European carbon storage resource requirements of climate change mitigation targets

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ABSTRACT

As a part of climate change mitigation plans in Europe, CO_2 storage scenarios have been reported for the United Kingdom and the European Union with injection rates reaching 75 – 330 $MtCO_2\ yr^{-1}$ by 2050. However, these plans are not constrained by geological properties or growth rates with precedent in the analogous industry. We use logistic models to identify growth trajectories and the associated storage resource base consistent with European targets. All of the targets represent ambitious growth, requiring average annual growth 9% – 15% from 2030-2050. Modelled plans are not constrained by CO_2 storage availability and can be accommodated by the resources of offshore UK or Norway alone. Only if the resource base is significantly less, around 10% of current estimates, does storage availability limit mitigation plans. We further demonstrate the use of the models to define 2050 rate targets within conservative bounds of growth rate and storage resource needs.

Keywords: CO_2 storage; Logistic modelling; Storage resource requirement; Growth rates; Mitigation targets; Europe

1 INTRODUCTION

Very large-scale carbon capture and geological storage (CCS) may be needed to mitigate climate change[1,2,3,4,5,6,7]. Assessments of technological pathways available for limiting global warming to less than 1.5 °C and 2°C suggest that CO_2 may be injected underground at rates of 10 Gt per year by mid-century, and that >1000 Gt will need to have stored by the end of the century[7]. This is a similar scale to that of the fluids currently being handed by the hydrocarbon industry globally[8]. The European Union (EU) and the United Kingdom (UK) have a commensurate scale of carbon storage in their climate change mitigation plans including scenarios with combined over 500 Mt CO_2 injected underground per year by 2050 (Figure 1; Table 1)[9,10,11,12].

There are several indications that this scale of deployment is achievable. There are currently 26 facilities around the world with injection rate capacities ranging from 0.5 – 2 Mt yr^{-1} demonstrating the large-scale use of CCS technology[13]. Within Europe, there are two operational CCS facilities in Norway (Sleipner and Snøhvit) and one in Croatia; these three projects have a combined injection capacity of 1.7 Mt yr^{-1} [13,14]. Global estimates of storage resources suggest there are vast volumes of pore space underground suitable for sequestering CO_2. We adopt the definition of resources from the classification framework of the CO_2 Storage Resources Management System[15]. Recent evaluations identify a storage resource base between 10,000 – 30,000 Gt available worldwide[16,17,18]. This is potentially 3 – 10 times more than the maximum global storage resources needed to support the most aggressive CO_2 storage scaleup trajectories identified by the IPCC limiting global warming to less than 2°C[19]. The combined estimate of resources in Europe is 259 Gt, including resources distributed among EU member states (88 Gt), and offshore UK (78 Gt) and Norway (94 Gt; Figure 1)[20,21,22,23,24,18]. A recent comparison of the suggested global scaleup of CO_2 storage with historical rates of hydrocarbon wells drilled show that there is direct industrial precedent in the engineering needed to achieve Gt-tonne-scale injection rates by mid-century[25].

At the same time, there are significant uncertainties in the scaleup of CCS to achieve climate change mitigation targets. The integrated assessment models that are used to create results used by the IPCC and others are effectively unconstrained by limitations to injection rates and their scaleup[5]. These include hydrogeological limits to the pressurisation of reservoirs, latencies in project development including the discovery and appraisal of suitable injection sites, and economic, social, and political constraints that may play significant roles in the rate at which subsurface CO_2 injection may be expanded[26,27,28,29,30,31,32,33,34]. The amount of CO_2 stored underground in integrated assessment models does not reflect attributes from these potentially limiting economic, political, and geophysical processes[35].

In this work, we investigate growth trajectories for the scaleup of CO_2 storage in the UK and the EU identified in climate change mitigation roadmaps. We make use of a simple growth modelling framework widely used in analogous industries, like the oil and gas industry, that aggregates impacts of geophysical and engineering limitations to subsurface resource management, with non-geological factors like securing finance and navigating governmental regulations[19,36,37]. These models are particularly useful for understanding the interconnections between early growth rate, the duration of sustained exponential growth, and the size of the resource base required to support that growth. While mature industries can make use of data from the historical development to use these models predictively, this is not possible for the emerging CO_2 storage industry. Rather we use the models to identify limiting features – minimum growth rates and the resource base needed to support this growth consistent with CO_2 storage rate targets published in climate change mitigation plans for the UK and the European Union. This allows us to place these plans in the context of historical growth in analogous technologies, the estimates for the CO_2 storage resource base in each region, and to specify quantitatively the role that the UK and Norwegian continental shelf will need to play as a storage hub for emissions from the EU. Additionally, we show how the framework can be used to identify storage rate scenarios subject to conservative limitations to rates of growth and storage resource requirements.

