# An estimate of the amount of geological CO2 storage over the period 1996-2020

| | |
|---|---|
| Journal: | *Environmental Science & Technology Letters* |
| Manuscript ID | ez-2022-00296x.R1 |
| Manuscript Type: | Letter |
| Date Submitted by the Author: | 14-Jun-2022 |
| Complete List of Authors: | Zhang, Yuting; Imperial College London, Earth Science and Engineering<br>Krevor, Samuel; Imperial College London, Earth Science & Engineering<br>Jackson, Christopher; The University of Manchester, Department of Earth and Environmental Sciences |
| | |

# An estimate of the amount of geological $CO_2$ storage over the period 1996-2020

Yuting Zhang*
Royal School of Mines
Imperial College London
Prince Consort Road
South Kensington
London
SW7 2BP
+44 7446137581
yuting.zhang16@imperial.ac.uk

Christopher Jackson
Department of Earth and Environmental Sciences, The University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, UK
christopher.jackson@manchester.ac.uk

Samuel Krevor
Department of Earth Science and Engineering
Imperial College London
s.krevor@imperial.ac.uk

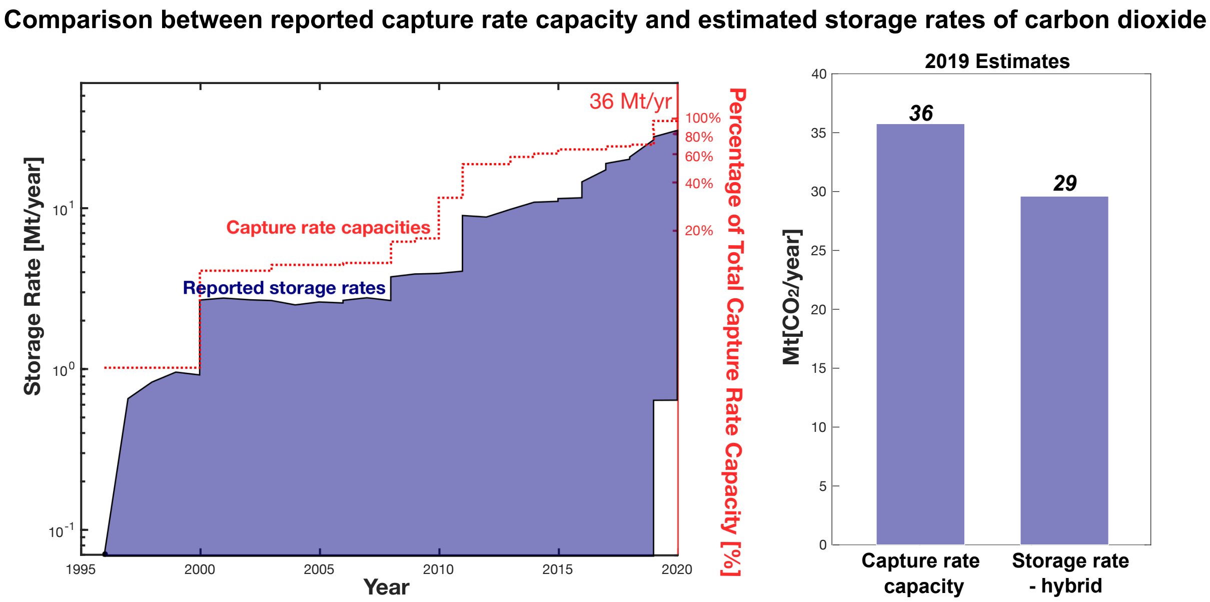
ABSTRACT

The climate change impact of carbon capture and storage (CCS) depends on how much $CO_2$ is stored underground, yet databases of industrial-scale projects frequently use capture capacity as a measure of project size. We review a variety of publicly available sources to estimate the amount of $CO_2$ that has been captured and stored by operational CCS facilities since 1996. We organise these sources into three categories broadly corresponding to the associated degree of assurance: 1) legal assurance, 2) quality assurance through auditing, 3) no assurance. Data were found for 20 facilities, with an aggregate capture rate capacity of 36 $MtCO_2\ yr^{-1}$. Combining data from all three categories, we estimate that 29 $MtCO_2$ was geologically stored in 2019 and there was cumulative storage of 197 Mt over the period 1996-2020. The widely used capture capacity for these projects is in aggregate 19-30% higher than the estimated storage rates suggesting that capture capacity is not a good proxy for storage rates. The difference between capture capacity and storage rates is project-specific and not always a reflection of project performance. This work provides a snapshot of storage amounts and highlights the need for uniform project reporting on capture and storage rates with quality assurance.

Keywords: CCS; carbon storage; energy; climate change mitigation; CCS statistics

Synopsis: current measures of CCS project size report capture rate capacity; we find stored $CO_2$ could be less than this by 30%.

Table of Contents/Graphical Abstract



# INTRODUCTION

Modelled energy systems development pathways limiting global warming to less than 2°C suggest that rapid upscaling of carbon capture and storage (CCS) with global injection rates reaching 5-10 $GtCO_2$ per year by 2050 may be required [1]. Due to the importance of CCS in modelled climate mitigation pathways, the feasibility of achieving these rates by mid-century is central to our understanding of the potential to avoid dangerous climate change. With increasing numbers of industry-scale storage projects operating around the world, data is becoming available through which project performance, and scaleup potential, may be evaluated.

The most centralised and up to date information comes from the annual reports and database of the Global CCS Institute (GCCSI)[2]. Similar datasets were produced in the recent past by the MIT Carbon Capture and Sequestration Technologies Program[3] and the National Energy Technology Laboratory (NETL)[4]. However, they stopped updating in 2016 and 2019, respectively. Additionally, there are several websites compiling lists of active CCS projects[5,6]. In many cases, the GCSSI is used as the primary source of these compilations[3,4,5,6]. The measure used in the databases to describe the size of projects is the capture capacity reported in megatonnes per annum (Mtpa). As of 2021, the global capture capacity was estimated at 40 $MtCO_2$ $yr^{-1}$ from 26 operational CCS facilities[2,7,8,9].

Despite this reporting, there are information gaps that present challenges to quantifying the current state of CCS.  There is no set definition of capture capacity. It appears to take on various meanings among projects including aspirational target, maximum based on capture facility design, and capture rate achieved in a particular year. Actual rates of capture, transport, and storage are not centrally reported. This information is necessary for the evaluation of the climate change mitigation impact of existing operations. Tracking amounts of $CO_2$ captured, transported, and stored can help to identify factors arising throughout a CCS chain. Variations in the performance of industry-scale CCS may also help us to understand and mitigate the range of issues affecting the performance of projects.

In this study, we investigate publicly available information on $CO_2$ storage rates for industrial scale CCS projects since 1996, the first year of injection for the Sleipner project in Norway. We first classify the data sources and review how current statistics are reported. From this, we compile a global $CO_2$ storage database and estimate the amount of $CO_2$ that has been captured and geologically stored. We analyse discrepancies between estimated storage rates and the more widely reported capture capacity. Finally, we provide recommendations for future reporting.

# 2 MATERIALS & METHODS

## 2.1 Project Selection

We use the database of the GCCSI, cross-checked against other databases where possible, to identify industrial scale projects[2]. Of the 26 operational carbon capture facilities listed in GCCSI, we estimate captured and stored amounts for 20 of these projects, representing 93% of the existing global operational capture capacity. The 2020 GCCSI database only provides the name of the capture facility[2], so we first identify the associated storage operators and sites for each capture project by performing an extensive review of online resources using the capture facility name as initial keywords in search engines. We find relevant web pages that provide descriptions of the capture and storage projects i.e., project websites, CCS databases or operator's websites[3,4,5,6]. We provide the final data references used in the sources column in Table 1-12 of the Supporting Information. In our database, 14 projects are enhanced oil recovery (EOR) in which the $CO_2$ is injected into depleted oil reservoirs to recover additional oil and six projects are storing $CO_2$ in deep saline aquifers for dedicated long-term geological storage[2,8]. We did not find sufficient data reported across the literature, press releases, or company documents for the remaining six operational projects from the GCCSI 2020 database[2] and these were excluded from our analysis.

## 2.2 Measures of storage performance

We compile estimates of four performance measures for each project (Table 1). The capture rate capacity is taken as a benchmark from the reporting of the GCCSI. The capture rate is an estimate of the $CO_2$ captured. Two storage rates are estimated that we label hybrid and average, due to the non-uniformity in data reporting. These are each described in more detail here. The year for which we found the most reporting is 2019 and we provide aggregate capacity and storage estimates for this year. We also compile time-series for each project and in aggregate.

The capture rate capacity is obtained from the GCCSI's report for the period 2019-2020. Capture rate capacity can have a variety of meanings for different projects, including the maximum quantity of $CO_2$ that has been captured in a year during its operational lifetime, the maximum amount of $CO_2$ that can be captured in a year based on the facility design, the average capture rate for a given period, and the intended capture target for a year. Despite the varied meanings, we refer to this figure as the capture rate capacity and use it as a reference for comparison because of its widespread use as a measure of project size.

The capture rate is an estimate of the annual amount of $CO_2$ that has been captured after the project commenced. Of the captured amount, some may be recycled or re-used for producing chemicals. Therefore, it is necessary to additionally distinguish the amount of $CO_2$ that is geologically sequestered from the initial capture rate. However, for many projects, the capture rate is not reported. In this case, either the reported annual storage rate or the lifetime average from the project cumulative storage is used as the capture rate for the project.

Due to a lack of uniformity in the data reported we use two metrics to compare the storage performance. The storage rate – average is an estimated average over the lifetime of a project. This was calculated using either the reported cumulative storage or the sum of annual storage reported for projects. The storage rate – hybrid is an estimate that uses the annual storage rate where possible (only some projects provided this data) and the average storage rate for projects that only provided the cumulative storage.

*Table 1: Summary of definitions for performance metrics.*

| Performance Metric | Definitions |
|---|---|
| Capture rate capacity | 1) Maximum $CO_2$ captured in a particular year<br>2) Maximum amount of $CO_2$ that can be captured in a year based on the facility design<br>3) Average capture rate for a given period<br>4) Intended capture target |
| Capture rate | An estimate of the annual amount of $CO_2$ that has been captured after the project commenced |
| Storage rate – hybrid | An estimate that uses the annual storage rate where possible (only some projects provided this data) and the average storage rate |
| Storage rate – average | An estimated average over the lifetime of a project |

2.3 Data sources and source categorisation

We compile our database using multiple sources for projects when possible. We placed these sources into three categories (Table 2), broadly corresponding to the degree of legal liability or auditing associated with the reporting. The highest degree of assurance is Category 1 data, and the lowest degree of assurance is Category 3.

Data in the first category are reported under authoritative legal frameworks including the National Inventory Report submitted to the United Nations Framework Convention on Climate Change and the Greenhouse Gas Reporting Program at the US Environment Protection Agency (EPA ; Category 1)[10,11]. These reporting frameworks follow the requirements of the institutions for quality assurance such as internal technical reviews by an expert review team and verification protocols[12,13,14]. As a result, these types of international and national frameworks employ relatively rigorous quality control and assurance of the reported $CO_2$ capture and storage data.

