CO_2 storage resource use trajectories consistent with US climate change mitigation scenarios

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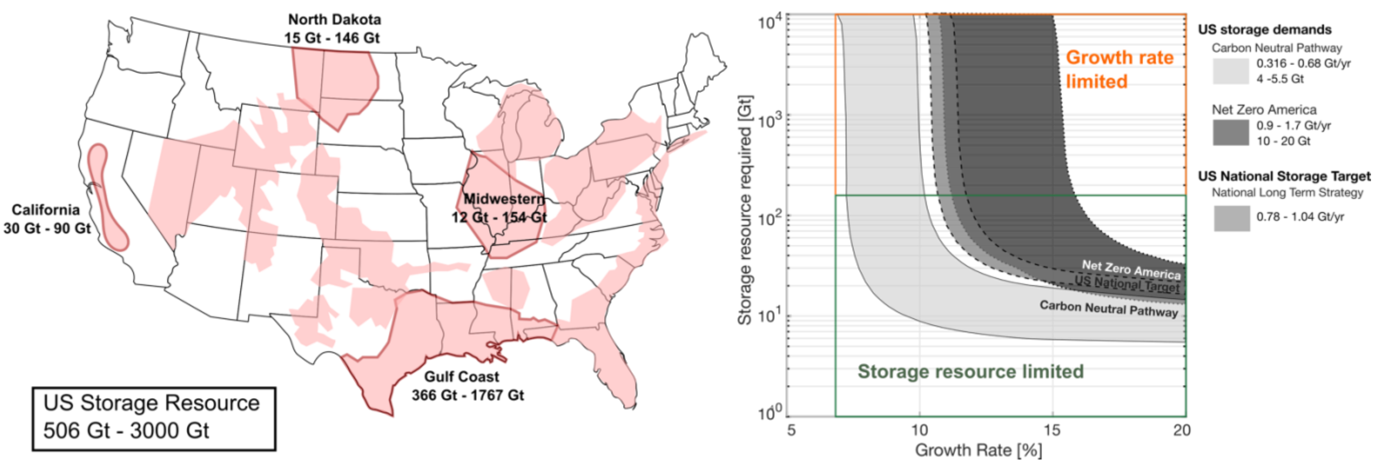
ABSTRACT

To help decarbonisation the United States, numerous techno-economic models have projected scenarios including CO_2 storage deployment at annual injection rates of 0.3 – 1.1 Gt yr^{-1} by 2050. However, these projections do not often include the availability of geological storage resource base and socio-economic factors that could limit the technological growth of CCS. Here, we apply a logistic modelling framework to evaluate CO_2 storage scenarios proposed in the Net Zero America, Carbon Neutral Pathways, and the Long-Term Strategy report. Our modelling framework allows us to analyse the feasibility of growth trajectories under constraints imposed by the associated storage resource availability. We show that scaleup is not limited by the availability of storage resources, given that the entire demand can be accommodated by the resources available in the Gulf Coast alone. Deployment trajectories require annual growth >10% nationally and between 3% - 18% regionally across four storage hubs. These scale-up rates are high relative to those characterising analogous, large-scale energy infrastructure projects (9%), 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 used herein.

KEYWORDS: Logistic 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. Logistical modelling shows deployment trajectories of CCS require historically high annual growth of >10% nationally.

GRAPHICAL ABSTRACT



INTRODUCTION

To mitigate climate change and limit global warming to <1.5 °C we need to reduce global greenhouse emissions to net-zero by mid-century[1]. In nearly all techno-economic model scenarios, carbon capture and storage (CCS) is considered necessary, injecting CO_2 underground at rates of gigatons per year by mid-century[1]. The United States is one of the top global emitters of CO_2 due to its heavy dependence on fossil fuel, satisfying 80% of its primary energy demand[2]. There is a commensurate scale to the global target of geologic CO_2 storage identified in recently published decarbonisation pathway models for the USA. For example, scenarios with up to 20 Gt of cumulative storage by 2050, with injection rates reaching nearly 2 Gt of CO_2 annually by 2050, have been outlined[3,4,5,6] (Figure 1; Table 1). These volumes are significant, noting that the envisioned scale for US CO_2 transport and storage is 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 for 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, accounting for geophysical considerations such as pressure increase upon injection, subsequent storage resource assessment suggests the onshore storage resource may be significantly less. For example, Teletzke et al.[10] estimate 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 initial first order estimates by the USGS[8] and DOE[9]. Nonetheless, this significantly downscaled resource base is still sufficiently abundant to sustain a large-scale CO_2 storage industry nationally.

There are, however, significant uncertainties surrounding the scaleup of CCS 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 base consumption in these models[14,15] . For example, the models underpinning the US technology roadmaps consider an upper limit on the available storage resource base and a maximum injection rate for CCS[3]. These single-value limits are inherently uncertain, and as a result, these constraints are insufficient to describe the development of subsurface storage sites. Despite current CO_2 storage resource estimates are rigorously assessed, these estimates typically range over two orders of magnitude[16]. The uncertainties in these estimates are driven by incentives and limitations to growth imposed by geophysical factors, i.e., injection limits due to pressure increase in the reservoir, and socio-economic factors, namely obtaining permits, financing, and public acceptance for CCS technology[17] .

