Carbon dioxide storage resource use trajectories consistent with US climate change mitigation scenarios

Yuting Zhang*
Department of Earth Science and Engineering
Imperial College London
+44 7446137581
yuting.zhang16@imperial.ac.uk

Christopher Jackson
Department of Earth Science and Engineering
Imperial College London
c.jackson@imperial.ac.uk

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

Nihal Darraj
Department of Earth Science and Engineering
Imperial College London
nihal.darraj20@imperial.ac.uk

***Correspondence:**
Yuting Zhang
+44 7446137581
yuting.zhang16@imperial.ac.uk

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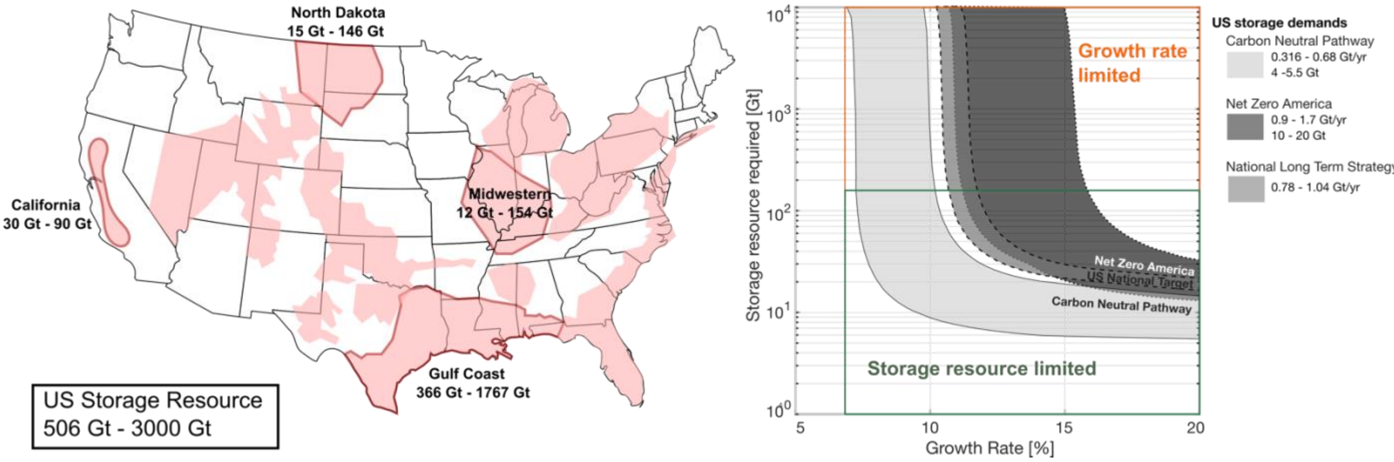
ABSTRACT

To progress decarbonisation in the United States, numerous techno-economic models have been built projecting climate change mitigation scenarios that include CO_2 storage deployment at annual injection rates of 0.3 – 1.7 Gt yr^{-1} by 2050. However, these projections do not include geological, technical, or socio-economic factors that could impede the growth of geological storage resource use. Here, we apply a growth modelling framework to evaluate CO_2 storage scenarios proposed in the Net Zero America, Carbon Neutral Pathways, Long-Term Strategy, and Decarb America reports. Our modelling framework uses logistic curves to analyse the feasibility of growth trajectories under constraints imposed by the associated storage resource availability. We show that the entire storage demand for the US can be accommodated by the resources available in the Gulf Coast alone. Deployment trajectories require sustained average annual (exponential) growth at rates >10% nationally and between 3% - 20% regionally across four storage hubs. These scale-up rates are high relative to those characterising analogous, historical, large-scale energy infrastructure projects in the US (4%), suggesting that modelled projections in current reports are too aggressive in their deployment of CCS. These models could be easily constrained to more realistic deployment trajectories with the type of modelling framework we present here.

KEYWORDS: Growth modelling, CO_2 storage, growth rates, storage resource requirement, United States, net zero, climate change mitigation

SYNOPSIS: Current projections of CO_2 storage to reach net zero by 2050 in the US are unconstrained. Growth modelling shows deployment trajectories of CO_2 storage require annual growth rates of >10% nationally, which are high when compared to historical rates for other resources.

GRAPHICAL ABSTRACT



INTRODUCTION

To mitigate climate change and limit global warming to <1.5 ^{o}C, we need to reduce global greenhouse emissions to net-zero by mid-century[1]. In most techno-economic model scenarios evaluating climate change mitigation, carbon capture and storage (CCS) is deployed at large scales, injecting CO_2 underground at rates of gigatons per year by mid-century[1]. The United States (US) is one of the top global emitters of CO_2 due to its heavy dependence (i.e., 80% of its primary energy demand) on fossil fuel[2]. In models of decarbonisation pathways for the US, there are projections of geologic CO_2 storage deployed nationally, commensurate with the global CO_2 storage scenarios. For example, in major assessments there are scenarios with up to 20 Gt of cumulative storage by 2050 nationally in the US, with injection rates reaching nearly 2 Gt of CO_2 annually by 2050[3,4,5,6]. These volumes are significant, with the envisioned scale for US CO_2 transport and storage being 2.4 times the current US equivalent volume of oil production[3].

Historically, the US has been a leader in both the innovation of CCS technology and the policy support driving investment from the private sector[2]. Currently, more than half (i.e., 14 of 26) of all operational, commercial, large-scale CCS facilities reside in the US, with a combined capacity to capture nearly 20 million tonnes of CO_2 per annum. In 2020, due to the enhanced 45Q tax credit, 12 of the 17 new CCS facilities being developed globally are in the US[7]. National volumetric-based evaluations of storage resources estimate that there is 3,000 – 6,000 Gt of storage resource available in the US onshore and state waters[8,9]. However, some assessments suggest that onshore storage resources may be significantly less when explicitly accounting for geophysical considerations such as the injectivity of CO_2 and reservoir pressure build-up, and constraints on subsurface lateral plume migration due to the presence of faults or legacy wells that may provide leakage pathways[10]. For example, accounting for some of these issues, Teletzke et al. 2018[10] estimate a resource base of 506 Gt, which they refer to as the practicable storage resource base for the US. This more conservative estimate is only 8-17% of the estimates provided by the USGS[8] and DOE[9]. Nonetheless, this significantly reduced resource base is still sufficient to sustain a large-scale CO_2 storage industry nationally.

Despite these advances in our understanding, significant uncertainties remain surrounding the scaleup of CO_2 storage in the US and globally. The techno-economic models used to identify CO_2 storage demands in decarbonisation pathways are predominantly constrained by the relative price of technologies[11,12,13]. Therefore, gaps exist in the representation of storage resource consumption in these models[14,15]. For example, the models underpinning the US technology roadmaps consider an upper limit on the available storage resource and a maximum injection rate for CCS[3]. Moreover, these single-value limits are inherently uncertain. Geologically based storage resource assessments have irreducible uncertainties that range over two orders of magnitude[16]. The models are absent a number of potential leading-order limitations to subsurface CO_2 storage scaleup arising from geophysical factors including injection rate limits due to pressure increases in the reservoir, in conjunction with socio-economic factors, including regulatory requirements, financing, and activity for generating public acceptance[17,18,19,20,21].

In this work, we use a logistic growth model to identify plausible trajectories for the scaleup of subsurface CO_2 storage in the US consistent with national and regional CO_2 storage scenarios identified in four reports. Logistic models are widely used in analogous energy industries, and particularly the hydrocarbon industry[22,23,24,25,26]. We impose a range of storage resource constraints to identify limiting features: the minimum growth rates required to meet CO_2 storage demands and the necessary storage resource base to support growth trajectories. It is important to note that we are not predicting likely trajectories of CCS deployment or the actual quantity of storage resource use. Instead, using this modelling framework we can evaluate plausibility and potential bottlenecks to the proposed upscaling of CCS at both the national and regional scale in the US. Moreover, we aim to develop the spatial dimension of the diffusion of CCS across the US. We identify variations of the geographic distribution of CO_2 storage supply and demand at both the national and regional level and illustrate quantitatively the potential of the Gulf Coast to serve as a national storage hub for the USA.