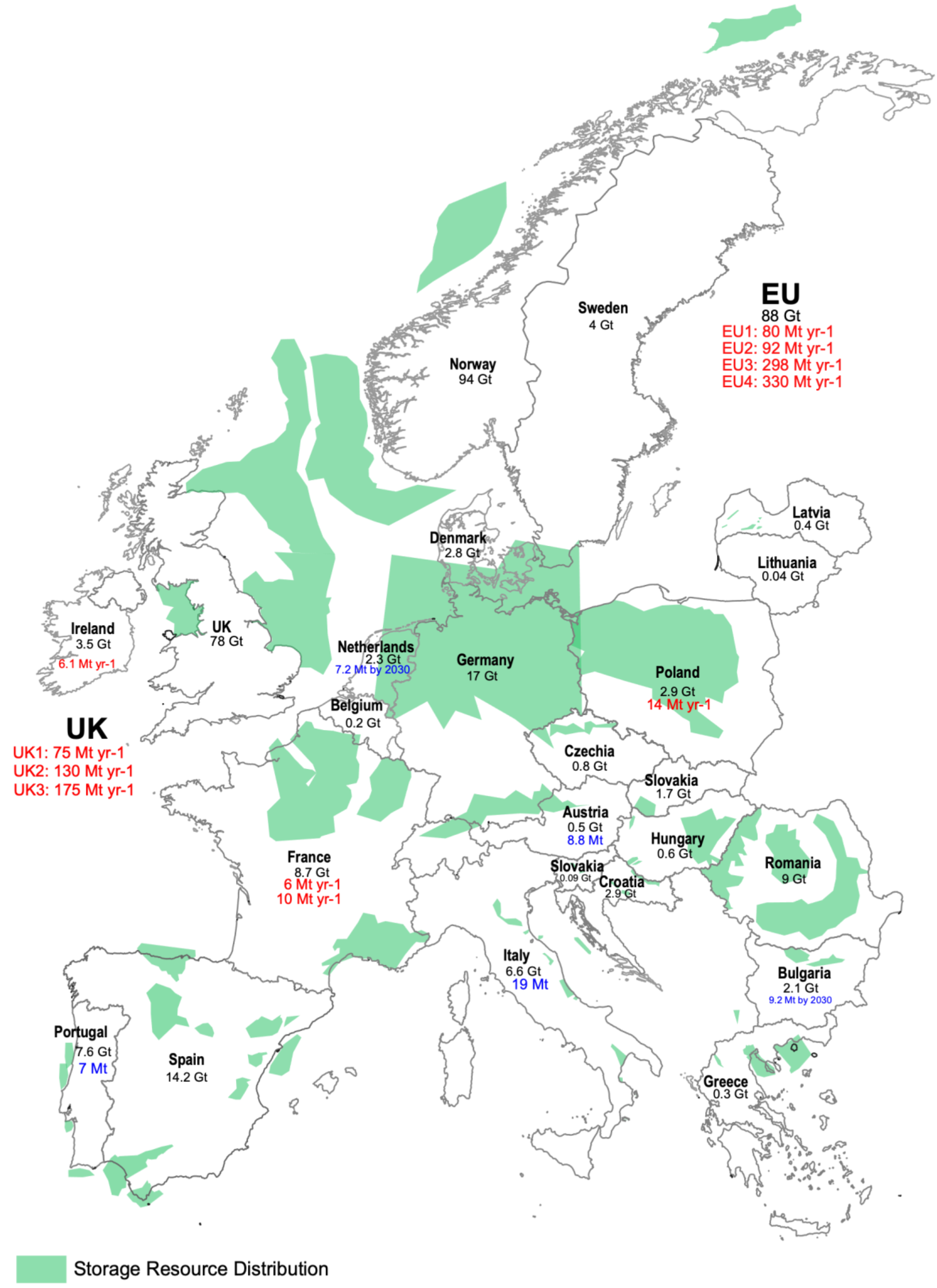

Figure 1: A map of Europe showing the storage resources available in black text, storage rate in red text or cumulative storage targets in blue text. All targets are for 2050 unless indicated otherwise.

Green polygons indicate major storage resource locations comprising predominately saline aquifers analysed by the EU GeoCapacity Project[20], CGS Europe report[21], CO2StoP project[23], the UK Storage Resource Appraisal Project[22], and the Norwegian CO_2 storage atlas[24].

Storage Scenario	*Target ($MtCO_2$ yr^{-1})*
EU1	80
EU2	92
EU3	289
EU4	330
UK1	75
UK2	130

Table 1: A summary of carbon storage deployment scenarios showing the anticipated annual storage rates of CO_2 in 2050 in the EU[9] and the UK[11,12].

2 METHODS

2.1 Identifying resources, targets, and plans of CO_2 storage in the European Union

The majority of the storage potential of EU member states was estimated by the EU GeoCapacity consortium[20]. Other reports provided the storage resource estimate for Sweden, Portugal, Austria and Ireland[21,23]. As a result, a total storage resource of 88 Gt in the EU (the member states, not including offshore UK or Norway) has been identified. Figure 1 displays a map of Europe summarising the national and regional targets, and the storage resource available in the indicated region or country. For EU member states of Estonia, Finland, Malta, Cyprus, and Luxembourg there are no indications of national targets, storage resource estimations, or CCS development. Therefore, our analysis of the EU only refers to the remaining 22 member states.

The European Commission strategic long-term report, 'A Clean Planet for All', outlined the decarbonization pathways for the EU to achieve net-zero commitments[9]. In this report, three CO_2 storage targets stating that in 2050, injection rates of 80, 92, and 298 $MtCO_2$ yr^{-1} will be necessary to limit warming to 2 °C. Another decarbonization scenario was created by Shell International B.V for the entire world, but identifying emissions reductions associated with particular geographic regions. In Europe, the Shell Sky Scenario in 2018 anticipates an even more ambitious storage rate target of 330 $MtCO_2$ yr^{-1} for 2050[38]. These four annual storage rate targets are subsequently referred to as EU1-4

(Fig. 1; Table 1). To date, there is one operational CCS facility and 13 planned CCS facilities in the EU by eight member states of Ireland, France, Belgium, Croatia, Italy, Sweden, Denmark and the Netherlands[13].

From this data, we analyse a group of scenarios that we refer to as the 'EU Member State Scenarios'. With the EU scenarios, we determine a range of growth rates and the necessary storage resource requirements needed to meet EU-wide storage rate targets. We place this in the context of storage resources identified within EU states. As described in subsequent sections, we then evaluate resource use across borders with the UK and Norway.

2.2 Identifying resources, targets, and plans of CO_2 storage in the United Kingdom

A landmark commitment to the mitigation of climate change in the UK was the 2008 Climate Change Act[39]. With this, the UK became the world's first major economy to pass a law requiring a reduction in greenhouse gas emissions by 80% compared to 1990 levels by 2050[40]. Carbon capture and storage has been identified by the UK parliament as a critical technology to facilitate their climate commitments. Similar to the EU, three storage rate targets have been identified; 75, 130, or 175 $MtCO_2\ yr^{-1}$ by 2050[40,11,12]. These three storage rate targets are hereafter referred to as UK1-3 respectively (Fig. 1; Table 1).

Although the UK does not currently have an operating CO_2 storage facility, four industrial clusters have been announced aiming to reach a storage rate of 10 $MtCO_2\ yr^{-1}$ by 2030[10]. Storage resources for the UK are mostly located in the UK North Sea and the East Irish Sea. An inventory of 579 sites has been compiled with an estimated combined storage resource of 78 Gt[22].