In this work, we use a logistic growth model to identify plausible growth trajectories for the scaleup of subsurface CO_2 storage in the US consistent with national and regional CO_2 storage scenarios identified in three reports. Logistic models are widely used in analogous energy industries, and particularly the hydrocarbon industry[18,19,20,21,22]. 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 in serving as a national storage hub for the USA.

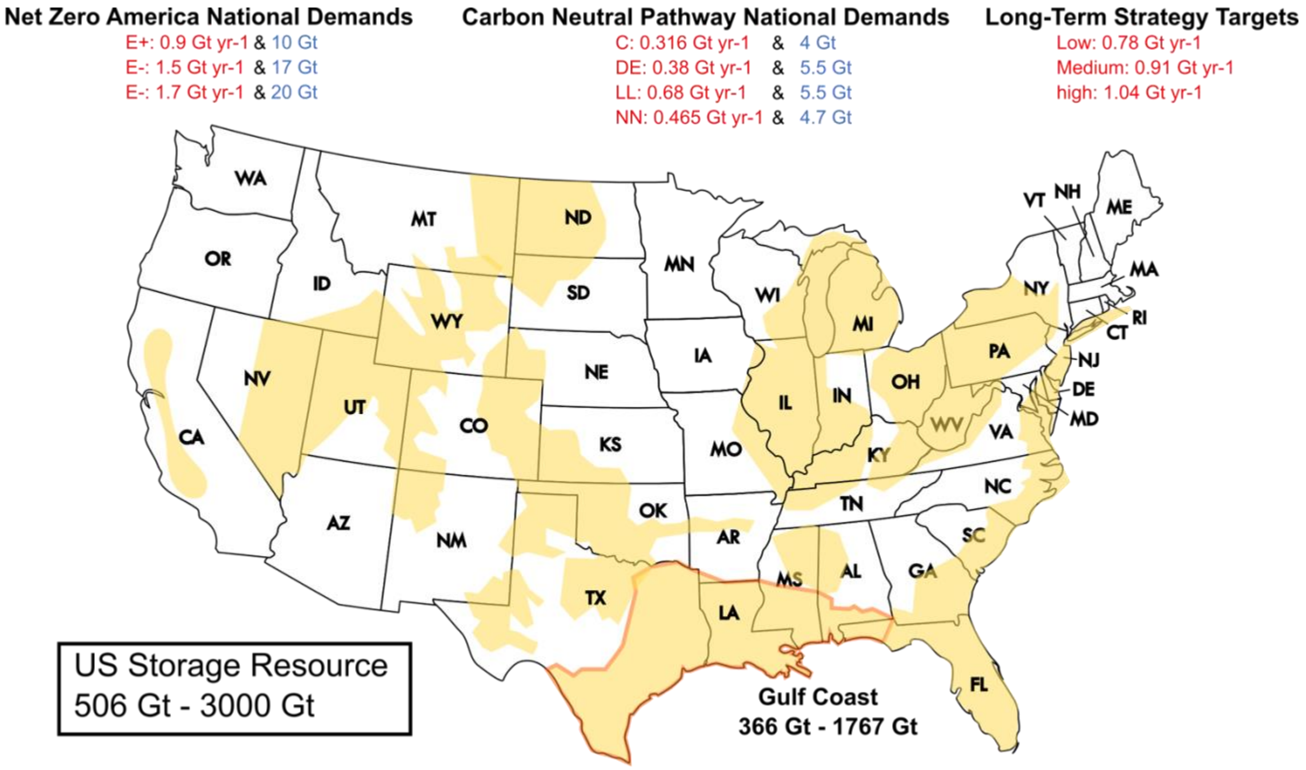


Figure 1: A map of the conterminous United States showing the storage resource available in the US and the gulf coast. The lower bounds are conservative estimates of storage resources by Teletzke et al.[10] whilst the upper bound is first order storage resource estimates made by the USGS[8]. Storage 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.[10]. Individual states are indicated by bold black text.

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/target and an associated cumulative storage demand for 2050 unless indicated otherwise.

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
		Storage rate target [$GtCO_2\ yr^{-1}$]	Cumulative storage target [Gt]
Long-Term Strategy	Low	0.78	N/A
	Medium	0.91	N/A
	High	1.04	N/A

MATERIALS & METHODS

2.1 Growth trajectories using the logistic modelling framework

The logistic model is one of many curve-fitting techniques to describe patterns of growth in natural resource consumption and it has been widely employed in various sectors across the energy and technology domain[23,24,25,20,26,27,28,29,30,31]. The S-shaped curve is characterised by three distinct phases: an initial formative phase of high cost and uncertainty where growth is unstable[32,21] is followed by a 'take off' point, defining when the reliable expansion of deployment begins, and a rapid exponential growth phase is supported by mechanisms of continued incentivisation and the exploration of new sites. Subsequently, geological constraints such as the complexity of reservoirs with poorer reservoir properties for storage begin to restrict growth, and eventually the exhaustion of resources is reached[17] (Figure 2).