MATERIALS & METHODS

2.1 Growth trajectories using the logistic modelling framework

The logistic model is one of many models used to describe patterns of growth in natural resource consumption, and it has been widely employed in various sectors across energy and technology domains[22,23,24,25,26,27,28,29,30,31,32,33,34,35,36]. The S-shaped curve is characterised by three distinct phases: an initial formative phase of high cost and uncertainty where growth is unstable is followed by a take-off point, defining when the reliable expansion of deployment begins[25, 36], and an exponential growth phase that is supported by mechanisms of continued incentivisation and the exploration of new sites. Finally, geological constraints such as the restricted availability of high-quality reservoirs begin to restrict growth, and eventually the resources are exhausted[17].

This modelling framework was recently applied by Zahasky & Krevor[16] in the context of CCS to evaluate the global storage resource requirements for CCS scaleup. In their anaylsis, the strengths for implementing this particular approach to CCS were discussed; the relationship between the early growth rate for a trajectory and the storage resource base can be captured using the logistic model, unlike linear or purely exponential models that assume indefinite resource consumption. This is a key relationship that illustrates the interconnection between the geophysical factors – the physical quantity of subsurface geology potentially suitable for CO_2 storage – and techno-economic dimensions (regulations, financing, latencies in project development, public acceptance) that will determine trajectories of CCS deployment. Subsequently, Zhang et al.[17] demonstrate the application of this model at a regional scale to evaluate the growth scenarios and storage resource requirements for European climate change mitigation plans. They demonstrated the use of this tool for regional analyses, and included a discussion of the associated temporal and spatial limitations to the modelling framework[17]. As a result, in our analysis for the US, we avoid using the model to monitor storage demand projections that are earlier than 2050. Similarly, our geographical consideration goes no smaller than the regional scale, avoiding the granularity of assessing storage development state-by-state.

We use a three-parameter, symmetric logistic growth model given in Equations 1 and 2, describing the cumulative storage, $P(t)$ [$GtCO_2$], and storage rate, $Q(t)$ [$GtCO_2$ yr^{-1}], of CO_2 storage at time, t [yr], respectively. The growth curve is characterised by an initial exponential growth at rate r [yr^{-1}]. Upon approaching the peak year, t_p [yr], growth declines until the storage resource base, C [Gt], is reached.

$$P(t) = \frac{C}{1+exp\left(r\left(t_p-t\right)\right)} \quad \text{..........(1)}$$

$$Q(t) = \frac{C \cdot r \cdot exp\left(r\left(t_p-t\right)\right)}{\left(1+exp\left(r\left(t_p-t\right)\right)\right)^2} \quad \text{..........(2)}$$

We use the first inflection point in the rate time series as a point at which growth has significantly deviated below exponential. This occurs in year t_n given by

$$t_n = t_p - \ln\left(2 + \sqrt{3}\right)/r \quad \text{..........(3)}$$

The cumulative and rate trajectories to achieve CO_2 storage demands for 2050 are determined through solutions to Equations 1 and 2, which are found numerically. We iterate, finding every combination of the early growth rate and storage resource requirement that meet a fixed CO_2 storage demand. Subsequently, we can identify the minimum growth rates supported by the available storage resources.

2.2 National analysis model description

We first analyse CCS scaleup nationwide for the USA. The United States' commitment to tackling climate change has been reinstated following the election of the Biden-Harris administration. Alongside re-joining the Paris Agreement, a new nationally determined target has been announced, aiming at a 50%-52% reduction in US greenhouse emission from 2005 levels by 2030[6]. Subsequently, several reports written by different organisations have been released, detailing various decarbonisation scenarios. We make use of three groups of national scenarios arising from these studies (Table 1)[3,4,6].

The first group of national scenarios comes from the Net Zero America study, a Princeton University-led, industry-funded academic research project that investigates possible technological pathways to net-zero by mid-century for the US[3]. Within the Net Zero America report, six approaches to nationwide decarbonisation have been outlined including a reference scenario and a scenario excluding any subsurface sequestration of CO_2 (100% renewable scenario). From this, three core scenarios with distinctly different levels of demand for CO_2 storage are presented: the E+ (high electrification) scenario storing 10 Gt of CO_2 cumulatively with an annual injection rate of 0.9 Gt yr^{-1} by 2050, the E- (less-high electrification) scenario with demands of 17 Gt of cumulative storage and an annual storage rate of 1.5 Gt yr^{-1} by 2050, and E+RE- (constrained renewable) scenario stating 20 Gt of cumulative storage and an annual storage rate of 1.7 Gt yr^{-1} by 2050[3] (Table 1; Figure 1).

A second group of national scenarios comes from the Carbon-Neutral Pathways report, an academic study funded by the United Nations Sustainable Development Solutions Network[4]. A total of eight scenarios are described in the Carbon Neutral Pathway analysis, and in each scenario a cumulative storage demand and an associated storage rate demand for 2050 is outlined. We analyse four of these scenarios with distinctly varied CO_2 storage demands, labelled "central", "delayed electrification", "low land" and "net negative", with cumulative storage demands ranging from 4 Gt – 5.5 Gt and storage rate demands between 0.3 Gt yr^{-1} – 0.7 Gt yr^{-1} (Table 1; Figure 1).

A final group of national scenarios are derived from the "Long-Term Strategy of the United States", a report in which the US government outlines various decarbonisation pathways[6] that have been submitted to the United Nations Framework Convention on Climate Change (UNFCCC) under the Paris Agreement[37]. To reach net-zero emissions by 2050, CO_2 injection rates of 0.78 Gt yr^{-1} – 1.04 Gt yr^{-1} are proposed (Table 1; Figure 1).

The reports have varying representation of the storage resource base. The resource base considered in the Net Zero America report was based on the analysis in Teletzke et al. 2018[10]. In their assessment of storage resources, they applied a series of restrictions to the USGS[8] estimates of storage resources (3000 Gt). Including technical and cost-related filters they identified 506 Gt as a practicable storage resource. Both analyses show that the Gulf Coast Region contains a significant proportion of the total estimated storage resource available in the US: 1767 Gt as the upper estimate[8] and 366 Gt as the practicable estimate[10]. The Carbon Neutral Pathway analysis did not include an upper limit for the storage resource base; only a maximum annual injection rate of 1.2 Gt yr^{-1} was used to constrain the modelling for CO_2 storage demands[4]. The Long-Term Strategy report did not specify any geological constraints used to model the deployment of CO_2 storage[6].

We initiate the models from 2030 onwards, using to the extent possible current CCS deployment and plans. The US has the longest record of injecting anthropogenic CO_2 into the subsurface, albeit for enhanced oil recovery. The Terrel natural gas plant in southern Texas commenced in 1972 and began capturing CO_2 through its natural gas stream, injecting the CO_2 into a nearby oilfield for enhanced oil recovery[38]. As of 2020, there are 13 operational projects in the US injecting anthropogenic CO_2 for storage, reaching an annual capture capacity of 21 Mt CO_2 yr^{-1} (ref.[7]). According to databases maintained by the Global CCS institute[7] and the International Oil and Gas Climate Initiative[39], 22 new CCS projects in the US are planned, with operational start dates before 2030. Presently, the overall CCS development in the US since 2000 is commensurate with storing potentially 1 Gt of CO_2 cumulatively by 2030. Note that actual storage rates have thus far been 19-30% less than capture capacity, but growth in storage rates and capture capacity are similar[40].

