

Negative emissions technologies and CCS to achieve the Paris Agreement commitments

Supplementary publication with : <http://dx.doi.org/10.1098/rsta.2016.0447>

Database and analysis of past and future CCS project build rates and CO₂ storage rates

Compiled by Dr Stephanie Flude, and verified by Professor R Stuart Haszeldine August 2017

Purpose of study

Calculate how much anthropogenic CO₂ has been injected (and presumed successfully stored) into the geological subsurface, and project the rate of capture forward in time.

Method

Data Compilation and verification

A compilation was made of data presented in the GCCSI (1) and SCCS (2) databases and this was used to extract start date, end date (where applicable) and yearly tonnage of CO₂ injection (or storage if such data is available). These databases rely heavily on data from companies, and news or media and trade press sources. These are frequently not peer reviewed in an academic sense. The data is considered reliable enough for the present purposes of comparing past and future CCS project build tonnages, and rate of build. Comparing the two databases shows many similarities, with differences in tonnages clearly attributable to rounding errors. Consequently the information held in these two independently compiled databases is regarded to have been verified by cross-checking, and is the best publicly available information.

Projects included in the compilation are both historic and future projects.

Projects are only included in our compilation if there is an indication that captured CO₂ was injected. Where it is known that natural CO₂ was injected (e.g. Cranfield EOR Project), these experiments have been excluded from the compilation. Projects injecting less than 1 kt CO₂ are also excluded, along with pilot and future projects for which there is no data on the amount of CO₂ injected, or reliable start dates. Solid capture techniques (e.g. Hazlewood Pilot Capture and Sequestration Plant, Australia) are also excluded.

If data is conflicting between databases, or if there is a lack of necessary data (e.g. years of operation or amount injected), the sources of information listed by the databases are checked. If these do not supply the required information a brief Google search is carried out.

Some projects were excluded from our compilation for reasons not wholly described above. The reasons for exclusion are as follows:

- Otway Projects, Australia: SCCS provides total stored values for the Otway experiments, but these mostly use natural CO₂, rather than anthropogenic. When Callide CO₂ was injected, this was back-produced (Haese et al., 2016).
- Callide CO₂ capture, Australia: SCCS seems to claim that 0.02 Mtpa of Callide CO₂ was injected and lists the Denison Trough in a storage comment. As far as we can tell, Callide CO₂ was only injected into the Otway formation. See note above.
- Bow City Power Project, Canada: This project is listed in the SCCS database, but due to a lack of recent information, we assume that this project is on hold or cancelled.

- Harbin thermal power plant capture facility, China: Due to a lack of recent information, we assume that this capture project, which was supposed to provide CO₂ for EOR, is not operating. (SCCS database).
- Bio-diesel from algae project, Inner Mongolia, China: Due to lack of recent information, we assume that this project is on hold or cancelled
- Killingholme coal pre-combustion capture plant, UK: Since the UK CCS competition cancellation, this project appears to be decarbonising by shifting to gas power, rather than applying CO₂ capture, so this project is excluded:
<http://www.modernpowersystems.com/features/featurecgen-looks-to-capacity-market-for-north-killingholme-ccgt-5819815/>
- Riley Ridge, USA: A lack of recent data leads us to suspect this project has been cancelled.
- South Heart IGCC capture plant, USA: This project has an estimated capture rate and start year, but the latter is 2017 and there doesn't seem to be any information more recent than ~ 2011. Assume this project is on hold or cancelled
- Polk CCS Demonstration plant, USA: This project is not included due to lack of information on whether captured CO₂ is being stored.
- Projects listed on the SCCS map as “no storage” or “0 million tonnes CO₂ per year” are generally not included, unless the project is highlighted by the GCCSI database.

Potential Sources of Error in the data

Distinguishing between types of project (capture vs storage) is not always clear and it is possible that some tonnages of CO₂ injection have been counted twice. For instance, the GCCSI entry for the Ketzin project states that 670,000 t CO₂ were injected between 2008 and 2013. A separate GCCSI entry for the Schwarze Pumpe oxyfuel pilot states that 11,000 t CO₂ from the project were injected into the Ketzin storage site in 2011. In this case, it has been assumed that the Schwarze Pumpe CO₂ is included in the Ketzin values and we did not create a separate entry for Schwarze Pumpe. Similar situations may occur elsewhere that have not been identified, but these are considered minor.

