Carbon Capture & Storage

An analysis of research activity based on a review of patent literature

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Executive Summary

Climate change presents one of the biggest challenges of our times according to the European Environment Agency. Global warming is caused by the emission of greenhouse gases of which carbon dioxide (CO_2) and methane represent more than 90%. About 65% of greenhouse gas emissions are caused by CO_2 emissions due to the use of fossil fuel and industrial processes. Carbon Capture and Storage (CCS) is essential in achieving the ambitions of the Paris Agreement on climate.

This report provides an analysis of the innovative activities in the field of carbon capture and storage by a review of the patent activity in this field. Patent datasets were evaluated using "Patent Inspiration" whereby insight was obtained with respect to activity over time, main players and technologies used. Patent value analysis was used to obtain the key innovations in the respective data sets.

The patent activity in CCS saw its peak around 2013-2014 but signs of an increase again in 2020 are seen. The dominant technologies used in CCS are absorption, which is nowadays mostly used in capturing carbon dioxide from exhaust gases, and adsorption, but also membrane technology is gaining. Pre-combustion has the potential of capturing carbon dioxide in a more efficient way in power plants but cannot be retrofitted. An interesting development in pre-combustion is the use of fuel cells and in particular molten carbonate fuel cells. These are being piloted by ExxonMobil in a power plant in the US. The patent filing activity is dominated by American companies but also European companies are showing a high amount of activity as well as Korean and Japanese applicants. China is lagging significantly behind. The top 5 of most active companies in the CCS field is lead by Alstom and contains 3 European companies. ExxonMobil, Shell and Saudi Arabian are oil companies figuring in the top 10 list.

Amines are the most commonly used sorbents and are used in absorption as solvents but may also be used on a supporting substrate in adsorption technology. Zeolites are an important adsorbent but also polymeric adsorbents are used amongst adsorption technologies.

1. Introduction

Climate change presents one of the biggest challenges of our times according to the European Environment Agency[1]. The harmful effects of climate change can already be noted: temperatures are rising, drought and wild fires are starting to occur more frequently, storms are getting more violent, rainfall patterns are shifting, glaciers and snow are melting and the global mean sea level is rising. The global warming is caused by the emission of greenhouse gases of which carbon dioxide (CO_2) and methane represent more than 90%[2]. About 65% of greenhouse gas emissions are caused by CO_2 emissions due to the use of fossil fuel and industrial processes[3]. In Flanders, the chemical industry, refinery and steel industry (basic industries) represent about 80% of industrial emissions of carbon dioxide that is captured by the European carbon dioxide emission trade. To make the basic industries climate neutral by 2050, there are four main themes that are being explored[4]:

1. Use of biomass
2. Circularity (of plastics)
3. Electrification and use of hydrogen
4. Carbon Capture and Storage (CCS) and reuse (CCU)

CCS and CCU are essential in achieving the ambitions of making the basic industries climate neutral as well as achieving the ambitions of the Paris Agreement on climate[5].

Accordingly, this report aims to provide an analysis of the innovative activities in the field of carbon capture and storage. The analysis is performed through a review of the patent activity in this field. Using "Patent Inspiration"[6] various datasets were created as set out in the next section on search strategy and datasets. For these datasets various analysis were carried including activity over time, main players, text pattern analysis enabling insight in nature of the activity as well as a patent value analysis for providing an indication of key innovations in the respective data sets.

2. Search strategy and datasets

In order to explore the patent landscape of CCS, a number of different patent datasets were created using "Patent Inspiration". Firstly, a large dataset of 3235 patent families for the last 20 years (2001-2021) was created to make an overall analysis. The dataset was obtained by combining the CPC codes Y02C including its children and B01D53/00 and its children with the appearance of "carbon dioxide" together with the keywords "capture", "combustion", "absorb*", "recover" or "storage" in the title or abstract. This dataset was then further cleaned out to remove irrelevant patents.

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[1] https://www.eea.europa.eu/themes/climate/climate-change-is-one-of (visited June 11th, 2021)

[2] Olivier, J. G. J.; Peters, J. A. H. W. (2019). Trends in global CO_2 and total greenhouse gas emissions. The Hague: PBL Netherlands Environmental Assessment Agency.

[3] https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (visited June 11th, 2021)

[4] Naar een koolstofcirculaire en CO_2-arme Vlaamse industrie, Studie in opdracht van het Agentschap Innoveren & Ondernemen (VLAIO), november 2020. Studie uitgevoerd door Deloitte België in samenwerking met VUB-IES, Climact en AMS

[5] Rogelj, J.; Elzen, M.D.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2 C. Nature 2016, 534, 631–639

[6] https://www.patentinspiration.com/

More focused datasets were created to explore absorption, adsorption, membranes, pre-combustion and fuel cells within the field of CCS. These were obtained as follows:

Absorption:

Patents containing “carbon dioxide” in the root claims and further “carbon dioxide” in combination with “capture”, “remove” or “recover” in the title or abstract. This was further combined with the CPC classes B01D2252/00 or B01D53/14 each time including their children. This yielded 585 patents.

Adsorption:

Patents from B01D2253/00, B01D53/02 or Y02C10/08 (always children included) were combined with the keywords “carbon dioxide” in the root claims and “carbon dioxide” in combination with “capture”, “remove” or “recover” in the title or abstract. This result was further combined with the CPC classes B01J20/00 or B01J2220/00 (including children). The result was a dataset of 139 patent families.

Membranes:

Patents with the keywords “carbon dioxide” in the root claims and “carbon dioxide” in combination with “capture”, “remove” or “recover” in the title or abstract were searched and combined with either of the following CPC classes (always children included): B01D69/00, B01D67/00, B01D71/00, B01D2311/00, B01D2313/00, B01D2315/00, B01D2317/00, B01D2319/00, B01D2321/00, B01D2323/00, B01D2325/00 or Y02C10/10. A dataset of 74 families resulted.

Pre-combustion:

Patents with the keywords “carbon dioxide” in the root claims and “carbon dioxide” in combination with “capture”, “remove” or “recover” in the title or abstract were searched and combined with either of the following CPC classes: C01B2203/062, C01B2203/0283, C01B2203/1241 or C01B2203/0233. From the resulting dataset, patents in the classes relating to fuel cells were removed to avoid overlap with the fuel cell dataset. A total of 201 patent families were contained in the results.

Fuel cells:

Patents with the keywords “carbon dioxide” in the root claims and “carbon dioxide” in combination with “capture”, “remove” or “recover” in the title or abstract were searched and combined with either of the following CPC classes: Y02E60/50, Y02P70/56, H01M8/00 or H01M2008/1095. The dataset created had 93 patent families.

3. Overall analysis of patents in the field of CCS

The large dataset as set out above was used to make an overview analysis of the field of CCS.

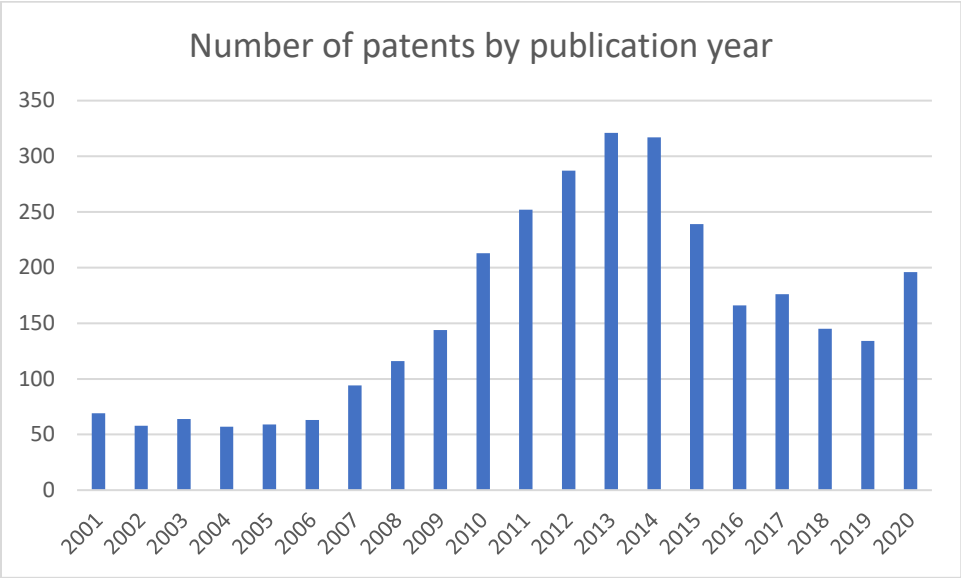

Figure 3.1: patent activity in CCS overall

From figure 3.1 it can be seen that the peak activity appeared around 2013 and 2014. However, it seems we may be starting to see a new increase as of 2020.