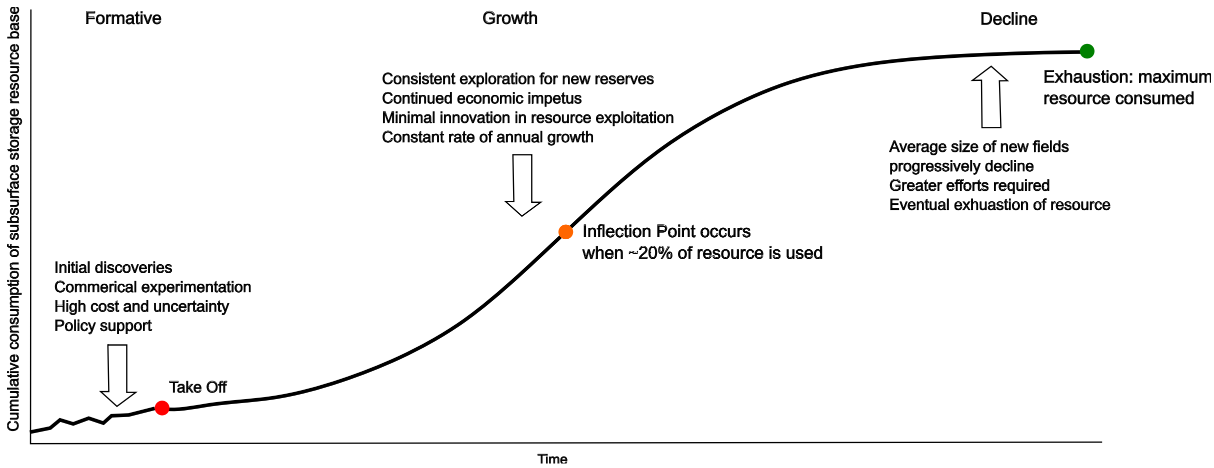


Figure 2: Mechanisms and phases characterising the consumption of subsurface storage resources. Modified from Cherp et al.[20].

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 early growth rate and storage resource base can be captured using the logistic model, unlike linear or purely exponential models that assumes indefinite resource consumption[16]. 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 determine the trajectories of CCS deployment. Subsequently, Zhang et al.[17] demonstrate the application of this model at a regional scale to evaluate the plausible growth scenarios and storage resource requirement of Europe. They further illustrate the robustness of this tool, and also recogise that there are both temporal and spatial limitations associated with this statisical approach[17]. As a result, in our analysis for the US, we avoid using the model to monitor storage demand targets that are earlier than 2050, and our geographical consideration extends only to the regional scale, avoiding the granularity of assessing storage development state-by-state.

The three-parameter, symmetric logistic growth model is given in Equation 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 phase of exponential growth rate, r [yr^{-1}]. Upon approaching the peak year, t_p [yr], growth rate begins to deviate significantly away from the exponential trend and becomes negative, until the storage resource base, C [Gt], is reached.

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

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

The first inflection point in the rate time series can be used as a time when growth has significantly fallen below exponential, and occurs in year t_n given by

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

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 that are supported by the maximum storage resource available.

2.2 National analysis model description

The United States' commitment to tackle 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 (The White House, 2020). 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 key studies[3,4,6].

The first group of national scenarios comes from the Net Zero America study, a Princeton University-based, 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 (Table 1; Figure 1; Larson et al. 2020).

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 target and an associated storage rate target for 2050 is outlined. For our purpose, we will 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[33]. 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 US storage resource base considered in the Net Zero America report was based on an analysis by Teletzke et al. (2018). In their assessment of storage resources, they applied a series of restrictions, including technical and cost-related filters to the initial USGS[8] first order estimate of storage resource (3000 Gt) and identified 506 Gt of storage resource. Both analyses show that the Gulf Coast Region contains a significant proportion of the total estimated storage resource available in the US: 366 Gt as the conservative estimate[10] and 1767 Gt as the first order estimate[8] On the other hand, the Carbon Neutral Pathway analysis did not include an upper limit for 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.

Despite the limited existing deployment of CCS technology globally, 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[34]. As of 2020, there are 13 operational projects reaching an annual capture capacity of 21 Mt CO_2 yr^{-1} in the US[7]. According to databases maintained by the Global CCS institute[7] and International Oil and Gas Climate Initiative[35], 22 new CCS projects in the US are being planned, with operational start dates before 2030. Presently, the overall CCS development in the US since 2000 is experiencing average annual growth of 9% in capture capacity, a rate that 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[36].

2.3 Regional analysis model description

In addition to outlining national storage demands, the Net Zero America study also provides granular, state-by-state technology portfolios[3]. Detailed state-level CO_2 transport infrastructure and storage systems were modelled for the E+ scenario. Figure 3 highlights the source-to-sink flows based on the modelled CO_2 pipelines from the Net Zero America study (light brown lines in Figure 3. 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 emission by 2050. In the Decarb America report, regional and state-level opportunities for a decarbonised economy are analysed. For comparison with the Net Zero America analysis, we aggregate state-level storage demands from the Decarb America report into four regional storage hubs based on the pipelines modelled by 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 for CO_2 storage site characterisation and from this, we selected four that had the most abundant storage resource available based on the conservative estimates[10]. These are California (30 Gt; bold black text in Figure 3), the Gulf coast (366 Gt), North Dakota (15 Gt), and Midwestern states (Illinois, Indiana, Kentucky, Tennessee, and Missouri; 12 Gt). We also include USGS' first order estimates for each hub (bold red text in Figure 3) 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.