In this study, we will evaluate a group of scenarios we refer to as the 'UK Domestic Scenarios' and identify growth rates and the storage resource requirements for UK storage targets. We also evaluate the capability of the UK carbon storage resource to act as a regional CCS hub, servicing additional storage needs from the EU in a group of scenarios we refer to as 'EU + UK Scenarios'. We identify a range of annual growth rates and the necessary storage resource base required to achieve these scenarios.

2.3 Identifying carbon dioxide storage resources in Norway

Norway has played a central role in the demonstration of industrial-scale CO_2 storage. The Norwegian government, from as early as 1989, identified CCS as a key innovation technology to reconcile ambitious climate targets with the growing emissions from the country's hydrocarbon industry[41]. There are two operating CO_2 storage projects in Norway, Sleipner and Snøhvit, which have been operating since 1996 and 2008, respectively. A new full-scale CCS project called Longship has been announced in 2020 and aims to begin operation by 2024 to further help Norway meeting its climate targets[13].

Because of the relatively small greenhouse emissions originating in Norway, in this analysis, we only consider storage resources as potentially contributing to the EU and UK climate change mitigation targets. Similar to the UK, a vast quantity of resources for CO_2 storage (94 Gt) is available offshore Norway[18]. This is considered the most prospective region for geologic storage of CO_2 in Europe[42] and could play a significant role in offsetting EU-wide industrial emissions. Here, we explore the extent to which the Norwegian storage resources enhance the viability of large-scale CO_2 storage within Europe, combining mitigation targets from the EU and UK.

2.4 Growth modelling with logistic curves

Consumption of finite natural resources often follows a pattern starting with a period of exponential growth (annual growth at a constant rate) and subsequently a slowdown in the early growth rate or even a decline as market conditions shifts or resource availability declines. As a result, S-shaped curves are commonly used to describe the cumulative exhaustion of a resource. Of these, the logistic model is the most widespread, and it has been used to describe growth in oil and coal consumption, and trends in energy systems, infrastructure, and technology development[43,44,45,46,47,48]. Recently, the logistic modelling framework was applied to the analysis of global carbon storage resources[19]. In this context, the model can be used to approximate the relationship between the growth needed to achieve near-term scaleup targets and the resource base that would be required to support that growth. Because of the lack of historical CCS development, it cannot be used predictively. Rather, it is used to identify limiting features of CCS scaleup – minimum growth rates and storage resource requirements to support growth trajectories.

The model is outlined in Equations 1 and 2 specifying the cumulative storage, $P(t)$ [$GtCO_2$], and storage rate, $Q(t)$ [$GtCO_2\ yr^{-1}$] of CO_2 sequestration as a function of time, t [yr]. The curves are initially exponential, characterised by an early annual growth rate, r [yr^{-1}]. As the peak time, t_p [yr], is approached, growth rates decline and are then negative until the storage resource amount, C [Gt], is approached.

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

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

An inflection point in the rate time series occurs in year t_n given by

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

We take the inflection point to represent the time at which growth begins to deviate significantly below exponential growth.

These equations describe a symmetric logistic model, with equal growth and decline trajectories. In practice, symmetry only occurs under a rare combination of circumstances including undisturbed resource exploration for new reserves, consistent economic impetus, limited innovation in resource exploration, and eventually exhaustion of the resource. Asymmetric growth profiles frequently occur, e.g., due to innovation in resource use or decline in market demand[47,49].

This model is not used to predict likely trajectories, but rather to identify constraints on minimum sustained growth rates required to meet climate change mitigation targets, and the resource base needed to support those trajectories[19]. Historical development in analogous industries like the oil and gas sector shows an important interlink between the growth pattern and the physical quantity of the resources available. In other words, the growth trajectory used to achieve a certain storage target is dependent on both the size of the storage resource base and the storage rate target (or cumulative target) in a given year. Sustained annual growth is dependent on a large enough resource base so that limits to growth imposed by the geology, or the practicalities of exploiting ever more marginal sites, will not be encountered. As a result, there is a tradeoff between initial annual growth rates and storage resource requirements in considering trajectories that may achieve a storage rate or cumulative storage target in a given year.

We numerically solve Equations 1 and 2 to meet climate change mitigation targets for a region. This identifies rate and cumulative storage trajectories that meet proposed plans. Iterating over a range of parameter space of storage resource requirement and initial (exponential) annual growth rate allows us to identify the scenarios over which these plans may be achieved. From this, minima in the initial growth rate that is supported by the maximum storage resource available can also be identified.

2.5 Model for the European Union targets and the domestic United Kingdom targets

A schematic showing constraints applied to the logistic model for the EU and UK scenarios is shown in Figure 2. The EU member state model is constrained by CCS activities located among EU member states and the four 2050 storage rate targets from the scenarios EU1 (80 $MtCO_2$ yr^{-1}), EU2 (92 $MtCO_2$ yr^{-1}), EU3 (298 $MtCO_2$ yr^{-1}) and EU4 (330 $MtCO_2$ yr^{-1}; Figure 2). Similar to the EU member state scenarios, two standard constraints are applied to the modelling for the domestic UK scenarios. The constraints are 1) cumulative storage reached by 2030 based on planned facilities in the UK, and 2) storage rate targets of UK1 (75 $MtCO_2$ yr^{-1}), UK2 (130 $MtCO_2$ yr^{-1}) and UK3 (175 $MtCO_2$ yr^{-1}). The modelled scenarios identify a group of minimum growth rates supported by the maximum storage resource available (88 Gt for the EU or 78 Gt for the UK) to meet the storage targets of the respective region. However, CO_2 storage resource assessment is also uncertain to over an order of magnitude[19]. Thus, an additional conservative group of higher growth scenarios that depend on only 10% of the currently identified storage resources are also identified. The inflection year of each growth rate curve indicates the duration of exponential growth. In Figure 2, we use a solid line for the part of the trajectory where storage rate growth is close to exponential. Beyond the inflection year, the trajectory is dashed to emphasise that these are not predictive growth trajectories but rather used to identify the resource base required to support the early growth.