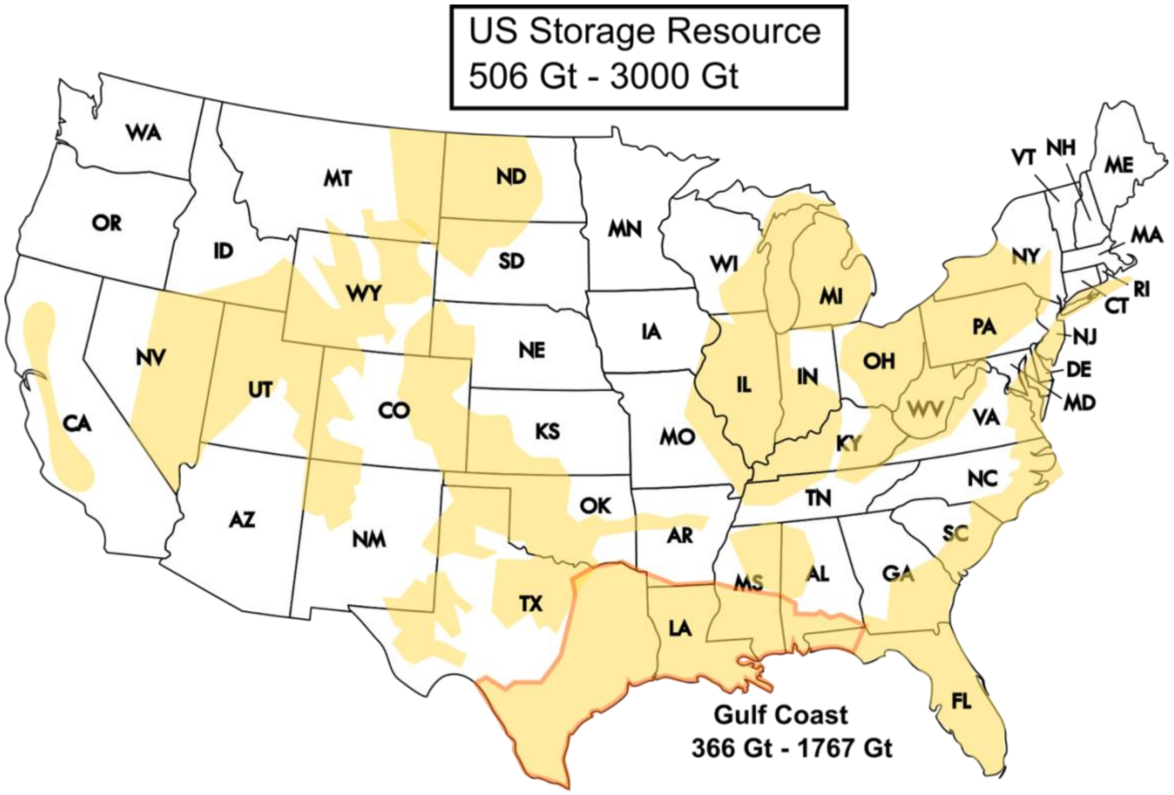


Figure 1: A map of the conterminous United States showing the storage resource available in the US and the gulf coast. The lower bounds are conservative estimates of storage resources by Teletzke et al. 2018[10] whilst the upper bound are storage resource estimates made by the USGS[8]. Storage rate scenarios are illustrated in red text and cumulative storage demands in blue text. All storage scenarios are for 2050. Yellow polygons illustrate the distribution of major storage resource locations analysed by the USGS[8] and Teletzke et al. 2018[10].

Table 1: National CO_2 storage scenarios for the US from three reports: Net Zero America, Carbon Neutral Pathways, and the Long-Term Strategy. Each scenario includes a storage rate demand and an associated cumulative storage demand for 2050 unless indicated otherwise. The Long-Term Strategy did not provide associated cumulative storage projections, this is indicated by N/A in the table.

Report	Scenario	Storage rate demand [$GtCO_2$ yr^{-1}]	Cumulative storage demand [Gt]
Net Zero America	E+	0.9	10
	E-	1.5	17
	E+RE-	1.7	20
Carbon Neutral Pathways	Central	0.316	4
	Delayed Electrification	0.38	5.5
	Low Land	0.68	5.5
	Net Negative	0.465	4.7
Long-Term Strategy	Low	0.78	N/A
	Medium	0.91	N/A
	High	1.04	N/A

2.3 Regional analysis model description

In addition to analysing national storage deployment, we use two studies providing state-by-state technology portfolios, the Net Zero America study, and a report provided by the Decarb America research initiative[3,5] (Table 2). For these studies we apply our analysis at the regional scale.

In the Net Zero America study state-level CO_2 transport infrastructure and storage systems were modelled for the E+ scenario. Figure 2 highlights the source-to-sink flows based on the modelled CO_2 pipelines from the Net Zero America study (light brown lines in Figure 2). The annual flows of captured CO_2 are geographically distributed according to the geospatially located point sources. Based on this information provided, we identified four regional storage demands for each hub by aggregating individual state demands that are linked by the pipelines. For the Net Zero America study, the regional storage demands are: 80 Mt yr^{-1} by 2050 (California), 769 Mt yr^{-1} by 2050 (Gulf Coast), 47 Mt yr^{-1} by 2050 (North Dakota), and 32 Mt yr^{-1} by 2050 (Midwestern).

The second study we used is a report created by the Decarb America research initiative, which documented state and regional storage demand[5]. This is led by non-profit organisations and policy think tanks, including the Clean Air Task Force. They have looked at various technology pathways for the US to reach net-zero greenhouse gas emissions by 2050. For comparison with the Net Zero America analysis, we aggregate state-level storage demands from the Decarb America report into the four regional storage hubs identified from the Net Zero America study. The Decarb America regional storage demands are: 63 Mt yr^{-1} by 2050 (California), 674 Mt yr^{-1} by 2050 (Gulf Coast), 32 Mt yr^{-1} by 2050 (North Dakota), and 265 Mt yr^{-1} by 2050 (Midwestern).

Six priority regions have been highlighted by the Net Zero America report for CO_2 storage site characterisation and from this, we select four that had the most abundant storage resource available based on the estimates of practicable storage resources from Teletzke et al. 2018[3,10]. These are California (30 Gt; bold black text in Figure 2), the Gulf coast (366 Gt), North Dakota (15 Gt), and Midwestern states (Illinois, Indiana, Kentucky, Tennessee, and Missouri; 12 Gt). We also include the USGS estimates for each hub (bold red text in Figure 2) as a maximum storage resource constraint on growth considered in the regional models. Finally, currently announced plans for CCS in each hub are commensurate with storing 12 $MtCO_2$ (California), 455 $MtCO_2$ (North Dakota), 360 $MtCO_2$ (Gulf Coast), and 122 $MtCO_2$ (Midwestern) by 2030.

