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Global geologic carbon storage requirements of climate change mitigation scenarios†

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Integrated assessment models have identified carbon capture and storage (CCS) as an important technology for limiting climate change. To achieve 2 °C climate targets, many scenarios require tens of gigatons of CO_2 stored per year by mid-century. These scenarios are often unconstrained by growth rates, and uncertainty in global geologic storage assessments limits resource-based constraints. Here we show how logistic growth models, a common tool in resource assessment, provide a mathematical framework for stakeholders to monitor short-term CCS deployment progress and long-term resource requirements in the context of climate change mitigation targets. Growth rate analysis, constrained by historic commercial CO_2 storage rates, indicates sufficient growth to achieve several of the 2100 storage targets identified in the assessment reports of the Intergovernmental Panel on Climate Change. A maximum global discovered storage capacity of approximately 2700 Gt is needed to meet the most aggressive targets, with this ceiling growing if CCS deployment is delayed.

Broader context

Carbon capture and storage (CCS) has been identified as an important technology for limiting climate change. To achieve the climate targets outlined by the Intergovernmental Panel on Climate Change (IPCC), many scenarios require over 1000 gigatons of CO_2 stored underground by the end of the century. Yet the extent of global CO_2 storage capacity resources are highly uncertain. This analysis focuses on the more tractable question of quantifying the storage resource that is needed to achieve climate change targets. Growth model analysis, constrained by historical technology development and CCS deployment, indicates that a range of mitigation scenarios are achievable, even at current rates of growth in CCS. However, there are tradeoffs between the growth in annual storage rates and long-term resource requirements needed to achieve these targets; faster growth leads to lower demand for storage resources. No more than 2700 Gt of storage resource is required under any scenario to meet the most ambitious climate change mitigation targets. These findings, and the associated modeling framework, will provide tools for policy makers, industrial developers, non-governmental organizations, and scientific institutions to monitor short term emission reductions and long-term resource needs for the deployment of large-scale carbon capture and storage.

Nearly all integrated assessment model scenarios compiled by the United Nations Intergovernmental Panel on Climate Change (IPCC) that limit climate change to less than 2 °C require the large-scale deployment of carbon capture and storage (CCS).[1,2] Large-scale deployment scenarios include capturing and geologically sequestering CO_2 from fossil fuel and biomass power generation plants, large industrial point sources, oil and gas production facilities, and in some cases direct air capture.[1,3] Proposed deployment scenarios will require an enormous scale-up of CO_2 storage, with global injection at rates of gigatons per year by mid-century. However, it remains challenging to incorporate historic commercial CO_2 storage data into these models, and to properly account for the highly uncertain and depletable nature of CO_2 geologic storage resources.[4]

Similar to other aspects of CCS technology, global geologic storage capacity assessment is early in its development. As a result, regional-scale resource estimates span several orders of magnitude (Fig. 1). Current approaches for resource assessment combine geologic information with statistical (volumetric methods in Fig. 1), analytical (closed volumetric methods in Fig. 1), and/or numerical analysis (dynamic methods in Fig. 1). These approaches handle complex geologic uncertainty by defining storage efficiency factors. These and other model inputs are sampled from statistical distributions defined over loosely constrained parameter ranges.[5]

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† Electronic supplementary information (ESI) available: Supplemental data is compiled in zahasky_and_krevor_supplemental_data.xlsx and is provided in the data repository referenced in the Acknowledgments. This spreadsheet contains the storage capacity summary data from Fig. 1, raw IPCC data used for Fig. 2, and the cumulative storage data in Fig. 3. See DOI: 10.1039/d0ee00674b