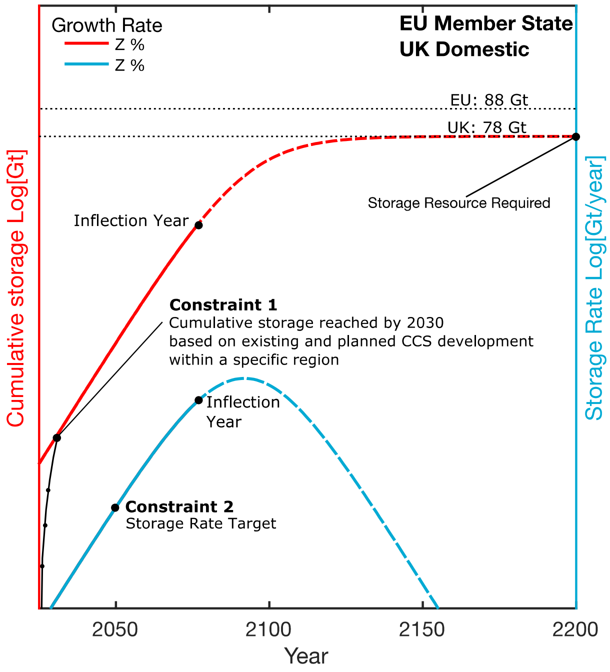

Figure 2: Schematic plot illustrating the key constraints and features of the logistic growth model. Cumulative CO_2 storage is shown in red (Equation 1) and the annual injection rate in blue (Equation 2). Black dots indicate the cumulative storage from existing or planned CCS development within a

region which is used to constrain the cumulative storage in 2030 – constraint 1. The storage rate target in 2050 provides the second constraint on the curve. The inflection year (t_n, Equation 3) indicates the point when the growth rate is taken to have diverged below the exponential trend. The storage resource based required is taken to be the cumulative storage achieved (C, Equation 1). Trajectories are explored subject to upper bounds (78 Gt or 88 Gt) and 10% of storage resource available. Note that the plot is illustrative, so numbers are not included for the vertical axes, but curves are shown for plots with logarithmic vertical axes.

2.6 Model for the UK + EU targets

To evaluate the potential of CO_2 storage resources located in the North Sea to fulfil the combined storage needs of the UK and EU, the following constraints are used (Figure 3): first, CCS development to establish the initial average growth rates in Europe are assembled based on existing or planned projects announced by EU member states that are taking place in the North Sea region, including offshore Norway and the UK. Second, every possible combination of the EU and the UK's storage rate targets for 2050 are calculated, leading to 12 new combined (UK + EU) regional storage rate targets (Table 2). From these constraints, the minimum growth rates are computed for the 12 combined targets. Furthermore, growth trajectories subjected to 10% of storage resource available in the UK, Norway and the combined storage resource of the UK and Norway are explored.

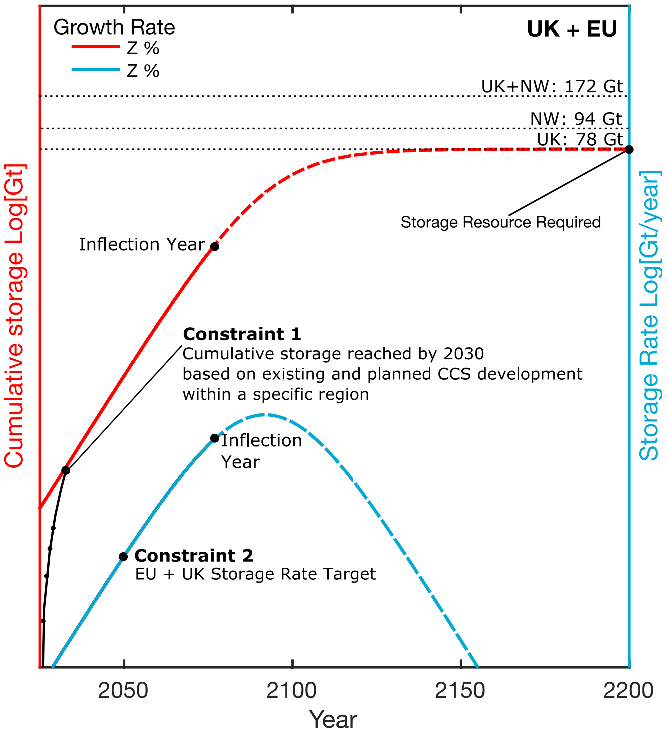

Figure 3: Schematic plots of analysis for the 'EU + UK Scenarios' illustrating each constraint used on an exemplary growth trajectory of Z%. Note that the plot is illustrative, so numbers are not included for the vertical axes, but curves are shown for plots with logarithmic vertical axes.

'EU + UK' Scenarios		UK Storage needs			
		UK1: 75 Mt yr^{-1}	UK2: 130 Mt yr^{-1}	UK3: 175 Mt yr^{-1}	
EU member state storage needs	EU1: 80 Mt yr^{-1}	155 Mt yr^{-1}	210 Mt yr^{-1}	255 Mt yr^{-1}	Group A
	EU2: 92 Mt yr^{-1}	167 Mt yr^{-1}	222 Mt yr^{-1}	267 Mt yr^{-1}	Group B
	EU3: 298 Mt yr^{-1}	373 Mt yr^{-1}	428 Mt yr^{-1}	473 Mt yr^{-1}	Group C
	EU4: 330 Mt yr^{-1}	405 Mt yr^{-1}	460 Mt yr^{-1}	505 Mt yr^{-1}	Group D

Table 2: The 'EU + UK' scenarios including the combined storage rate in 2050 between the EU and UK. Each group contains all possible combinations of growth scenarios of one EU storage target with all the UK targets. The colour of each target scenario corresponds to isocontours in Fig.6.

2.7 Trade-off between annual growth rate and storage resource requirements

In the logistic model, there is a relationship between the initial annual growth rate or trajectory, the duration of near-exponential growth, and the storage resource required. This is suggestive of the real-world relationships between growth trajectories and storage resources. The initial exponential phase of growth can be considered a time period during which growth limitations due to the finite nature of the resource do not impinge on the development, otherwise incentivised financially. The slow down and decline of growth reflects the challenges faced as resources are consumed. In the case of CO_2 storage, the highest quality reservoirs with the largest structural traps will be used before more marginal sites, e.g., in less permeable reservoirs with smaller traps.