Precise dates are available for the beginning and end of some projects – in most of these situations, the yearly injection rate is normalised to the number of months the project was operational in the beginning and end years. In other cases, the full yearly rate is presumed. Sometimes it is most convenient for the yearly storage calculations to round the start / end dates to a single year – such cases are described in the summary table.

Actual masses of CO₂ injected into the subsurface are not available for every project. In many cases, the databases list the capture capacity of the relevant capture plant, but this does not always translate into the amount stored.

Projecting into the future

When projecting into the future, only projects with estimated start dates and injection rates are included. There are some projects that are likely to go ahead but that do not have anticipated start dates (e.g. Teesside Collective; the Indonesian Gundih CCS Pilot), or estimates of the tonnage of CO₂ that will be stored (e.g. the NetPower Allam Cycle Pilot) and so these have been excluded. Similarly, there are some future pilot projects that are expected to progress to larger scale projects upon completion, e.g. the Surat Basin Integrated CCS project in Australia, but for which no updated

estimates are available. These projects are conservatively assumed to stop at the end of the pilot; but in reality may well continue.

CCS Build up curve calculation

A spreadsheet was compiled that has a row entry for every year of every project. Projects that are listed as currently operational (or set to be commissioned in the future), with no indication of an end date, are projected forwards to 2050.

From this a pivot table enabled extraction of data on a year-by-year basis to compile global yearly and cumulative CO₂ injection values.

Sources

[1] SCCS www.sccs.org.uk/map Accessed July and Aug 2017

[2]GCCSI <https://www.globalccsinstitute.com/projects/large-scale-ccs-projects> , Accessed July and Aug 2017

Results: Projects summary lists

Sources [1] *SCCS* www.sccs.org.uk/map Accessed July and Aug 2017

[2] *GCCSI* <https://www.globalccsinstitute.com/projects/large-scale-ccs-projects> , Accessed July and Aug 2017

Supplementary Table 1: Existing Projects Summary

Country	Project	Operation dates	CO ₂ injected / stored	Capture Source	Storage Type	Notes
Algeria	In Salah	2004-2011	1.2 Mtpa	Natural gas processing	Storage	A total of 17 Mt stored ^[1] .
Brazil	Buracica	1995-Present	0.35 Mtpa	Petrochemical	EOR	“mid 1990s”. 600 kt stored by 2005 ^[1]
Brazil	Miranga	Nov2009-Apr2011	370 t/d ^[2] / 0.14 Mtpa		EOR and Storage	0.011 Mt/month = 0.023 Mt in 2009, 0.045 Mt in 2011. 0.135 Mt in 2010
Brazil	Petrobras / Lula / Pre-Salt	2012 ^[2] or 2013 ^[1] – present	1 Mtpa	Natural gas processing	EOR	Assume mid 2012. Now halted
Canada	Zama Project	Oct-2005-Jul2009 ^[2] / from 2006 ^[1]	0.025 Mtpa / 1.3 Mt total ^[1]	Natural gas processing	EOR + MMV	Assume 0.025 Mtpa. 2005= 0.00625 Mt. 2009 = 0.0146 Mt
Canada	Boundary Dam – Weyburn / Aquistore	2014-Present ^[1,2]	1 Mtpa ^[1,2]	Post Combustion	EOR & Storage	Continuing storage to EOR
Canada	Pembina	Feb2005-Mar2008 ^[2]	70 kt by end of 2007 ^[2]		Storage	70 kt over 34 months = 2,059 t/m = 24,706 tpa. 2005 = 20,588 t; 2008 = 6,176 t
Canada	Husky Energy	Since 2012	315 tpd (=0.115 Mtpa) ^[2] / 0.09 Mtpa ^[1]	Gas power plant	EOR	Mtpa are similar. Assume 0.09 Mtpa to allow for plant downtime
Canada	Quest	Since 2015	1 Mtpa	SMR	Storage	
China	Sinopec Zhongyuan	2006-2014	0.02 Mtpa	Petrochemical	EOR	