Table 3.1: Number of patents per applicant country

Country	Count
United States	1190
Japan	413
Germany	281
Korea, Republic of	281
France	196
Switzerland	167
Canada	110
Netherlands	105
United Kingdom	100
China	99
Norway	79
Australia	48
Saudi Arabia	48
Spain	38
Italy	33
Taiwan	26
India	26
Denmark	25
Sweden	21
Finland	16
Belgium	14

Table 3.1 shows the patent count by country. The USA leads with a large gap towards the other countries. European countries are also well represented evidencing the emphasis Europe is placing on climate change policies. Japan and Korea have a significant number of companies researching in the field as well and China, is lagging far behind considering in particular the overall large number of patent applications that China generates on an annual basis and that typically account for about 1/3 of all worldwide patent applications.

The list of the Belgian applications is presented in table 3.4 at the end of this section.

In figure 3.2. the activity with time for the countries active in CCS is given. Generally this follows the overall trend seen in figure 3.1. There is no sign that China is picking up in activity. On the other hand, it seems that Korea is diminishing in activity since the peak in 2013.

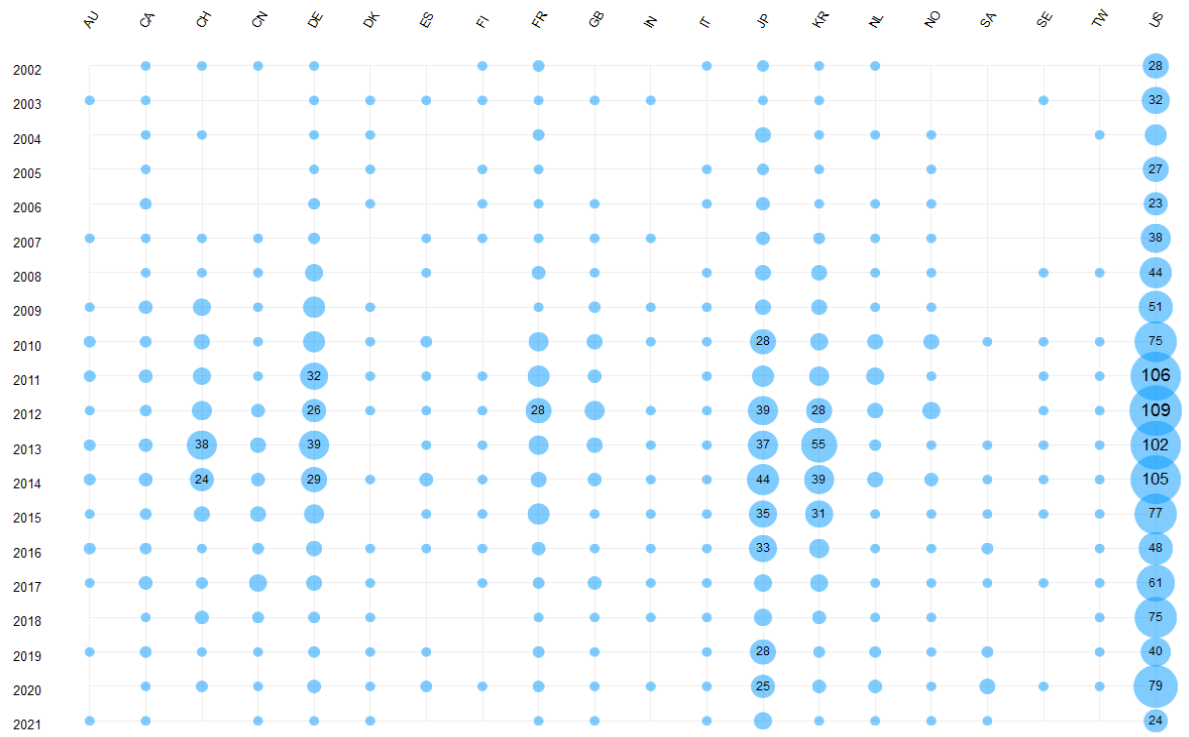

Figure 3.2.: patent activity by publication year per applicant country.

The top patent publication list of companies is shown in table 3.2.. The list is lead by Alstom but also oil companies are figuring in the list. The filing activity of these companies over time is shown in figure 3.3. Whereas Alstom does not seem to show activity in recent years, some of the oil companies such as Saudi Arabian Oil and ExxonMobil are increasing their activity. Table 3.3 shows the top 10 for academic institutes. As can be seen, the top 10 is dominated by Korean institutes and US institutes with a French institute taking second place (INST FRANCAIS DU PETROLE).

Table 3.2.: companies with the largest number of patent publications

Company	Patent publications
ALSTOM TECHNOLOGY LTD	118
MITSUBISHI HEAVY IND LTD	87
AIR LIQUIDE	79
AIR PROD & CHEM	52
SIEMENS AG	51
UOP LLC	48
EXXONMOBIL RES & ENG CO	48
GEN ELECTRIC	45
TOSHIBA KK	44
SHELL OIL CO	39
SAUDI ARABIAN OIL CO	34
PRAXAIR TECHNOLOGY INC	33
KANSAI ELECTRIC POWER CO	32
LINDE AG	29
FLUOR TECH CORP	26
KOREA ELECTRIC POWER CORP	26
INST FRANCAIS DU PETROLE	26
SHELL INT RESEARCH	25
CO2 SOLUTIONS INC	24
CHEVRON USA INC	23

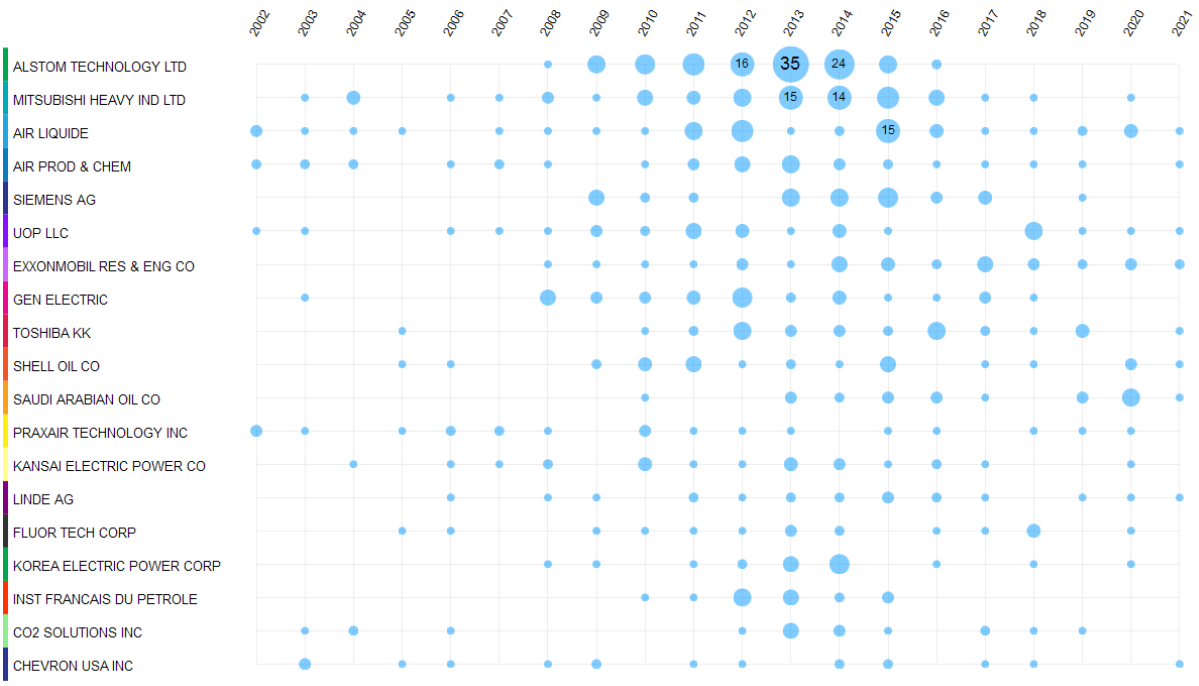

Figure 3.3.: company filing activity with time

Table 3.3: Academic institutes with largest number of patents

Academic Institute	Number of patents
KOREA ENERGY RESEARCH INST	54
INST FRANCAIS DU PETROLE	27
RES INST IND SCIENCE & TECH	24
UNIV TEXAS	10
UNIV RICE WILLIAM M	10
UNIV KOREA RES & BUS FOUND	10
UNIV KENTUCKY RES FOUND	9
UNIV COLUMBIA	8
UNIV KING FAHD PET & MINERALS	8
KOREA ADVANCED INST SCI & TECH	8

Some of the technologies used in CCS and their activity over time are depicted in figure 3.4. This figure was obtained by doing text pattern analysis amongst the claims. Absorption and adsorption are dominating the picture but also membrane technology is seeing good activity. A further topic analysis was undertaken by analysing the various CPC classes that appear in the dataset. This is shown in figure 3.5. From this it can be seen that a big topic is the treatment of flue gas. Amines are used as absorbents and zeolites play a significant role amongst the adsorbents.

