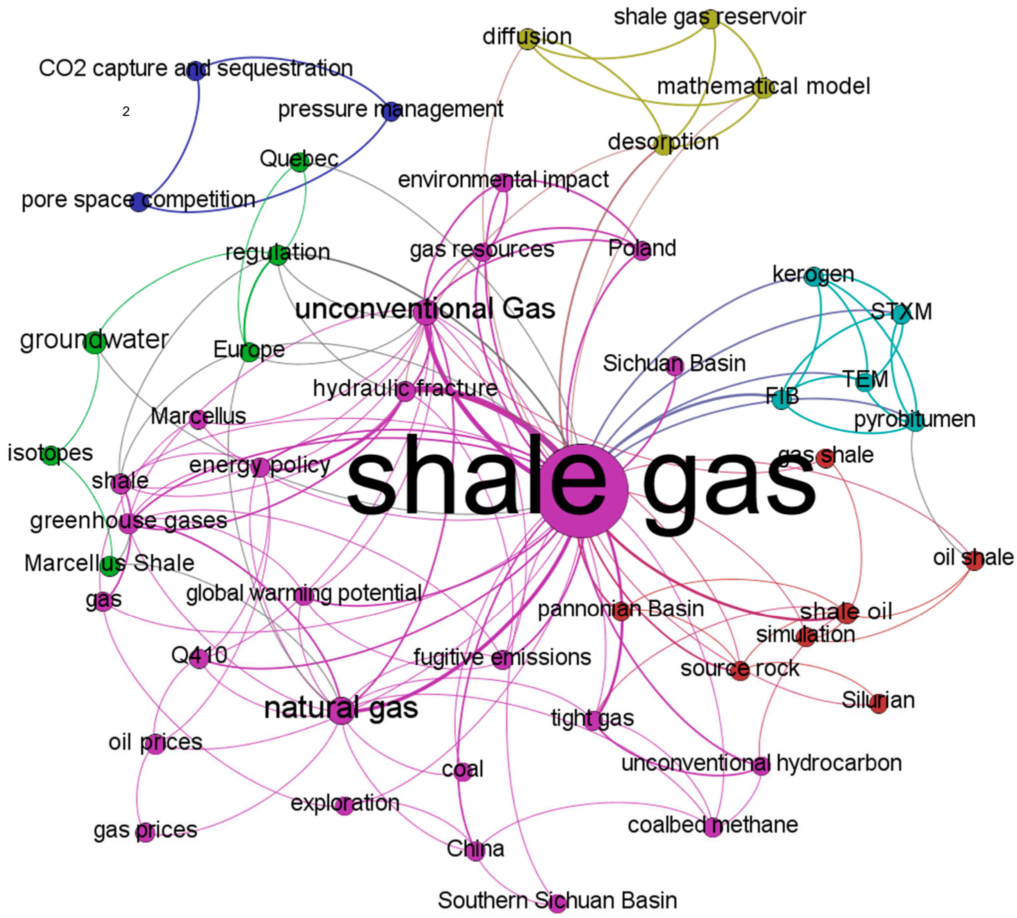

Figure 4. The co-word network during 2011–2012 (density = 0.112, network diameter = 4, average degree = 5.48, average density = 8.36, average clustering coefficient = 0.697, average path length = 2.02.

From Figure 4, we can clearly see the network pattern is divided into six modules, which prominently indicate several key topics such as shale gas, hydraulic fracture, natural gas, unconventional gas, shale, shale oil and tight gas. It can be seen from the network, dark blue area consists of three keywords: CO_2 capture and sequestration, pore space competition and pressure management. During this period, there were many publications that mainly talked about CO_2 capture and sequestration (CCS) pore-space competition with emerging activities like SG production. In short, because of the production of SG, eight percent of the ideal storage area of carbon dioxide captured from power plants and industrial activities coincides with the underground shale that was undergoing drilling fracturing activity. Around CCS, the associated research close to SG started. There are complex interactions between SG exploitation and carbon capture storage (CCS) [53,54].

Fade blue area consists of five keywords: kerogen, TEM, STXM, FIB and pyrobitumen. During this period, we find there were many publications that mainly talked about the hydrocarbon generation reactions occur within organic-rich shale as a response to thermal maturation. The TEM, STXM and FIB, as the technologies that detect the hydrocarbon generation reactions, were widely focused [55,56]. Yellow area consists of four keywords: mathematical model, desorption, diffusion and SG reservoir. At this stage, some literature analyzed the PTA on the multi-stage fractured horizontal well in SG reservoirs incorporating desorption and diffusive flow in the matrix [57]. In short, we can link this kind of topics to the mathematical model establishment of the SG reservoir, indicating that the SG extraction and utilization at this stage was still in its initial exploration process.

Green area consists of six keywords: isotopes, groundwater, Europe, regulation, Quebec and Marcellus shale. The literature in this aspect mainly talked about when the SG after large-scale development will have a greater impact on the natural environment, such as groundwater, geochemistry, microbiology and other fields [58]. The red part contains "shale oil" and other six keywords. We find the literature in this period was mainly researching for the SG exploration prospect and strategic arrangement, indicating that during this period, SG exploitation has been putted on the agenda. The purple part is the core of the network in which the more prominent keywords are "shale gas, unconventional gas, nature gas," significantly reflecting the thesis of our analysis. The SG reservoir consists of Sichuan Basin, Pannonia Basin, Marcellus and so on. Ranging from Asia, Europe and America to other countries, we can notice that SG as a new resource has attracted worldwide attention. While in terms of policy, the keywords involve environment impact, greenhouse gases and global warming potential, oil price, gas price, energy policy and regulations. During this period, the environmental impact of SG exploitation and utilization, as well as the national policy and the impact on other energy prices, have also attracted the attention of the global scholars, sufficiently highlighting the future development trends of SG exploitation.

It is noteworthy that during this period we can see the content about "China" at the first time, it can be sure that China was also interested in SG, even enough it was still at the initial stage and did not arouse great attention of Chinese scholars during 2011–2012.

3.1.3. Research Hotspot Analysis during 2013–2014

Now, we analyze the keywords in 2013–2014 and select the top 25 of them with high frequency, listing their frequency, degree, betweenness centrality and the associated ranks in Table 3.

Table 3. Statistical analysis of the top 25 keywords of SGR during 2013–2014.

Number	Keyword	Degree (Rank)	Frequency (Rank)	Betweenness Centrality (Rank)
1	shale gas	44(1)	204(1)	679.988(1)
2	hydraulic fracture	23(2)	77(2)	126.439(2)
3	natural gas	18(3)	39(3)	51.096(3)
4	shale	16(4)	25(4)	48.748(4)
5	unconventional gas	10(5)	13(6)	16.353(5)
6	regulation	10(6)	6(21)	6.845(11)
7	China	9(7)	21(5)	7.617(9)
8	climate change	9(8)	10(9)	5.830(14)
9	tight gas	8(9)	11(7)	9.445(6)
10	Marcellus shale	8(10)	11(8)	7.713(8)
11	unconventional	8(11)	4(37)	5.797(15)
12	gas	7(12)	8(15)	5.602(17)
13	development	6(13)	5(31)	7.477(10)
14	methane	6(14)	9(10)	6.420(12)
15	Sichuan Basin	6(15)	9(11)	5.253(18)
16	gas shale	6(16)	9(12)	5.097(20)
17	porosity	6(17)	6(22)	4.408(22)
18	seepage	6(18)	4(38)	3.774(24)
19	adsorption	6(19)	8(16)	3.647(25)
20	coal	6(20)	4(39)	3.344(26)
21	produced water	6(21)	6(23)	2.750(29)
22	coalbed methane	6(22)	6(24)	2.383(30)
23	hydrofracking	6(23)	4(40)	1.350(34)
24	energy policy	6(24)	8(17)	1.111(36)
25	Knudsen diffusion	5(25)	6(25)	7.907(7)

Beside Table 3, Figure 5 further draws the co-word network based on the top 50 keywords, tending to show the relationship between these high frequency keywords during 2013–2014.

