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# National climate strategies show inequalities in global development of carbon dioxide geological storage

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Carbon dioxide geological storage (CGS) is considered critical for limiting global average temperature rise to below 1.5 °C by mitigating fossil industrial emissions and delivering permanent Carbon Dioxide Removals. Here we examine the role of CGS in long-term national emission reduction strategies submitted to the UNFCCC under the Paris Agreement. We find that a third of countries plan to develop CGS for emissions mitigation only, and a third for both emissions mitigation and carbon removals, but no countries plan on CGS for carbon removals alone. Neither the presence or performance of CGS maturity assessments correspond to CGS plans. Climate strategies of high income countries with high historic oil and gas production show firmest commitment to CGS. These countries already have multiple advantages for implementing and benefiting from CGS, which raises inequalities and sensitivities that must be carefully considered when designing carbon market and climate finance policies and frameworks for CGS development.

Contracting parties to the Paris Agreement have committed to limiting global average temperature rise to well below 2 °C with aspirations to reach 1.5 °C[1]. Meeting these climate goals requires wide scale deployment of carbon capture and geological storage (CCS) for decarbonising industrial processes ("fossil CCS") and atmospheric carbon dioxide removal (CDR) for achieving negative emissions by storing $CO_2$ in the subsurface ("subsurface CDR"), using bioenergy with CCS (BECCS) or direct air capture with CCS (DACCS). These climate technologies, which aim to permanently remove $CO_2$ from atmospheric carbon cycles, rely on subsurface storage of captured $CO_2$, an engineered approach that we hereafter refer to as $CO_2$ geological storage (CGS)[2].

The scale up of CGS required to curb dangerous climate change and limiting average warming to 1.5 °C ranges between 7.5–10 $GtCO_2$ per year[2–5] depending on the climate models and mitigation pathways used (Supplementary Note 1). All modelled IPCC scenarios require deployment of CDR to meet climate goals[2], and the scale of CDR requirements depends on rate of emissions reduction[2,6,7]. These scenarios include a range of CDR technologies, not specifically subsurface CDR. While developing a diverse portfolio of CDR solutions is a robust climate strategy[5,8], subsurface CDR offers favourable value in the climate models that underpin IPCC scenarios[8,9]. For example, 95% of CDR pathways in climate mitigation scenarios include BECCS and 34% include DACCS[5].

It is widely acknowledged that CGS buildout is not on track[10–12] for the gigatonne scales required to prevent climate breakdown. Global operational capture capacity for CGS in 2023 was 49 $MtCO_2$ per year[13] (of which less than 10 $MtCO_2$ per year is dedicated CGS[14], and 0.6 $MtCO_2$ per year is subsurface CDR[5]), with global injection rates being routinely 19–30% lower than capture capacity[15]. Thus rapid scale up of CGS is anticipated over coming decades[16] through country and region-specific technology deployment[17–19].

While CGS as part of a portfolio of climate mitigation measures is expected to reduce the overall economic cost of achieving climate goals[19], climate finance mechanisms will be important for supporting CGS development in terms of capacity building and project funding, and particularly in lower income countries[20,21]. There are urgent calls for governments to accelerate policies that will establish a revenue stream for CGS and facilitate private sector investment and similarly for the financial sector to develop novel financing approaches[21]. CGS is an important growth category for compliance and voluntary carbon markets[22,23]; storage operators can sell capacity to $CO_2$ capture operators or could be contracted to offtake emissions from high-carbon industries, including cross border arrangements for international offtake. CGS projects could also be financed through credits purchased by private and public sector organisations both in the short term while they work to reduce their emissions, or longer term to offset residual or irreducible emissions. Private investment is deemed critical to meet CGS capital requirements and is sensitive to the conditions established by national and international policy both to invest in and to drive CGS deployment[21,22]. CGS projects could generate particularly high value carbon credits due to the longevity and security of storage compared with other

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CDR solutions[22,24]. Further, there are proposals to place CGS requirements for extended fossil fuels use[25].

Ultimately, there is set to be financial benefit from developing CGS infrastructure for carbon management business[26]. Such growth raises questions around the potential future wealth distribution in terms of who pays and who gains—particularly where public sector funding is required to drive private investment in CGS[27]. However, the timeframes of financial reward may not be immediate, with expected profit margins of $CO_2$ removal companies to peak around 2050, presenting distributional implications of financing of CDR and requiring careful consideration for market design[28]. Action and inaction on CGS and the distribution of benefits and burdens across time presents important climate justice considerations from multiple dimensions including economic, distributive, intra and intergenerational, and corrective justice[29].

Currently the CGS knowledge economy is based in the Global North and higher income countries. CGS activity has predominantly focussed on fossil CCS applications in Organisation for Economic Co-operation and Development (OECD) countries[18,20,30]. This is despite substantial growth anticipated in emerging economies, particularly fossil CCS applied to manufacturing industries and biomass supply chains for BECCS. Regions with historic oil and gas industries are advantaged for CGS development, including in terms of technical data and experience, skills and supply chain, legislative frameworks, and economic wealth from resource production. Further, there is emphasis on benefit from re-use of oil and gas infrastructure, such as pipelines and wells, from both an economic and infrastructure carbon life cycle analysis perspective[31].

