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This manuscript is a peer-reviewed preprint submitted to EarthArXiv

## European carbon storage resource requirements of climate change mitigation targets

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29 HIGHLIGHTS

- 30 • European CCS plans imply >9% annual growth in injection rates from 2030-2050
- 31 • The resource base of either offshore Norway or the UK alone can meet scaleup needs
- 32 • Logistic models provide a simple framework to evaluate European CO<sub>2</sub> storage scale-up
- 33 • Growth models can be used to constrain output from energy systems models

34

35 ABSTRACT

36 As a part of climate change mitigation plans in Europe, CO<sub>2</sub> storage scenarios have been reported for  
37 the United Kingdom and the European Union with injection rates reaching 75 – 330 MtCO<sub>2</sub> yr<sup>-1</sup> by 2050.  
38 However, these plans are not constrained by geological properties or growth rates with precedent in  
39 the hydrocarbon industry. We use logistic models to identify growth trajectories and the associated  
40 storage resource base consistent with European targets. All of the targets represent ambitious growth,  
41 requiring average annual growth in injection rates of 9% – 15% from 2030-2050. Modelled plans are  
42 not constrained by CO<sub>2</sub> storage availability and can be accommodated by the resources of offshore UK  
43 or Norway alone. Only if the resource base is significantly less, around 10% of current estimates, does  
44 storage availability limit mitigation plans. We further demonstrate the use of the models to define 2050  
45 rate targets within conservative bounds of both growth rate and storage resource needs.

46

47 Keywords: CO<sub>2</sub> storage; Logistic modelling; Storage resource requirement; Growth rates; Mitigation  
48 targets; Europe

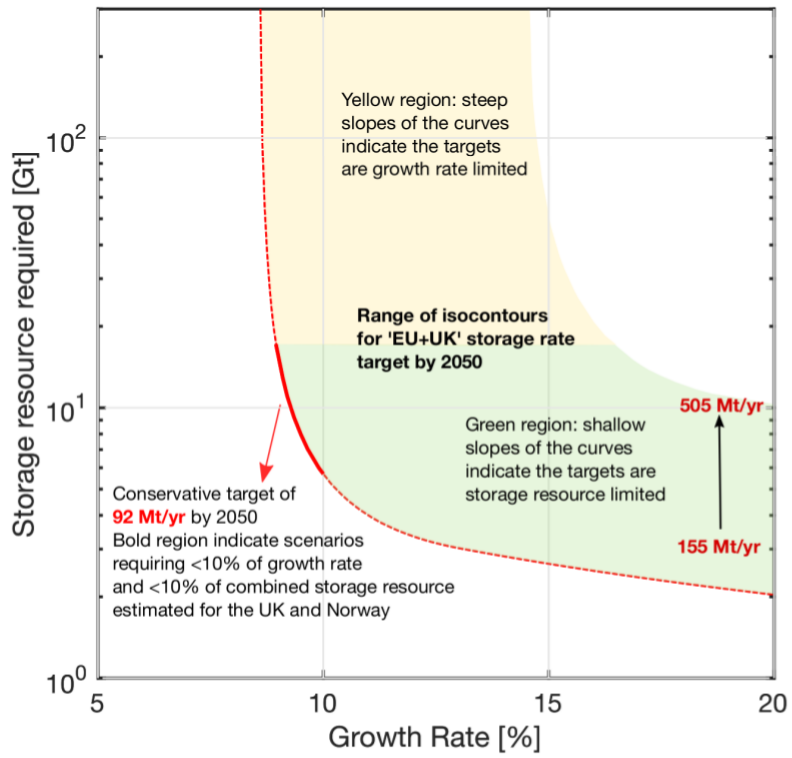
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## 67 1 INTRODUCTION

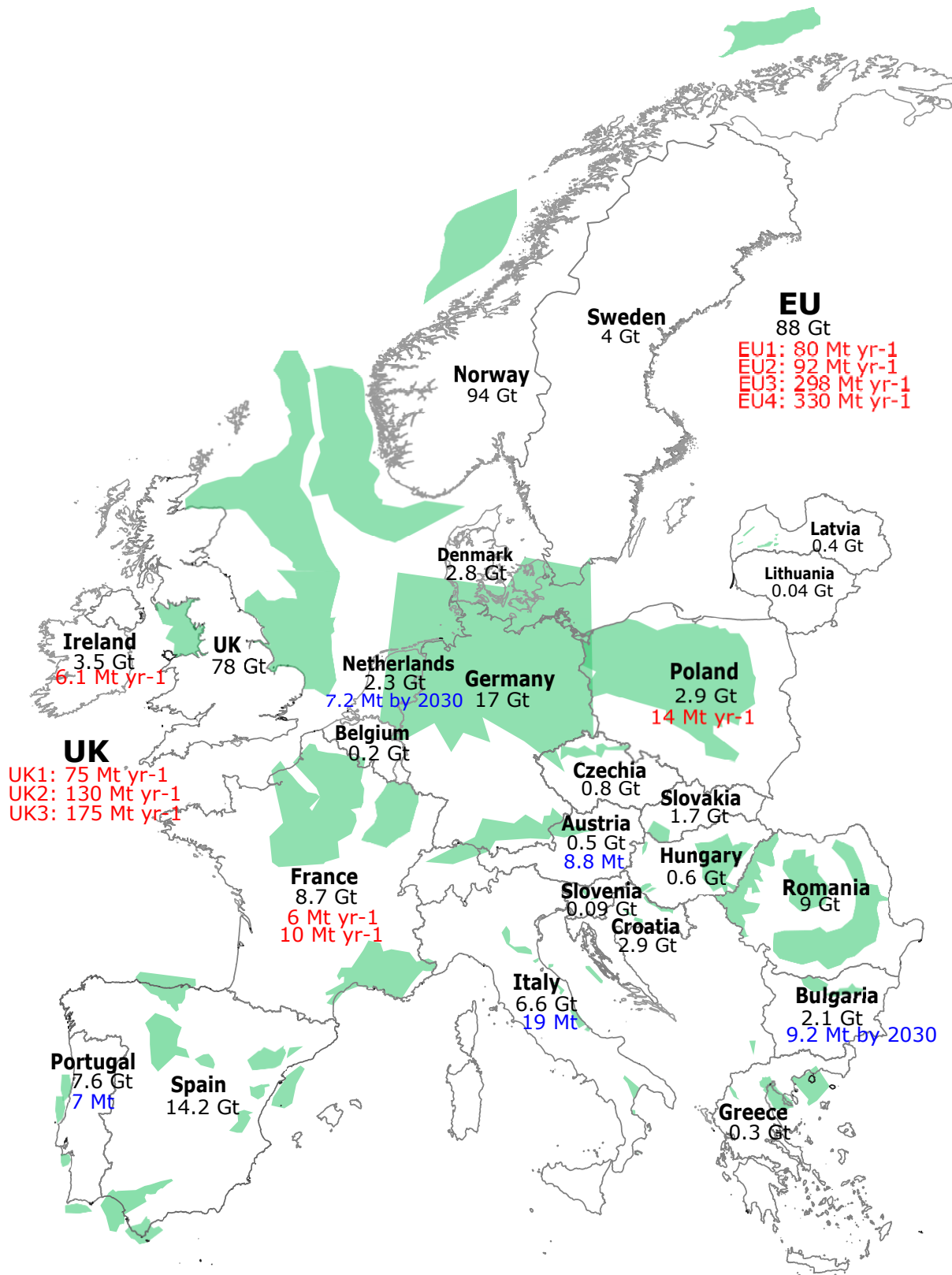
68 Very large-scale carbon capture and geological storage (CCS) may be needed to mitigate  
69 climate change<sup>1,2,3,4,5,6,7</sup>. Assessments of technological pathways available for limiting global warming  
70 to less than 1.5 °C and 2°C suggest that CO<sub>2</sub> may be injected underground at rates of 10 Gt per year by  
71 mid-century, and that >1000 Gt will need to have been stored by the end of the century<sup>7</sup>. This is a  
72 similar scale to that of the fluids currently being handled by the hydrocarbon industry globally<sup>8</sup>. The  
73 European Union (EU) and the United Kingdom (UK) have a commensurate scale of carbon storage in  
74 their climate change mitigation plans including scenarios with combined over 500 Mt CO<sub>2</sub> injected  
75 underground per year by 2050 (Figure 1; Table 1)<sup>9,10,11,12,13</sup>.