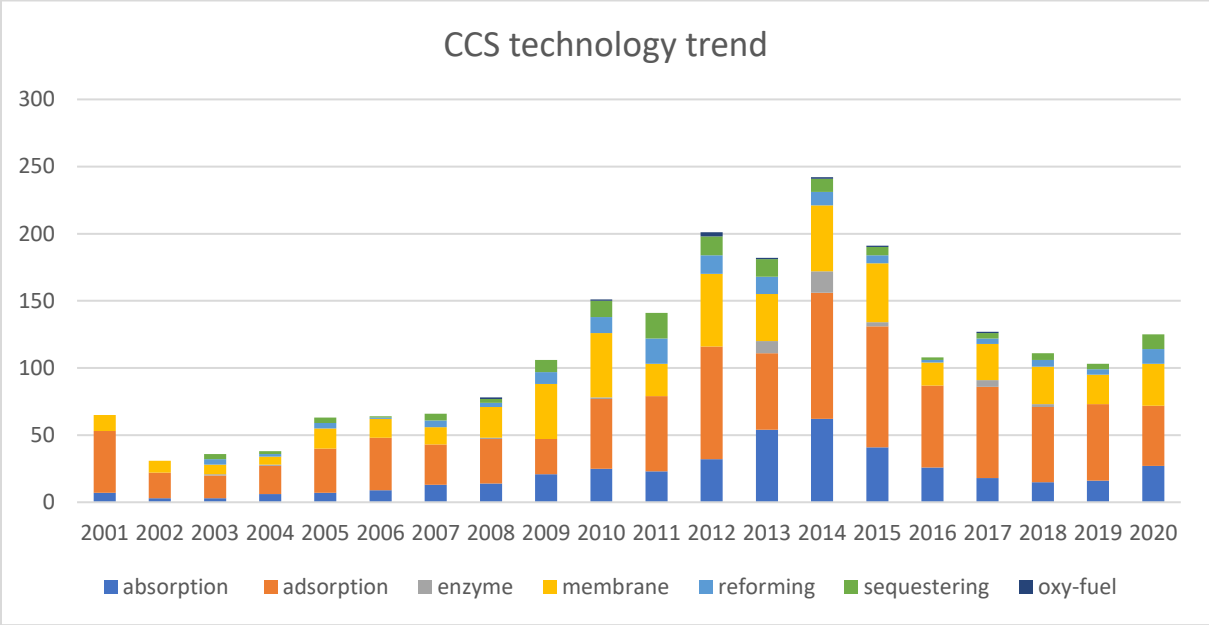

Figure 3.4: technologies used in CCS

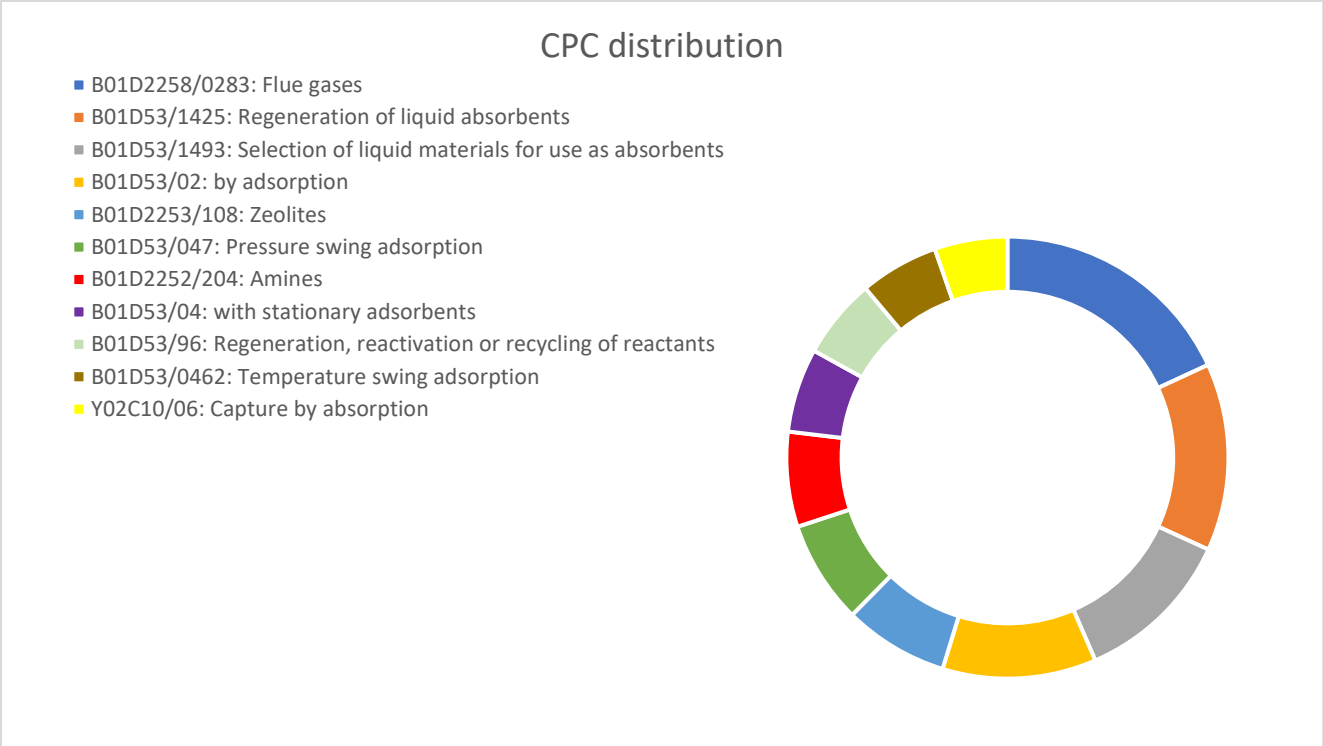

Figure 3.5: Analysis of CPC classes in CCS

Table 3.4: Patents with contributions from Belgian inventors

PUBLICATION NUMBER	PUBLICATION DATE	TITLE	APPLICANT
WO2020083854A1	30 apr 2020	Ammonia deposition precipitation process for producing a copper-nickel/gamma-alumina catalyst, said catalyst and its use in the conversion of exhaust gases	UNIV ANTWERPEN [BE],LUREDERRA CENTRO TECNOLOGICO [ES],UNIVERSITA' DEGLI STUDI DI PADOVA [IT]
US2020070123A1	05 mrt 2020	Advanced porous carbon adsorbents for co2 capture and separation	SOLVAY [BE]
US2018326352A1	15 nov 2018	Method and system for reducing co2 emissions from industrial processes	DOW GLOBAL TECHNOLOGIES LLC [US]
WO2017017102A1	02 feb 2017	System and method for capturing carbon dioxide from air	VITO NV [BE]
WO2015177333A1	26 nov 2015	Improved acid gas removal process by absorbent solution comprising amine compounds	TAMINCO [BE]
WO2014207035A1	31 dec 2014	Method and plant for capturing co2	SARGAS AS [NO]
US2013205796A1	15 aug 2013	Heat integration in co2 capture	SARGAS AS [NO]
US2013119667A1	16 mei 2013	Jet engine with carbon capture	
WO2011101469A1	25 aug 2011	Method for purifying gases including co2 and corresponding device	AGC GLASS EUROPE [BE],CARMEUSE GROUP [BE]
WO2011054803A1	12 mei 2011	Centrifugal separation of condensed co2 from a flue gas	SHELL INT RESEARCH [NL]
US2011064635A1	17 mrt 2011	Method for reducing aerosol emissions in a urea granulation plant	UHDE FERTILIZER TECHNOLOGY BV [NL]
WO2009156474A1	30 dec 2009	Treatment of gaseous effluents	AGC FLAT GLASS EUROPE SA [BE]
FR2853005A1	01 okt 2004	Exhaust gas purifier for vehicle, has centrifugal system to agitate gas to definite speed leading to their complete combustion and decreasing carbon dioxide content from gas, filter block to filter gas that is directed to reducer	
US2003047037A1	13 mrt 2003	Process for removal of carbon dioxide for use in producing direct reduced iron	UOP LLC [US]
US2002152891A1	24 okt 2002	Method of feeding, with impure nitrogen, the combustion chamber of a gas turbine combined with an air distillation unit, and corresponding electricity generation plant	AIR LIQUIDE [FR]

4. Selection of topics

4.1. Absorption

As discussed in section 3.1, absorption is one of the more important technologies used to capture CO_2. Absorption is the most widely used carbon dioxide capturing technology today.

