Spatial-Temporal Distribution of Carbon Capture Technology Drawing on Patent Data

火力発電所等から出る二酸化炭素の回収・貯蔵（CCS）技術の研究開発と導入がどこまで進んでいるかを、各国の特許取得状況から解析した。

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Abstract

Carbon capture & storage (CCS) is a currently available technology that can allow industrial sectors to meet deep emissions reduction goals. The development of carbon capture technology is vital to make CCS viable. As a significant output indicator of innovation, patent can provide a comprehensive view on innovation activities. This study aims to present an overview on carbon capture technology, in the attempt to characterize spatial and temporal distribution based on patent bibliometrics. We make a retrieval strategy and built a database set of 9847 patents in span of forty years from Derwent Innovations Index database. About temporal trend, this study reveals slow increasing phase and sharp increasing phase by annual patent count. Then we presents emerging stage and growth stage by cumulative patent count, drawing on theoretical model of technology life cycle. Year of 2006 is the turning point apparently, but it’s not an accident due to shifts emerged in governments, innovators and firms in years before. About spatial distribution, this study highlights eight countries (Japan, USA, France, China, Germany, Netherlands, UK and Korea) who have most of patents in the world in terms of top 50 patent assignee codes. We also introduce another means of CCS project for comparing study between innovation and operation, finding an obvious spatial overlap between patent layer and project layer. Then four categories of countries are found by distinguishing innovational features and (or) commercial statuses. The study tries to show the relative technical development trends across major countries. French occupies top mostly, China ranks up quickly, Japan, USA and Germany rank down relatively. Based on analysis above, we speculate that “Good Time” of carbon capture technology is coming, but operation of CCS project is still in slow growth due to some limitations.

Keywords Carbon Capture Technology, Spatial-Temporal Distribution, Patent Bibliometrics, CCS

1 Introduction

1.1. Climate change and CCS

2015 was the warmest year on record by far [1]. Most of the observed increase in global average temperatures since the mid-20th century is very likely (>90% probability) due to observed increase in anthropogenic greenhouse gases (GHGs) concentrations [2]. The climate will continue to change over the coming decades as more and more heat-trapping GHGs emitted by human activities accumulate in the atmosphere. On the other hand, if not focusing on costs, humanity can solve the GHGs concentrations problem by fifteen available and implemented technologies, including carbon dioxide (CO_2) capture and storage (CCS) [3]. CCS is a currently available technology that can allow industrial sectors (e.g., fossil-fuel power generation, iron and steel, cement, natural gas processing, oil refining, etc.) to meet deep emissions reduction goals. CCS can contribute one-sixth of CO_2 emission reductions required in 2050, and can contribute 14% of the cumulative emissions reductions between 2015 and 2050 compared to a business-as-usual approach, which would correspond to a 6°C rise in average global temperature [4].

CCS is not a single technology but involves the implementation of the following processes in an integrated manner: separation of CO_2 from mixtures of gases (e.g., the flue gases from a power station or a stream of CO_2-rich natural gas) and compression of this CO_2 to a liquid-like state; transport of the CO_2 to a suitable storage site; injection of the CO_2 into a geologic formation where it is retained by a natural (or engineered) trapping mechanism and monitored as necessary [5]. For enhancing CO_2 usage, utilization of CO_2 is integrated into CCS as CCUS in some countries, such as China [6]. Due to the fact that CO_2 is used maturely in fields such as enhanced oil recovery (EOR), enhanced coal-bed methane (ECBM), CO_2 chemical utilization and CO_2 biotransformation. Nonetheless, these is no essential difference between CCS and CCUS.

Many CCS technologies are commercially available today and can be applied across different sectors. CO_2 capture technologies include types of capture systems (see Fig. 1) such as post-combustion, pre-combustion and oxyfuel combustion, which have been available in natural gas processing, fertilizer manufacturing and hydrogen production. CO_2 transport technologies are the most technically mature in CCS, including pipeline and shipping. CO_2 storage technologies include many of same in oil and gas industry and have been proven to be economically feasible under specific conditions.

1.2. Carbon capture innovation activity

In most CCS systems, the cost of capture (including compression) is the largest cost component due to an additional high energy penalty, which could be reduced by technical development and economies of scale [8,9]. Furthermore, in the view of technology, the development of CO_2 capture technologies is vital to make CCS viable [10]. Meanwhile, in the view of patent bibliometrics, we find that most of CCS patents refer to CO_2 capture technologies in testing extractions which were done at the beginning of this study. Some former studies also revealed that carbon capture patents account for a large part in CCS patents (e.g., [11,12]). Hence, suitability of CCS in industrial applications mostly depends on the costs and readiness of carbon capture [4]. For focusing on the most key point, we study on carbon capture technology in this paper.

There are a number of possibilities for the measurement of innovation [13], which can be divided into two categories: input-based indicators and output-based indicators. Patent is considered as a significant output indicator of innovation or a tangible sign of knowledge, which can give a valuable insight into innovative activity of an object technology [14]. The main advantage of patent is that they are publicly available for rather long time periods and provide detailed technological information [15]. Patent is used in providing a comprehensive view

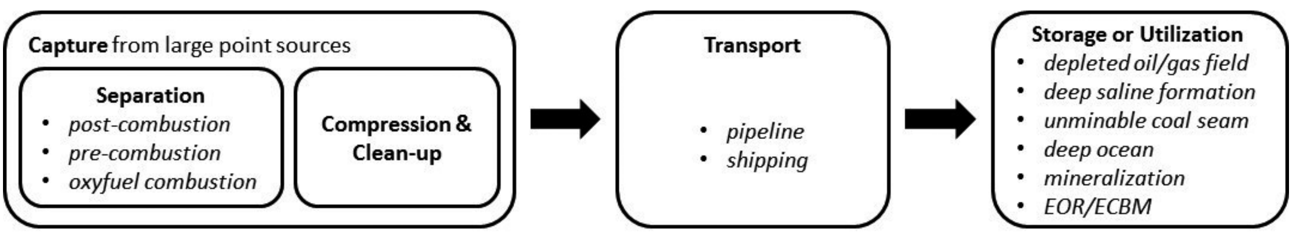

Fig. 1. Carbon capture and storage (CCS) chain. (Note: Modified based on Rubin et al., 2012 [7] and IEA, 2013 [5].)

on innovation activities in many domains, including low-carbon without a doubt. In former refers on low-carbon innovation activities, patent count provides a wealth of information on innovations and inventors as a kind of indication, e.g., [16–23].

Several studies investigated CCS technology or carbon capture technology by using patent bibliometrics. Dechezlepretre [24], WIPO [25] and OECD [18] analyzed a cluster of CCMTs (climate change mitigation technologies) which included CCS as a part, gave brief overviews on CCS technology. Cristina [10], Li [26] and Zhang [27] focused on specific technical routes and reagents in carbon capture drawing on patent bibliometrics or drawing on patent bibliometrics and article bibliometrics together. Wang [11] drew patent map of CCS and discussed technological features in nine countries. Miao [12] drew development paths by a different method from others which was patent citation analysis. We review these studies and make a general comparison (see Table 1).