76 There are several indications that this scale of deployment is achievable. There are currently  
77 26 facilities around the world with injection rate capacities ranging from 0.5 – 2 Mt yr<sup>-1</sup> demonstrating  
78 the large-scale use of CCS technology<sup>14</sup>. Within Europe, there are two operational CCS facilities in  
79 Norway (Sleipner and Snøhvit) and one in Croatia; these three projects have a combined injection  
80 capacity of 1.7 Mt yr<sup>-1</sup><sup>14,15</sup>. Global estimates of storage resources suggest there are vast volumes of  
81 pore space underground suitable for sequestering CO<sub>2</sub>. We adopt the definition of resources from the  
82 classification framework of the CO<sub>2</sub> Storage Resources Management System<sup>16</sup>. Recent evaluations  
83 identify a storage resource base between 10,000 – 30,000 Gt available worldwide<sup>17,18,19</sup>. This is  
84 potentially 3 – 10 times more than the maximum global storage resources needed to support the  
85 most aggressive CO<sub>2</sub> storage scaleup trajectories identified by the IPCC, limiting global warming to less  
86 than 2°C<sup>20</sup>. The combined estimate of effective storage resources in Europe is 260 Gt, including  
87 resources distributed among EU member states for both onshore and offshore (88 Gt in total), and  
88 offshore UK (78 Gt) and Norway (94 Gt; Figure 1)<sup>19,21,22,23,24,25</sup>. However, concerns over onshore  
89 storage of CO<sub>2</sub> in the EU, e.g., by the European Commission<sup>26</sup>, could limit its use to offshore resources  
90 alone (19 Gt, or 22% of the total, for EU member states<sup>21,27,28,29</sup>).

91 At the same time, there are significant uncertainties in the scaleup of CCS to achieve climate  
92 change mitigation targets. It has been recognised that current integrated assessment models (IAMs)  
93 that identify scaleup trajectories for CO<sub>2</sub> storage contain gaps in the representation of realistic  
94 consumption of depletable natural resources<sup>30,31</sup>. The constraints used in IAMs to determine  
95 deployment projections of technologies are predominantly costs. For CCS, while some IAMs do  
96 include an upper limit on available storage resources or a maximum injection rate, these are only  
97 single-value constraints<sup>5, 32</sup>. As a comparison, the upscaling of other low-carbon technologies i.e., solar  
98 and wind technologies in IAMs are constrained by a historical annual growth limit i.e., 10% yr<sup>-1</sup><sup>32</sup>.  
99 Zahasky and Krevor<sup>20</sup> have further pointed out that estimates of storage resources based on

100 geological features alone are inherently uncertain and can range in up to two orders of magnitude. As  
101 a result, geological considerations alone are insufficient to describe actual development trajectories  
102 of CCS. Rather, there is a range of factors that could potentially limit the growth of subsurface storage  
103 sites, including the geophysical limit to the injectivity rate of CO<sub>2</sub> as a result of the pressurisation of  
104 the reservoir in repose to injection, latencies in project development, i.e., the discovery and appraisal  
105 of suitable injection sites, and a combination of economic, social, and political constraints  
106 <sup>33,34,35,36,37,38,39,40,41</sup>. The amount of CO<sub>2</sub> stored underground in IAMs or regional or national energy  
107 systems models does not reflect attributes from these potentially limiting processes<sup>42</sup>.

108           In this work, we make use of the logistic growth model – a simple framework that has been  
109 widely used in analogous industries, like the oil and gas industry, to investigate plausible growth  
110 trajectories for the scaleup of CO<sub>2</sub> storage in the UK and the EU that are identified in climate change  
111 mitigation roadmaps. Under the logistic modelling framework, the impacts of geophysical and  
112 engineering limitations to subsurface resource management are combined with non-geological  
113 factors like securing finance and navigating governmental regulations to determine deployment  
114 trajectories <sup>20,43,44</sup>. Furthermore, this model is particularly useful for understanding the  
115 interconnections between early growth rate, the duration of sustained exponential growth, and the  
116 size of the resource base required to support that growth, a relationship not currently captured by  
117 the energy systems models and IAMs. While mature industries can make use of data from the  
118 historical development to use logistic models predictively, this is not possible for the emerging CO<sub>2</sub>  
119 storage industry. Rather, we use the models to apply a range of storage resource constraints and to  
120 identify limiting features – minimum growth rates supported by the available storage resource base  
121 that is consistent with CO<sub>2</sub> storage rate targets published in climate change mitigation plans for the  
122 UK and the European Union. This allows us to place these plans in the context of historical growth in  
123 analogous technologies, the estimates for the CO<sub>2</sub> storage resource base in each region, and to  
124 specify quantitatively the role that the UK and Norwegian continental shelf will need to play as a  
125 storage hub for emissions from the EU. Additionally, we show how the framework can be used to  
126 identify storage scaleup scenarios subject to conservative limitations of rates of growth and storage  
127 resource requirements.



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 Storage Resource Distribution

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130 Figure 1: A map of Europe showing the distribution of storage resources and the regional/national  
 131 CO<sub>2</sub> storage targets for 2050 unless indicated otherwise (storage rate targets in red and cumulative  
 132 storage targets in blue). Green polygons indicate major storage resource locations comprising  
 133 predominately of saline aquifers. The total effective storage resource estimated to be available in  
 134 Europe is 260 Gt. Of this estimate, 66% is located offshore of UK and Norway. A total of 88 Gt of  
 135 effective storage resources is available among Member States of the EU, however, only 22% is located  
 136 offshore.

137

<i>Storage Scenario</i>	<i>Target (MtCO<sub>2</sub> yr<sup>-1</sup>)</i>
<i>EU1</i>	80
<i>EU2</i>	92
<i>EU3</i>	289
<i>EU4</i>	330
<i>UK1</i>	75
<i>UK2</i>	130

138 Table 1: A summary of carbon storage deployment scenarios showing the anticipated annual storage  
 139 rates of CO<sub>2</sub> in 2050 in the EU<sup>9,13</sup> and the UK<sup>11,12</sup>.

140

## 141 2 METHODS

### 142 2.1 Identifying resources, targets, and plans of CO<sub>2</sub> storage in the European Union

143 The majority of the storage potential of EU member states was estimated by the EU  
 144 GeoCapacity consortium<sup>21</sup>. Of the three reservoir types analyzed by the EU GeoCapacity consortium,  
 145 which are deep saline aquifers, depleted hydrocarbon fields and unmineable coal beds, storage  
 146 resources in deep saline aquifers constitute 85% of the total estimate for the EU (88 Gt). As a result,  
 147 the approach and assumptions used to estimate storage resources in deep saline aquifers are the  
 148 most significant. In the GeoCapacity database, estimates of storage resources in deep saline aquifers  
 149 are based on formulas provided by Bachu et al.<sup>45</sup>. The initial potential storage sites and sealing units  
 150 are determined through a screening process using a cut-off criterion. Subsequently, the effective  
 151 estimates of storage resources for each structural or stratigraphic trap are determined volumetrically  
 152 by applying a storage efficiency factor. In GeoCapacity's assessment, they have used trap specific

153 storage efficiency factors which vary depending on the assumption of whether the aquifer system is  
154 open/semi-closed or closed. For their conservative estimates of storage resources in each member  
155 state, they typically use a reduced storage efficiency factor between 1% – 20% depending on the type  
156 of aquifer system (open or closed)<sup>21</sup>. We have reported here the sum of their conservative estimates  
157 rather than the optimistic estimate that uses a higher efficiency factor for each basin. Other reports  
158 provided the effective storage resource estimate for Sweden, Portugal, Austria and Ireland using a  
159 similar approach<sup>22,24</sup>. As a result, a total conservative effective storage resource estimate of 88 Gt in  
160 the EU (the member states, not including offshore UK or Norway) has been identified. Of this  
161 estimate, 19 Gt is available offshore of EU member states and the rest is located onshore<sup>26,27,28,29</sup>.  
162 Figure 1 displays a map of Europe summarising the national and regional targets, and the storage  
163 resource available in the indicated region or country. For EU member states of Estonia, Finland,  
164 Malta, Cyprus, and Luxembourg there are no indications of national targets, storage resource  
165 estimations, or CCS development. We have not included the storage resource available offshore of  
166 the UK in the 88 Gt estimate as the UK has officially left the EU in 2020. Therefore, our analysis of the  
167 EU only refers to the remaining 22 member states.

168 The European Commission strategic long-term report, ‘A Clean Planet for All’, outlined the  
169 decarbonization pathways for the EU to achieve net-zero commitments<sup>9</sup>. In this report, three CO<sub>2</sub>  
170 storage targets stating that in 2050, injection rates of 80, 92, and 298 MtCO<sub>2</sub> yr<sup>-1</sup> will be necessary to  
171 limit warming to 2 °C. Another decarbonization scenario was created by Shell International B.V for the  
172 entire world, but identifying emissions reductions associated with particular geographic regions. In  
173 Europe, the Shell Sky Scenario in 2018 anticipates an even more ambitious storage rate target of 330  
174 MtCO<sub>2</sub> yr<sup>-1</sup> for 2050<sup>13</sup>. These four annual storage rate targets were determined based on the EU28  
175 prior to the exit of the UK from the EU and are subsequently referred to as EU1-4 (Fig. 1; Table 1). To  
176 date, there is one operational CCS facility and 13 planned CCS facilities in the EU by eight member  
177 states of Ireland, France, Belgium, Croatia, Italy, Sweden, Denmark and the Netherlands<sup>14</sup>.