While individual trajectories are of interest in considering a particular development pathway, graphs showing these trajectories in the context of the tradeoffs between storage rate and resource base provide more general information about the plausibility of the scenarios under consideration. These figures are computed for the 'EU Member State Scenarios', 'UK Domestic Scenarios' and the 'EU + UK Scenarios', by finding a range of growth rates and storage resource required for a fixed 2050 storage rate target (Figure 4). We represent individual scenarios with points on the graph.

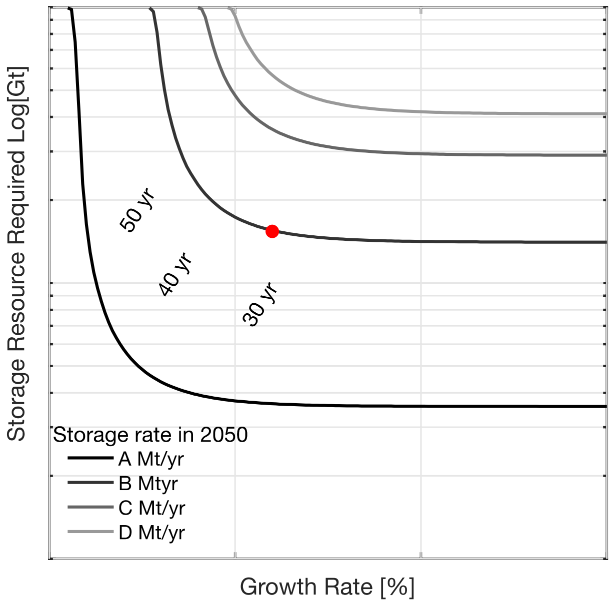

Figure 4: An example of a tradeoff graph between post-2030 growth rates and the storage resource required to support that growth. The thick grey lines are isocontours of storage rate targets in 2050. The dotted lines are contours of t_n (Equation 3), the duration of sustained constant annual (exponential) growth from 2030. The coloured point corresponds to a single trajectory, i.e., Fig.3. Note that this is illustrative, and we have kept numbers off of the axes, but the vertical axis is logarithmic and the horizontal axis linear.

3 RESULTS

3.1 EU Member State Scenarios

Storage rate target scenarios ranging from 80-330 MtCO$_2$ yr^{-1} in 2050 have been outlined by the European Commission[9] and Shell International B.V.[38] (Table 1). Currently announced plans for carbon capture and storage within EU member states are commensurate with storing 126 Mt of CO$_2$ cumulatively by 2030[13,14] and we use this as the starting point for modelled trajectories. We show growth in annual injection rate from 2030 onwards at a range of rates from 9.5% - 17.2% in Figure 5 and values are reported in Table 2. The minimum rates to achieve EU1 (80 MtCO$_2$ yr^{-1} in 2050) and EU2 (92 MtCO$_2$ yr^{-1} in 2050) are 9.5% and 10%, respectively. For the more ambitious scenarios EU3 (298 MtCO$_2$ yr^{-1} in 2050) and EU4 (330 MtCO$_2$ yr^{-1} in 2050), the minimum growth rates necessary to meet these targets are 14.2% and 14.7%, respectively (darker green curves in Fig.5). These depend on the existence of a storage resource base at the maximum permitted in our model, 88 Gt, the resource currently estimated to be available[20,21,23]. Applying constraints on the storage resource available to

10% of that currently estimated results in the need for higher initial growth rates, 10.1% - 17.2% for EU1-4, albeit sustained for much shorter periods.

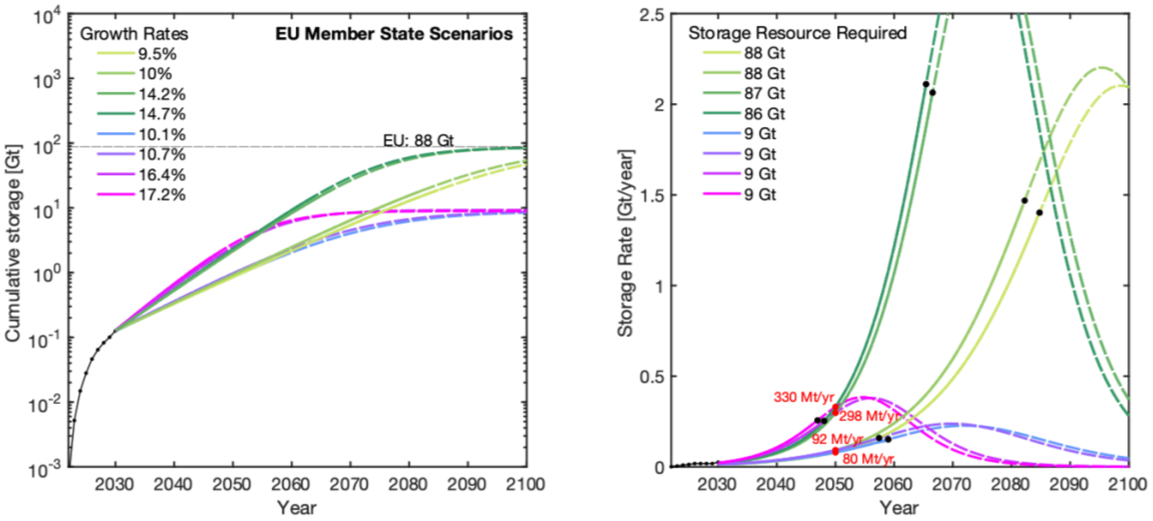

Figure 5: (Left) Cumulative CO_2 storage as a function of time for EU Member State scenarios. The black markers represent storage from the planned CCS facilities within the EU up to 2030 including one operational facility in Croatia (see supporting information for tabulated raw data). The legend shows the initial growth rate in storage rate modelled from 2030 onwards. The horizontal line at 88 Gt indicates the storage resource available in the EU. (Right) EU member state CO_2 storage rate as a function of time for various growth scenarios. The legend indicates the storage resource required to support each growth trajectory. The inflection years (black dots) indicate the points where the growth rate diverges from the exponential trend and there are dashed lines thereafter to emphasize that these trajectories are not predictive. The red points indicate the storage rate targets of EU1 (80 $MtCO_2\ yr^{-1}$), EU2 (92 $MtCO_2\ yr^{-1}$), EU3 (298 $MtCO_2\ yr^{-1}$, and EU4 (330 $MtCO_2\ yr^{-1}$). Model parameters are provided in Table 3.