First, we can divide these articles into two categories by distinguishing the purpose of study. One category is a general report which take CCS as a supplemental field rather than an essential part. Another category is full of specialized words which focus on technical routes mainly. But few studies pay attention on an overall spatial-temporal analysis in scale of all carbon capture technologies, for a deeper understand on developmental trend and technological distribution.

Second, patent count differs widely across studies from 945 to 9840, probably due to various databases, diverse retrieval strategies and distinguishing time span. In general but not absolutely, searching in sev-

Table 1 Former studies related to carbon capture technology by patent bibliometrics.

Refer	Description	Database set	Source
Dechezlepretre 2009 [24]	Took CCS as one of thirteen climate change mitigation technologies, provided an analysis of geographic distribution and international diffusion in an overall view. CCS is negligible, 0.35% of all fields' patents.	954 CCS patents	PATSTAT
WIPO 2009 [25]	Took CCS as one of nine alternative energy technologies, described CCS trends very briefly in terms of technology, although CCS is not, strictly speaking, an alternative energy	6858 CCS patents	EPO, WIPO, USPTO, JPO, KIPO, SIPO
OECD 2010 [18]	Took carbon capture as one of ten CCMTs, presented growth rate, inventive activity, major applicants and average patent family size with other technologies together.	8069 carbon capture patents	PATSTAT
Wang 2010 [11]	Presented CCS patent key word map by Thomson Data Analyzer and Aureka, described growth and IPC distribution briefly, discussed nine countries' technological features.	1171 CCS patents	DII
Cristina 2011 [10]	Gave an overview through patents applications and scientific articles together, presented five technical routes: absorption, adsorption, membranes, enzymatic and thermodynamics.	1123 carbon capture patents	EPO
Miao 2013 [12]	Put forward research ideas based on patent citation analysis approach, different from other refers in this table. Drew the CCS development map and identified the main paths by algorithm of path recognition which based on patent citation.	1498 CCS patents	USPTO
Li 2013 [26]	Gave details on seventy-nine representative patents, presented three technical routes: solvent, sorbent and membrane, made perspectives on potential technical routes.	9840 carbon capture patents	Espacenet
Zhang 2014 [27]	Gave a briefly overview of four technical routes (absorption, adsorption, cryogenic and membrane) and three reagents (absorption reagent, adsorption reagent and membrane reagent) by patent and article analysis, discussed CCS policies in China.	1344 carbon capture patents	USPTO

Note: PATSTAT for European Patent Office Worldwide Patent Statistical Database, EPO for European Patent Office, WIPO for World Intellectual Property Office, USPTO for United States Patent and Trademark Office, JPO for Japan Patent Office, KIPO for Korean Intellectual Property Office, SIPO for State Intellectual Property Office of the People's Republic of China, DII for Derwent Innovations Index database.

eral databases (e.g., WIPO [25] used six databases) or search in an integrated database (e.g., OECD [18] used PATSTAT and Li [26] used Espacenet), could provide a more suitable result. However, Dechezlepretre [24] and Wang [11] got fewer patents from integrated database PATSTAT and Derwent Innovations Index database. The reason we examine is the incomplete search expression in their studies.

Finally, patent family was used popularly. A patent family is a set of similar patents taken in various countries to protect a single invention. Therefore analysis by patent family reflects the number of inventions present more accurately.

Thereby, our study aims at extending these previous studies through the creation of a more complete database set from Derwent Innovations Index database, by using a more suitable search expressions. Then, highlights development stages in forty years and analyzes geographical feature in terms of countries. In addition, employs database of CCS projects at first in similar studies, thus making us able to reveal overlap of patent layer and project layer.

The remainder of this article is structured as follows: Section 2 outlines the data source and retrieval strategy. Database in Section 2 is used in Section 3 to analyze temporal distribution of carbon capture in terms of yearly and cumulative. Section 4 shows spatial distribution, and adopts another means of CCS project count for comparative study between patent and project. Section 5 contains a concluding discussion.

2 Patent database set and retrieval strategy

In this study, Derwent Innovations Index (DII) database of Web of Science (from the I.S.I. Web of Knowledge) is used to search and analyze patent data set. DII database is a widely accepted patent data source that covers over 14.3 million basic inventions from 40 worldwide patent-issuing authorities. For patent bibliometrics study, the most fundamental task is to set the range of retrieval and choose appropriate index words. Based on former studies (see Table 1), search indicators in this study include two dimensions: search topics and search IPC codes.

About search topics, we collected key words of types of carbon capture processes, combined them as one topic search expression by logic operators. Whilst, for a more rigorous search result, we identified thesaurus details of IPC codes related to those key words, combined them as one IPC codes search expression by logic operators too. IPC system is the most popular hierarchical classification system of patents among countries or organizations with official patent offices, launched by the World Intellectual Property Organization (WIPO). We tested dozens of combined search topics and search IPC codes, compared results of inputting different expressions, adopted the most suitable expressions after trial and error. In testing, we found a dozen of world famous vehicle companies, which are not professional in domain of carbon capture at all. Most of patents applied by those vehicle companies related to automobile exhaust gases pollution control. Therefore, we excluded this interference technology expressions by using logic operator “not”. Comparing with foregoing studies, as far as we know, it is the first time to exclude exhaust control technologies in patent data searching by logic operator, for accessing a more concentrative database set of carbon capture patents.

Expressions of search topics and search IPC codes used in this study are as below:

Search topics (description see Table 2a): (CO2 or (carbon dioxide)) and (captur* or recover* or separat* or remov* or absor* or adsor* or membran* or cryogen* or enzm* or combust* or puri* or concentrat* or extract* or compress* or thermo*) not (car or auto* or vehicl* or engin* or exhaust*).

Search IPC codes (thesaurus description see Table 2b): (B01D-000/00 or B01D-053/00 or B01D-053/02 or B01D-053/04 or B01D-053/14 or B01D-053/18 or B01D-053/22 or B01D-053/78 or B01D-053/86 or B01D-053/94 or C01B-003/38 or C01B-031/20 or F23J-015/00 or F25J-001/00 or F25J-003/00 or F25J-003/02 or F25J-003/04 or

F25J-003/08) not (H01M-008/04 or H01M-008/06).

The final patent data searching was conducted on April 2016. A total of 9847 patent files were found in time span of forty years from 1976 to 2015. For each patent in our database, several data fields were extracted such as authorization year, assignee name, assignee code and IPC code etc.