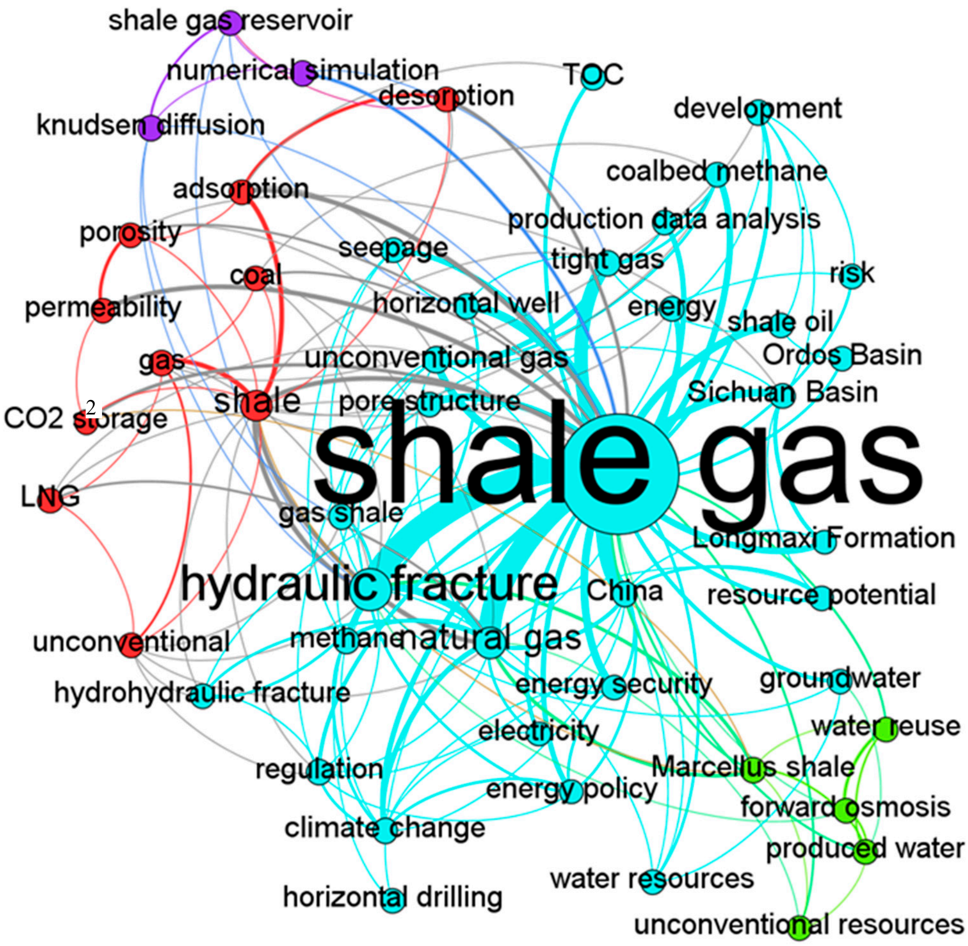

Figure 5. The co-word network during 2013–2014 (density = 0.145, network diameter = 3, average degree = 6.939, average density = 15.633, average clustering coefficient = 0.573, the average path length = 1.908).

From Figure 5, we can clearly see the network pattern is divided into four modules, in which the more prominent keywords are shale gas, hydraulic fracture, China, numerical simulations, produced water, desorption and adsorption, permeability and porosity. The purple area consists mainly of three keywords, which are numerical simulations, Knudsen diffusion and SG reservoirs. We have found that during this period, these three keywords were mainly linked by simulating the mining of SG reservoirs by applying numerical simulations. Knudsen diffusion means that when the diameter is very small, the diffusion resistance mainly comes from the diffusion of gas molecules and pipe walls. Knudsen diffusion is an important parameter that characterizes the resistance of natural gas in the SG diffusion. Therefore, it is not difficult to conclude that this kind of the studies is a simulation of SG extraction. This can also be confirmed by the meeting of the 1st Energy System Modeling and Optimization Conference (ESMOC) [59]. The emergence of the keywords "water production" and "water reuse" in the blue area reflects that in this period, researchers paid attention to the control of the mining process cost. This also reveals the fact that SG mining in this period tended to be stable. The study on the SG extraction technology has also been more in-depth. Hydraulic fracturing, as a key technology in SG extraction, is second only to the central word "shale gas" at this stage. The keywords such as desorption, adsorption, permeability and porosity of the desorption in the green region indicate that the mechanism of SG formation and the exploration process have been carried out continuously [60].

In 2013 and 2014, the keyword "China" had a great deal of connection with SG. Among the top 50 keywords, Chinese SG storage sites—Sichuan Basin, Ordos Basin and Longmaxi Formation have shown that an unprecedented climax has been appearing in the development of SG in China at this stage. Researchers focused on studying the characteristics and the main controlling factors of a particular SG reservoir [61]. Using the two keywords "shale gas" and "China" as the retrieval terms, we got 2 papers from 1970 to 2009, 27 papers from 2011 to 2012, 146 papers from 2013 to 2014 and up to 324 in 2015 to 2016 in the Web of Science database. Thus, we conclude that the study of China's SG has begun to show a blowout development since 2013.

3.1.4. Research Hotspot Analysis during 2015–2016

In this part, we still select the top 25 keywords with high frequency in 2015–2016 for analysis. Table 4 gives the frequency, degree, betweenness centrality and the ranks of the top 25 keywords.

Table 4. Statistical analysis of the top 50 keywords of SGR during 2015–2016.

Number	Keyword	Degree (Rank)	Frequency (Rank)	Betweenness Centrality (Rank)
1	shale gas	47(1)	433(1)	520.495(1)
2	hydraulic fracture	34(2)	178(2)	200.804(2)
3	shale	26(3)	53(3)	81.652(3)
4	pore structure	21(4)	38(5)	47.158(4)
5	shale gas reservoir	16(5)	34(6)	26.308(5)
6	Sichuan Basin	14(6)	28(7)	15.476(6)
7	adsorption	13(7)	18(11)	10.655(7)
8	permeability	12(8)	21(9)	6.624(11)
9	desorption	11(9)	14(18)	7.820(9)
10	porosity	11(10)	17(15)	4.134(16)
11	natural gas	10(11)	42(4)	6.705(10)
12	anisotropy	10(12)	9(33)	3.476(19)
13	Marcellus shale	9(13)	23(8)	8.895(8)
14	flowback	9(14)	12(23)	4.922(12)
15	pore size distribution	9(15)	8(49)	4.391(14)
16	organic matter	9(16)	10(31)	3.483(18)
17	Knudsen diffusion	9(17)	17(13)	3.284(20)
18	diffusion	9(18)	9(34)	2.310(27)
19	methane	8(19)	20(10)	4.760(13)
20	gas shale	8(20)	8(44)	3.267(21)
21	fractal dimension	8(21)	11(25)	3.217(22)
22	numerical simulation	8(22)	18(12)	2.816(24)
23	Ordos Basin	7(23)	15(16)	3.694(17)
24	hydraulic fracture network	7(24)	11(26)	2.792(25)
25	thermal maturity	7(25)	14(19)	2.617(26)

In order to further show the relationship between these high frequency keywords, we use Gephi to draw the co-word network of keywords for our visualizations (Figure 6).

In this period of 2015 to 2016, as shown in Figure 6, it is apparent that the global research on SG can be roughly divided into three areas. The red area is on hydraulic fracturing techniques, the formation process and physicochemical properties of SG. It is easy to see from the network that the red area occupies most of the keywords and the keywords' degrees are generally larger than the other parts, which suggest that this field of research has been relatively mature and this cluster is the current hot research direction.

Listed below are the main keywords in the green area: numerical simulation, desorption, stress sensitivity, apparent permeability, surface diffusion, Knudsen diffusion. It is sure that the focus should be researching for SG reserves and production technology by using numerical simulation method related to flow mechanics. In fact, gas flow in shale is believed to be a complex process with multiple flow mechanisms including continuum flow, slip flow, diffusion, ad-desorption and the stress sensitivity of fractures (natural or induced) permeability in multiscale systems of nano to macro porosity [62]. Accurate simulation models of gas transport in SG reservoirs must consider complex gas transport mechanisms and phase behavior in nanopores, as well as different pore types. The gas transport mechanisms in SG reservoirs include viscous flow, Knudsen diffusion, surface diffusion, adsorption and desorption [63]. Recent studies have shown that adsorbed gas and its surface diffusion have profound influence on micro gaseous flow through organic pores in SG reservoirs [56]. It is found that the surface transport plays a significant role in determining the apparent permeability and the variation of apparent permeability with pore size and pressure is affected by the adsorption and surface diffusion [64].

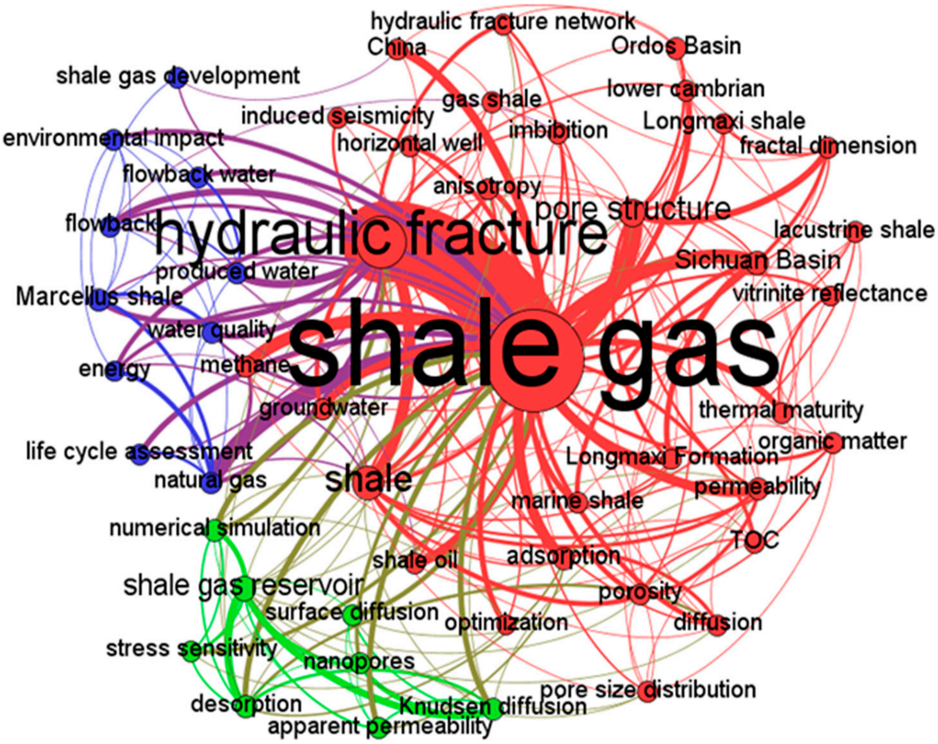

Figure 6. The co-word network during 2015–2016 (density = 0.19, network diameter = 3, average degree = 9.32, average density = 28.84, average clustering coefficient = 0.632, average path length = 1.822).