178 From this data, we analyse a group of scenarios that we refer to as the ‘EU Member State  
179 Scenarios’. With the EU scenarios, we determine a range of growth rates and the necessary storage  
180 resource requirements needed to meet EU-wide storage rate targets. We place this in the context of  
181 storage resources identified within EU states without the contribution from the UK. As described in  
182 subsequent sections, we then evaluate resource use across borders with the UK and Norway and  
183 examine the potential for the North Sea alone to accommodate storage demands from the EU given  
184 that a significant proportion of the EU storage resource base is located onshore.

185 2.2 Identifying resources, targets, and plans of CO<sub>2</sub> storage in the United Kingdom



186 A landmark commitment to the mitigation of climate change in the UK was the 2008 Climate  
187 Change Act<sup>46</sup>. With this, the UK became the world's first major economy to pass a law requiring a  
188 reduction in greenhouse gas emissions by 80% compared to 1990 levels by 2050<sup>47</sup>. Carbon capture  
189 and storage has been identified by the UK parliament as a critical technology to facilitate the nation's  
190 climate commitments. Similar to the EU, three storage rate targets have been identified; 75, 130, or  
191 175 MtCO<sub>2</sub> yr<sup>-1</sup> by 2050<sup>47,11,12</sup>. These three storage rate targets are hereafter referred to as UK1-3  
192 respectively (Fig. 1; Table 1).

193 Although the UK does not currently have an operating CO<sub>2</sub> storage facility, four industrial  
194 clusters have been announced, which aim to reach a storage rate of 10 MtCO<sub>2</sub> yr<sup>-1</sup> by 2030<sup>10</sup>. Storage  
195 resources for the UK are mostly located in the UK North Sea and the East Irish Sea. An inventory of  
196 579 sites has been compiled with an estimated combined storage resource of 78 Gt<sup>23</sup>. These  
197 resources include basin scale formations like the open saline aquifers in the Triassic Bunter Sandstone  
198 Formation in the Southern North Sea, the Forties and Captain Sandstone formations in the Central  
199 North Sea. Moreover, low pressure depleted gas fields such as the Ormskirk sandstone and the  
200 Hamilton gas field in the East Irish Sea and the Leman sandstone in the Viking gas field both have  
201 significant storage potential. Overall, significant development opportunities have been identified to  
202 be present in both saline aquifers and depleted oil and gas fields sea that are within proximity to UK's  
203 major emission sources in the UK North Sea and the East Irish Sea<sup>23</sup>.

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

### 210 2.3 Identifying carbon dioxide storage resources in Norway

211 Norway has played a central role in the demonstration of industrial-scale CO<sub>2</sub> storage. The  
212 Norwegian government, from as early as 1989, identified CCS as a key innovation technology to  
213 reconcile ambitious climate targets with the growing emissions from the country's hydrocarbon  
214 industry<sup>48</sup>. There are two operating CO<sub>2</sub> storage projects in Norway, Sleipner and Snøhvit, which have  
215 been operating since 1996 and 2008, respectively. A new full-scale CCS project called Longship has  
216 been announced in 2020 and aims to begin operation by 2024 to further help Norway meeting its  
217 climate targets<sup>14</sup>.

218 As a result of the relatively small greenhouse emissions originating in Norway, in this analysis,  
219 we only consider storage resources as potentially contributing to the EU and UK climate change  
220 mitigation targets. Similar to the UK, a vast quantity of resources for CO<sub>2</sub> storage (94 Gt) is available  
221 offshore Norway<sup>19</sup>. Formations of Bryne and Sandnes, Utisra and Skade, and Sognefjord Delta have  
222 been identified to contribute most of the storage resource potential for saline aquifers. Within  
223 petroleum provinces, the main contribution to the storage resource comes from the Frigg Field in the  
224 Frigg-Hemidal Formation aquifer<sup>25</sup>. The storage resources located offshore of Norway is considered  
225 the most prospective region for geologic storage of CO<sub>2</sub> in Europe<sup>49</sup> and could play a significant role in  
226 offsetting EU-wide industrial emissions. Here, we explore the extent to which the Norwegian storage  
227 resources enhance the viability of large-scale CO<sub>2</sub> storage within Europe, combining mitigation targets  
228 from the EU and UK.

## 229 2.4 Growth modelling with logistic curves

230 Consumption of finite natural resources often follows a pattern starting with a period of  
231 exponential growth (annual growth at a constant rate) and subsequently a slowdown in the early  
232 growth rate or even a decline as market conditions shifts or resource availability declines. As a result,  
233 S-shaped curves are commonly used to describe the cumulative exhaustion of a resource as opposed  
234 to linear or J-shaped exponential models which assume indefinite resource consumption<sup>20</sup>. Several  
235 curve-fitting models exist to describe the S-Shaped pattern, but the logistic model is the most  
236 widespread. The logistic model has been widely used to predict peak production in oil and coal  
237 consumption, and projecting long-term trends in energy systems, infrastructure, and technology  
238 development<sup>50,51,52,53,54</sup>

239 Recently, the logistic model was applied to the analysis of global carbon storage resources<sup>20</sup>.  
240 In this context, the model can be used to approximate the relationship between the growth needed  
241 to achieve near-term scaleup targets and the resource base that would be required to support that  
242 growth which is key for understanding the deployment trajectory of CCS. Thus, another reason we do  
243 not use linear or exponential models here is that they cannot capture the relationship between early  
244 rates of growth and the available storage resource base.

245 As aforementioned, a variety of logistic-like curve-fitting models exist, i.e., Gaussian, and  
246 normal curves. The differences between these models are significant in their ability to fit existing data  
247 or when used to predict future production and peak years<sup>52,55</sup>. However, our purpose here is to  
248 explore a range of regional short-term growth trajectories of CCS that are dependent on fixed  
249 constraints of storage resources available<sup>19</sup>. A modelling approach developed by Ringrose and Meckel

250 made use of historical rates of hydrocarbon well construction in major oil and gas provinces to  
 251 demonstrate potential development trajectories of global cumulative CO<sub>2</sub> injection<sup>56</sup>. They reached  
 252 similar conclusions as to the analysis of global storage resources and growth trajectories as Zahasky &  
 253 Krevor<sup>20</sup> despite the distinct approaches.

254 The model is outlined in Equations 1 and 2 specifying the cumulative storage,  $P(t)$  [GtCO<sub>2</sub>],  
 255 and storage rate,  $Q(t)$  [GtCO<sub>2</sub> yr<sup>-1</sup>] of CO<sub>2</sub> sequestration as a function of time,  $t$  [yr]. The curves are  
 256 initially exponential, characterised by an early annual growth rate,  $r$  [yr<sup>-1</sup>]. As the peak time,  $t_p$  [yr], is  
 257 approached, growth rates decline and are then negative until the storage resource amount,  $C$  [Gt], is  
 258 approached.

259 
$$P(t) = \frac{C}{1 + \exp(r(t_p - t))} \dots\dots\dots(1)$$

260 
$$Q(t) = \frac{C \cdot r \cdot \exp(r(t_p - t))}{(1 + \exp(r(t_p - t)))^2} \dots\dots\dots(2)$$

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

262 
$$t_n = t_p - \ln(2 + \sqrt{3})/r \dots\dots\dots(3)$$

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

265 Equation 1 and 2 describe a simple, three-parameter symmetric logistic model, with equal  
 266 growth and decline trajectories. In practice, symmetry only occurs under a rare combination of  
 267 circumstances including undisturbed resource exploration for new reserves, consistent economic  
 268 impetus, limited innovation in resource exploration, and eventually exhaustion of the resource.  
 269 Asymmetric growth profiles frequently occur, e.g., due to innovation in resource use or decline in  
 270 market demand<sup>50,52</sup>. However, this is not a particular weakness of the model for our purpose. Due to  
 271 the lack of historical CCS development, this model is not used to predict likely trajectories, but rather  
 272 to identify constraints of minimum sustained growth rates required to meet climate change  
 273 mitigation targets, and the minimum associated resource base needed to support those trajectories<sup>20</sup>.

274 Historical development in analogous industries like the oil and gas sector shows an important  
 275 interlink between the growth pattern and the physical quantity of the resources available. In other  
 276 words, the growth trajectory used to achieve a certain storage target is dependent on both the size of  
 277 the storage resource base and the storage rate target (or cumulative target) in a given year. Sustained

278 annual growth in injection rates is dependent on a large enough resource base so that limits to  
279 growth imposed by the geology, or the practicalities of exploiting ever more marginal sites, will not be  
280 encountered. As a result, a key feature of the logistic model is the inclusion of the tradeoff between  
281 initial annual growth rates and storage resource requirements in the definition of growth trajectories.

