# European carbon storage resource requirements of climate change mitigation targets

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## HIGHLIGHTS

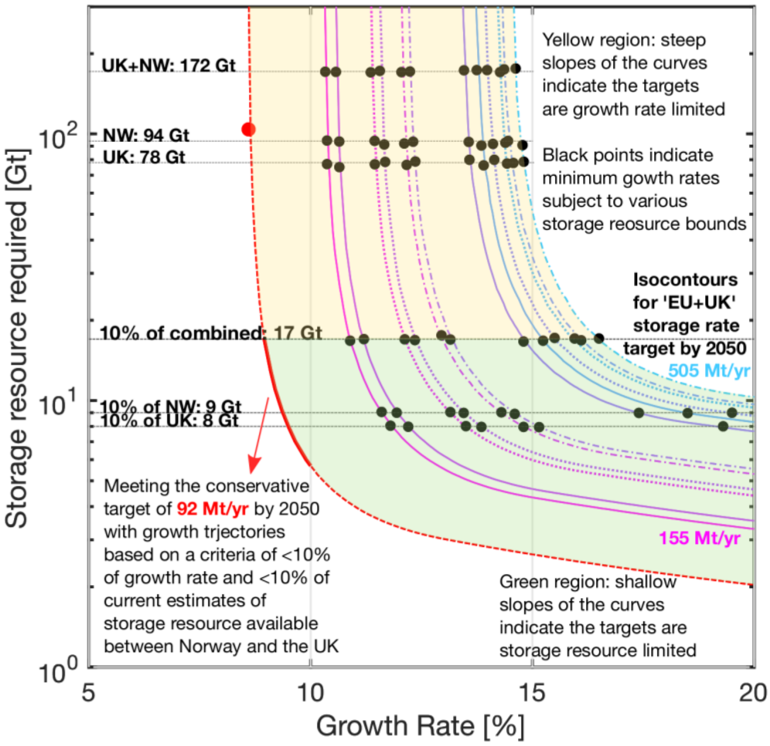
- European CCS plans imply >9% annual growth in injection rates from 2030-2050
- The resource base of either offshore Norway or the UK alone can meet scaleup needs
- Logistic models provide a simple framework to evaluate European $CO_2$ storage scale-up
- Growth models can be used to constrain output from energy systems models

## 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 hydrocarbon 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 in injection rates 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 both growth rate and storage resource needs.

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

# GRAPHICAL ABSTRACT



## 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)[9,10,11,12,13].

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[14]. 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 $yr^{-1}$ [14,15]. 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[16]. Recent evaluations identify a storage resource base between 10,000 – 30,000 Gt available worldwide[17,18,19]. 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[20]. The combined estimate of effective storage resources in Europe is 260 Gt, including resources distributed among EU member states for both onshore and offshore (88 Gt in total), and offshore UK (78 Gt) and Norway (94 Gt; Figure 1)[19,21,22,23,24,25]. However, concerns over onshore storage of $CO_2$ in the EU, e.g., by the European Commission[26], could limit its use to offshore resources alone (19 Gt, or 22% of the total, for EU member states[21,27,28,29]).

At the same time, there are significant uncertainties in the scaleup of CCS to achieve climate change mitigation targets. It has been recognised that current integrated assessment models (IAMs) that identify scaleup trajectories for $CO_2$ storage contain gaps in the representation of realistic consumption of depletable natural resources[30,31]. The constraints used in IAMS to determine deployment projections of technologies are predominantly costs. For CCS, while some IAMs do include an upper limit on available storage resources or a maximum injection rate, these are only single-value constraints[5, 32]. As a comparison, the upscaling of other low-carbon technologies i.e., solar and wind technologies in IAMs are constrained by a historical annual growth limit i.e., 10% $yr^{-1}$ [32]. Zahasky and Krevor[20] have further pointed out that estimates of storage resources based on geological features alone are inherently uncertain and can range in up to two orders of magnitude. As a result, geological considerations alone are insufficient to describe actual development trajectories of CCS. Rather, there is a range of factors that could potentially limit the growth of subsurface storage sites, including the geophysical limit to the injectivity rate of $CO_2$ as a result of the pressurisation of the reservoir in repose to injection, latencies in project development, i.e., the discovery and appraisal of suitable injection sites, and a combination of economic, social, and political constraints[33,34,35,36,37,38,39,40,41]. The amount of $CO_2$ stored underground in IAMs or regional or national energy systems models does not reflect attributes from these potentially limiting processes[42].

