National climate strategies show inequalities in global development of geological storage of CO_2

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Abstract

CO_2 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. 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 CO_2 storage maturity assessments correspond to CGS plans. The 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.

1. Introduction

Signatories 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 removals approaches coupled with CO_2 geological storage (CGS)[2] which aims to permanently remove CO_2 from atmospheric carbon cycles. Different technologies and applications inject CO_2 for subsurface storage, including carbon capture and storage (CCS) for CO_2 emissions reduction from industrial processes and energy production ("fossil CCS"), and subsurface Carbon Dioxide Removals (CDR) for negative emissions, including bioenergy with CCS (BECCS) or direct air capture and storage (DACCS) ("subsurface CDR") (Table 1).

The scale up of CGS required to curb dangerous climate change depends on the climate models used; scenarios reported by the Intergovernmental Panel on Climate Change (IPCC) indicate that by 2050, up to 7.5 Gt/yr of geological CDR will be required[2][1]. Other assessments are similar; for the energy system alone the International Energy Agency (IEA)[3] suggests 7.6 Gt/yr and the Energy Transition Commission[4] 7–10 Gt/yr by 2050. All modelled IPCC scenarios require deployment of CDR to meet climate goals[2], though not specifically subsurface CDR.

By comparison, global operational capture capacity for CGS in 2022 was 42.6 $MtCO_2$/yr[5], with global injection rates being routinely 19–30% lower than capture capacity[6]. It is widely acknowledged that CCS buildout is not on track[7,8,9]. Thus, rapid scale up of CGS is anticipated over coming decades[10], though technology deployment will be country and region specific[11,12,13].

While CGS as part of a portfolio of climate mitigation measures is expected to reduce the overall economic cost of achieving climate goals[13], climate finance mechanisms will be important for supporting CGS development in terms of capacity building and project funding, and particularly in lower income countries[14,15]. 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[15]. CGS is an important growth category for compliance and voluntary carbon markets[16,17]; storage operators can sell capacity to CO_2 capture operators or could be contracted to offtake emissions from high-carbon industries. 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 CCS deployment[15,16]. CGS projects could generate particularly high value carbon credits due to the longevity and security of storage compared with other carbon removal solutions[16,18]. Further, there are proposals to place CGS requirements for extended fossil fuels use[19].

Ultimately, there is set to be financial benefit from developing CGS infrastructure for carbon management business[20]. 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[21]. 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[22]. 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[23].

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[12,14,24]. This is despite significant 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 carbon perspective[25].

CGS deployment will likely be country and region specific[11]. 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 CCS deployment is low[12,14] by comparison with countries with a mature oil and gas sector and developed hydrocarbon provinces, and higher GDP[26]. 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[12,22,27]. To date, CGS developments in lower income countries have relied on multilateral development banks and climate change funds[15].

The Paris Agreement (Article 4, paragraph 19) invites signatories 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 speculative and are expected to evolve[28]. 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 1 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 January 2024. We consider the results in the context of current and historic oil and gas production, economic circumstance and constraints such as CGS resource indicators.

2. Results

2.1 Storage indicator, historic oil and gas production, and economic status

Of the 197 countries that are signatories of the Paris Agreement, 186 (94%) have income status categorised by the World Bank. Of these, 112 (57%) countries have historical oil and gas production (HOGP) data, and 75 (38%) have a CGS storage indicator (CSI), a measure of the countries' storage resource development assigned by the Global CCS Institute (www.globalccsinstitute.com).

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 (> 1000 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 = 0.23 and 0.2 respectively). With the exception of Japan, no country with low HOGP has a CSI above 60. In contrast all high income countries with high HOGP and CSI have above median CSI (x ~ 39, see Table 2), with the exception of Brunei and Trinidad and Tobago. For upper middle income countries, only China and Brazil - both with high HOGP - have CSI values above 56, whereas there is no distinct relationship between HOGP and CSI for the remaining countries in this income class. With the exception of Morocco, Kenya and Cambodia, which have low HOGP, all other lower middle income countries with a CSI have high HOGP. Whilst there is a large overlap of CSI values between upper and lower middle income countries, the median CSI for upper middle income countries (x ~ 40) is higher than for lower middle income (x ~ 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[29]. 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 ~ 52 and 87 respectively).