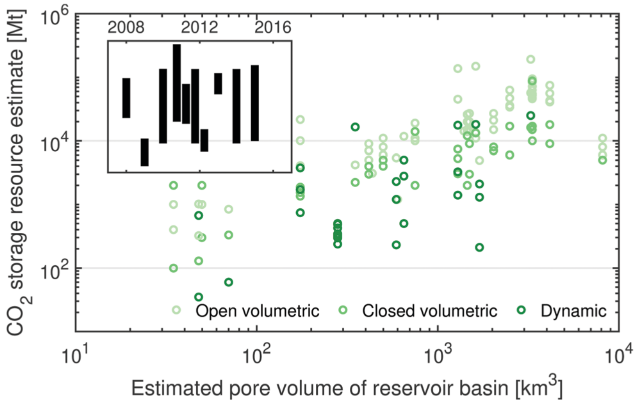

Fig. 1 Sampling of CO_2 storage capacity estimates in different saline aquifer basins using open volumetric, closed volumetric/static estimates, and dynamic/simulation estimates. An individual basin size is described by the pore volume, with the vertical array of points at a given location along the *x*-axis indicating the range of estimates made for a single basin. The inset image illustrates the range of storage estimates in the Mt Simon formation as function of time. The vertical axis of both plots are equal such that the vertical axis values of the main figure can be applied to the inset figure. Data in the main plot is sourced from ref. 7–14. Mt Simon storage estimates are sourced from ref. 12 and 15–23. Raw data is tabulated in the ESI† dataset.

The resulting capacity estimates are both variable and inconsistent. For example, the Mt. Simon formation—the injection target of the largest operating carbon storage project in the United States—has been characterized with approximately 21 wells drilled greater than 4500 ft and ten natural gas storage projects dating back to the middle of the 20th century.[6] Despite this, CO_2 storage resource assessments span over an order of magnitude and sometimes fail to overlap (inset chart in Fig. 1).

Nontechnical factors such as regulations, siting, property leasing, public acceptance, and financing drive even greater uncertainties in CCS project development.[24] Recent efforts from industry and regulatory bodies have placed CO_2 storage capacity evaluation into the framework of resource classification.[25–27] In these resource classification frameworks, technical, economic, and political factors are considered. These factors reduce the global prospective storage resource, approximated at over 10 000 Gt,[27,28] to a discovered resource of less than 400 Gt.[26,27]

In light of these uncertainties, the focus of this study is to identify the rates of growth and ultimate discovered storage resources needed to meet climate change targets. Growth rate models anchored with historical data provide an approach for depletable resource assessment across the lifespan of resource utilization. Models with finite resource availability use S-shaped curves, as opposed to purely exponential growth models that produce J-shaped curves. The logistic model and the cumulative normal models are the main models used for depletable resource modeling. Logistic models have steeper, exponential growth and decline rates. Cumulative normal models have less steep growth rates and are largely incompatible with constraints from historical growth in CCS and climate change mitigation targets. Logistic curves have been widely used to describe the growth and decline of resources such as oil,[29,30] coal,[31] and groundwater aquifer depletion.[32] In addition to resource utilization, logistic models are widely used to describe trends in energy systems, infrastructure, and technology development.[33–35]

Logistic growth models provide a tool to analyze storage demand consistent with climate change mitigation targets. These models are not predictive, nor do they include mechanistic descriptions of specific policies or technologies. Rather, we show that they can provide a benchmark for identifying minimum rates of growth and maximum discovered storage resource requirements consistent with climate change mitigation targets and historical carbon storage data.

Constraints on logistic growth curve models

We make use of both current activity in CCS development and historical analogues in large energy infrastructure to constrain growth model scenarios. Carbon storage is currently in an early phase, characterized by exponential growth in the logistic model. Growth acceleration will be sustained by incentivization and sustained resource availability. The duration of the initial exponential phase provides a constraint. Analysis of global energy technology shows that maintaining exponential growth for over half a century is unprecedented.[35] Thus, the growth period of a depletable resource utilization must be followed by a deceleration and a decline. The inflection point in the growth rate marks the beginning of this deceleration. Under the logistic model constraints, this inflection point occurs when approximately 20% of the resource base has been exploited if the deceleration is driven by resource limitations. The cumulative global storage of CO_2 levels off over time as the utilized storage capacity is reached and annual storage rates decline to zero.