Table 2a Descriptions of search topics

	Search topics	Descriptions
1	CO2	CO2, CO_2.
2	carbon dioxide	carbon dioxide.
3	captur*	capture, captured, capturing, etc.
4	recover*	recover, recovery, recovered, recovering, etc.
5	separat*	separate, separated, separating, separation, etc.
6	remov*	remove, removed, removing, remover, etc.
7	absor*	absorb, absorbed, absorbing, absorbent, absorpt, absorptive, absorption, etc.
8	adsor*	adsorb, adsorbed, adsorbing, adsorbable, adsorp, adsorption, adsorptive, etc.
9	membran*	membrane, membranous, etc.
10	cryogen*	cryogen, cryogenic, etc.
11	enzym*	enzyme, enzymes, enzymic, enzymolysis, etc.
12	combust*	combust, combusted, combusting, combustion, combustible, etc.
13	puri*	purify, purified, purifying, purification, etc.
14	concentrat*	concentrate, concentrated, concentrating, concentration, etc.
15	extract*	extract, extracted, extracting, extractive, extraction, extractable, extractant, etc.
16	compress*	compress, compressed, compressing, compressive, compressible, compression, etc.
17	thermo*	thermo, thermodynamics, etc.
18	car	car.
19	auto*	auto, automobile, automotive, etc.
20	vehicl*	vehicle, etc.
21	engin*	engine, etc.
22	exhaust*	exhaust, exhausted, exhausting, etc.

Table 2b Thesaurus descriptions of search IPC codes

	IPC codes	Thesaurus descriptions
1	B01D-000/00	Separation
2	B01D-053/00	Separation of gases or vapours; Recovering vapours of volatile solvents from gases
3	B01D-053/02	by adsorption
4	B01D-053/04	with stationary adsorbents
5	B01D-053/14	by absorption
6	B01D-053/18	Absorbing units; Liquid distributors therefor
7	B01D-053/22	by diffusion
8	B01D-053/78	with gas-liquid contact
9	B01D-053/86	Catalytic processes
10	B01D-053/94	by catalytic processes
11	C01B-003/38	using catalysts
12	C01B-031/20	Carbon dioxide
13	F23J-015/00	Arrangements of devices for treating smoke or fumes
14	F25J-001/00	Processes or apparatus for liquefying or solidifying gases or gaseous mixtures
15	F25J-003/00	Processes or apparatus for separating the constituents of gaseous mixtures involving the use of liquefaction or solidification
16	F25J-003/02	by rectification, i.e. by continuous interchange of heat and material between a vapour stream and a liquid stream
17	F25J-003/04	for air
18	F25J-003/08	Separating gaseous impurities from gases or gaseous mixtures
19	H01M-008/04	Auxiliary arrangements or processes, e.g., for control of pressure, for circulation of fluids
20	H01M-008/06	Combination of fuel cell with means for production of reactants or for treatment of residues

3 Temporal distribution of carbon capture technology

Practitioners and researchers are often interested in, regarding to a certain technology field, what the tendency is and where it will drive to. For evaluating progress in carbon capture innovation approach, we extract data of authorization year from database set, identify shifts by yearly growth and cumulative development, and then draw some similar conclusions from diverse views.

3.1. Yearly development of patent count

Fig. 2 presents authorized carbon capture patents yearly since 1976, as measured by patent count. The trend shows two phases clearly: 1) fluctuant and slow increasing phase; 2) sharp increasing phase. Apparently, year of 2006 is the turning point of technology development. In fluctuant and slow increasing phase before 2006, annual patent count increased slowly, even negative growth in some years. The AAGR (average annual growth rate) was only 2.6%. The annual average is about 133 patents. In sharp increasing phase since 2006, annual patent count increases quickly, the AAGR was 23.8% from 2006 to 2013. This phase presents a linear increasing with high curve similarity: $R^2 = 0.9908$ (see Fig. 2). The annual average count from 2006 to 2015 is about 636, nearly 5 times of former phase.

The shape increasing since 2006 is not an accident of course, implies many shifts.

First, there is a wide agreement among 100 experts surveyed in Alphen's study [9] that capture facilities are not substantially different from conventional industrial facilities. Thus in most years, carbon capture technology was applied in general sector and grew slowly. As carbon capture being a crucial technology in CCS chain, innovation activities have been booming.

Second, considering it usually needs years to deploy and implement innovation activities by governments and innovators, the increasing trend in carbon capture technology from new century seems to reflect a significant influence of climate change policies since the signing of the Kyoto Protocol in 1997. Dechezlepretre [24] also pointed out that Kyoto Protocol affected innovations in a cluster of climate change mitigation technologies including CCS technology, probably due to innovators reacted swiftly to policy changes, private sector received a strong signal and many countries took early action before ratification.

Third, the increasing trend is also related to environmental concerns and commercial drives [26]. Sleipner project in Norwegian continental shelf is a milestone effort of carbon mitigation, which is called "the mother of all CCS projects", separates and injects 1 Mt CO_2 into saline formation each year since 1996 [28]. On the other hand, several CCS projects are driven by commercial utilization of CO_2 like CO_2 injection for enhanced oil recovery (EOR).

In addition, patent counts in 2014 and 2015 do not correspond with the reality, due to the time lag between application and authorization. Thereby, the last two years are used for comparing rather than analyzing exactly.

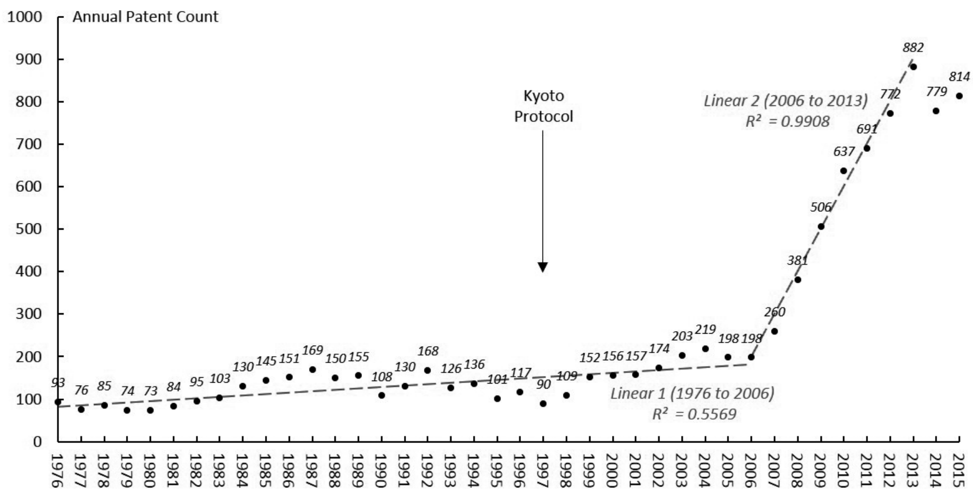

Fig. 2. Annual patent count of carbon capture by authorized year, linear 1 presents trend from 1976 to 2006, linear 2 presents trend from 2006 to 2013. (Data Source: Derwent Innovations Index Database, 2016.)

3.2. Technology life cycle of carbon capture

The concept of technology life cycle is always presented to measure technological changes, beginning from Arthur [29], and it includes two dimensions and four stages. Two dimensions are competitive impact and integration in products or process ---- patent can be regarded as a product of innovation activities. Four stages are emerging, growth, maturity and saturation stages. According to Arthur's definition, the emerging stage is a new technology with low competitive impact and low integration in products or processes. In the growth stage, there are pacing technologies with high competitive impact that have not yet been integrated in new products or processes. In the maturity stage, some pacing technologies are integrated into products or processes. In the saturation stage, a technology becomes a base technology and might be replaced by a new technology. Fig. 3a illustrates the S-curve definition of four stages.

