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Long-term national climate strategies bet on forests and soils to reach net-zero

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The deployment of carbon dioxide removal is essential to reach global and national net-zero emissions targets, but little attention has been paid to its practical deployment by countries. Here, we analyse how carbon dioxide removal methods are integrated into 41 of the 50 Long-term Low Emission Development Strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC), before 2022. We show that enhancing forest and soil carbon sinks are the most advocated strategies but are only explicitly quantified in 12. Residual emissions by 2050 are only quantified in 20 strategies and most of them use forests to achieve national net-zero targets. Strategies that quantify both residual emissions and carbon dioxide removal identify national constraints, such as wildfire risks to forests and limited geological CO_2 storage capacity. These strategies also highlight the need for international cooperation. Taken together, we suggest that the UNFCCC should urgently strengthen its reporting requirements on long-term national climate strategies.

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As net-zero becomes an organising principle of climate policy, countries are beginning to consider the practical and policy dimensions of deploying Carbon Dioxide Removal (CDR) and the implications for achieving national climate targets[1–4]. Since the adoption of the Paris Agreement, 124 countries have agreed to a net-zero emissions target, defined as a balance of emission sources and anthropogenic removals[5,6]. Despite being central to net-zero ambitions, CDR is rarely made explicit in policy plans[7]. We present a systematic analysis of CDR in 41 (of 50) long-term national climate strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC) before the start of 2022. These cover 58% of global 2019 greenhouse gas (GHG) emissions[8] and around 74% of global GDP[9].

CDR has largely been analysed within global assessments, attracting debate regarding the credibility and sustainability of CDR methods if deployed at scale[10,11]. CDR, however, will largely be delivered by individual countries through national climate policies. National analysis is therefore required to understand the practical questions of deployment, policy, and governance[12,13]. CDR methods are characterised by different potentials and limitations, including cost, readiness, energy requirements, permanence, and social and political acceptability[14–16]. These may be implicit or arise from their national or local configuration and policy design[17,18]. Domestic policies to incentivise CDR deployment need to be designed within these considerations, requiring different types of policy depending on the CDR method, moving from research and development towards full integration within new or existing policy mechanisms[13,19]. National considerations combine with an urgent need to scale-up CDR methods ahead of 2050, to match the giga-tonne scales projected to be required to meet the 1.5 °C or 2 °C Paris Agreement temperature target[20].

CDR has a role in achieving global (or national) net-zero by counterbalancing residual emissions from difficult to decarbonise sectors in the mid-century[4,13]. The trading of removals between countries may also be required for certain countries to reach their net-zero targets, owing to the level and make-up of residual emissions from economic sectors and country-level biophysical, social, or political limits[4,21]. There is a need, therefore, to consider the adoption of national net-negative targets as well as policy mechanisms to facilitate international transfers[21–23]. These dynamics suggest a decisive role for national governments in realising CDR, yet to date there are few comparative studies into CDR in national net-zero planning[1,2].

CDR methods remove CO_2 from the atmosphere and permanently store it in geological, terrestrial, or ocean reservoirs, or in specific products[24]. CDR methods produce negative emissions, whereby the total quantity of atmospheric CO_2 removed and permanently stored is greater than the total quantity of GHGs emitted to the atmosphere[25]. We group CDR into two categories, '*nature-based CDR*', i.e. sequestration of carbon in forests, soils, or coastal blue carbon, and '*engineered-CDR*', i.e. biomass energy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS)[14,26]. Debate exists on whether to explicitly avoid the common heuristic of 'technological' and 'natural' forms of CDR, as this distinction is normative, and 'natural' may constrain the discussion of CDR methods based on their perceived desirability, with implications for climate policy[27–30]. However, we use our two main groupings as it most accurately reflects the categorisations used within long-term national climate strategies.