The symmetry, or lack of symmetry, of a logistic model provides another constraint. A symmetric model is predicated on continued incentivization, minimal innovation in resource exploitation, uninterrupted resource exploration, and resource exhaustion.[36] Technology development concurrent with continued resource demand frequently leads to skewed growth models with decline rates slower than growth.[30] In a CCS context, technology development could emerge from advances in subsurface engineering leading to more efficient use of pore space.[37] Such technology development would result in a skewed growth model that ultimately utilizes a larger storage resource relative to a symmetric growth model. Alternatively, decline rates steeper than growth rates may occur when technology replacement, not resource limitations, limit growth. This type of technology replacement would result in smaller storage resource utilization. The symmetric model used in this study has the benefit of resulting in conservative estimates because while more resource may eventually be exploited relative to a symmetric model (slower decline), it is not needed to support the early growth trajectory. If less storage resource is utilized (faster decline), it is because the resource is no longer required—not because the resource is limited.

Logistic growth curves can be further constrained by current cumulative CO_2 storage data and cumulative global CO_2 storage

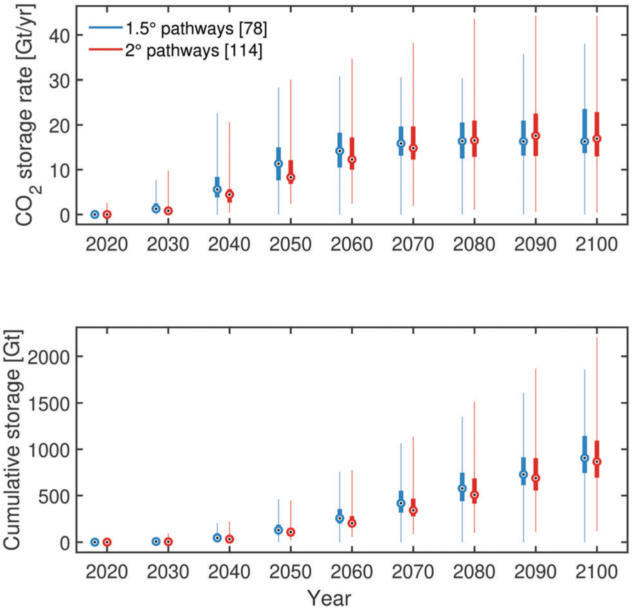

Fig. 2 Boxplot of total CCS CO_2 storage rate in Gt per year (top) and cumulative storage in Gt based on the IPCC 1.5 °C (78 models) and 2 °C (114 models) pathways sourced from ref. 38. For clarity, the low and high pathways at each temperature target, as defined in ref. 1, are lumped together. Models with targets below 1.5 °C and above 2 °C were excluded. The full dataset is tabulated in the spreadsheet in the ESI.† The bottom and top of the boxes indicate the interquartile range and the lines correspond to the full range of models. The black circle near the center of the boxes indicates the median model. To calculate cumulative storage, the model storage rates were linearly interpolated between decadal increments and summed. 1.5 °C and 2 °C pathways are very similar because 1.5 °C scenarios implement more bioenergy with CCS (BECCS), while 2 °C scenarios utilize less BECCS but more CCS with gas and coal. See Section 2.4.2 and Fig. 2.17 in ref. 1 for more details.

targets in 2100 identified by the IPCC.[1] Cumulative CO_2 storage data is used because it is a measure of CCS deployment that is relatively insensitive to abrupt changes in annual storage rates[31] and provides an analogue for accumulated technological learning.[35] The techno-economic model IPCC pathway targets evaluated here represent cumulative storage targets in 2100 that are below (348 Gt, P2 in ref. 1), between (687 Gt, P3 in ref. 1), and slightly above (1218 Gt, P4 in ref. 1) the interquartile range of both the 1.5 °C and 2 °C pathway models shown in Fig. 2.

