Mind the gap: will slow progress on CO_2 storage undermine net zero by 2050?

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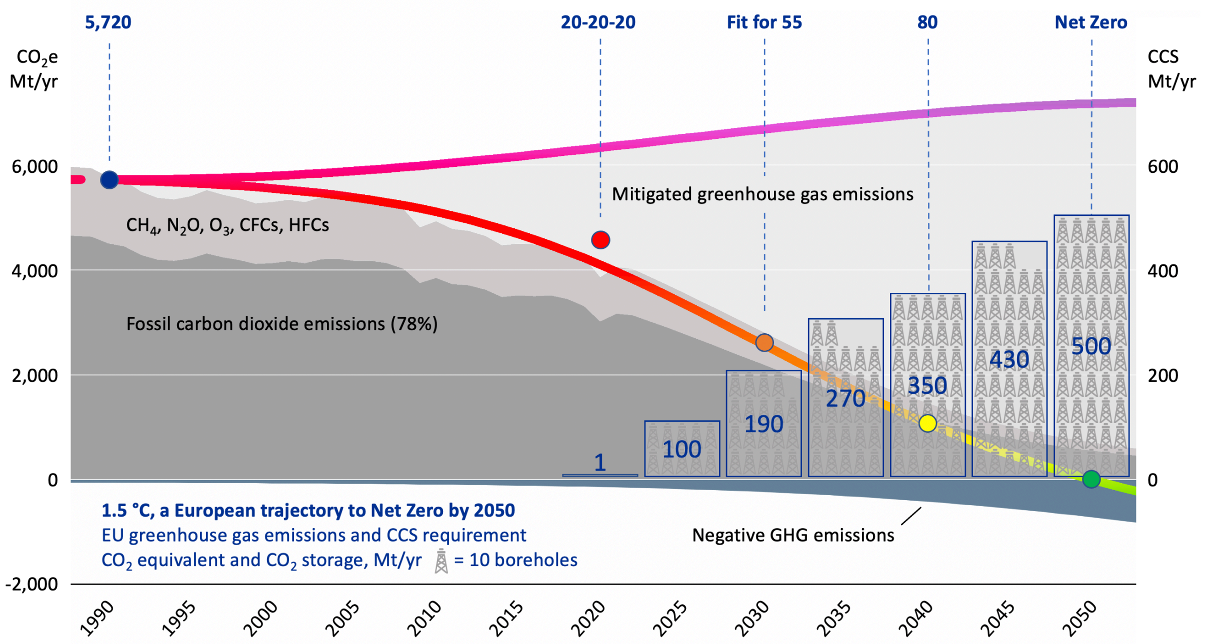
Abstract: A global path to net zero requires the permanent storage of carbon dioxide to reduce and remove atmospheric greenhouse gas emissions. We present an analysis of the gap between the CO_2 storage required to meet net zero targets and the slow maturation of regional storage resources. We estimate that European storage rates need to increase 30-to-100x by 2030 to meet net zero by 2050. China and North America face a similar challenge. The slow global progress of CO_2 storage undermines the latest IPCC, IEA, and EU transition pathways to net zero by 2050. These pathways imply a radically increased demand for carbon capture and storage and negative emission technologies, NETs, contributing 500 of 700 megatonnes of CO_2 removal annually by 2050. Here, we investigate if sufficient storage can be developed in time. China (30%), North America (15%) and Europe (10%) dominate global emissions. We choose to analyse Europe as a data-rich exemplar. Assuming net zero in 2050, we back-calculate the storage required under three scenarios of low, medium, and high CCS demand. Even the low demand scenario requires 0.2 Gt of storage by 2030, increasing to 1.3 Gt by 2050. The moderate and high demand scenarios require 5-to-8 Gt by 2050. The current storage rate in Europe is 0.001 Gt/yr. There is a huge gap between policy demand and storage supply. Adaptation of existing hydrocarbon technology has the potential to close this gap, with CCS for the entire EU requiring less than half the historic rate of hydrocarbon exploration and development in the UK North Sea from 1980 to 2010. Counter to expectation, storage cannot be delivered by exponential growth but requires an early and sustained investment of 30-to-50 boreholes per year starting before 2030 to build sufficient capacity. A five-year lead-time to identify and mature prospects needs policy intervention before 2025. Continued policy deferral will lock Europe into a low CCS pathway that restricts the contribution of NETs at a potential cost of €100 billion for every gigatonne delayed beyond 2050. North America and China require similar policy intervention to close the gap on CO_2 storage and net zero.

Graphical Abstract:



Mind the Gap. The European Union's pathway (red-to-green line) to net zero in 2050 (green circle) via agreed 2020 and 2030 targets (red and orange circles) and interpolated 80% milestone for 2040 (yellow circle). Approximately three quarters of greenhouse gas emissions are CO_2*; additional emissions such as methane (pale grey) are combined and expressed in tonnes of* CO_2 *equivalent (left axis). The 1990 benchmark for emissions reduction is 5,720 Mt/yr* CO_2*e. The required carbon capture and storage (columns and right axis) is for the IEA's SDS-FIC scenario, which increases European* CO_2 *storage rates from 1 Mtpa in 2020 to 500 Mtpa in 2050, banking 8 gigatonnes by 2050 and 1 additional gigatonne every 2 years from 2050. Europe has currently stored 0.02 Gt and is currently banking 0.002 Gt every 2 years.*

Climate Change and Policy

In spite of many conferences, treaties, policies, and contracts, the concentration of CO_2 in the atmosphere continues to rise at an alarming rate[1]. Based on this simplest of measures, the world is losing the battle to prevent rapid climate change[2]. For context, human activities currently emit 49 Gt CO_2e of greenhouse gases annually, of which 38 Gt are fossil fuel emissions – Table 1.

The concept of net zero, where global emissions are balanced by CO_2 removal, is profoundly reframing efforts to limit global warming to a sustainable level by mid-century[3]. IPCC AR6 summarises the climate models that inform the urgent need to reduce emissions to net zero by 2050 to achieve a 66% probability of 1.5 ºC warming compared to pre-industrial levels[4]. This is the preferred limit for parties that signed the legally binding UNFCC's Paris Agreement at COP 22 in 2016[5]. Deferring net zero to 2090 has the same probability for 2 ºC of warming. The most recent reporting indicates that the 1.5 ºC threshold may be crossed in the early 2030s[2,6].

EDGAR v5.0 Emissions Database	**1990 Emissions, Gt/yr Fossil CO_2 / GHG**	**2015 Emissions, Gt/yr Fossil CO_2 / GHG**	**2018 / 1990 Fossil CO_2**	**2018 share Fossil CO_2**
Global	22.637 / 32.772	36.312 / 49.113	+ 67%	100%
China	2.398 / 3.859	10.821 / 13.068	+ 369%	30%
North America	5.519 / 6.731	5.815 / 7.224	+ 6%	15%
EU28	4.409 / 5.743	3.492 / 4.500	- 22%	10%
UK	0.584 / 0.807	0.413 / 0.560	- 36%	1%
Norway	0.037 / 0.063	0.046 / 0.072	+ 35%	0.1%

Table 1. *Global and regional fossil CO_2 emissions by year and relative change, 1990 to 2015[7], 2018[8]. The EU and UK are notable for having achieved significant emissions cuts, driven by domestic targets. While the tonnages have changed, fossil CO_2 emissions for the three largest regions sum to 55% in 2018 (54% in 1990), averaging 78% of GHG emissions, CO_2e.*

The role of CCS in Europe

Carbon capture and storage has been demonstrated at an industrial scale for decades but has only recently begun to be deployed at the regional abatement scale envisioned in these scenarios. Advocates for CCS argue for the redeployment of existing industrial technologies to rapidly decrease carbon emissions whilst minimising impact on industrial lifestyles[9]. Advocates against argue that CCS enables the continued extraction of fossil fuels, which ought to cease immediately[10]. Recent IEA guidance to policy makers continues to position CCS as an essential net zero technology, delivering 15% (SDS-FIC) of fossil fuel emissions reductions[11,12], equivalent to one of seven Pacala & Socolow stabilisation wedges[13]. The European Commission's 'long-term strategic vision' anticipates a more moderate 2.4% (1.5LIFE) to 9% (1.5TECH) contribution from CCS as part of the European Green Deal and proposed legally binding target of net zero emissions by 2050[14]. For all scenarios, CCS in Europe requires gigatonne CO_2 storage within 30 years[15,16] – Table 2.