In this work, we make use of the logistic growth model – a simple framework that has been widely used in analogous industries, like the oil and gas industry, to investigate plausible growth trajectories for the scaleup of $CO_2$ storage in the UK and the EU that are identified in climate change mitigation roadmaps. Under the logistic modelling framework, the impacts of geophysical and engineering limitations to subsurface resource management are combined with non-geological factors like securing finance and navigating governmental regulations to determine deployment trajectories [20,43,44]. Furthermore, this model is 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, a relationship not currently captured by the energy systems models and IAMs. While mature industries can make use of data from the historical development to use logistic models predictively, this is not possible for the emerging $CO_2$ storage industry. Rather, we use the models to apply a range of storage resource constraints and to identify limiting features – minimum growth rates supported by the available storage resource base that is 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 scaleup scenarios subject to conservative limitations to rates of growth and storage resource requirements.

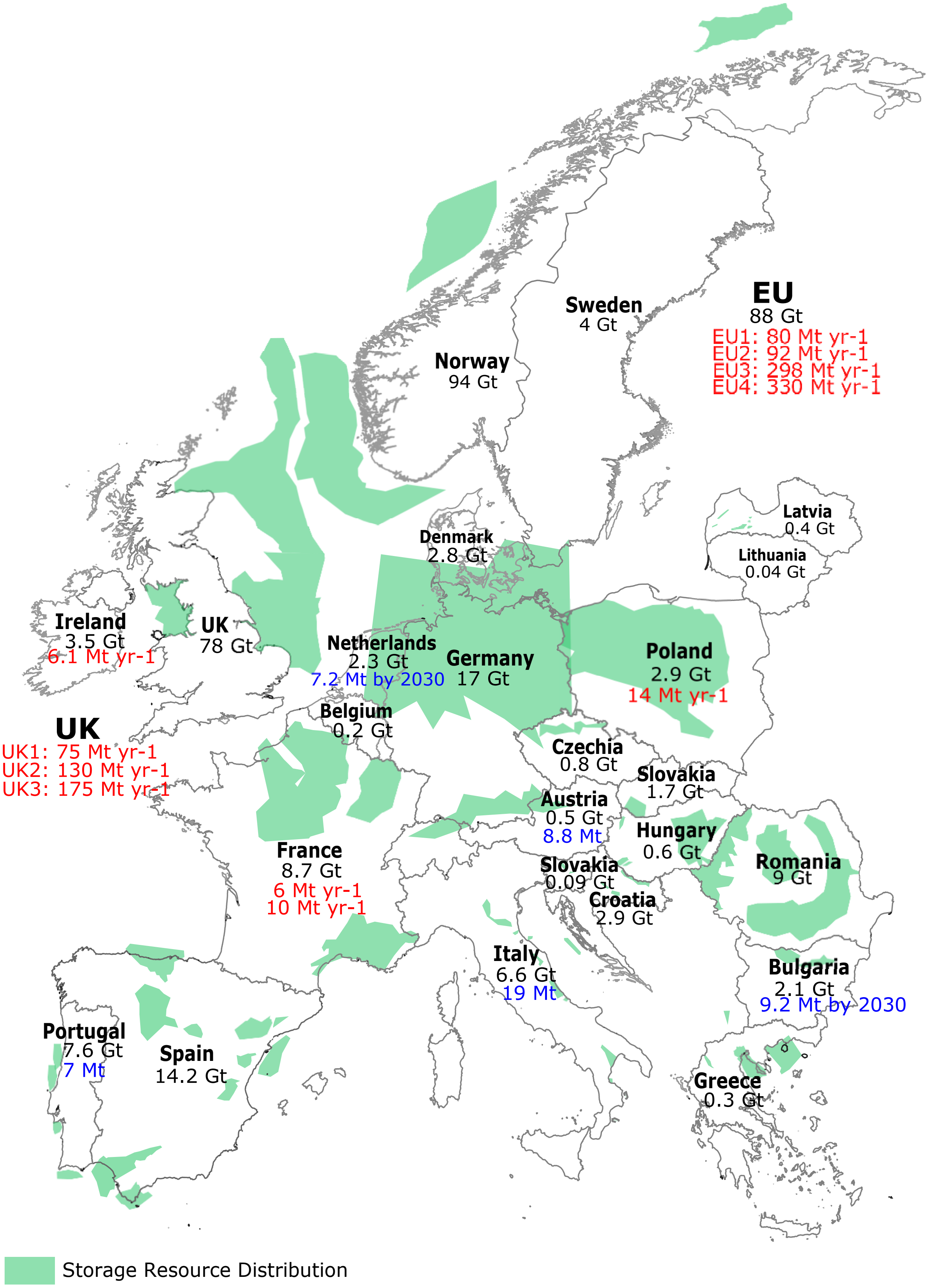

EU
88 Gt
EU1: 80 Mt yr-1
EU2: 92 Mt yr-1
EU3: 298 Mt yr-1
EU4: 330 Mt yr-1
Sweden
4 Gt
Norway
94 Gt
Latvia
0.4 Gt
Lithuania
0.04 Gt
Denmark
2.8 Gt
Ireland
3.5 Gt
6.1 Mt yr-1
UK
78 Gt
Netherlands
2.3 Gt
7.2 Mt by 2030
Germany
17 Gt
Poland
2.9 Gt
14 Mt yr-1
Belgium
0.2 Gt
UK
UK1: 75 Mt yr-1
UK2: 130 Mt yr-1
UK3: 175 Mt yr-1
Czechia
0.8 Gt
Slovakia
1.7 Gt
Austria
0.5 Gt
8.8 Mt
Hungary
0.6 Gt
Romania
9 Gt
Slovakia
0.09 Gt
Croatia
2.9 Gt
France
8.7 Gt
6 Mt yr-1
10 Mt yr-1
Italy
6.6 Gt
19 Mt
Bulgaria
2.1 Gt
9.2 Mt by 2030
Portugal
7.6 Gt
7 Mt
Spain
14.2 Gt
Greece
0.3 Gt
🟩 Storage Resource Distribution

Figure 1: A map of Europe showing the distribution of storage resources and the regional/national $CO_2$ storage targets for 2050 unless indicated otherwise (storage rate targets in red and cumulative storage targets in blue). Green polygons indicate major storage resource locations comprising predominately of saline aquifers. The total effective storage resource estimated to be available in Europe is 260 Gt. Of this estimate, 66% is located offshore of UK and Norway. A total of 88 Gt of effective storage resources is available among Member States of the EU, however, only 22% is located offshore.

| *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[9,13] 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[21]. Of the three reservoir types analyzed by the EU GeoCapacity consortium, which are deep saline aquifers, depleted hydrocarbon fields and unmineable coal beds, storage resources in deep saline aquifers constitute 85% of the total estimate for the EU (88 Gt). As a result, the approach and assumptions used to estimate storage resources in deep saline aquifers are the most significant. In the GeoCapacity database, estimates of storage resources in deep saline aquifers are based on formulas provided by Bachu et al.