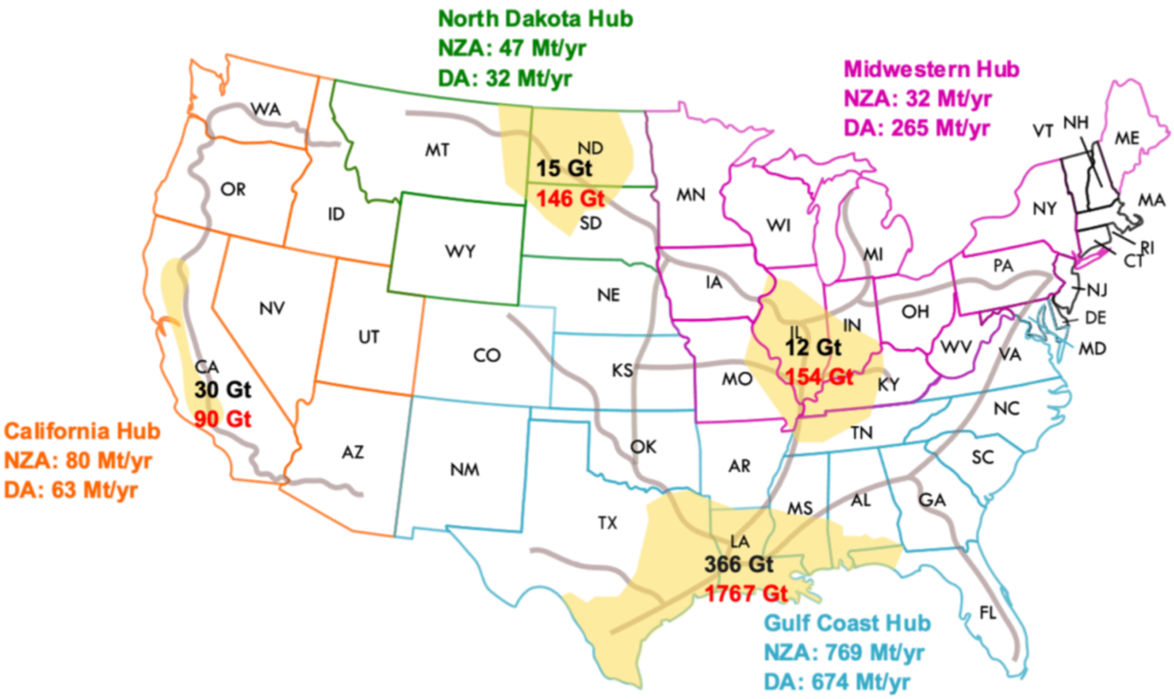


Figure 2: A map of the United States showing the regional conservative estimates (bold black text) and the first order estimates (bold red text) of storage resource in the US. All annual storage demands are for 2050. Pink, green, orange, and blue outlines the states included in the Midwestern, North Dakota, California, and Gulf Coast Hub, respectively. These states are determined based on the connectivity of the pipeline (light brown lines). Yellow polygons indicate major storage resource locations analysed by the USGS[8] national assessment of geologic carbon storage resources.

Table 2: Regional CO_2 storage scenarios for the US from two reports: Net Zero America, and Decarb America. The aggregated storage rate demand is shown associated to a particular storage hub.

Report	Storage rate demand [$MtCO_2\ yr^{-1}$]	Storage hub
Net Zero America E+ Scenario	47	North Dakota
	33	Midwestern
	769	Gulf Coast
	80	California
Decarb America High Electrification	32	North Dakota
	265	Midwestern
	674	Gulf Coast
	63	California

2.4 Constraints on logistic growth models and trade-offs

The first constraint is the starting point of the trajectory, which we take to be cumulative storage in 2030. We make use of the stated capture capacity for projects that are listed in the 2020 Global status report by the Global CCS Institute[7] and the database by the International Oil and Gas

Climate Initiative[39] to estimate cumulative storage reached by 2030. These projects include both operational and planned CCS activities. Cumulative storage by 2030 is the first constraint for our growth model scenarios (Figure 3). For national scenarios, cumulative storage identified for 2030 is rounded up to 1 Gt. For the individual regional hubs these are: 0.011 Gt by 2030 for California, 0.46 Gt by 2030 for North Dakota, 0.12 Gt by 2030 for Midwestern, and 0.36 Gt by 2030 for Gulf Coast.

The second constraint used is the modelled storage deployment in 2050 outlined in the Net Zero America, Carbon Neutral Pathway, Long-term Strategy, and Decarb America reports (Figure 3)[3,4,5,6]. Deployment can be given in terms of injection rate or cumulative storage. For each deployment, we analyse a range of minimum initial growth rates subject to total storage resource constraints from the practicable storage resource estimate of Teletzke et al. 2018[10] or the larger storage resource estimates of the USGS[8]. In the national models, we also evaluate the potential for the Gulf Coast to act as a national hub, serving the entire national demand for CO_2 storage, by constraining the growth trajectories with a storage resource total of 366 Gt. Storage resource assessments are inherently uncertain between one and two orders of magnitude[16]. Thus, we additionally analyse a range of growth trajectories that depend on the storage resource available more conservatively, only allowing 10% of current estimates of storage resource available in the US and Gulf Coast. These various storage resource estimates provide the third constraint for the model (Figure 3).

In our model, growth is near exponential up to the first inflection point on the rate curve. To emphasise that these trajectories are not predictive, we show dashed lines for the trajectory beyond this inflection year (Figure 3). Once we have identified individual trajectories meeting storage scenarios, we reformulate the information into graphs showing the tradeoff inherent in the model between early growth rate and storage resource requirements (Figure 3). Identifying the location of proposed scenarios on this graph allows for the rapid identification of the plausibility of scenarios and their limitations with respect to both available storage resources and the initial growth rate in the scaleup. At extreme ends of the curves, scenarios can be identified as either limited by storage resource availability or the rates of annual exponential growth required to achieve a scenario.

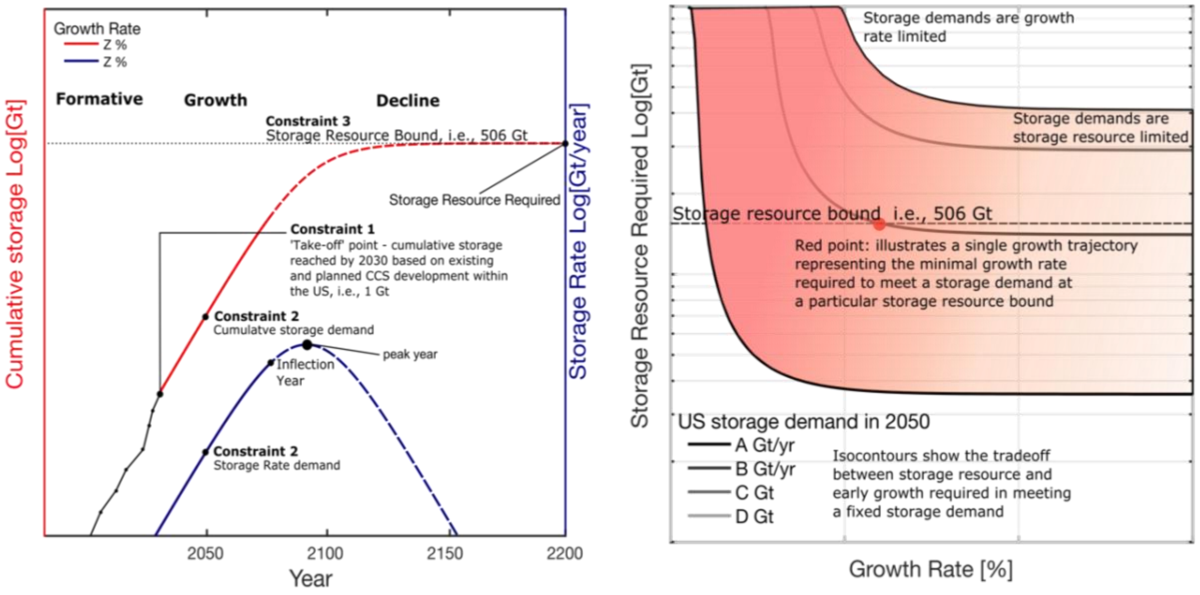


Figure 3: (left) Schematic plot illustrating the constraints and key features of the logistic modelling framework using an exemplary growth trajectory of Z%. Equation 1 describes the cumulative storage of CO_2 (red), and Equation 2 describes the annual CO_2 injection rate (blue). Black dots represent the cumulative storage from existing and planned CCS facilities (Right) Explementary plot illustrating the trade-off relationship between storage resource requirement and early growth rate. The gradational colour change indicates an evolution of the storage demand from growth rate limited (pink) to storage resource limited (white). Note that the plots are for illustrative purposes, numbers are not included for the logarithmic vertical axes and the horizontal axes are linear.