The range of possible initial growth rate and storage resource base combinations needed to achieve 2050 targets are shown with isocontours in Figure 6. Points illustrate those particular scenarios shown in Figure 5 where growth rates are minimised making use of either all or just 10% of the estimated storage resource base. All of the 2050 targets required sustained annual growth of greater than 9.5%, with the more ambitious targets (EU3 and EU4) requiring over 14% average annual growth for at least 20 years. While these rates are frequently seen over short timescales, sustaining them for multiple decades is unusual for energy technologies[48]. Similarly, 2-3 Gt of CO_2 storage resources are the minimum necessary to accommodate any of the mitigation plans and the identification of at least 7 Gt of storage resource is the minimum needed for all of the targets to be possible.

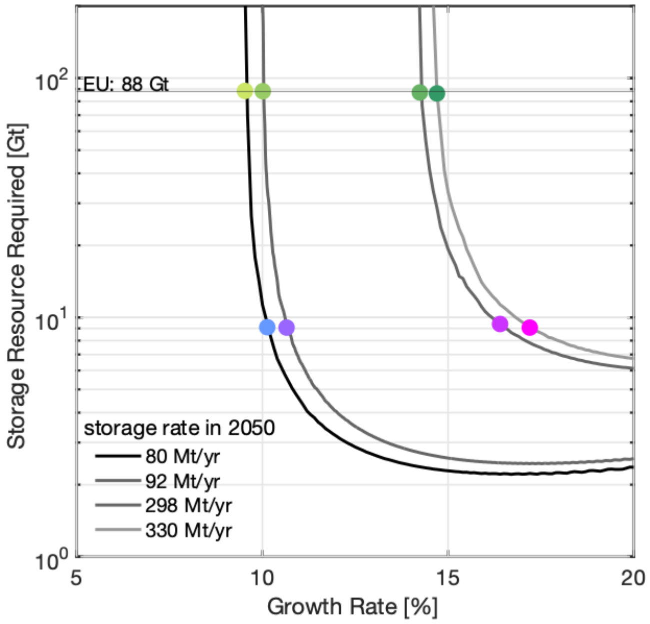

Figure 6: Tradeoff between storage resource requirements and early growth rates for EU member state scenarios. The thick solid grey lines show isocontours of trajectories that meet storage rate targets in 2050. The thin black horizontal line at 88 Gt is the current estimate of storage resources available in the EU. The coloured points correspond to the growth trajectories in Fig.2 that achieve targets at minimum growth rates subject to the existence of all or 10% of the currently estimated storage resource.

Growth rate [%]	*Storage resource required [Gt]*	*Storage rate target achieved*
9.5	88	EU1
10	88	EU2
14.2	87	EU3
14.7	86	EU4
10.1	9	EU1
10.7	9	EU2
16.4	9	EU3
17.2	9	EU4

Table 3: A summary of modelled growth scenarios details which corresponds to coloured lines in Fig.5 and dots in Fig.6.

3.2 UK Domestic Scenarios

Storage rate target scenarios ranging from 75-175 $MtCO_2$ yr^{-1} in 2050 for the UK have been recommended by the Committee on Climate Change and the Oil and Gas Authority[11,12] (Table 1). The currently planned CCS activities in the UK between 2022 and 2030 are to have stored a cumulative of 81 $MtCO_2$ offshore[13,14]. Figure 7 shows trajectories from 2030 with annual growth in injection rates between 10.9%-15.1% meeting the storage rate targets of the UK for 2050. Achieving the UK government's lowest carbon storage rate target of 75 $MtCO_2$ $year^{-1}$ (UK1) requires a minimum annual growth rate of 10.9% (yellow curve in Fig. 7) achieved when dependent upon the maximum resource base allowed, 78 Gt. This rises to 12.8% for UK2 (130 MtCO2 yr^{-1}) and 14% to reach the most aggressive target of 175 $MtCO_2$ $year^{-1}$ (UK3) in 2050. Limiting the resource base to 10% of that currently estimated results in minimum growth rates increasing to 11.4%, 13.7% and 15.1% to meet UK1-3, respectively. Table 4 provides a summary of these values for the UK domestic scenarios.

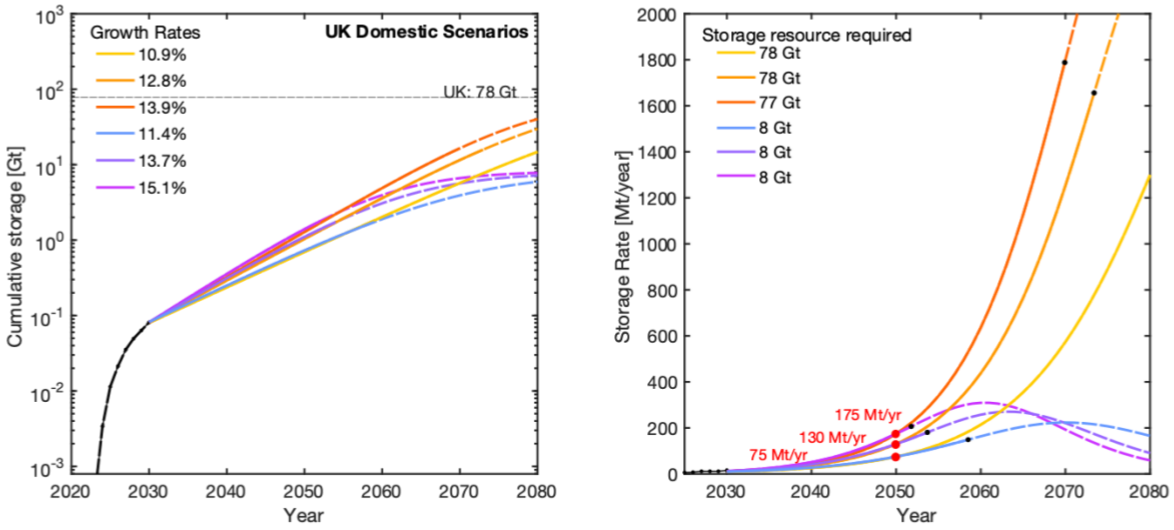

Figure 7: (Left) Cumulative CO_2 storage for the UK domestic scenarios. The black markers are the planned CCS facilities within the UK up to 2030. The legend indicates the annual growth rate from 2030 onwards. The horizontal line at 78 Gt indicates the storage resource estimated for the offshore UK. (Right) CO_2 storage rate for the UK domestic scenarios. The legend indicates the storage resource required to support each growth trajectory. The inflection year (black dots) indicates the point where the growth rate diverges from the exponential trend. The red points indicate the storage rate target