[45]. The initial potential storage sites and sealing units are determined through a screening process using a cut-off criterion. Subsequently, the effective estimates of storage resources for each structural or stratigraphic trap are determined volumetrically by applying a storage efficiency factor. In GeoCapacity's assessment, they have used trap specific storage efficiency factors which vary depending on the assumption of whether the aquifer system is open/semi-closed or closed. For their conservative estimates of storage resources in each member state, they typically use a reduced storage efficiency factor between 1% – 20% depending on the type of aquifer system (open or closed)[21]. We have reported here the sum of their conservative estimates rather than the optimistic estimate that uses a bigger efficiency factor for each basin. Other reports provided the effective storage resource estimate for Sweden, Portugal, Austria and Ireland using a similar approach[22,24]. As a result, a total conservative effective storage resource estimate of 88 Gt in the EU (the member states, not including offshore UK or Norway) has been identified. Of this estimate, 19 Gt is available offshore of EU member states and the rest is located onshore[26,27,28,29]. 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. We have not included the storage resource available offshore of the UK in the 88 Gt estimate since the UK has officially left the EU in 2020. 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 $^{o}$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[13]. These four annual storage rate targets were determined based on the EU28 prior to the exit of the UK from the EU and 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[14].

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 without the contribution from the UK. As described in subsequent sections, we then evaluate resource use across borders with the UK and Norway and examine the potential for the North Sea alone to accommodate storage demands from the EU given that a significant proportion of the EU storage resource base is located onshore.

### 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[46]. 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[47]. 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[47,11,12]. 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[23]. These resources include basin scale formations like the open saline aquifers in the Triassic Bunter Sandstone Formation in the Southern North Sea, the Forties and Captain Sandstone formations in the Central North Sea. Moreover, low pressure depleted gas fields such as the Ormskirk sandstone and the Hamilton gas field in the East Irish Sea and the Leman sandstone in the Viking gas field both have significant storage potential. Overall, significant development opportunities have been identified to be present in both saline aquifers and depleted oil and gas fields sea that are within proximity to UK's major emission sources in the UK North Sea and the East Irish Sea[23].

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[48]. 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[14].