Fig. 3b presents cumulative patent count of carbon capture from 1976 to 2015. Comparing to theoretical model of technological life cycle showed in Fig. 3a, turning period of emerging stage to growth stage is highlighted in Fig. 3b, from 2010 to 2020 around. As a consequence, two stages of technological life cycle can be found: 1) the emerging stage and 2) the growth stage. We believe that the growth stage is coming, a sharp increasing of patent count will be available in future years. Need to point out that, two stages of technological life cycle are in

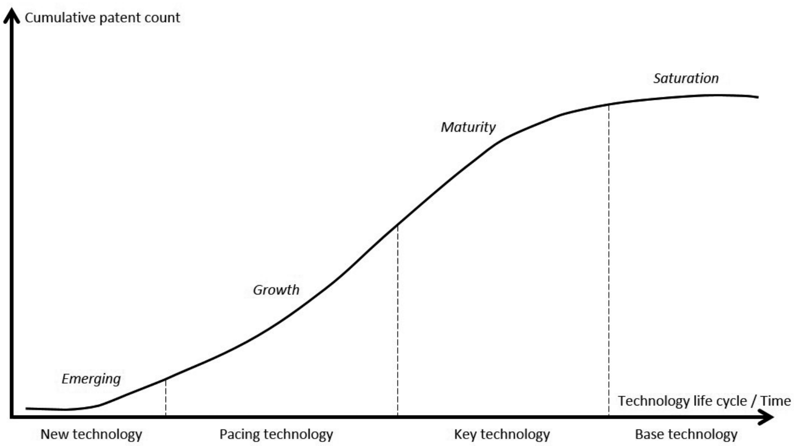

Fig. 3a. The S-curve concept of a technological life cycle by cumulative patent count. (Note: Modified based on Ernst, 1997 [30].)

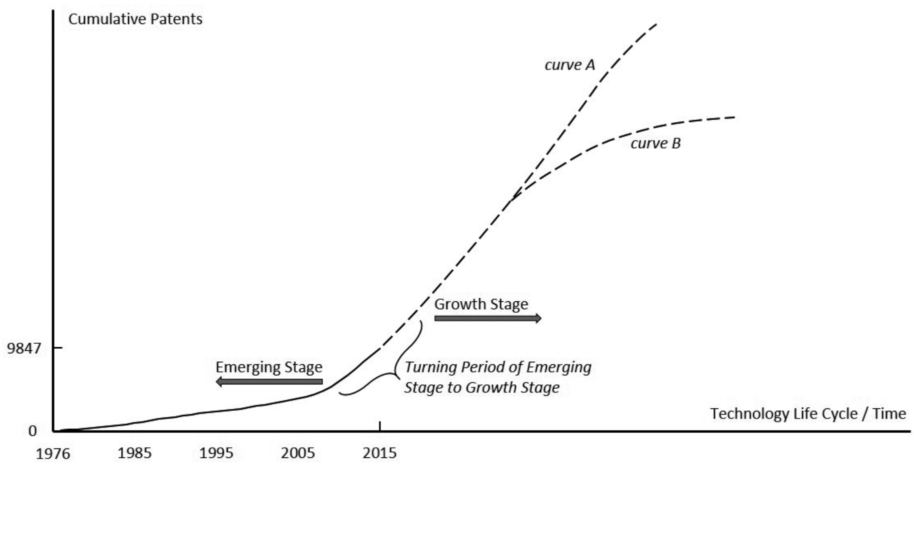

Fig. 3b. Technological life cycle of carbon capture by cumulative patent count. (Data Source: Derwent Innovations Index Database, 2016.)

terms of cumulative patent count, different from two phases by annual patent count mentioned in Fig. 2.

4 Spatial distribution of carbon capture technology

In the previous section, we give a discussion on temporal trend in overall countries. For assessing which countries are leading the innovation and which countries are more active in project operation, we focus on spatial distribution of technology and project together. At first, distribution of patent is presented in terms of top 50 assignee codes. Then, spatial comparison between patent and project is presented. Lastly, we try to discuss relative development trends among high-tech countries.

We identify spatial distribution of patent across countries in terms of assignee code, and try to highlight the relative development trends among high-tech countries by using data of assignee code too. Thus, assignee code should be discussed in front. The wide range of company name variations that can exist in any patent database is a documented problem. Between misspellings, transliterations from other languages, and abbreviations for common words (such as "Co." for "Company" or "Ltd" for "Limited"), many different versions of a company name can be recorded in a patent database, and this can hamper accurate keyword retrieval [31]. Luckily, Derwent indexers address this problem by assignee code. Every patentee in DII has one assignee code, however one assignee code usually contains many patentee names. Patentee names that are contained in one assignee code always have relationships to each other in many cases, such as belonging to a same company, company merger and restructuring, even misspelling of name. Consequently, when we try to survey the innovational level of a company in DII, we extract patents by assignee code, then we won't exclude valid data or include invalid data. Need not to point out that DII is the only patent database that include assignee code. It is also an important reason for us to choose DII as patent data source.

4.1. Spatial distribution of technology

We extract data of assignee codes in carbon capture patent database set. For a more clear and valid result, we choose top 50 assignee codes from total 4613 codes (see Table 3). Top 50 assignee codes own 4232 patent files, account for 42.97% of all

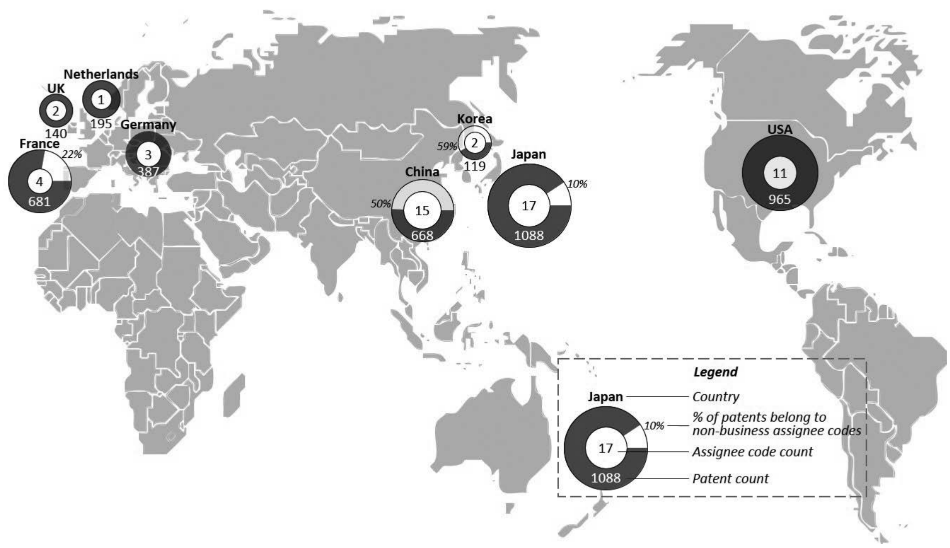

Fig. 4a. Spatial distribution of top 50 assignee codes, of patents belong to top 50, of patent belong to non-business assignee codes in top 50. (Data Source: Derwent Innovations Index Database, 2016.)