Bridging the gap between an immature CO_2 storage resource base and a bankable storage reserve sufficient to support net zero scenarios requires formulations for rapidly increasing CO_2 storage in the North Sea, the main regional resource. Assuming exponential growth, we discovered that doubling and tripling reserves of CO_2 storage capacity every five years resulted in unreasonably high borehole completion rates in the 2040s while failing to support all but a modest 1.5LIFE scenario – Supplement A1, Storage Scenarios. Unlikely start dates, unreasonable completion rates, and the lack of an established conversion rate of prospects to bankable storage, all hamper the credibility of an optimistic exponential approach.

	CO_2 Storage Rates (Mtpa)			**Banked CO_2 Storage (Gt)**		
Year (Target)	*SDS-FIC*	*1.5TECH*	*1.5LIFE*	*SDS-FIC*	*1.5TECH*	*1.5LIFE*
2020 (20%)	**1**	**1**	**1**	**0**	**0**	**0**
2025	95	60	15	0.3	0.2	0.1
2030 (55%)	**190**	**120**	**30**	**1.1**	**0.7**	**0.2**
2040	350	220	55	3.9	2.4	0.7
2050 (100%)	**500**	**300**	**80**	**8.2**	**5.0**	**1.4**

Table 2. *European CO_2 storage rates, Mtpa (left), and banked storage requirement, Gt (right), for IEA and EU net zero 2050 scenarios. Rows in bold represent EU target years for 20%, 55%, and 100% GHG emissions reduction*[14]*. SDS-FIC assumes a 15% contribution to fossil CO_2 reduction from CCS*[12]*; 1.5TECH and 1.5LIFE assume 9% and 2.4% contributions*[14]*.*

Globally, a slow start and lack of policy to rapidly mature theoretical CO_2 storage resources to bankable storage reserves obscures the role of CCS in net zero pathways. For Europe, the current slow rate of progress will lock out the CCS-dependent 1.5TECH pathway within a decade. This prediction reflects the five-to-ten years of maturation time required to explore CO_2 storage prospects and establish qualified reserves. With delayed action, the contribution of negative emissions technologies that rely on CO_2 storage, will inevitably be severely limited. A slow start over the decade 2025-2035 will bind Europe into a low CCS pathway that requires negative emissions technologies while limiting their performance.

To gain the deployment needed, a sustained campaign of regional storage hub development must be underway at full-scale by no later than 2025 to allow for a five-year lead-in time of storage site evaluation before CO_2 is injected in 2030. A sustained campaign of fifty boreholes per year in Europe before 2030 will deliver sufficient storage to fulfil policy requirements for net zero by 2050. While this is feasible, historical build-out rates for oil and gas suggest a Gaussian distribution is more likely if global or regional policy can stimulate the market. That requires urgency, profitable incentives, and a mandate for storage such as a carbon take back obligation or CBTO[17], where fossil fuel producers are required to balance carbon production with storage. Without a sustained radical response, CO_2 storage rates will remain 30-to-100x too slow to deliver net zero in 2050, risking 2ºC of warming as a default global policy through inaction.

Policy gap for Europe, North America, China

This paper presents an analysis of the gap between the CCS demand embedded in European net zero 2050 policy scenarios and the slow maturation of regional CO_2 storage resources, that by extrapolation indicate an endemic failure to supply CO_2 storage reserves worldwide. This failure to anticipate CO_2 storage demand and respond with a timely maturation of the abundant resource base will lock the European Union into a low CCS pathway that risks the delivery of net zero by 2050. North America and China, as large regional actors for net zero, face a similar dilemma through lack of action. Today, Europe accounts for approximately 10 percent of global emissions, ranking third behind China at 30 percent and North America at 15 percent – Table 1.

It follows that the EU is an important indicator of CO_2 storage resource development and its policy impact on net zero pathway selection for these large regions. The UK and Norway, at approximately 1% and 0.1% of global emissions respectively, are states within Europe that are able to supply CO_2 storage quickly, thus indicating the fastest emerging European pathway and the likely CCS contribution. Given this, we can then ask with respect to CO_2 storage and net zero 2050: where are we now and where will we be in ten, twenty, and thirty years?

Scenarios for Net Zero

The IEA and EC have recently set out net zero 2050 pathways with high, moderate, and low demand scenarios: SDS-FIC, 1.5TECH, and 1.5LIFE, described below. These three scenarios rely to a greater or lesser degree on CCS as a contributing technology [12,14]. The moderate and high demand scenarios, 1.5TECH and SDS-FIC, require incremental increases in CO_2 storage rates that add 100-to-165 Mtpa for each of the next three decades, equivalent to several gigatonnes of cumulative banked storage by 2050 – Table 2. 'Banked' in this context is defined as CO_2 stored underground, depleting a fraction of the justified reserve matured as a bankable resource[18]. This is in close agreement with recent analysis of global storage resources[15,16]. Even the low demand scenario, 1.5LIFE, requires a gigatonne of CO_2 to be banked before 2050.

SDS-FIC: the IEA's Faster Innovation Case, FIC, is a special net zero 2050 case for its Sustainable Development Scenario, SDS. The IEA states that "*there is little or no precedent for the required pace of innovation in the Faster Innovation Case and it does not leave any room for delays or unexpected operational problems during demonstration or at any other stage*" [11]. To paraphrase, there is no room for error.

1.5TECH: the EC's technology-dependent scenario for net zero 2050. 1.5TECH "*aims to further increase the contribution of all the technology options and relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage*" [14]. In this scenario CCS comes to the rescue.

1.5LIFE: the EC's social-change and nature-based scenario for net zero 2050. 1.5LIFE "*assumes a drive… towards a more circular economy… lifestyle changes and consumer choices… less carbon intensive diets, the sharing economy in transport, limiting growth in air transport demand… more rational use of energy demand for heating and cooling*" [14]. This would be highly disruptive to society.

Note that the IEA's hitherto most challenging scenario, SDS-FIC, has now been replaced by NZE, a "net zero emissions" scenario, not analysed here, that further increases the demand for bankable storage by 1.4x in 2050[19]. This urgency is reflected in SSP1-1.9, IPCC AR6's very low emissions scenario, which anticipates that the 1.5 ºC threshold will be crossed in the 2030s and overshoot in 2050 by 0.1 ºC for net zero 2050 pathways[20].

Engineered Storage Supply

Subsurface resources such as hydrocarbons, gold, and mineral deposits, can be qualified as commercial reserves using rigorous criteria that screen for economic viability, establishing the 'bankable' fraction of the known resource. Qualification schema for CO_2 storage have been developed by the CSLF and SPE[18,21] to establish the bankable fraction, equivalent to the 'matched' or 'justified' reserve – Fig 1. At present, European CO_2 storage is a largely theoretical resource base in excess of 266 Gt – Fig 1 (left). The 'theoretical' qualification is significant, a first approximation referring to the lowest level of assessment in the CSLF resource pyramid, equivalent to unproven 'exploration' assets in the SPE's SRMS classification – Fig 1 (right). Experience to date suggests that the maturation of a prospect from theoretical resource to matched reserve takes a decade, with a final investment decision approximately five years prior to the start of injection[22,23].

For the European region, the 'effective / prospective' resource tier consists of identified but undrilled prospects that sum to 8.5 Gt, almost entirely located offshore in the North Sea[24,25]. This resource tier is barely sufficient for the SDS-FIC scenario if entirely converted to a justified reserve. The 'practical' or 'contingent' resource tier consists of identified, drilled, and maturing prospects which, at 2 Gt, sum to less than a quarter of the effective resource, and is less than half of the 5 Gt of bankable storage needed for a 1.5TECH scenario – Table 2. The justified reserve, 0.05 Gt, is a small fraction, 4 percent, of the storage required for a 1.5LIFE scenario. These gaps indicate that the maturation of the European CO_2 storage portfolio needs to be urgently accelerated to provide sufficient storage reserves for net zero 2050 under any scenario. In summary, the matured storage supply, left pyramid, does not match the policy-indicated storage demand, right pyramid – Fig 1.