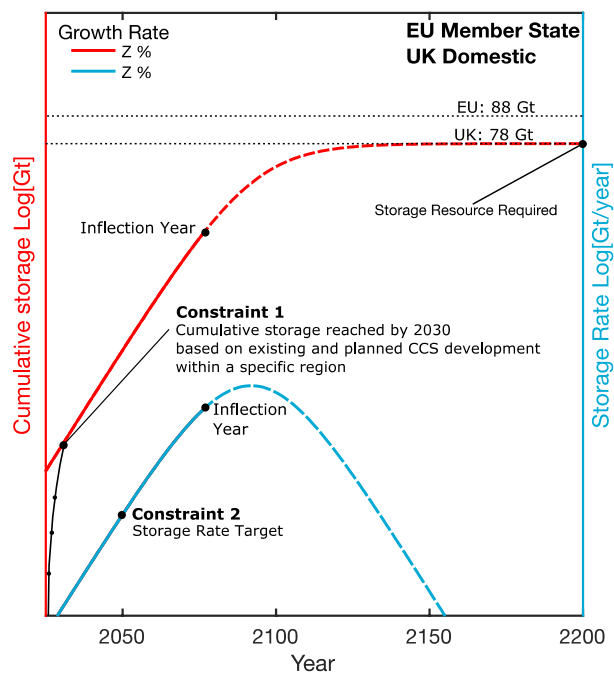
282 We numerically solve Equations 1 and 2 to meet climate change mitigation targets for a  
283 region. This identifies rate and cumulative storage trajectories that meet proposed plans. Iterating  
284 over a range of parameter space of storage resource requirement and initial (exponential) annual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

288 The logistic modelling framework is ultimately a statistical model and comes with associated  
289 limitations. First, we avoid using the model for monitoring targets that are earlier than 2050; early  
290 growth rates in technology often fluctuate dramatically and the model does not include any  
291 exogenous economic or political factors that could impact near-term trajectories of CO<sub>2</sub> storage rates.  
292 Second, the lack of data for storage resources, or deployment plans for CCS in some regions means  
293 that there is a limit to the spatial resolution that can be achieved, e.g., we did not find it useful in  
294 application to most individual EU member states. Finally, we do not consider trajectories where the  
295 inflection point (the time at which growth falls below the exponential trend) occurs before 2050. If  
296 trajectories begin to decline prior to 2050, due to an unexpected severe limitation in storage resource  
297 availability, CCS might not be considered by major industry players as a feasible long-term option.  
298 Therefore, we add a constraint to all models that inflection points of storage rates must occur post-  
299 2050.

## 300 2.5 Model for the European Union targets and the domestic United Kingdom targets

301 A schematic showing constraints applied to the logistic model for the EU and UK scenarios is  
302 shown in Figure 2. The EU member state model is constrained by CCS activities located among EU  
303 member states (constraint 1 in Figure 2) and the four 2050 storage rate targets from the scenarios  
304 EU1 (80 MtCO<sub>2</sub> yr<sup>-1</sup>), EU2 (92 MtCO<sub>2</sub> yr<sup>-1</sup>), EU3 (298 MtCO<sub>2</sub> yr<sup>-1</sup>) and EU4 (330 MtCO<sub>2</sub> yr<sup>-1</sup>; constraint 2  
305 in Figure 2). Similar to the EU member state scenarios, two standard constraints are applied to the  
306 modelling for the domestic UK scenarios. The constraints are 1) cumulative storage reached by 2030  
307 based on planned facilities in the UK, and 2) storage rate targets of UK1 (75 MtCO<sub>2</sub> yr<sup>-1</sup>), UK2 (130  
308 MtCO<sub>2</sub> yr<sup>-1</sup>) and UK3 (175 MtCO<sub>2</sub> yr<sup>-1</sup>). The modelled scenarios identify a group of minimum growth  
309 rates supported by the maximum storage resource available (88 Gt for the EU or 78 Gt for the UK) to

310 meet the storage targets of the respective region. However, CO<sub>2</sub> storage resource assessment is also  
 311 uncertain to over an order of magnitude<sup>19</sup>. Thus, an additional conservative group of higher growth  
 312 scenarios that depend on only 10% of the currently identified storage resources are also identified.  
 313 The inflection year of each growth rate curve indicates the duration of exponential growth since 2030.  
 314 In Figure 2, we use a solid line for the part of the trajectory where storage rate growth is close to  
 315 exponential. Beyond the inflection year, the trajectory is dashed to emphasise that these are not  
 316 predictive growth trajectories but rather are used to identify the resource base required to support  
 317 the early growth.



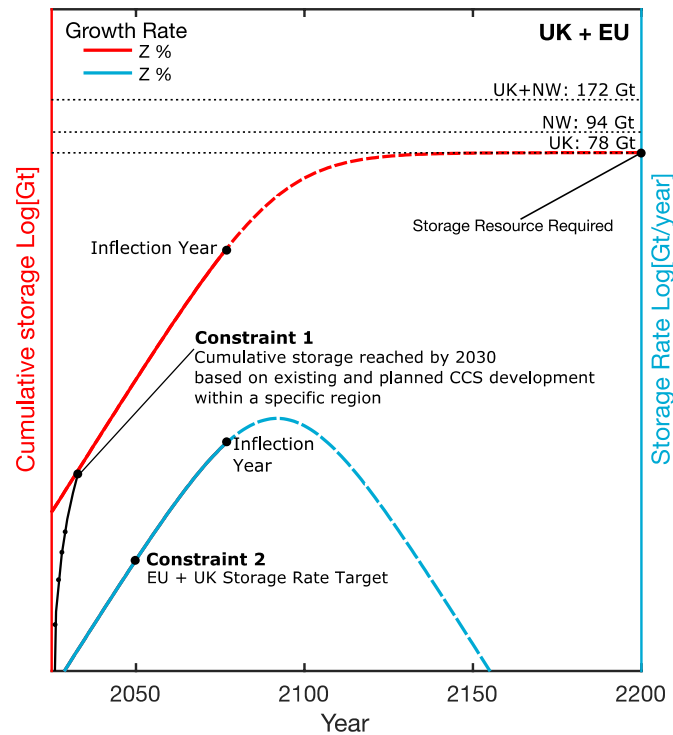
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319 Figure 2: Schematic plot illustrating the key constraints and features of the logistic growth model.  
 320 Cumulative CO<sub>2</sub> storage is shown in red (Equation 1) and the annual injection rate in blue (Equation  
 321 2). Black dots indicate the cumulative storage from existing or planned CCS development within a  
 322 region. Note that the plot is illustrative, so numbers are not included for the vertical axes, but curves  
 323 are shown for plots with logarithmic vertical axes.

## 324 2.6 Model for the UK + EU targets

325 To evaluate the potential of CO<sub>2</sub> storage resources located in the North Sea to fulfil the  
 326 combined storage needs of the UK and EU, the following constraints are used (Figure 3): first, CCS  
 327 development to establish the initial average growth rates in Europe are assembled based on existing  
 328 or planned projects announced by EU member states that are taking place in the North Sea region,  
 329 including offshore Norway and the UK. Second, we evaluate 12 storage scenarios (constraint 2 in

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



334

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

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

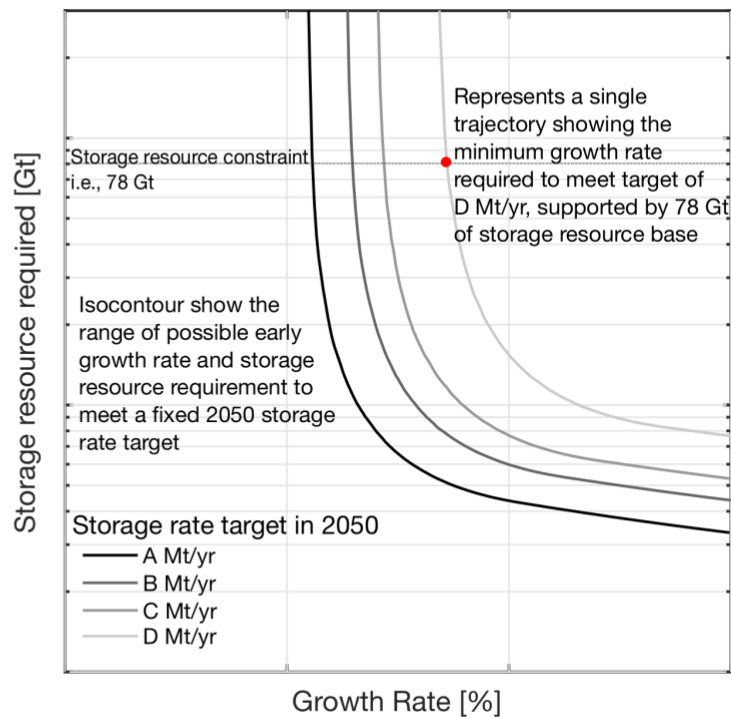
338 Table 2: The 'EU + UK' scenarios including the combined storage rate in 2050 between the four EU  
 339 scenarios and the three UK scenarios. Each group contains combinations of growth scenarios of one

340 EU storage target with all the UK targets. The colour of each target scenario corresponds to  
341 isocontours in Fig.9.