Table 3 Basic Information of Top 50 Assignee Codes. (Note: Totally 55 assignee codes because of 6 tying in 50th. Data Source: Derwent Innovations Index Database, 2016.)

Assignee code		Main assignee name	Patent count	Country	Classification
1	AIRL-C	AIR LIQUIDE SA	349	France	Company
2	LINM-C	LINDE AG	229	Germany	Company
3	AIRP-C	AIR PROD & CHEM INC	216	USA	Company
4	MITO-C	MITSUBISHI HEAVY IND CO LTD	211	Japan	Company
5	SHEL-C	SHELL INT RES MIJ BV	195	Netherlands	Company
6	INSF-C	INST FRANCAIS DU PETROLE	152	France	Institute
7	ALSM-C	ALSTOM TECHNOLOGY LTD	148	France	Company
8	ESSO-C	EXXONMOBIL RES & ENG CO	144	USA	Company
9	UNVO-C	UOP LLC	130	USA	Company
10	PRAX-C	PRAXAIR TECHNOLOGY INC	114	USA	Company
11	BRTO-C	BOC GROUP	108	UK	Company
12	HITA-C	HITACHI LTD	108	Japan	Company
13	SHAN-N	SHANDONG SERI PETROTECH DEV CO LTD	100	China	Company
14	TOKE-C	TOSHIBA KK	90	Japan	Company
15	NIIO-C	NIPPON SANSO	88	Japan	Company
16	BADI-C	BASF AG	87	Germany	Company
17	SNPC-C	CHINA PETROLEUM & CHEM CORP	85	China	Company
18	GENE-C	GENERAL ELECTRIC CO	81	USA	Company
19	YAWA-C	NIPPON STEEL CORP	79	Japan	Company
20	UNIC-C	UNION CARBIDE CORP	72	USA	Company
21	SIEI-C	SIEMENS AG	71	Germany	Company
22	KOER-C	KOREA INST ENERGY RES	70	Korea	Institute
23	KANT-C	KANSAI ELECTRIC POWER	55	Japan	Company
24	DOWC-C	DOW CHEM CO	52	USA	Company
25	FUJF-C	FUJI FILM CORP	51	Japan	Company
26	CALI-C	CHEVRON USA INC	50	USA	Company
27	HITG-C	BABCOCK-HITACHI	49	Japan	Company
28	ISHI-C	ISHIKAWAJIMA HARIMA HEAVY IND	49	Japan	Company
29	KEPC-C	KOREA ELECTRIC POWER CORP	49	Korea	Company
30	KOBM-C	KOBE STEEL LTD	48	Japan	Company
31	UBEI-C	UBE IND	44	Japan	Company
32	UYZH-C	UNIV ZHEJIANG	44	China	University
33	BEIJ-N	BEIJING YEJING TECHNOLOGY CO LTD	42	China	Company
34	UTIJ-C	UNIV TIANJIN	42	China	University
35	SEIT-C	SUMITOMO SEIKA CHEM CO LTD	41	Japan	Company
36	CHIK-N	CHIKYU KANKYO SANGYO GIJITSU KENKYU	40	Japan	Institute
37	CHHU-N	CHINA HUANENG GROUP CLEAN ENERGY TECHNOL	39	China	Company
38	RENA-N	RES INST NANJING CHEM IND GROUP	39	China	Company
39	CHSC-N	CHINESE ACAD SCI PROCESS ENG INST	38	China	Institute
40	DUPO-C	DU PONT DE NEMOURS & CO E I	38	USA	Company
41	UYQI-C	UNIV QINGHUA	38	China	University
42	MATU-C	MATSUSHITA ELEC IND CO LTD	37	Japan	Company
43	WANG-I	WANG Y	36	China	Individual
44	FLUO-C	FLUOR TECHNOLOGIES CORP	35	USA	Company
45	ZHAN-I	ZHAN-I	35	China	Individual
46	KAWI-C	KAWASAKI STEEL CORP	34	Japan	Company
47	MEMB-N	MEMBRANE TECHNOLOGY & RES INC	33	USA	Company
48	UYCH-N	UNIV CHINA PETROLEUM	33	China	University
49	UYDA-C	UNIV DALIAN TECHNOLOGY	33	China	University
50	AGEN-C	AGENCY OF IND SCI & TECHNOLOGY	32	Japan	Institute
51	BRPE-C	BP ALTERNATIVE ENERGY INT LTD	32	UK	Company
52	GEOR-N	GEORGE LORD METHOD RES & DEV AIR LIQUIDE	32	France	Company
53	JIAN-N	JIANGSU RUIFENG TECHNOLOGY IND CO LTD	32	China	Company
54	NIIT-C	DOKURITSU GYOSEI HOJIN SANGYO GIJUTSU SO	32	Japan	Institute
55	UYSE-C	UNIV SOUTHEAST	32	China	University

9847 patent files. Top 50 assignees include most of influential companies, institutes and universities in carbon capture technology in the world. In addition, because of 6 assignee codes tying in 50th, there are fifty-five assignee codes in top 50.

Fig. 4a shows that top 50 assignee codes, 4232 patents, are concentrated in eight countries—Japan, USA, France, China, Germany, Netherlands, UK and Korea in order from most to fewer. First, East Asia, EU and North America have most of patents in the world, comparing the economic vitalities in these areas. The only developing country is China, whose patent count is increasing quickly in last 5 years. Second, the performance of Japan is particularly impressive as it ranks first both in patent count and assignee code count. Nevertheless, inventors from EU have more patents in average. Each inventor in Netherlands has 195 patents, in France has 170 and in Germany has 129. On the other hand, each inventor from USA, UK, Japan, Korea and China has 88, 70, 64, 60 and 45 patents. Third, countries in East Asia and France have more non-business assignees such as universities, institutes and individuals. 59% of patent files in Korea, 50% in China, 22% in France and 10% in Japan are contributed by non-business inventors. This status highlights the fundamental role of research-based organizations who get the financial assistances from governments in some countries.

4.2. Comparison between technology and project

All of our discussions above are trying to characterize features of spatial-temporal distribution by patent. However, patent is not the only innovation indicator. Another widely used indirect approach is the effect of technology. We consider large-scale integrated CCS project as an approximate effect of carbon capture technology, also a final-output production of innovation. Thus this study employs count of projects for understanding the spatial relationship between patents and projects. In addition, a large-scale integrated CCS project is a full-chain project (see Fig. 1), which is defined as a project involving the capture, transport and storage of CO_2 at a scale of 1) at least 800,000 tons of CO_2 annually for a coal–based power plant; 2) at least 400,000 tons of CO_2 annually for other emissions–intensive industrial facilities [32].