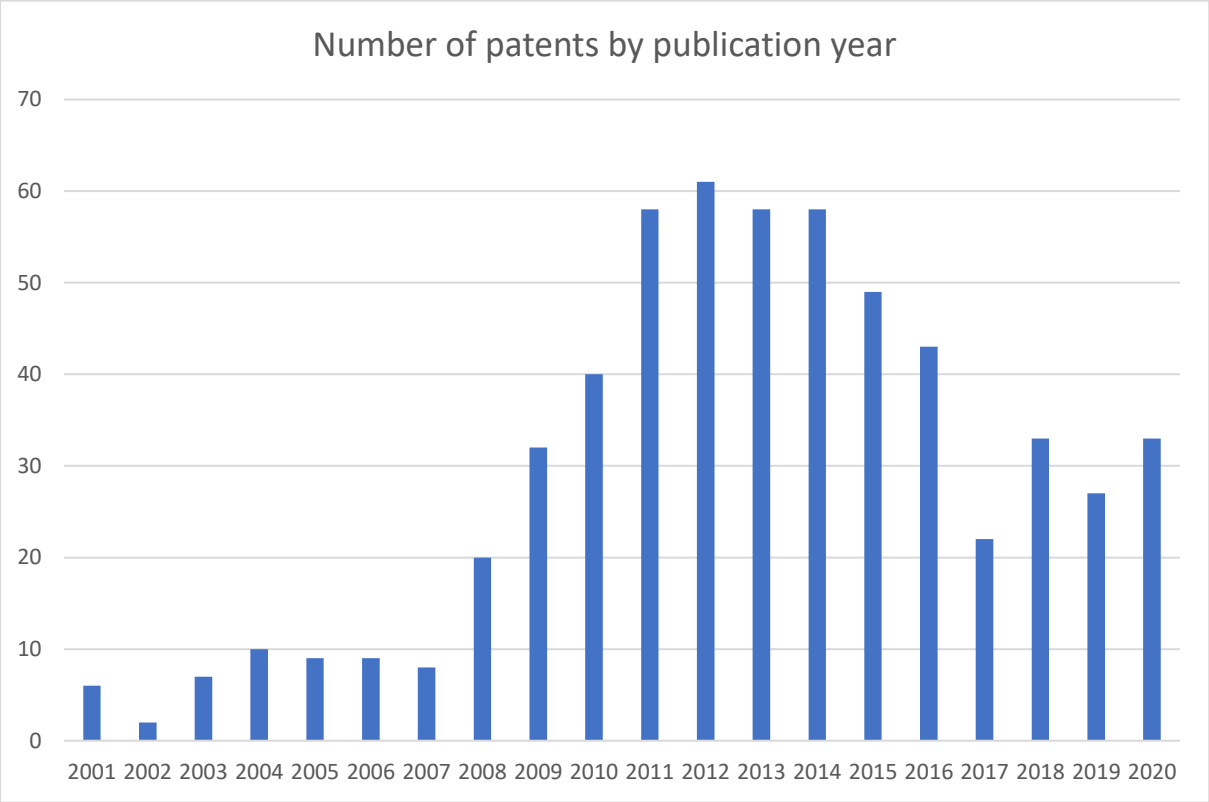

Figure 4.1.1: patent activity relating to absorption

As can be seen from figure 4.1.1., the patent publication trend in absorption is very similar to that of the overall field (compare figure 3.1) with an increase from 2007 towards about 2012 whereafter the activity is declining to stabilize between 2018 and 2020. Table 4.1.1 below shows the top 10 company publications. The list is somewhat different to that of the top 10 of the overall CCS field (table 3.1.1) although Alstom also leads this list. However, Toshiba, General Electric and UOP now figure higher. Of the oil companies, only Shell figures in the top 10 list. Table 4.1.2 depicts the top 5 list of academic institutions. There is a clear dominance of the Korean Energy research institute.

Table 4.1.1.: Top 10 company applicant publications relating to absorption technology

Company	Number of patent publications
ALSTOM TECHNOLOGY LTD	42
TOSHIBA KK	33
GEN ELECTRIC	20
UOP LLC	20
MITSUBISHI HEAVY IND LTD	18
SHELL OIL CO	14
FLUOR TECH CORP	11
SIEMENS AG	9
GENERAL ELECTRIC TECHNOLOGY GMBH	9
SHELL INT RESEARCH	8

Table 4.1.2: Top 5 academic applicant publications relating to adsorption technology

Academic	Number of patent publications
KOREA ENERGY RESEARCH INST	12
UNIV TEXAS	3
UNIV KENTUCKY RES FOUND	3
UNIV NAT TSING HUA	3
UNIV REGINA	2

Figure 4.1.2 depicts an analysis of a selection of the more relevant CPC codes found in the absorption dataset. As can be seen absorption is used in particular to scrub flue gases and the absorbents used belong to the class of amines. A significant portion of the patents also deal with regeneration of the absorbent. In figure 4.1.3 the trend of the CPC classes with time is depicted. It can be seen that there is continued activity on the use of absorption to recover CO_2 from flue gas (B01D2252/204) and the main topics continue to be the selection of suitable absorbents (B01D53/1493) as well as regeneration thereof (B01D53/1425).

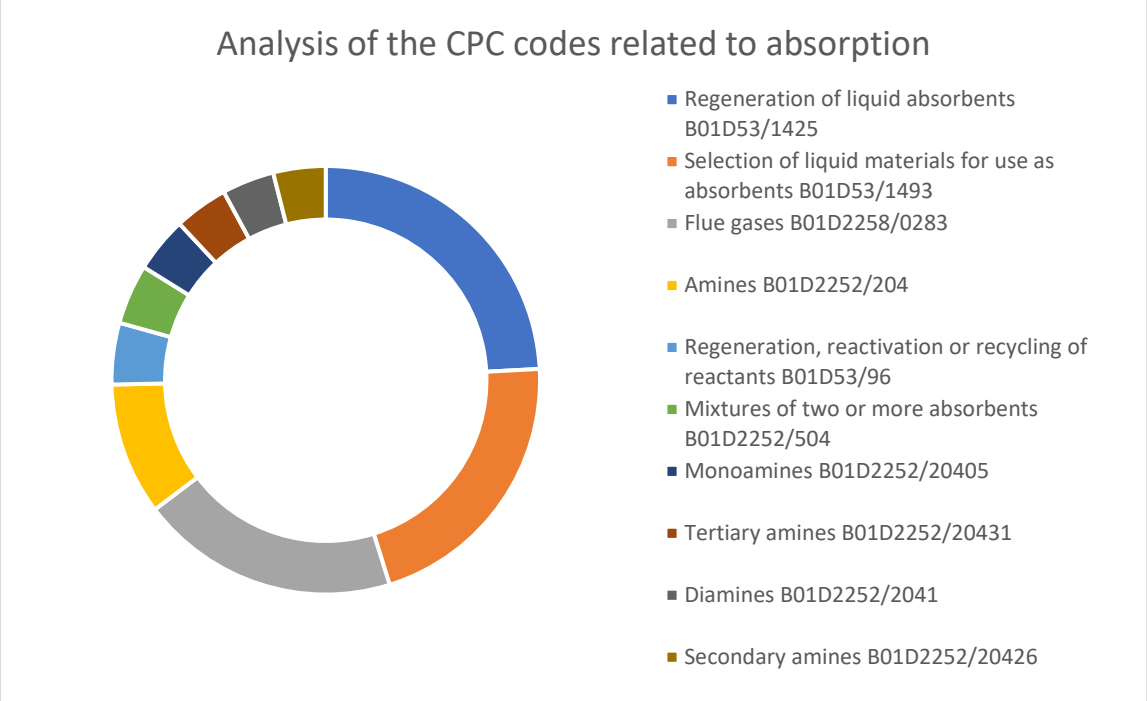

Figure 4.1.2

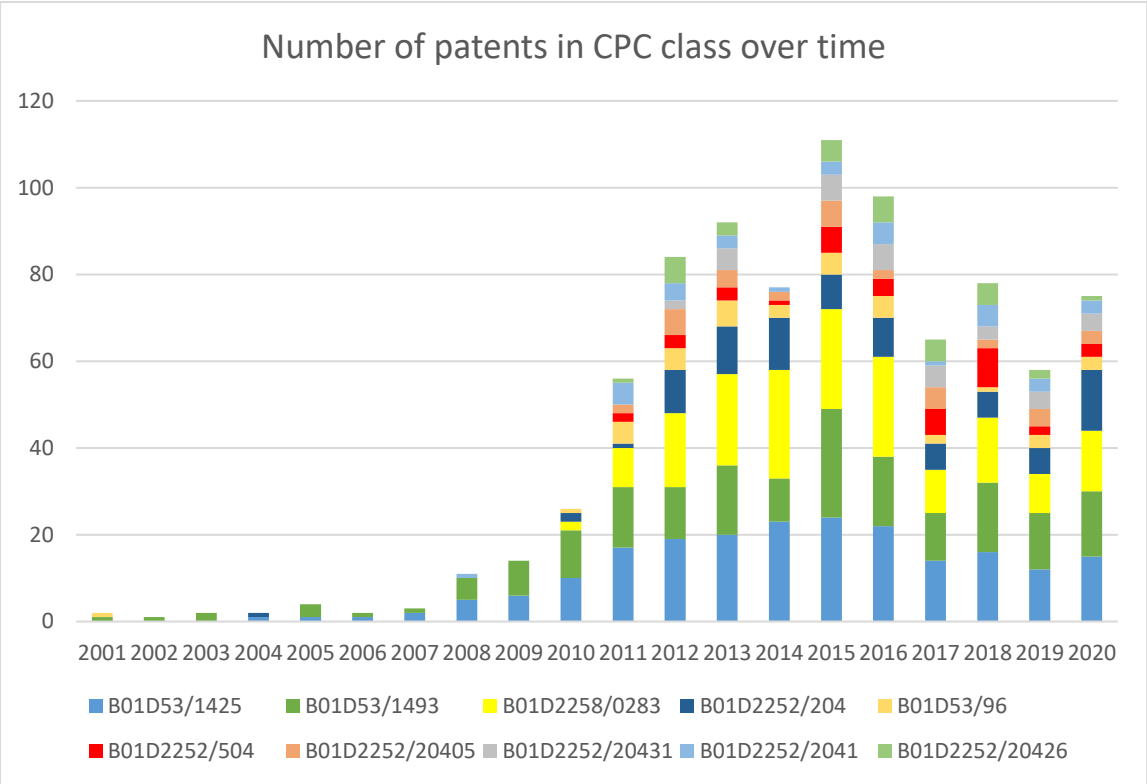

Figure 4.1.3 (for meaning of CPC codes, see figure 4.1.2)