3 RESULTS & DISCUSSION

3.1 Net Zero America National Scenarios

We show short-term cumulative storage and storage rate trajectories at a range of rates from 11% to 20%, from 2030 onwards to meet published CO_2 storage demands of the E+, E- and E+RE- scenarios from the Net Zero America report (Figure 1). To achieve the cumulative storage projections of 10 Gt in the E+ scenario, considering the availability of the entire conservative storage resource of the US (506 Gt), the minimum annual exponential growth in injection rate required is 11.9% (cyan curve in Fig.4). For the more ambitious scenarios of E- (17 Gt) and E+RE- (20 Gt), the minimum growth rates required are 14.2% and 15.5%, respectively (light yellow and light green curves in Fig.4, respectively). Alternatively, with an increase of <0.1% for each minimum growth rate identified, the associated cumulative storage demands can be supported by the storage resource estimated to be available in the Gulf Coast alone (366 Gt). Achieving the trajectories is still possible when constraining the US storage resource base to only 10% of current estimates, but much higher growth rates are required, of at least 12%, and up to 20%, to meet the cumulative storage demands of E+, E- and E+RE- by 2050 (Figure 4).

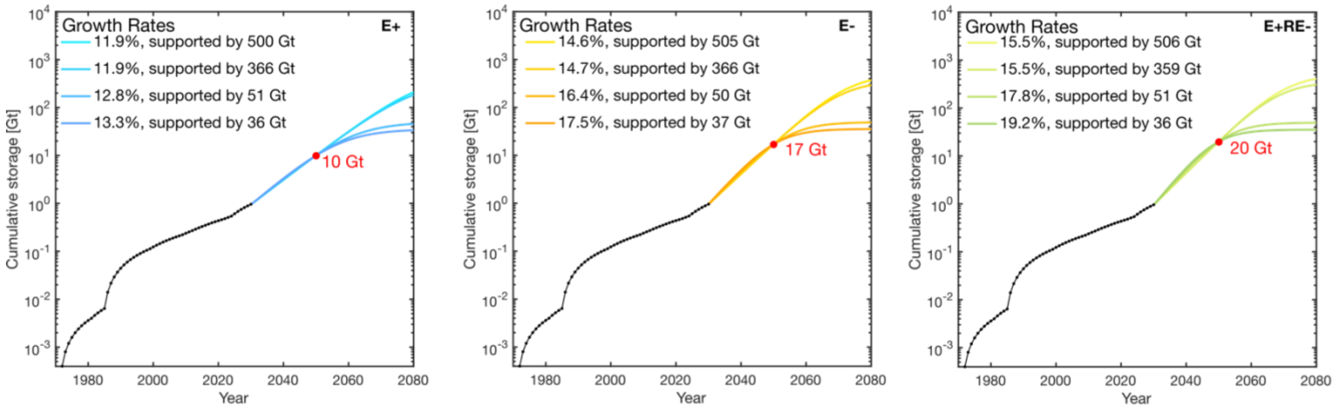


Figure 4: Cumulative CO_2 storage plot as a function of time for three Net Zero America scenarios to meet 2050 cumulative storage demands (10 Gt; 17 Gt; 20 Gt; red points). Cumulative CO_2 injection based on existing and planned CCS facilities is indicated by black markers. We compare the range of growth rates required to meet storage demands at four storage resource bounds of 506 Gt (conservative estimate of the US), 366 Gt (conservative estimate of the Gulf Coast), and 10% of each estimate. Model parameters are summarised in Table 3.

Generally, growth rates needed to meet the storage rate demand of E+ (0.9 Gt yr^{-1}), E- (1.5 Gt yr^{-1}) and E+RE- (1.7 Gt yr^{-1}) for 2050 are lower than growth rates needed to meet the corresponding cumulative storage demands of each scenario, except for the E+RE- scenario (19.5% of growth supported by 10% of the storage resources available in the Gulf Coast; Figure 5).

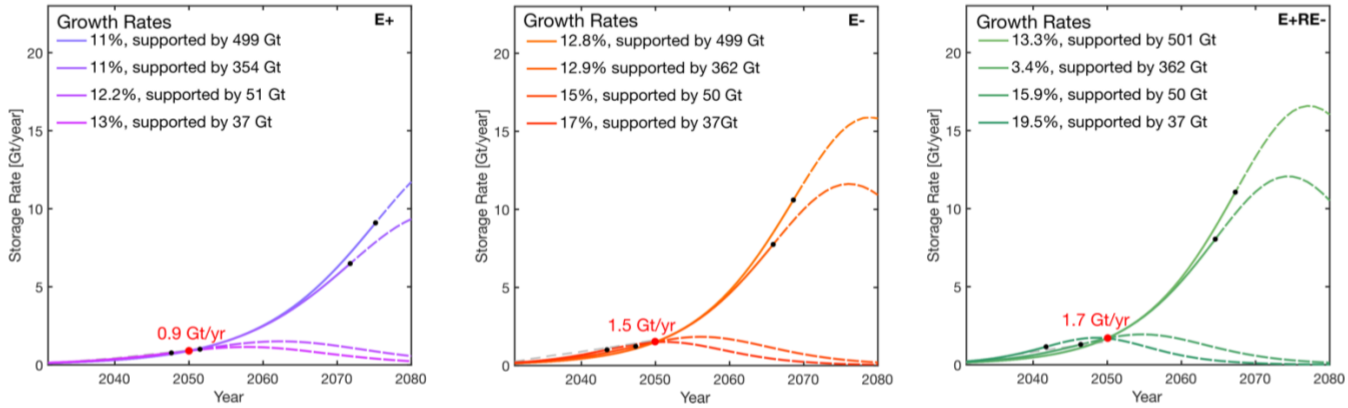


Figure 5: Plot showing the CO_2 storage rate as a function of time for Net Zero America scenarios to meet storage rate demands for 2050 (0.9 Gtyr^{-1}; 1.5 Gtyr^{-1}; 1.7 Gtyr^{-1}; red points). The legend shows the logistic curve growth rate from 2030 onwards and the necessary storage resource required to support that growth at various storage resource bounds. The grey dash lines illustrate the modelled pathway in the Net Zero America report for each scenario. Model parameters are summarised in Table 3.

Growth rates identified that can meet both the cumulative and annual storage demands for these three scenarios are within a similar range, between 13% - 18%. A summary of the results from Net Zero America scenarios are provided in Table 3.

Table 3: A summary of modelled growth trajectories and storage resource requirements which corresponds to coloured lines in Fig.4 and 5.

Scenario	*Growth rate [%]*	*Storage resource required [Gt]*	*Demand achieved*
E+	11.9	500	10 Gt
	11.9	366	10 Gt
	12.8	51	10 Gt
	13.3	36	10 Gt
E-	14.6	505	17 Gt
	14.7	366	17 Gt
	16.4	50	17 Gt
	17.5	37	17 Gt
E+RE-	15.5	506	20 Gt
	15.5	359	20 Gt
	17.8	51	20 Gt
	19.2	36	20 Gt
E+	11	499	0.9 Gt yr^{-1}
	11	354	0.9 Gt yr^{-1}
	12.2	51	0.9 Gt yr^{-1}
	13	37	0.9 Gt yr^{-1}
E-	12.8	499	1.5 Gt yr^{-1}
	12.9	362	1.5 Gt yr^{-1}
	15	50	1.5 Gt yr^{-1}
	17	37	1.5 Gt yr^{-1}
E+RE-	13.3	501	1.7 Gt yr^{-1}
	13.4	362	1.7 Gt yr^{-1}
	15.9	50	1.7 Gt yr^{-1}
	19.5	37	1.7 Gt yr^{-1}

Meeting combined storage demands

Scenario	Growth rate [%]	Storage resource required [Gt]	Demand achieved
E+	13.6	30	10 Gt & 0.9 Gt yr^{-1}
E-	17.7	36	17 Gt & 1.5 Gt yr^{-1}
E+RE-	18.3	38	20 Gt & 1.7 Gt yr^{-1}