	Pilot Phase 1					
China	Jilil Oil Field	Since 2006 ^[2] or 2007 ^[1]	1 Mt by first half of 2016; Current capacity 0.35 Mtpa ^[2] . 0.2 Mtpa until 2015; 0.8-1 Mtpa thereafter ^[1] .	Natural gas processing	EOR	Assume 1 Mt was injected from Mid 2006-Mid 2016 = 0.1 Mtpa. Mid 2016 onwards, assume 0.35 Mtpa
China	Shenhua CTL, Inner Mongolia	2011 – 2014 ^[2] or 2015 ^[1]	30 kt total ^[1]	CTL	Storage	30 kt / 4 years = 0.0075 Mtpa
China	Shenhua Ordos CCS Pilot	Jul 2005 ^[2]	0.3 Mt total ^[2]	CTL	Storage	
China	Karamay Dunhua	Since 2015 ^[2]	0.1 Mtpa ^[2]	Methanol production	EOR	
China	Sinopec Zhongyuan Pilot Phase 2	Since 2015	0.1 Mtpa ^[2] / 0.12 Mtpa ^[1]	Petrochemical	EOR	Assume 0.11 Mtpa
China	Yangchan / Jongbian Phase 1	Sept2012 – May 2015	0.1 Mtpa ^[1]	Coal to chemicals	EOR	2012 = 0.033 Mt; 2015 = 0.042 Mtpa
China	Sinpoec Shengli Oilfield	Since mid 2010 ^[2]	0.3-0.4 Mtpa ^[2]	Power plant	EOR	Assume 0.35 Mtpa since 2011. Half of that for 2010.
France	Lacq	Jan 2010 – Mar 2013	51 kt total ^[2] / 0.06 Mtpa with c. 50 kt total ^[1]	Natural Gas Processing	Storage	Assume 50 kt total = 0.015 Mtpa with 0.0038 Mt in2013.
Germany	Ketzin	2008-2013	0.67 Mt total ^[1,2]	Various	Storage	0.67 Mt over 6 years =
The Netherlands	K12-B	2004-2015	100 kt by end October 2015 ^[2] ; 0.02 Mtpa ^[1] .	Natural Gas Processing	Storage	K12-B website is no longer operating, so assume the project ended in 2015. (0.1 Mt / 12 years =
Japan	Nagaoka Storage Project	2002 ^[1] or 2003 ^[2] until 2004 ^[1] or Jun 2005 ^[1]	10.4 kt ^[2] / 0.01 Mt ^[1] total		Storage	Assume 0.014 Mt total between 2005 and 2005 = 0.0035 Mtpa

Japan	Tomokomai CC Demo	2016 – 2018	0.1 Mtpa	Hydrogen Production	Storage	
Mexico	Pemex EOR	Since 1998	8,459,550 t CO ₂ stored between 2004-2013	Natural Gas Processing	EOR	8.5 Mt between 2004-2013 = 0.85 Mtpa. Assume this applies to the whole period.
Norway	Sleipner	Since 1996	1 Mtpa	Natural Gas Processing	Storage	16.5 Mt CO ₂ by Jan 2017
Norway	Snohvit	Since 2008	0.7 Mtpa	Natural Gas Processing	Storage	4 Mt CO ₂ since 2008
Saudi Arabia	Uthmaniyah	2015 for 4-5 years	0.8 Mtpa	Natural Gas Processing	EOR	Assume project ends in 2020
UAE	Abu Dhabi CCS Phase 1 / Al Reyadh	Since November 2016	0.8 Mtpa	Iron / Steel	EOR	
USA	Terrel Natural Gas	Since 1972	0.4 to 0.5 Mtpa ^[2]	Natural Gas Processing	EOR	Assume 0.45 Mtpa
USA	Enid Fertiliser plant	Since 1982	0.7 Mtpa	Fertiliser	EOR	
USA	Shute Creek	Since 1986	4 Mtpa until 2010 ^[1] . 7 Mtpa thereafter.	Natural Gas Processing	EOR	
USA	Val Verde Plants	Since 1998	1.3 Mtpa but this includes the Terrel natural gas plant	Natural Gas Processing	EOR	Assume 1.3-0.45 = 0.85 Mtpa
USA	Great Plains Synfuel Plant	Since 2000	3Mtpa	Synfuel	EOR	US Synfuel plant supplies CO ₂ to Canadian EOR Site (Weyburn)
USA	Frio Brine Pilot	2004	1600 t CO ₂ total ^[2]		Storage	
USA	Oakdale / Apple Tree	Since 2007	0.4 Mtpa ^[1]	Natural Gas Processing	EOR	
USA	Michigan Basin Phase II Field test	2008-2009	60 kt total		Storage	
USA	Century Plant	Since 2010	5 Mtpa until 2012; 8.4 Mtpa frm 2013-2015. 5 Mtpa thereafter ^[1]	Natural Gas Processing	EOR	