We obtain Category 2 data from annual corporate sustainability or Environmental, Social and Governance reports that describe the quantitative performance of CCS projects. These reports are also accompanied by statements that offer some assurance, provided by an independent assurance service, e.g., KPMG. In this category we also include the China Annual Report 2019 prepared by the Chinese Academy of Environmental Planning, an organisation founded by the Chinese government[15].

In Category 3 sources we include company websites, press releases, and presentations that provide information on capture and storage rates, but without an associated statement of legal assurance or quality control of the data. The categories are summarised in Table 2.

*Table 2: A summary of the three categories of sources of reporting on $CO_2$ storage with varying degrees of data assurance and quality control associated with each category. Category 1 sources (green) have the highest degree of assurance, followed by category 2 (blue), and category 3 (red).*

| Category 1 | Category 2 | Category 3 |
|---|---|---|
| • UNFCCC<br>• US EPA | • Corporate Sustainability report<br>• Corporate ESG report<br>• Non-governmental organisation prepared reports | • Press releases<br>• Webpages<br>• Company presentations |

2.3 Data analysis

As described above we report data in four categories: capture rate capacity, capture rate, storage rate – hybrid, and average. These are estimates based on data that can be gathered from publicly available resources provided by operators. The exclusion of projects that have not publicly reported data may result in these estimates to be lower than the quantity of $CO_2$ stored in practice. We provide these values in units of $MtCO_2$ per year and report the capture and storage rates as a fraction of the capture rate capacity. We also quantify the fraction of the capture rate that is sequestered. Finally, we calculate the average annual growth rate in capture rate capacities and storage rates between 1996-2020 using the aggregate capture rate capacities time series and the aggregate storage hybrid time series.

For each project, we compile data from multiple sources with varying levels of assurance. As a result, several projects in our database have data collected for each performance metric found using more than one category of source. We record all collected data and indicate their respective source category. Data associated with the most rigorously assured source for each project is used to calculate the measures used in comparing between projects. We provide a measure of uncertainty by recalculating the aggregate using data associated with sources that have the lowest level of assurance. In this approach, uncertainty is a reflection of the deviation that exists in the reporting among various sources. Different sources often report the same numbers. As a result, performance metrics for each project have no more than two entries of data. Therefore, we do not report mean or standard deviations because they are likely statistically irrelevant.

# 3 RESULTS & DISCUSSION

## 3.1 Aggregate rates and cumulative storage

Here, we show comparisons between the 2019 aggregate capture rate capacity, capture rate, storage rate – hybrid and average for the 20 CCS projects for which we found information (Figure 1 and Table 3; full data are provided in the Supporting Information). The total capture rate capacity in 2019 is 36 $MtCO_2$ $yr^{-1}$. Including all categories (1-3) of data for these projects, we estimate an aggregate capture rate of 31 $MtCO_2$ $yr^{-1}$ - 88% of the aggregate capture rate capacity. The aggregate storage rate - hybrid is 29 $MtCO_2$ $yr^{-1}$ (81% of aggregate capture rate capacity and 92% of the aggregate capture rate). The aggregate storage rate - average is 25 $MtCO_2$ $yr^{-1}$, representing 70% of the aggregate capture rate capacity or 80% of the aggregate capture rate. Notably, we find that data for >90% of the estimated capture and storage rates fall into Category 1 or 2 sources (green and blue shades in Figure 1).

Variation in reported values among sources is reported in Table 4 and shown as an uncertainty bar over the average storage rate estimate in Figure 1. For the storage rate - hybrid, variations in estimates using different categories of sources are entirely due to the significant figures reported by different sources. For the storage rate - average, the variation is more significant when considering the varying sources, particularly for the Century project. This is mostly due to the high annual storage data reported by the operator Occidental Petroleum of 12.4 $MtCO_2$ $yr^{-1}$ in 2017 (Category 2 source)[16] compared to the data reported in the EPA database (Table 4)[17,18]. Thus, for the most part, there is consistency in reporting when multiple channels of reporting have taken place.

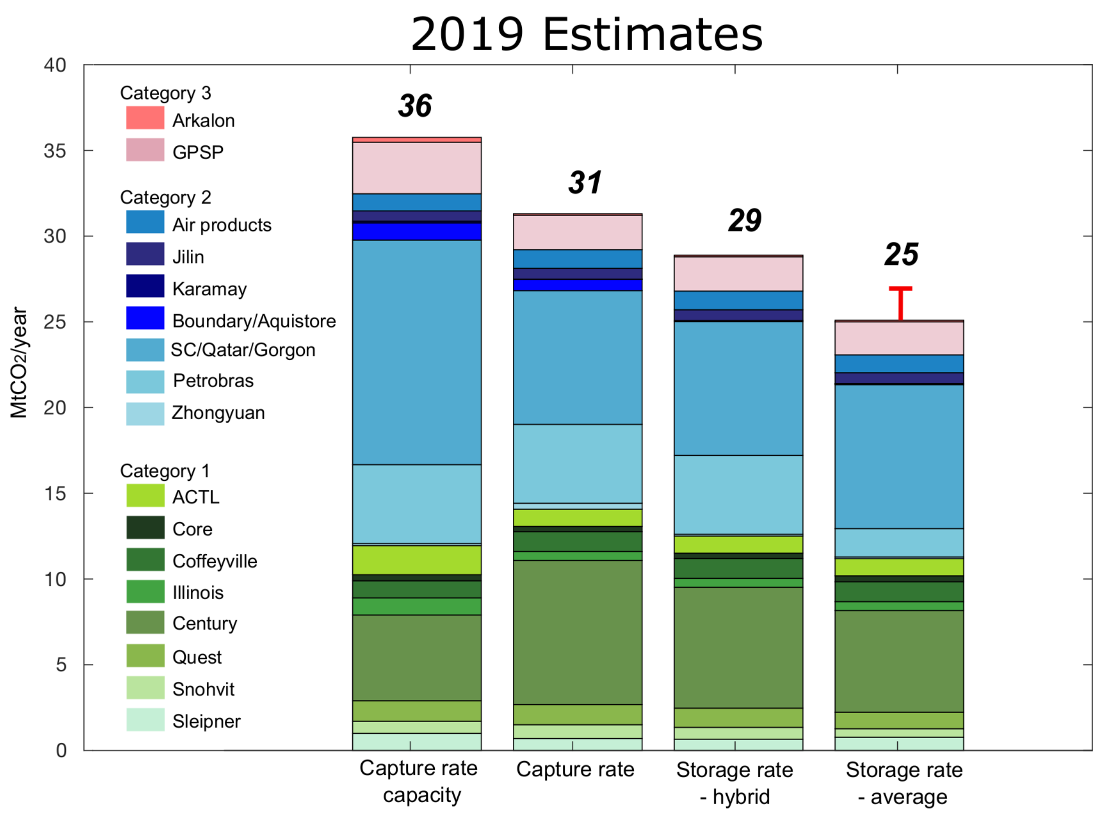



*Figure 1: Plot comparing the compiled 2019 estimates of capture rate capacity, capture rate, average storage rate and storage rate for 20 operational CCS projects. The range of colours illustrate the distribution of projects across the three reporting categories (definitions of each category are summarised in Table 1) and it is showing the maximum reporting category identified for each project. The uncertainty bar is only illustrable for "storage rate - average shown in red. Definitions of rates compared here and source categorisation is provided in* ***Methods.*** *Summary statistics are provided in Table 2.*

*Table 3: Summary statistics for data presented in Figure 1 differentiating the proportion of estimates for each performance metric that is associated with the three categories of sources. Comparison between the capture rate capacity with other key performance metrics as well as the proportions of aggregate capture rate that is translated into storage are also provided.*

| | 2019 capture and storage rates | | | |
|---|---|---|---|---|
| Source Category | Capture rate capacity [Mt$CO_2$ $yr^{-1}$] | Capture rate [Mt$CO_2$ $yr^{-1}$] | Storage rate – hybrid [Mt$CO_2$ $yr^{-1}$] | Storage rate – average [Mt$CO_2$ $yr^{-1}$] |
| Category 1 | 11.95 | 14.11 | 12.51 | 11.19 |
| Category 2 | 20.52 | 15.22 | 14.28 | 11.89 |
| Category 3 | 3.29 | 2.09 | 2.09 | 2.02 |
| **Total** | **35.76** | **31.42** | **28.89** | **25.09** |
| % of aggregate capture rate capacity | | 88% | 81% | 70% |
| % of aggregate capture rate | | | 92% | 80% |

*Table 4: Summary statistics for four projects that have multiple categories of sources collected for various performance metrics. The upper and lower bound of aggregate estimates for each performance metric are also indicated. Uncertainty is estimated relative to a baseline which is provided by the reporting with the highest degree of assurance, e.g., category 1 data for a project will provide the baseline, variation from that baseline is calculated for category 2 and 3 data. The storage rate - average that are indicated in bold are obtained from the reported cumulative storage reported as opposed to the sum*

*of year-on-year data. N/A indicate where no meaningful comparison can be derived from different estimates of cumulative storage because the number of years included in the averaging period is not consistent.*

| | 2019 Storage rates, cumulative storage, and reporting variation | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ capture facility | Storage rate– hybrid [$MtCO_2\ yr^{-1}$] | | Storage rate – average [$MtCO_2\ yr^{-1}$] | | Cumulative storage [$MtCO_2$] | | Averaging Period | Source category |
| Quest | 1.128 | Baseline | 0.96 | Baseline | 4.8 | Baseline | 2015-2019 | 1 |
| | 1.13 | +0.2% | 0.9 | -6.25% | 5.39 | +12% | 2016-2020 | 2 & 3 |
| Sleipner + Snhovit | 0.65 + 0.7 | Baseline | 0.77 + 0.5 | Baseline | 18.5 + 6.5 | N/A | 1996-2019 | 1 |
| | 1.37 | -1.5% | **1.1** | -13% | 26.2 | | 1996-2020 | 2 |
| Illinois Industrial CCS | 0.52 | Baseline | 0.52 | Baseline | 1.55 | N/A | 2017-2019 | 1 |
| | 0.52 | 0 | 0.52 | 0 | 1.042 | | 2019-2020 | 2 |
| Century (Denver + Hobbs) | 3.39 + 3.66 | Baseline | 3.232 + 2.70 | Baseline | 16.16 + 10.78 | N/A | 2016-2020 | 1 |
| | 7.1 | -0.7% | **8.56** | +44% | 25.66 | | 2017-2019 | 2 |
| Overall aggregate (all 20 projects) | 28.89 | Baseline | 25.10 | Baseline | 196.68 | Baseline | | Highest assurance available |
| Overall aggregate (all 20 projects) | 28.97 | +0.28% | 27.02 | +7.6% | 196.68 | 0 | | Lower assurance |

3.2 Annual reported storage rates 1996 - 2020

We compiled 17 time series of projects for the time period 1996-2020 in Figure 2. We illustrate differences between times series of specified annual storage data for some projects (black line joined with dots in Figure 2) and their associated capture rate capacities (coloured lines in Figure 2). Our results show that 12 out of 20 projects report storage rates (average or annual storage) that are < 85% of their capture rate capacity in 2019. These are Sleipner, Century, Illinois, ACTL projects, Zhongyuan, combined estimates of Shute Creek, Gorgon and Qatar, Karamay, Great Plains Synfuel Plant (GPSP), Arkalon, and Aquistore. Taking the second year of operation at Sleipner (i.e., 1998) as our initial point (to avoid the initial ramp up in operation at Sleipner which would skew the average growth rate), the average annual growth for aggregate capture rate capacity has been 24.6% and the annual growth in storage rates has been 23.1% using the aggregate hybrid time-series.