As a result 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[19]. Formations of Bryne and Sandnes, Utisra and Skade, and Sognefjord Delta have been identified to contribute most of the storage resource potential for saline aquifers. Within petroleum provinces, the main contribution to the storage resource comes from the Frigg Field in the Frigg-Hemidal Formation aquifer[25]. The storage resources located offshore of Norway is considered the most prospective region for geologic storage of $CO_2$ in Europe[49] 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 as opposed to linear or J-shaped exponential models which assume indefinite resource consumption[20]. Several curve-fitting models exist to describe the S-Shaped pattern, but the logistic model is the most widespread. The logistic model has been widely used to predict peak production in oil and coal consumption, and projecting long-term trends in energy systems, infrastructure, and technology development[50,51,52,53,54]

Recently, the logistic model was applied to the analysis of global carbon storage resources[20]. 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 which is key for understanding the deployment trajectory of CCS. Thus, another reason we do not use linear or exponential models here is that they cannot capture the relationship between early rates of growth and the available storage resource base.

As aforementioned, a variety of logistic-like curve-fitting models exist, i.e., Gaussian, and normal curves. The differences between these models are significant in their ability to fit existing data or when used to predict future production and peak years[52,55]. However, our purpose here is to explore a range of regional short-term growth trajectories of CCS that are dependent on fixed constraints of storage resources available[19]. A modelling approach developed by Ringrose and Meckel made use of historical rates of hydrocarbon well construction in major oil and gas provinces to demonstrate potential development trajectories of global cumulative $CO_2$ injection[56]. They reached similar conclusions as to the analysis of global storage resources and growth trajectories as Zahasky & Krevor[20] despite the distinct approaches.

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.

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

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

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

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

We take the inflection point to represent the time at which growth begins to deviate significantly below exponential growth. This occurs when approximate 20% of the resource base is used.

Equation 1 and 2 describe a simple, three-parameter 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[50,52]. However, this is not a particular weakness of the model for our purpose. Due to the lack of historical CCS development, this model is not used to predict likely trajectories, but rather to identify constraints of minimum sustained growth rates required to meet climate change mitigation targets, and the minimum associated resource base needed to support those trajectories[20].

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 in injection rates 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, a key feature of the logistic model is the inclusion of the tradeoff between initial annual growth rates and storage resource requirements in the definition of growth trajectories.

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.

The logistic modelling framework is ultimately a statistical model and comes with associated limitations. First, we avoid using the model for monitoring targets that are earlier than 2050; early growth rates in technology often fluctuate dramatically and the model does not include any exogenous economic or political factors that could impact near-term trajectories of $CO_2$ storage rates. Second, the lack of data for storage resources, or deployment plans for CCS in some regions means that there is a limit to the spatial resolution that can be achieved, e.g., we did not find it useful in application to most individual EU member states. Finally, we do not consider trajectories where the inflection point (the time at which growth falls below the exponential trend) occurs before 2050. If trajectories begin to decline prior to 2050, due to an unexpected severe limitation in storage resource availability, CCS might not be considered by major industry players as a feasible long-term option. Therefore, we add a constraint to all models that inflection points of storage rates must occur post-2050.

### 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 (constraint 1 in Figure 2) 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 $MtCO_2$ $yr^{-1}$; constraint 2 in 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 since 2030. 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.

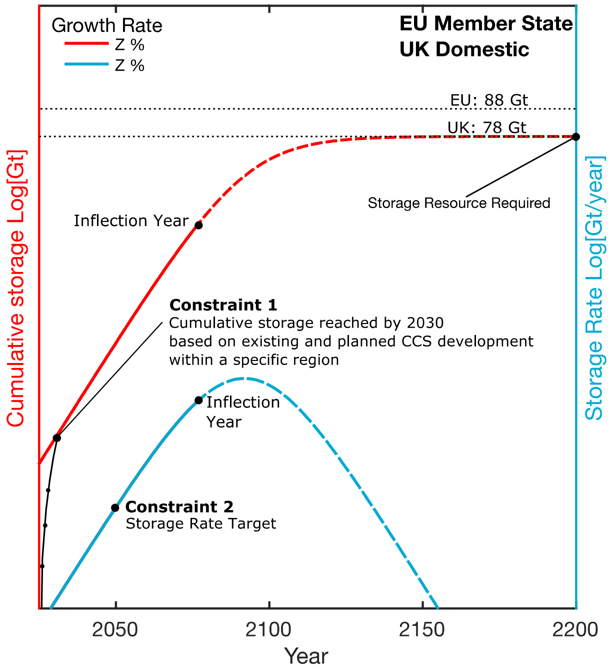


Figure 2: Schematic plot illustrating the key constraints and features of the logistic growth model. Cumulative $CO_2$ storage is shown in red (Equation 1) and the annual injection rate in blue (Equation 2). Black dots indicate the cumulative storage from existing or planned CCS development within a region. 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, we evaluate 12 storage scenarios (constraint 2 in

Figure 3) combining the three UK scenarios from the UK Committee on Climate Change[11] and the four EU scenarios from the European Commission and Shell[9,13]. Furthermore, growth trajectories subjected to 10% of storage resources available in the UK, Norway and the combined storage resource of the UK and Norway are explored.