Separately, we analyse carbon capture and storage (CCS) and carbon capture and utilisation (CCU), using the term CCUS (Carbon Capture Utilisation and/or Storage) to cover both. CCS is a process where CO_2 from industrial point sources are captured and permanently stored in geological reservoirs, reducing CO_2 emissions[31]. CCU is defined as a process in which CO_2 is captured from an industrial point source or ambient air, and is subsequently used in, or as, a product[32]. The CO_2 stored within the product is typically re-emitted in the product's use, meaning no negative emissions are produced beyond temporary storage[32]. CCUS is seen as a potential means of scaling CDR, either as a physical steppingstone using shared or repurposed infrastructure, or by means of finance by crowding in investments[33,34]. The role of CCUS in decarbonisation is contested[32,35] but we argue CCUS is an adjacent consideration to CDR for national governments.

We systematically analyse CDR within long-term national climate strategies, examining the specification of long-term targets, the CDR methods employed, the quantities of CDR in modelled scenarios relative to residual emissions, and statements concerning feasibility or international cooperation. From this dataset we identify two emerging challenges for the deployment of CDR; 1. the limitations of CDR methods by land-use and geological storage, and 2. the need for cooperation in CDR between countries to reach net-zero targets. We end by advocating that the requirements of long-term national climate strategies be urgently strengthened by the UNFCCC, making their reporting compulsory. We advocate long-term targets be clearly communicated, supported by the modelling of the extent of CDR necessary to compensate for residual emissions, and the assessment of CDR methods with respect to national circumstances.

Role and Relevance of Long-term National Climate Strategies. The Paris Agreement has two relevant reporting obligations towards national net-zero planning: Nationally Determined Contributions (NDCs) [Article 4.2] and Long-term Low Emission Development Strategies (LT-LEDS) [Article 4.19]. NDCs are required under the Paris Agreement and currently represent short-term commitments by countries up to 2030. Reviews of NDCs note that many include increased forest and soil carbon as near-term mitigation options[3,36,37], whilst the consideration of engineered-CDR is limited[2,38]. The shorter-term mechanism of NDCs are ill-suited to consider CDR, which is primarily used in the national context to counterbalance residual emissions from difficult to decarbonise sectors to reach net-zero[13]. CDR may have a national role in accelerating near-term mitigation prior to a national net-zero target[36], and post, in achieving net-negative emissions[13]. Compensating for residual emissions, however, appears to be the primary emphasis for national governments[1].

LT-LEDS are optional, they have no formal reporting requirements in the Paris Agreement but the accompanying decision (Decision 1/CP.21, paragraph 35) notes that LT-LEDS should consider up to the mid-century and are encouraged to be submitted to the UNFCCC Secretariat by 2020[39] (referred to as the 'submission date' in Fig. 1). LT-LEDS have a longer-term focus allowing more detailed consideration of CDR methods, governance, and feasibility[2,3,40]. They are one of the few areas of reporting within the UNFCCC where CDR, conceptually, is explored[2,13,16,40].

Considerable discretion is given to national governments about the design of LT-LEDS in comparison to NDCs. In practice LT-LEDS are highly heterogenous in their depth and breadth of analysis. NDCs and LT-LEDS can be considered interrelated as the long-term planning detailed in LT-LEDS may inform the design of NDCs, identifying barriers to climate action in the near-term[41]. LT-LEDS may prove to be a crucial corrective mechanism for reconciling the long-term needs of net-zero with shorter-term NDCs and policy cycles[42]. Given the general absence of CDR within current policy processes[12], and the need for CDR in the latter stages of decarbonisation to reach net-zero targets, mechanisms that bring long-term needs into the near-term