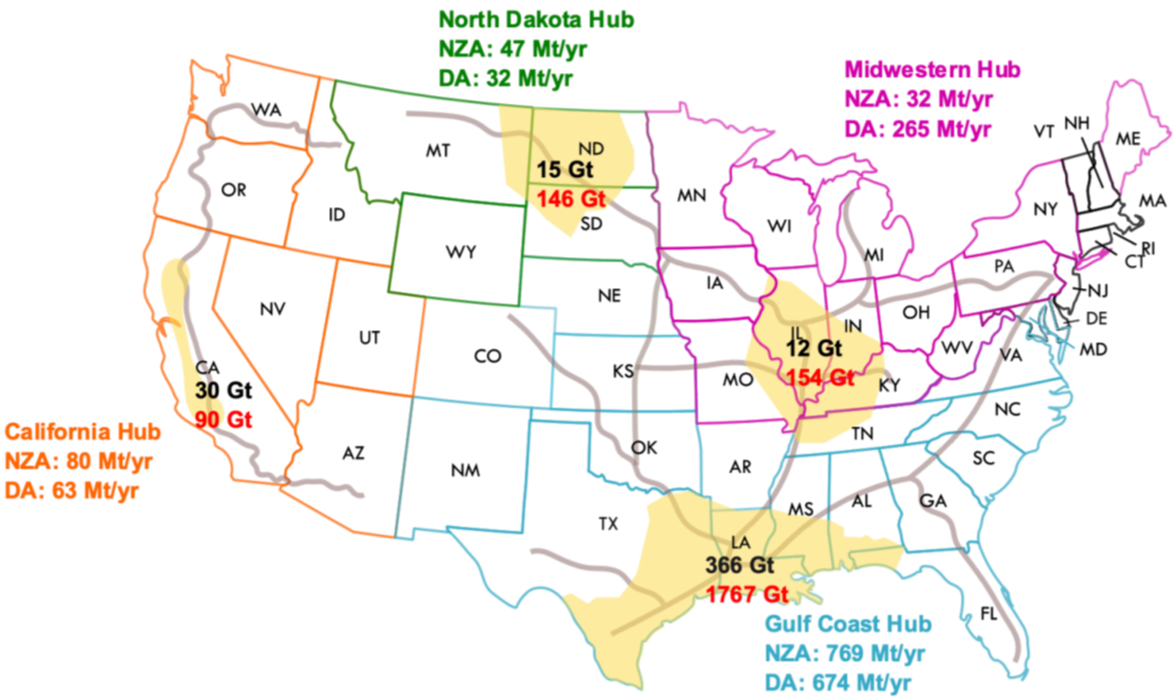


Figure 3: A map of the United States showing the regional conservative estimates (bold black text) and the first order estimates (bold red text) of storage resource in the US. All annual storage demands are for 2050. Pink, green, orange, and blue outlines the states included in the Midwestern, North 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.

2.4 Constraints on logistic growth models and trade-offs

We make use of the stated capture capacity for projects that are listed in the 2020 Global status report by the Global Institute of CCS[7] to compile cumulative storage reached by 2030, noting these projects can be both operational and planned CCS activities within a particular region. Cumulative storage by 2030 is the first constraint for our growth model scenarios; for national scenarios, cumulative storage identified for 2030 is 1 Gt and for the 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 storage demand by 2050 outlined in the Net Zero America, Carbon Neutral Pathway, Long-term Strategy, and Decarb America reports which can be an injection rate *or* cumulative storage. For each storage demand, we analyse a range of minimum growth rates that are supported by the conservative storage resource estimate of Teletzke et al.[10] or the first order storage resource estimate of USGS[8]. In the national models, we also evaluate the capability for the Gulf Coast to act as a national hub, serving the entire national demand for CO_2 storage alone, by constraining the growth rates at the storage resource bound of 366 Gt. Current 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 conservative estimates of storage resource available in the US and Gulf Coast. Therefore, storage resource estimates provide the third constraint. In our logistic model, growth is near exponential up to an inflection point. To emphasise that these trajectories are not predictive, we provided dashed lines for the decline trajectory beyond the inflection year (Figure 4).

Once we have identified individual trajectories of interest in meeting storage scenarios, we compile the tradeoff curves between early growth rate and storage resource requirement for targets onto a single graph (Figure 4). This provides more general information about the plausibility of the targets and allows us to explore the extent to which varying storage resource availability enhances or diminishes the viability of potential CO_2 storage demand in the US.