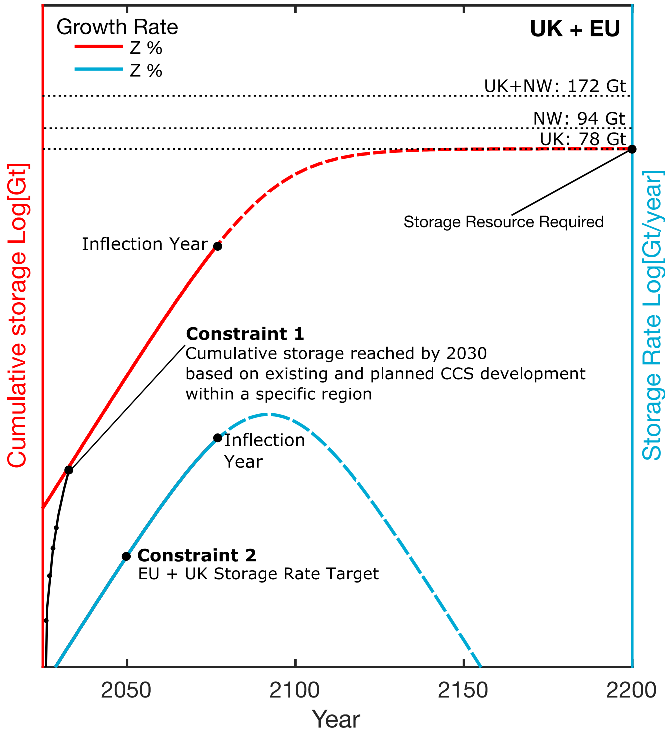


Figure 3: Schematic plots of analysis for the 'EU + UK Scenarios' illustrating each constraint used on an exemplary growth trajectory of Z%. Note that the plot is illustrative, so numbers are not included for the vertical axes, but curves are shown for plots with logarithmic vertical axes.

| '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 four EU scenarios and the three UK scenarios. Each group contains 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.9.

## 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 in injection rates, 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 resources required for a fixed 2050 storage rate target (Figure 4). We represent individual scenarios with points on the graph (red point in Figure 4).

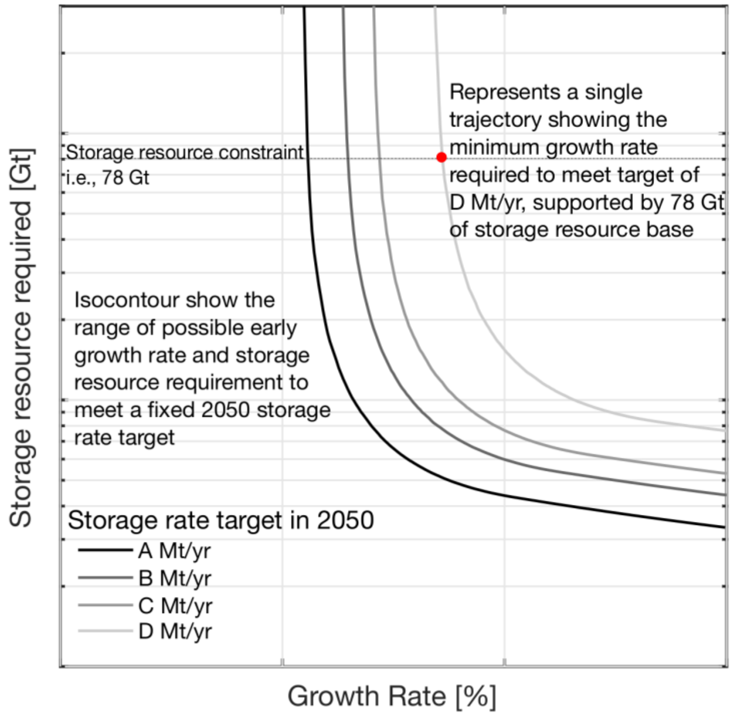


Figure 4: An example of a tradeoff graph between post-2030 growth rates and the storage resource required to support that growth. The thick grey lines are isocontours of storage rate targets in 2050. The coloured point corresponds to a single trajectory, i.e., Fig.3. Note that this is illustrative, and 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.[13] (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[14,15] and we use this as the starting point for modelled trajectories (black marker at 2030 on the cumulative graph in Figure 5). 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 3. The range of minimum rates to achieve EU1-4 (80 - 330 $MtCO_2$ $yr^{-1}$ in 2050) are 9.5% - 14.7% (green curves in Figure 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 in the EU including onshore storage resources[21,22,24]. However, given that current storage resource estimates are inherently uncertain, applying conservative constraints on the storage resource available to just 10%

of 88 Gt results in the need for higher initial growth rates, 10.1% - 17.2% for EU1-4 (purple curves in Figure 5), albeit sustained for much shorter periods. The inflection years (black dots on the rate graph in Figure 5) 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.