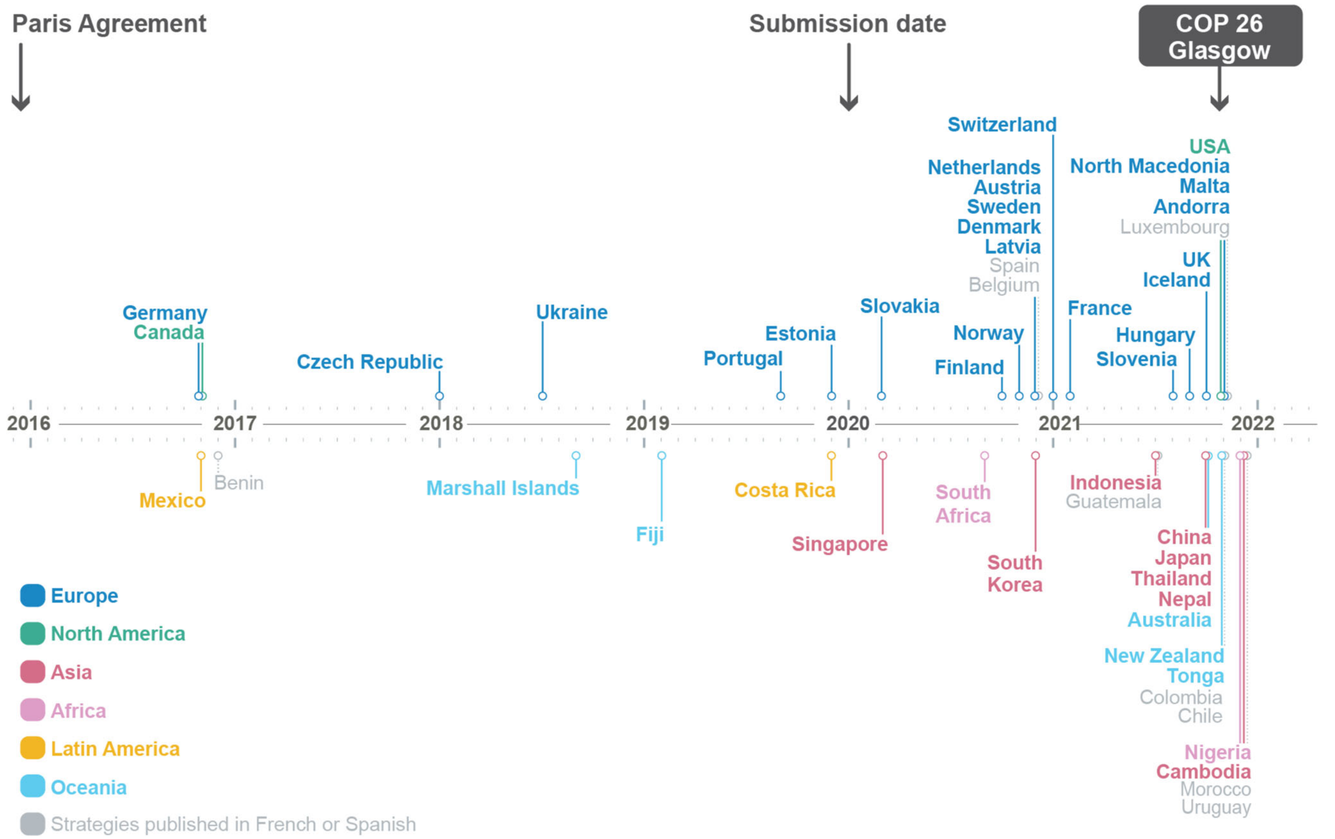

Fig. 1 Timeline of submissions of Long-term national climate strategies to the UNFCCC Secretariat or European Commission, categorised by region. Regions based upon the United Nations M49 standard 'Standard Country or Area Codes for Statistical Use' for region or sub-region. Dates are publication by the UNFCCC Secretariat, except for Estonia which is the date of submission to the European Commission. Strategies published in French or Spanish which were not analysed, are shown in grey. 'COP 26' refers to the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), held in Glasgow, United Kingdom. 'Submission date' refers to the submission period detailed in Decision 1/CP.21, paragraph 35. 'Paris Agreement' refers to the date of adoption, the agreement later entered into force in November 2016. Omitted are the publication dates for strategies made obsolete by the publication of a more recent strategy by the same country. This applies to the USA (previous strategy: November 2016), France (previous strategy: December 2016), the UK (previous strategy: April 2018) and Japan (previous strategy: June 2019).