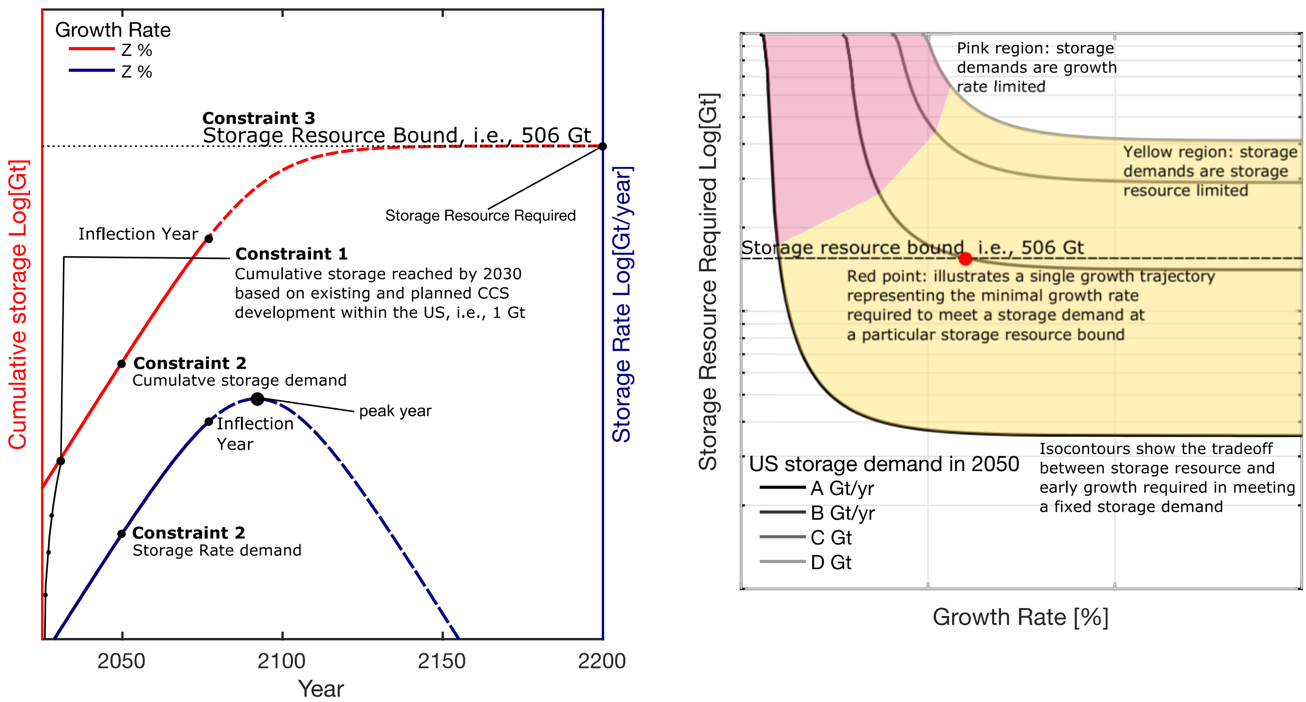


Figure 4: (left) Schematic plot illustrating the constraints and key features of the logistic modelling framework using an exemplary growth trajectory of Z%. Equation 1 describes the cumulative storage of CO_2 (red), and Equation 2 describes the annual CO_2 injection rate (blue). Black dots represent 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. 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 here 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 target of 10 Gt in the E+ scenario, considering the availability of the entire conservative storage resource of the US (506 Gt), the minimum annual 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.5, 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). Constraining the dependence on the US storage resource base to only 10% of current estimates of the entire region or the Gulf Coast illustrates that much higher growth rates of at least 12%, and up to 20% are required to meet the cumulative storage demands of E+, E- and E+RE- by 2050 (Figure 5).

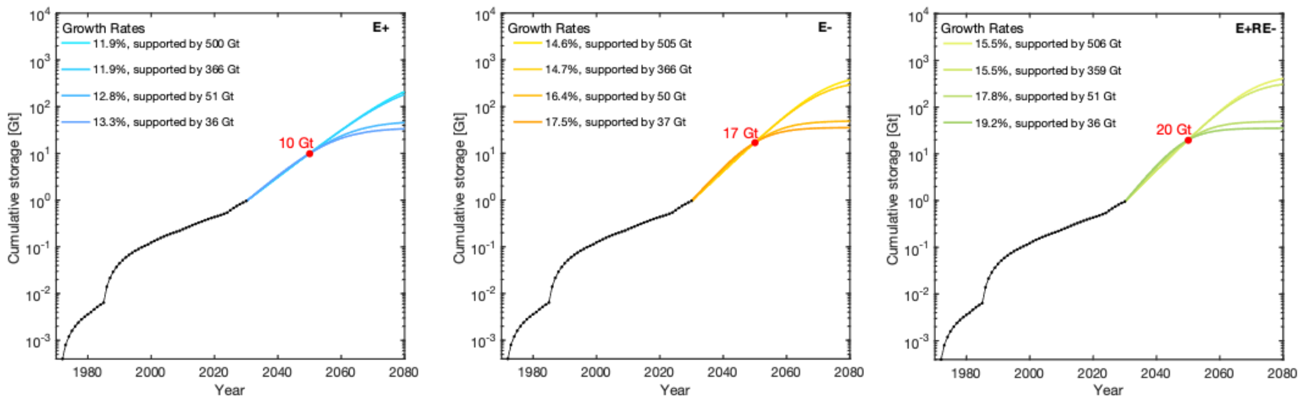


Figure 5: Cumulative CO_2 storage plot as a function of time for Net Zero America scenarios to meet 2050 cumulative storage demands (10 Gt; 17 Gt; 20 Gt; red points). Cumulative CO_2 injection based on existing and planned CCS facilities is indicated by black markers. We compare the range of growth rates 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 2.

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). All growth rates identified in Figure 6 are within a similar range, between 11%-20%. A summary of the results from Net Zero America scenarios are provided in Table 2.