of UK1 (75 MtCO$_2$ year^{-1} in 2050), UK2 (130 MtCO$_2$ year^{-1} in 2050), and UK3 (175 MtCO$_2$ year^{-1} in 2050).

Storage rate isocontours for 2050 UK targets are shown in Figure 8 with points corresponding to trajectories shown in Figure 7. All of the scenarios require sustained annual growth of greater than 10.9% and the UK3 target can only be achieved with scenarios with at least 14% sustained annual growth. The minimum resource base required for the lowest target in UK1 is around 2 Gt. At least 4 Gt of storage resource is needed for all of the potential targets to be possible.

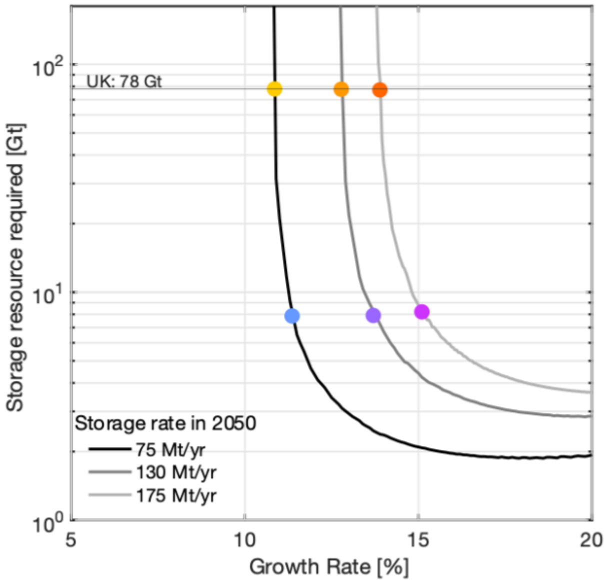

Figure 8: Tradeoff between storage resource requirements and early growth rates for UK domestic scenarios. The solid grey lines show the storage resource required as a function of post-2030 growth rates to reach the storage rate targets in 2050. The coloured points correspond to the growth trajectories in Fig.7. The black horizontal line at 78 Gt indicates the storage resource available offshore of the UK.

Growth rate [%]	*Total storage resource required [Gt]*	*Storage rate target achieved*
10.9	78	UK1
12.9	78	UK2
13.9	78	UK3
11.4	8	UK1
13.7	8	UK2
15.1	8	UK3

Table 4: A summary of the results for growth scenarios of the UK domestic model, each corresponds to the colour lines in Fig.7 and dots in Fig.8.

3.3 EU + UK Scenarios

The tradeoff graph for the combined scenarios (Figure 9) illustrates the minimum growth rates bounded by the available storage resource in the UK (78 Gt), the Norwegian storage resource (94 Gt), and the UK and Norway combined storage resource (172 Gt). The higher the storage rate target, the higher the minimum growth rate necessary to achieve the target. Notably, the range of minimum growth rates illustrated in Figure 6 is between 10.3%-14.8% depending on the size of the supporting resource base (Table 5). Combining storage resources from the UK and Norway does not significantly impact the growth rate requirements for scaleup trajectories. The requirements are primarily driven by the 2050 rate targets and are not limited by the availability of storage resources.

The storage resource base of the UK and Norway are sufficiently large that geophysical limitations to scaleup would only emerge if there were major overestimates in the current resource assessment. For all of the rate targets to be viable, at least 15 Gt of storage resource is required. In the case where we limit the resource to 17 Gt, or 10% of current estimates, the combined resource base of both the UK and Norway are needed to accommodate all of the injection rate targets. The geological limitations must also be compensated by higher initial rates of growth. Around half of the targets depend on sustained annual growth of 15% or greater. For the lower storage rate targets, i.e., Group A-B targets in Figure 9, the demands on the injection growth rate are decreased by multiple percentage points when the combined resource base is available compared with that of either the UK or Norway alone.

This analysis lends itself to the easy identification of growth trajectories subject to criteria that may be considered plausible or otherwise of interest to explore. We illustrate an example for a conservative rate target in Figure 9 of 92 Mt yr^{-1} in 2050. This target could be achieved by sustaining annual growth in injection at the current global average of 8.6% (red point in Figure 9) whereby cumulative storage of 1.1 Gt would be achieved by 2050. Alternatively, a range of trajectories dependent on the existence of 10% or less of the currently estimated resource base can be made with sustained annual growth of less than 10% (bold red line in Figure 9). These types of considerations and constraints are computationally efficient and could be easily incorporated into energy systems models of climate change mitigation