Current growth in CO_2 storage capacity

Historic CO_2 storage capacity data between 1996—the year that the first commercial geologic storage project (Sleipner, Norway) began[28]—and 2020 indicate an annual growth rate of 8.6%. A continuation of growth at this rate through 2100 would result in cumulative storage in 2100 of 441 Gt (light blue line in Fig. 3). This pathway is below the median IPCC 2 °C model pathway target of 865 Gt in 2100 (Fig. 2). Reaching the IPCC[1] illustrative model pathway of 348 Gt (P2) is feasible at the current growth rate (dark blue line in Fig. 3). To maintain the current growth rate, the cumulative storage capacity will have to be doubled approximately every 8.4 years for a period of 60 years, the upper limit of historical exponential growth duration for energy technologies.[35] In the short term, this implies that by 2030 the global CO_2 storage rate will be roughly 110 Mt per year, up from the current rate of just over 30 Mt per year.

Increases in growth required to reach IPCC illustrative model pathway targets

Achieving the IPCC[1] illustrative model pathway targets of 687 Gt (P3) and 1218 Gt (P4) requires an increase in cumulative storage growth rates to at least 9% and 10%, respectively. The orange curves in Fig. 3 illustrate two scenarios with growth rate increases in 2030 that reach the 1218 Gt storage target by 2100. In the scenario with a lower growth rate of 10.6% (light orange line in Fig. 3), the storage rate per year has to continue to accelerate through 2089. The associated storage capacity implied for this scenario is 2692 Gt CO_2. Alternatively, if a higher growth rate of 12.1% can be reached starting in 2030 (medium orange line in Fig. 3), then the annual storage rates may decelerate in 2077 due to resource limitations while still achieving the IPCC target of 1218 Gt in 2100. In this case, the discovered storage resource need—1505 Gt—is nearly half as much as in the lower-growth scenario.

A similar growth rate comparison is illustrated for the IPCC[1] illustrative pathway target of 348 Gt (P2). If the growth rate can increase from the current rate to 12.1% starting in 2030 (dark red line), then the total necessary capacity (369 Gt) is almost a third of the scenario where growth is maintained at 8.6% until 2090 (dark blue line in Fig. 3). The results of these model scenarios are summarized in Table 1.

Trade-offs between storage targets, capacity, growth rates, and growth duration

The logistic growth descriptions of storage capacity indicate that there is a tradeoff between early growth rates and total storage capacity required to support that growth. The solid lines in Fig. 4 show different scenarios with current growth (8.6%) maintained until 2030. After 2030 there is an increase in growth to meet the three IPCC illustrative pathway 2100 CO_2 storage targets (348 Gt, 687 Gt, and 1218 Gt). As the exponential growth rate increases, the storage capacity needed to support the trajectory decreases hyperexponentially. This illustrates a relationship between growth rates and storage capacities required to support them. If storage capacity is limited, then the storage growth rate needs to be higher. Likewise, if the growth rate is higher, then less storage capacity is ultimately required.

If future increases in growth rate are delayed, greater storage capacities or growth rates are required to meet IPCC targets. The dashed grey line in Fig. 4 illustrates growth rate-capacity