There are a variety of reasons driving these differences. For Sleipner with a declining storage rate and Snohvit with an increasing storage rate, the performance of the CCS system is linked to the production of natural gas which is the source of $CO_2$. Data provided by the Norwegian Petroleum Directorate suggest Sleipner's annual production of gas between 2000-2020 has been declining at an annual average rate of 14% while the annual production of Snohvit is increasing at 8%[19,20]. Technical difficulties are a factor for some projects. The Gorgon project in Western Australia experienced a delay in start-up due to corrosion of injection pipes and problems with their water production pressure management wells; injection rates were limited by governmental regulators[21,12]. At the Boundary Dam capture facility, suspensions of the CCS facility occurred due to scheduled maintenance, outages at the power station, and technical difficulties with the $CO_2$ compressor[23]. For Quest, the main contributor to the reduced capture rate in 2019 were minor technical issues in the capture unit resulting in trips, planned maintenance and periods of lowered hydrogen production demand[24,25]. Finally, projects that have just begun operation i.e., Qatar LNG and ACTL may be undergoing a period of ramp-up.

There are inconsistencies in the definitions of capture rate capacity used in the reporting. Thus, the differences between capture rate capacity and the observed storage amounts may not reflect the operating performance of the CCS system. At Sleipner, the capture rate capacity (1 Mt $yr^{-1}$) appears to be the maximum $CO_2$ captured in 2001; the discrepancy between the amount stored and the capture capacity inevitably increases over time as natural gas production declines even if the project is operating without issue. In contrast, with Snohvit, Petrobras, and Air products, the capture rate capacity (0.7 Mt $yr^{-1}$, 4.6 Mt $yr^{-1}$, and 1 Mt $yr^{-}$1, respectively) appears to be reported as an intended target and does not reflect the technical capture capacity of the system. As a result, the actual capture and storage rates can at times exceed their capture capacity. For Quest, the definition is unclear. According to the most recent performance review[25], the percentage of $CO_2$ captured from the raw hydrogen gas stream did not reach the anticipated target of 80%. It is unclear whether this is the equivalent to the reported capture capacity of 1.2 Mt $yr^{-1}$. At Century, Illinois, Shute Creek, Gorgon and Qatar, the capture rate capacity appears to be the maximum design capacity of the capture facility; for these projects, no information was found about the discrepancies between capture capacity and storage rates. Similarly, for projects that only reported a single figure of cumulative storage (Zhongyuan, Coffeyville, Aquistore, Jilin, GPSP, Karamay and Arkalon), we could not critically evaluate the operating performance. The estimates of storage figures suggest that the use of capture capacity as a proxy for storage rates may overestimate the amount of $CO_2$ stored by 19-30%. At the same time, there are no systematic trends in the metrics. The reasons for differences in these figures remain specific to each project.

The cumulative storage of $CO_2$ (between 1996 and 2020) is estimated to be 197 Mt, combining all reporting categories (coloured area in Figure 2) - this is significant, equivalent to what had been achieved by existing solar photovoltaics by 2015[26, 27]. The annual growth in CCS deployment required to achieve gigatonne scale impacts by 2050 is similar to current rates of growth in solar photovoltaics[28]. The estimate storage rate – hybrid of 29 $MtCO_2$ $yr^{-1}$ is approximately half of the estimated emissions avoided as a result of solar photovoltaics deployment in the United States in 2018[29]. The large-scale nature of each CCS installation has been identified as a significant barrier to growth[30], but the benefit of large projects is observed here in the disproportionately large climate impact of a technology early in its development, with only scores of operational projects.

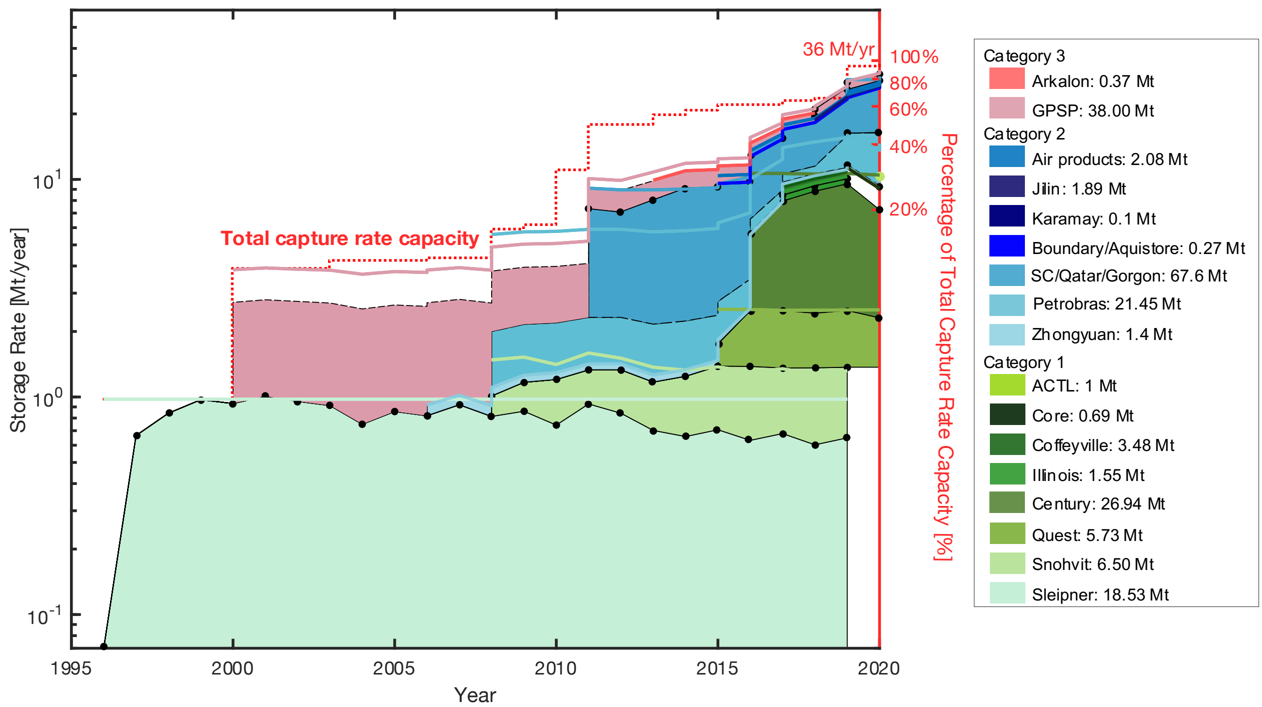



*Figure 2: Stacked times series of annual $CO_2$ storage between 1996 – 2020 to show the overall trend in storage operations. The annual storage rate (black smooth lines joined by dots) is compared with the capture rate capacity (coloured lines) for Sleipner, Snohvit, Quest, Century and combined Shute Creek, Qatar and Gorgon. Black dashed line illustrates time series compiled using the average storage rate as no specified annual storage was reported for these projects. The annual total capture rate capacity is indicated by the red dot line which culminates in 36 Mt $yr^{-1}$ in 2020. Note, the GCCSI indicates that the Shute Creek facility began operation in 1986 with a stated capture capacity of 7 Mt $yr^{-1}$. However, we only found storage data for Shute creek starting in 2011 and this is when it is included in the total capture capacity time series. Similarly, the GCCSI indicates capture capacity for Petrobras starting in 2013, but we have found storage data since 2008 and this is where that time-series begins contributing to the total capture capacity. The area under each time series represents the cumulative stored and the value is provided in the legend. The three ranges of colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1. The green dot represents the storage rate for the Alberta Carbon Trunk Line projects including Nutrien and Sturgeon which only began operation in 2020. Note, the vertical axis is only using the logarithmic scale so that all the projects can be seen in the graph. The bars in Figure 1 provide a better visual of the relative project size.*

## 3.3 Implications

Our database provides further insight into the status of CCS, and it can be used as a reference in the near term for understanding the total performance of project chains. This data provides a snapshot of a climate change mitigation technology which is emerging but nonetheless already contributing significantly to emissions mitigation today. The significant difference between reported storage data and the more frequently reported capture capacity reveals an important gap in the availability and use of data necessary for evaluating the climate change impact of CCS. While the use of capture capacity as a proxy overstates the storage rate, the growth in capture capacity and storage rates track each other. A number of studies have analysed existing growth in the context of climate change mitigation scenarios, generally identifying that CCS deployed by mid-century in these projections will be difficult to achieve, whereas current growth is significant with very large-scale mitigation achieved by the end of the century[31,32,33,34].

The need for consistent reporting on storage performance by industry projects is evident. The framework should include key details necessary for evaluating storage performance, including clarity in definitions of project sizes and the identification of a common nomenclature, e.g., capture capacity, identifying annual quantities of $CO_2$ stored for individual projects without aggregating projects, specifying the quality control of measurements at the site-level to assess uncertainty and an association of the capture facility with its one or multiple storage operators. Specific measures that would be useful in such a reporting framework include: 1) intended capture rate capacity, 2) maximum capture rate capacity, 3) annual capture of $CO_2$, 4) annual transport of $CO_2$, 5) annual storage of $CO_2$, 6) quality assurance measures such as auditing by third parties and quantification of key uncertainties, and 7) reasons for any offline periods where the CCS facility could not operate as intended. This would enable the accurate assessment and monitoring of climate change mitigation benefits explicitly attributed to CCS operations[30,31,32].

## ABBREVIATIONS

CCS – Carbon Capture and Storage
$CO_2$ – carbon dioxide
EOR – Enhanced Oil Recovery
EPA – Environmental Protection Agency
GHG – Greenhouse Gas
GCCSI – Global Carbon Capture and Storage Institute
GHG – Greenhouse Gas
GPSP – Great Plains Synfuel Plant
IPCC – International Panel on Climate Change
Mtpa – Megaton per annum

## ACKNOWLEDGEMENT

Funding for this work was provided by the Engineering and Physical Sciences Research Council.

## REFERENCES

1. Shukla, P.R. *et al. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC, 2022. doi: 10.1017/9781009157926
2. Page, B., Turan, G., Zapantis, A. *Global Status of CCS: 2020, 2020*; Global CCS Institute; https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf (accessed October 6, 2021).
3. *Carbon Capture and Sequestration Project Database*. Carbon Capture & Sequestration Technologies at MIT. *http://sequestration.mit.edu/tools/projects/index.html* (accessed October 6, 2021).
4. *Carbon Capture and Storage Database.* National Energy Technology Laboratory; https://netl.doe.gov/coal/carbon-storage/worldwide-ccs-database (accessed October 6, 2021).
5. *CCS Database.* ZeroCO2. http://www.zeroco2.no/projects (accessed Octorber 6, 2021).
6. *Global pipeline of commercial CCUS facilities operating and in development, 2010-2021.* International Environmental Agency Website. https://www.iea.org/data-and-statistics/charts/global-pipeline-of-commercial-ccus-facilities-operating-and-in-development-2010-2021 (accessed October 6, 2021).