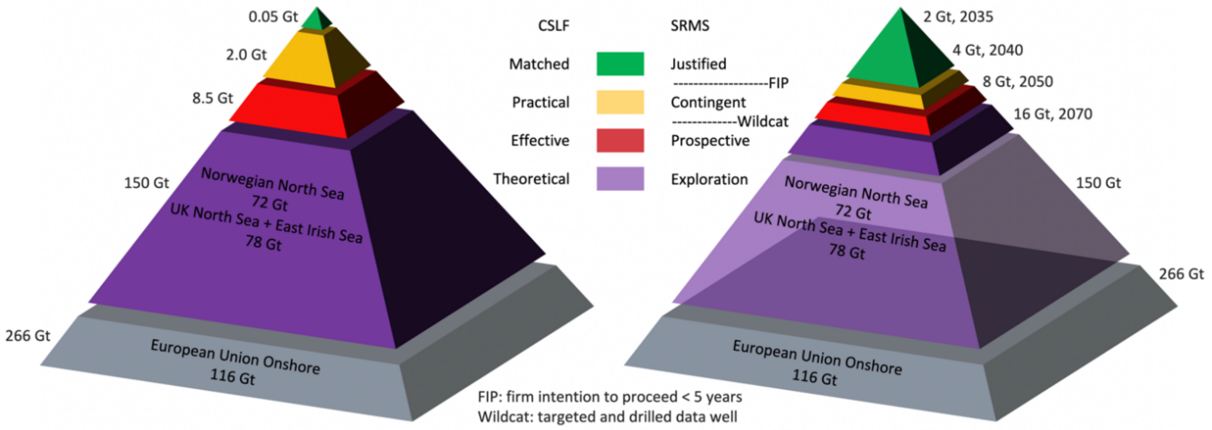


Figure 1. *European CO_2 storage resources and reserves [22,26], as qualified by SRMS and CSLF (left pyramid), and as required for an SDS-FIC 15% contribution to EU targets on a net zero 2050 pathway (right pyramid). The SRMS scheme is based on the SPE's preceding classification of petroleum reserves, PRMS[17]. The CSLF scheme is based on a techno-economic-resource-to-reserve analysis, TERR[21]. Both SRMS and CSLF indicate an order-of-magnitude reduction in capacity from the 'theoretical / exploration' resource base to the 'matched / justified' reserve pyramidion.*

European Pathways

In 2020, the European Green Deal increased the 2030 greenhouse gas emissions reduction target from 40% to 55%, with the aim of achieving net zero by 2050[27,28]. This 'Fit for 55' target substantially alters the European Union pathway, with annual reduction rates from all contributions, including fuel switching, electrification and CCS, effectively quadrupling in the 2020s – Fig 2. Given that fossil CO_2 emissions account for 78% of EU GHG emissions[7], this is equivalent to 0.9 Gt/yr of fossil CO_2 reductions in 2020, increasing to 1.8 Gt/yr in 2030 and 3.6 Gt/yr in 2050.

Assuming a high demand SDS-FIC scenario where CCS delivers 15% of fossil CO_2 reductions in the coming decades [10,11], European CO_2 storage injection rates would increase from 1 Mtpa in 2020 to 190 Mtpa in 2030 and 500 Mtpa in 2050. This would require banking 1 Gt by 2030, 4 Gt by 2040 and 8 Gt by 2050 – Fig 1. The low 1.5LIFE and moderate 1.5TECH pathways require 1 to 5 Gt of banked storage by 2050 – Table 2. The significant rate changes occur in the 2020s and 2030s.

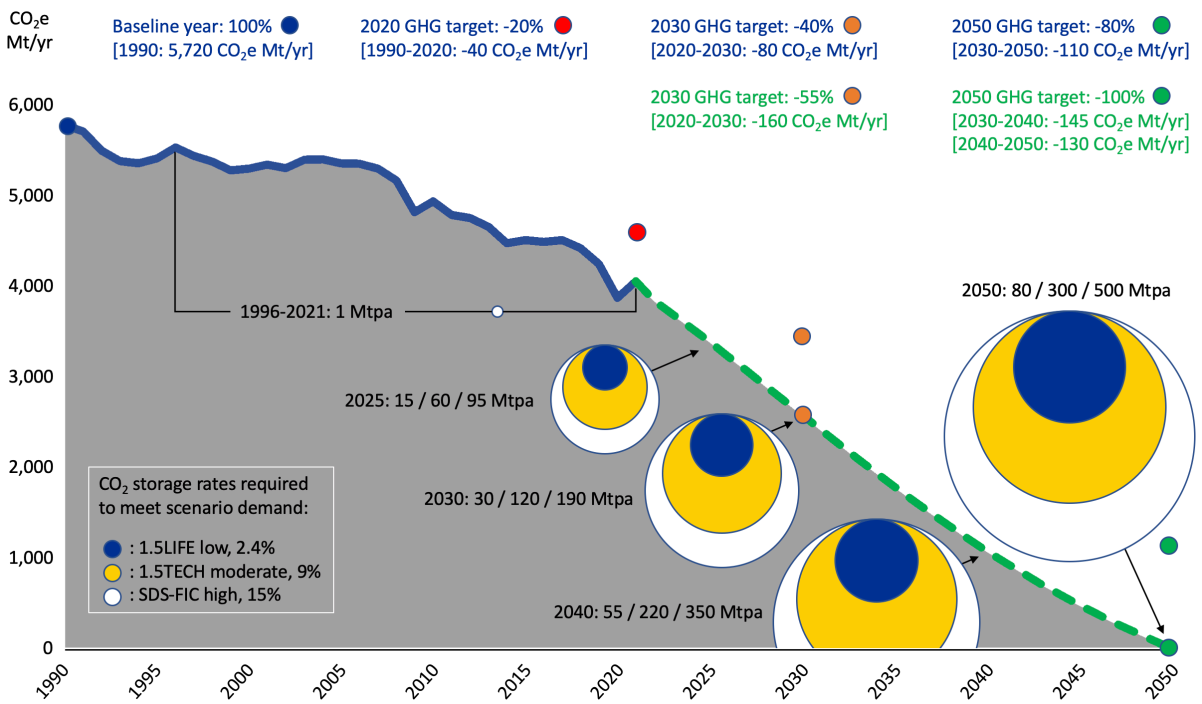


Figure 2. *CO$_2$ storage demand embedded in the European net zero pathway[26,27]. Blue text preserves the pre-2020 EU28 'Roadmap' targets[26]. Green text represents the 'European Green Deal' targets, retaining the 1990 5,720 Mtpa baseline for the EU27+UK[27]. CO$_2$ storage rates (blue, yellow, and white circles) for the three scenarios: SDS-FIC, 1.5TECH, 1.5LIFE assuming the GHG emissions reduction rates in brackets. Post-Brexit EC reporting has rebased to 4,658 Mtpa CO$_2$e in 1990.*

Where is this storage and when will it be ready?

On 16 March 2023, the EC proposed the Net Zero Industry Act[29], acknowledging a co-ordination failure with respect to CO$_2$ storage. A CO$_2$ injectivity capability of 50 Mtpa by 2030 was proposed, with the intention of supporting a possible pathway to 550 Mtpa of CCS by 2050. However, according to the proposal, CO$_2$ storage sites must be located within the European Union member states.

This positive intervention by the Commission to urgently realise European CO$_2$ storage begins to address the gap but substantially underestimates the storage rates required to sustain 1.5TECH and SDS-FIC as viable pathways, which, according to this analysis, require 100-to-200 Mtpa by 2030 – Table 2. The emphasis on member state provision and onshore storage also unnecessarily excludes 150 Gt of resources that represent the most mature and rapidly available storage capacity, located offshore in UK and Norwegian waters of the North Sea – Fig 2.

The North Sea

Norway has pioneered offshore CO_2 storage for over 20 years, storing 24 Mt of CO_2 from 1996 to 2019 at the Sleipner and Snøhvit sites, equivalent to an average combined injection rate of 1 Mtpa[20]. Norway continues to build capacity in the North Sea with the Northern Lights project expecting to add 1.5 Mtpa and a justified 100 Mt reserve to European storage by 2025, potentially increasing to 5 Mtpa and a justified 300 Mt reserve by 2030[21]. The UK is in negotiation to develop two North Sea clusters, Acorn and Endurance, that potentially store 10 and 17 Mtpa respectively by the mid 2030s, maturing the prospects to a justified 670 Mt reserve [23,25]. The UK has committed to developing two further clusters that will potentially increase the rate to 20-30 Mtpa by 2030[30].