USA	Marshall County ECBM	2010-2013 ^[2]	4.5 kt total ^[2]		ECBM	4.5 kt / 4 years = 0.001125 Mtpa
USA	Arkalon ethanol	Since 2010	0.1 ^[1] to 0.19 ^[2] Mtpa	Ethanol	EOR	Assume 0.145 Mtpa
USA	Mountaineer Valley	October 2009- May2011	37 kt total ^[2]	Post combustion	Storage	For simplicity, 0.037 Mt injected in 2010
USA	Farnsworth Project	2011-2015	0.2 Mtpa ^[2] until 1 Mt injected. 640 kt injected by October 2013, of which 595 kt was stored	Various	EOR	2011-2015 dates estimated based on injection. Net storage is 93% of the injected CO ₂ ; so 93% of 0.2 = 0.186 Mtpa
USA	Bonanza Bioenergy	Since 2011	0.1 Mtpa	Ethanol	EOR	
USA	Illinois Basin Decatur Project	November 2011- November2014	Total = 999,215 t	Ethanol	Storage	Simplify to 2012-2014, 0.33Mtpa
USA	Plant Barry / Citronelle	August 2012- September 2014	114 kt total	Post combustion	Storage	Assume 114 kt / 3 years = 0.038 Mtpa
USA	Air products	Since Jan 2013	1 Mtpa	SMR	EOR	
USA	Coffeyville	Since 2013	1 Mtpa ^[2] / 0.85 Mtpa ^[1]	Fertiliser	EOR	Assume average of the quoted injection rates
USA	Lost Cabin	Since 2013	0.9 Mtpa ^[2] to 1 Mtpa ^[1]	Natural Gas Processing	EOR	Assume average
USA	PCS Nitrogen Plant	Since 2013	0.4 Mtpa ^[1]	Fertiliser	EOR	
USA	Michigan Basin Large Scale Injection Test	Since March 2013	Up to 1 Mt over 4 years ^[1] . As of April 2017, 700 kt has been injected ^[2]	Natural Gas Processing	Storage	700 kt as of April 2017 is the equivalent of 14.3 kt/month, or 0.17 kt/y. At this injection rate, the target of 1 Mt is expected to be reached in 2018
USA	Bell Creek	Since May 2013 ^[3]	3.7 Mt by May 2015 ^[2]			Average of 1.85 Mtpa. Assume this rate is constant and that EOR at the site continues
USA	Borger	2015 ^[2]	0.22 Mt in 2015 ^[2]	Fertiliser Plant	EOR	

	Compression Facility					
USA	Ramsey Gas Processing Plant	Since January 2016	0.115 Mtpa ^[1]	Natural Gas Processing	EOR	
USA	Illinois Industrial CCS	Since 2017	1 Mtpa ^[2]	Ethanol	Storage	
USA	Petra Nova	Since 2017	1.6 Mtpa ^[1]	Post Combustion	EOR	

^[1]=SCCS ^[2]=GCCSI ^[3]=(NETL, 2015)

Supplementary Table 2: Future Projects Summary

Country	Project	Operation dates	CO ₂ injected / stored	Capture Source	Storage Type	Notes
Australia	Gorgon	From 2017	3.4 ^[2] to 4.0 ^[1,2] Mtpa	Natural Gas Processing	Storage	Assume 4 Mtpa
Australia	Surat Basin Integrated CCS	2020 ^[1] -2023	0.06 Mtpa ^[1]	Post Combustion ^[1]	Storage ^[1]	Project running for three years
Australia	CarbonNet Pipeline	From "Mid 2020s" ^[2]	1-5 Mtpa ^[2]	Various ^[2]	Storage ^[2]	Assume 2025 start date and 5 Mtpa
Australia	Collie Southwest Hub	From "Mid 2020s" ^[2]	2.5 Mtpa	Fertiliser Plant	Storage	Assume 2025 start date
Canada	Alberta Carbon Trunk Line-Agrium	From 2018	0.58 Mtpa ^[1] / 0.3 to 0.6 Mtpa ^[2]	Fertiliser Plant	EOR	Assume 0.58 Mtpa
Canada	Alberta Carbon Trunk Line-NW Sturgeon	From 2018	1.2 ^[1,2] to 1.4 ^[2] Mtpa	Oil refinery	EOR	Assume 1.4 Mtpa