Fig. 4b presents spatial distribution of forty large-scale integrated CCS projects, which are distinguished in five stages [33]: identify, evaluate, define, execute and operate. Namely some of projects are in operation and some of them will begin in the coming years, although a few of them will be cancelled.

First, as more and more countries drawing a plan for CCS development, CCS demonstration projects are operated world widely. Canada, Norway, UK, Netherlands, USA and Australia are early birds, who planned full-scale CCS demonstrations in a variety of applications before 2009 [34], then China, Korea, Algeria, Brazil, Saudi Arabia and United Arab Emirates are involved in the list.

Second, an obvious spatial overlap is found between patent layer (Fig. 4a) and project layer (Fig. 4b). There are 31 large-scale integrated CCS projects in USA, China, EU and Canada, accounts for 77.5% of 40 projects in the world. On the other hand, as we have discussed above, East Asia, EU and North America own the most patents in the world. The overlaps between patents and projects imply a crucial role of innovation to development of CCS.

Finally, CO_2-EOR (enhanced oil recovery) is the most primary storage type in CCS chain, drives twenty-three large-scale integrated CCS projects. As a practiced commercially technology since the early 1970s in USA, injection of CO_2 to improve recovery of oil was operated in nearly 140 projects globally since 2010 [5]. Significantly, CO_2-EOR improves large-scale integrated CCS projects not only in so-called high-tech countries, also in so-called low-tech but oil-rich countries, such as Saudi Arabia, United Arab Emirates and Brazil. CCS projects are much meaningful for technical diffusion, by channels of international trade and foreign direct investment [35].

Fig. 5 presents fifteen countries in terms of patent and project, reveals four categories. The four categories point out three main aspects. First, a cor-

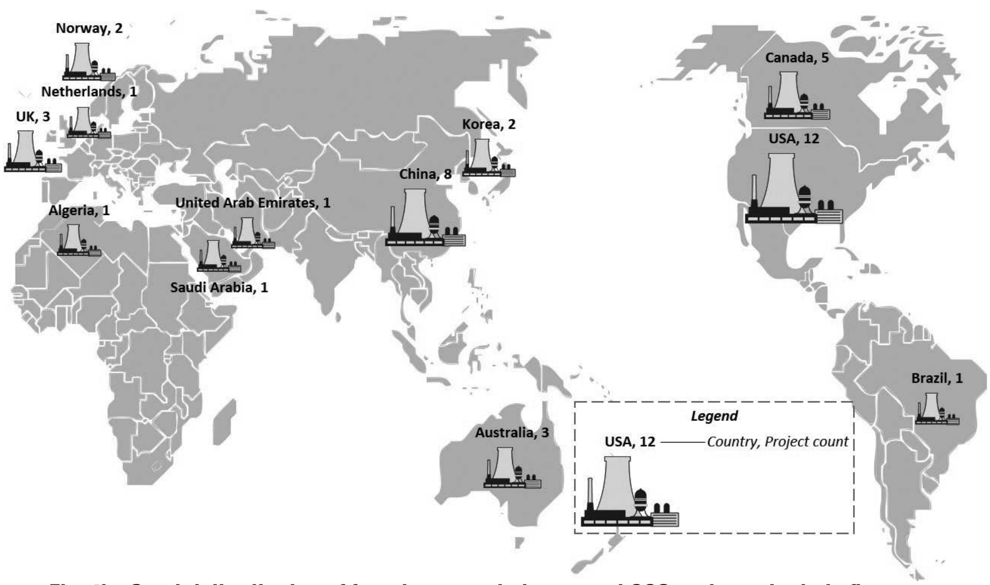

Fig. 4b. Spatial distribution of forty large-scale integrated CCS projects, include five stages of identify, evaluate, define, execute and operate. (Note: More details can be found in data source: Global CCS Institute, 2016 [33].)

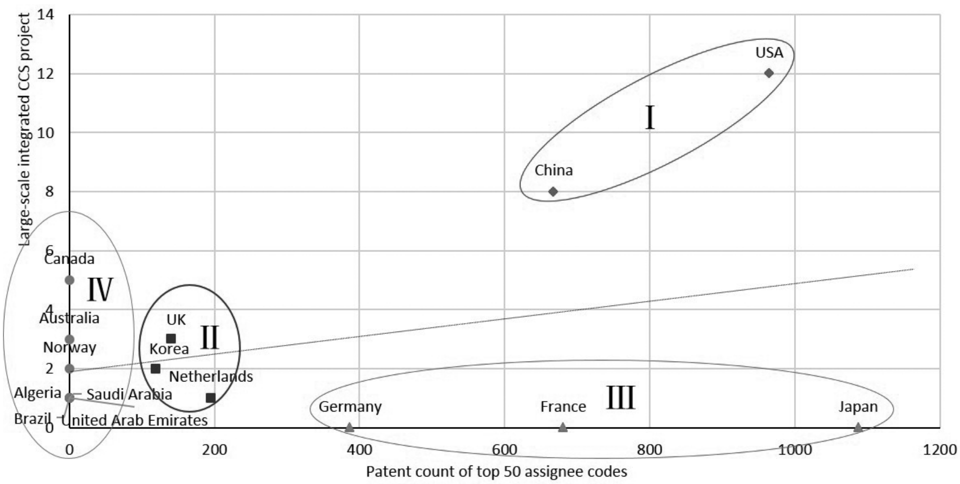

Fig. 5. Four categories of fifteen countries in terms of patent count of top 50 assignee codes and large-scale integrated CCS project. (Data Source: Derwent Innovations Index Database, 2016 and Global CCS Institute, 2016.)

relation is found between projects and technologies, although is weak. Second, lack of technology cannot block project operated, on contrary, high-tech is not the sufficient condition of CCS project. Third, as a complex system project, CCS project is limited by many factors, but CO_2 sources and sinks lie at the core of feasibility [36].

Category Ⅰ includes USA and China, the biggest developed and developing country, each of them has more patents and more projects at the same time. USA and China both are oil (gas) producing countries and depend heavily on coal as a fuel [4]. Furthermore, as they all have vast territories and waters, it's possible to find more appropriate geologic formations. By IEA, almost 80% of CCS projects is expected to be deployed in China and USA, in where CCS could grow to become a major industry in itself [37].

Category Ⅱ includes Netherlands, UK and Korea, each of them has fewer patents and fewer projects than Category Ⅰ. Most of projects in Category Ⅱ are in stage of evaluate, standing for needing around five years to be in stage of operate.

Category Ⅲ includes Japan, France and Germany, which are all developed and high-tech countries in carbon capture. Category Ⅲ and Ⅰ stand out as world leaders in innovation of carbon capture together. However category Ⅲ countries do not implement any large-scale project, partly due to restriction of suitable geological storage options (e.g., Japan) and lack of CO_2 sources (e.g., France and Germany).