However, the EU 2030 target and 1.5TECH requires 60 Mtpa and 0.2 Gt underground by 2025, and 100x the current injection rate of 1 Mtpa by 2030 – Table 2. The SDS-FIC pathway to 500 Mtpa of storage by 2050 increases the injection rate to 190 Mtpa by 2030 and a banked storage requirement of at least 1 Gt – Fig 2. This seems highly unlikely without an urgent mandate and use of the 970 Mt of UK and Norwegian nominal reserves.

Assuming a common simplifying metric of 1 Mtpa for an average CO_2 storage well, all but the low demand 1.5LIFE scenario require 100-to-200 such storage wells by 2030, and 100-to-150 additional storage wells in each of the following decades. Recent analysis of global resources reached similar conclusions, estimating that regional hubs such as the North Sea and Gulf of Mexico each require gigatonnes of matured storage and 100-to-200 storage wells within a decade[14]. Is this possible?

If the emerging Norwegian and UK projects rapidly develop to reach peak injection rates in 2030, these will potentially sum to 0.3 Gt banked storage and 60 Mtpa by 2030 – Supplement A2, North Sea storage prospects. By comparison, the low demand 1.5LIFE pathway requires 0.2 Gt banked and 30 Mtpa by 2030. Early indications are that the emerging European CO_2 storage pathway supports 1.5LIFE. However, a low pathway selection will lock out the moderate 1.5TECH pathway before

2040 which requires a 30-fold increase in banked storage from 24 Mt to 0.7 Gt by 2030, followed by a 3-fold increase in the 2030s and a 2-fold increase in the 2040s – Table 2.

By comparison of rapid growth rates, even solar PV only achieved 20x growth over the last decade, from a global capacity of 24 gigawatts in 2009 to 480 gigawatts in 2020[31] - an exponential growth rate attributed to tumbling costs and soaring market-driven demand. CCS policy needs to radically stimulate the market to replicate a similar acceleration.

From Resources to Reserves, an Urgent Campaign

The theoretical storage resource appears to be more than adequate for any European scenario, with an estimated offshore capacity of 150 Gt total: 72 Gt and 78 Gt respectively for the Norwegian and UK North Sea [23,25]. However, reframing resource perception through the lens of reserve maturation for net zero highlights the need for a campaign of exploration wells and site appraisals over the coming decade. The above analysis suggests that Europe needs to build a justified reserve of at least 1 to 4 Gt by 2030 in order to deliver banked capacity for 2040 and prepare bankable reserve capacity for 2050. How reliable are theoretical resource estimates and how do they convert to a justified storage reserve?

Scrutiny of the regional resource reveals that only 1.8 Gt of UK storage has matured to an effective portfolio of nine candidate sites and twenty shortlisted prospects[25]; Norway estimates 1.1 Gt of its North Sea resource as effective based on a single appraisal target and operational site[32]. However, the Northern Lights project adds just one candidate site to the North Sea portfolio – Supplement A2. The onshore European resource remains entirely theoretical but is currently being reappraised to shortlist three prospects for rapid maturation[22]. A recent review by the OGCI[26] using the CO_2 storage resource management system (SRMS), a tool for commercial CO_2 storage evaluation based on decades of experience from the oil and gas industry[18], downgraded much of the Norwegian resource to undiscovered due to a lack of drilled prospects, and much of the UK portfolio to contingent resources due to a lack of commercial progression.

This reflects the SRMS qualification barriers to technical and commercial maturity. The low technical barrier to a prospect being ranked as contingent is a targeted discovery with an appraisal well that tests the prospect. For Norway, undrilled prospects within a storage formation like the Utsira Formation, which hosts the Sleipner storage site, are effectively undiscovered and the associated capacity is theoretical. The high barrier to commercial ranking is FIP, a 'firm intention to proceed' with site development within five years[18,26]. For example, the Northern Lights prospect, Aurora, was identified in 2016 but only 'discovered' on being drilled early in 2020. The final investment decision and FIP was taken later that year with a planned operational start date of 2024. This matured the contingent prospect to a 'justified' site and bankable reserve, estimated at 50 Mt, within a decade. The Sleipner site managed the same transition in just five years; the Snøhvit site in eight years[33].

In summary, much of the European contingent resource was classified by the OGCI as economically unviable given a lack of commercial progression. For the UK, large prospects such as Endurance have stalled at the FIP stage, though this could be rapidly changing[34,35]. Globally, the OGCI found the resource base to be largely unexplored, with most prospects undrilled[24]. In 2017, the reserve estimate was just 160 Mt of bankable and justified storage, with a matured resource base of only 600 Mt of economically viable contingent storage that still required appraisal and development. This is not good.

Closing the Gap

To a first approximation, if North Sea CO_2 storage development approached less than half the level of recent historic hydrocarbon activity – Fig 3, the outcome could be a sustained campaign of fifty boreholes a year - Supplement A1, Storage Scenarios. Such a formulation might consist of fifteen exploration and appraisal wells for ten prospects a year, of which, assuming 70% success, seven prospects might progress as sites to be developed with an average of five injection wells per site. Assuming a fifty-boreholes-per-year campaign has commenced in 2025, and the first seven sites became operational in 2030, the sustained contribution of 35 storage wells a year from 2030 would match the SDS-FIC demand of 8 Gt banked storage in 2050, enabling BECCS and DACCS negative emission technologies (NETs) to remove CO_2 before 2050. Delaying the onset of injection by five years to 2035, would result in only 5 Gt of storage, equivalent to 1.5TECH, enabling NETs by 2050. A delay of ten years, and a more modest thirty borehole-a-year campaign would likely contribute just 1 Gt by 2050, ruling out NETs by mid-century, and delivering only the low demand 1.5LIFE scenario. It is clear that actions on storage provision over the next 10 years for Europe, and by inference, North America, and China, needs to be front-loaded, with small delays of just a few years having hard-to-reverse consequences for CCS and NET contributions to net zero under any scenario.

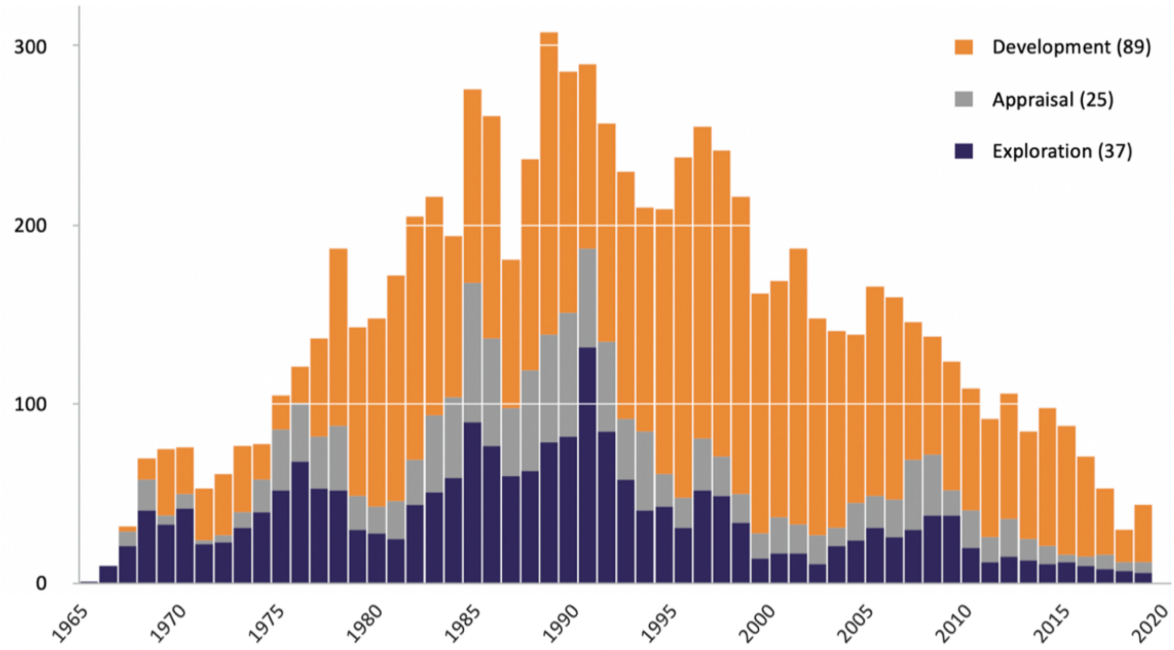


Figure 3. *North Sea exploration, appraisal, and development wells by year for the UK sector. After OGA*[36]*. Drilling peaked in the late 1980s and remained above 100 boreholes a year from the mid-1970s to 2010. Drilling activity has only recently dipped below 50 development wells a year. Figures in brackets represent average well completion rates.*