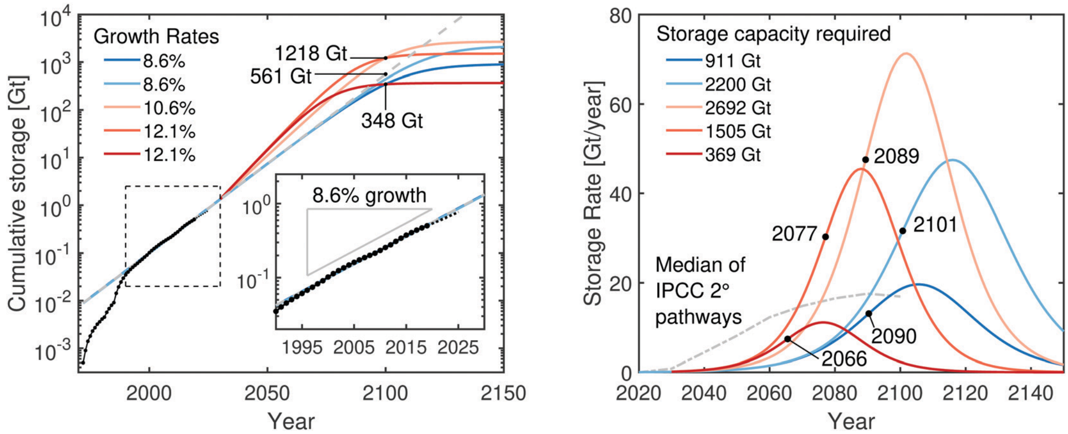

Fig. 3 (left) Plot of cumulative CO_2 storage as a function of time. The black markers indicate the historic cumulative CO_2 injection along with planned projects up to 2025 (see ESI† for tabulated data). The inset plot, indicated by the black box, provides a zoomed view of the historic data and model fit between 1996 and 2020 (linearized $R^2 = 0.998$). The blue lines illustrate logistic curves with different 2100 storage targets assuming continued growth at the historic rate of 8.6%. The orange and red lines illustrate logistic curves with increases in growth rate starting at 2030. The light orange line describes the scenario where the growth rate increases from 8.6% to 10.6%, in 2030 while the medium orange line indicates an increase of 3.5%, from 8.6% to 12.1% in 2030. The rates were constrained to reach either the 348 Gt or 1218 Gt IPCC targets of CO_2 stored by 2100. The full description of model parameters are summarized in Table 1. Historic CO_2 storage data was tabulated by ref. 39 and expanded on with recent data from ref. 40. See the spreadsheet in the ESI† for raw data. (right) Plot of corresponding global CO_2 storage rate as a function of time for the different logistic models. The legend indicates the total storage capacity required for each logistic model. The years correspond to model inflection points, indicating when growth diverges from the exponential trend. The dashed grey line illustrates the median of all 114 IPCC 2° model pathways.[1]

Table 1 Growth model details of five scenarios corresponding to the lines in Fig. 3 and colored dots in Fig. 4

Growth rate [%]	2100 storage [Gt]	Total storage capacity required [Gt]	Years of exponential growth
8.6	348	911	60
8.6	441	2200	71
10.6	1218	2695	59
12.1	1218	1505	47
12.1	348	369	36

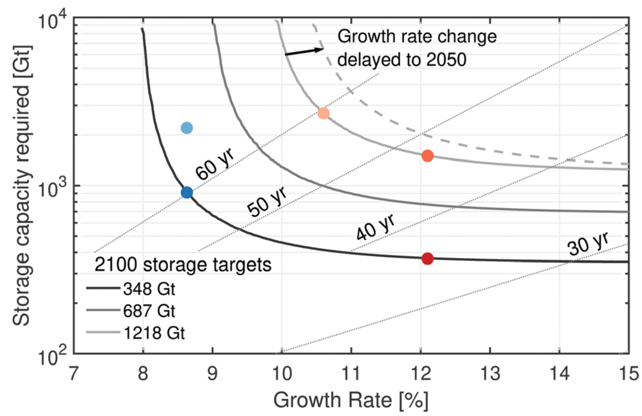

Fig. 4 The thick solid grey lines show the storage capacity required to meet the three IPCC illustrative model pathway targets by 2100 as a function of post-2030 growth rate. These are calculated assuming continued growth of 8.6% until 2030. The thick dashed grey line shows how the 1218 Gt storage conditions change if an increase in growth is delayed until 2050. The thin dotted lines indicate the number of years—starting from 2030—when growth begins to decelerate, as indicated by the inflection point on a given logistic curve. Colored points correspond to scenarios plotted in Fig. 3.

scenarios if the growth rate change is delayed from 2030 to 2050 for scenarios reaching the IPCC 1218 Gt target by 2100. This 20-year delay shifts the growth rate-capacity curve to the right by approximately one percentage point. Therefore, for a fixed storage capacity, the growth rate from 2050 needs to be approximately one percentage point higher to reach the IPCC storage target than it would need to be if the growth rate were to increase in 2030. Similarly, for a fixed growth rate, much higher storage capacities are required in the delayed-growth scenarios.