CGS deployment will be country and region specific[17]. However, recent analysis finds that while there is a very high need for fossil CCS in several lower income countries, their level of readiness for CGS deployment is low[18,20] by comparison with countries with a mature oil and gas sector and developed hydrocarbon provinces[32], and higher income[20]. These inequalities raise a suite of issues around different moral and ethical justice dimensions regarding how and where to fund CGS, and how to prioritise subsurface space[18,28,33]. To date, CGS developments in lower income countries have relied on multilateral development banks and climate change funds[21].

The Paris Agreement (Article 4, paragraph 19) invites contracting parties to submit long-term low greenhouse gas emissions development strategies (LT-LEDS) to the UNFCCC, outlining country-level strategies for reaching net zero[1]. It is intended that these documents should be treated as working documents that provide indicative scenarios for possible futures, i.e. they are expected to evolve[34]. As such, there is no set framework or process for the development of the LT-LEDS; they are purposefully individual to national circumstances. As of 1st January 2024, there were 67 country-level LT-LEDS submitted to the UNFCCC.

Here, we perform a stocktake on CGS inclusion in country-level climate policy worldwide by examining the presence and prevalence of CGS, and differentiating fossil CCS and subsurface CDR, in decarbonisation pathways outlined in LT-LEDS submitted to the UNFCCC prior to 1st January 2024. We consider the results in the context of historic oil and gas production, current economic circumstance and $CO_2$ storage indicators. Previous work has linked these constraints with CGS development[20,31], but we examine these variables together to present a global analysis of national climate commitment to CGS which differentiates CGS for emissions mitigation and removals, considers how these compare with climate mitigation pathways, and explores justice dimensions of the trends our analyses reveal. Hence, with LT-LEDS playing a critical role in evaluating progress towards 2050[34], CGS development not on track[11], carbon market conditions to support CGS in formulation[26,27], and many subsurface CDR technologies still nascent[35], our work is important for not only assessing whether national long term strategies are commensurate with climate mitigation pathways, but also ensuring inequity is not baked in to climate action frameworks.

## Results

### $CO_2$ storage indicator, historic oil and gas production, and economic status

Of the 197 Paris Agreement participants (countries that have signed, ratified, accepted, approved or accessioned the Paris Agreement, Supplementary Methods 1), 192 (97%) have income status categorised by the World Bank. Of these, 112 (57%) countries have historical oil and gas production (HOGP) data, and 76 (39%) have a $CO_2$ storage indicator (CSI), a measure of the countries' storage resource development[32].

We find that, while high income countries are more likely to have a CSI, and median CSI increases with country income, the assessed CSI is largely independent of economic status but is not independent of HOGP (Fig. 1). By contrast, economic status and HOGP are linked, with high income countries more likely to have high HOGP (>1214 TWh) than low income countries (Fig. 1).

For high income countries there is some positive correlation (correlation coefficient $r^2 = 0.5$) between HOGP and CSI, whereas there is no clear correlation for upper or lower middle income countries ($r^2 = 0.19$ and 0.14 respectively). No country with low HOGP has a CSI above 71 (Japan). In contrast all high income countries have above median CSI ($x \sim 39$, see Table 1), with the exception of Brunei and Trinidad and Tobago. For upper middle income countries, there is no distinct relationship between HOGP and CSI for the countries in this income class. All lower middle income countries with a CSI have high HOGP, with the exception of Morocco, Kenya and Cambodia, which have low HOGP. Whilst there is a large overlap of CSI values between upper and lower middle income countries, upper middle income countries have higher median CSI ($x \sim 40$) than lower middle income countries ($x \sim 24$).

Of note, the only low income country to have a CSI, Mozambique, has received World Bank funding to advance CGS through the CCS Trust Fund[36]. Other countries that received this funding include Algeria, Morocco, and Vietnam, all lower middle income countries with CSI values above average for this income group. In fact, Algeria and Vietnam have the highest CSI ranking for their economic status (CSI of 63 and 56, respectively). Similarly, the Asian Development Bank Carbon Capture and Storage Fund supported projects in Indonesia and China, both of which have above median CSI for their economic group ($x \sim 52$ and 87 respectively).

### $CO_2$ geological storage in climate strategies

Two thirds of LT-LEDS include CGS: 33 submissions (49%) indicate firm commitment to using CGS as an explicit part of their climate strategy, and a further ten submissions (15%) include CGS in some mitigation pathways, or mention it as a possible technology but do not commit to its use. Two submissions (3%; Latvia and Portugal) specifically disregard the use of CGS in their LT-LEDS, although remain open to CGS implementation in future scenarios should economic conditions change. The remaining 22 submissions (33%) make no mention at all of CGS. The geographic distribution of CGS commitment in LT-LEDS is shown in Fig. 2. Despite EU targets for CGS, of the 20 EU countries that have submitted LT-LEDS, nine (45%) show firm commitment to CGS (Supplementary Discussion 3).

Of the 43 countries that plan to use CGS, 20 (47%) specifically mention subsurface CDR; the remaining 23 (54%) refer only to fossil CCS application, i.e. CGS for fossil emissions reduction rather than for carbon removals. None of the LT-LEDS refer to subsurface CDR only, i.e. no emission strategies include subsurface CDR in the absence of fossil CCS. Most countries that explicitly specify a type of subsurface CDR mention BECCS (17, 89%), and approximately half (10, 53%) mention DACCS. There are more mentions of $CO_2$ utilisation in LT-LEDS (34, 59%) than subsurface CDR. In contrast, nearly all submissions (66, 99%; the exception is Marshall Islands) explicitly mention commitment to nature-based removals (i.e. Land Use, Land Use Change and Forestry, LULUCF), and thus recognise the need for CDR to balance emissions and intend to use CDR methods different from BECCS or DACCS.