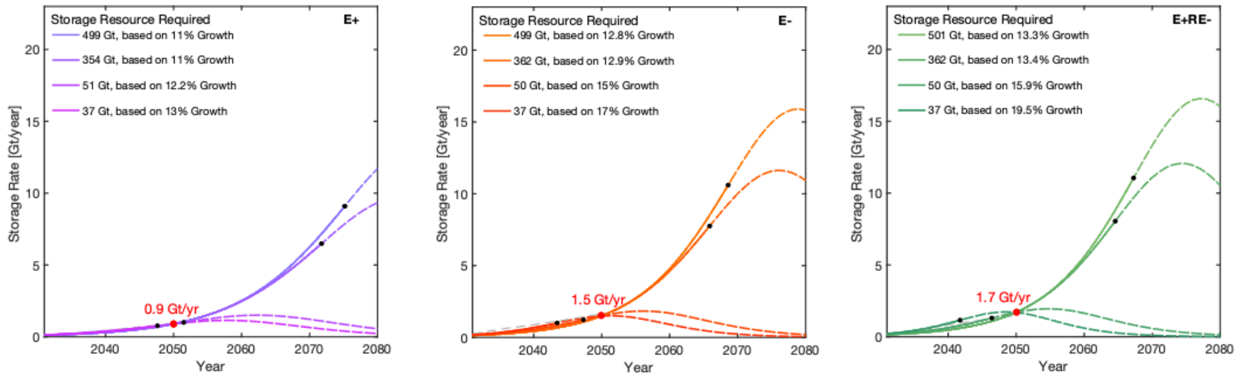


Figure 6: Plot showing the CO_2 storage rate as a function of time for Net Zero America scenarios to meet storage rate demands for 2050 (0.9 $Gtyr^{-1}$; 1.5 $Gtyr^{-1}$; 1.7 $Gtyr^{-1}$; red points). The legend shows the logistic curve growth rate from 2030 onwards and the necessary storage resource 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 2.

Table 2: A summary of modelled growth trajectories and storage resource requirements which corresponds to coloured lines in Fig.5 and 6.

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}

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 (Williams et al. 2020; Table 1). We show minimum annual 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 Appendix). Figure 7 shows the illustrative plot of cumulative storage and storage rate trajectories modelled for the Central scenario. A summary of the outcomes is provided in Table 3.

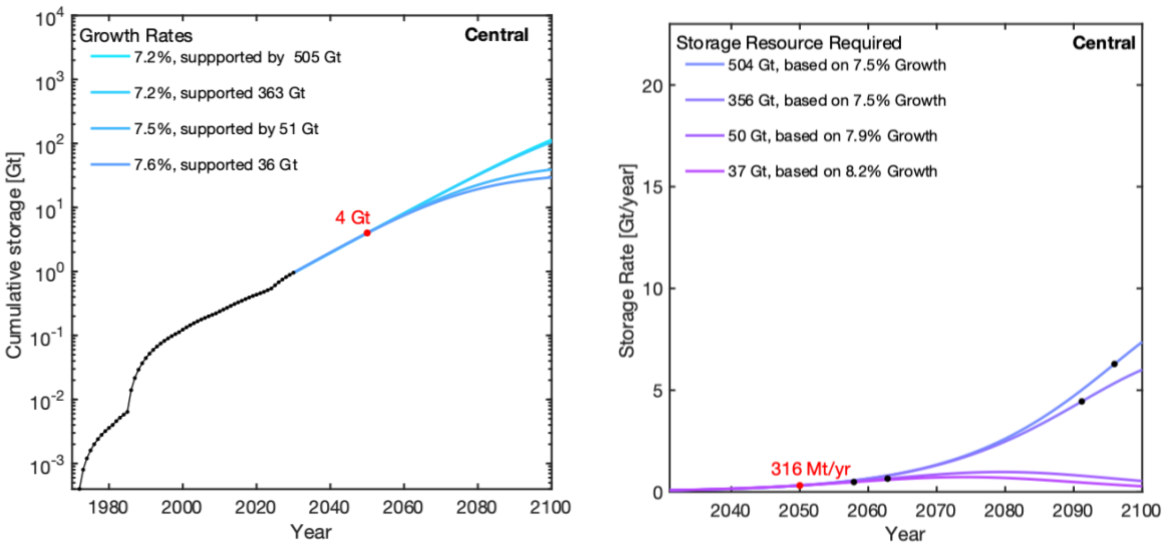


Figure 7: (Left) CO_2 cumulative storage for Central scenario from Carbon Neutral Pathway report. (Right) Plot of corresponding CO_2 storage rate as a function of time for Central scenario to meet an associated storage demand of 316 Mt yr^{-1} by 2050. Within each plot, we compare the necessary growth rate required to meet the modelled storage demand for 2050 constrained at various storage resource bounds. Model parameters are summarised in Table 3.

Table 3: Growth model parameters of the Central scenario from Carbon Neutral Pathway report corresponding to lines in Fig.7.

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

	7.5	51	4 Gt
	7.6	36	4Gt
Central –	7.5	504	316 Mt yr^{-1}
storage rate	7.5	356	316 Mt yr^{-1}
	7.9	50	316 Mt yr^{-1}
	8.2	37	316 Mt yr^{-1}

3.3 Long-Term Strategy National Scenarios

Three storage rate target scenarios ranging from 0.78 – 1.04 GtCO$_2$ yr^{-1} are proposed as part of the Long-Term Strategy of the US to reach net-zero greenhouse gas emission by 2050[6]. From 2030 onwards, we illustrate storage resource-constrained, minimum growth rates between 10.4% - 13.8% are required to meet these targets (Figure 8). Within each scenario, we show that to meet the same storage target, 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 targets require higher growth rate to be achieved from 2030.