The blue area is on environmental impact of SG development. Hydraulic fracture has enabled rapid development of SG resources. However, wastewater management has been one of the most contentious and widely publicized issues in SG production. The flowback and produced water (known as FP water) generated by HF may pose a serious risk to the surrounding environment and public health because this wastewater usually contains many toxic chemicals and high levels of total dissolved solids (TDS) [65]. During 2015–2016, environmental impact of SG development gradually comes into the human field of vision, causing human's attention. Life cycle assessment is a technique or method for assessing the environmental impact of the product on its entire life cycle, from raw material acquisition, product production up to product disposal. As a new environmental management tool and preventive environmental protection, life cycle assessment is applied to evaluate the impact of SG development. Life cycle assessment approach was achieved out focusing on both exploration and development stages of hydraulic fracturing process [66].

3.2. More Implications from the Evolution of SGR's Hotspots at Each Stage

From the dynamic co-word network, we can find more evolutionary dependence and trends which is shown in Figure 7.

In 1998–2010, the boundary between the topics in the network pattern as in Figure 3 is clear and the contact between the topics is weak. There is little communication between the ten sub-domains at this stage. SGR was at the initial stage; the research focus was not prominent and the contents were diverse. The research directions included geological structure, resource distribution, gas composition, storage volume and so on. SG generation mechanism, geological framework and related characteristics were the main hotspots during the period.

In 2011–2012, as can be seen from Figure 4, the number of the topics in the network was reduced at that stage, while the links between the sub-domains were enhanced and many topics significantly increased their connections with the keyword "shale gas." Compared with the previous stage, the more prominent phenomenon was the emergence of more economic and political factors. Hydraulic fracturing as practical technology of SG extraction also appeared at this stage and had a greater degree of connectivity with the keywords "shale gas."

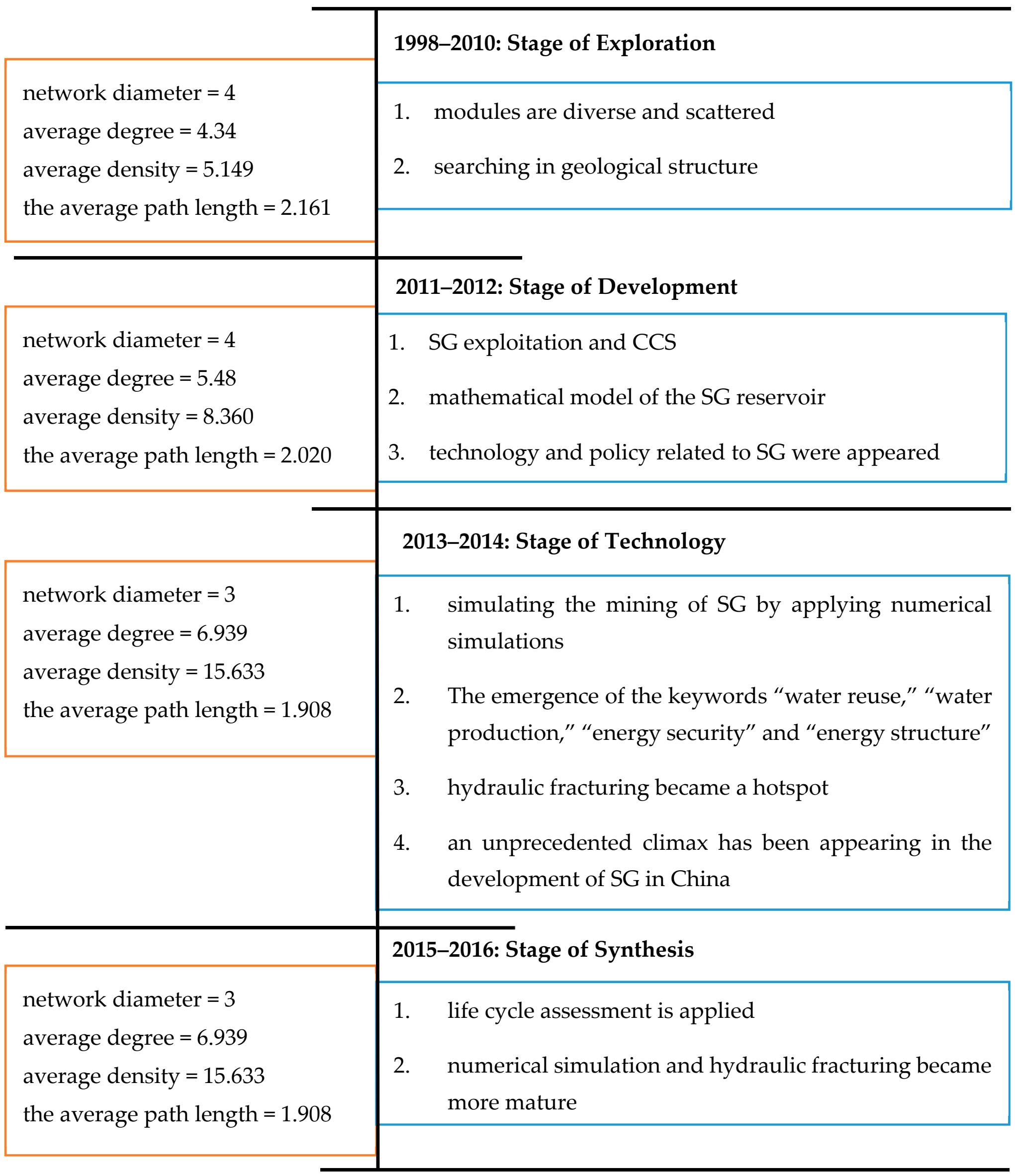

Figure 7. Evolutionary dependence and trends during 1998–2016.

In 2013–2014, the number of sub-domains of topics decreased to four and the connection degree in each field was further strengthened. The link between the sub-domains was strengthened and the connectivity between the keywords was significantly increased. The keyword "hydraulic fracturing," as the key technology in SG extraction, its frequency only was less than "shale gas" at this stage and the technology research related to the SG mining has gradually become the focus of research in this field. Compared with the previous stage, the emergence of energy security, energy structure and other keywords was a new focus point for the SGR. At the same time, in this period, a lot of keywords related to China have been appearing.

In 2015–2016, the number of sub-domains decreased to three, the degree of closeness between the fields was further greatly increased. This phenomenon clearly reflects that in the development of the domain, self-organized feature has prevailed. It is obvious that there were two definite directions for the SGR at this stage: the application of life cycle assessment method of exploring the impact of SG extraction process on the environment and the numerical simulation of studying SG diffusion, desorption, flow and other series of behavior in the shale. We can confidently predict that the two directions about SG may dominate the future SGR for a long time.

3.3. Analysis of the Underlying Evolutionary Law of SGR's Knowledge Domain

To find more underling evolutionary law of SGR's knowledge domain, now we conduct the detailed and rigorous analyses on the co-word network based on the concept and theory of complex network. We use all the keywords of each stage to construct the dynamic co-word network as shown in Figure 8.

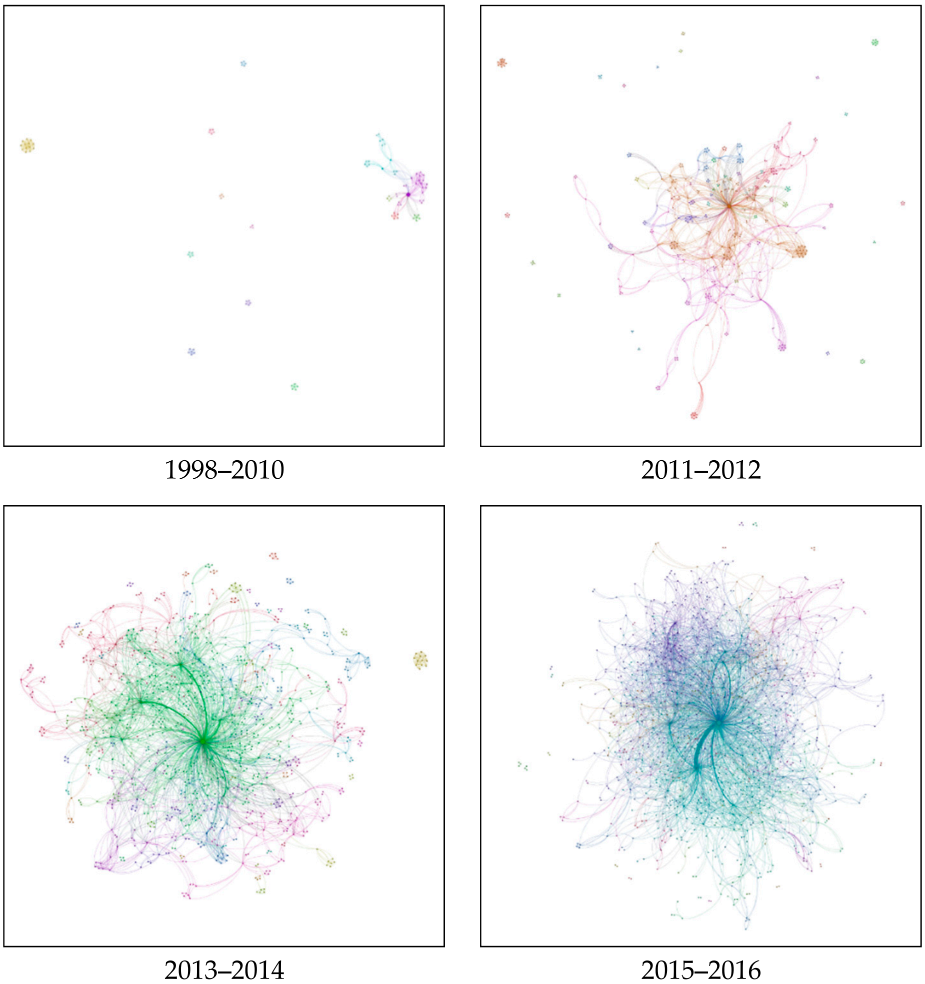

Figure 8. The evolving pattern of the co-word network at each stage.