## 342 2.7 Trade-off between annual growth rate and storage resource requirements

343 In the logistic model, there is a relationship between the initial annual growth in injection  
344 rates, the duration of near-exponential growth, and the storage resource required. This is suggestive  
345 of the real-world relationships between growth trajectories and storage resources. The initial  
346 exponential phase of growth can be considered a time period during which growth limitations due to  
347 the finite nature of the resource do not impinge on the development, otherwise incentivised  
348 financially. The slow down and decline of growth reflects the challenges faced as resources are  
349 consumed. In the case of CO<sub>2</sub> storage, the highest quality reservoirs with the largest structural traps  
350 will be used before more marginal sites, e.g., in less permeable reservoirs with smaller traps.

351 While individual trajectories are of interest in considering a particular development pathway,  
352 graphs showing these trajectories in the context of the tradeoffs between storage rate and resource  
353 base provide more general information about the plausibility of the scenarios under consideration.  
354 These figures are computed for the 'EU Member State Scenarios', 'UK Domestic Scenarios' and the  
355 'EU + UK Scenarios', by finding a range of growth rates and storage resources required for a fixed  
356 2050 storage rate target (Figure 4). We represent individual scenarios with points on the graph (red  
357 point in Figure 4).



358

359 Figure 4: An example of a tradeoff graph between post-2030 growth rates and the storage resource  
 360 required to support that growth. The thick grey lines are isocontours of storage rate targets in 2050.  
 361 The coloured point corresponds to a single trajectory, i.e., Fig.3. Note that this is illustrative, and we  
 362 have kept numbers off of the axes, but the vertical axis is logarithmic and the horizontal axis linear.

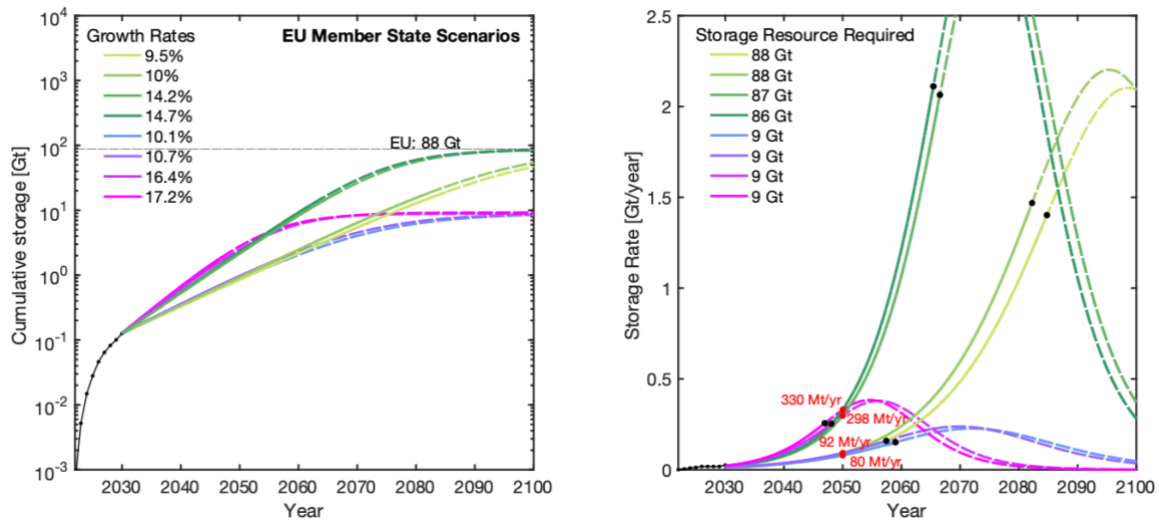
### 363 3 RESULTS

#### 364 3.1 EU Member State Scenarios

365 Storage rate target scenarios ranging from 80-330 MtCO<sub>2</sub> yr<sup>-1</sup> in 2050 have been outlined by  
 366 the European Commission<sup>9</sup> and Shell International B.V.<sup>13</sup> (Table 1). Currently announced plans for  
 367 carbon capture and storage within EU member states are commensurate with storing 126 Mt of CO<sub>2</sub>  
 368 cumulatively by 2030<sup>14,15</sup> and we use this as the starting point for modelled trajectories (black marker  
 369 at 2030 on the cumulative graph in Figure 5). We show growth in annual injection rate from 2030  
 370 onwards at a range of rates from 9.5% - 17.2% in Figure 5 and values are reported in Table 3. The  
 371 range of minimum rates to achieve EU1-4 (80 - 330 MtCO<sub>2</sub> yr<sup>-1</sup> in 2050) are 9.5% - 14.7% (green  
 372 curves in Figure 5). These depend on the existence of a storage resource base at the maximum  
 373 permitted in our model, 88 Gt, the resource currently estimated to be available in the EU including  
 374 onshore storage resources<sup>21,22,24</sup>. However, given that current storage resource estimates are  
 375 inherently uncertain, applying conservative constraints on the storage resource available to just 10%



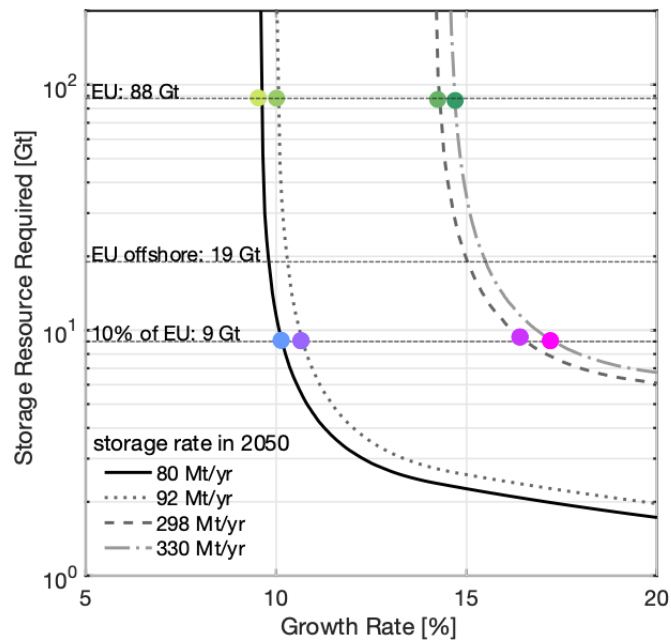
376 of 88 Gt results in the need for higher initial growth rates, 10.1% - 17.2% for EU1-4 (purple curves in  
 377 Figure 5), albeit sustained for much shorter periods. The inflection years (black dots on the rate graph  
 378 in Figure 5) indicate the points where the growth rate diverges from the exponential trend and there  
 379 are dashed lines thereafter to emphasize that these trajectories are not predictive.



380  
 381 Figure 5: (Left) Cumulative CO<sub>2</sub> storage as a function of time for EU Member State scenarios. (Right)  
 382 EU member state CO<sub>2</sub> storage rate as a function of time for various growth scenarios. We compare  
 383 the range of growth rates required to meet storage rate targets of EU1-4 (80 - 330 MtCO<sub>2</sub> yr<sup>-1</sup>),  
 384 indicated by the red points, at two storage resource bounds: 88 Gt (entire EU) and 9 Gt (10% of  
 385 current best estimate). Model parameters are provided in Table 3.

386 The range of possible initial growth rate and storage resource base combinations needed to  
 387 achieve 2050 targets are shown with isocontours in Figure 6. The hyperexponentially distributed  
 388 isocontours indicate the pattern where the higher the initial growth rate reached by 2030, the lower  
 389 the storage resource requirement to support that given growth rate. The initial steep slopes of the  
 390 isocontours indicate the rate of change in growth rate is very slow compared to the rate of change in  
 391 storage resource requirement; this suggests the target is growth rate limited. For the horizontal  
 392 portion of the curve, storage resource limitations occur where the rate of change in storage resource  
 393 requirement is very minimal whilst the rate of change in growth rate is substantial. Points illustrate  
 394 those particular scenarios shown in Figure 5 where growth rates are minimized making use of either  
 395 all (green points) or just 10% of the estimated storage resource base (purple points). When  
 396 constrained at 88 Gt, all of the 2050 targets required sustained annual growth of greater than 9.5%,  
 397 with the more ambitious targets (EU3 and EU4) requiring over 14% average annual growth for at least  
 398 20 years. While these rates are frequently seen over short timescales, sustaining them for multiple

399 decades is unusual for energy technologies<sup>57</sup>. If only offshore storage resource is available in the EU,  
 400 the growth rate required to meet EU1-4 is within a similar range of 10% - >15%. Additionally, Figure 6  
 401 shows that if <7 Gt of CO<sub>2</sub> storage resources is identified, then EU3 and EU4 become significantly  
 402 difficult to achieve from a growth rate perspective – rates of growth that are >20% are ultimately  
 403 required. This is the case for EU1 and 2 if <2 Gt of storage resource is developed.