China	Yangchan Demonstration, Jingbian	From 2018	0.36 ^[1] / 0.4 ^[2] Mtpa	Coal to chemicals	EOR	Assume 0.36 Mtpa
China	Dongguan Taiyangzhou	From 2019	1 Mtpa ^[1]	IGCC	Storage	
China	Sinpoec Qilu Chemicals	From 2019	0.5 Mtpa	Coal / coke gasification	EOR	
China	Sinopec Eastern China CCS	From 2020	0.5 Mtpa	Fertiliser Production	EOR	
China	China Resources Power (Haifeng)	From 2018 ^[1] / "2020s" ^[2]	1 Mtpa	Post combustion	Storage	Assume begins in 2020
China	Huaneng GreenGen IGCC (Phase 3)	From 2020 ^[1] / "2020s" ^[2]	2 Mtpa	Gasification	EOR	Assume begins in 2020
China	Shanxi International Energy Group	From "2020s" ^[2]	2 Mtpa ^[2]	Oxyfuel	Unknown	Assume begins in 2025
China	Shenhua Ningxia CTL	From 2018 ^[1] / "2020s" ^[2]	2 Mtpa	CTL	Unknown	Assume begins 2020
China	Sinpoec Shengli Power Plant	From "2020s" ^[2]	1 Mtpa ^[2]	Post Combustion	EOR	Assume begins 2025
Indonesia	Gundih CCS Pilot	2019 ^[2] -2020	30 t per day for 2 years	Natural Gas Processing	Storage or EGR (enhanced gas recovery)	10,950 tpa = 0.0195 Mtpa
Norway	Longyearbyen	From 2017 ^[1]	0.06 Mtpa ^[1]	Post Combustion	Storage	Assume 2018 start due to lack of recent information. Probably cancelled
Norway	Norway Full Chain CCS	From 2022 ^[2]	1.3 Mtpa ^[2]	Multiple	Storage	Sources = Yara Porsgrunn, Klemetsrud, and Norcem

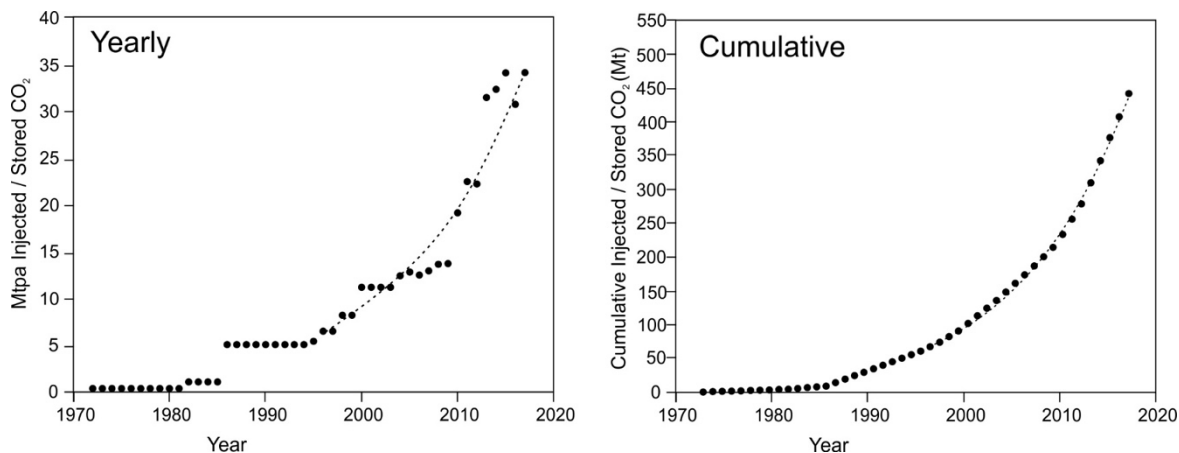
South Korea	Korea CCS-1	From 2017 ^[1] / "2020s" ^[2]	1 ^[2] to 1.5 ^[1] Mtpa	Post Combustion	Storage	Assume begins 2020. Assume 1.5 Mtpa
South Korea	Korea CCS-2	>2020 ^[1] / "2020s" ^[2]	1 ^[2] to 2 ^[1] Mtpa	Oxyfuel or IGCC	Storage	Assume begins 2025 and stores 2 Mtpa.
Taiwan	Tai-chung CCS Pilot	2017-2020 ^[1]	10 ktpa ^[1]	Post ^[1] Combustion	Storage ^[1]	
Taiwan	Tai-chung CCS Demonstration	From 2020 ^[1]	1 Mtpa ^[1]	Post Combustion ^[1]	Storage ^[1]	
UK	Caledonia Clean Energy	From 2022	3.8 Mtpa	Gasification	Storage	
UK	Acorn Project	From 2022	0.4 Mtpa ^[1]	Post Combustion	EOR	
UK	Teeside Collective	From "2020s" ^[2]	0.8 Mtpa ^[2]	Various	Storage	Assume begins 2025
USA	Sargas Texas	From 2017	0.8 Mtpa ^[1]	NGCC	EOR	
USA	Texas Clean Energy Project	From 2018	2 Mtpa ^[1]	IGCC	EOR	
USA	Riley Ridge Gas Plant	From 2020 ^[2]	2.5 Mtpa ^[2]	Natural Gas Processing	EOR	
USA	Lake Charles Methanol	From 2021 ^[2]	4.2 Mtpa ^[2]	Pet-coke Syngas	EOR	
USA	Texas Clean Energy	From 2021 ^[2]	1.5 to 2 Mtpa ^[2]	Coal gasification	EOR	Assume 2 Mtpa