Using the patent value analysis, patents are scored based on the size of the patent family and the number of forward patent citations. A high score is obtained if the family is large, which would be an indicator of the market significance of the patent, and the number of forward citations is large, which is an indicator of the significance of the technology described. From the analysis done, the patents with a high value score as well as patents that have a large number of citations were selected and listed in table 4.1.3. US 2012/279728 has the highest patent value score and is related to the removal of CO_2 when recovering natural gas, whereby the carbon dioxide is reinjected into the a subterranean formation under pressure. According to the patent this was in 2012 a relatively new technology practiced in limited fields.

Table 4.1.3: Patent value analysis of absorption technology

PATENT NUMBER	SCORE	PUBLICATION DATE	SIZE FAMILY	NUMBER OF FORWARD CITATIONS
US2012279728A1	74	08 nov 2012	14	82
US2008178733A1	71	31 jul 2008	15	77
US2011023539A1	69	03 feb 2011	14	52
US2009199713A1	68	13 aug 2009	13	60
US6228145B1	67	08 mei 2001	10	107
US2008025893A1	66	31 jan 2008	10	65
US2010310439A1	65	09 dec 2010	8	70
US2008159937A1	65	03 jul 2008	9	64
US2010236242A1	64	23 sep 2010	7	71
US2004221578A1	61	11 nov 2004	6	81
US2005028529A1	60	10 feb 2005	4	109
US2006051274A1	52	09 mrt 2006	1	117
US2009220406A1	49	03 sep 2009	1	72

US 2006/51274 has the largest number of citations and describes a laminar scrubbing intended to capture carbon dioxide from air using a strong hydroxide solution which may be a sodium hydroxide solution or amines may be used. The technology is stated to be useful to capture carbon dioxide from gas streams that have a low concentration of carbon dioxide.

US 6228145 has one of the highest number of citations combined with a high patent value score. The patent describes a method for removing carbon dioxide from flue gas or a natural gas using a solvent as an absorbent and then regenerating the solvent in a desorber. Membranes are being used in both the absorbing unit as well as the desorbing unit to achieve an optimized process with regard to weight, cost and energy consumption.

4.2. Adsorption

As described above in section 2, a dedicated data set was created to examine the adsorption technology in CCS in more detail. In figure 4.2.1 is shown the activity with time relating to this technology.

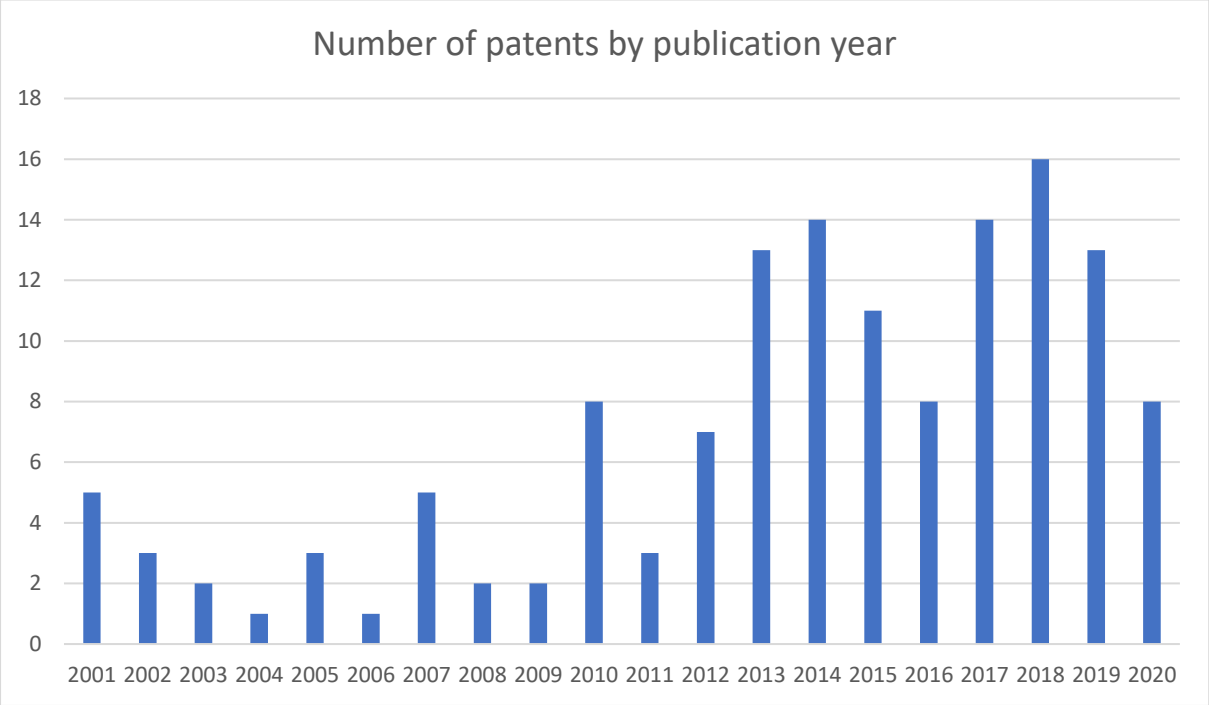

Figure 4.2.1.: patent activity relating to absorption

There is an increasing trend observed from 2010 towards 2018. Some decline is happening in recent years. The overall activity also appears less than that in absorption.

Tables 4.2.1 and 4.2.2 show the top 5 applicants amongst respectively companies and academics. Different companies are making the top of the list as compared to the top list in the overall field. The academics are dominated by US institutions.

Table 4.2.1.: Top 5 company applicant publications relating to adsorption technology

Company	Number of patents
SAMSUNG ELECTRONICS CO LTD	9
HITACHI CHEMICAL CO LTD	9
AIR PROD & CHEM	8
CORNING INC	7
ENTEGRIS INC	3

Table 4.2.2.: Top 5 academic applicant publications relating to absorption technology

Academic	Number of patent publications
UNIV RICE WILLIAM M	4
UNIV SOUTHERN CALIFORNIA	3
UNIV WEST VIRGINIA	2
UNIV KING FAHD PET & MINERALS	2
UNIV MISSOURI	2

Figure 4.2.2 shows an analysis of selected CPC codes in the adsorption dataset. Notable is the importance of zeolites as adsorbents. Polymeric adsorbents are figuring as well and both temperature swing and pressure swing adsorption are used with temperature swing adsorption being used somewhat more.