We find that higher income countries are more likely to have submitted LT-LEDS and are more likely to have firm commitment to CGS (Fig. 3). By

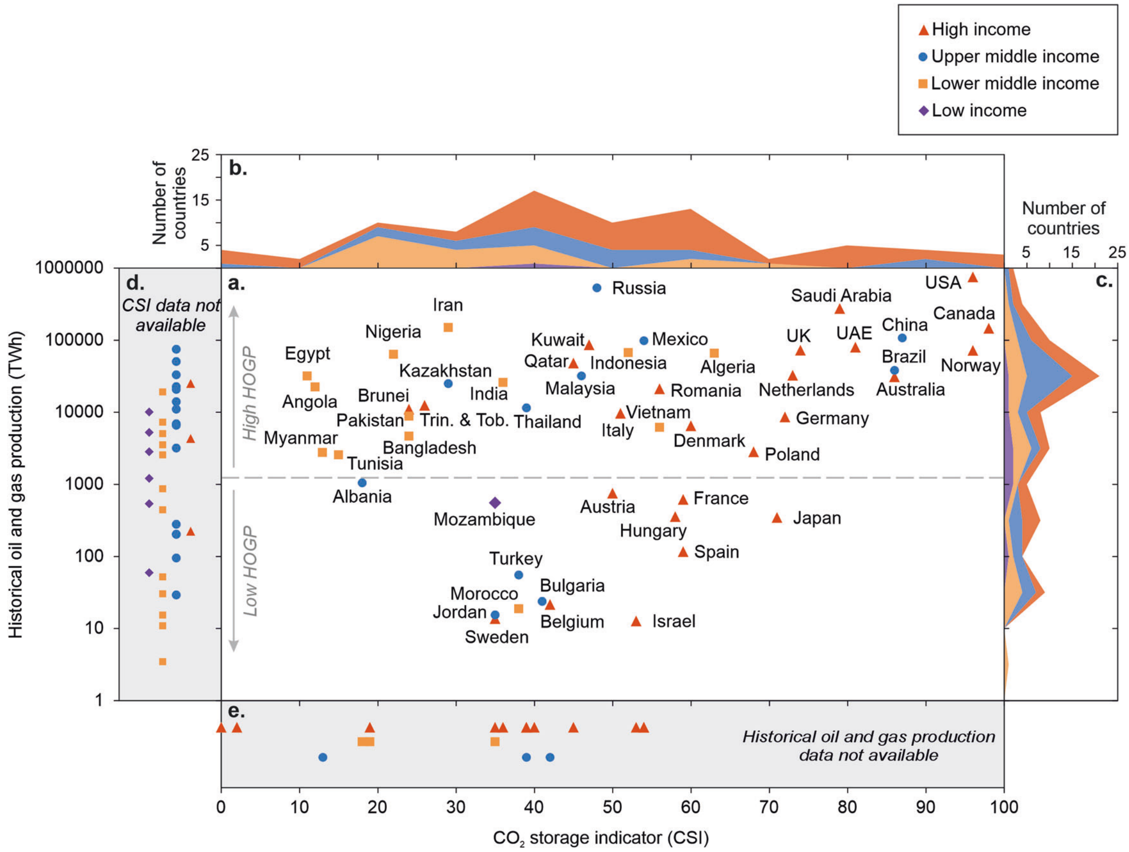


**Fig. 1 | $CO_2$ storage indicator (CSI) as a function of historic oil and gas production (HOGP) shown at country level.** **a** Distribution of countries with both CSI and HOGP data available. **b** aggregate distribution of CSI level and **c** of HOGP value. Of the 197 countries analysed, 55 have CSI, income and HOGP data available. **d** Distribution of HOGP for countries with no CSI assessment. **e** Distribution of CSI for countries with no HOGP. Data is colour-coded to show income status: red = high income, blue = upper middle income, yellow = lower middle income, purple = low income. In plots **b**–**e** data is stratified according to country income to aid visibility. Only one low income country has an assigned CSI: Mozambique.

contrast, countries with high HOGP (19, 28%) are overall less likely to have submitted LT-LEDS than countries with low HOGP (48, 72%). This proportion is particularly stark considering that the number of Paris Agreement participants with high or low HOGP is comparable (59 and 54, respectively). Indeed, Nigeria is the only member of the Organization of the Petroleum Exporting Countries (OPEC) that has submitted an LT-LEDS. Interestingly, countries with high HOGP are similarly likely to have firm commitment to CGS (15/33, 45%) compared to low HOGP countries (18/33, 55%), but no countries with high HOGP reject CGS, and only one high HOGP country that has submitted an LT-LEDS does not mention CGS (Argentina).

Thus, our analysis finds that income is an important factor in determining a country's likelihood to commit to CGS, whilst within a given income class, HOGP is a strong predictor of commitment to CGS. Importantly, all the 16 LT-LEDS that include firm commitment to both fossil CCS and subsurface CDR are high income except for Indonesia and Thailand (which are lower and upper middle income, respectively). All countries that include DACCS are high income and indicate firm commitment to CGS. While high HOGP countries are less likely to have submitted LT-LEDS than low HOGP countries, where they do, they are twice as likely to have firm commitments to CGS than low HOGP countries (79% vs 38%).