3.2 Carbon Neutral Pathway National Scenarios

Cumulative storage demands ranging from 4-6 Gt, and storage rate demands ranging from 0.3-0.7 Gt yr^{-1} by 2050, are outlined in the Carbon Neutral Pathway analysis[4] (Table 1). We show minimum annual exponential growth rates between 7%-10% are required from 2030 onwards, depending on various storage resource constraints to meet the demands of the central scenario (4 Gt by 2050), delayed electrification and low land scenario (5.5 Gt by 2050), and the net negative scenario (4.7 Gt by 2050). Similarly, to meet storage rate demands of 316 $MtCO_2\ yr^{-1}$ – 680 $MtCO_2\ yr^{-1}$, a range of initial growth rates of 7% - 11% are needed subject to various storage resource constraints (Additional figures are provided in the Supporting Information). Figure 6 shows the illustrative plot of cumulative storage and storage rate trajectories modelled for the Central scenario. Only the delayed electrification scenario has a trajectory (growth rate of 10%) that meets both the cumulative and annual storage demand. Our modelling framework could not fit growth trajectories constrained by both modelled annual storage and cumulative demands within the scenarios of central, low land, and net negative. A summary of the outcomes is provided in Table 4.

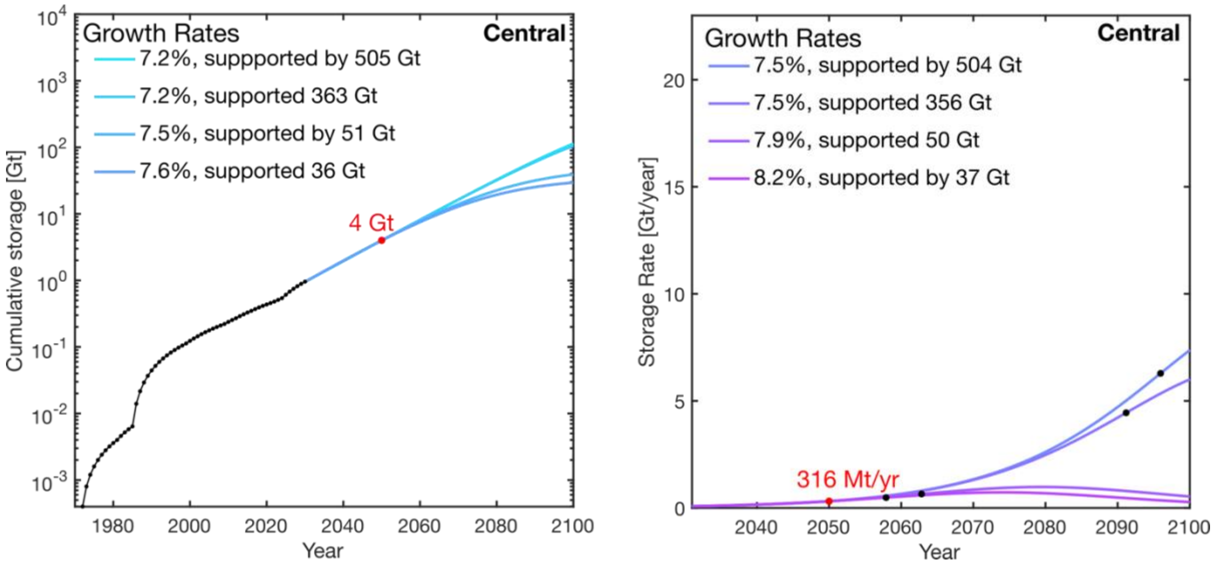


Figure 6: (Left) CO_2 cumulative storage for Central scenario from Carbon Neutral Pathway report. (Right) Plot of corresponding CO_2 storage rate as a function of time for Central scenario to meet an associated storage demand of 316 Mt yr^{-1} by 2050. Within each plot, we compare the necessary growth rate required to meet the modelled storage demand for 2050 constrained at various storage resource bounds. Model parameters are summarised in Table 4.

Table 4: Growth model parameters of the Central scenario from Carbon Neutral Pathway report corresponding to lines in Fig.6. N/A denotes scenarios where the logistic model could not fit the combined storage constraints.

Scenario	*Growth rate [%]*	*Storage resource required [Gt]*	*Demand achieved*
Central - cumulative	7.2	505	4 Gt
	7.2	363	4 Gt
	7.5	51	4 Gt

	7.6	36	4 Gt
Central – storage rate	7.5	504	316 Mt yr^{-1}
	7.5	356	316 Mt yr^{-1}
	7.9	50	316 Mt yr^{-1}
	8.2	37	316 Mt yr^{-1}
	Meeting combined storage demands		
Scenario	Growth rate [%]	Storage resource required [Gt]	Demand achieved
Central	N/A	N/A	4 Gt & 316 Mt yr^{-1}
Delayed electrification	10.5	18	5.5 Gt & 380 Mt yr^{-1}
Low land	N/A	N/A	5.5 Gt & 680 Mt yr^{-1}
Net negative	N/A	N/A	4.7 Gt & 465 Mt yr^{-1}

3.3 Long-Term Strategy National Scenarios

Three storage rate scenarios ranging from 0.78 – 1.04 GtCO$_2$ yr^{-1} are projected as part of the Long-Term Strategy of the US to reach net-zero greenhouse gas emission by 2050[6]. We show storage resource-constrained, minimum growth rates between 10.4% - 13.8% are required to meet these projections (Figure 7). Within each scenario, to meet a given storage projection, higher growth rates are required to compensate for the constrained storage resource available. Furthermore, across scenarios, given the same storage resource constraint, higher storage rate projections require higher growth rate to be achieved from 2030. A summary of the outcomes is provided in Table 5.

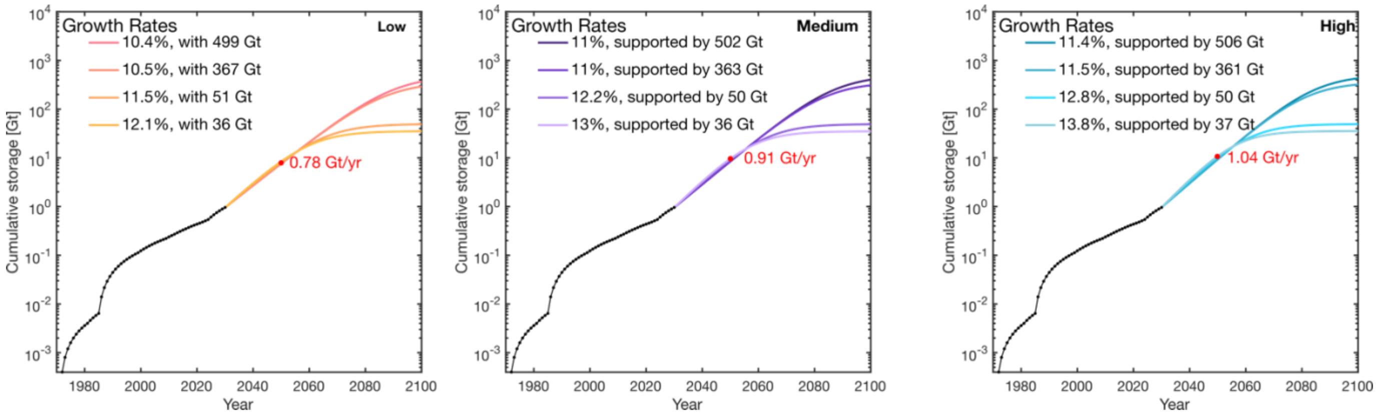


Figure 7: Cumulative CO$_2$ storage plot as a function of time for Long-Term Strategy scenarios to meet 2050 storage rate projections (0.78 Gt yr^{-1}; 0.91 Gt yr^{-1}; 1.04 Gt yr^{-1}; red points). Cumulative CO$_2$ injection based on existing and planned CCS facilities is indicated by black markers. We compare the range of growth rates required to meet storage demands at four storage resource bounds of 506 Gt (conservative estimate of the US), 366 Gt (conservative estimate of the Gulf Coast), and 10% of each estimate. Model parameters are summarised in Table 5.