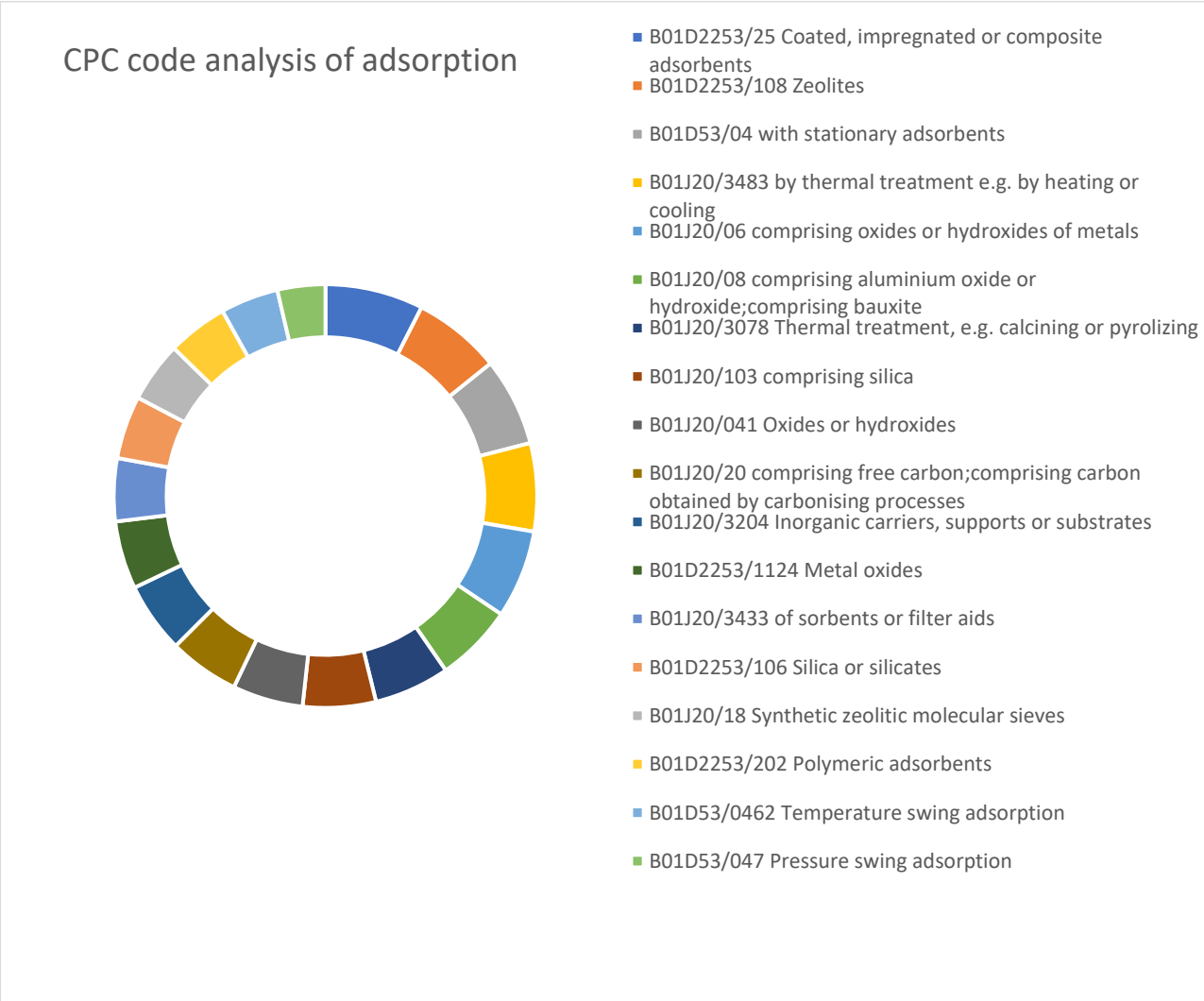

Figure 4.2.2

Table 4.2.3: Patent value analysis of adsorption technology

Patent number	Score	Publication Date	Family Size	Number of Citations
US2008293976A1	76	27 nov 2008	10	105
US2010154636A1	71	24 jun 2010	11	42
US6280503B1	67	28 aug 2001	10	52
US8012446B1	66	06 sep 2011	8	35
US2007068389A1	58	29 mrt 2007	2	94

US 2008/293976 has the highest score as well as a large number of citations and describes regenerative, supported amine sorbents that includes an amine or an amine/polyol composition deposited on a nano-structured support such as nanosilica. The aim of the patent is to provide an improved sorbent for capturing CO_2, which is efficient, economical, readily available and regenerative, and which provides a high removal capacity at ambient as well as elevated temperatures. In addition the patent aims at an efficient absorption system that solves corrosion and evaporation problems.

US 2007/68389 has the second highest number of citations and is related to the use of a metal-organic framework that is capable of adsorbing a large amount of carbon dioxide at room temperature.

Because of the importance of zeolites amongst adsorbents used, a separate patent value analysis thereof was undertaken using a dataset on zeolites (see section 2). The top 5 patents with the highest value score are given in table 4.2.4.

Table 4.2.4: Patent value analysis of zeolites as adsorbents

Patent number	Score	Publication Date	Family Size	Number of Forward citations
US2006117952A1	77	08 jun 2006	24	43
US2008282887A1	72	20 nov 2008	8	98
US2014338425A1	71	20 nov 2014	12	31
US6616732B1	67	09 sep 2003	26	14
US2011079145A1	65	07 apr 2011	10	25

4.3. Membranes

Activity with time for the use of membranes in the separation of carbon dioxide from a gas stream is shown in figure 4.3.1. Ongoing activity is seen from 2011 forward. The use of membranes in the recovery of carbon dioxide is less common than that for absorption and adsorption.

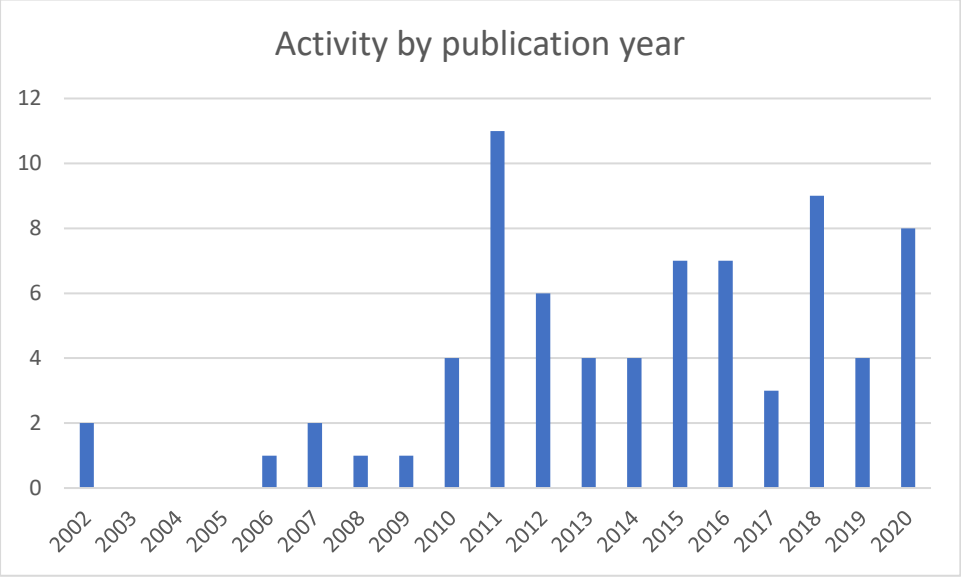

Figure 4.3.1: patent activity for membranes by year of publication

The players amongst companies and academic institutions are given in tables 4.3.1 and 4.3.2. Membrane Tech & Res Inc is dominating the leading company list with a significant gap to other companies. There are also two oil companies having activity in this field.

Table 4.3.1.: Top 10 company applicant publications relating to membrane technology

Company	Patent publications
MEMBRANE TECH & RES INC	10
HITACHI SHIPBUILDING ENG CO	3
SAUDI ARABIAN OIL CO	3
ZENON ENVIRONMENTAL INC	2
GEN ELECTRIC	2
SHELL OIL CO	2
AIR LIQUIDE	2
RENAISSANCE ENERGY RES CORP	2
KOREA SOUTH EAST POWER CO LTD	2
KOREA WESTERN POWER CO LTD	2

Table 4.3.2.: Academic institutes with publications relating to membrane technology

Academic institute	Patent publications
KOREA ENERGY RESEARCH INST	3
UNIV PITTSBURGH	4
UNIV SOUTH CAROLINA	2
UNIV FLORIDA	1
UNIV KENTUCKY RES FOUND	1
NORWEGIAN UNIV SCI & TECH NTNU	1
MASSACHUSETTS INST TECHNOLOGY	1

Table 4.3.3 shows the most significant patents amongst the use of membranes in CCS as based on the patent value analysis. US 2011/167821 and US 2011/262328 uses sweep based membrane units to treat flue gas. US 2011/219949 is a patent from Membrane Tech & Res Inc using membranes to recover carbon dioxide from gaseous fuel combustion. US 2010/260657 uses hydrogen and carbon dioxide separation membranes in the production of hydrogen from a carbon-containing fuel in a reformer.

Table 4.3.3: Patent value analysis of membrane technology used for CCS

Patent number	Score	Publication Date	Family Size	Number of Forward Citations
US2011167821A1	81	14 jul 2011	9	43
US2010260657A1	69	14 okt 2010	6	22
US2011262328A1	67	27 okt 2011	6	18
US2011219949A1	66	15 sep 2011	6	16

4.4. Pre-combustion

One of the issues with the capturing of carbon dioxide from flue gases is that the concentration of carbon dioxide in the flue gas is low making the removal of carbon dioxide therefrom expensive and inefficient. Accordingly, alternatives have been sought whereby the hydrocarbon fuel (natural gas or otherwise) is converted into syngas that contains hydrogen and carbon monoxide. The latter may be further converted into hydrogen through a shift reaction producing also carbon dioxide. The hydrogen can then be used in power plants to generate electricity. In this process, the concentration of carbon dioxide is much larger and can be more efficiently captured. A downside of the technology however is that it cannot be easily retrofitted to existing power plants.