7. Martin-Roberts, E. *et al.* Carbon capture and storage at the end of a lost decade. *One Earth,* 4(11), 1569-1584 (2021). https://doi.org/10.1016/j.oneear.2021.10.002

8. Loria, P. & Bright, M.B.H. Lessons captured from 50 years of CCS projects. *The Electricity Journal,* **34** (7), 196998 (2021).

9. IEA; *About CCUS*; International Environmental Agency: Paris, 2021 https://www.iea.org/reports/about-ccus (accessed October 6, 2021).

10. *National Inventory Submissions 2020.* United Nations Convention on Climate Change Website; *https://unfccc.int/ghg-inventories-annex-i-parties/2020* (accessed October 6, 2021).

11. *EPA Facility Level Information on GreenHouse gases Tool.* U.S. Environmental Protection Agency Website. *https://ghgdata.epa.gov/ghgp/main.do#/facility/?q=Find%20a%20Facility%20or%20Location&st=&bs=&et=&fid=&sf=11001100&lowE=-20000&highE=23000000&g1=1&g2=1&g3=1&g4=1&g5=1&g6=0&g7=1&g8=1&g9=1&g10=1&g11=1&g12=1&s1=1&s2=1&s3=1&s4=1&s5=1&s6=1&s7=1&s8=1&s9=1&s10=1&s201=1&s202=1&s203=1&s204=1&s301=1&s302=1&s303=1&s304=1&s305=1&s306=1&s307=1&s401=1&s402=1&s403=1&s404=1&s405=1&s601=1&s602=1&s701=1&s702=1&s703=1&s704=1&s705=1&s706=1&s707=1&s708=1&s709=1&s710=1&s711=1&s801=1&s802=1&s803=1&s804=1&s805=1&s806=1&s807=1&s808=1&s809=1&s810=1&s901=1&s902=1&s903=1&s904=1&s905=1&s906=1&s907=1&s908=1&s909=1&s910=1&s911=1&si=&ss=&so=0&ds=E&yr=2020&tr=current&cyr=2020&ol=0&sl=0&rs=ALL* (accessed October 6, 2021).

12. *Guidelines for the technical review of information reported under the Convention related to greenhouse gas inventories, biennial reports and national communication by parties included in Annex I to the Convetion*, FCCC/CP/2014/10/Add.3 (General. Feb 2, 2015)

13. *GHGRP methodology and verification.* U.S. Environmental Protection Agency Website. https://www.epa.gov/ghgreporting/ghgrp-methodology-and-verification

14. *GRI mission & history.* Global Reporting Initiative Website. https://www.globalreporting.org/about-gri/mission-history/ (accessed October 6, 2021).

*15. Cai, B., Li, Q., Lin, Q., Ma, J. China Carbon Capture Utilisation and Storage (CCUS) Report 2019;* Chinese Academy of Environmental Planning; Beijing, 2020.

*16. Oxy 2020 Annual ESG Performance Indicators*. Occidental Petroleum Website. *https://www.oxy.com/globalassets/documents/sustainability/annualperformancesummarytable.pdf* (accessed October 6, 2021).

17. *Information on Geological Sequestration of Carbon Dioxide, Hobbs Field.* U.S. Environmental Protection Agency Website.

https://ghgdata.epa.gov/ghgp/service/facilityDetail/2019?id=1012121&ds=A&et=&popup=true

18. *Information on Geological Sequestration of Carbon Dioxide, Denver Unit.* U.S. Environmental Protection Agency Website. https://ghgdata.epa.gov/ghgp/service/facilityDetail/2019?id=1011767&ds=A&et=&popup=true (accessed October 6, 2021).

19. *Sleipner.* Norwegian Petroleum Directorate Website. https://www.norskpetroleum.no/en/facts/field/sleipner-ost/ (accessed October 6, 2021).

20. *Snohvit.* Norwegian Petroleum Directorate Website. https://www.norskpetroleum.no/en/facts/field/snohvit/ (accessed October 6, 2021).

21. *Gorgon project carbon dioxide injection project low emission technology demonstration fund annual report 1 July 2016 - 30 June 2017*; Department of Industry, Innovation and Science Western Australia Government: Western Australia, 2017.

22. *Gorgon project carbon dioxide injection project low emission technology demonstration fund annual report 1 July 2019 – 30 June 2020*; Department of Industry, Innovation and Science Western Australia Government: Western Australia, 2020.

23. *Boundary Dam Carbon Capture Project.* Saskpower Website. https://www.saskpower.com/Our-Power-Future/Infrastructure-Projects/Carbon-Capture-and-Storage/Boundary-Dam-Carbon-Capture-Project (accessed Octorber 6, 2021).

24. *Quest Carbon Capture and Storage Project Annual Summary Report*; Department of Energy: Alberta, 2019a; https://open.alberta.ca/dataset/f74375f3-3c73-4b9c-af2b-ef44e59b7890/resource/ff260985-e616-4d2e-92e0-9b91f5590136/download/energy-quest-annual-summary-alberta-department-of-energy-2019.pdf (accessed Octorber 6, 2021).

25. *Quest CO2 Capture Ratio Performance*; Department of Energy: Alberta, 2019b; http://pubsapp.acs.org/paragonplus/submission/esthag/est-citation-sample.pdf? (accessed Octorber 6, 2021).

26. Pacala, S., & Socolow, R. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*. 2004, *305*(5686), 968-972. doi: 10.1126/science.1100103

27. *Snapshot of Global PV Markets 2021;* Report IEA-PVPS T1-39:2021; Paris, 2021; https://iea-pvps.org/wp-content/uploads/2021/04/IEA_PVPS_Snapshot_2021-V3.pdf (accessed November 12, 2021).

28. *Statistical Review of World Energy;* BP website;2021 (accessed June 13, 2022)

29. Avoided Emissions Calculator. IRENA website. https://www.irena.org/climatechange/Avoided-Emissions-Calculator (accessed June 9, 2022)
30. Abdulla, A. *et al.* Explaining sucessful and failed investments in U.S. carbon capture and storage using empirical and expert assessments. *Enviornmental Research Letters.* **2021**, *16(1).* doi: 10.1088/1748-9326/abd19e
31. Zahasky, C., & Krevor, S. Global geologic carbon storage requirements of climate change mitigation scenarios. *Energy Environment. Sci.* **13,** 1561-1567 (2020). https://doi.org/10.1039/D0EE00674B
32. Zhang, Y., Jackson, C., Zahasky, C., Nadhira, A. & Krevor, S. European carbon storage resource requirements of climate change mitigation targets. *Int. J. Greenh. Gas Control* **114,** 103568 (2022). https://doi.org/10.1016/j.ijggc.2021.103568
33. Ringrose, P. S., & Meckel, T. A. Maturing global CO2 storage resources on offshore continental margins to achieve 2DS emissions reductions. *Scientific reports*, **9**(1), 1-10 (2019).
34. Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. Carbon capture and storage at the end of a lost decade. *One Earth*, **4**(11), 1569-1584 (2021). https://doi.org/10.1016/j.oneear.2021.10.002
*35.* Petrobras*. ESG.* Petrobras: Rio de Janeiro 2020a. https://api.mziq.com/mzfilemanager/v2/d/25fdf098-34f5-4608-b7fa-17d60b2de47d/2a0029b5-75e7-ad89-7c3e-30793604118e?origin=1 (accessed November 12, 2021).
*36.* Petrobras*. Sustainability report 2019*. Petrobras: Rio de Janeiro, 2020b. https://sustentabilidade.petrobras.com.br/en/src/assets/pdf/Sustainability-Report.pdf (accessed November 12, 2021).
*37. Our 2020 Sustainability report advances in 2020.* Petrobras Website. *https://petrobras.com.br/en/news/our-2020-sustainability-report-with-advances-in-esg.htm* (accessed November 12, 2021).
*38.* Petrobras*.* Sustainability report 2020. Petrobras: Rio de Janeiro, 2020c https://sustentabilidade.petrobras.com.br/en/ (accessed November 12, 2021).
*39.* Petroleum Technology Research Centre. Innovation, Alliances & Sustainability 2019 – 2020 Annual Report. Petroleum Technology Research Centr, 2020. https://ptrc.ca/pub/docs/annual-reports/Annual%20Report_Shortened.pdf (accessed November 12, 2021).
*40. BD3 Status Update: May 2021.* Saskpower Website https://www.saskpower.com/about-us/our-company/blog/2021/bd3-status-update-may-2021 (accessed November 12, 2021).

41. *Corporate Presentation.* Whitecap Resources Website. https://www.wcap.ca/application/files/3316/2403/8674/WCP_2021_06_18.pdf (accessed November 12, 2021).

42. *Eastern Saskatchenwan Business Unit.* Whitecap Resources Website. https://www.wcap.ca/operations/core-areas/southeast-saskatchewan (accessed November 12, 2021).

43. *CO2 Sequestration White Resources A Responsible Energy.* Whitecap Resources Website. *Story*https://www.wcap.ca/sustainability/co2-sequestration (accessed November 12, 2021).

44. *Carbon capture milestone reached at Dakota Gas.* Dakota Gas Website. https://dakotagas.com/News-Center/news-releases/carbon-capture-milestone-reached-at-dakota-gas (accessed November 12, 2021).

45. *Quest CCS facility capture and stores five million tonnes of CO2 ahead of fifth anniversary.* Shell Website. https://www.shell.ca/en_ca/media/news-and-media-releases/news-releases-2020/quest-ccs-facility-captures-and-stores-five-million-tonnes.html (accessed November 12, 2021).

46. Shell. *Sustainability report 2020*. Royal Dutch Shell: London, 2021 *https://reports.shell.com/sustainability-report/2020/servicepages/downloads/files/shell-sustainability-report-2020.pdf* (accessed October 6, 2021).

47. 2021-03-10 MP Blaine Calkins Member Statement. *Enhance Energy.* Vimeo, March 10, 2021. https://vimeo.com/527500313 (accessed November 1, 2021)

48. *Megatonne Milestone – Charting a new and cleaner path forward by capturing CO2 and producing lower carbon energy.* Enhance Energy Website. https://enhanceenergy.com/megatonne-milestone-charting-a-new-and-cleaner-path-forward-by-capturing-co2-and-producing-lower-carbon-energy/ (accessed March 7, 2022).

49. China National Petroleum Corporation. *Corporate Social Responsibility Report*. China National Petroleum Corporation: Beijing, 2021 https://www.cnpc.com.cn/en/csr2020enhmshn/202105/64f93c5684754f859b9b81602fba1979/files/e52454722e1c4c269071c16987f70255.pdf (accessed October 6, 2021)

50. Norwegian Environment Agency. *Greenhouse Gas Emissions 1990-2019 National Inventory Report*. Norwegian Environment Agency: Oslo, 2021. https://unfccc.int/documents/273425 (accessed October 6, 2021).