The above formulation of sustained campaigns results in 2x to 3x more storage wells in 2030 and 2050 than anticipated by the European Commission [13,27]. For example, the modest thirty boreholes-per-year campaign that supports 1.5LIFE results in 220 storage wells by 2050, not the anticipated 80. The more demanding 1.5TECH outcome for a fifty-borehole campaign commencing in 2030 requires 560 storage wells, not 300. Assuming immediate commencement, 1.5TECH and SDS-FIC require 115 to 190 storage wells by 2030, not the proposed 50 Mtpa of the Net Zero Industry Act[28]. This is a consequence of a delayed start and little significant storage in the early 2020s. It seems unlikely that this lost potential can be redressed with exponential campaigns either onshore or offshore that rely on unrealistically high storage rates in the 2040s - Supplement A1, Storage Scenarios.

Historic Drilling, Growth and Decline

These formulations suggest that a sustained campaign of exploration, appraisal, and development of the known resource, starting as early as 2025 and no later than 2030, is needed to close the gap that exponential campaigns are unlikely and unable to address. Considering the recent history of drilling activity in the UK North Sea, an annual campaign of fifty boreholes represents slightly less than half the average annual oil and gas drilling rates since 2000 – Fig 3. However, the historic distribution also suggests that flat-rate campaigns are not the norm. While such an approach might occur under a centrally mandated and subsidised regime, the histogram for commercial hydrocarbon development in the North Sea has approximately followed a normal distribution – Fig 3. It follows that a market-driven profile of growth and decline may better represent the role of many independent actors in regional storage development.

To model this, the historical profile of North Sea oil and gas borehole completion rates is charted as a gaussian distribution and rescaled for CO_2 storage, assuming that the exploration and appraisal wells are equivalent to prospect and site maturation wells, and development wells are equivalent to storage wells – Fig 4. Note that the 30-year range and 2050 termination is for the purpose of visualising a campaign that meets the net zero demand. A post-2050 net-negative economy will need a further investment in boreholes to replace the exhausted reserve and build out the required storage bank beyond 2050 based on an established resource-to-reserve conversion ratio.

The conversion ratio may take more than a decade to establish. For example, 364 ‘wildcat’ oil and gas wells were drilled on the Norwegian Shelf between 2010 and 2020 with a success rate of about 50 percent, which is high compared to the international success rate of around 30 percent[37]. The conversion ratio for CO_2 storage is an essential regional planning metric that is currently unknown and will likely only stabilise after some tens of sites have been matured to operational status.

The growth-and-decline approach results in a normally distributed SDS-FIC storage campaign that banks 8 Gt by 2050 with a peak drilling rate of 78 boreholes in 2037. The distribution requires much lower early and late completion rates than the fifty-borehole campaign: 24 exploration wells in 2030 and 6 storage wells in 2050. The distribution also lowers the total borehole count from 1300 to 1125 – Fig 4. A moderate 1.5TECH campaign, banking 5 Gt of storage by 2050, peaks at 47 boreholes per year and lowers the total borehole count from 1050 to 673. A campaign to deliver the 1.5 LIFE pathway and 1.3 Gt of storage by 2050 peaks at 12 boreholes per year and lowers the cumulative borehole count from 480 to 175. These improvements in total well counts are a result of earlier storage in the late 2020s and higher storage well completion rates in the early 2030s. The scenarios require significant growth curves in both maturation and storage from 2025 through to 2035 – Fig 4.

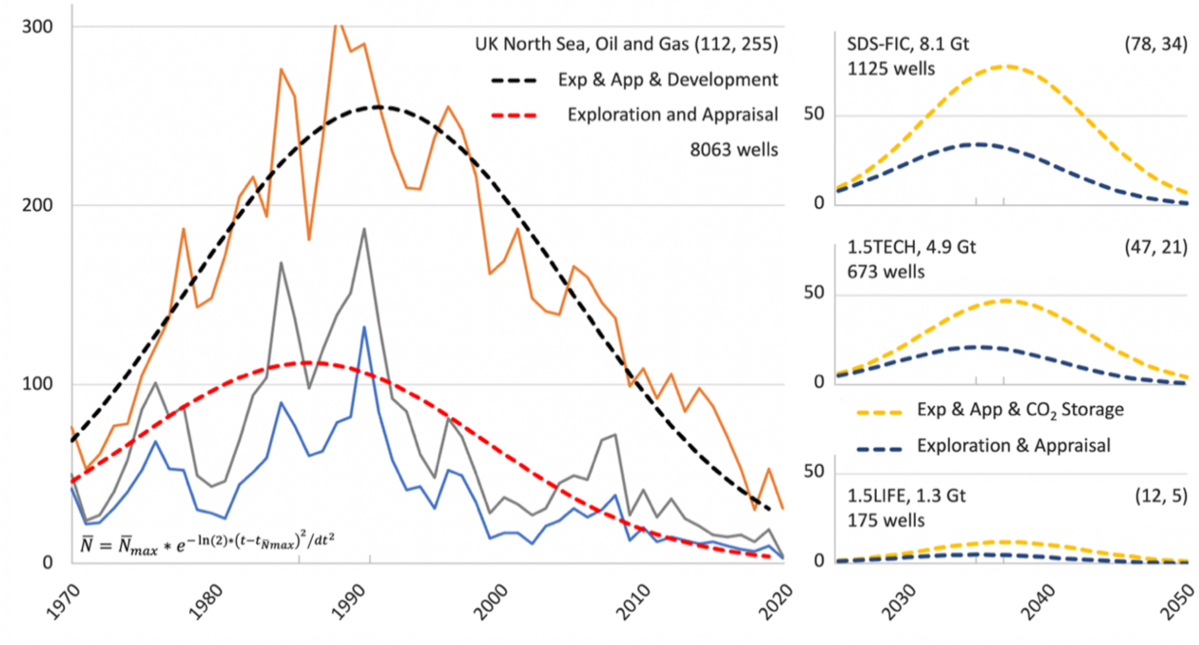


Figure 4. *Historic oil and gas drilling rates for the UK North Sea* [34]*, 1970-2020, averaged as Gaussian best-fit trends (left graph – see supplement A3 for formulation). Total oil and gas completions sum to 8,063 boreholes over a 50-year period, peaking at an average of 255 in 1991 (112 exploration and appraisal wells in 1986). Rescaling the distribution to a twenty-five-year period for* CO_2 *storage, a 7-year half-life, and peak activity in the mid-2030s (2035 for maturation wells, 2037 for storage wells), the SDS-FIC scenario requires a peak drilling rate of 78 boreholes per year (1.5TECH, 47; 1.5LIFE, 12).*

The Opportunity Cost

CCS as a contributing technology to net zero in 2050 for Europe and beyond rests on an immature CO_2 storage resource base. Drilling North Sea prospects that appraise and mature the effective resource is likely the quickest path to de-risking the European portfolio and growing the reserve over the coming decade[38]. Collectively, these immense gaps in bankable storage capacity highlight a disconnect between top-down policy demand and bottom-up engineered supply – Fig 2.

Spanning these technical and commercial gaps is quite possible. However, this requires a coordinated exploration campaign over the decade 2025-2035 to clarify the conversion ratio and establish the maturation campaign out to 2040 necessary to deliver bankable storage for 2050. A CO_2 storage shortfall measured in gigatonnes will profoundly limit and delay the contribution of negative emission technologies such as bioenergy and direct air capture CCS. The shortfall may also displace captured CO_2 into less proven and more challenging carbon sinks such as deep ocean storage.