From the evolving pattern of the co-word network at each stage as shown in Figure 8, we can find that the network of SGR has obvious complex network characteristics with time and it generally shows apparent self-organized phenomenon of from chaos to order. In details, with the growing complexity of the network, the number of clusters gradually decreases while the sizes of the clusters continue to grow. With the evolution of the knowledge domain, larger and larger clusters begin to shape and the clusters tend to centralize towards some specific nodes that could control their neighboring nodes. That is, a kind of self-organized force is driving the evolution of SGR's knowledge domain. In following section, we give more detailed analyses.

3.3.1. The Small-World Mechanism of the Evolving Domain

To analyze more underlying mechanism of SGR's domain, we further obtain the co-word network with all keywords as nodes during 1998–2016, as shown in Figure 9. For example, during the evolution of SGR, how different topics are connected? To find the mechanisms of connection is very important.

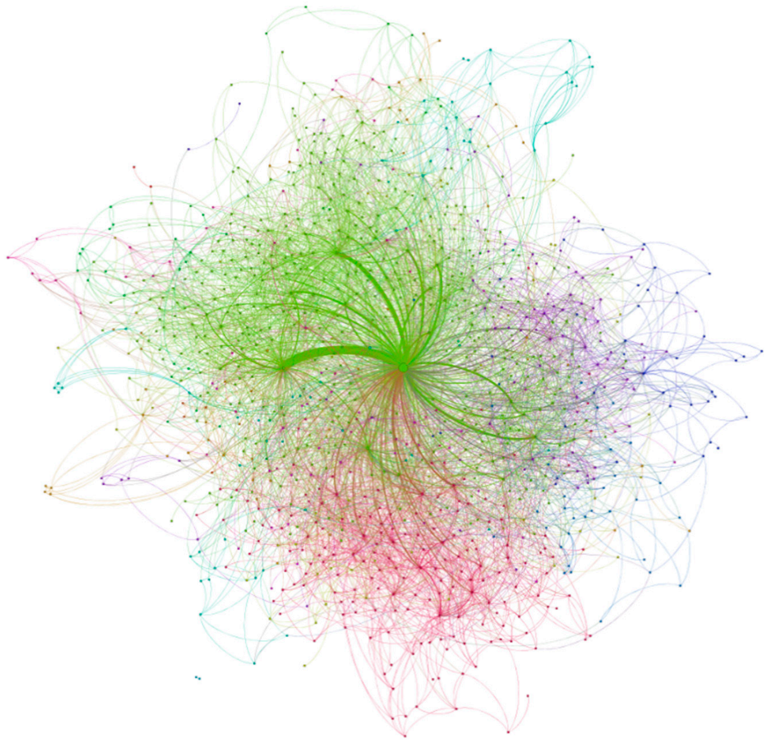

Figure 9. The co-word network including all keywords during 1998–2016.

We invoke some measures (e.g., clustering coefficient, average path length) of complex network to analyze the co-word network. The collectiveness is an important feature of complex network. The communities represent the acquaintance circles of the network. Members within the communities are familiar with each other. To characterize the clusters of a network, researchers have proposed the concept of clustering coefficients. The clustering coefficient measures the collective degree of the network. The clustering coefficient C_i of *i*-node describes the connection between nodes in the network that are directly connected to the *i*-node. The expression of C_i is $C_i = \frac{2e_i}{k_i(k_i-1)}$, where k_i represents the degree of the *i*-node and e_i is the number of actual edges between the neighbors of *i*-node. The clustering coefficient C of the complex network is the average of the clustering coefficients of all nodes with degrees higher than one, which is

$$C = \sum_{i=1}^{N} C_i,$$

The distance $l(i, j)$ between two i-nodes and j-nodes in the network is defined as the number of edges on the shortest path that connect the two nodes. The maximum distance between any two nodes in the network is called the diameter of the network. The average path length L of the network is defined as the average of the distances between any two nodes, which is

$$L = \frac{1}{\frac{1}{2}N(N-1)} \sum_{i>j} l(i,j),$$

The average path length of the network is also called the characteristic path length of the network.

It is generally thought that most networks can be divided into two types: regular networks and random networks. These two types of networks have their own characteristics. The regular networks have large clustering coefficients and large average path lengths, while the random networks have small clustering coefficients and large average path length. In contrast, Watts and Strogatz defined the "small-world networks" that not only have a small average path length L, which is same as a random network, but also have a large clustering coefficient that is same as a regular network. That is, it is worth noting that the small-world phenomenon of a network is usually accompanied by clustering phenomenon that means a high agglomeration coefficient and short-cut link effect that means a small average path length. This third type of network is different from both the random network and the regular network. In mathematics, physics and sociology, the small-world network is a special complex network in which most of the nodes are not adjacent to each other but most of the nodes can be reached from any other notes by a few steps. If a note in a small-world network represents a person and a link represents people know each other, the small-world network means that person can know strangers by a person who know both of them. We consider the co-word network has average path length L_g and clustering coefficient C_g, while a random network with a same number of nodes and edges has average path length L_{rand} and clustering coefficient C_{rand}. Obviously, if $L_g \geq L_{rand}$ and $C_g >> C_{rand}$ are satisfied, then the co-word network is verified to have a small-world effect. Let $r_g = \frac{C_g}{C_{rand}}$, $\lambda = \frac{L_g}{L_{rand}}$, $S = \frac{r_g}{\lambda_g}$, S is the small-world measure of the network.

In our research, we calculate all of these parameters, as listed in Table 5. We find that S is greater than 1. Thus, we rigorously verify that the co-word network of SGR has a small-world effect. In addition, we find that S of 2015–2016 is smaller than S of 2013–2014. The reason is in 2015–2016, there are more new research areas and keywords appear and most of them have low degrees and frequencies, so it weakened the small-world effect of 2015–2016. High efficient connection and high-speed level information transmission between nodes are the most important characteristics of the small-world network. In this way, the uncovered small-world property of the knowledge domain will lead to high speed information transmission across nodes. We may conclude that the small-world connection has been an important mechanism of driving the evolution of SGR's knowledge domain.

Table 5. The small-world measures of the network.

Stage	C_g	L_g	C_{rand}	L_{and}	S
1998–2010	0.957	2.111	0.054	2.664	22.365
2011–2012	0.934	2.670	0.015	3.411	79.547
2013–2014	0.886	3.062	0.007	4.125	170.512
2015–2016	0.716	2.739	0.007	3.809	142.244

3.3.2. The Scale-Free Mechanism of the Evolving Domain

During the evolution of SGR, how new topics are connected to prior topics? To find the mechanisms of connection is very important. The degree distribution is another important measure for recognizing the evolution mechanism of the domain. When nodal degrees of a network satisfy the power-law distribution (e.g., scale-free characteristics), we may say the network is scale-free network.

We obtain the degree distribution in different cases as in Figure 10. From 1998 to 2010, the fitting confidence coefficient is 0.139. Since this number is too small, the network in this period is not yet scale-free. The confidence coefficient reaches 0.476 during 2011–2012 and decreases to be 0.306 during 2013–2014. From 2015 to 2016, the confidence coefficient is up to 0.576. Among all cases during these years, the confidence coefficient during 2015–2016 is the biggest, holding the highest fitting degree. Obviously, though the fitting confidence coefficients of the networks have wave characteristics during these past years, the degree distributions at each stage all have power-law features and the power-law tendency has been generally increasing from 2011 to 2016. By including all the data from 1998 to 2016, we obtain the degree distribution, in which the fitted curve also satisfies the power-law distribution with confidence coefficient 0.3583. This means the network also has scale-free property during the whole range of time.