51. Equinor. *Sustainability Report 2020*. Equinor: Stavanger, 2021 https://www.equinor.com/en/investors/annual-reports.html#downloads (accessed October 6, 2021).

52. *2019 Information on Geological Sequestration of Carbon Dioxide*; Archer Daniels Midland Co. U.S. Environmental Protection Agency Website. https://ghgdata.epa.gov/ghgp/service/facilityDetail/2019?id=1005661&ds=E&et=&popup=true (accessed October 6, 2021).

53. Archer Daniels Midland. *2020 Corporate Sustainability Report*. Archer Daniels Midland: Chicago, Ilinois, 2021 https://assets.adm.com/Sustainability/3860041_20_Archer-Daniels-Midland_ESG-Report_WR.pdf (accessed October 6, 2021).

54. National Energy Technology Laboratory. *Farnsworth Unit Project*. National Energy Technology Laboratory, 2017. https://www.netl.doe.gov/sites/default/files/2018-11/Farnsworth-Unit-Project.pdf (accessed October 6, 2021).

55. U.S. Environmental Protection Agency. *Technical Review of Subpart RR MRV Plan for North Burbank Unit.* U.S. Environmental Protection Agency, 2020. https://www.epa.gov/sites/default/files/2020-12/documents/nbu_decision.pdf (accessed October 6, 2021).

56. Exxon Mobile. *Updated 2021 Energy & Carbon Summary.* Exxon Mobile: Irving, Texas, 2021. https://corporate.exxonmobil.com/-/media/Global/Files/energy-and-carbon-summary/Energy-and-Carbon-Summary.pdf (accessed October 6, 2021).

57. Chevron. *Climate Change Resilience Report.* Chevron: San Ramon, California, 2021. https://www.chevron.com/-/media/chevron/sustainability/documents/climate-change-resilience-report.pdf (accessed September 16, 2021).

58. Evens, D. Chevron filas to hit targets with giant CCS scheme at Gorgon LNG. *Energy Voice (Aberdeen)*, July 20, 2021. https://www.energyvoice.com/oilandgas/asia/337852/chevron-fails-to-hit-targets-with-giant-ccs-scheme-at-gorgon-lng/#:~:text=the%20WhatsApp%20logo.-,Chevron%20fails%20to%20hit%20targets%20with%20giant%20CCS%20scheme%20at,LNG)%20export%20project%20in%20Australia (accessed September 16, 2021).

59. Denbury. *2021 Corporate Responsibility Report.* Denbury: Plano, Texas, 2021. https://s27.q4cdn.com/166477028/files/doc_downloads/Denbury-2021-Corporate-Responsibility-Report.pdf (accessed October 6, 2021).

60. *Denbury 26th Annual Credit Suisse Energy Summit.* *https://s1.q4cdn.com/594864049/files/doc_downloads/2021/03/03-2021-Credit-Suisse-Presentation.pdf* (accessed October 6, 2021).

61. *Information on Geological Sequestration of Carbon Dioxide, Core Energy Otsego County EOR Operations.* U.S. Environmental Protection Agency Website.

https://ghgdata.epa.gov/ghgp/service/facilityDetail/2018?id=1010117&ds=A&et=&popup=true (accessed October 6, 2021).

62. *Key Performance.* Sinopec Website. http://www.sinopec.com/listco/en/csr/sustainability/ydqhbh.shtml (accessed Octorber 6, 2021).

DISCLOSURES

The authors declare no competing financial interest

## SUPPORTING INFORMATION

The supporting information includes the compiled geological database for each individual capture facility and its associated time series of $CO_2$ storage operations either using the reported annual storage rate or the average storage rate for projects where only the cumulative storage is provided. We show comparisons between the storage operation with the stated capture rate for the year 2019. The aggregate total for each estimate that we evaluate: the capture rate capacity, capture rate, storage rate– hybrid, storage rate – average over project lifetime, and cumulative storage is also provided in Table 15.

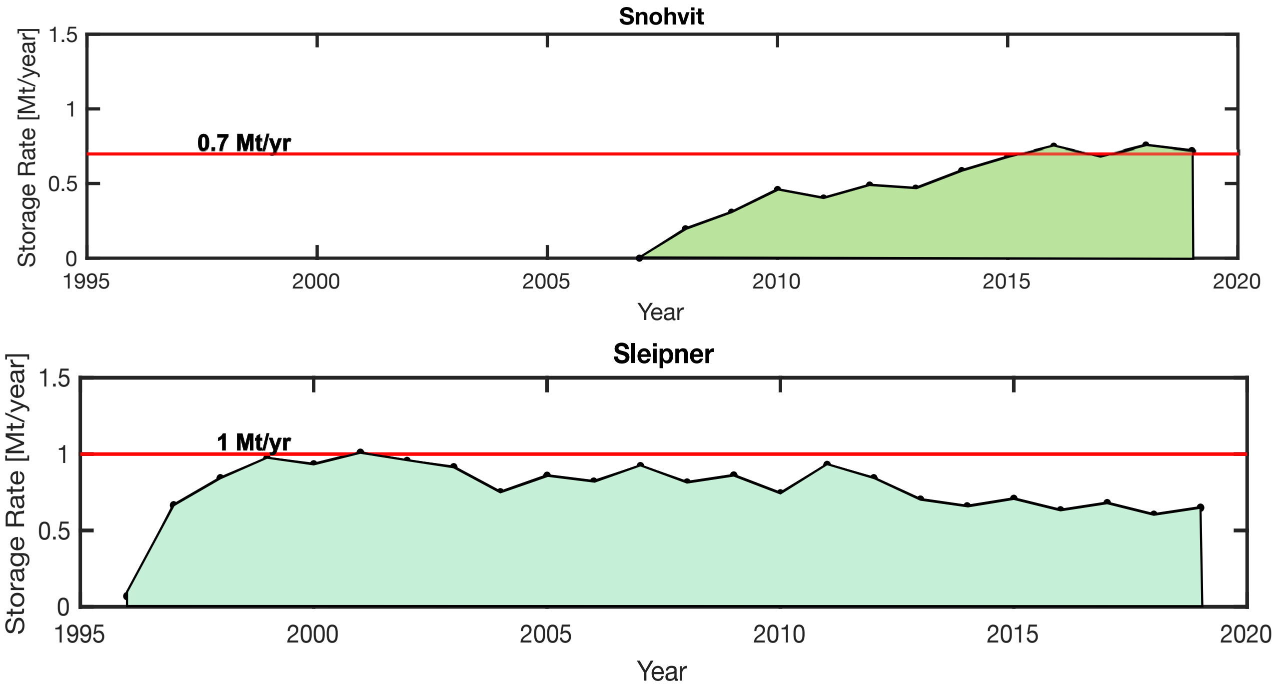



*Figure 1: Times series of $CO_2$ storage between 1996 – 2020 to show the overall trend in annual storage operations for Sleipner and Snohvit (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under each time represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 1 of Supporting Information.*

*Table 1: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed*

*lines. The storage rate - average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project. Where there are multiple sources available for each project, data that are highlighted in red (associated with a lower level of assurance) are used to*

*calculate uncertainty but are not included in the final aggregate estimate used for comparison or in Figure 1.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average over project lifetime [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sleipner | 1 | 0.7* | | 0.65* | 0.77 | 18.5 | 1996-2019 | 1 | 50 | |
| | | Snohvit | 0.7 | 0.8* | | 0.7* | 0.5 | 6.5 | 2007-2019 | 1 | 50 | |
| Norway | Geological Storage | Sleipner + Snohvit | 1.7 | 1.5 | Equinor | 1.37* | 1.1 | 26.2 | 1996-2020 | 2 | 51 | Equinor annual report provided the aggregate annual data for Sleipner and Snohvit without differentiation |

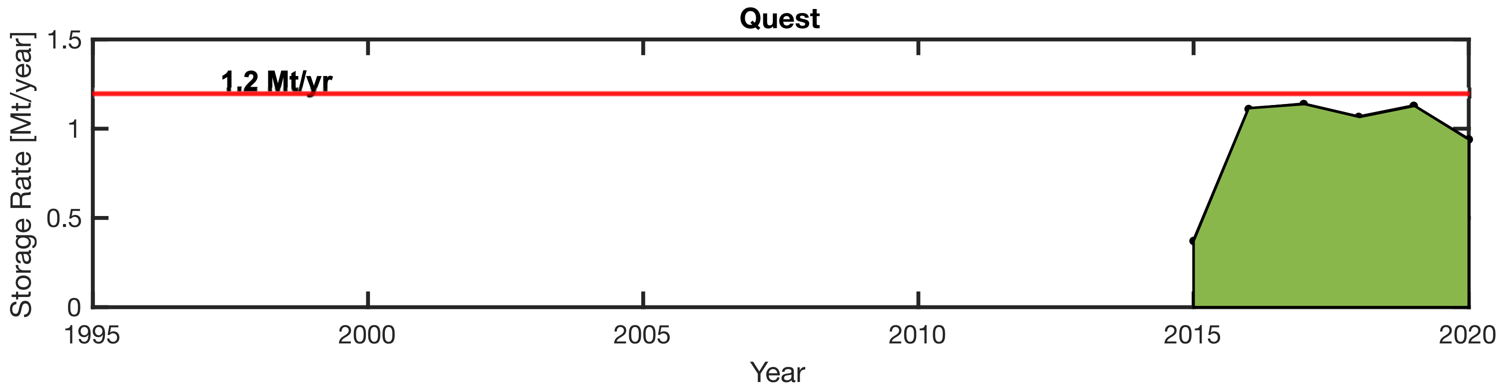



*Figure 2: Times series of $CO_2$ storage between 2015 – 2020 to show the overall trend in annual storage operations for Quest (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 2 of Supporting Information.*

*Table 2: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate - average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project. Where there are multiple sources available for each project, data that are highlighted in red (associated with a lower level of assurance) are used to calculate uncertainty but are not included in the final aggregate estimate used for comparison. The annual storage for 2019-2020 – 0.94 MtCO2 $yr^{-1}$ reported by Shell Sustainability Report [39] is however included in Figure 2.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt $yr^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt $yr^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt $yr^{-1}$] | Storage Rate - average over project lifetime [Mt $yr^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Canada | geological storage | Quest | 1.2 | 1.182* | Quest Shell | 1.13 | 0.9 | 5.39 | 2016-2020 | 2<br>3 | 45<br>46 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1.128* | 0.96 | 4.8 | 2015-2019 | 1 | 24 |