2.2 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 reject use of CGS in their emission pathway. 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.

Of the 43 countries that plan to use CGS, 19 (44%) specifically mention subsurface CDR; the remaining 24 (56%) 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 (19) 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 countries, 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 non-CGS CDR methods.

Compared with the income classification of Paris Agreement signatories, higher income countries are more likely to have submitted LT-LEDS and are more likely to have firm commitment to CGS (Fig. 3). However, when considering historical oil and gas production, 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 signatories 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 geological storage (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, income is a significant 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 assessment - or a CSI assessment at all - does not imply a commitment to CGS in the submitted LT-LED; 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%).

3. Discussion

The next decades are critical for CGS technology to scale up for emissions reduction (fossil CCS) and carbon removals (subsurface CDR)[10]. While our analysis is limited by lack of fully comprehensive data (only 67 countries have submitted LT-LEDS at the time of this work, 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 CGS storage assessment (CSI) 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.

Given the prevalence of CGS in LT-LEDS, there is urgent need to support the expansion of CGS storage 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, 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[30], 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 status, provided favourable geology.

Nearly all LT-LEDS include nature-based carbon removals, showing recognised need for CDR approaches to balance emissions. However, no country intends to develop subsurface CDR in the absence of fossil CCS. Subsurface CDR via BECCS and DACCS is critical for meeting climate goals[2] our analysis finds that DACCS is mentioned least in LT-LEDS and only two countries intend to use DACCS in the absence of BECCS. Our results could be interpreted to imply that subsurface CDR is currently dependent on a fossil CCS sector. Such dependency could have a partial physical basis in terms of infrastructure, knowledge, and legislation. Regardless, given that subsurface CDR is mentioned half as frequently as fossil CCS, and less than CGS for fossil power, our results indicate international direction prioritising CGS for emissions reduction and mitigation over removals. Such policy focus may reflect the maturity and certainty of anticipated scale up of these technologies; CDR scale up requirements depend significantly on action taken to mitigate emissions in immediate decades[2]. However, we do find that all except one country (66/67, 99%) are looking to develop CDR through nature-based removals. While a diverse CDR portfolio is preferable[31], recent work finds nature-based CDR proposed in LT-LEDS are poor quality[32] and that there is a mismatch in the scale of CDR proposed in LT-LEDS and that required globally[33]. There is a clear need for greater attention on the role and purpose of removals, and for frameworks to ensure that subsurface CDR is not dependent on fossil CCS or the presence of an oil and gas sector.

Higher income countries and those with high HOGP have contributed most to climate breakdown[34]. Income is a significant 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. In addition, high HOGP countries are 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, low 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[35]. For CGS and other subsurface net zero technologies, 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[25,36]. 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 countries.

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 or commitment of CGS. It is not possible to use LT-LEDS to identify spatial or temporal pinch points or discrepancies between capture rates, subsurface storage space, 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 climate pathways. This is also the case across all forms of CDR[32]. As well as providing more granular information within LT-LEDS, rapid improvement in standardising and harmonising this information will be critical for an integrated and coordinated effort to deliver on climate goals and balance inequalities.

4. Methods

To analyse the commitment of countries 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 we discard the LT-LEDS submission on behalf of the EU because, in accordance with Article 4.19 of the Paris Agreement, individual member states of the EU submit their own strategies.

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

The LT-LEDS documents were 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 the 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 implementing CGS. 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 firmly rejected CGS for their emissions reductions strategies; *Unspecified* - countries that made no mention of CGS at all.

The CGS search terms we used were: CCS, CCUS, CCU, CAC, CUAC, CSC, CSU, use, usage, utilization, Carbon Capture, Carbon Storage, Carbon removal, CDR, CO2 storage, CO2 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 identify 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.