purview of national climate policy has particular relevance to CDR. It is also necessary to study CDR within a context of national climate action, owing to CDR's connectedness to residual emissions when net-zero is treated as a national framework. Our study therefore considers CDR within a national climate strategy, specifically LT-LEDS, not a policy document concerning CDR in isolation. Previous analyses of CDR and LT-LEDS have focused on the conceptual role and national governance of CDR[2], or the criteria of assessment used to discern their feasibility at the national level[40]. We see a need, however, for an overview of CDR on the more recent and larger sample of LT-LEDS now available.

Materials. We analysed all LT-LEDS published in English by the UNFCCC Secretariat before 1st January 2022, plus one EU long-term strategy for Estonia (Fig. 1). For each strategy, we analysed the full text (a total of 3885 pages), using analytical categories based upon inductive and deductive coding[43]. Full details of our approach can be found in the Methods section, supported by multiple data tables found in Supplementary Data. Most strategies were published in 2020 and 2021 (22/41 strategies) by countries in the Global North (Fig. 1). Here, Global North refers to countries that are members of the OECD (Organisation for Economic Co-operation and Development) or classified as high-income economies by the World Bank[44]. These are largely, but not exclusively, countries in Europe, North America, East Asia, and Australasia. Some strategies, however, are considerably older, such as Germany and Canada (2016), where more ambitious legislation or climate action has taken place since the publication of their LT-LEDS. For example, Germany has since introduced a revised climate law aiming for net-zero greenhouse gas emissions by 2045 but is yet to lay out a long-term perspective in policy documents. Similarly, Canada introduced the Canadian Net-Zero Emissions Accountability Act in June 2021, enshrining a new target of net-zero emissions by 2050. Canada has since also introduced in March 2022 the '2030 Emissions Reduction Plan', which details proposed policy measures to 2030. Canada, like Germany, is yet to update its LT-LEDS or lay out a similar long-term perspective. This lessens their relevance in terms of providing an up to date understanding of CDR within the national context but remains instructive as to a national approach.

The prominence of European countries is expected because EU legislation requires member states to develop national long-term strategies (EU LTS)[41,45]. 13 LT-LEDS submitted to the UNFCCC for European countries hold a dual status, serving also as the country's EU LTS. We include Estonia's EU LTS, despite it not being also an LT-LEDS submitted to the UNFCCC, owing to this basis. We use the term 'long-term national climate strategies' throughout to describe the strategies within our sample. The term has precedent in prior literature to describe similar samples[2]. The lack of strategies from countries in Africa and Latin America (4/

41 strategies) is only partially explained by selection bias for English language (6 excluded). In total 9 long-term national climate strategies were excluded by our English language selection bias, shown in grey in Fig. 1. Additional detail on the long-term national climate strategies included within our sample can be found in Supplementary Data 1, within Supplementary Data.

Results

Inexact long-term targets. Increasingly, targets are subject to calls within literature for greater clarity, specifically regarding the extent of overall CDR, sectoral contributions, and the role of the land-use sector[18,36,46]. Several strategies have long-term targets that are inexact, expressing or implying an approach that conflicts with modelling or analysis later contained within the strategy itself. Within these strategies, targets serve a crucial guiding function. We report the headline target presented and then deduce from supporting information within the strategy the coverage of the target according to set characteristics, comparing both in Table 1. Several LT-LEDS (Japan, South Africa, France, Portugal, Cambodia, Malta, Fiji, Andorra) detail targets described in terms of 'carbon neutrality' but do not apply specifically to CO_2, but a range of GHGs. 'Climate neutrality' is the stated long-term target of six countries (Austria, Hungary, Slovakia, Denmark, Slovenia, Latvia), yet the treatment of this target elsewhere within the strategies implies this is analogous to net-zero for all main GHGs, as climate neutrality would seek to account for the bio-geophysical impacts of human activities, such as surface albedo[47]. Some countries fail to specify the exact sectoral coverage of their long-term target, or exclude specific sectors, e.g., Germany which exclude land use and forestry from their climate target assessments. Only two countries (UK and Switzerland) explicitly include the emissions from international aviation and shipping. Ten countries note the prospective or intended use of international offsets, or otherwise transferred mitigation outcomes, further complicating the extent of domestic emission reductions. More detail is available in Supplementary Data 2, found within Supplementary Data.