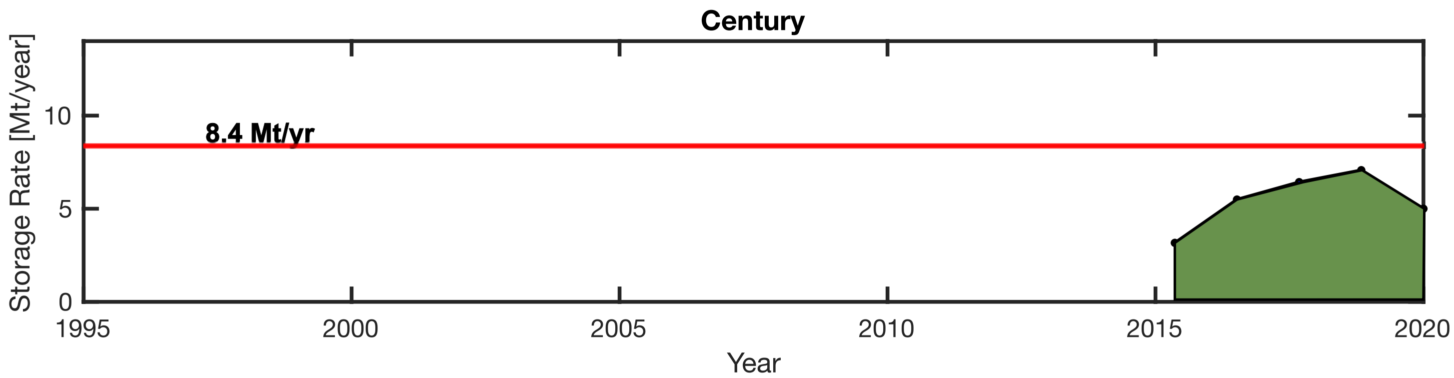



*Figure 3: Times series of $CO_2$ storage between 2016 – 2020 to show the overall trend in annual storage operations for Quest (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 3 of Supporting Information.*

*Table 3: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate – hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project. Where there are multiple sources available for each project, data that are highlighted in red (associated with a lower level of assurance) are used to calculate uncertainty but are not included in the final aggregate estimate used for comparison or in Figure 3.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average over project lifetime [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| US | EOR | Century | 5 | 8.4* | Occidental Petroleum | 7.1* | 8.55 | 25.66 | 2017-2019 | 2 | 16 | Occidental Petroleum Sustainability report |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Denver Unit | 3.39* | 3.232 | 16.16 | 2016-2020 | 1 | 17 | provides the aggregate data for $CO_2$ storage while US EPA provides the differentiated storage data at the two unit sites that are operated by Occidental Petroleum |
| | | | | | Hobbs Unit | 3.66* | 2.695 | 10.78 | 2017-2020 | 1 | 18 | |

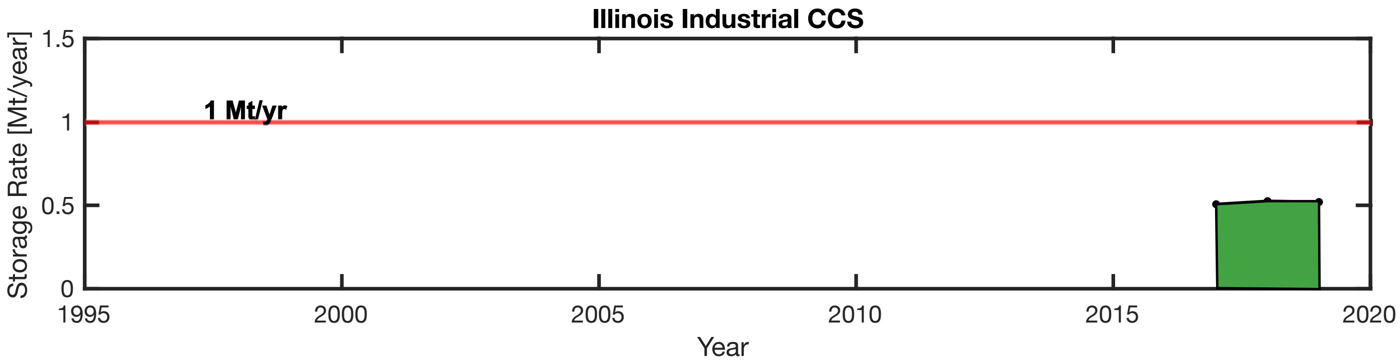



*Figure 4: Times series of $CO_2$ storage between 2017 – 2019 to show the overall trend in annual storage operations for Illinois Industrial CCS (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 4 of Supporting Information.*

*Table 2: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate – hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project. Where there are multiple sources available for each project, data that are highlighted in red (associated with a lower level of assurance) are used to calculate uncertainty but are not included in the final aggregate estimate used for comparison or in Figure 4.*

| Country | | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average over project lifetime [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|

| | Storage type | | | rates) [Mt $yr^{-1}$] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| US | Dedicated geological storage | Illinois Industrial CCS | 1 | 0.52 | Illinois ADM | 0.52* | 0.52 | 1.55 | 2017-2019 | 1 | 52 |
| | | | | | | 0.522* | 0.52 | 1.042 | 2019-2020 | 2 | 53 |

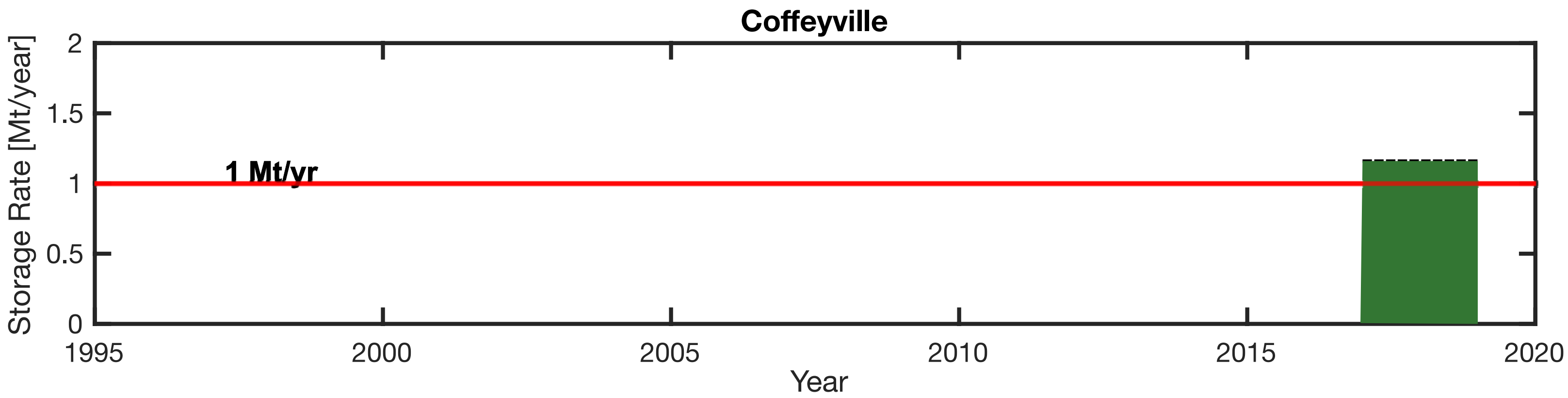



*Figure 5: Times series of $CO_2$ storage between 2017 – 2019 to show the overall trend in annual storage operations for Coffeyville (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 5 of Supporting Information.*

*Table 3: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate – average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt $yr^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt $yr^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt $yr^{-1}$] | Storage Rate - average over project lifetime [Mt $yr^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|

| | Storage type | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| US | EOR | Coffeyville | 1 | 1.16 | North Burbank Unit | 1.16 | 1.16 | 3.49 | 2017-2019 | 1 | 55 |

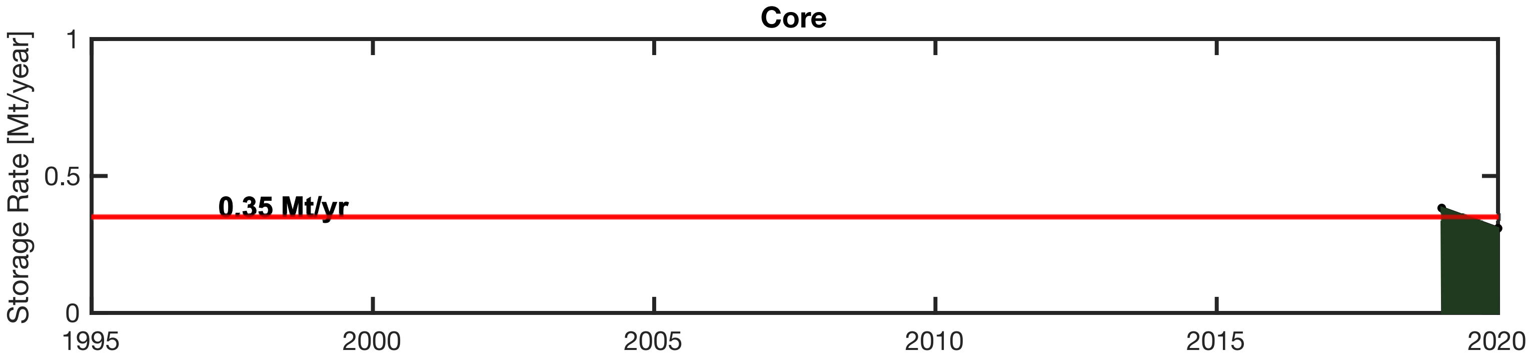



*Figure 6: Times series of $CO_2$ storage between 2019 - 2020 to show the overall trend in annual storage operations for Core Energy (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 6 of Supporting Information.*

*Table 4: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate – hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt $yr^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt $yr^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt $yr^{-1}$] | Storage Rate - average over project lifetime [Mt $yr^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| US | EOR | Core Energy | 0.35 | 0.35 | Core Energy | 0.31* | 0.35 | 0.69 | 2019-2020 | 1 | 61 |

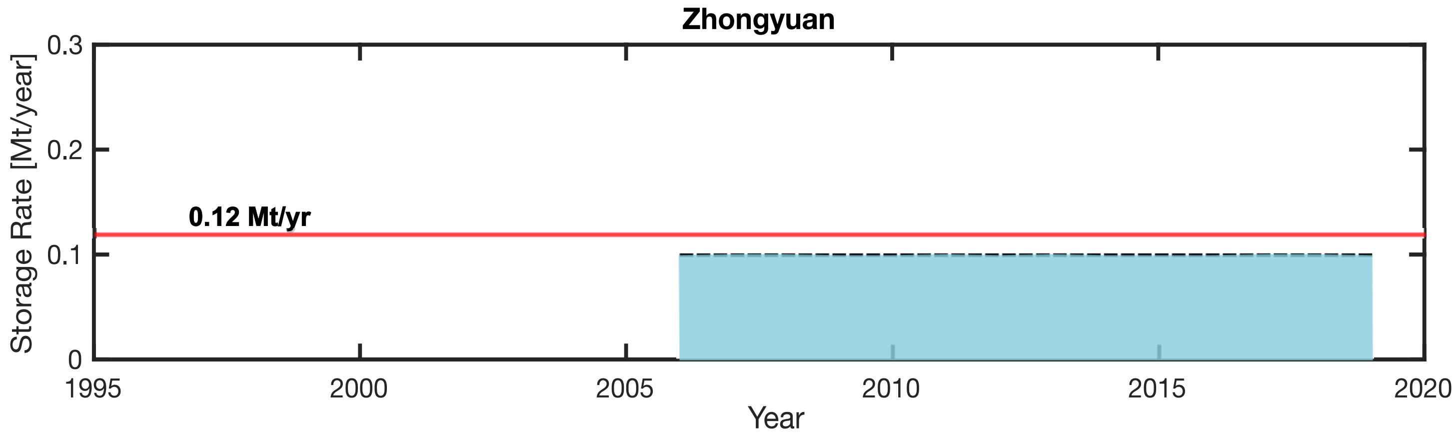



*Figure 7: Times series of $CO_2$ storage between 2006-2019 to show the average storage operations for Zhongyuan (black dash line) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 7 of Supporting Information.*