Category Ⅳ includes Canada, Australia, Norway, Algeria, Brazil, Saudi Arabia and United Arab Emirates, each of them is implementing or plan to implement CCS large-scale projects, although they are not high-tech countries in carbon capture field. Norway is the first country that operated a pilot-scale CCS project in 2008, capturing CO_2 from nature gas processing and injecting in geologic formation offshore without EOR. Canada and Australia are easy to explore feasible geologic formations due to vast territories and waters like USA and China. Projects in Canada, Algeria, Brazil, Saudi Arabia and United Arab Emirates are all about oil and gas industries, some of projects capture CO_2 from nature gas processing, some of storage CO_2 for EOR.

4.3. Rank changing in top 10 assignee codes

For trying to highlight the relative trends across major high-tech countries, we examine the top 10 assignee codes in last 10 years in terms of country. As noted in the previous section, countries such as Japan, USA, France, China, Germany, UK and Korea have more patents than other countries. Thus, companies or institutes from these countries are consequently involved in top 10 assignee codes.

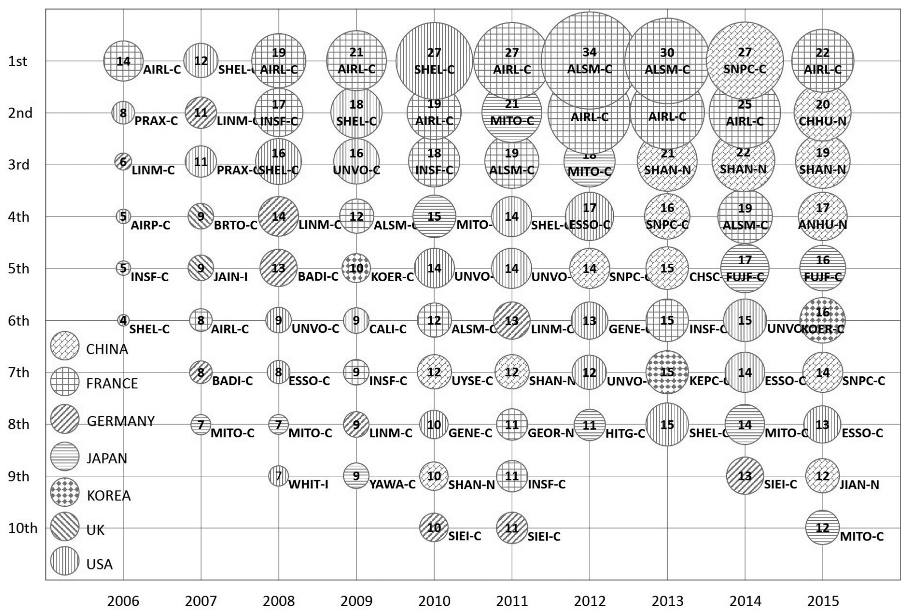

Fig. 6a. Top 10 assignee codes in 10 years, five-letter code presents assignee code, number in bubble presents patent count, bubble dimension represents the patent count belong to assignee code.

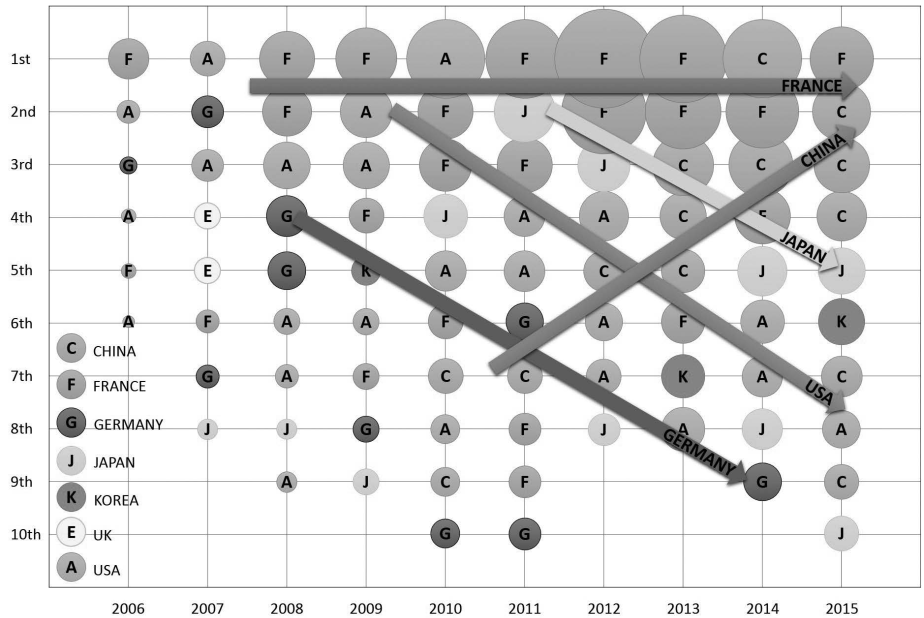

Fig. 6b. Top 10 assignee codes in 10 years and trends of countries, a bubble with capital letter represents an assignee code, capital letter in bubble represent country that own this assignee code, bubble dimension represents the patent count belong to assignee code, an arrow presents the relative development trend of country whose name is signed in arrow. (Note: Because of tied codes, assignee codes in last ranks were omitted in some years. Data Source: Derwent Innovations Index Database, 2016.)

About Fig. 6a and 6b, the y-axis reports ranking of top 10 assignee codes by year. Fig. 6b is based on Fig. 6a, presenting the trends more visually by some arrows that represent countries. First, it is very impressive that French companies occupied in 1^{st} and 2^{nd} mostly, such as Alstom (ALSM-C) and Air Liquide (AIRL-C) topped the list for seven times in ten years together. Second, Chinese companies emerged frequently since 2013, notably topped in 2014 (China Sinopec) and arranged from 2^{nd} to 4^{th} in 2015 (China Huaneng, Shanghai Longking and Anhui Huaertai). It seems that inventors from China will apply more patent files in years. Third, ranks of companies from Japan, USA and Germany are lower than before, mainly due to initiatives of Chinese companies.

5 Conclusion

This study adopts at least 6 patent indicators for quantifying spatial-temporal distribution of carbon capture technology by patent bibliometrics. Meanwhile, the study adopts data set of large-scale integrated CCS project for comparing with patent. First, we speculate that "Good Time" of carbon capture technology is coming, although later and weaker than some other low-carbon technologies. As count of authorized patents keeps increasing rapidly since 2006, the technology life cycle of carbon capture is or will be soon in growth stage. Second, carbon capture patents distribute mainly in East Asia, EU and North America. However CCS projects locate more widely. Third, in the view of innovation, carbon capture technologies is vital to make CCS viable. However, in the view of commercialization, CCS project operation is impeded by limitations, including CO_2 sources and geological conditions. From former studies [5,8,10,38], limitations also include lack of policy and economic drivers, restrictions from local laws and international conventions, environmental concerns on carbon escape from storage, etc.