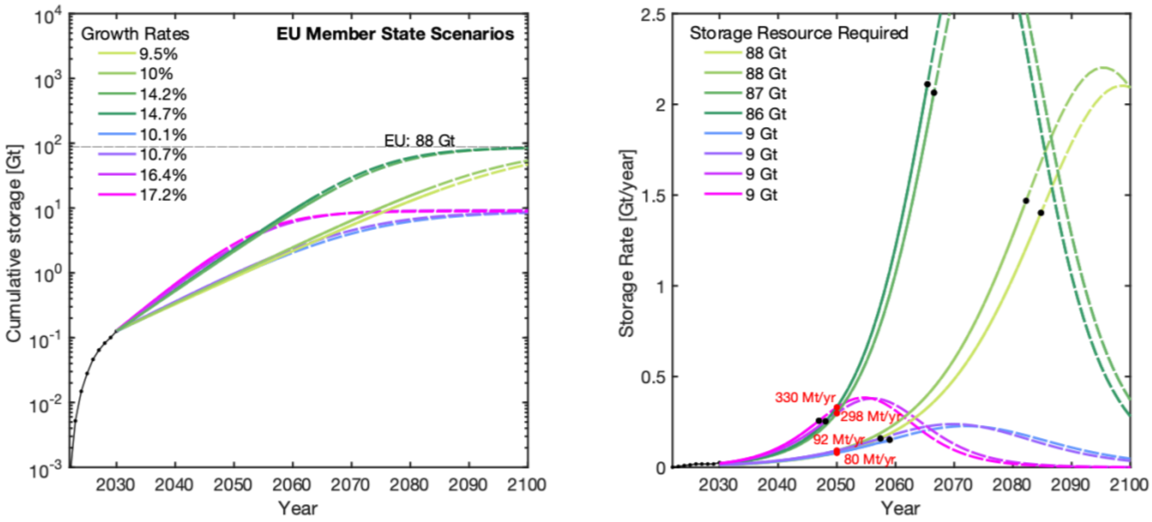


Figure 5: (Left) Cumulative $CO_2$ storage as a function of time for EU Member State scenarios. (Right) EU member state $CO_2$ storage rate as a function of time for various growth scenarios. We compare the range of growth rates required to meet storage rate targets of EU1-4 (80 - 330 $MtCO_2$ $yr^{-1}$), indicated by the red points, at two storage resource bounds: 88 Gt (entire EU) and 9 Gt (10% of current best estimate). 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. The hyperexponentially distributed isocontours indicate the pattern where the higher the initial growth rate reached by 2030, the lower the storage resource requirement to support that given growth rate. The initial steep slopes of the isocontours indicate the rate of change in growth rate is very slow compared to the rate of change in storage resource requirement; this suggests the target is growth rate limited. For the horizontal portion of the curve, storage resource limitations occur where the rate of change in storage resource requirement is very minimal whilst the rate of change in growth rate is substantial. Points illustrate those particular scenarios shown in Figure 5 where growth rates are minimised making use of either all (green points) or just 10% of the estimated storage resource base (purple points). When constrained at 88 Gt, 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[57]. If only offshore storage resource is available in the EU, the growth rate required to meet EU1-4 is within a similar range of 10% - >15%. Additionally, Figure 6 shows that if <7 Gt of $CO_2$ storage resources is identified, then EU3 and EU4 become significantly difficult to achieve from a growth rate perspective – rates of growth that are >20% are ultimately required. This is the case for EU1 and 2 if <2 Gt of storage resource is developed.