*Table 5: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt $yr^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt $yr^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt $yr^{-1}$] | Storage Rate - average [Mt $yr^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| China | EOR | Sinopec Zhongyuan | 0.12 | 0.35 | Zhongyuan Sinopec | 0.1 | 0.1 | 2.4 | 2006-2019 | 2<br>2 | 15<br>62 |

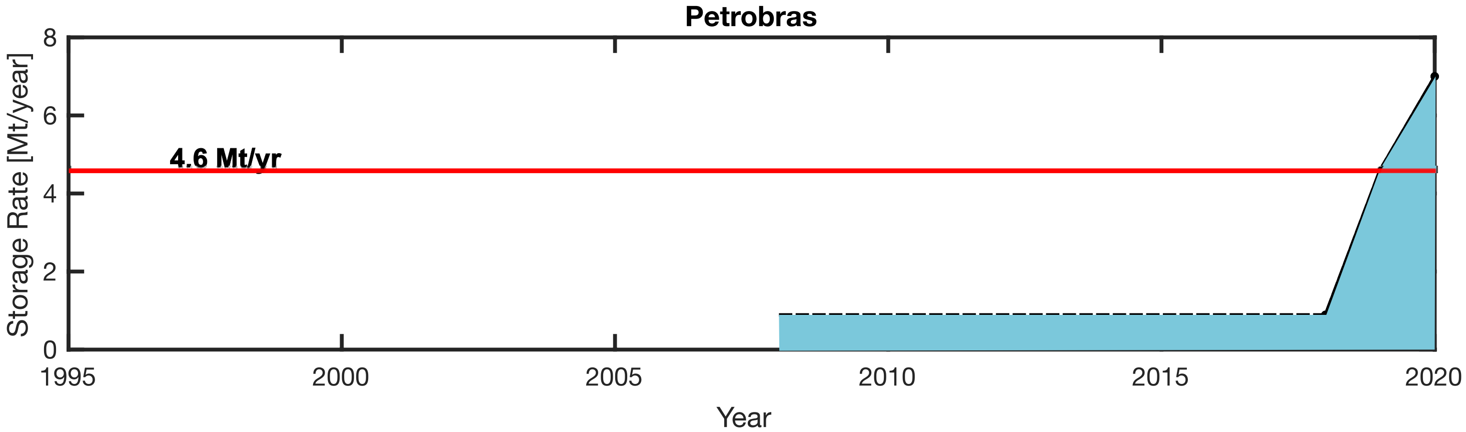



*Figure 8: Times series of $CO_2$ storage between 2008-2018 to show the average storage operation (black dash line) and annual storage rate from 2018 -2020 (black smooth line joined by dots) for Petrobras. The comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 8 of Supporting Information.*

*Table 6: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate – average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average over project lifetime [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Brazil | EOR | Petrobras | 4.6 | 4.6 | Santos Basin Petrobtras | 4.6* | 1.65 | 21.4 | 2008-2020 | 3<br>2<br>3<br>2 | 35<br>36<br>37<br>38 |

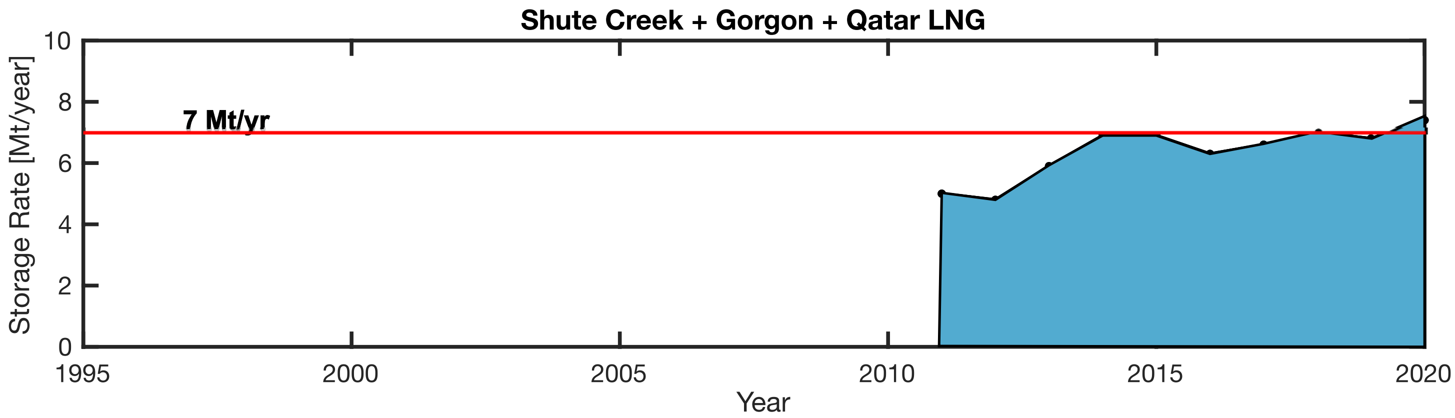



*Figure 9: Times series of $CO_2$ storage between 2011- 2020 to show the overall trend in annual storage operations for Shute Creek, Gorgon, and Qatar LNG (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 9 of Supporting Information.*

*Table 7: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average over project life time [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Qatar | Geological storage | Qatar LNG | 2.1 | 1 (C) + 6.8 (EM) | Chevron (C) & Exxon mobile (EM) | 1* (C) + 6.8* (EM) | 2 (C) + 6.4 (EM) | 4 (C) + 63.6 (EM) | 2019-2020 (C) 2011-2020 (EM) | 2 | 56 (EM) | Chevron only operates for the Gorgon project in Australia while Exxon mobile are involved in all three CCS projects including Shute Creek, Qatar LNG and Gorgon. However, the |
| Australia | Geological storage | Shute Creek | 7 | | | | | | | 2 | 57 (C) | |
| US | EOR | Gorgon | 4 | | | | | | | 3 | 58 (C) | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Exxon Mobile sustainability report did not provide differentiated annual storage data associated with each individual project only the aggregate annual storage data in this case. |

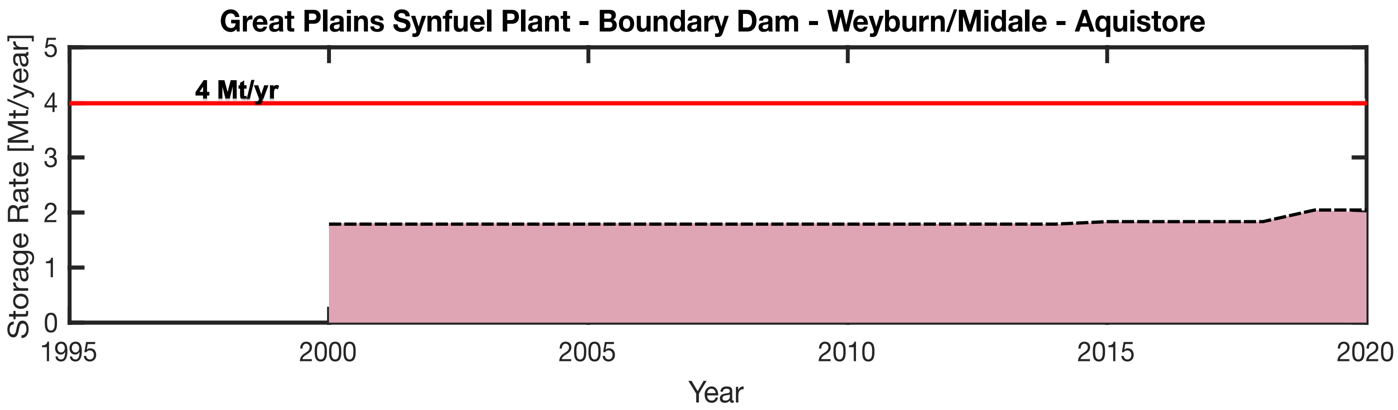



*Figure 10: Times series of $CO_2$ storage between 2000-2020 to show the average storage operations for Aquistore/Weyburn-Midale that are associated with Great Plains Synfuel Plant/Boundary Dam capture facilities (black dash line) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 10 of Supporting Information.*

*Table 8: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate – average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate – hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project. Where there are multiple sources available for each project, data that are highlighted in red (associated with a lower level of assurance) are used to calculate uncertainty but are not included in the final aggregate estimate used for comparison.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt $yr^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt $yr^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt $yr^{-1}$] | Storage Rate - average over project lifetime [Mt $yr^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Canada | EOR | Boundary Dam | 1 (A) + 3 (W) | 0.65*(A) +2 (W) | Project Aquistore (A) & Weyburn-Midale Whitecap Resources(W) | 0.045 (A) + 2*(W) | 0.045 (A) + 1.93 (W) 1.79 (W) | 0.27 (A) + 5.8 (W) + 32.2 (W) | 2015-2020 (A) 2018-2020 (W) 2000-2017 (W) | 2 | 39 (Aquistore) | In this case, there are multiple capture facilities: Boundary Dam and Great Plains Synfuel Plant (GPSP) transporting captured $CO_2$ to the Weyburn-Midale storage site that is operated by Whitecap Resources. Additionally, a small proportion of captured $CO_2$ from the Boundary Dam facility is transported to the demonstration project – Aquistore for storage. However, Whitecap resources did not differentiate how much $CO_2$ stored was from the Boundary Dam or GPSP plant. |
| | | | | | | | | | | 3 | 40 (Aquistore) | |
| | | | | | | | | | | 3 | 41 (Whitecap) | |
| | | | | | | | | | | 3 | 42 (Whitecap) | |
| | | | | | | | | | | 3 | 43 (Whitecap) | |
| US/Canada | EOR | Great Plains Synfuel Plant | | | | | | | | 3 | 44 (Whitecap) | |