Figure 4.4.1 sets forth the activity with time relating to pre-combustion capture of carbon dioxide. The pattern is following that of the overall activity in the field and hence a peak of activity is falling in 2010 to 2013.

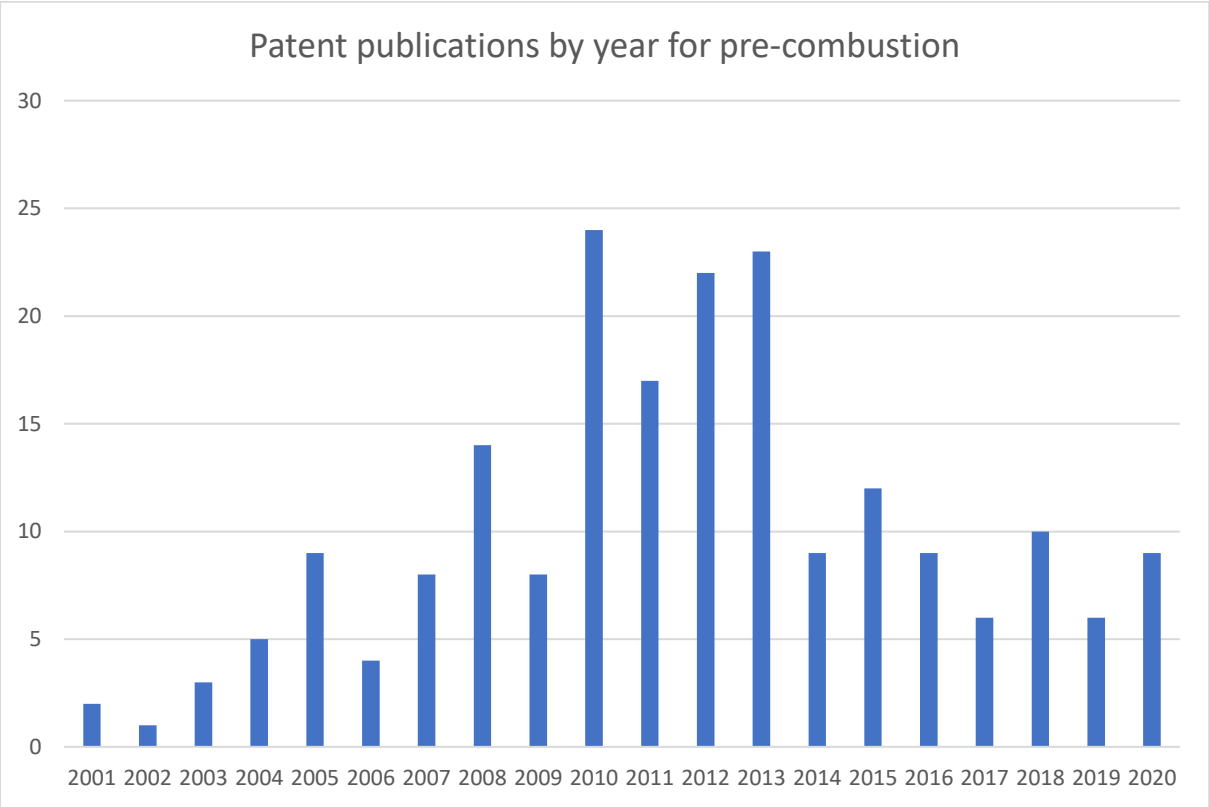

Figure 4.4.1: patent activity of pre-combustion technology in CCS

Table 4.4.1 sets forth the top 10 of company patent publications and table 4.4.2 gives the top applicants amongst academic institution. The company list is lead by Air Liquide Group and notable is also the presence of Shell in the top 5. The top academic institutes are from France, US and Korea.

Table 4.4.1: Top 10 company applicant publications relating to pre-combustion technology

Company	Patent publications
AIR LIQUIDE GROUP	31
SHELL OIL CO	15
JOHNSON MATTHEY PLC	11
MITSUBISHI HEAVY IND LTD	7
PRAXAIR TECHNOLOGY INC	7
GEN ELECTRIC	6
TOPSOE HALDOR AS	6
CASALE SA	6
AIR PROD & CHEM	5
TEXACO DEVELOPMENT CORP	5

Table 4.4.2: Academic applicant publications relating to pre-combustion technology

Academic institute	Patent publications
INST FRANCAIS DU PETROLE	3
UNIV SOUTHERN CALIFORNIA	2
UNIV SOUTH CAROLINA	1
UNIV KOREA RES & BUS FOUND	1

Figure 4.4.2 displays an analysis of a selected number of CPC codes in the dataset. As can be seen from the analysis, adsorption, absorption and membrane separation techniques are all used in combination with pre-combustion to capture the carbon dioxide. A significant source for pre-combustion are natural gas and methane.

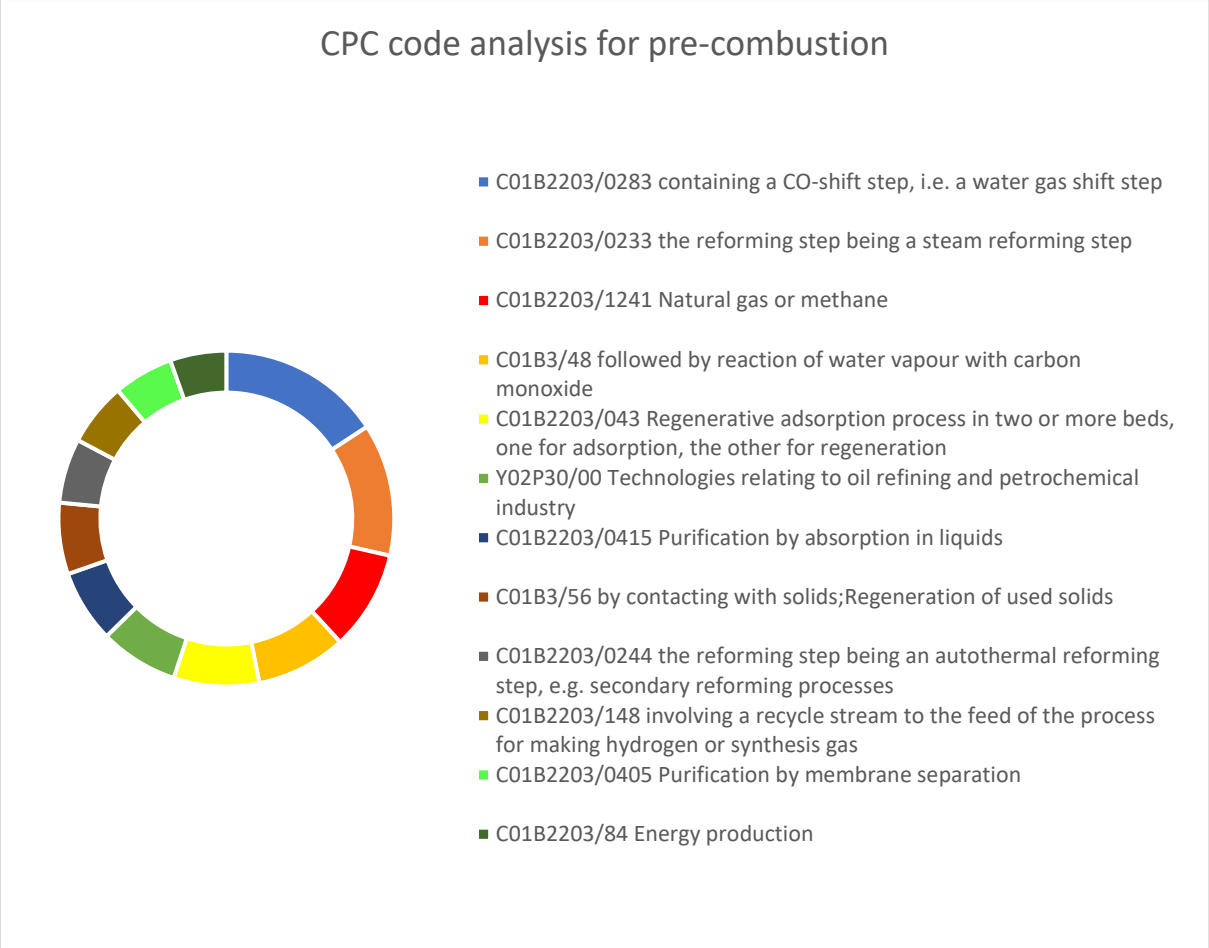

Figure 4.4.2: CPC code analysis for pre-combustion

Finally, the more significant patent publications in the data set of pre-combustion were selected using patent value analysis. These are given in table 4.4.3. US 2007/232706 is a patent of Praxair and relates to a method of producing a carbon dioxide product stream from a synthesis gas stream formed within a hydrogen plant. Vacuum pressure swing adsorption is used to separate out a crude CO_2 stream which is then purified in a distillation process. In this process both hydrogen of the syngas and CO_2 are considered desired products. US 2009/117024, with the highest number of citations, is similar in that both hydrogen and carbon dioxide are product streams. US 6,312,658 is a patent from Air Products and relates to a process for producing an essentially pure carbon monoxide (CO) product and an essentially pure hydrogen product by reforming a hydrocarbon such as methane and steam in the presence of a reforming catalyst to produce a reformate product enriched in CO, carbon dioxide and hydrogen. The reformate is subjected to an integrated series of separation steps and carbon dioxide present in a portion of the waste effluent recovered from such series of separation steps is shifted to CO in an integrated sorption enhanced reaction (SER) process.