404

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

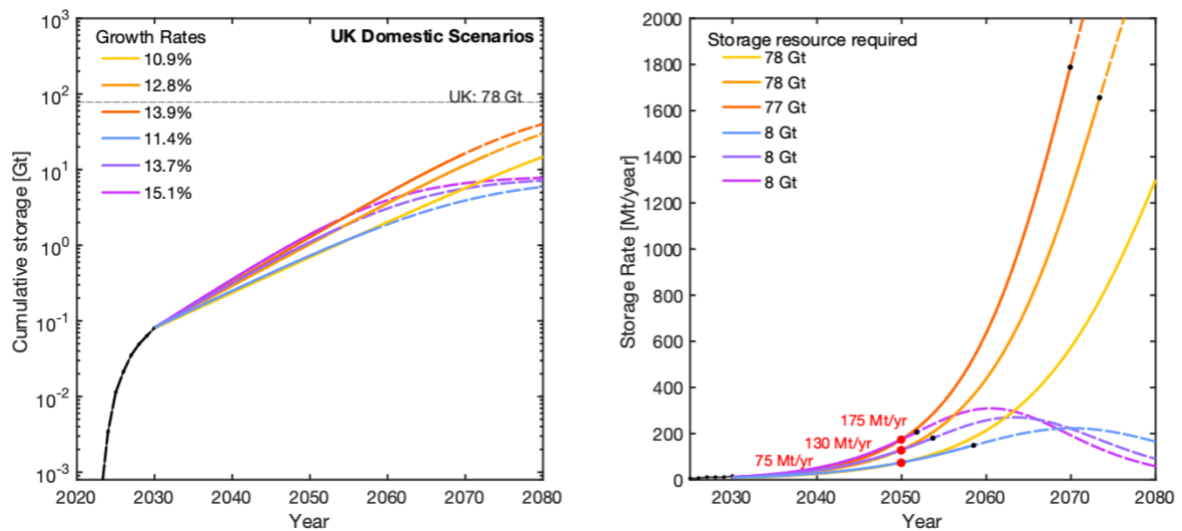
<i>Growth rate [%]</i>	<i>Storage resource required [Gt]</i>	<i>Storage rate target achieved</i>
9.5	88	EU1
10	88	EU2
14.2	87	EU3
14.7	86	EU4
10.1	9	EU1
10.7	9	EU2

16.4	9	EU3
17.2	9	EU4

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

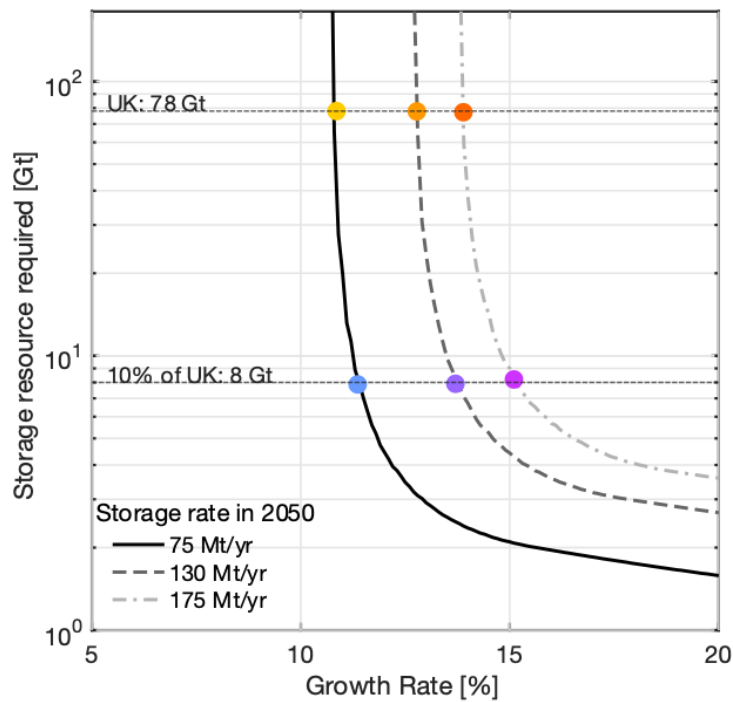
413 3.2 UK Domestic Scenarios

414 Storage rate target scenarios ranging from 75-175 MtCO<sub>2</sub> yr<sup>-1</sup> in 2050 for the UK have been  
 415 recommended by the Committee on Climate Change and the Oil and Gas Authority<sup>11,12</sup> (Table 1). The  
 416 currently planned CCS activities in the UK between 2022 and 2030 are to have stored a cumulative of  
 417 81 MtCO<sub>2</sub> offshore<sup>14,15</sup> (black marker at 2030 on the cumulative graph in Figure 7). Figure 7 shows  
 418 trajectories from 2030 with annual growth in injection rates between 10.9%-15.1% meeting the  
 419 storage rate targets of the UK for 2050. Achieving the UK government’s lowest carbon storage rate  
 420 target of 75 MtCO<sub>2</sub> year<sup>-1</sup> (UK1) requires a minimum annual growth rate of 10.9% (yellow curve in Fig.  
 421 7) achieved when dependent upon the maximum resource base allowed, 78 Gt. This rises to 12.8% for  
 422 UK2 (130 MtCO<sub>2</sub> yr<sup>-1</sup>) and 14% to reach the most aggressive target of 175 MtCO<sub>2</sub> year<sup>-1</sup> (UK3) in 2050.  
 423 In contrast, limiting the resource base to just 10% of the currently estimated 88 Gt results in  
 424 minimum growth rates increasing to 11.4%, 13.7% and 15.1% to meet UK1-3, respectively. Table 4  
 425 provides a summary of these values for the UK domestic scenarios.



426  
 427 Figure 7: (Left) Cumulative CO<sub>2</sub> storage for the UK domestic scenarios. (Right) CO<sub>2</sub> storage rate for the  
 428 UK domestic scenarios. We compare the range of growth rates required to meet storage rate targets  
 429 of UK1-3 (75 - 175 MtCO<sub>2</sub> yr<sup>-1</sup>), indicated by the red points, at two storage resource bounds: 78Gt (UK  
 430 offshore) and 8 Gt (10% of current best estimate).

431 Storage rate isocontours for 2050 UK targets are shown in Figure 8 with points corresponding  
 432 to trajectories shown in Figure 7. All of the scenarios (orange and purple points) require sustained  
 433 annual growth between 11% - 15% regardless of the available storage resource base (78 Gt or 8 Gt).  
 434 The difference in growth rate requirement illustrated by the purple and orange points suggest that  
 435 the effect of storage resource limitation is more significant for the target of UK3. For all targets to be  
 436 feasible from a growth rate perspective, at least 4 Gt of storage resource must be developed in the  
 437 UK.



438

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

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

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

### 444 3.3 EU + UK Scenarios

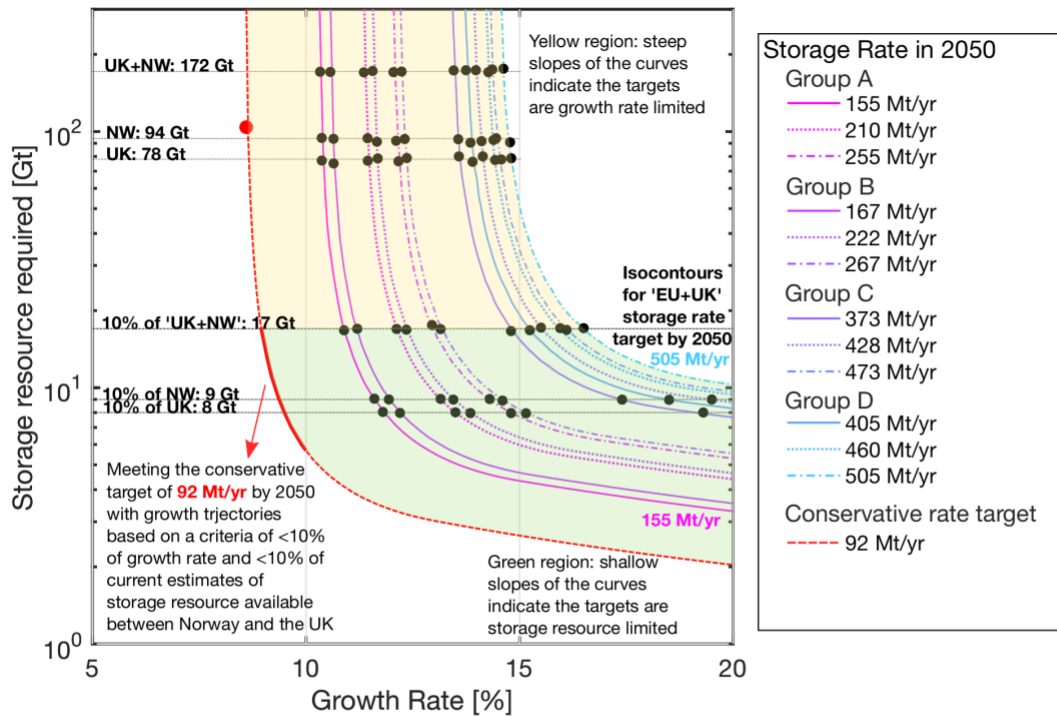
445 The tradeoff graph for the combined scenarios (Figure 9) illustrates the minimum growth  
446 rates bounded by the available storage resource in the UK (78 Gt), the Norwegian storage resource  
447 (94 Gt), and the UK and Norway combined storage resource (172 Gt). The higher the storage rate  
448 target, the higher the minimum growth rate necessary to achieve the target. Notably, the range of  
449 minimum growth rates illustrated in Figure 9 is between 10.3%-14.8% depending on the size of the  
450 supporting resource base (Table 5). Combining storage resources from the UK and Norway does not  
451 significantly impact the growth rate requirements for scaleup trajectories. The requirements are  
452 primarily driven by the 2050 rate targets and are not limited by the availability of storage resources.