Seven out of the ten strategies that set emission reduction targets relative to a specific base year, rather than a net-zero target, do not readily quantify CDR (Table 1). This could be explained by the target being achievable through emission reduction measures alone (e.g., the phase-out of fossil fuels), without recourse to CDR. It may also support the idea that, for those governments that set out strategies relative to a net-zero target, the net-zero target itself forces national governments to consider CDR. The degree to which net-zero acts as a national framework in informing CDR, however, requires further research. Examining the distinction between the headline target and the modelling detailed within the strategy itself, highlights a tension in defining long-term targets, as to what should be a characteristic internal to the definition of the target itself and what is a criterion for modelling (e.g., the use or non-use of international offsets).

Ambiguity in targets is a common problem identified by literature[47,48], but in mobilising CDR, ambiguity has notable implications, as the target definition determines the extent of CDR required[4]. Reaching net-zero for CO_2 alone requires less CDR than reaching net-zero for all GHGs, due to the exclusion of CH_4 and N_2O emissions from sectors like agriculture. This affects planning and policy decisions in the near-term, as the envisaged CDR demand could be met via a smaller portfolio of methods, 'locking-out' others[49]. 'Locking-out' is also foreseeable with differences in sectoral coverage, such as the inclusion, or exclusion, of emissions from international aviation and shipping. Emissions from international aviation and shipping are typically considered under international bodies, such as the International Maritime Organisation (IMO), but are readily calculated by countries through national emission inventories, on a fuel basis[50]. A range of methods now support national allocation considering past failures to reduce emissions[50], and the view that these emissions are hard-to-abate[51]. National allocation, therefore, may have important implications in terms of CDR demand. Similarly, retaining the potential use of emissions reductions from abroad to fulfil long-term targets, leaves the level of future domestic emissions unclear[21]. A target of climate neutrality may also imply counteracting the local or regional effects of CDR. Ambiguity in emission and sectoral coverage can obscure CDR demand, despite several countries actively quantifying negative emissions within their strategies. Devising a shared ideal definition of national net-zero, then communicating long-term targets relative to this agreed definition, would largely alleviate these issues[3,52].

CDR methods and reliance. Enhancing forest and soil carbon sinks are the most common CDR methods in our sample of long-term national climate strategies (Table 2). This aligns with previous analyses of smaller samples of strategies[2,40]. Enhancing forest carbon is the most quantified (12 strategies) and advocated (40) CDR method. Soil carbon enhancement is quantified in four (Indonesia, Australia, France, and Portugal) but advocated in 30 (Table 2). The dominance of forests and soils is to be anticipated given the legacy of forest and land management, the co-benefits for food security and biodiversity[26,53], and their integration into prior policy mechanisms[54]. Coastal blue carbon (seagrasses, mangroves, wetlands, and salt marshes) has limited policy legacy but comparatively broad support, advocated in 14 (yet only quantified by Fiji). Engineered-CDR methods feature in fewer strategies and their inclusion is notably more speculative, with countries highlighting limitations amongst a desire to explore their future potential. BECCS is advocated in 16 strategies and quantified in five whilst DACCS is advocated in seven and quantified in only two strategies (UK and Switzerland). Both BECCS and DACCS are more readily considered by countries in the Global North. For example, 14 of the 16 strategies that advocate BECCS are countries from the Global North, of which half (7) are European member states. DACCS is exclusively considered by countries within the Global North. CCUS, in itself not a CDR method but a technology that shares infrastructure with BECCS and DACCS, is quantified in five strategies and advocated in 31.