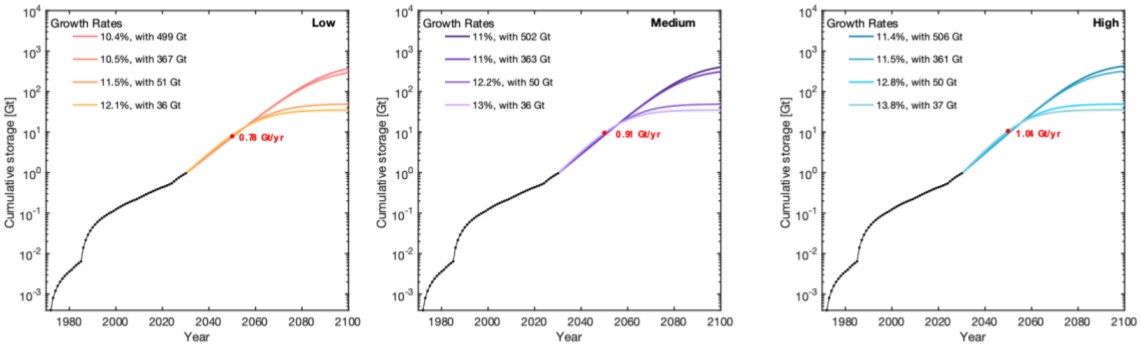


Figure 8: Cumulative CO$_2$ storage plot as a function of time for Long-Term Strategy scenarios to meet 2050 storage rate targets (0.78 Gt yr^{-1}; 0.91 Gt yr^{-1}; 1.04 Gt yr^{-1}; red points). Cumulative CO$_2$ injection based on existing and planned CCS facilities is indicated by black markers. We 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 4.

Table 4: Growth model parameters of three storage rate target scenarios from the Long-Term Strategy report corresponding to lines in Fig.8.

Scenario	*Growth rate [%]*	*Storage resource required [Gt]*	*Target 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

From the perspective of storage resource availability, all targets from both reports are feasible. The minimum storage resource base required to accommodate any potential target scenario is 5 Gt, with at least 37 Gt of storage resources being required for all CO_2 storage plans to be viable. This is outside the uncertainty range of current conservative storage resource base estimates in the US. The tradeoff graph illustrated in Figure 9 compares published scenarios from the Net Zero America and Carbon Neutral Pathway analyses with the targets 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 targets. The points indicate minimum growth scenarios modelled in Figure 5, 6 and 7 that are bounded by the conservative storage resource estimate for the US (506 Gt) and the Gulf Coast (366 Gt)[10]. Further growth rates are identified at additional boundaries that are an order of magnitude greater than current conservative estimates (3660 Gt and 5050 Gt) aligning with USGS/DOE' first order estimates[8], and at 10% of conservative estimates of Teletzke et al[10]. (51 Gt and 37 Gt), which are illustrated by solid bold lines and points, respectively.

On the other hand, all minimum growth 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, are >10%, and up to 16%. This is comparable with the range of growth trajectories identified to meet European CO_2 injection targets[17]. They suggested that to achieve and sustain such growth rates, significant incentivisation is required to mobilise wartime-like supply chain and manufacture capacity. 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 thick 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 limitation 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 the same storage demand, a higher growth rate is required to compensate for the geological limitation; 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.