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

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

471

472



473

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

478

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

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

#### 482 4 DISCUSSION

483 Plans for the deployment of CCS by the European Union and the UK imply sustained annual  
484 growth in CO<sub>2</sub> storage rates of at least 9%, and up to 15% from 2030 to 2050 (Figure 5 and 7). Others  
485 have shown that the scale of subsurface engineering required isprecedented<sup>57</sup>. Indeed, oil production  
486 from 1901 sustained a 15% average annual growth for 40 years<sup>58</sup>. However, market conditions driving  
487 the expansion of the demand for oil, which include the first World War, and relatively few limitations  
488 ensuring safety or environmental standards, reveal the magnitude of incentivisation required to  
489 achieve such growth<sup>59,60</sup>.

490 The storage resource of the UK and Norway, alone or combined, appear sufficiently abundant  
491 to serve as a regional CO<sub>2</sub> storage hub for the European continent (Figure 9). Significant limits  
492 imposed by geology only emerge if development is restricted to less than 10% of current estimates of  
493 the resource base. Even then, there is a range of significant 2050 rate targets that can be met without  
494 unduly high growth rates.

495 This analysis provides a framework to develop technology roadmaps including the scaleup of  
496 CO<sub>2</sub> storage within realms of plausible ranges of growth rate and storage resource base. For the last  
497 20 years, the global annual average scaleup of CO<sub>2</sub> storage rates is at around 8.6%<sup>20</sup>. Using this as a  
498 demonstrated benchmark, a trajectory with 8.6% annual growth from 2030 onwards for the European  
499 Continent, dependent on a combined storage resource base of 104 Gt is evidently plausible. This  
500 scenario translates into a 2050 regional storage rate target of 92 MtCO<sub>2</sub> yr<sup>-1</sup> (red dashed curve in  
501 Figure 9) and cumulative storage of 1.1 Gt. This rate target can also be met with a range of scenarios  
502 that can be achieved depending on less than 10% annual growth and less than 10% of the currently  
503 identified resource base.

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

509 5 CONCLUSIONS

510 In this study, we evaluate the scaleup of geological CO<sub>2</sub> storage identified in European climate  
511 change mitigation plans. We show that all storage targets require historically high rates of growth;  
512 minimum average annual growth in injection capacity from 2030 through 2050 needs to achieve 10%-  
513 15% to meet European targets. In contrast, CO<sub>2</sub> storage plans are not limited by current estimates of  
514 the resource base available and can be accommodated by the offshore reservoirs of the UK or Norway  
515 alone. Storage resource limitations will only occur if the resource base has been significantly  
516 overestimated, i.e., around 10% or less of current best estimates. In such a case, higher rates of near-  
517 term growth of 11% – 17% and the combined resources of the UK and Norway are ultimately required.  
518 Comparing these modelled growths with the production growth rates achieved by the petroleum  
519 industry reveals that wartime-like mobilisation of supply chain and manufacturing capacity may be  
520 required to meet published storage targets in Europe. Finally, we show how the logistic modelling  
521 framework can be used for constraining the deployment of CO<sub>2</sub> storage in energy systems models that  
522 are subject to conservative criteria and illustrate this by identifying a range of conservative storage rate  
523 target scenarios, i.e., 92 MtCO<sub>2</sub> yr<sup>-1</sup> in 2050.

524

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527 AUTHOR CONTRIBUTIONS

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

530 COMPETING INTERESTS

531 The authors declare no competing interests.

532 REFERENCES

- 533 1. Haszeldine, S. R. Carbon capture and storage: how green can black be? *Science* **325**, 1647-1652 (2009).  
534 <https://doi.org/10.1126/science.1172246>
- 535 2. Pires, J. C. M., Martins, F. G., Alvim-Ferraz, M. C. M., & Simões, M. Recent developments on carbon capture and  
536 storage: An overview. *Chemical Engineering Research and Design* **89**, 1446-1460 (2011).  
537 <https://doi.org/10.1016/j.cherd.2011.01.028>
- 538 3. Bui, M. *et al.* Carbon capture and storage (CCS): The way forward. *Energy and Environmental Science* **11**, 1062–  
539 1176 (2018). <https://doi.org/10.1039/c7ee02342a>
- 540 4. *IPCC Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment*



- 541 *Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer, O. et al.) (IPCC, 2014).
- 542 5. Koelbl, B. S., van den Broek, M. A., Faaij, A. P. C., & van Vuuren, D. P. Uncertainty in Carbon Capture and Storage
- 543 (CCS) deployment projections: A cross-model comparison exercise. *Climatic Change* **123(3-4)**, 461-476 (2014).
- 544 <https://doi.org/10.1007/s10584-013-1050-7>
- 545 6. Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K. Energy system transformations
- 546 for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change* **5**, 519-527. (2015).
- 547 <https://doi.org/10.1038/nclimate2572>
- 548 7. *IPCC Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-*
- 549 *industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global*
- 550 *response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds Masson-
- 551 *Delmotte, V. et al.) (IPCC, 2018).*
- 552 8. Oil information: Overview (IEA, 2020) <https://www.iea.org/reports/oil-information-overview>
- 553 9. *A Clean Planet for all: A European strategic long- term vision for a prosperous, modern, competitive and climate*
- 554 *neutral economy.* (European Commission, 2018)
- 555 10. *Ten Point Plan* (UK Government, 2020).
- 556 11. *UKCS Energy Intergration Final Report. Annex 2. Carbon Capture and Storage* (Oil and Gas Authority, 2020).
- 557 12. *Net Zero - The UK's Contribution to Stopping Global Warming* (Committee on Climate Change, 2019).
- 558 13. *Shell Sky Scenario* (Shell International B.V., 2018).
- 559 14. *Global Status of CCS: 2020* (Global CCS Institute, 2020).
- 560 15. *Global CCS Projects* (International Association of Oil and Gas Producers, 2020).
- 561 16. *CO<sub>2</sub> Storage Resources Management System* (Society of Petroleum Engineers, 2017).
- 562 17. Budinis, S., Dowell, N. Mac, Krevor, S., Dixon, T., Kemper, J., & Hawkes, A. Can Carbon Capture and Storage Unlock
- 563 “Unburnable Carbon”? *Energy Procedia* **114**, 7504-7515 (2016). <https://doi.org/10.1016/j.egypro.2017.03.1883>
- 564 18. Consoli, C. P., & Wildgust, N. Current Status of Global Storage Resources. *Energy Procedia* **114**, 4623-4628 (2017).
- 565 <https://doi.org/10.1016/j.egypro.2017.03.1866>
- 566 19. *Global Storage Resource Assessment – 2019 Update* (Pale Blue Dot Energy, 2020).
- 567 20. Zahasky, C., & Krevor, S. Global geologic carbon storage requirements of climate change mitigation scenarios.
- 568 *Energy Environment. Sci.* **13**, 1561-1567 (2020). <https://doi.org/10.1039/D0EE00674B>
- 569 21. *Assessing European Capacity for Geological Storage of Carbon Dioxide. EU GeoCapacity Consortium* (GeoCapacity,
- 570 2009).
- 571 22. *State of Play on CO<sub>2</sub> Geological Storage in 28 European Countries.* CGS Europe Report No. D2.10. pp. 1-89
- 572 (Rütters, H. and the CCS Europe Partners., 2013).
- 573 23. *Strategic UK CCS Storage Appraisal* (Energy Technologies Institute, 2016).
- 574 24. *CO<sub>2</sub>StoP Final Report: Assessment of CO<sub>2</sub> storage potential in Europe* (Geological Survey of Denmark and
- 575 Greenland, 2014)
- 576 25. *CO<sub>2</sub> Storage Atlas Norwegian North Sea* (Norwegian Petroleum Directorate, 2019).
- 577 26. *Communication From The Commission To The European Parliament, The Council, The European Economic and Social*
- 578 *Committee and The Committee of the Regions on the Future of Carbon Capture and Storage in Europe.* COM(2013)
- 579 180 final (European Commission, 2013)
- 580 27. Donda, F., Volpi, V., Persoglia, S., Parushev, D. CO<sub>2</sub> storage potential of deep saline aquifers: The case of Italy.
- 581 *International Journal of Greenhouse Gase Control* **5**, 327-335 (2011). <https://doi.org/10.1016/j.ijggc.2010.08.009>
- 582 28. Neele, F., ten Veen, J., Wilschut, F., Hofstee, C. *Independent assessment of high-capacity offshore CO<sub>2</sub> storage*