This study has some limitations that should be acknowledged. First, we give a review by means of patent count, but some biases exist due to the fact that patent count does not represent the whole portfolio of patent analysis. Second, there can be some biases in cross-country comparisons by top 50 or top 10 assignee codes rather than all assignees. Third, we can't give deep discussions on e.g., international technology diffusion and project development trend, due to insufficiency of research methods. In addition to address these limitations, further study will place more emphasis on the method of patent bibliometrics (e.g., citation analysis) by using visualizing and analyzing software, for providing a wider scale discussion and a precise analysis, characterizing technology spillover and diffusion across countries, and presenting suggestions of CCS development for organizations, governments, innovators and firms.

References

[1] WMO. WMO Statement on the Status of the Global Climate in 2015. 2016.

[2] IPCC. Climate Change 2007 Synthesis Report. 2008. doi:10.1256/004316502320517344.

[3] Socolow RH, Pacala SW. A plan to keep carbon in check. Sci Am 2006;295:50–7. doi:10.1038/scientificamerican0906-50.

[4] IEA. Energy Technology Perspectives 2012. 2012.

[5] IEA. Carbon Capture and Storage Technology Roadmap (2013 Edition), 2013.

[6] Ministry of Science and Technology (China). Technology roadmap study on carbon capture, utilization and storage in China. 2012.

[7] Rubin ES, Mantripragada H, Marks A, Versteeg P, Kitchin J. The outlook for improved carbon capture technology. Prog Energy Combust Sci 2012;38:630–71. doi:10.1016/j.pecs.2012.03.003.

[8] Leo MeyerMetz B, Davidson O, Coninck H de, Loos M, Meyer L. IPCC Special Report on Carbon Dioxide Capture and Storage. 2005.

[9] van Alphen K, Hekkert MP, Turkenburg WC. Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system. Int J Greenh Gas Control 2010;4:396–409. doi:10.1016/j.ijggc.2009.09.019.

[10] Quintella CM, Hatimondi SA, Musse APS, Miyazaki SF, Cerqueira GS, De Araujo Moreira A. CO2 capture technologies: An overview with technology assessment based on patents and articles. Energy Procedia 2011;4:2050–7. doi:10.1016/j.egypro.2011.02.087.

[11] Xuemei W, Jingjing Z, Jiansheng Q. Patent Analysis on the International Carbon Capture and Storage Technologies. Sci Focus 2010;Vol.5 No.4. doi:10.15978/j.cnki.1673-5668.2010.04.003.

[12] Hong M, Wei Z, Lucheng H. Research on Carbon Capture and Storage Technology Development Based on Patent Citation. J Intell 2013;32.

[13] OECD. Main Science and Technology Indicators. 2016.

[14] Griliches Z. Patent Statistics as Economic Indicators: A Survey. vol. 28. 1990. doi:10.1016/S0169-7218(10)02009-5.

[15] Oltra V, Kemp R, Vries FP De. Patents as a measure for eco-innovation. Int J Environ Technol Manag 2010;13:130. doi:10.1504/IJETM.2010.034303.

[16] Acs ZJ, Anselin L, Varga A. Patents and innovation counts as measures of regional production of new knowledge. Res Policy 2002;31:1069–85. doi:10.1016/S0048-7333(01)00184-6.

[17] Johnstone N, Hascic I, Popp D. Renewable energy policies and technological innovation: Evidence based on patent counts. Environ Resour Econ 2010;45:133–55. doi:10.1007/s10640-009-9309-1.

[18] OECD. Climate Policy and Technological Innovation and Transfer: An Overview of Trends and Recent Empirical Results. 2010.

[19] Liu JS, Kuan CH, Cha SC, Chuang WL, Gau GJ, Jeng JY. Photovoltaic technology development: A perspective from patent growth analysis. Sol Energy Mater Sol Cells 2011;95:3130–6. doi:10.1016/j.solmat.2011.07.002.

[20] Leu HJ, Wu CC, Lin CY. Technology exploration and forecasting of biofuels and biohydrogen energy from patent analysis. Int J Hydrogen Energy 2012;37:15719–25. doi:10.1016/j.ijhydene.2012.04.143.

[21] UKIPO. Eight Great Technologies Energy Storage - A Patent View. 2014.

[22] Albino V, Ardito L, Dangelico RM, Messeni Petruzzelli A. Understanding the development trends of low-carbon energy technologies: A patent analysis. Appl Energy 2014;135:836–54. doi:10.1016/j.apenergy.2014.08.012.

[23] Park JY. The evolution of waste into a resource: Examining innovation in technologies reusing coal combustion by-products using patent data. Res Policy 2014;43:1816–26. doi:10.1016/j.respol.2014.06.002.

[24] Dechezlepretre A, Glachant M, Hascic I, Johnstone N, Meniere Y. Invention and transfer of climate change mitigation technologies on a global scale: a study drawing on patent data. 2009.

[25] WIPO. Patent-based Technology Analysis Report–Alternative Energy Technology. 2009.

[26] Li B, Duan Y, Luebke D, Morreale B. Advances in CO2 capture technology: A patent review. Appl Energy 2013;102:1439–47. doi:10.1016/j.apenergy.2012.09.009.

[27] Wei Z, Man Z. CO2 Capture Situation Analysis Based on Patents and Articles. Sci Technol Manag Res 2014.

[28] Torp TA, Gale J. Demonstrating storage of CO2 in geological reservoirs: The Sleipner and SACS projects. Energy 2004;29:1361–9. doi:10.1016/j.energy.2004.03.104.

[29] Arthur D. Little. The strategic Management of Technology. Eur. Manag. Forum, Davos: 1981.

[30] Ernst H. The Use of Patent Data for Technological Forecasting: The Diffusion of CNC-Technology in the Machine Tool Industry. Small Bus Econ 1997;9:361–81. doi:10.1023/A:1007921808138.

[31] Intellogist. Report:Derwent World Patents Index/File Data n.d. http://www.intellogist.com/wiki/Report:Derwent_World_Patents_Index/Special_Indexing/Derwent_Assignee_Codes.

[32] Global CCS Institute. CCS in Australia | Global Carbon Capture and Storage Institute n.d. http://www.globalccsinstitute.com/projects/large-scale-ccs-projects-definitions.

[33] Global CCS Institute. Large Scale CCS Projects | Global Carbon Capture and Storage Institute 2015. https://www.globalccsinstitute.com/projects/large-scale-ccs-projects.

[34] Coninck H, Stephens JC, Metz B. Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration. Energy Policy 2009;37:2161–5. doi:10.1016/j.enpol.2009.01.020.

[35] Keller W. International Technology Diffusion. J Econ Lit 2004;42:752–82. doi:10.1257/0022051042177685.

[36] IEA. Technology Roadmap Carbon Capture and Sotrage in Industrial Applications. 2011.

[37] IEA. Carbon Capture and Storage : The solution for deep emissions reductions. 2015.

[38] Ying F, Lei Z, Xiaobing Z. An Analysis on Carbon Capture and Storage Technology, Regulations and Its Emission Reduction Potential. Adv Clim Chang Res 2010;6:362–9.