Supplementary Table 3: Calculated yearly CO₂ injection and storage

Year	Mt CO ₂ injected that year	Cumulative injection
1972	0.45	0.5
1973	0.45	0.9
1974	0.45	1.4
1975	0.45	1.8
1976	0.45	2.3
1977	0.45	2.7
1978	0.45	3.2
1979	0.45	3.6
1980	0.45	4.1
1981	0.45	4.5
1982	1.15	5.7
1983	1.15	6.8
1984	1.15	8.0
1985	1.15	9.1
1986	5.15	14.3
1987	5.15	19.4
1988	5.15	24.6
1989	5.15	29.7
1990	5.15	34.9
1991	5.15	40.0
1992	5.15	45.2
1993	5.15	50.3
1994	5.15	55.5
1995	5.5	61.0
1996	6.591	67.5
1997	6.591	74.1
1998	8.287	82.4
1999	8.287	90.7
2000	11.29	102.0
2001	11.29	113.3
2002	11.29	124.6
2003	11.29	135.9
2004	12.51	148.4
2005	12.92	161.3
2006	12.59	173.9
2007	13.04	186.9
2008	13.75	200.7
2009	13.81	214.5
2010	19.24	233.7
2011	22.59	256.3
2012	22.34	278.6
2013	31.59	310.2
2014	32.47	342.7
2015	34.24	376.9
2016	30.86	407.8
2017	34.25	442.0

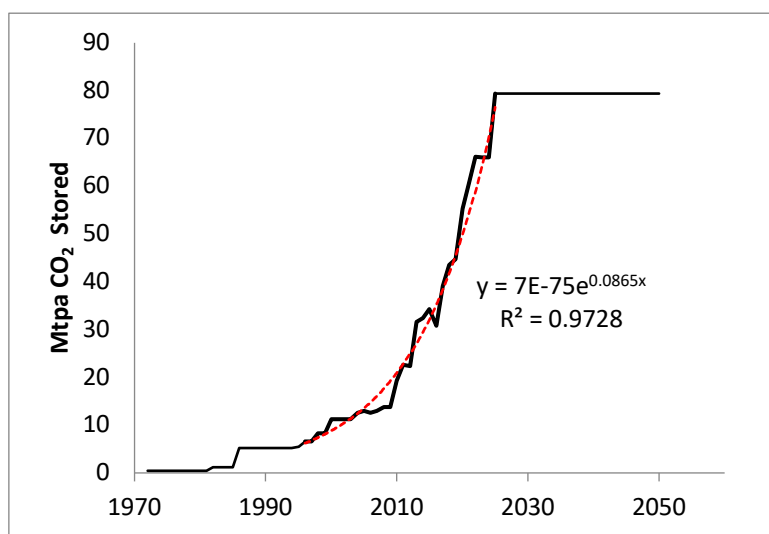
Results Summary (see main text for more detailed discussion):