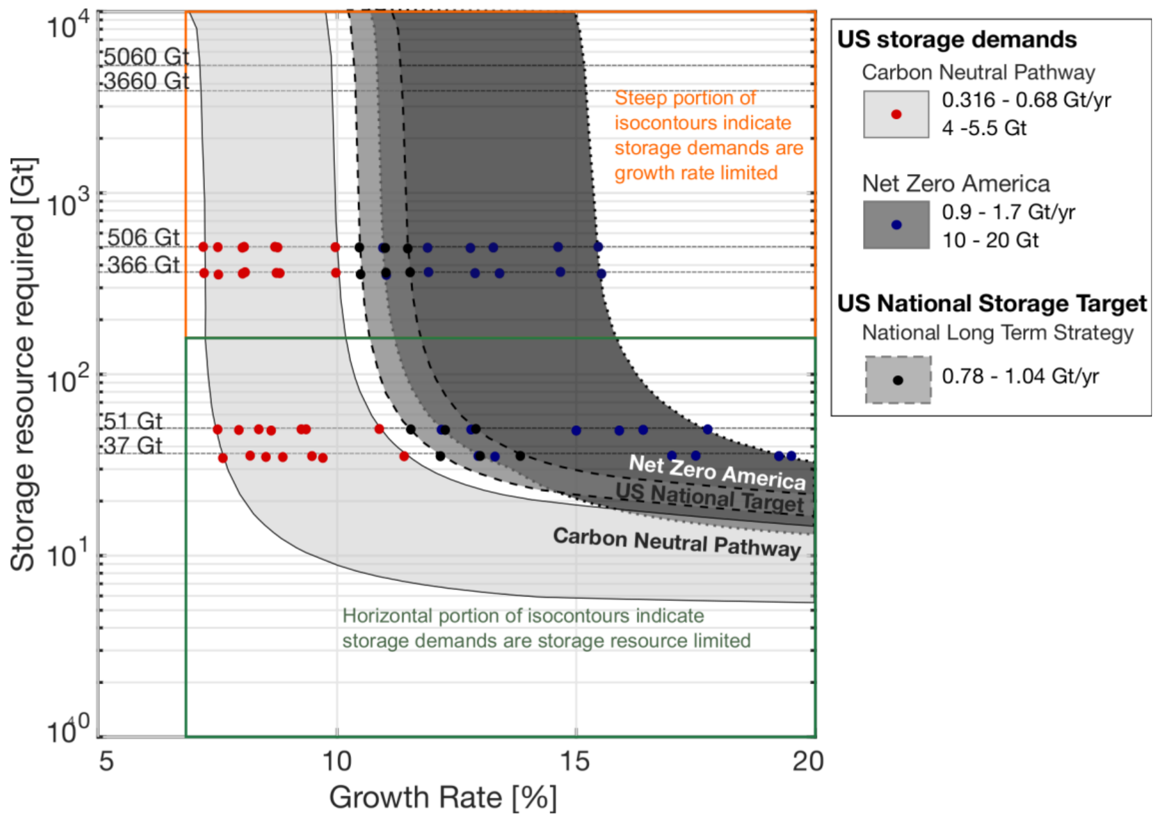


Figure 9: Trade-off between storage resource requirement and growth rates for 2050 US storage demands and targets illustrated with three ranges of isocontour bands. The coloured points correspond to minimal growth rates subject to various storage resource constraints that we have investigated including 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 10. These points in Figure 10 represent minimum growth rates that are dependent on either the regional first order storage resource for each hub (red text in Figure 10 based on USGS[8] estimate), the conservative storage resource available in each hub (black text in Figure 10 based on Teletzke et al[10] estimate), or 10% of the conservative estimates (blue text in Figure 10). The range of growth rate requirement from 2030 onwards illustrated in Figure 8 is between 3% - 19%.

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 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.

Notably, we identified 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 according to the reports. Thus, the required upscaling of CCS is very demanding from a growth rate perspective. On the other hand, in both the Net Zero American and Decarb America report, storage demands of the North Dakota hub require the most conservative growth rate requirement where annual growth can be as low as 3%. This is evidently more plausible compared to the growth requirement of 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.

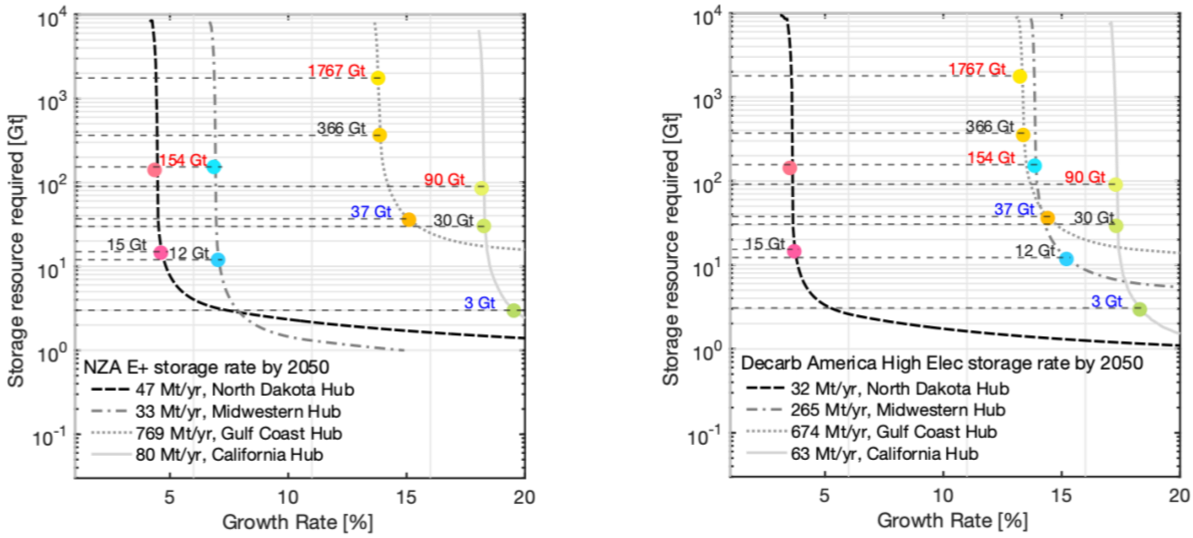


Figure 10: (Left) Trade-off between storage resource requirement and growth rates for four regional hubs meeting modelled demands analysed in the E+ scenario of the Net Zero America report for 2050. (Right) Tradeoff between storage resource requirement and growth rates for four regional hubs meeting modelled demands in the High Electricity 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

It is worth noting that we have identified discrepancies between the stated capture capacity (which we use to assume the first constraint on our model) and actual storage amounts of CO_2 in the subsurface from existing operational CCS projects. For the US in 2020, there is an observable discrepancy of approximately 0.31 $MtCO_2$ between the stated capture capacity and estimated storage amounts for seven currently operational CCS projects[36]. Thus, the modelled growth rate requirements in this analysis establish a minimum criterion to reach proposed targets. Any delays or shortfalls in the envisioned CCS development plan for the US will ultimately demand more ambitious scaleup rates and large storage resource bases to meet storage targets[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[37]. 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, for California, there are challenging short-term growth trajectories required by 2030 to meet proposed storage demands.

While significant opportunities have been identified in the Gulf Coast, challenges reside with aggregating state action and promoting communication across the country 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 upscaling and the role of the federal government to lead 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]. The results presented here should provide reasonable confidence in the short-term plausibility of CCS deployment in meeting climate change mitigation targets in the US.

ABBREVIATIONS

CCS – Carbon Capture and Storage

CO_2 – carbon dioxide

UNFCCC – United Nations Framework Convention on Climate Change

US – United States

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DISCLOSURES

The authors declare no competing financial interest