4.2 Classifying country income

We started with the 197 countries that are signatories to the Paris Agreement as of January 1, 2023[37]. These countries have been further subdivided based on their per capita income level according to the income classification established by the World Bank[38]: *High income country, HIC* (US$13,205 or more); *Upper-middle income country, UMIC* (between US$4,256 and US$13,205); *Lower-middle income country, LMIC*, (between US$1,086 and US$4,255); *Low income country, LIC* (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. Eleven (6%) of the countries signatory to the Paris Agreement lack an income level classification.

Of the 197 countries analysed 186 (94%) have an income status assigned by the World Bank.

4.3 Classifying historical oil and gas production

To determine the historical level of oil and gas (HOG) production, we have summed up the cumulative production of oil and gas (in TWh) from 1900 to 2019, available in Our World in Data as of January 1, 2023[39]. In order to subdivide the countries, we have set a threshold at 1000 TWh of cumulative production, where those with values above 1000 TWh are considered "High", and those below 1000 TWh are considered "Low". In total, 59 countries (30%) are considered “High” historical oil and gas producers, 54 (27%) are “Low” producers. A further 84 countries (43%) lack historical oil and gas production data.

Of the 197 countries analysed, 113 (57%) have HOGP data.

4.4 Classifying CO_2 Storage Index

To determine the readiness to implement CGS, we used the CCS Storage Indicator (CSI), a classification developed by the Global CCS Institute (GCCSI) with the intention 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 and track record of storage projects.

Of the 197 total countries analysed, 75 (38%) have a CSI, ranging from 0 to 98. Data sources include GCCSI[40] supplemented by more recent information in the CO2RE data portal (https://co2re.co/). Of these countries, 51 (68%) have submitted an LT-LED.

Declarations

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Footnotes

1. Interquartile range 2.5–7.5 Gt per year CDR (BECCS and DACS) by 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot.

Tables

Table 1

CO_2 for subsurface geological storage can come from different sources, namely CCS for emissions reduction (fossil CCS) and CDR for negative emissions (subsurface CDR). IPCC definitions of carbon source are used[41].

CO_2 Geological Storage (CGS)		
Application	Carbon Capture & subsurface Storage (CCS)	Subsurface Carbon Dioxide Removal (CDR)
Purpose	Emissions mitigation: Reduction of CO_2 emissions to the atmosphere by decarbonising point sources.	Negative emissions: Removal of CO_2 from the atmosphere to offset residual greenhouse gas emissions, stabilise and/or reverse warming.
Carbon Source	Slow Domain: carbon stored in rocks and sediments	Fast Domain: carbon in the atmosphere, the ocean, surface ocean sediments and on land in vegetation, soils and freshwaters
Example CO_2 source processes	Industrial processes e.g. cement production. Energy production e.g. natural gas processing, geothermal processes Fossil fuel combustion, refining, or reforming, blue hydrogen production.	BECCS: Bio-energy with CCS DACCS: Direct Air Capture with CCS
Terminology used in this paper	Fossil CCS	Subsurface CDR

Table 2: CO_2 Storage Indicator (CSI) and historical oil and gas production (HOGP) data availability and statistics of the countries signatory to the Paris Agreement.

	CSI data available (%)	Median CSI value (range)	HOGP data available	High HOGP (%)
All countries	75 (38%)	39 (0-98)	113	59 (52%)
By income class				
High	40 (70%)	50 (0-98)	31	18 (58%)
Upper middle	16 (31%)	40 (13-87	37	19 (51%)
Lower middle	18 (34%)	24 (11-63)	34	17 (50%)
Low	1 (4%)	35	10	4 (40%)