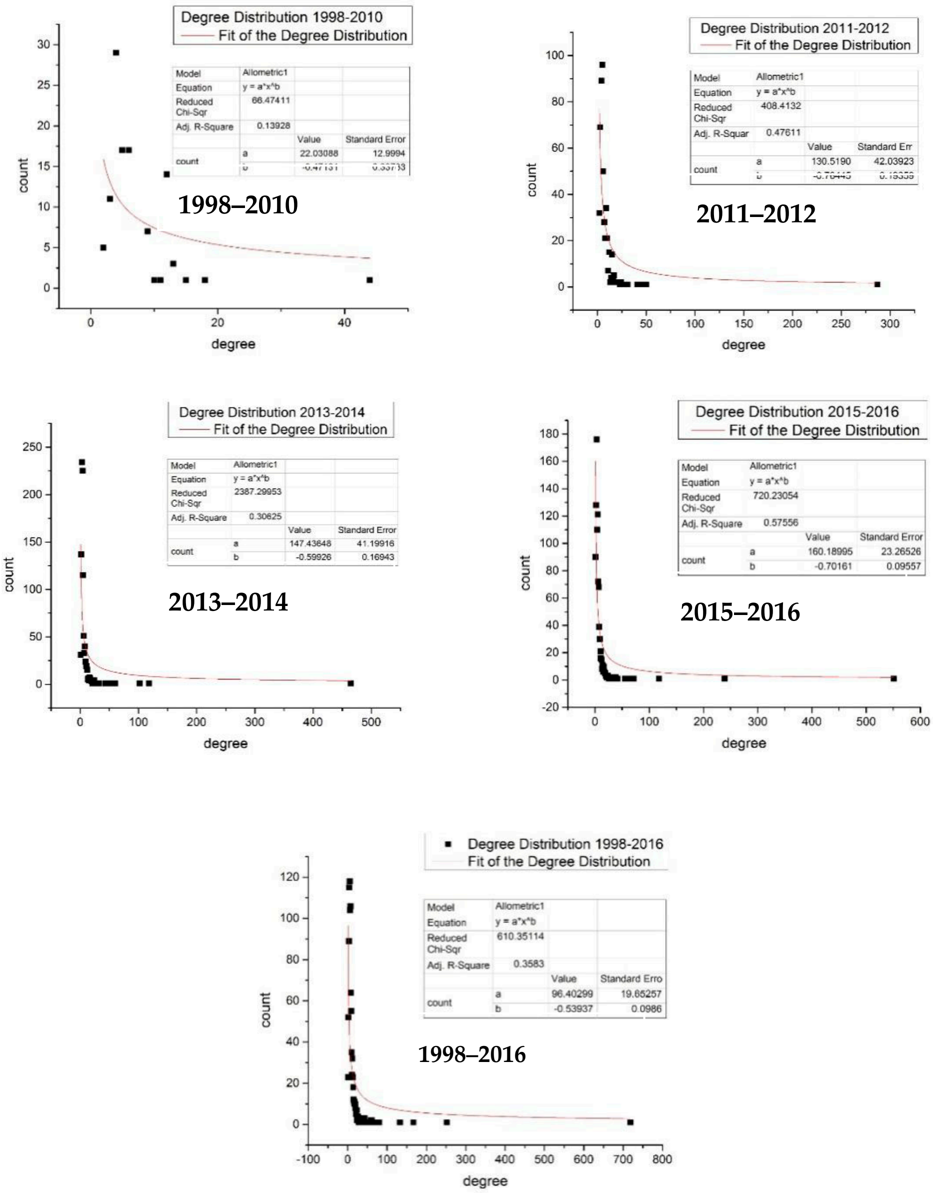

Figure 10. Degree distributions at different stages.

Scale-free feature means the preferential connection prevails during the evolution of a network. Thus, by finding the scale-free features of the network, we here verify that the preferential attachment has been an important mechanism of driving the evolution of SGR's knowledge domain. That is, in the scale-free network, when new nodes appear, they are more likely to connect to nodes that already have more connections. Over time, the "hub-nodes" have more connections than other nodes.

In our research, it can be found the nodes such as shale gas, hydraulic fracture and shale gas reservoir in the network of SGR can be acted as the "hub-nodes," whose degrees at each stage are shown in Table 6. In this connection, a scale-free effect means that there are very few "hub-nodes" with a large number of connections in the network and many "end nodes" with a small number of connections, indicating that the network is extremely "non-uniform." This non-uniform topology leads to some special properties. For example, SGR's domain is robust against random blows but is exceptionally fragile in the face of selective strikes. Non-uniformity also makes the scale-synchronization more difficult. Therefore, here we not only reveal the preferential connection mechanism of the evolving SGR's domain but also provide significant guidance to the optimization and stable control of the domain based on the quantitative measurement or analysis on the non-uniformity of the scale-free co-word network topology.

Table 6. The degrees of some "hub-nodes" at each stage.

Degree / Stage / Node	2011–2012	2013–2014	2015–2016
shale gas	287	485	551
hydraulic fracture	50	118	239
shale gas reservoir	10	20	62

3.4. Analysis of SGR in Regional Evolution of SG: Example of China

China, as the largest developing country and the largest country in the shale gas reserves [67], has significantly affected the global SG and SGR. Thus, after the forgoing analyses on the global SGR, we now conduct analyses on China's SGR during past years. Since China's SGR before 2009 is very few, we start our analysis from 2009. The date is based on CNKI database, one of the most authoritative database in china, which has become a leading international online publishing platform includes periodicals, dissertations, dissertations, conference papers, newspapers, reference books, yearbooks, patents, standards, Chinese studies and overseas literature resources. We searched from CNKI's all databases with the topic word "shale gas" as the retrieval term and we total get 17,305 publications.

As shows in Figure 11, the degree of each keywords in 2009–2010 is small, indicating that basic research and exploration of SG has just entered an initial start-up stage. The development of unconventional oil gas and oil gas substitutes has become major topics of non-conventional oil gas exploration and development. Similarly, as an important unconventional oil gas, SG caused a high extent of attention. Chinese tight sandstone gas has entered the development stage. The development and utilization of Coalbed methane and SG were starting. The basic research work on natural gas hydrate and other resources were also gradually commencing [68,69].

In Figure 12, The high frequency of the keyword "natural gas price" and the other related keywords "natural gas market", "natural gas consumption" reflects that at this stage researchers had further studies on the relationship between natural gas prices and SG extraction. In the gray area, the emergence of a series of keywords (e.g., "energy structure", "energy supply", "energy independence", "renewable energy" and "energy resources") shows that a large number of scholars focused on the impact of SG development from the angle of national energy structure. The emergence of the keywords "policy," "resource potential evaluation", "development plan", "land resources" and "strategic research center" proved that China's government has emphasized the importance of SG development from the perspective of the national strategic significance. At this stage, a lot of research to promote the development of shale gas has been carried out [70].

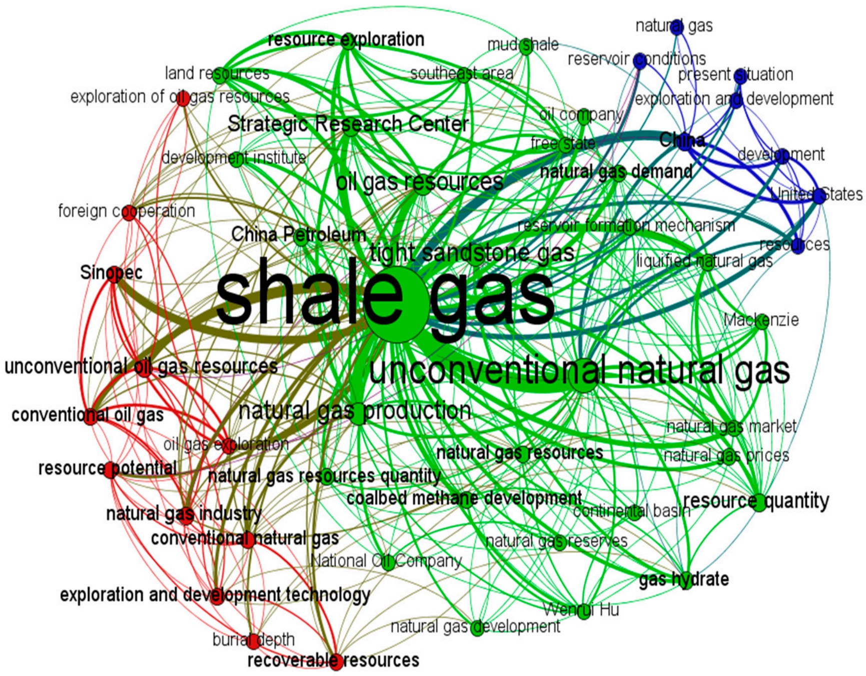

Figure 11. The co-word network of China's SGR during 2009–2010: start-up stage.

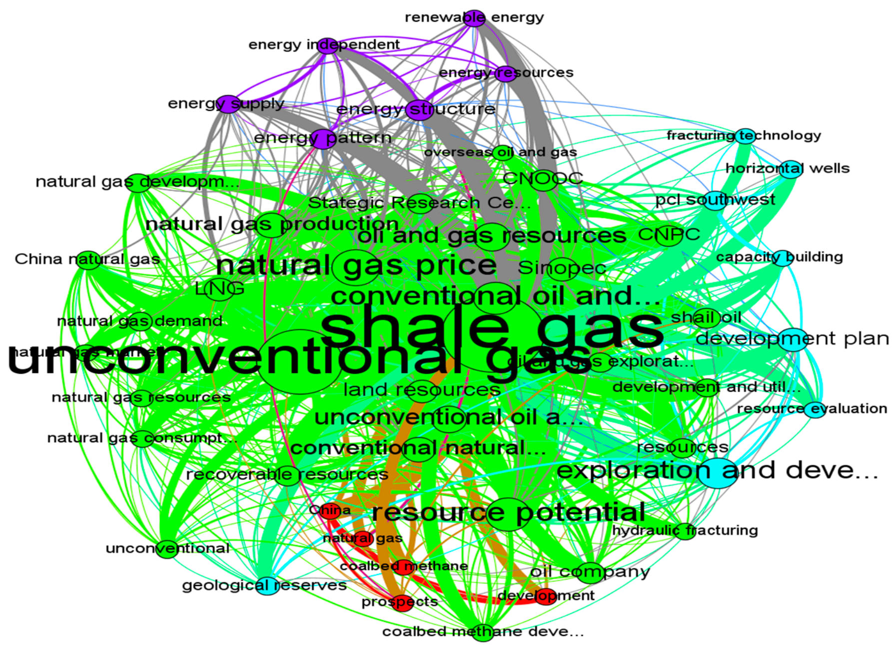

Figure 12. The co-word network of China's SGR during 2011–2012: energy structure, policy, economic market.

During 2013–2014, as shown in Figure 13, the connection between the topics also increased significantly. In the keywords associated with SG exploration, we find the keywords "Southwest Oilfield," "JiangHan Oilfield," "Longmaxi Formation" and "Geological Survey" appeared at this time, by reviewing the relevant literature, which shows that China has begun to explore the SG [71]. SG exploration was the general trend during this stage, the SGR has entered the application stage of the actual technology for SG extraction.

During 2015–2016, as shown in Figure 14, "oil and gas exploration," "horizontal wells," "exploration and development technology" have high degrees, the reserves and mining technologies of SG were become the research focus [72]. Exploration and simulation of horizontal wells and hydraulic fracturing have been the most effective methods for the development of SG [73–75].