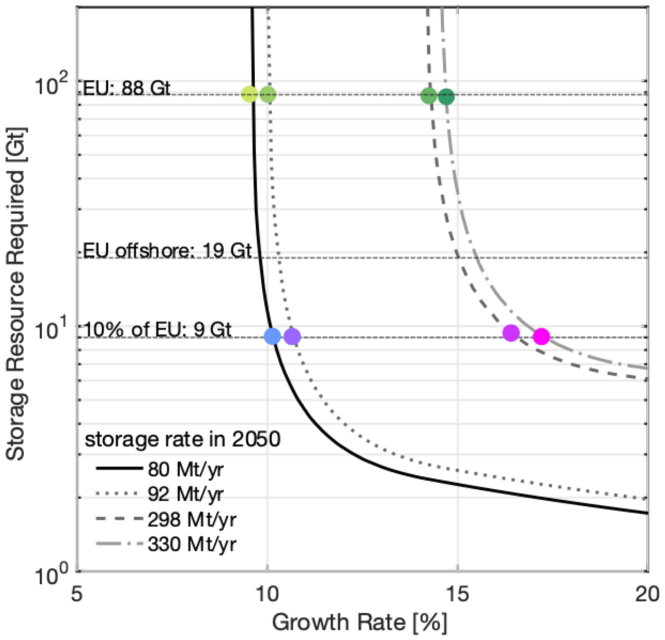


Figure 6: Tradeoff between storage resource requirements and early growth rates for EU member state scenarios. The grey lines show isocontours of trajectories that meet storage rate targets in 2050. The difference in the level of ambition between the targets for the range of growth rate and storage resource requirement is illustrated; higher targets of 298 Mt $yr^{-1}$ and 330 Mt $yr^{-1}$ are more demanding from a growth rate perspective. Higher growth rates are required when storage resource available is limited (indicated by the purple points)

| *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[14,15] (black marker at 2030 on the cumulative graph in Figure 7). 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. In contrast, limiting the resource base to just 10% of the currently estimated 88 Gt 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.

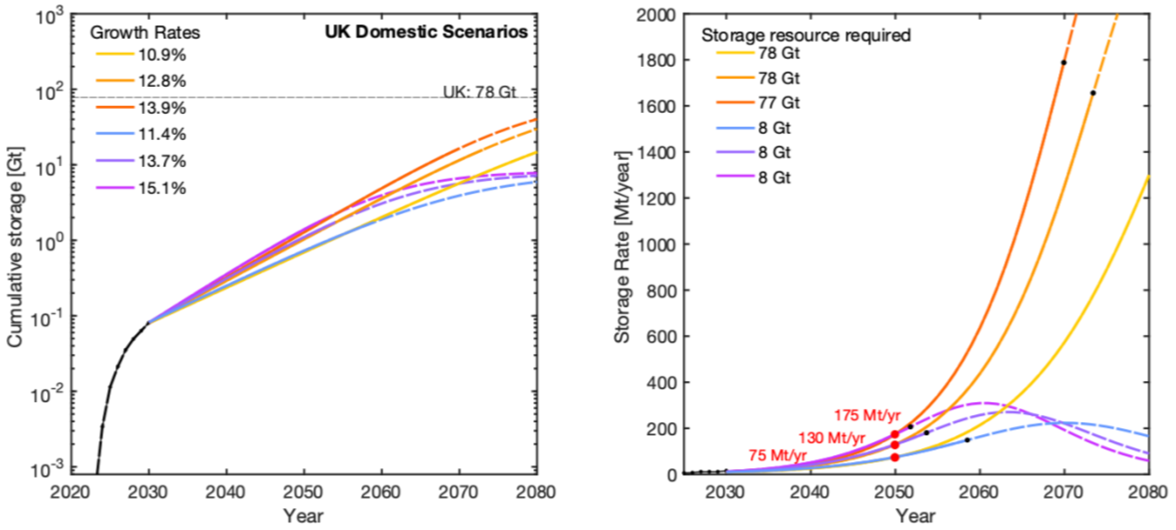


Figure 7: (Left) Cumulative $CO_2$ storage for the UK domestic scenarios. (Right) $CO_2$ storage rate for the UK domestic scenarios. We compare the range of growth rates required to meet storage rate targets of UK1-3 (75 - 175 $MtCO_2$ $yr^{-1}$), indicated by the red points, at two storage resource bounds: 78Gt (UK offshore) and 8 Gt (10% of current best estimate).

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 (orange and purple points) require sustained annual growth between 11% - 15% regardless of the available storage resource base (78 Gt or 8 Gt). The difference in growth rate requirement illustrated by the purple and orange points suggest that the effect of storage resource limitation is more significant for the target of UK3. For all targets to be feasible from a growth rate perspective, at least 4 Gt of storage resource must be developed in the UK.