Figures

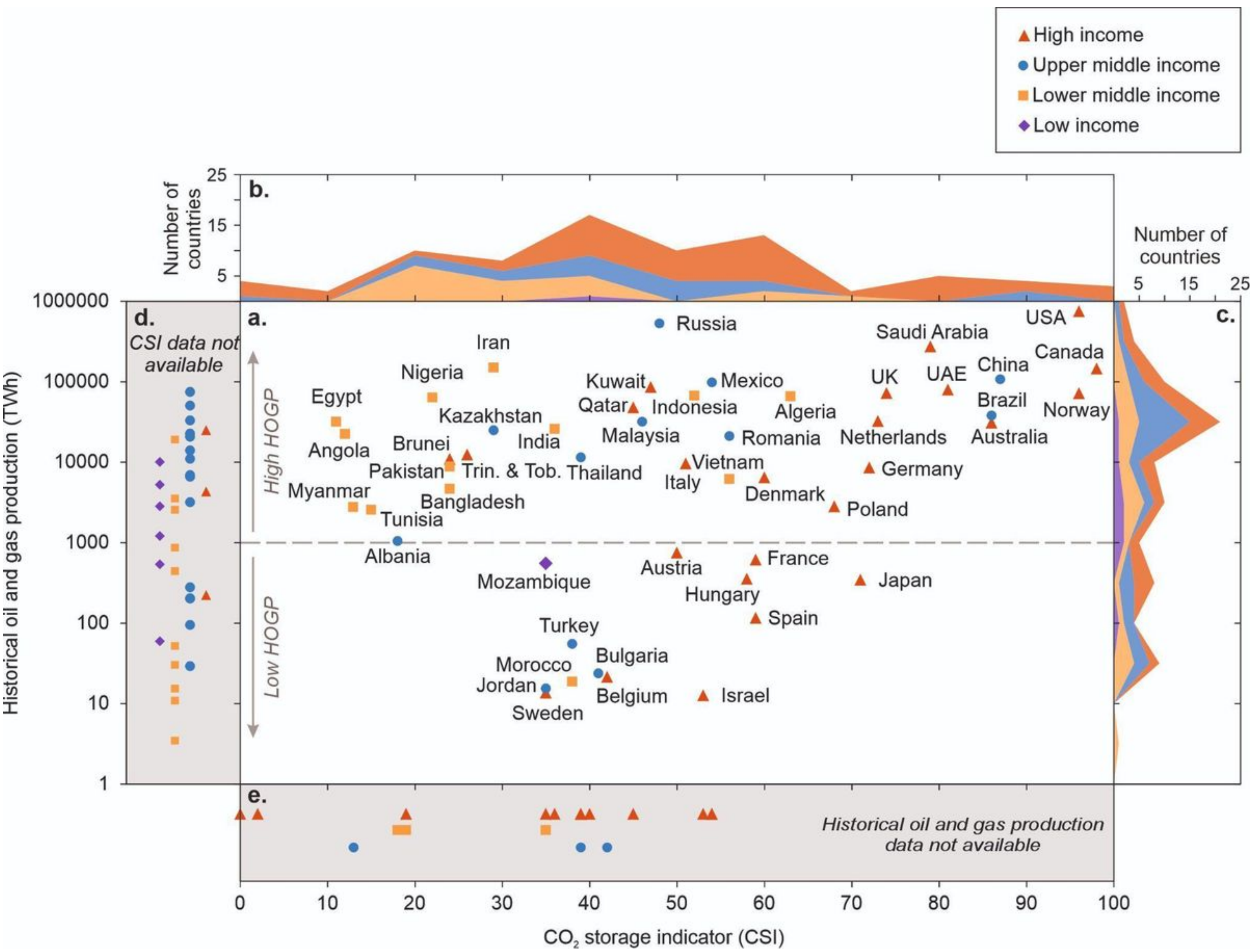

Figure 1

CO_2 storage indicator (CSI) and historic oil and gas production (HOGP) shown at country level (central graph area) with aggregate distribution plotted above (b) and right (c) respectively. Data is colour-coded to show income status: red = high income, blue = upper middle income, yellow = lower middle income, purple = low income. Of the 197 countries analysed, 75 have CSI, income and HOGP data available. HOGP for countries with no CSI assessment are plotted to the left of the central graph (d), and CSI for countries with no HOGP are plotted beneath the central graph (e). For both plots, data is stratified according to country income to aid visibility. One low income country has an assigned CSI; Mozambique.