Table 5: Growth model parameters of three storage rate scenarios from the Long-Term Strategy report corresponding to lines in Fig.7.

Scenario	*Growth rate [%]*	*Storage resource required [Gt]*	*Projection achieved [Gt yr^{-1}]*
Low	10.4	499	0.78
	10.5	367	0.78
	11.5	51	0.78
	12.1	36	0.78
Medium	10.97	502	0.91
	11	363	0.91
	12.2	50	0.91
	13	36	0.91
High	11.4	506	1.04
	11.5	361	1.04
	12.8	50	1.04
	13.8	37	1.04

3.4 Comparison of National Scenarios: Net Zero America, Carbon Neutral Pathway, and Long-Term Strategy

The tradeoff graph illustrated in Figure 8 compares published scenarios from the Net Zero America and Carbon Neutral Pathway analyses with the projections outlined in the Long-Term strategy report. The three grey regions indicate the range of isocontours with combinations of early growth and storage resource requirements that meet 2050 storage projections. The points indicate minimum growth scenarios modelled in Figure 4, 5, 6, and 7 that are bounded by the practicable storage resource estimate for the US (506 Gt) and the Gulf Coast (366 Gt)[10]. We explore uncertainty in the resource base by identifying further growth rates constrained by a resource base that is an order of magnitude greater and less than the practicable estimates (37 - 3660 Gt for the Gulf Coast, 51 - 5050 Gt for the US). These bounds are illustrated by solid bold lines and points, respectively (Figure 8).

From the perspective of storage resource availability, all projections from reports are feasible. The minimum storage resource base required to accommodate any potential scenario is 5 Gt, with at least 37 Gt of storage resources being required for all CO_2 storage projections to be viable. This is outside the uncertainty range of current conservative storage resource base estimates in the US.

On the other hand, all scenarios to meet Net Zero America demands located along the horizontal line of 506 Gt – the conservative storage resource estimated to be available in the US, require minimum sustained annual exponential growth of >10%, and up to 16%. This is comparable with the range of growth trajectories identified to meet European CO_2 injection projections[17].

Overall, it is evident that all scenarios are growth rate limited – the growth rate requirements are driven by 2050 storage scenarios and are not limited by the storage resource available. In other words, increasing the storage resource base does not significantly affect the growth rate required to achieve published scenarios; this is illustrated by the solid bold black lines in Figure 8 which represent the ranges of growth rates identified at storage resource bounds of 3660 Gt and 5060 Gt (an order of magnitude larger than current conservative estimates).

Impacts of storage resource limitations will emerge only if the available storage resource base is 10% or less of the current best conservative estimates of the storage resource base. In such a case, to achieve a given storage demand, a higher growth rate is required to compensate for the geological limitations; this is more apparent for storage demands from the Net Zero America report. In contrast, for the majority of the Carbon Neutral Pathway demands, growth rate requirements remain almost unchanged (<0.1% difference in growth rate) when storage resource is limited to 10% of current conservative estimates.

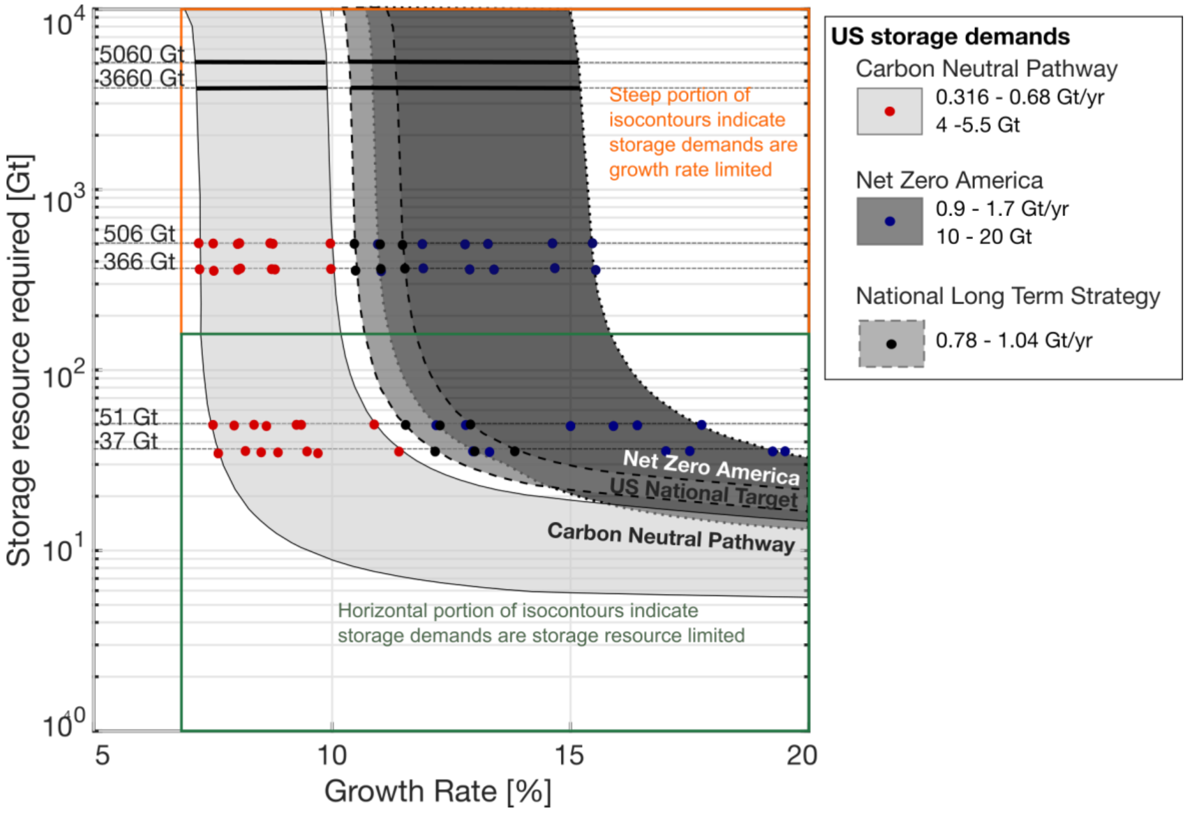


Figure 8: Trade-off between storage resource requirement and growth rates for 2050 US storage demands and scenarios illustrated with three ranges of isocontour bands. The points are coloured depending on the report where they originated and correspond to minimal growth rates subject to various storage resource constraints that we have investigated including 506 Gt (conservative estimate for the US), 366 Gt (conservative estimate for the Gulf Coast), as well as one order of magnitude higher and lower of these.

3.5 Comparison of regional scenarios: Net Zero America and Decarb America Hubs

The range of conceivable combinations of early growth rate and storage resource requirement to meet various regional scenarios of CO_2 storage demand are illustrated with isocontours in Figure 9. These points in Figure 9 represent minimum growth rates that are dependent on either the regional first order storage resource estimates (red text in Figure 9 based on USGS[8] estimate), conservative storage resource estimates (black text in Figure 9 based on Teletzke et al. 2018[10] estimate), or 10% of the conservative estimates (blue text in Figure 9) for each hub. The range of growth rate requirement from 2030 onwards illustrated in Figure 9is between 3% - 20%.

Comparing the regional storage rate demands by 2050 between the two reports, the Midwestern hub in the Decarb America scenario has a storage rate demand that is eight times more ambitious than the equivalent hub from the Net Zero America report. As a result, the dash-dot isocontour in Figure 9 representing the Midwestern hub shifts from the lower left quadrant in the Net Zero America regional tradeoff graph into the upper right quadrant in the Decarb America regional tradeoff plot. Thus, when constrained to the same storage resource bound of 154 Gt[8] and 12 Gt[10], the growth rate required to meet the demand increases by more than five percentage points.