Having an above average CSI—or a CSI assessment at all—does not translate into commitment to CGS in the submitted LT-LEDS; 33 countries with a CSI have not submitted LT-LEDS, and five countries with CSI values that have submitted LT-LEDS do not mention CGS. However, each of the 18 countries that commit to CGS for mitigation and removals, except Oman, have a CSI assessment, though not all have above median CSI values.

Finally, many LT-LEDS lack detail on specific fossil CCS applications, but where provided, application to hard-to-abate industry is most common (23/43, 53%), followed by power generation (13/43, 30%).

## Discussion

The next decades are critical for CGS technology to scale up for emissions reduction (fossil CCS) and carbon removals (subsurface CDR)[16]. While our analysis is limited by lack of fully comprehensive data (only 67 countries had submitted LT-LEDS prior to January 2024, and LT-LEDS are working documents, variable in quality, that are expected to be updated) we find that the data gaps themselves are informative. Our analysis of LT-LEDS together with country-level economic and resource status including $CO_2$ storage indices provides insight into the roles that CGS is anticipated to play and highlights emerging inequalities and sensitivities which must be carefully considered when designing policy and finance instruments to support CGS development.

Higher income countries and those with high HOGP have contributed most to climate breakdown[37]. We find economic status is an important factor in determining a country's likelihood to commit to CGS, whilst within a given income class, HOGP is a strong predictor of commitment to CGS, with high HOGP countries twice as likely to have firm commitments to CGS than low HOGP countries. Further, of the 20 countries that refer to subsurface CDR, all but two are high income, and only high income countries plan to develop DACCS. These findings unearth several justice dimensions that will drive further inequality if not recognised and mitigated through specific targeted interventions.

There are corrective, climate and distributive justice arguments that higher income and/or high HOGP countries should take the responsibility or burden of driving down technology costs and developing successful and transferable policy and legal instruments and frameworks. Such arguments could also apply if those countries also offtake carbon from other (lower income, lower HOGP) countries under particular conditions. However, issues around economic justice come into play if policy and investment mechanisms to incentivise CGS bring the anticipated commercial and financial benefit, with carbon markets anticipated to peak towards 2050. In addition, CGS drives down costs of meeting national emissions reduction targets, with cost savings the earlier that CGS is developed[38]. For CGS there is an additional material injustice in terms of the subsurface data, infrastructure, knowledge, skills and supply chain assets from the hydrocarbon sector that can be transitioned to support CGS development[31,39]. Such agility places such countries at an advantage, and being or becoming CGS knowledge and technology leaders would exacerbate power imbalances already held by hydrocarbon producing nations. That said, our finding that countries with high HOGP are not submitting LT-LEDS at the same rate as their low HOGP counterparts also exposes the vulnerabilities of such hydrocarbon producing countries.

Given the prevalence of CGS in LT-LEDS, there is urgent need to support the expansion of CSI assessments, particularly for lower income and low HOGP countries, and countries which outline clear intent to use CGS in their LT-LEDS but currently have no CSI assessment nor specify intent for cross-border offtake, like Colombia, Ethiopia, Oman, Sri Lanka and Uruguay. Country-appropriate mechanisms to increase CSI must also be identified to ensure CGS deployment in line with the LT-LEDS timeframes. Although CGS development has had a minor role in climate finance[40], we find lower income countries with above average CSI have received support from Development Banks to further CGS, indicating that these are successful mechanisms to move countries to higher CSI, provided favourable geology.

While subsurface CDR via BECCS and DACCS is critical for meeting climate goals[2] our analysis joins a body of work showing that national climate policies are not commensurate with the science. BECCS and Agriculture, Forestry and Other Land Use (AFOLU, which includes LULUCF) are in 95% and 98% of all CDR models (compatible or not with meeting the Paris Agreement)[5], yet we find that LULUCF features far more in LT-LEDS than BECCS (99% compared with 32%) and DACCS (in 34% of CDR models, but featuring in 18% of LT-LEDS)[35]. Our finding that all countries but one (66/67, 99%) are looking to develop CDR through nature-based removals shows recognised need for LT-LEDS to include CDR approaches to balance emissions. However, only 20 countries have plans for subsurface CDR and no country intends to develop subsurface CDR in the absence of fossil CCS. DACCS is mentioned least in LT-LEDS and only two countries intend to use DACCS in the absence of BECCS. Although subsurface CDR has greater removal potential and permanence[41,42], its higher cost and lower technological maturity compared to LULUCF likely contributes to its less frequent mention in LT-LEDS, and particularly for DACCS.

Given that fossil CCS is mentioned twice as frequently as subsurface CDR, and there are more mentions of $CO_2$ utilisation (which does not necessarily offer permanent storage or removals) than subsurface CDR, our results indicate international direction prioritising CGS for emissions

**Table 1 | $CO_2$ Storage Indicator (CSI) and historic oil and gas production (HOGP) data availability and statistics for the 197 countries analysed**

| | CSI data available (%) | Median CSI value (range) | HOGP data available | High HOGP (%) |
|---|---|---|---|---|
| Number of countries | 76 (39%) | 39 (0–98) | 113 | 57 (50%) |
| By income class | | | | |
| High | 41 (71%) | 50 (0–98) | 31 | 18 (58%) |
| Upper middle | 16 (30%) | 40 (13–87) | 37 | 18 (49%) |
| Lower middle | 18 (33%) | 24 (11–63) | 34 | 17 (50%) |
| Low | 1 (4%) | 35 | 10 | 3 (30%) |

Overall, CSI, income and HOGP data is available for 55 countries.