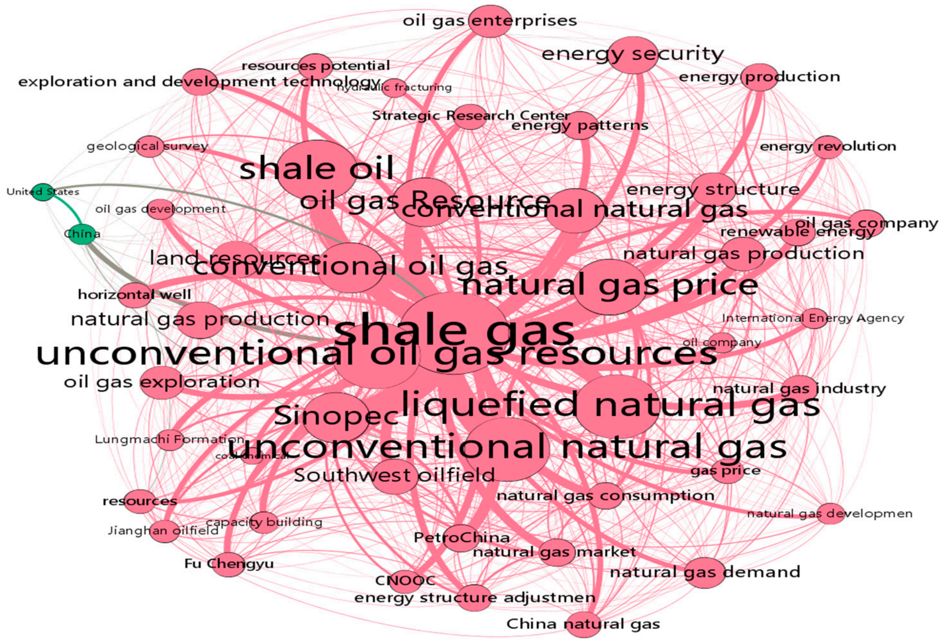

Figure 13. The co-word network of China's SGR during 2013–2014: actual technology for SG extraction.

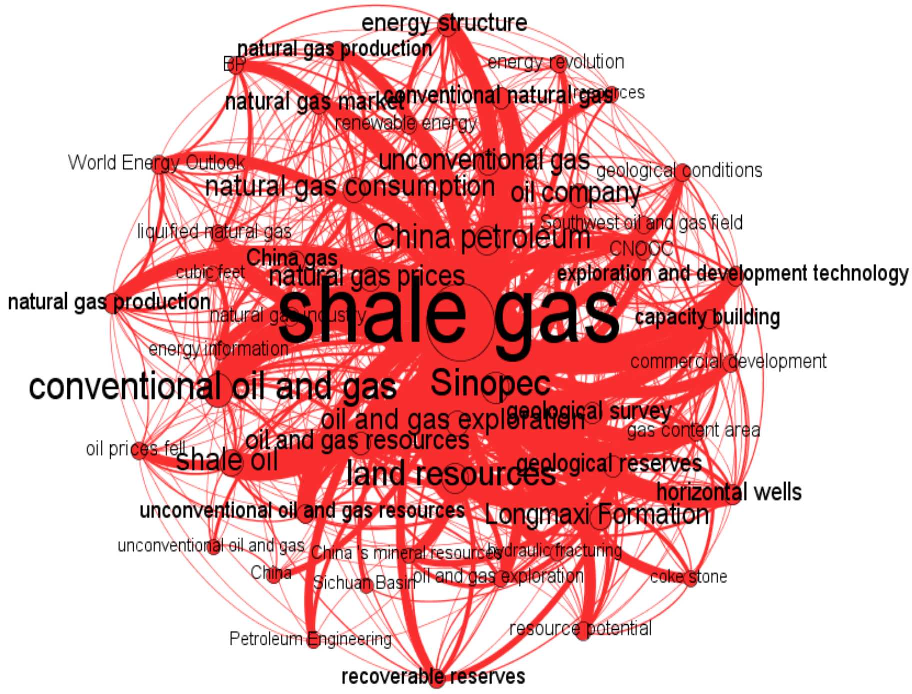

Figure 14. The co-word network of China's SGR during 2015–2016: mining technologies of SG.

Considering the dynamic change of the co-word network pattern of SGR's co-word network in China from 2009 to 2016 (Figure 15), the evolutionary analysis shows that China's SGR has constantly approached to new development stages from 2009 to 2016, China's SGR has a similar evolution process and self-organized phenomena with the international co-word network. At the same time, China's focus shifted from the improvement of GS policy to the study of related technologies such as hydraulic fracturing and horizontal wells. But compared to the international research in shale gas, to the environment impact on keywords are not expressed, China should pay attention to this aspect.

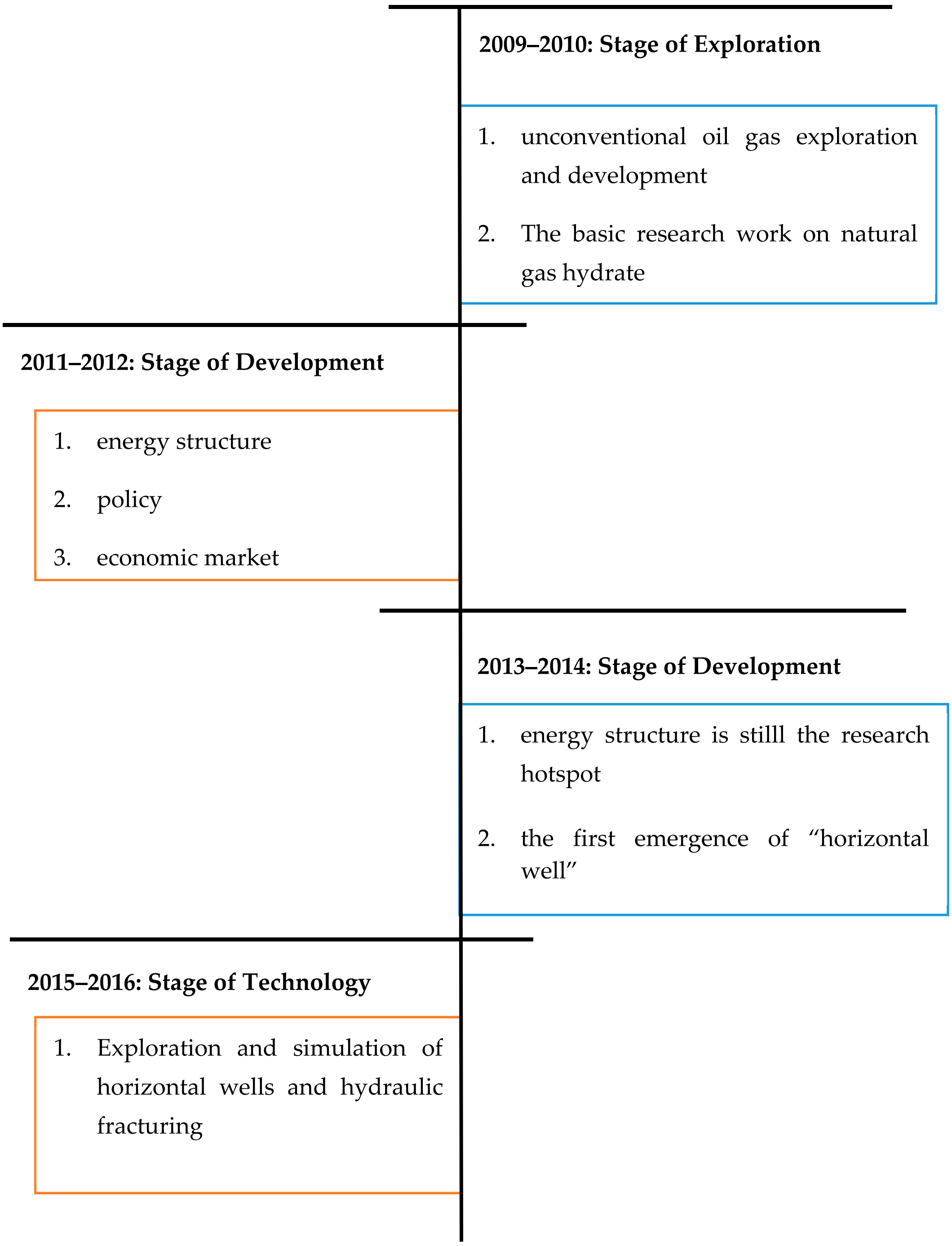

Figure 15. Evolutionary dependence and trends during 2009–2016 in China.

4. Conclusions

This paper provides comprehensive analyses for SGR based on a large scale of publications and their co-word networks. We here summarize some main results.

By the keyword analysis and co-word network, we visually elucidate the development of SGR in each period. We not only recognize the key topical development at each stage but also reveal the underlying evolutionary codes. We give how SGR evolves in theory, technique and related aspects.

We predict life cycle assessment method application, numerical simulation in SG extraction process and so on may be the future directions about SGR. These results provide comprehensive and mechanistic views of the evolving SGR's domain.

In general, we can find that the network of SGR has obvious complex network characteristics, showing the self-organized phenomenon from chaos to order. We uncover the small-world and scale-free properties of the knowledge domain, which lead to high-speed information transmission across and preferential connections between the nodes. The small-world and scale-free effects have been important mechanisms of driving the evolution of SGR's knowledge domain, which has provided important instructions for the domain optimization and control.

We take China's SGR as an important regional case for analysis. It is found that the co-word network in China has the same evolution process and self-organized phenomenon with the international one. At the same time, China is in urgent need of SG technology development stage, the next stage is to improve the development of SG technology.