We also identify that there is a miss-match between the outlined demands and the existing development of CCS technology for the California hub in both reports. California has no existing subsurface CO_2 storage operations, and the first project will only be in operation by 2025. As a result, California must reach an annual injection rate of 63 Mt yr^{-1} – 80 Mt yr^{-1} within a five-year window of this project starting to reach projections. Thus, the required scaleup rates are very demanding. On the other end of the scale, in both the Net Zero American and Decarb America report, storage demands of the North Dakota hub can be achieved with annual exponential growth as low as 3%. This is evidently more plausible than the scenarios identified for the California hub.

All regional storage rate demands are considered feasible from the perspective of available storage resources. The minimum storage resource base required for all storage rate demands to be viable is within the uncertainty bounds of the conservative storage resource estimate.

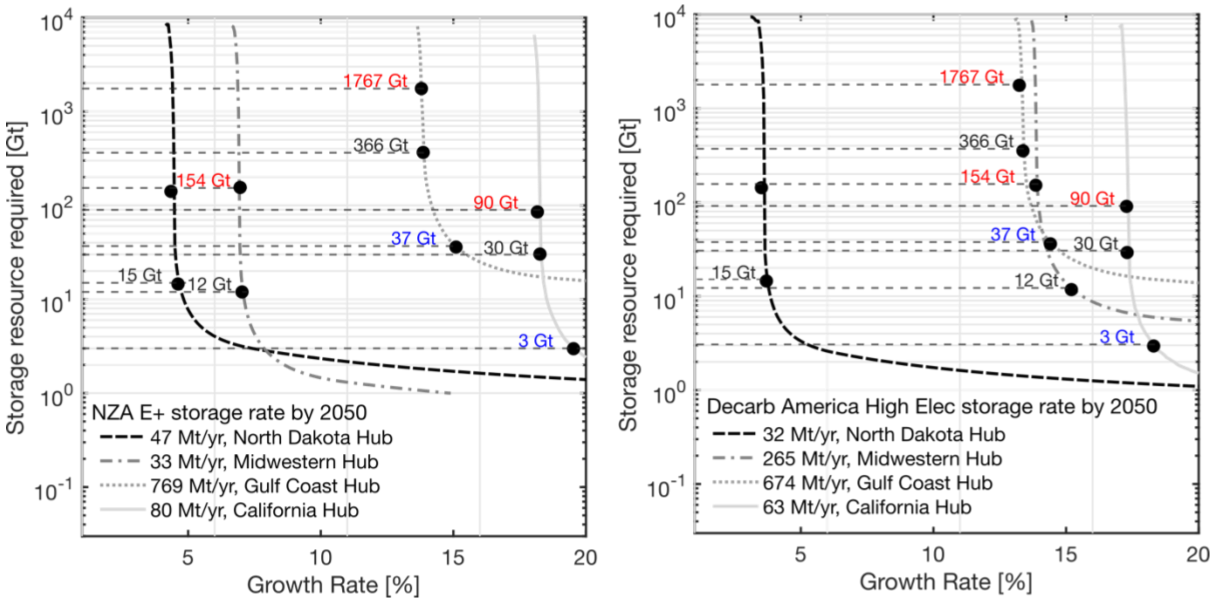


Figure 9: (Left) Trade-off between storage resource requirement and growth rates for four regional hubs meeting modelled demands analysed in the E+ scenario of the Net Zero America report for 2050. (Right) Tradeoff between storage resource requirement and growth rates for four regional hubs meeting modelled demands in the high electrification (E+) scenario from the Decarb America report. Coloured points represent minimal growth rates subject to various storage resource bounds: first order estimates for each hub are given in red text, the conservative estimate of each hub is given in black text, and 10% of the conservative estimate is given in blue text.

3.5 Implications

There is significant uncertainty in both reported and near term planned deployment of CCS. For example, for the US in 2020, there is an identifiable discrepancy of approximately 0.31 $MtCO_2$ between the stated capture capacity and estimated storage amounts for seven currently operational CCS projects[40]. Thus, the modelled growth rate requirements in this analysis establish a minimum criterion to reach proposed scenarios. Any delays or shortfalls in the envisioned CCS development plan for the US will ultimately demand more ambitious scaleup rates and a larger storage resource base to meet storage projections[17].

This analysis points towards the prospect of the Gulf Coast as serving as a national storage hub. A recent analysis translating the historical performance of well-development in the entire Gulf of Mexico as a proxy for growth to demonstrate the regional scaleup of CO_2 storage show the scale of engineering required for Gt-scale injection rates by mid-century is feasible[41]. In fact, a single 'Gulf of Mexico' equivalent development for CO_2 storage will be able to inject seven times the most ambitious scenario considered in this analysis in 2050 (1.7 Gt yr^{-1}). Additionally, storage resources in North Dakota, Midwestern region and California are useful to serve as regional storage hubs for local sources. However, as discussed above for California, there are challenging short-term growth trajectories required by 2030 to meet proposed storage demands.

The hydrocarbon industry provides one industrial analogue for evaluating the feasibility of growth trajectories for CO_2 storage. National oil production in the US achieved an annual exponential growth of 4% between 1925 and 1970[42]. Regionally, offshore oil production of crude oil in the Gulf of Mexico sustained annual exponential growth of merely 2% between 1981 and 2011[43]. In Europe, historical oil production in the UK continental shelf sustained an aggressive average annual growth rate at 120% over a 10-year period from 1974 before growth declined. In contrast, the Norwegian sector of the North Sea, and the Norwegian Sea and Barents Seas, collectively achieved average annual growth rate of 35% over a 20-year period commencing from 1974[44]. These rates are extraordinary in terms of its combined magnitude and duration, illustrating the impact that a mature industry may have in the acceleration of development in new areas. Regional historical experiences thus provide a precedent to the development of subsurface resources projected in the reports studied herein. It should be noted that the CO_2 storage industry has, however, neither the incentive structure nor maturity of the hydrocarbon industry. Achieving scaleup plans projected in these reports will require substantial increases in financial incentivisation for CO_2 storage (notwithstanding the 2022 enhancements of 45Q), the addressment of concerns surrounding long-term environmental liability currently limiting investment confidence, and advances in regulatory enablement including innovative permitting procedures to reduce the timescale from project conception to operation. Although distinct, regional historical oil production provides a snapshot of the market conditions that might be required to drive deployment of CCS to meet published storage scenarios of CO_2 in the US.

While significant opportunities have been identified in the Gulf Coast, challenges remain with aggregating state action for the cross-state border transportation of captured CO_2 and management of pipelines. The required pipeline network in the Net Zero America scenarios is potentially larger than the existing oil and gas pipe system[3]. The urgency of CCS scaleup and the role of the federal government in leading the steep delivery of CO_2 reduction is recognised by US policy makers. Actions to implement policy and regulatory packages to achieve near-term and long-terms goals are underway according to the long-term strategy report released by the US government[6] but the policy landscape is still inadequate for the envisioned storage demand in 2050. The results presented here identify incentivised growth as the key barrier to deployment in meeting climate change mitigation scenarios in the US, while also quantifying the abundance and identifying various geographies of the storage resource base.

ABBREVIATIONS

CCS – Carbon Capture and Storage

CO_2 – carbon dioxide

UNFCCC – United Nations Framework Convention on Climate Change

US – United States

SUPPORTING INFORMATION

Additional results including figures and table for the Carbon Neutral Pathway scenarios (PDF)

Additional raw data of current capture capacity from existing and planned CCS projects in the US (XLSX)

Additional MATLAB scripts for the generation of logistic analysis.

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DISCLOSURES

The authors declare no competing financial interest