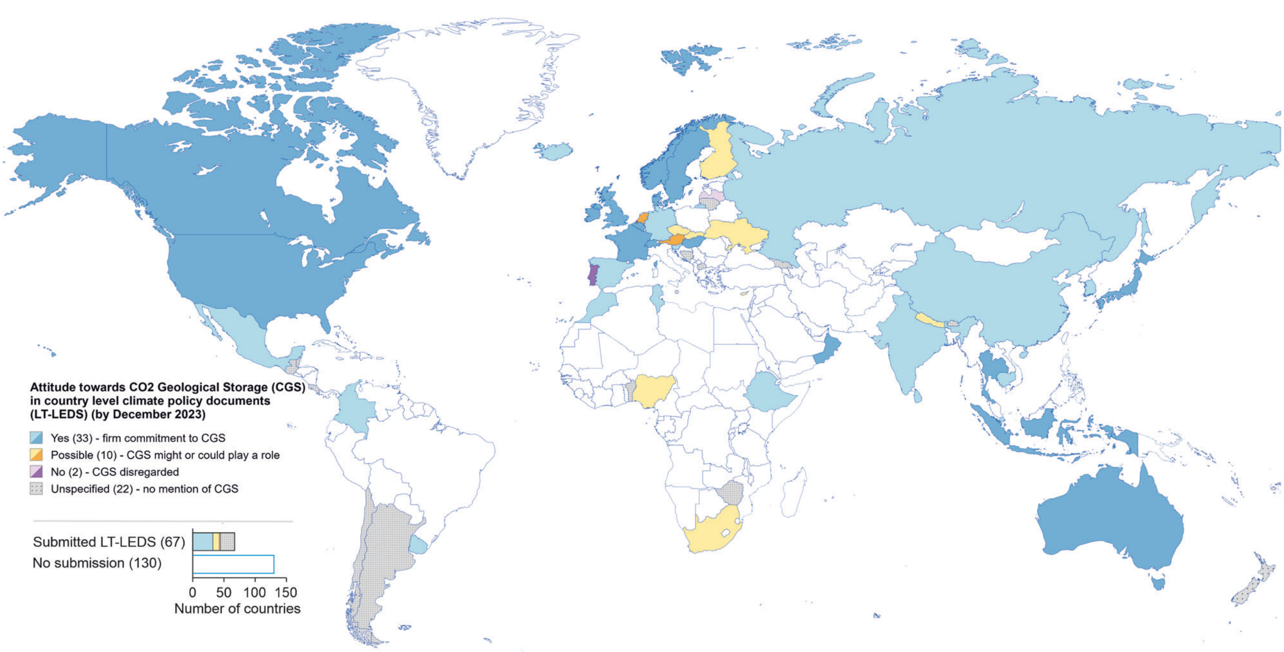


**Fig. 2 | Global map of country intention to use carbon dioxide geological storage (CGS) as indicated in LT-LEDS submitted prior to January 2024.** All countries that mention CGS do so with reference to fossil CCS (light colour fill), and approximately half of these specify subsurface CDR (dark colour fill). Countries that have not submitted an LT-LEDS are colourless. Inset: Graph showing commitment to CGS in LT-LEDS in terms of number of countries versus the number of countries that have yet to submit an LT-LEDS to the UNFCCC prior to January 2024. Background map created with www.mapcharts.com.

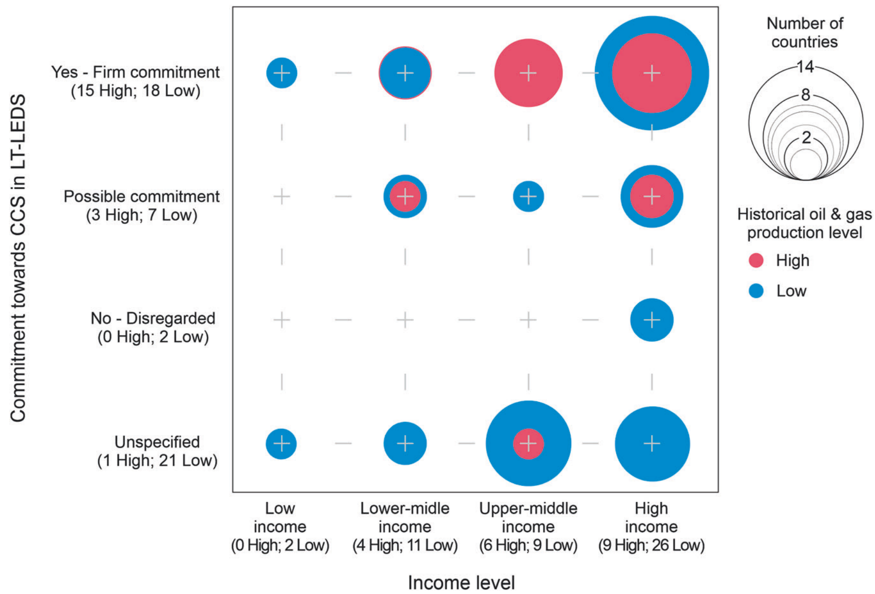


**Fig. 3 | Intended commitment towards CGS in LT-LEDS submitted prior to January 2024 for different country income classifications.** The number of countries is indicated by the size of the circle, and circles are colour coded according to high (pink) or low (blue) historic oil and gas production (HOGP).