Our above findings would provide useful references for the future SGR of scholars, optimization or control of the domain and the strategy/policy of countries or globalization. Authors should discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

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

References

1. Gao, J.; You, F. Design and optimization of shale gas energy systems: Overview, research challenges, and future directions. *Comput. Chem. Eng.* **2017**, *106*, 699–718. [CrossRef]
2. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries outside the United States. Available online: https://www.eia.gov/ (accessed on 25 November 2017).
3. Bilgili, F.; Koçak, E.; Bulut, Ü.; Sualp, M.N. How did the US economy react to shale gas production revolution? An advanced time series approach. *Energy* **2016**, *116*, 963–977. [CrossRef]
4. Wang, Q.; Chen, X.; Jha, A.N.; Rogers, H. Natural gas from shale formation—The evolution, evidences and challenges of shale gas revolution in united states. *Renew. Sustain. Energy Rev.* **2014**, *30*, 1–28. [CrossRef]
5. Peebles, M.W.H. *Evolution of the Gas Industry*; Macmillan: Oxford, UK, 1980.
6. Hill, D.G.; Lombardi, T.E.; Martin, J.P. Fractured shale gas potential in New York. *Northeast. Geol. Environ. Sci.* **2004**, *26*, 1–49.
7. Melikoglu, M. Shale gas: Analysis of its role in the global energy market. *Renew. Sustain. Energy Rev.* **2014**, *37*, 460–468. [CrossRef]
8. Geng, J.B.; Ji, Q.; Fan, Y. The impact of the North American shale gas revolution on regional natural gas markets: Evidence from the regime-switching model. *Energy Policy* **2016**, *96*, 167–178. [CrossRef]
9. Chen, Z.; Hannigan, P. A shale gas resource potential assessment of Devonian horn river strat. *Can. J. Earth Sci.* **2016**, *53*, 156–167. [CrossRef]
10. Ross, D.J.K.; Bustin, R.M. Characterizing the shale gas resource potential of Devonian-Mississippian strata in the western canada sedimentary basin: Application of an integrated formation evaluation. *AAPG Bull.* **2008**, *92*, 87–125. [CrossRef]
11. Wang, H.; Ma, F.; Tong, X.; Liu, Z.; Zhang, X.; Wu, Z.; Li, D.; Wang, B.; Xie, Y.; Yang, L. Assessment of global unconventional oil and gas resources. *Pet. Explor. Dev.* **2016**, *43*, 925–940. [CrossRef]
12. Measham, T.G.; Fleming, D.A.; Schandl, H. A conceptual model of the socioeconomic impacts of unconventional fossil fuel extraction. *Glob. Environ. Chang.* **2016**, *36*, 101–110. [CrossRef]
13. Karnkowski, P.H.; Pikulski, L.; Wolnowski, T. Petroleum geology of the polish part of the Baltic region—An overview. *Geol. Q.* **2010**, *54*, 143–158.
14. Lis, A.; Stankiewicz, P. Framing shale gas for policy-making in Poland. *J. Environ. Policy Plan.* **2017**, *19*, 53–71. [CrossRef]
15. Warner, D. Shale gas in Australia: A great opportunity comes with significant challenges. *APPEA J.* **2011**, *53*, 18–21. [CrossRef]

16. Rees, N.; Carter, S.; Heinson, G.; Krieger, L. Monitoring shale gas resources in the cooper basin using magnetotellurics. *Geophysics* **2016**, *81*, A13–A16. [CrossRef]
17. Schulz, H.M.; Horsfield, B.; Sachsenhofer, R.F. Shale gas in Europe: A regional overview and current research activities. In Proceedings of the 7th Petroleum Geology Conference, London, UK, 30 March–2 April 2009; Volume 1, pp. 1079–1085.
18. Mair, R.; Bickle, M.; Goodman, D.; Koppelman, B.; Roberts, J.; Selley, R.; Shipton, Z.; Thomas, H.; Walker, A.; Woods, E.; et al. *Shale Gas Extraction in the UK: A Review of Hydraulic Fracturing*; Royal Society and Royal Academy of Engineering: London, UK, 2012; Volume 1–2, pp. 73–84.
19. Westaway, R. Repurposing of disused shale gas wells for subsurface heat storage: Preliminary analysis concerning UK issues. *Q. J. Eng. Geol. Hydrogeol.* **2016**, *49*, 213–227. [CrossRef]
20. Black, D.E.; Booth, P.W.K.; Wit, M.J.D. Petrographic, geochemical and petro-physical analysis of the collingham formation near jansenville, Eastern Cape, South Africa—Potential cap rocks to shale gas in the karoo. *S. Afr. J. Geol.* **2016**, *119*, 171–186. [CrossRef]
21. Pietersen, K.; Kanyerere, T.; Levine, A.; Matshini, A.; He, B. An analysis of the challenges for groundwater governance during shale gas development in South Africa. *Water SA* **2016**, *42*, 421–431. [CrossRef]
22. Bertassoli, D.J., Jr.; Sawakuchi, H.O.; Almeida, N.S.; Castanheira, B.; Alem, V.A.T.; Camargo, M.G.P.; Krusche, A.V.; Brochsztain, S.; Sawakuchi, A.O. Biogenic methane and carbon dioxide generation in organic-rich shales from southeastern Brazil. *Int. J. Coal Geol.* **2016**, *162*, 1–13. [CrossRef]
23. Mendhe, V.A.; Mishra, S.; Varma, A.K.; Kamble, A.D.; Bannerjee, M.; Sutay, T. Gas reservoir characteristics of the lower gondwana shales in Raniganj basin of eastern India. *J. Pet. Sci. Eng.* **2016**, *149*, 649–664. [CrossRef]
24. Yao, J.; Sun, H.; Fan, D.Y.; Wang, C.C.; Sun, Z.X. Numerical simulation of gas transport mechanisms in tight shale gas reservoirs. *Pet. Sci.* **2013**, *10*, 528–537. [CrossRef]
25. Clarkson, C.R.; Haghshenas, B.; Ghanizadeh, A.; Qanbari, F.; Williams-Kovacs, J.D.; Riazi, N.; Debuhr, C.; Deglint, H.J. Nanopores to megafractures: Current challenges and methods for shale gas reservoir and hydraulic fracture characterization. *J. Nat. Gas Sci. Eng.* **2016**, *31*, 612–657. [CrossRef]
26. Chen, X.; Bao, S.; Hou, D.; Mao, X. Methods and key parameters for shale gas resource evaluation. *Pet. Explor. Dev. Online* **2012**, *39*, 605–610. [CrossRef]
27. Hill, R.J.; Zhang, E.; Katz, B.J.; Tang, Y. Modeling of gas generation from the barnett shale, fort worth basin, texas. *AAPG Bull.* **2007**, *91*, 501–521. [CrossRef]
28. Civan, F.; Rai, C.S.; Sondergeld, C.H. Shale-gas permeability and diffusivity inferred by improved formulation of relevant retention and transport mechanisms. *Transp. Porous Media* **2011**, *86*, 925–944. [CrossRef]
29. Rutqvist, J.; Rinaldi, A.P.; Cappa, F.; Moridis, G.J. Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs. *J. Pet. Sci. Eng.* **2013**, *107*, 31–44. [CrossRef]
30. Cho, Y.; Ozkan, E.; Apaydin, O.G. Pressure-dependent natural-fracture permeability in shale and its effect on shale-gas well production. *SPE Reserv. Eval. Eng.* **2013**, *16*, 216–228. [CrossRef]
31. Lee, S.J.; Lee, K.S. Performance of shale gas reservoirs with nonuniform multiple hydraulic fractures. *Energy Sources Part A Recovery Util. Environ. Eff.* **2015**, *37*, 1455–1463. [CrossRef]
32. Wang, G.; Carr, T.R. Organic-rich marcellus shale lithofacies modeling and distribution pattern analysis in the Appalachian basin. *AAPG Bull.* **2013**, *97*, 2173–2205. [CrossRef]
33. Gracceva, F.; Zeniewski, P. Exploring the uncertainty around potential shale gas development—A global energy system analysis based on tiam (times integrated assessment model). *Energy* **2013**, *57*, 443–457. [CrossRef]
34. Jia, A.; Wei, Y.; Jin, Y. Progress in key technologies for evaluating marine shale gas development in China. *Pet. Explor. Dev.* **2016**, *43*, 1035–1042. [CrossRef]
35. Luo, X.; Wang, S.; Jing, Z.; Xu, G. Analysis of Dry CO_2 Fracturing Technology for Efficient Development of Shale Gas Reservoirs. In Proceedings of the 2016 5th International Conference on Measurement, Instrumentation and Automation, Shenzhen, China, 17–18 September 2016; Volume 138, pp. 30–33.
36. Liss, W.E. Impacts of shale gas advancements on natural gas utilization in the United States. *Energy Technol.* **2015**, *2*, 953–967. [CrossRef]
37. Wilkins, R.F.; Menefee, A.H.; Clarens, A.F. Environmental life cycle analysis of water and CO_2-based fracturing fluids used in unconventional gas production. *Environ. Sci. Technol.* **2016**, *50*, 13134–13141. [CrossRef] [PubMed]