Accelerating storage maturation, on the other hand, will support capture deployment and position Europe as a global technology driver and innovator in both capture and storage. Delays that create a bottleneck of demand in the 2030s will drive up costs through technology imports and increased competition for exploration and development assets such as seismic survey vessels and drilling rigs. If regional hubs from North America and Europe to Australia and China each require hundreds-to-thousands of storage-well completions a decade[9], competition and cost will favour early movers.

The maturation of Europe's CO_2 storage competes in a global context. Assuming a current CCS cost of €50/tonne for greenhouse gas emissions reduction, adjusted for 2.5% annual inflation to €100/tonne in 2050, and a post-2050 cost of €100/tonne, the penalty for each gigatonne of storage deferred beyond net zero 2050 is approximately €20 Bn. However, the larger penalty is in deferring action from reduction to removal, given the additional cost of direct air capture. Assuming a DAC cost of €200/tonne[39], the penalty for each gigatonne deferred to removal after 2050 is likely to exceed €100 Bn. Early and sustained action radically reduces costs and improves outcomes.

Implications for Europe, North America, and China

The European gap between net zero policy and CO_2 storage maturation may be best addressed by sustained drilling that rapidly matures the resource base, and - vital to delivery - banks significant storage in the 2030s while also establishing the resource-to-reserve conversion ratio.

The history of the North Sea hydrocarbon industry suggests that campaigns of thirty-to-fifty boreholes a year are quite possible if the business case is robust. It is worth noting that recent global analysis[15] indicated regional drilling rates of only 100-to-200 wells per decade. However, that optimistic analysis assumed action from 2020 and a high level of activity throughout the 2020s. That option is already cut off. Analysis in this paper requires flat-rate campaigns of 30 and 50 boreholes per year, indicative of the need for much higher sustained drilling rates due to delayed action. Gaussian-distributed growth-and-decline campaigns marginally improve these outcomes. Any delay beyond 2025 and less substantial 2030 activity will inevitably lock the European Union into 1.5LIFE or even lower pathways that depend on extraordinary social change and land use change with no technology safety net. 1.5LIFE provides the least support for the development of negative emissions technologies which may be needed to address outcomes that overshoot net zero 2050.

The IEA's SDS-FIC, the high-demand scenario considered here, has been replaced in their latest analysis by NZE, a 'net zero emissions' scenario[18]. NZE estimates global carbon capture to increase from 0.04 Gt/yr in 2020 to 4 Gt/yr in 2035, and 7.6 Gt/yr in 2050, of which 95 percent will be geologically stored. Assuming an equitable 10 percent contribution (Table 1), NZE storage rates for Europe are 720 Mtpa in 2050, 1.4x the previous SDS-FIC rates (Table 2). To meet such an outcome, European banked storage increases from 8 to 11 Gt in 2050.

The gap from policy to delivery continues to widen. A successful net zero 2050 campaign that matures regional storage hubs capable of supporting new pathways and changing demand in a post-2050 net negative emissions economy will require urgent policy action to close the gap. Net zero actions that decrease emissions such as reduced hydrocarbon production and efficiency of hydrocarbon use, and emerging phenomena that increase emissions such as wildfires, soil degradation, and warming oceans, will set the required NETs contribution from DACCS and BECCS beyond 2050 to address any net zero overshoot. Engineered carbon dioxide removal provides humans with a small lever of control against uncertainty – Fig 5.

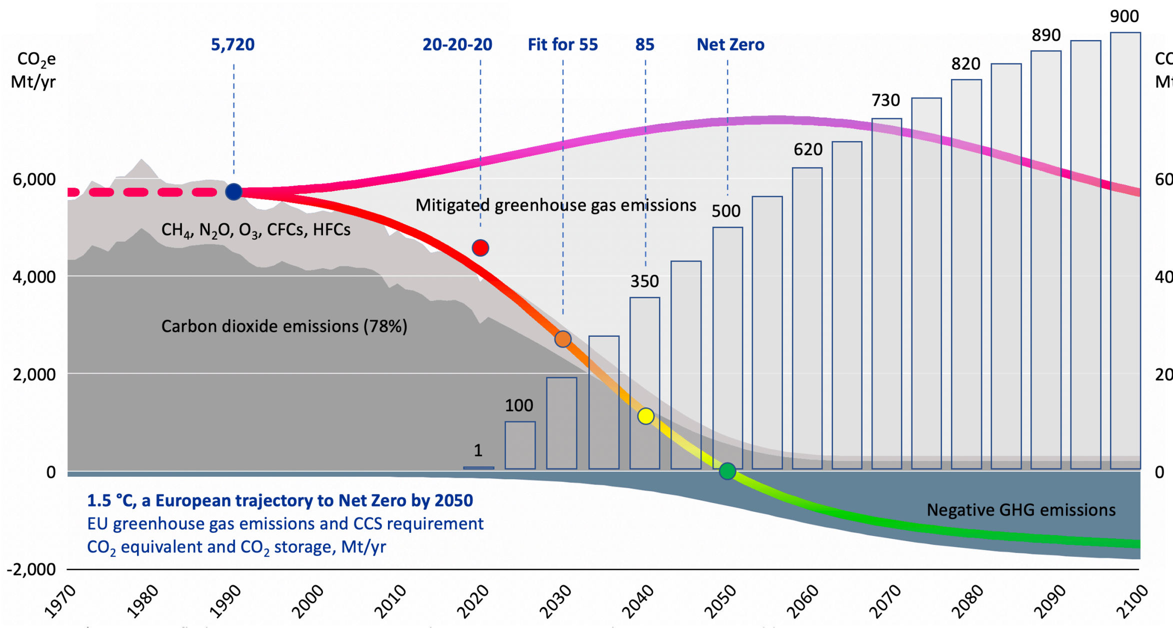


Figure 5. The pathway beyond net zero and 2050 (green circle) may require a net negative emissions profile with substantial and sustained contributions from CCS (storage rates, columns and right axis) and NET removal of CO_2 directly from the atmosphere. A negative emissions economy for Europe approaching -2 Gt/yr by 2100 (left axis), potentially doubles the required storage rate by the end of the century assuming an equal contribution of nature-based greenhouse gas reduction (LULUFC) and negative emissions technologies (DAC+BEC). The CO_2 storage capacity required for such a scenario is 45 Gt, more than 40x the SDS-FIC regional capacity required in 2030 (1.1 Gt) and more than 5x that required in 2050 (8 Gt). These values approximate a quarter of the North Sea resource and a fifth of the total European resource, onshore and offshore.

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Given the global context of net zero and relative size of large regional actors, similarly ambitious campaigns are needed beyond Europe. The above analysis suggests that North America, with 1.5x the emissions of the EU, requires 500-to-700 wells per decade by 2030; China, at 3x the emissions, will require over 1,000 wells per decade. While these numbers seem large, it is worth noting that the Gulf of Mexico frequently exceeded one thousand well completions a year in the 1980s and 1990s, peaking at over 1,300 wells in 1984.

Not addressed here, carbon capture and transport development may progress independently of storage resource maturation; however, banked storage requires the demand from these related sectors to keep pace. If bold action on CCS is again deferred for another 5 or 10 years, a likely consequence is a major shortfall in geological CO_2 storage, measured in gigatonnes for Europe by 2030, and tens of gigatonnes for Europe, North America, and China by 2040. This will diminish the potential of CCS to support rapid and low-cost hydrogen manufacture from hydrocarbons and decrease the capacity to store negative CO_2 emissions from direct air capture and biomass energy before 2050.

Inevitably, that jeopardises the concept of net zero, where diffuse or expensive emissions are balanced by negative emission technologies. The implication for Europe is that if the region has not tested ten storage sites as a bankable reserve by 2025, it has hardly begun. If Europe has drilled and appraised fewer than fifty prospects by 2030, it has probably excluded 1.5TECH as a viable pathway to net zero by 2050. European policy needs to urgently reflect this vanishing opportunity, enabling actions that capitalise on the extraordinary resource that is the North Sea as a carbon sink.

Conclusions

1) There is a huge gap between the policy aspiration for CCS and the practical delivery of CO_2 storage necessary to deliver net zero. Carbon capture and storage is essential for all global pathways to net zero. But CO_2 storage sites are currently known only in outline and, as such, are immature investments. About 1-to-10 Gt of CO_2 storage is needed for Europe by 2050. Prospective storage sites need to be examined in detail using established oil industry methods including pilot drilling to mature the long-identified resource to a timely reserve. This is already decades overdue.