reduction and mitigation over permanent removals. Such policy focus may reflect the maturity and certainty of anticipated scale up of these technologies; CDR scale up requirements is dependent on action taken to mitigate emissions in immediate decades[2]. While a diverse CDR portfolio is preferable[5,43], recent work finds nature-based CDR proposed in LT-LEDS are poor quality[44] and that there is a mismatch in the scale of CDR proposed in LT-LEDS and that required globally[45]. There is a clear need for greater attention on the role and purpose of CDR, and for frameworks to ensure that subsurface CDR development is not dependent on fossil CCS or the presence of an oil and gas sector (current or historic), and, as our work shows, it is imperative to do so for justice and equity argument in addition to meeting climate goals.

Finally, it is difficult to obtain a perspective of the expected international scale up of CGS due to quality and detail variation across the LT-LEDS. In several cases, lack of detail and/or ambiguity made it difficult to determine consideration of or commitment to CGS. It is not possible to use LT-LEDS to identify spatial or temporal pinch points or discrepancies between capture rates, subsurface storage capacity, and other enabling factors such as transboundary policies or infrastructure, and supply chain maturity. In the absence of country-level technology scale-up in the LT-LEDS it is not possible to triangulate against fossil CCS and subsurface CDR projections modelled in IPCC and other climate pathways. This is also the case across all forms of CDR[35,44]. As well as providing more granular information within LT-LEDS, rapid improvement in standardising and harmonising this information (Supplementary Note 2) will be critical for an integrated and coordinated effort to deliver on climate goals and balance inequalities.

## Methods

To analyse the commitment of Paris Agreement participant countries[46] (Supplementary Method 1) to the adoption of geological $CO_2$ storage (CGS), including fossil CCS and subsurface CDR, we focused on the role of CGS outlined in country level Long-Term Low-Emission Development Strategies (LT-LEDS). We did not consider the Nationally Determined Contributions (NDCs) due to their short-term nature (projected for 2030, in some cases lasting less than a decade), which is inadequate for the scale-up of fossil CCS or subsurface CDR. 68 LT-LEDS were submitted to the UNFCCC prior to January 1st 2024, but, in line with previous LT-LEDS studies[5] we discard the LT-LEDS submission on behalf of the European Union (EU) because, in accordance with Article 4.19 of the Paris Agreement, individual member states of the EU must submit their own national climate strategy, and the EU does not bind its member states to the climate strategies outlined in the EU LT-LEDS (Supplementary Method 1).

### Analysing and classifying country-level commitment to CGS in LT-LEDS

The LT-LEDS documents are written either in English, Spanish, or French. To identify reference to CGS and nature-based removals within the LT-LEDS reports we searched for the full range of possible ways to refer to CGS and its various components and nature-based removals in the different languages. Based on this search, we categorised countries according to their intended commitment to using CGS (whether domestically or cross-border). The categories included: Yes—countries with a firm intention to implement CGS as an explicit part of their emission reduction strategies; Possible commitment—countries that included CGS in some emissions reductions pathways or mentioned it as a possible technology; No—countries that consider but explicitly disregard CGS for their current emissions reductions strategies (note that this does not mean that CGS is ruled out of future updated strategies); Unspecified—countries that made no mention of CGS at all (Supplementary Method 2).

The CGS search terms we used were: CCS, CCUS, CCU, CAC, CUAC, CSC, CSU, use, usage, utilization, Carbon Capture, Carbon Storage, Carbon removal, CDR, $CO_2$ storage, $CO_2$ capture, negative, removal, captage, stockage, de carbone, captura/almacenamiento de carbono, captura y secuestro, sequestration, stor*, sequest*, remov*, capt*, almac*, stock*.

For CDR through nature-based removals, we used the following search terms: LULUCF, land use, land use change, forest, forestry, afforestation, reforestation, AFOLU, utilisation des terres, forêt, foresterie, boisement, reboisement, uso de la tierra, bosque, silvicultura, forestación, reforestación.

Where possible, we identified specific CGS applications in the LT-LEDS. In some cases, the terminology used can make this difficult: for example, reference to use of CCS for negative emissions could be inferred to mean DACCS or BECCS, in which case we infer commitment to subsurface CDR but not to specific technologies.

### Classifying country income

The 197 countries included in our analysis were subdivided based on their per capita income level according to the income classification established by the World Bank[47]: high income country (US$13,205 or more); upper middle income country (between US$4,256 and US$13,205); lower middle income country (between US$1,086 and US$4,255); low income country (US$1,085 or less). In total, 57 countries (31%) are classified as high income, 51 (27%) as upper middle, 53 (28%) as lower middle and 25 (13%) as low income countries.

Of the 197 countries analysed 192 (97%) have an income status assigned by the World Bank, whereas five do not.

### Classifying historical oil and gas production

To determine the historical level of oil and gas production (HOGP), we calculated the cumulative production of oil and gas (in TWh) from 1900 to 2019, available in Our World in Data as of 1st January 2024[48]. Of the 197 countries analysed, 112 (57%) have HOGP data.