Historic energy technology growth provides insights into maximum growth duration achievable in logistic frameworks. The thin solid grey line in the upper-left of Fig. 4 indicates scenarios that would require 60 years of accelerating growth. Scenarios above and to the left of this line indicate storage capacity scenarios with accelerating growth beyond 2090. These scenarios would be unprecedented when compared with historic energy growth trends.[35] Further constraints, such as a maximum total global injection rate, could be incorporated into the analysis. The IPCC 2 °C pathways shown in the top plot of Fig. 2 include scenarios with global injection rates that range from zero to over 40 Gt per year by the end of the century. All but the most ambitious logistic model scenarios demonstrated in Fig. 3, specifically the 1218 Gt target with a growth rate less than 12%, fall within this range of global injection rates.

The tradeoffs illustrated by the model and plotted in Fig. 4 highlight that storage targets alone do not define global CO_2 geologic storage capacity requirements. Rather it is a combination of targets and growth rates that determine these requirements. Lower growth rates and delays in achieving higher growth rates result in a longer period of near-exponential growth, higher peak global storage injection rates, and a significant increase in long-term global storage capacity requirements.

Discussion and conclusion

This analysis suggests that resource assessment for CO_2 storage identifying 2700 Gt of discovered storage resource in locations with the ability to sustain peak injection rates of 40–60 Gt per year will be sufficient to meet conceivable demand under <2 °C climate change scenarios. The maximum global storage rates of logistic scenarios achieving these targets are at the upper end of scenarios considered by the IPCC.[1,2] A maximum achievable rate could easily be used as an additional model constraint. However, it is difficult to constrain from current knowledge or historical analogues.

Future technology development will determine if the growth trajectory is symmetric. The scenarios illustrated here use equal growth and decline rates. The cumulative storage resource utilization will be larger if the storage growth rate is slower than the decline rate. This skewed resource use trajectory is commonly observed in resource assessments[30] and is often driven by technology innovation. Technology development and innovation in CCS could arise from more efficient saline aquifer storage, or vast amounts of storage in unconventional formations such as basalt and coal seams.[28,41–44] In addition, local, regional, and global storage resource exploration and evaluation has steadily progressed (*e.g.* Fig. 1) and is poised to continue due to collaborative efforts in academia, governments, and industry.[26,45,46] Alternatively, the cumulative storage resource requirements will be less if the storage growth rate is higher than the decline rate. Decline rates steeper than the growth rates could be driven by replacement of CO_2 storage technology with alternative low-emission energy technologies.

Incentivization of CO_2 storage drives commercial growth. Presently, pilot projects make up less than 1% of annual CO_2 storage while 84% of stored CO_2 is used for commercial enhanced oil recovery (CO_2-EOR) operations.[40] The growth in CO_2-EOR with CCS has been steady over several decades as shown in the inset in Fig. 3, while the growth from power generation facilities and other industrial point sources has been sporadic. For this reason, the 2050 storage rates of all of the logistic scenarios in the right plot in Fig. 3—that range from 0.6–1.8 Gt per year—align remarkably well with techno-economic assessments of future storage rates (0.5–1.8 Gt per year in ref. 47) when CO_2-EOR remains the leading incentive. The economic forcing of CO_2 utilization has therefore been an important mechanism for accumulating technological learning in the absence of significant additional incentivization. However, maintaining or increasing CO_2 storage growth rates, while meeting other emission targets in the IPCC scenarios, will require additional emission mitigation incentivization. This may arise from a range of governmental incentives including carbon markets, tax incentives, and direct financing.[48,49] The extent of this will ultimately determine growth and CO_2 storage resource utilization.