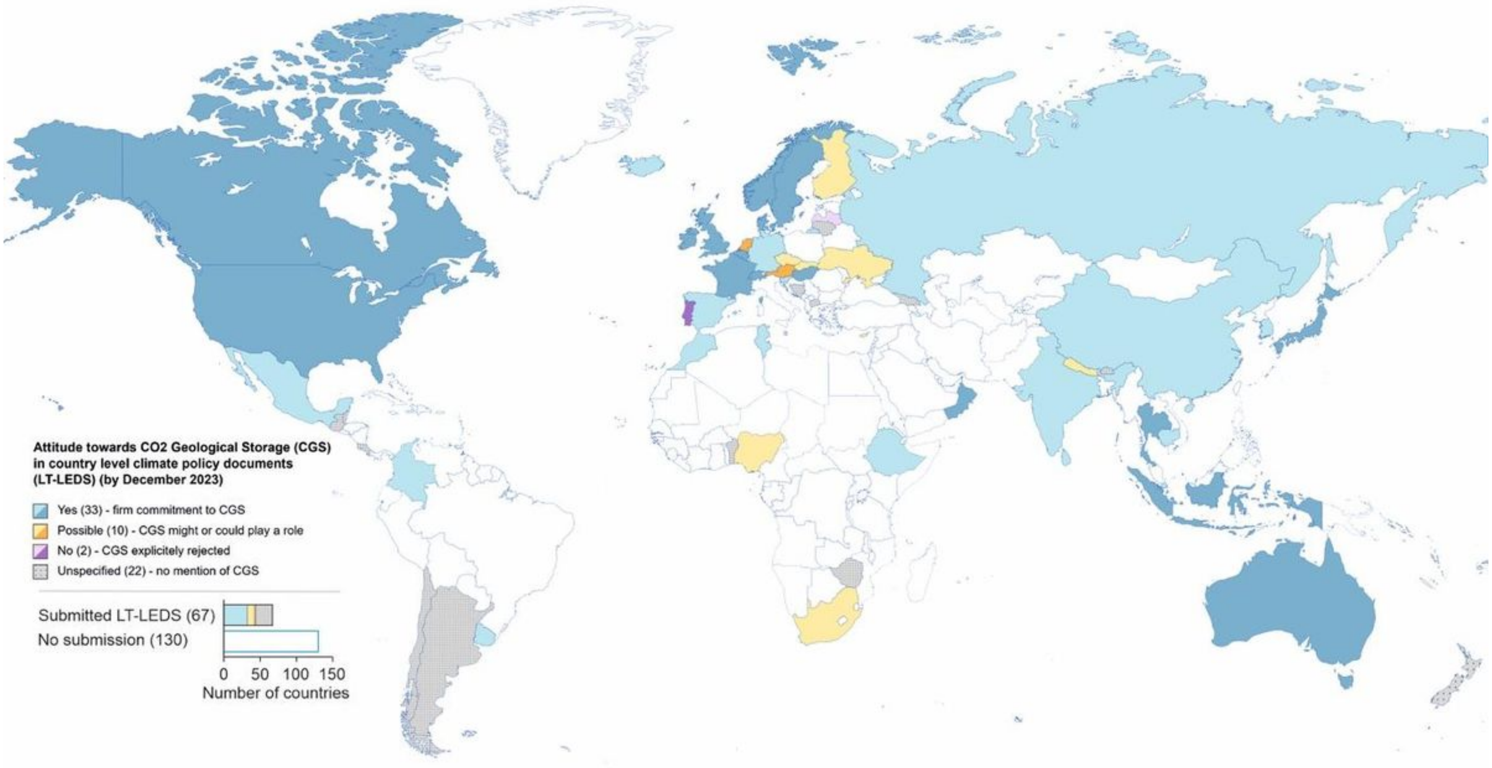

Figure 2

Global map of country intention to use 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