Historic CO₂ storage – until end 2017

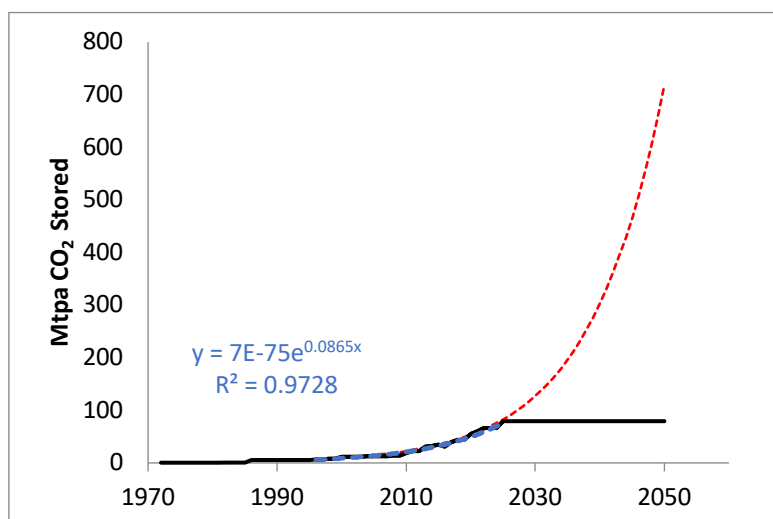


Supplementary Figure 1: Historic build up curves. Dashed lines are exponential fits to the data, used to project the trend forwards in time (see main text for details).

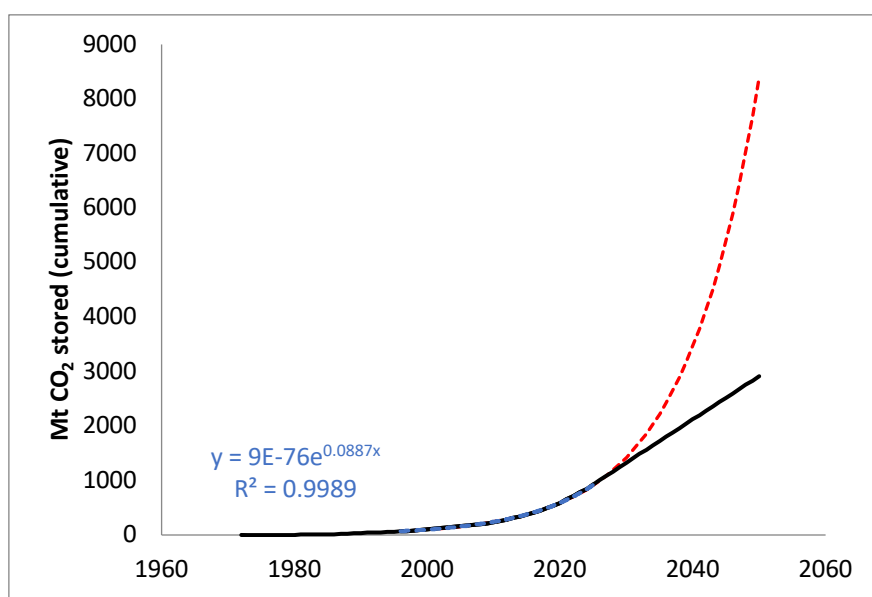
Future CO₂ storage - Incorporating estimates of CCS from planned future projects



Supplementary Figure 2: Historic and planned CCS. There is no quantified, planned increase in CO₂ storage beyond 2025. Red dotted line is exponential fit to data between 1996 and 2025.