Finally, it is to be noted that carbon dioxide is also used in the recovery of oil from oil fields and it may need to be transported to the well where it is pumped into the well under high pressure to recover oil. This poses the problem of (i) the need to transport carbon dioxide and secondly that pumping carbon dioxide into the well increases the amount of carbon dioxide in the recovered oil. US 2011/88896 aims to solve these problems by integrating syngas production with the oil recovery process. The gaseous hydrocarbon stream produced by the well is combined with the synthesis gas to recover carbon dioxide from both and this carbon dioxide is then re-used in the oil recovery.

Table 4.4.3 : Patent value analysis of pre-combustion

Value	Score	Publication Date	Family Size	Number of Forward Citations
US2007232706A1	67	04 okt 2007	8	67
US2010264374A1	66	21 okt 2010	21	11
US2009186952A1	65	23 jul 2009	10	34
US2008267842A1	64	30 okt 2008	24	8
US2011088896A1	64	21 apr 2011	5	62
US6312658B1	63	06 nov 2001	16	19
US2009117024A1	63	07 mei 2009	3	127
US2008155984A1	62	03 jul 2008	4	86
US2007130957A1	53	14 jun 2007	1	113

4.5. Fuel cells

An interesting development in the field of CCS appears to be the use of fuel cells to produce electricity using natural gas or other hydrocarbon fuels or in combination with reforming technology whereby the hydrogen produced is used in a fuel cell. It is thus also a pre-combustion capture of CO_2. Figure 4.5.1 shows the patent activity for fuel cell usage in CCS. The activity appears to be more or less stable over the last decade.

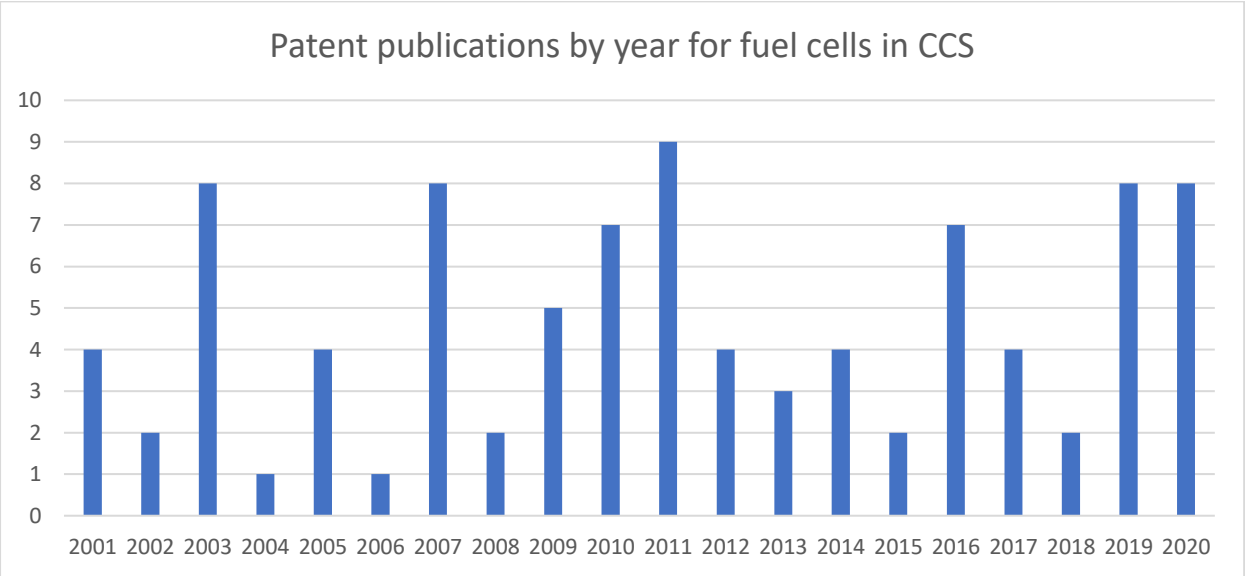

Figure 4.5.1: patent activity for use of fuel cell technology in CCS

Table 4.5.1 shows the top 5 of companies with the most patent publications on fuel cells in CCS. The list is lead by FuelCell Energy Inc., a US engineering company that is trying to market molten carbonate fuel (MCF) cells for the capture of carbon dioxide. The patents of FuelCell Energy on MCF have only recently been published and the five most recent are set forth in table 4.5.2. FuelCell Energy Inc. has a collaboration with ExxonMobil and a pilot is being run at an Alabama power plant[7]. The activity of academics is significantly less than for other technologies in CCS and hence a table is not included in this section.

Table 4.5.1: Top 5 company patent publications in fuel cells for CCS

Company	Patent Publications
FUELCELL ENERGY INC	9
SIEMENS AG	4
ALBERTA LTD 1304342	4
SAUDI ARABIAN OIL CO	3
BLOOM ENERGY CORP	2

Table 4.5.2: Patents of FuelCell Energy Inc. on molten carbonate fuel cells

Publication number	Publication date	Title
US2019140296A1	09 mei 2019	Carbon dioxide removal system for anode exhaust of a fuel cell
US2019131645A1	02 mei 2019	Carbon dioxide sequestration using molten carbonate fuel cell and hydrogen separation technology
US2019062643A1	28 feb 2019	Fluidized catalytic cracking unit system with integrated reformer-electrolyzer-purifier
US2018261865A1	13 sep 2018	System for capturing co2 from a fuel cell
US2018261864A1	13 sep 2018	Fuel cell system having enhanced co2 capture

The most significant patents relating to fuel cell usage in CCS were selected by using the patent value analysis. The top 5 of patents with the highest score and/or highest number of citations is given in table 4.5.3. Although FuelCell Energy Inc. is actively trying to promote fuel cells based on molten carbonate, none of its patents make the top 5, likely because their patents are very young and hence

[7] "Fuel Cells Finally Find a Killer App: Carbon Capture": https://spectrum.ieee.org/green-tech/fuel-cells/fuel-cells-finally-find-a-killer-app-carbon-capture

have not gathered a lot of citations. Nevertheless, US 2007/287046 (CENTRAL RES INST ELECT) and US 2011/22350 (TOKYO GAS CO LTD) are two patents relating to the use of MCF cells in CCS and hence it does appear to be a promising technology for the future. US 2011/315560 describes the use of a fuel cell in combination with micro-organisms to which the carbon dioxide produced in the fuel cell is fed. The micro-organisms then produce desired chemicals.

Table 4.5.3: patent value analysis

Patent Number	Score	Publication Date	Family Size	Number of Forward Citations
US2007077480A1	69	05 apr 2007	13	24
US2011315560A1	62	29 dec 2011	8	18
US2011223501A1	59	15 sep 2011	5	30
US2007287046A1	59	13 dec 2007	5	39
US6221117B1	53	24 apr 2001	1	283

5. Conclusions

Climate change presents one of the biggest challenges of our times according to the European Environment Agency. The global warming is caused by the emission of greenhouse gases of which carbon dioxide (CO_2) and methane are the most important. Reducing carbon dioxide in the atmosphere is urgently needed and carbon capture is an essential technology to achieve the climate ambitions of the Paris Agreement on climate. This report aims to provide an analysis of the innovative activities in the field of carbon capture and storage. The analysis is performed through a review of the patent activity in this field using “Patent Inspiration”.

It was found that the patent activity in CCS saw its peak around 2013-2014 but signs of an increase again in 2020 are seen. The dominant technologies used in CCS are absorption, which is nowadays mostly used in capturing carbon dioxide from exhaust gases, and adsorption but also membrane technology is gaining. Pre-combustion has the potential of capturing carbon dioxide in a more efficient way in power plants but cannot be retrofitted to power plants. An interesting development in pre-combustion are fuel cells and in particular molten carbonate fuel cells that are being piloted by ExxonMobil in a power plant in the US. The patent filing activity is dominated by American companies but also European companies are showing a high amount of activity as well as Korean and Japanese applicants. China is lagging significantly behind. The top 5 of most active companies in the CCS field is lead by Alstom and contains 3 European companies. ExxonMobil, Shell and Saudi Arabian are oil companies figuring in the top 10 list.

Amines are the most commonly used sorbents and are used in absorption as solvents but may also be used on a supporting substrate in adsorption technology. Zeolites are an important adsorbent but also polymeric adsorbents are used amongst adsorption technologies.