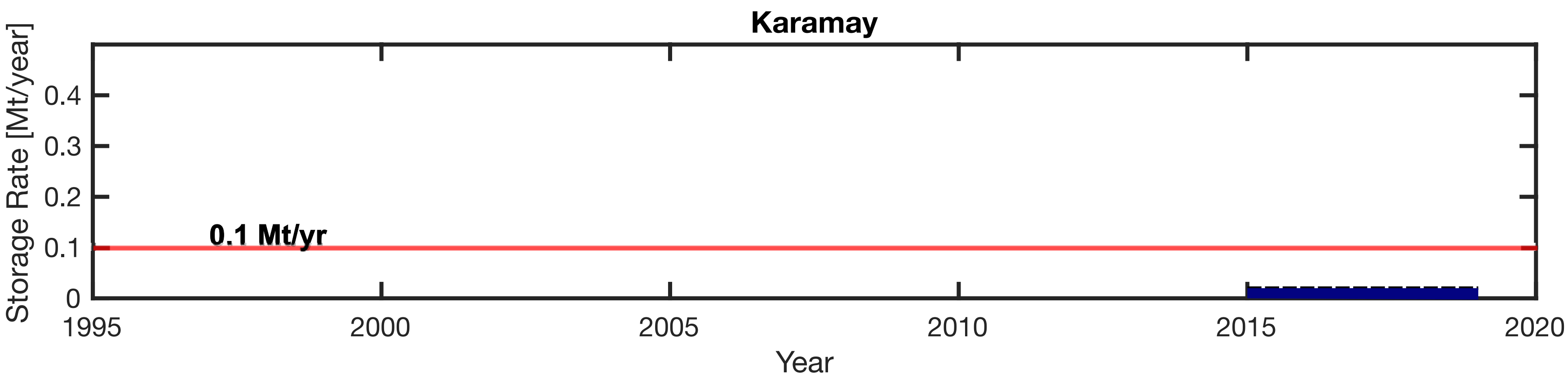



*Figure 11: Times series of $CO_2$ storage between 2015-2019 to show the average storage operations for Karamay Dunhua (black dash line) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 11 of Supporting Information.*

*Table 9: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report*

*cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| China | EOR | Karamay Dunhua | 0.1 | 0.1 | Karamay Dunhua | 0.02 | 0.02 | 0.2 | 2015-2019 | 2 | 15 |

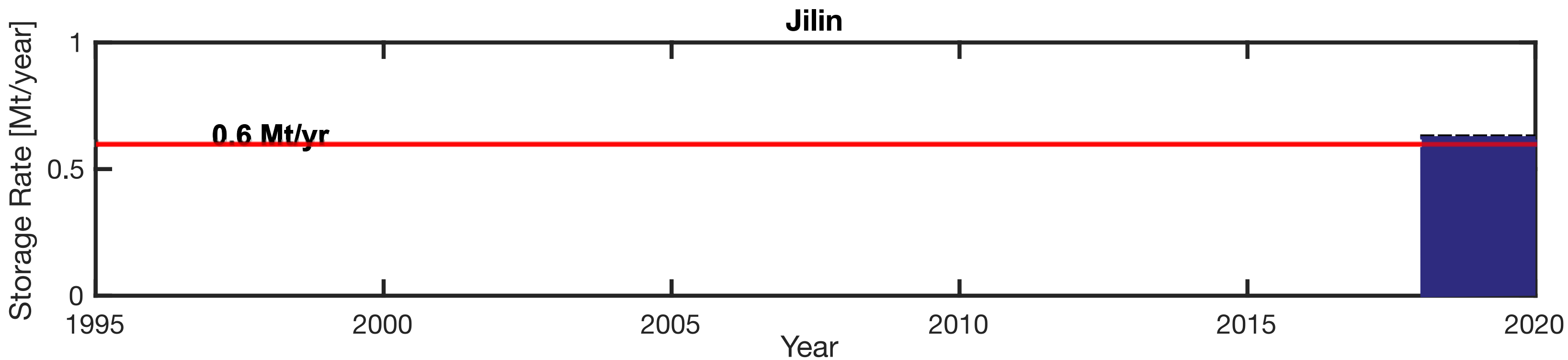



*Figure 12: Times series of $CO_2$ storage between 2018-2020 to show the average storage operations for Karamay Dunhua (black dash line) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 12 of Supporting Information.*

*Table 10: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate – average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each*

*capture project. Where there are multiple sources available for each project, data that are highlighted in red (associated with a lower level of assurance) are used to calculate uncertainty but are not included in the final aggregate estimate used for comparison or in Figure 12.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | EOR | | | | | | 0.3 | | | 2 | 15 |
| China | | CNPC Jilin | 0.6 | 0.63 | Jilin CNPC | 0.63 | 0.63 | 1.9 | 2018-2020 | 2 | 49 |

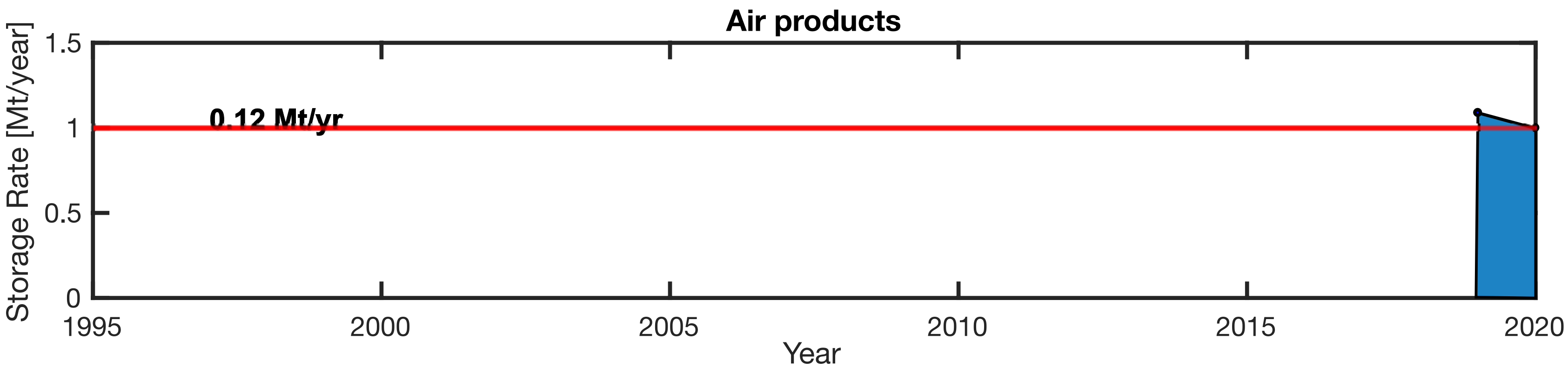



*Figure 13: Times series of $CO_2$ storage between 2018-2020 to show the overall trend in annual storage operations for Air products (black smooth lines joined by dots) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 13 of Supporting Information.*

*Table 11: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | | $CO_2$ Capture Facility | Capture rate Capacity | Capture Rate (* when reported, else | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else | Storage Rate- average over | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|

| | Storage type | | 2019-2020 [Mt yr$^{-1}$] | from storage rates) [Mt yr$^{-1}$] | | from storage rate in 2019 - average) [Mt yr$^{-1}$] | project lifetime[Mt yr$^{-1}$] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| US | EOR | Air products | 1 | 1.09 | Gulf Coast Denbury | 1.09* | 1.04 | 2.08 | 2019-2020 | 2<br>3 | 59<br>60 |

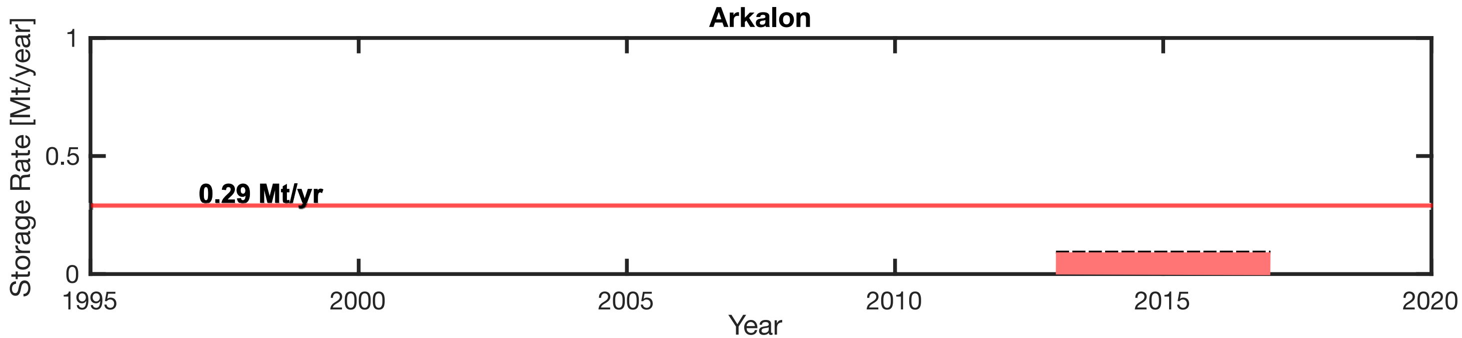



*Figure 14: Times series of $CO_2$ storage between 2013-2017 to show the average storage operations for Arkalon (black dash line) and the comparison with stated capture rate capacities (red line) is for 2019. The area under the time series represents the cumulative storage. The colours are associated with the maximum source category identified for each project and the definition of each category corresponds to the summary provided in Table 1 in the main text. Summary statistics are provided in Table 14 of Supporting Information.*

*Table 12: The capture rate capacity stated for 2019-2020 is sourced from the GCCSI global status of CCS 2020" report (GCCSI, 2020). The capture rate estimated here is determined based on 1) individual sources (indicated with an asterisk), or 2) the storage rate - hybrid, depending on the availability of data. Multiple sources and data for each project are separated by thin dashed lines. The storage rate– average is calculated based on the reported cumulative storage over the number of years specified in the Period column. We indicate the categories for each source with source categories defined in Table 1 in the main text. The storage rate– hybrid uses annual storage reported for 2019 where possible and average storage rate for projects that only report cumulative storage. The colour in the Sources column corresponds to the colour introduced in Table 1 in the main text and indicates the maximum category of sources collected for each capture project.*

| Country | Storage type | $CO_2$ Capture Facility | Capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Capture Rate (* when reported, else from storage rates) [Mt yr$^{-1}$] | Associated $CO_2$ storage facility/operator | Storage Rate - hybrid (* when annual storage is reported, else from storage rate in 2019 - average) [Mt yr$^{-1}$] | Storage Rate - average over project lifetime [Mt yr$^{-1}$] | Cumulative storage [Mt] | Period | Source Categorisation | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| US | EOR | Arkalon | 0.29 | 0.092 | Farnsworth Unit | 0.092 | 0.092 | 0.46 | 2013-2017 | 3 | 54 |

*Table 13: The compiled global geological CCS statistical database for 20 operational commercial-scale CCS facilities between 1996-2020 shows the aggregate 2019 estimates of capture rate capacity, the capture rate, storage rate– hybrid, storage rate– average over individual project lifetime and the cumulative storage. These estimates are compiled using data (black font) from Table 1-14 of the Supporting Information.*

| Aggregate capture rate Capacity 2019-2020 [Mt yr$^{-1}$] | Aggregate Capture Rate [Mt yr$^{-1}$] | Aggregate storage Rate - hybrid [Mt yr$^{-1}$] | Aggregate storage Rate - average over individual project lifetime [Mt yr$^{-1}$] | Cumulative storage [Mt] |
|---|---|---|---|---|
| **35.76** | **31.30** | **28.90** | **25.09** | **196.68** |