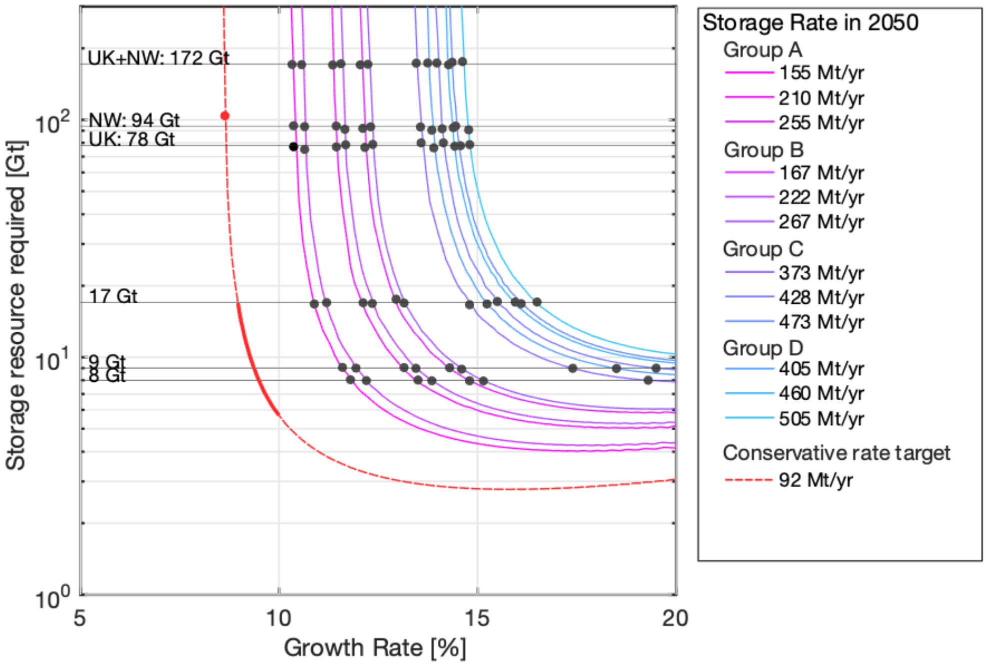

Figure 9: Tradeoff between storage resource requirement and growth rates for the four groups of combined "EU + UK" storage targets for 2050 indicated by the legend (See Tables 4 and 5 for associated values). The red dashed line is an example contour identifying conservative storage rate target for 2050 of 92 Mt yr^{-1}; this rate can be achieved with annual growth of 8.6% (red point, and the current global average) or alternatively trajectories dependent on less than 10% of the currently estimated resource base and less than 10% annual growth (bold red). The horizontal lines at 78 Gt, 93 Gt and 172 Gt are the estimated storage resource available offshore UK, Norway and the combined storage resource of the UK and Norway, respectively. The horizontal lines at 17 Gt, 9 Gt and 8 Gt are 10% of the storage resource of "UK+NW', 'NW' and 'UK', respectively. The black points correspond to minimal growth rates subject to these storage resource constraints.

Storage resource Requirement [Gt]	*Range of minimum growth rates for Group A [%]*	*Range of minimum growth rates for Group B [%]*	*Range of minimum growth rates for Group C [%]*	*Range of minimum growth rates for Group D [%]*
78	10.37-12.16	10.65-12.36	13.58-14.57	13.90-14.80
94	10.37-12.11	10.64-12.31	13.56-14.45	13.85-14.78
172	10.33-12.05	10.57-12.24	13.46-14.36	13.74-14.62

	Range of higher growth rates for Group A [%]	Range of higher growth rates for Group B [%]	Range of higher growth rates for Group C [%]	Range of higher growth rates for Group D [%]
8	11.8-14.8	12.2-15.2	19.3->20	>20
9	11.6-14.3	11.9-14.6	17.4->20	18.5->20
17	10.9-13	11.2-13.2	14.8-16.1	15.2-16.5

Table 5: A summary of the results for growth scenarios identified for 'EU+UK' storage targets requiring the entire and 10% of storage resource available offshore of UK, Norway and combined storage resource.

4 DISCUSSION

Plans for the deployment of CCS by the European Union and the UK imply sustained annual growth in CO_2 storage rates of at least 9%, and up to 15% from 2030 to 2050 (Figure 3 and 5). Others have shown that the scale of subsurface engineering required is precedented[25]. Indeed, oil production from 1901 sustained a 15% average annual growth for 40 years[50]. However, market conditions driving the expansion of the demand for oil, which include the First World War, and few limitations ensuring safety or environmental standards, reveal the magnitude of incentivisation required to achieve such growth[51,52].

The storage resource of the UK and Norway, alone or combined, appear sufficiently abundant to serve as a regional CO_2 storage hub for the European continent (Figure 6). Significant geological limitations only emerge if development is restricted to less than 10% of current estimates of the resource base. Even then, there is a range of significant 2050 rate targets that can be met without unduly high growth rates.

This analysis provides a framework to develop technology roadmaps including the scaleup of CO_2 storage within realms of plausible ranges of growth rate and storage resource base. For the last 20 years, the global annual average scaleup of CO_2 storage rates is at around 8.6%[19]. Using this as a demonstrated benchmark, a trajectory with 8.6% annual growth from 2030 onwards for the European Continent, dependent on a combined storage resource base of 104 Gt is evidently plausible. This scenario translates into a 2050 regional storage rate target of 92 $MtCO_2\ yr^{-1}$ (red dashed curve in Figure 6) and cumulative storage of 1.1 Gt. This rate target can also be met with a range of scenarios that can be achieved depending on less than 10% annual growth and less than 10% of the currently identified resource base.

This analysis also points to the period between 2021 and 2030 as a critical window for Europe to establish large-scale CCS operations. It has assumed storage rates starting in 2030 based on published plans for the coming decade. However, delays or shortfalls in achieving these plans will place larger demands on the scaleup rates required and the storage resource base needed to support storage rate targets.

5 CONCLUSIONS

In this study, we evaluate the scaleup of geological CO_2 storage identified in European climate change mitigation plans. We show that all storage targets require historically high rates; minimum average annual growth from 2030 through 2050 needs to achieve 10%-15%. In contrast, CO_2 storage plans are not limited by current estimates of the resource base available and can be accommodated by the offshore reservoirs of the UK or Norway alone. However, there are large uncertainties in current storage resource assessments, and we show that storage resource limitations will occur if the resource base has been significantly overestimated, i.e., around 10% or less of current best estimates. In such a case, higher rates of near-term growth of 11% – 17% and the combined resources of the UK and Norway are ultimately required. Finally, we show how the logistic modelling framework can be used for constraining the deployment of CO_2 storage in energy systems models that are subject to conservative criteria and illustrate this by identifying a range of conservative storage rate target scenarios, i.e., 92 $MtCO_2\ yr^{-1}$ in 2050.

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AUTHOR CONTRIBUTIONS

Y.Z. and S.K. conceived the study. Y.Z. performed the research and led the writing of the manuscript. C.Z. and Y.Z. developed the computer code. All authors contributed to the writing of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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