- 583 options. (2012).
- 584 29. Lothe, A., Emmel, B., Bergmo, P., Mortensen, G. M., Frykman, P. *A first estimation of storage potential for selected*
- 585 *aquifer cases*. (2014).
- 586 30. *CCS in Energy and Climate Scenarios*. (IEAGHG, 2019)
- 587 31. Iyer, G. *et al.* Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technological*
- 588 *Forecasting and Social Change* **90**, 103-118 (2015)
- 589 32. Larson, E. *et al.* Net-Zero America: potential pathways, infrastructure, and impacts. Interim report, Princeton
- 590 University. (2020)9
- 591 33. *Peterhead CCS project FEED Summary Report for Full CCS Chain* (Shell, 2016)
- 592 34. *Peterhead CCS project Conceptual Completions & Well Intervention Design Report* (Shell, 2014)
- 593 35. *Peterhead CCS project Geochemical Reactivity Report* (Shell, 2015)
- 594 36. *Peterhead CCS project Dynamic Reservoir Modelling Report* (Shell, 2014)
- 595 37. *Peterhead CCS project Storage Development Plan* (Shell, 2015)
- 596 38. *Peterhead CCS Cost Estimate Report* (Shell, 2016)
- 597 39. *Peterhead CCS project Permits and Consents Register* (Shell, 2016)
- 598 40. *Peterhead CCS project Summary of Bidder considerations in arriving at a Final Investment Decision* (Shell, 2016)
- 599 41. *Peterhead CCS project Stateholder and Public Engagement and Communications* (Shell, 2016)
- 600 42. Bachu, S. Review of CO<sub>2</sub> storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*
- 601 **40**, 188–202 (2015). <https://doi.org/10.1016/j.ijggc.2015.01.007>
- 602 43. Bradshaw, J. *et al.* CO<sub>2</sub> storage capacity estimation: issues and development of standards. *International Journal of*
- 603 *Greenhouse Gas Control* **1**, 62-68 (2007). [https://doi.org/10.1016/S1750-5836\(07\)00027-8](https://doi.org/10.1016/S1750-5836(07)00027-8)
- 604 44. Budinis, S., Krevor, S., Dowell, N. Mac, Brandon, N., & Hawkes, A. An assessment of CCS costs, barriers and
- 605 potential. *Energy Strategy Reviews* **22**, 61-81 (2018). <https://doi.org/10.1016/j.esr.2018.08.003>
- 606 45. *Bachu, S. et al. Estimation of Co2 storage capacity in Geological Media*. (CSLF, 2007)
- 607 46. Lockwood, M. The political sustainability of climate policy: The case of the UK Climate Change Act. *Global*
- 608 *Environmental Change* **23**, 1339-1348 (2013). <https://doi.org/10.1016/j.gloenvcha.2013.07.001>
- 609 47. UK Government. UK becomes first major economy to pass net zero emissions law.
- 610 <https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law> (2019).
- 611 48. Tjernshaugen, A. The growth of political support for CO<sub>2</sub> capture and storage in Norway. *Environmental Politics* **2**,
- 612 227-245 (2011). <https://doi.org/10.1080/09644016.2011.551029>
- 613 49. Anthonsen, K. L. *et al.* CO<sub>2</sub> storage potential in the Nordic region. *Energy Procedia* **37**, 5080-5092 (2013).
- 614 <https://doi.org/10.1016/j.egypro.2013.06.421>
- 615 50. Hubbert, M. K. Nuclear energy and the fossil fuels. *Drilling and Production Practice 1956*, 7-15 (1956).
- 616 51. Grubler, A., Nakićenović, N., & Victor, D. G. Dynamics of energy technologies and global change. *Energy Policy* **5**,
- 617 247-280 (1999). [https://doi.org/10.1016/S0301-4215\(98\)00067-6](https://doi.org/10.1016/S0301-4215(98)00067-6)
- 618 52. Brandt, A. R. Testing Hubbert. *Energy Policy* **35**, 3074-3088 (2007). <https://doi.org/10.1016/j.enpol.2006.11.004>
- 619 53. Rutledge, D. Estimating long-term world coal production with logit and probit transforms. *International Journal of*
- 620 *Coal Geology* **85**, 23-33 (2011). <https://doi.org/10.1016/j.coal.2010.10.012>
- 621 54. Höök, M., Li, J., Oba, N., & Snowden, S. (2011). Descriptive and Predictive Growth Curves in Energy System
- 622 Analysis. *Natural Resources Research* **20**, 103-116 (2011). <https://doi.org/10.1007/s11053-011-9139-z>
- 623 55. Brandt, A. Review of mathematical models of future oil supply: Historical overview and synthesizing critique.
- 624 *Energy* **35**, 3958-3974 (2010). <https://doi.org/10.1016/j.energy.2010.04.045>

- 625 56. Ringrose, P. S., & Meckel, T. A. Maturing global CO2 storage resources on offshore continental margins to achieve  
626 2DS emissions reductions. *Sci Rep* **9**, 17944 (2019). <https://doi.org/10.1038/s41598-019-54363-z>
- 627 57. Wilson, C., Grubler, A., Bauer, N., Krey, V., & Riahi, K. Future capacity growth of energy technologies: are scenarios  
628 consistent with historical evidence? *Climate Change* **118**, 381-395 (2013). [https://doi.org/10.1007/s10584-012-](https://doi.org/10.1007/s10584-012-0618-y)  
629 [0618-y](https://doi.org/10.1007/s10584-012-0618-y)
- 630 58. *World Primary Energy Production* (Theshiftdataportal, 2020). [https://www.theshiftdataportal.org/energy/primary-](https://www.theshiftdataportal.org/energy/primary-energy?chart-type=line&chart-types=stacked&chart-types=stacked-percent&chart-types=pie&chart-types=line&chart-types=ranking&disable-en=false&energy-families=Oil&energy-families=Gas&energy-unit=Mtoe&gdp-unit=GDP%20(constant%202010%20US%24)&group-names=World&is-range=true&dimension=byEnergyFamily&end=2016&start=1900&multi=false&type=Production)  
631 [energy?chart-type=line&chart-types=stacked&chart-types=stacked-percent&chart-types=pie&chart-](https://www.theshiftdataportal.org/energy/primary-energy?chart-type=line&chart-types=stacked&chart-types=stacked-percent&chart-types=pie&chart-types=line&chart-types=ranking&disable-en=false&energy-families=Oil&energy-families=Gas&energy-unit=Mtoe&gdp-unit=GDP%20(constant%202010%20US%24)&group-names=World&is-range=true&dimension=byEnergyFamily&end=2016&start=1900&multi=false&type=Production)  
632 [types=line&chart-types=ranking&disable-en=false&energy-families=Oil&energy-families=Gas&energy-](https://www.theshiftdataportal.org/energy/primary-energy?chart-type=line&chart-types=stacked&chart-types=stacked-percent&chart-types=pie&chart-types=line&chart-types=ranking&disable-en=false&energy-families=Oil&energy-families=Gas&energy-unit=Mtoe&gdp-unit=GDP%20(constant%202010%20US%24)&group-names=World&is-range=true&dimension=byEnergyFamily&end=2016&start=1900&multi=false&type=Production)  
633 [unit=Mtoe&gdp-unit=GDP%20\(constant%202010%20US%24\)&group-names=World&is-](https://www.theshiftdataportal.org/energy/primary-energy?chart-type=line&chart-types=stacked&chart-types=stacked-percent&chart-types=pie&chart-types=line&chart-types=ranking&disable-en=false&energy-families=Oil&energy-families=Gas&energy-unit=Mtoe&gdp-unit=GDP%20(constant%202010%20US%24)&group-names=World&is-range=true&dimension=byEnergyFamily&end=2016&start=1900&multi=false&type=Production)  
634 [range=true&dimension=byEnergyFamily&end=2016&start=1900&multi=false&type=Production](https://www.theshiftdataportal.org/energy/primary-energy?chart-type=line&chart-types=stacked&chart-types=stacked-percent&chart-types=pie&chart-types=line&chart-types=ranking&disable-en=false&energy-families=Oil&energy-families=Gas&energy-unit=Mtoe&gdp-unit=GDP%20(constant%202010%20US%24)&group-names=World&is-range=true&dimension=byEnergyFamily&end=2016&start=1900&multi=false&type=Production)
- 635 59. Craig, J., Gerali, F., Macaulay, F., & Sorkhabi, R. The history of the European oil and gas industry (1600s-2000s).  
636 *Geological Society Special Publication* **465**, 1-24 (2018). <https://doi.org/10.1144/SP465.23>
- 637 60. Neordhauser, N. Origins of Federal Oil Regulation in the 1920's. *Business History Review* **47**, 53-71 (1973).  
638 <https://doi.org/10.2307/3113603>

639