38. Vidic, R.D.; Brantley, S.L.; Vandenbossche, J.M.; Yoxtheimer, D.; Abad, J.D. Impact of shale gas development on regional water quality. *Science* **2013**, *340*, 1235009. [CrossRef] [PubMed]
39. Warner, N.R.; Christie, C.A.; Jackson, R.B.; Vengosh, A. Impacts of shale gas wastewater disposal on water quality in western pennsylvania. *Environ. Sci. Technol.* **2013**, *47*, 11849–11857. [CrossRef] [PubMed]
40. Burnham, A.; Han, J.; Clark, C.E.; Wang, M.; Dunn, J.B.; Palourivera, I. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environ. Sci. Technol.* **2012**, *46*, 619–627. [CrossRef] [PubMed]
41. Rahm, B.G.; Riha, S.J. Toward strategic management of shale gas development: Regional, collective impacts on water resources. *Environ. Sci. Policy* **2012**, *17*, 12–23. [CrossRef]
42. Jenner, S.; Lamadrid, A.J. Shale gas vs. coal: Policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States. *Energy Policy* **2013**, *53*, 442–453. [CrossRef]
43. Cotton, M.; Rattle, I.; Alstine, J.V. Shale gas policy in the United Kingdom: An argumentative discourse analysis. *Energy Policy* **2014**, *73*, 427–438. [CrossRef]
44. Dilmore, R.M.; Iii, J.I.S.; Glosser, D.; Carter, K.M.; Bain, D.J. Spatial and temporal characteristics of historical oil and gas wells in pennsylvania: Implications for new shale gas resources. *Environ. Sci. Technol.* **2015**, *49*, 12015–12023. [CrossRef] [PubMed]
45. Tagliaferri, C.; Lettieri, P.; Chapman, C. Life cycle assessment of shale gas in the UK. *Energy Procedia* **2015**, *75*, 2706–2712. [CrossRef]
46. McJeon, H.; Edmonds, J.; Bauer, N.; Clarke, L.; Fisher, B.; Flannery, B.P.; Hilaire, J.; Krey, V.; Marangoni, G.; Mi, R.; et al. Limited impact on decadal-scale climate change from increased use of natural gas. *Nature* **2014**, *514*, 482–485. [CrossRef] [PubMed]
47. Goodwin, S.; Carlson, K.; Knox, K.; Douglas, C.; Rein, L. Water intensity assessment of shale gas resources in the Wattenberg field in northeastern Colorado. *Environ. Sci. Technol.* **2014**, *48*, 5991–5995. [CrossRef] [PubMed]
48. Lutz, B.D.; Lewis, A.N.; Doyle, M.W. Generation, transport, and disposal of wastewater associated with marcellus shale gas development. *Water Resour. Res.* **2013**, *49*, 647–656. [CrossRef]
49. Ross, D.J.K.; Bustin, R.M. The importance of shale composition and pore structure upon gas storage potential of shale gas reservoirs. *Mar. Pet. Geol.* **2009**, *26*, 916–927. [CrossRef]
50. Pollastro, R.M.; Jarvie, D.M.; Hill, R.J.; Adams, C.W. Geologic framework of the Mississippian Barnett shale, barnett-paleozoic total petroleum system, bend arch–fort worth basin, Texas. *AAPG Bull.* **2007**, *91*, 405–436. [CrossRef]
51. Hill, R.J.; Jarvie, D.M.; Pollastro, R.M.; Bowker, K.A.; Claxton, B.L. Geochemistry of an unconventional gas prospect: The Barnett Shale gas model. *Geochim. Cosmochim. Acta* **2004**, *68*, A231.
52. Watkins, E.M. Mitsubishi, PWE to form Canadian shale gas joint venture. *Oil Gas J.* **2010**, *108*, 27–28.
53. Court, B.; Celia, M.A.; Nordbotten, J.M.; Elliot, T.R. Active and integrated management of water resources throughout CO_2, capture and sequestration operations. *Energy Procedia* **2011**, *4*, 4221–4229. [CrossRef]
54. Court, B.; Elliot, T.R.; Dammel, J.; Buscheck, T.A.; Rohmer, J.; Celia, M.A. Promising synergies to address water, sequestration, legal, and public acceptance issues associated with large-scale implementation of CO_2 sequestration. *Mitig. Adapt. Strateg. Glob. Chang.* **2012**, *17*, 569–599. [CrossRef]
55. Bernard, S.; Wirth, R.; Schreiber, A.; Schulz, H.M.; Horsfield, B. Formation of nanoporous pyrobitumen residues during maturation of the barnett shale (fort worth basin). *Int. J. Coal Geol.* **2012**, *103*, 3–11. [CrossRef]
56. Bernard, S.; Horsfield, B.; Schulz, H.M.; Wirth, R.; Schreiber, A.; Sherwood, N. Geochemical evolution of organic-rich shales with increasing maturity: A stxm and tem study of the posidonia shale (lower toarcian, northern Germany). *Mar. Pet. Geol.* **2012**, *31*, 70–89. [CrossRef]
57. Guo, J.; Zhang, L.; Wang, H.; Feng, G. Retracted article: Pressure transient analysis for multi-stage fractured horizontal wells in shale gas reservoirs. *Transp. Porous Media* **2012**, *93*, 635–653. [CrossRef]
58. Kirk, M.F.; Martini, A.M.; Breecker, D.O.; Colman, D.R.; Takacs-Vesbach, C.; Petsch, S.T. Impact of commercial natural gas production on geochemistry and microbiology in a shale-gas reservoir. *Chem. Geol.* **2012**, *332*, 15–25. [CrossRef]
59. Patwardhan, S.D.; Famoori, F.; Gunaji, R.G.; Govindarajan, S.K. Simulation and mathematical modeling of stimulated shale gas reservoirs. *Ind. Eng. Chem. Res.* **2014**, *53*, 19788–19805. [CrossRef]
60. Zhai, Z.; Wang, X.; Jin, X.; Sun, L.; Li, J.; Cao, D. Adsorption and diffusion of shale gas reservoirs in modeled clay minerals at different geological depths. *Energy Fuels* **2014**, *28*, 7467–7473. [CrossRef]

61. Feng, Z.Q.; Bing-Song, Y.U.; Zeng, Q.N.; Yu-Fei, L.I.; Jiang, H.J. Characteristics and main controlling factors of shale gas reservoir in the southeastern Ordos basin. *Spec. Oil Gas Reserv.* **2013**, *20*, 40–43.
62. Zhang, R.; Zhang, L.; Wang, R.; Zhao, Y.; Huang, R. Simulation of a multistage fractured horizontal well with finite conductivity in composite shale gas reservoir through finite-element method. *Energy Fuels* **2016**, *30*, 9036–9049. [CrossRef]
63. Song, W.; Yao, J.; Li, Y.; Sun, H.; Zhang, L.; Yang, Y.; Zhao, J.; Sui, H. Apparent gas permeability in an organic-rich shale reservoir. *Fuel* **2016**, *181*, 973–984. [CrossRef]
64. Wang, J.; Kang, Q.; Chen, L.; Rahman, S.S. Pore-scale lattice Boltzmann simulation of micro-gaseous flow considering surface diffusion effect. *Int. J. Coal Geol.* **2017**, *169*, 62–73. [CrossRef]
65. Zhang, X.; Sun, A.Y.; Duncan, I.J. Shale gas wastewater management under uncertainty. *J. Environ. Manag.* **2016**, *165*, 188–198. [CrossRef] [PubMed]
66. Jaballah, H.J.B.; Ammar, F.B. Life cycle assessment impact of fraking shale gas in Tunisia. In Proceedings of the 2015 6th International Renewable Energy Congress, Sousse, Tunisia, 24–26 March 2015; IEEE: New York, NY, USA, 2015.
67. Li, Y.; Li, Y.; Wang, B.; Chen, Z.; Nie, D. The status quo review and suggested policies for shale gas development in china. *Renew. Sustain. Energy Rev.* **2016**, *59*, 420–428. [CrossRef]
68. Brandt, A.R. Converting oil shale to liquid fuels with the Alberta taciuk processor: Energy inputs and greenhouse gas emissions. *Energy Fuels* **2015**, *23*, 6253–6258. [CrossRef]
69. Han, X.X.; Jiang, X.M.; Cui, Z.G. Studies of the effect of retorting factors on the yield of shale oil for a new comprehensive utilization technology of oil shale. *Appl. Energy* **2009**, *86*, 2381–2385. [CrossRef]
70. Guan, X.X.; Fan, Y.X.; Cao, Q. Thoughts on unconventional oil and gas development in China. *Appl. Mech. Mater.* **2012**, *121–126*, 3034–3038. [CrossRef]
71. Liang, C.; Jiang, Z.; Zhang, C.; Guo, L.; Yang, Y.; Li, J. The shale characteristics and shale gas exploration prospects of the lower Silurian Longmaxi shale, Sichuan basin, south China. *J. Nat. Gas Sci. Eng.* **2014**, *21*, 636–648. [CrossRef]
72. Chen, S.S.; Sun, Y.; Tsang, D.C.; Graham, N.J.; Ok, Y.S.; Feng, Y.; Li, X.-D. Potential impact of flowback water from hydraulic fracturing on agricultural soil quality: Metal/metalloid bioaccessibility, microtox bioassay, and enzyme activities. *Sci. Total Environ.* **2017**, *579*, 1419–1426. [CrossRef] [PubMed]
73. Liu, N.; Wang, G. Shale gas sweet spot identification and precise geo-steering drilling in Weiyuan block of Sichuan basin, SW China. *Pet. Explor. Dev.* **2016**, *43*, 1067–1075. [CrossRef]
74. Sun, Y.; Bai, B.; Ma, Y.; Flori, R., Jr. Flow behavior characterization of a polyacrylamide-based friction reducer in microchannels. *Ind. Eng. Chem. Res.* **2014**, *53*, 20036–20043. [CrossRef]
75. Tabatabaei, M.; Zhu, D. Fracture-stimulation diagnostics in horizontal wells through use of distributed-temperature-sensing technology. *SPE Prod. Oper.* **2012**, *27*, 356–362. [CrossRef]