In order to subdivide the countries, we set a threshold at 1214 TWh of cumulative production, the median of the range evaluated (corresponding to Chad); hence, those with values above 1214 TWh are considered high HOGP, and those below 1214 TWh are considered low HOGP. In total, 59 countries (30%) are considered high HOGP, 54 (27%) are low HOGP, and the remaining 84 countries (43%) lack HOGP data.

### Classifying $CO_2$ storage indicator

To determine the readiness to implement CGS, we used the $CO_2$ Storage Indicator (CSI), a classification developed by the Global CCS Institute (GCCSI) intended to provide a unified, quantified assessment that enables harmonised tracking of country-level CCS development and deployment. To calculate CSI, the GCCSI considers technical aspects required for CGS within a country's borders including the geology, the maturity of storage assessments, track record of storage projects, site characterisation development and technical ability to store $CO_2$[49]. Data sources include GCCSI[49] supplemented by more recent information in the CO2RE data portal (https://co2re.co/).

Of the 197 total countries analysed, 76 (39%) have a CSI, ranging from 0 to 98. Of these countries, 51 (68%) have submitted an LT-LEDS.

## Data availability

All data underpinning our work, including analysed data are provided as publicly available data file at: https://doi.org/10.15129/8792861c-eec9-450e-9416-28415cfe8565[50].

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## References

1. United Nations, CHAPTER XXVII ENVIRONMENT, 7. d Paris Agreement Treaty Series, vol. 3156 (2015).
2. IPCC: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P. R. Shukla, *et al*eds.)]. Cambridge University Press (2022).
3. IEA Net Zero by 2050 A Roadmap for the Global Energy Sector. Available at: https://www.iea.org/reports/net-zero-by-2050 (2021).
4. Energy Transition Commission Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited. Available at: https://www.energy-transitions.org/publications/carbon-capture-use-storage-vital-but-limited/ (2022).
5. Smith, S. M., *et al*eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. https://doi.org/10.17605/OSF.IO/F85QJ (2024).
6. Lamb, W. F. et al. Current national proposals are off track to meet carbon dioxide removal needs. *Nat. Clim. Chang.* **14**, 555–556 (2024).
7. Ganti, G. et al. Evaluating the near- and long-term role of carbon dioxide removal in meeting global climate objectives. *Commun Earth Environ* **5**, 377 (2024).
8. Realmonte, G. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat Commun* **10**, 3277 (2019).
9. Köberle, A. C. The Value of BECCS in IAMs: a Review. *Curr Sustainable Renewable Energy Rep* **6**, 107–115 (2019).
10. Haszeldine R. Stuart, Flude, S., Johnson, G., and Scott, V. Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Phil. Trans. R. Soc. A.3762016044720160447 https://doi.org/10.1098/rsta.2016.0447 (2018).
11. Martin-Roberts, E. et al. Carbon capture and storage at the end of a lost decade. *One Earth* **4**, 1569–1584 (2021).
12. IEA Energy System - Carbon Capture, Utilisation and Storage Tracking https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage (accessed September 2023) (2023).
13. GCCSI Global Status of CCS 2023. Australia. Available at: https://status23.globalccsinstitute.com/.
14. Greenfield, C., Budinis, S. & Fajardy, M. $CO_2$ Transport And Storage - Energy System. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage (2023).
15. Zhang, Y., Jackson, C., Krevor, S. An Estimate of the Amount of Geological CO2 Storage over the Period of 1996–2020 Environmental Science & Technology Letters 2022 9, 693–698 (2022).
16. Krevor, S. et al. Subsurface carbon dioxide and hydrogen storage for a sustainable energy future. *Nat Rev Earth Environ* **4**, 102–118 (2023).
17. Vaughan, N. E. et al. Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environ. Res. Lett.* **13**, 044014 (2018).
18. Lane, J., Greig, C. & Garnett, A. Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nat. Clim. Chang.* **11**, 925–936 (2021).
19. Strefler, J. et al. Carbon dioxide removal technologies are not born equal. *Environ. Res. Lett.* **16**, 074021 (2021).
20. Rassool, D. & Havercroft, I. *Financing CCS in Developing Countries. Australia* https://www.globalccsinstitute.com/resources/publications-reports-research/financing-ccs-in-developing-countries/ (2021).
21. Clean Energy Ministerial Forum Key Financing Principles for Carbon Management. Available at: https://www.cleanenergyministerial.org/content/uploads/2023/07/key-financing-principles-for-carbon-management.pdf (accessed September 2023) (2023)
22. Rassool, D. Unlocking private finance to support CCS investments. Global Carbon Capture and Storage Institute Australia. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2022/01/Unlocking-Private-Finance-For-CCS-Thought-Leadership-Report-1-1.pdf (2021).
23. Taskforce on Scaling Voluntary Carbon Markets Taskforce on Scaling Voluntary Carbon Markets Phase 1- Final Report. Available at: https://www.iif.com/Portals/1/Files/TSVCM_Report.pdf (2021).
24. Mac Dowell, N., Reiner, D.M. and Haszeldine, R.S. Comparing approaches for carbon dioxide removal. Joule, 6, pp.2233–2239 (2022).
25. Jenkins, S., Kuijper, M., Helferty, H., Girardin, C. & Allen, M. Extended producer responsibility for fossil fuels. *Environ. Res. Lett.* **18**, 011005 (2023).
26. Serin, E. et al. *Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK. Centre for Economic Performance. London, United Kingdom*, (2021). Available at: https://www.lse.ac.uk/granthaminstitute/publication/seizing-sustainable-growth-opportunities-from-carbon-capture-usage-and-storage-in-the-uk/.
27. Mintz-Woo K, Lane J. Why and Where to Fund Carbon Capture and Storage. Sci Eng Ethics. 2021 Nov 18;27:70. https://doi.org/10.1007/s11948-021-00344-3. PMID: 34796377; PMCID: PMC8602127.
28. Andreoni, P., Emmerling, J. & Tavoni, M. Inequality repercussions of financing negative emissions. Nat. Clim. Chang. https://doi.org/10.1038/s41558-023-01870-7 (2023).
29. McKinnon, C. Climate justice in a carbon budget. *Climatic Change* **133**, 375–384 (2015).
30. IEA IEA Technology Roadmap - Carbon Capture and Storage. Available at: https://www.iea.org/reports/technology-roadmap-carbon-capture-and-storage-2013 (2013).