2) Three scenarios have been examined to elicit the high, medium, and low CO_2 storage demand for European net zero pathways. An important finding is that delay has likely closed the high SDS-FIC pathway and is risking the medium 1.5TECH pathway, where required borehole completion rates may become implausible in the 2040s. If action is deferred to 2030, then net zero by 2050 can only be

reached with a minimal contribution from CCS and the profound social disruption implied in 1.5LIFE. That also means a very limited ability to deploy DACCS and BECCS beyond 2050.

3) Proposed EU plans[29] to mandate the availability of storage from 2030 need to circumvent delays at onshore storage sites due to licensing and public acceptance. Development of large offshore sites can proceed quicker through current European regulations. The proposed 50 Mtpa mandate needs to be doubled or trebled to support pathways that approach a 500 Mtpa storage rate by 2050.

4) Europe represents 10% of global CO_2 emissions, North America, 15%, and China, 30%. Europe provides very well documented storage data and so has been used as the basis for this investigation. The global development of CO_2 storage beyond pilot demonstrations has been delayed for decades. This now means that Europe needs a starting platform of 50 boreholes in 2025, with a rate thereafter of an extra 50 boreholes per year. Assuming a proportionate share, North America and China need 75-150 newly commissioned boreholes each year from 2025. CO_2 storage worldwide is starting 20 years too late to emerge by exponential market growth. Mandates are urgently needed.

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Supplementary Material

A1 Storage Scenarios

This supplement documents the formulations for storage development rates that bridge the storage gap for a range of net zero 2050 scenarios. The formulations are compared to the history of UK North Sea hydrocarbon development that establishes the macro-engineering plausibility.

Exponential: doubling every 5 years

A simple thought experiment for regional CO_2 storage might speculate a reasonable progression to be exponential with a five-year doubling time. For example, the FIP for Northern Lights potentially adds 1.5 Mtpa to the longstanding and current contribution of 1 Mtpa from Sleipner and Snøhvit. This is equivalent to 2.5 Mtpa by 2025, an approximate doubling of the injection rate circa 2020. The Northern Lights ambition to increase operational capacity to 5 Mtpa by 2030 further doubles capacity. Assuming a doubling rate in the North Sea every 5 years, this would achieve the 80 Mtpa injection rate in 2050 indicated for a low demand 1.5LIFE scenario but only bank 0.6 Gt, not the required 1.3 Gt (Table 2). This formulation fails to bank enough storage by 2050 for even a low demand scenario.

Exponential: trebling every 5 years

To achieve more, the thought experiment could be reformulated as a trebling rate. Back-casting from the moderate-demand 1.5TECH rate of 300 Mtpa in 2050, the injection rate would be 100 Mtpa in 2045, 33 Mtpa in 2040, and 3-to-4 Mtpa in 2030. However, this would result in only 1.5 Gt of storage, sufficient for 1.5LIFE but not the required 5 Gt for 1.5TECH. This formulation results in high injection rates sufficient to match the moderate scenario but fails to bank enough storage. The outcomes indicate that an early start and steep initial climb to high rates is required. The exponential growth curve has low initial rates. Early plateaus of sustained rates are necessary to deliver 1.5TECH and SDS-FIC as viable options – Fig A3.

Waves, beyond exponential

An alternative approach might anticipate an extremely high demand and rapid early deployment of the available resource. Focusing on CO_2 storage only, what might such an approach achieve over the coming decades given all storage portfolio options available now?

In this thought experiment, we combine the nine shortlisted UK candidate sites with the Northern Lights project in Norway – Supplementary Table A2. We optimistically assume that (a) all ten projects have qualified in 2020 as justified and bankable storage with FIP, a firm intention to proceed within five years, and injection commences on all ten projects in 2025; (b) twenty UK prospects currently long-listed as follow-on storage sites also rapidly mature to operational status within a decade, with an FIP in 2025 and injection commencing in 2030; and (c) a third wave of one hundred sites from the hundreds of potential exploration targets join the first two waves within another decade. This wave formulation delivers three plateaus of rapid deployment and envisions the fastest possible maturation of resources to reserves.

- The first wave requires injection to begin simultaneously at the ten most mature sites circa 2025 and storage rates to match the appraised performance, averaging 5 Mtpa for each site[25].

- Twenty long-listed prospects then mature to FIP in 2025 and become operational in 2030. We assume no issues and no bottlenecks in the second wave, as per SDS-FIC, and an injection rate and capacity for the twenty prospects based on mean estimates for the better appraised ten sites.

- The first two waves are followed in 2040 by a further one hundred sites, successfully matured from exploration targets to banked reserves. In this wave formulation, CO_2 storage has become a major industry primarily based around a North Sea hub.

What contribution does this highly optimistic formulation make to EU emissions reductions, and how does it compare to the high demand SDS-FIC scenario? By 2030, the first wave has stored 285 Mt, averaging a site injection rate of 5.7 Mtpa and banking 14% of the available capacity for ten sites. The banked storage increases to 1.4 Gt, 68% of the reserve by 2050. Averaging this across all sites, this is equivalent to a 2 Gt reserve and exhausted capacity for the ten sites by 2060. The average capacity and lifetime of a first wave site is 200 Mt and 35 years. The high demand SDS-FIC scenario requires 8.1 Gt of banked storage in 2050. Assuming an injection rate of 5 Mtpa for twenty prospects operational from 2030, the second wave increases banked storage to 1.8 Gt by 2040. And again, for one hundred exploration targets operational from 2040, the third wave banks 8.4 Gt by 2050 – Fig A3.

The approximate banked storage deficits for SDS-FIC are as follows: 0.8 Gt in 2030, increasing to 2.1 Gt in 2040 and decreasing to -0.3 Gt in 2050 (Fig 3). An injection rate of 150 Mtpa by 2030 is 44 Mtpa below the SDS-FIC scenario requirement of 190 Mtpa for 2030, but at 650 Mtpa in 2050, is significantly higher than the scenario's 500 Mtpa (Table 2). In summary, the banked storage gap increases from less than 1 Gt in 2030 to 2 Gt in 2040, and closes by 2050, achieving a 15% contribution to net zero fossil CO_2 emissions reductions. Hence, simple waves of deployment are a good approximation of what might be required to achieve an SDS-FIC contribution to net zero 2050 in Europe. North America and China would require 1.5x and 3x this level of activity respectively.

Clearly, this regional vision of early and substantial first (2025), second (2030), and third waves (2040) of CO_2 storage is highly optimistic. The first wave formulation assumes that the storage rate exceeds 50 Mtpa from 2025. The current ambition is 50 Mtpa by 2030, and indications suggest only five of the ten projects will be operational by the end of the decade, delivering 30 Mtpa by 2030[34]. These numbers frame the extraordinary scale-up required for an SDS-FIC high demand scenario.

Matching

The preceding thought experiments illustrate (a) the insufficiency of achieving exponential growth rates without banking the necessary early storage for low and moderate demand scenarios, and (b) the extremity of unrealistic growth rates that match a long-standing 15% estimate of CCS as a contributing technology when applied to net zero 2050. These outcomes lead us to a third thought experiment that considers the middle ground, matching the moderate demand 1.5TECH scenario for banked storage in 2050, assuming reasonable initial conditions over the period 2025 to 2035.
We first assume that the current European storage rate of 1 Mtpa increases to 2.5 Mtpa with Northern Lights in 2025. We also assume that expansion and additions increase the rate to 5 Mtpa in 2030, and 15 Mtpa in 2035 with the rapid emergence of UK hubs. We then forward-cast the storage rate curve from 2035 to 2050 to close the gap on the moderate demand 1.5TECH scenario of 5 Gt banked storage for net zero 2050. To close the gap, the matching formulation requires storage rates that substantially exceed the SDS-FIC scenario of 500 Mtpa by 2050. The simple matching formulation illustrates the consequence of a slow start and unbanked storage in the 2020s and 2030s – Fig A3.