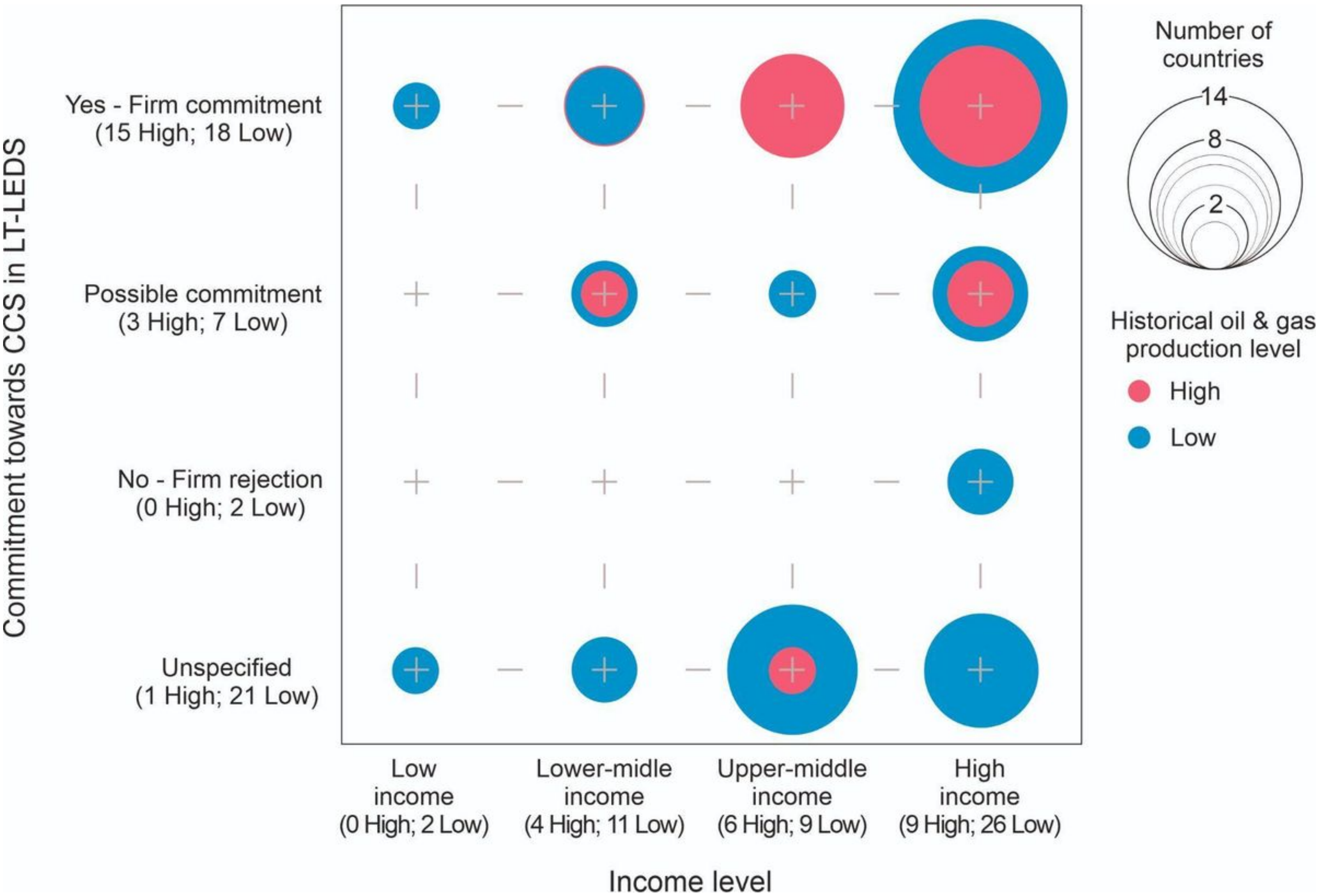

Figure 3

Intended commitment towards CGS in country-level emission pathways for different income classifications, colour coded according to historic oil and gas production. The number of countries is indicated by the size of the circle.