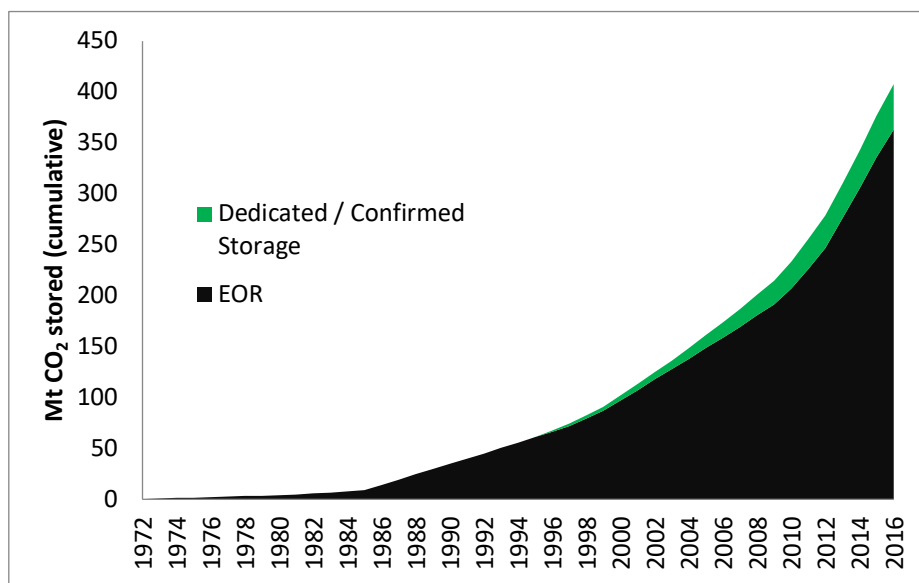


Supplementary Figure 3: Projected future yearly CCS, based on historic and planned implementation. Black line = observed CCS up to 2016, observed and anticipated CCS in 2017, and anticipated CCS from 2018-2050, based on planned CCS projects. Blue dashed line = exponential fit to the data between 1996 (start of CCS, rather than just EOR) and 2025 (the last planned future launch of a CCS project) (equation and R-squared value shown in blue text). The red dashed line is a future projection of CO₂ storage based on the exponential fit. Yearly storage according to this red line is 127 Mtpa in 2030, and 718 Mtpa in 2050.

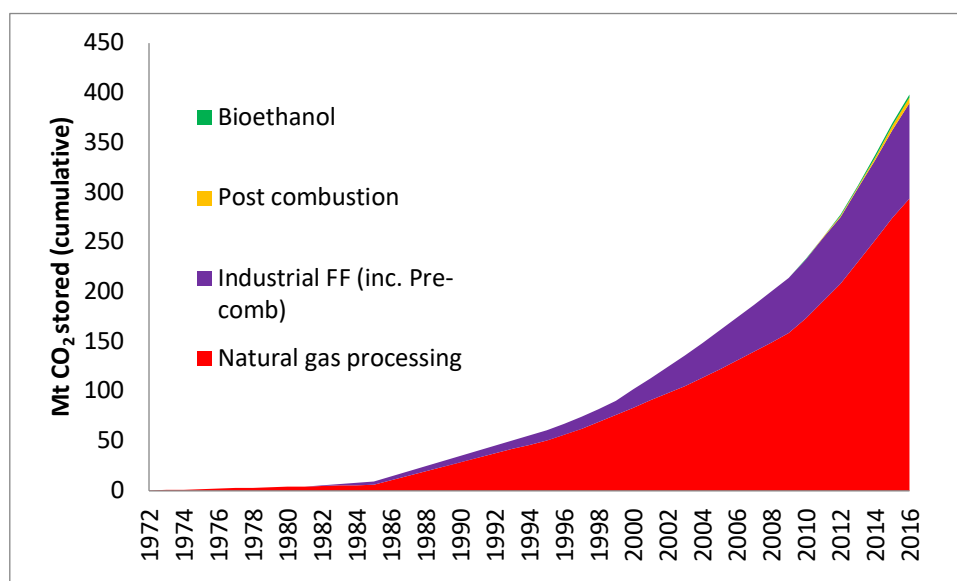


Supplementary Figure 4: Future projections of cumulative CO₂ storage. Black line = observed cumulative CCS up to 2016, observed and anticipated CCS in 2017, and anticipated CCS from 2018-2050, based on planned CCS projects. Blue dashed line = exponential fit to the data between 1996 (start of CCS, rather than just EOR) and 2025 (the last planned future launch of a CCS project) (equation and R-squared value shown in blue text). The red dashed line is a future projection of CO₂ storage based on the exponential fit. Cumulative storage according to this red line is 1,425 Mt by 2030, and 8,398 Mt by 2050. If the exponential build up used to extrapolate into the future is based on purely installed CCS (i.e. 1996-2017) then the cumulative stored CO₂ at 2050 is about 400 Mt lower.

Historic CO₂ storage operational factors:



Supplementary Figure 5: Historic partitioning of CCS between EOR operations and dedicated CO₂ storage.



Supplementary Figure 6: Comparing capture technique / anthropogenic CO₂ source of installed CCS. "FF" = fossil fuels.

References

Haese, R.R., Black, J.R., Vu, H.P., 2016. The impact of CO₂ impurities (SO₂, NO_x, O₂) on fluid-rock reactions and water quality in a CO₂ storage reservoir (CO₂CRC Report No. RPT16-5501).
NETL, 2015. Carbon Storage Atlas: 5th Edition. US Department of Energy.