Fifty boreholes per year campaign

The final set of formulations assume sustained flat rates for drilling activity. Such a formulation might consist of fifteen exploration and appraisal wells for ten prospects a year, of which, assuming 70% success, seven prospects might progress as sites to be developed with an average of five storage wells per site. Assuming a fifty boreholes-per-year campaign has commenced in 2025, and the first seven sites became operational in 2030, the CO_2 storage contribution would match the SDS-FIC demand of 8.1 Gt banked storage in 2050. Delaying the onset by five years to 2030 would result in only 4.8 Gt of storage, equivalent to 1.5TECH. A delay of ten years, and a more modest thirty well campaign of ten exploration wells a year, with only fifty percent conversion, and four injection wells for each of the five sites commencing in 2040, contributes just 1.3 Gt by 2050, equivalent to the low demand 1.5LIFE scenario – Fig A3.

A2 North Sea Storage Prospects

Ten Sites	**Capacity, Mt**	**Rate, Mt/yr**	**2030, Mt**	**2040, Mt**	**2050, Mt**	**Banked**
Northern Lights, NNS *	200	5	25	75	125	63%
Captain X, NNS	60	3	15	45	60	100%
Goldeneye, NNS	30	3	15	30	30	100%
Forties 5, CNS	300	6	30	90	150	50%
Acorn, CNS *	150	5	25	75	125	83%
Hamilton, EIS *	125	5	25	75	125	100%
Endurance, SNS *	520	13	65	195	325	63%
Bunter 36, SNS	280	7	35	105	175	63%
Hewett, SNS	200	5	25	75	125	63%
Viking A, SNS. *	130	5	25	75	125	96%
Sum and (average)	**1995**	**(5)**	**285**	**840**	**1365**	**(68%)**
Twenty Discoveries	(200)	5	-	1000	2000	50%
One Hundred Prospects	(200)	5	-	-	5000	25%

Table A2. Potential capacity and storage rates for the North Sea based on ten matured offshore sites. In the absence of a known capacity for Northern Lights, we assume 200 Mt, the average metric for the nine UK sites. The average capacity and storage rate for the matured sites is then applied to 'Twenty Discoveries' and follow-on 'One Hundred Prospects'. SNS, Southern North Sea; CNS, Central North Sea; NNS, Northern North Sea; EIS, East Irish Sea. Average capacities for the twenty discoveries and one hundred prospects are from the UK strategic portfolio[13]. Data: PBD, Strategic 2016; PBD ACTACORN 2018 (East Mey), government.no 2020 (Northern Lights). *Sites that show early indications of government support and/or FIP decisions that may deliver the expected storage rate between 2025 and 2030.

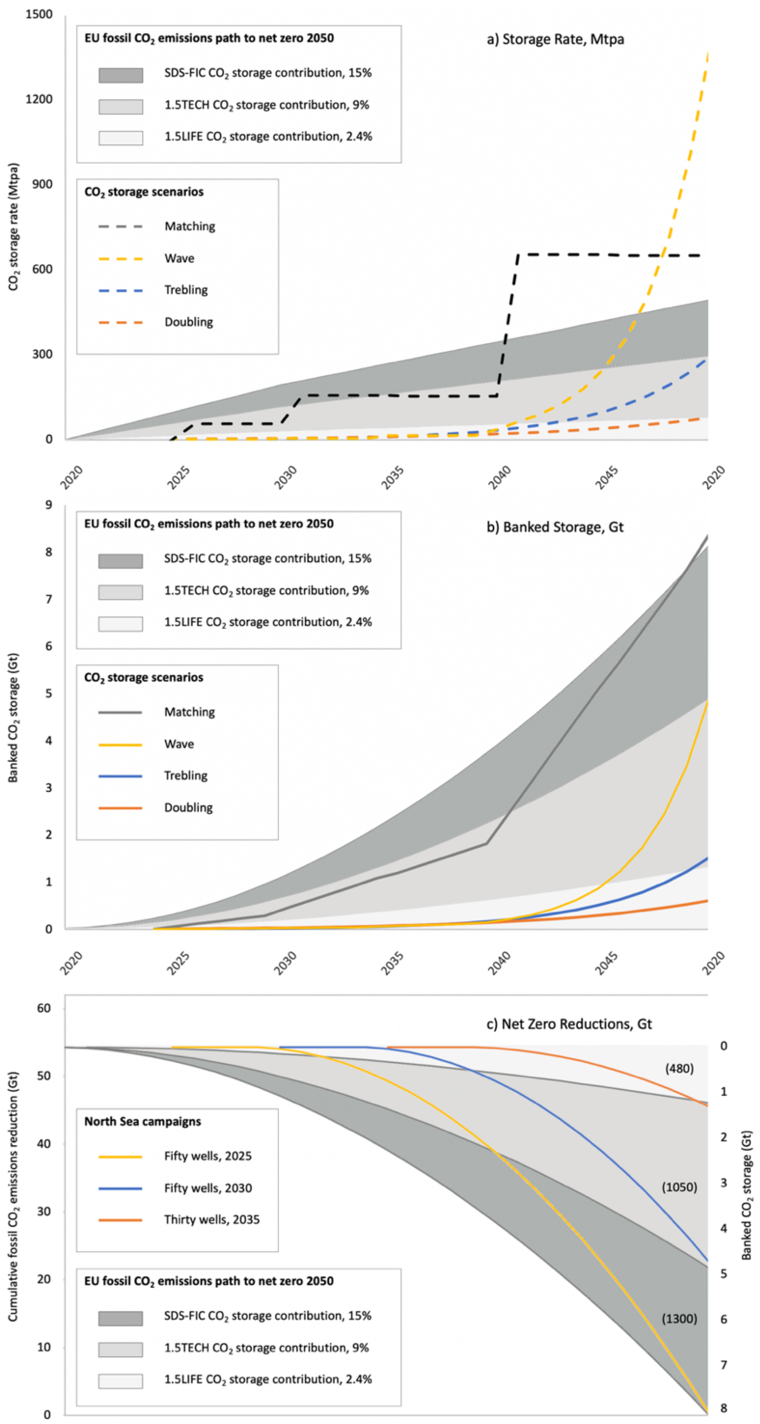

Figure A3. (a) Storage rates and (b) banked storage: doubling, trebling, and wave formulations for possible storage scenarios. A matching formulation that delivers 4.9 Gt of banked storage by 2050, equivalent to the EC's moderate 1.5TECH scenario, results in the highest storage rate by 2050. Exponential growth rates fail to achieve significant banked storage prior to 2040. (c) North Sea campaigns for net zero 2050: Fifty wells assume fifteen exploration and appraisal wells per year, maturing seven of ten prospects for development within five years, and five injection wells per site. The thirty well campaign assumes ten exploration and appraisal wells, maturing five of eight prospects, and four injection wells per site. These flat-rate campaigns deliver banked storage equivalent to 2.4%, 9%, and 15% of EU 2050 fossil CO_2 emissions.

A3 UK North Sea Histogram Model

Gaussian best fit for UK Oil and Gas Authority (OGA) well completions (N) by calendar year (t), for all boreholes (exploration and appraisal, and development: E&A&D), and maturation boreholes (E&A).

$$\overline{N} = \overline{N}_{max} * e^{-\ln(2)*\left(t-t_{\overline{N}max}\right)^2/dt^2}$$

SDS-FIC, 15%			1.5TTECH, 9%		1.5LIFE, 2.4%	
YEAR	E&A&D	E&A	E&A&D	E&A	E&A&D	E&A
2025	10	8	6	5	2	1
2026	14	11	8	7	2	2
2027	19	14	11	8	3	2
2028	25	17	15	10	4	3
2029	31	21	19	12	5	3
2030	39	24	23	14	6	4
2031	47	27	28	16	7	4
2032	55	30	33	18	8	5
2033	62	32	37	19	10	5
2034	68	34	41	20	11	5
2035	73	34	44	21	11	5
2036	77	34	46	20	12	5
2037	78	32	47	19	12	5
2038	77	30	46	18	12	5
2039	73	27	44	16	11	4
2040	68	24	41	14	11	4
2041	62	21	37	12	10	3
2042	55	17	33	10	8	3
2043	47	14	28	8	7	2
2044	39	11	23	7	6	2
2045	31	8	19	5	5	1
2046	25	6	15	4	4	1
2047	19	4	11	3	3	1
2048	14	3	8	2	2	0
2049	10	2	6	1	2	0
2050	7	1	4	1	1	0