Current rates of CCS deployment are consistent with achieving some of the IPCC 2100 cumulative storage targets. However, there is significant divergence from the integrated assessment model year-on-year trajectories (*e.g.* Fig. 2). This divergence is illustrated by the dashed grey line in Fig. 3 that represents the median of all 114 2°-IPCC-model pathways shown in Fig. 2. Deployment under the median scenario requires an unprecedentedly high exponential growth of over 28% between 2020 and 2050. Evaluating the progress of CCS against these scenarios is predetermined to show development well behind targets.

In contrast to the CCS deployment trajectories compiled by the IPCC, the use of logistic growth models provides an alternative view of current development that is by some measures optimistic. The current growth rate trajectory, constrained by 20 years of commercial-scale CO_2 storage data, could lead to as much as 441 Gt of CO_2 stored by 2100. This would be sufficient to achieve many of the climate change mitigation trajectories with less than 2 °C of warming. The identification of a maximum storage resource need of 2700 Gt is less than the highly uncertain estimates of the prospective resource available, of 10 000 Gt or more. It can also provide a tractable target for governments and industry for the identification of resources to increase certainty around the viability of CCS as a large-scale CO_2 abatement technology. By other measures, this work highlights the challenges ahead to meet the most ambitious emission reduction targets. Increases in growth rate by at least two percentage points are required to meet the most aggressive <2 °C trajectories.

Achieving the sustained growth in CCS outlined in these models may require additional policies and financial mechanisms to incentivize the capture and storage of CO_2 from power generation facilities and other industrial point sources. To date, CO_2 enhanced oil recovery has been a leading financial driver of CCS. However, this may not be sufficient to maintain or increase growth throughout the second half of the century as needed to reach 2100 emissions abatement targets. Regardless of changes in future incentivization structures and storage growth rates, the analytical methods presented here provide a practical tool for stakeholders to evaluate future storage resource needs and to measure CO_2 storage progress in the context of climate change mitigation targets.

Methods

Logistic growth curves used to describe cumulative storage and CO_2 storage rate are given by eqn (1) and (2), respectively.

$$P(t) = \frac{C}{1 + \exp\left(r\left(t_{\mathrm{p}} - t\right)\right)} \tag{1}$$

$$Q(t) = \frac{C \cdot r \cdot \exp\left(r\left(t_{\mathrm{p}} - t\right)\right)}{\left(1 + \exp\left(r\left(t_{\mathrm{p}} - t\right)\right)\right)^2} \tag{2}$$

$P(t)$ refers to the cumulative storage (in Gt) at time t, $Q(t)$ refers to the storage rate (in Gt per year) at time t, C is the total storage capacity (in Gt), t_{p} is the year of peak capacity, and r is the rate of growth. The first inflection time (t_n) on the growth rate curve (years annotated on the right plot in Fig. 3) is given by $t_n = t_p - \ln(2+\sqrt{3})/r$. Solutions for the analytical equations at specific storage targets in specified years were determined computationally by calculating every solution in the parameter space and finding the minimum squared difference in the specified year. This was done by writing a script in Matlab to discretize the peak year (*e.g.* a vector of $\sim$3 month increments from 2030 to 2350) and cumulative storage (*e.g.* a vector of $\sim$2 Gt increments from 100 Gt to 11 000 Gt) and calculating every solution.

Conflicts of interest

There are no conflicts to declare.

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MATLAB script for generation of logistic analysis in Fig. 3 and the corresponding data are permanently available at doi.org/10.5281/zenodo.3576627. Funding for this work was provided by ACT ELEGANCY, Project No. 271498, has received funding from DETEC (CH), BMWi (DE), RVO (NL), Gassnova (NO), BEIS (UK), Gassco, Equinor and Total, and cofunded by the European Commission under the Horizon 2020 programme, ACT Grant No. 691712, and the UK CCS Research Centre 2017 EPSRC Grant EP/P026214/1.

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