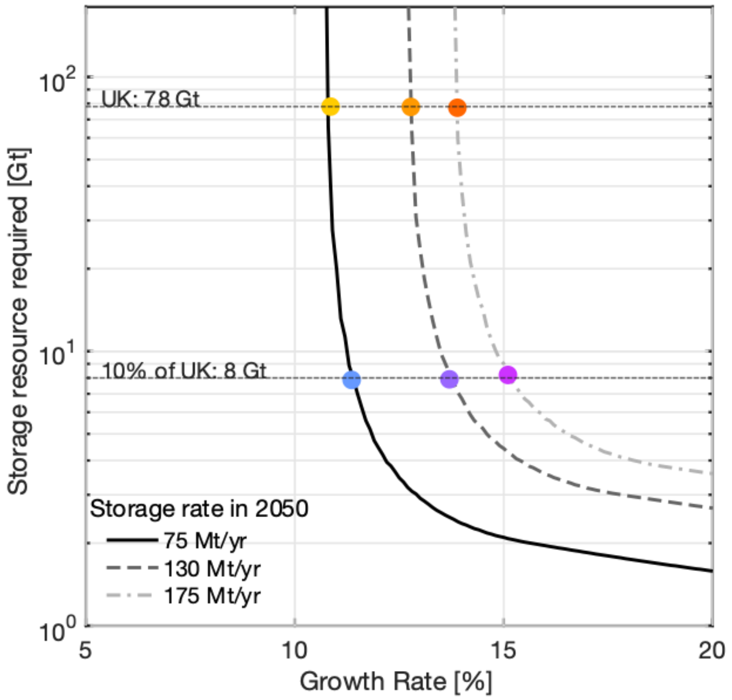


Figure 8: Tradeoff between storage resource requirements and early growth rates for UK domestic scenarios. The solid grey lines show the storage resource required as a function of post-2030 growth rates to reach the storage rate targets in 2050.

| *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 9 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 limits imposed by the geology to scaleup would only emerge if there were major overestimates in the current resource assessment. 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. A smaller storage resource base 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

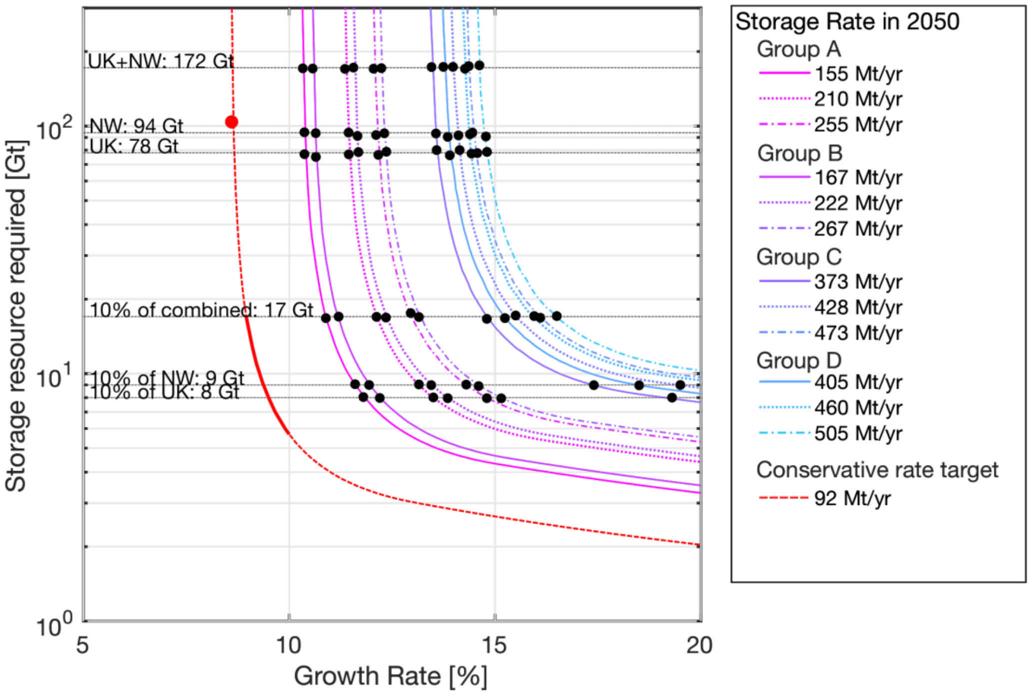


Figure 9: Tradeoff between storage resource requirement and growth rates for the four groups of combined "EU + UK" storage targets for 2050 indicated by the legend (See Tables 2 for associated targets). The black points correspond to minimal growth rates subject to various storage resource constraints (See Table 5 for values of minimum growth rates).

| *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 5 and 7). Others have shown that the scale of subsurface engineering required is precedented[57]. Indeed, oil production from 1901 sustained a 15% average annual growth for 40 years[58]. However, market conditions driving the expansion of the demand for oil, which include the first World War, and relatively few limitations ensuring safety or environmental standards, reveal the magnitude of incentivisation required to achieve such growth[59,60].

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 9). Significant limits imposed by geology 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%[20]. 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 9) 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 of growth; minimum average annual growth in injection capacity from 2030 through 2050 needs to achieve 10%-15% to meet European targets. 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. Storage resource limitations will only 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. Comparing these modelled growths with the production growth rates achieved by the petroleum industry reveals that wartime-like mobilisation of supply chain and manufacturing capacity may be required to meet published storage targets in Europe. 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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