31. Alcalde, J. et al. Acorn: Developing full-chain industrial carbon capture and storage in a resource-and infrastructure-rich hydrocarbon province. *J. Cleaner Product.* **233**, 963–971 (2019).
32. Consoli, C. Hovercraft, I. and Irlam, L. Carbon Capture and Storage Readiness Index: A global comparative analysis of CCS indicators for the wide-scale deployment of carbon capture and storage projects. GCCSI (2016).
33. Sovacool, B. K. Expanding carbon removal to the Global South: Thematic concerns on systems, justice, and climate governance. *Energy Climate Change* **4**, 100103 (2023).
34. Buck, H. J. et al. Why residual emissions matter right now. *Nat. Clim. Chang.* **13**, 351–358 (2023).
35. Buylova, A., Fridahl, M., Nasiritousi, N. & Reischl, G. Cancel (out) emissions? The envisaged role of carbon dioxide removal technologies in long-term national climate strategies. *Front. Climate* **3**, 675499 (2021).
36. Kulichenko, N., Ereira, E. Carbon Capture and Storage in Developing Countries: A Perspective on Barriers to Deployment. World Bank. Washington. ISBN: 978-0-8213-9610-0 (2012).
37. Ritchie, H. "Global inequalities in CO2 emissions" Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/inequality-co2' [Online Resource] (2023).
38. Bacilieri, A., Black, R., & Way, R. Assessing the relative costs of high-CCS and low-CCS pathways to 1.5 degrees. Oxford Smith School Working Paper 23-08. Available at: https://www.smithschool.ox.ac.uk/sites/default/files/2023-12/Assessing-the-relative-costs-of-high-CCS-and-low-CCS-pathways-to-1-5-degrees.pdf (accessed December 2023) (2023).
39. Turan, G. Brief - CCS: Applications and Opportunities for the Oil and Gas Industry. Global Carbon Capture and Storage Institute. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2020/05/Brief-_CCS-in-OAG-3.pdf.
40. Warren, P. The role of climate finance beyond renewables: demand-side management and carbon capture, usage and storage. *Climate Policy* **19**, 861–877 (2019).
41. Chiquier, S., Patrizio, P., Bui, M., Sunny, N. & Mac Dowell, N. A comparative analysis of the efficiency, timing, and permanence of CO2 removal pathways. *Energy Environ. Sci.* **15**, 4389–4403 (2022).
42. Minx, J. C. et al. Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.* **13**, 063001 (2018).
43. Fuhrman, J. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Chang.* **13**, 341–350 (2023).
44. Smith, H. B., Vaughan, N. E. & Forster, J. Long-term national climate strategies bet on forests and soils to reach net-zero. *Commun Earth Environ* **3**, 305 (2022).
45. Lamb, W. F., et al. The carbon dioxide removal gap. *Nature Climate Change*, 1–8 (2024).
46. UNTC United Nations, Treaty Series, vol. 3156. Available at: https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en (Last accessed: 1st January 2024) (2023).
47. World Bank World Bank Data, World Bank Country and Lending Groups, Country Classification. Available at: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups (last accessed: 1st January 2023) (2023).
48. Ritchie, H., Roser, M., and Rosado, P. Our World in Data - Energy. [Online Resource] Available at https://ourworldindata.org/energy Accessed January 2023 (2022).
49. Consoli, C. CCS Storage Indicator (CCS-SI). Australia. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2020/04/CCS-Storage-Indicator-CCS-SI-DIGITAL-1.pdf (2018).
50. Alcalde, J., Johnson, G., Roberts, J. J Data for "National climate strategies show inequalities in global development of carbon dioxide geological storage". University of Strathclyde. https://doi.org/10.15129/8792861c-eec9-450e-9416-28415cfe8565 (2025).



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## Author contributions
All authors contributed substantially to the work. All authors conceptualised the research and agreed the scope and approach. J.A. led on the data collection and analysis with collaborative input from J.R. and G.J. J.R. contributed substantially to data analysis and led on the drafting and revision of the work, with specific contribution from J.A. and G.J. All authors drafted, read, and commented on the manuscript, and J.R. and J.A. agreed the original, revised, and final manuscript. G.J. contributed to the paper only while working at the University of Strathclyde.

## Competing interests
Co-author G.J. works at Drax Group which is developing technology for carbon dioxide removals. G.J. contributed to the research while working at the University of Strathclyde, before moving to Drax Group.

## Additional information
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