Residual emissions are quantified in 20 long-term national climate strategies (Fig. 2). In 13 strategies (USA, Indonesia, Thailand, France, Cambodia, Sweden, Finland, Portugal, North Macedonia, Slovakia, Costa Rica, Hungary, Slovenia) increased forest carbon or nature-based CDR is primarily or solely relied upon to compensate for residual emissions, achieving long-term targets (Fig. 2). Other strategies also rely on forest carbon, but demonstrate a sizeable projected sink compared to residual emissions, such as Nepal and Fiji (Fig. 2). Not all strategies follow this pattern, the UK is notably dependent on BECCS, whilst Switzerland is split across BECCS and DACCS, fully compensating for residual emissions. The 'sink status' column (Table 2) reports the net balance of the land-use carbon sink historically and in future projections (see Methods for further details). For many this does not appear to have a discernible bearing on CDR method choice or quantification, while emphasising the challenge posed by some strategies. For example, Cambodia relies on forests to compensate for residual emissions, where this has historically been a net-source of emissions, implying stopping and then reversing deforestation. These results are documented in Supplementary Data 3, found in Supplementary Data.

Table 1 Long-term targets stated in long-term national climate strategies.

Target type	Stated target	Country	Negative emission quantification	All sectors	All GHGs	No international offsets	Int'l aviation & shipping included
Forms of Net-Zero	Net-zero by 2050	USA	✓	✓	✓	✓	×
	Net-zero by 2050	Australia	✓	✓	✓	×	×
	Net-zero by 2050	UK	✓	✓	✓	×	✓
	Net-zero by 2050	Switzerland	✓	✓	✓	×	✓
	Net-zero by 2050	Costa Rica	✓	✓	✓	–	–
	Net-zero by 2050	Marshall Islands	×	–	✓	×	×
	Climate neutrality by 2050	Austria	✓	✓	✓	–	–
	Climate neutrality by 2050	Hungary	✓	✓	✓	–	×
	Climate neutrality by 2050	Slovakia	✓	✓	✓	–	–
	Climate neutrality by 2050	Denmark	×	✓	✓	–	×
	Climate neutrality by 2050	Slovenia	✓	✓	✓	–	×
	Climate neutrality by 2050	Latvia	×	✓	✓	–	×
	Net-zero by 2045	Nepal	✓	✓	×	×	–
	Climate neutrality by 2040, on the path to net-negative emissions	Iceland	×	✓	✓	–	×
	Net-zero by 2045, net-negative emissions thereafter	Sweden	✓	×	✓	×	×
	Net-zero 'long lived gases', 24–27% CH_4 emission reduction by 2050	New Zealand	×	✓	✓	×	×
	Net-zero by 2060	Indonesia	✓	✓	✓	–	–
	Net-zero by 2060	Nigeria	×	✓	✓	–	–
	Net-zero in the second half of century, carbon neutrality by 2065	Thailand	✓	✓	×	–	–
	Carbon neutrality by 2050	Japan	×	✓	✓	×	×
	Carbon neutrality by 2050	South Korea	✓	✓	×	–	–
	Carbon neutrality by 2050	South Africa	×	✓	✓	–	–
	Carbon neutrality by 2050	France	✓	✓	✓	✓	×
	Carbon neutrality by 2050	Portugal	✓	✓	✓	✓	×

Table 1 (continued)

Target type	Stated target	Country	Negative emission quantification	All sectors	All GHGs	No international offsets	Int'l aviation & shipping included
	Carbon neutrality by 2050	Cambodia	✓	✓	✓	—	—
	Carbon neutrality by 2050	Malta	×	✓	✓	—	×
	Net-zero carbon by 2050	Fiji	✓	✓	✓	—	×
	Carbon neutrality by 2050	Andorra	✓	✓	✓	—	—
	Carbon neutrality by 2060	China	×	—	×	—	—
Emission reduction targets	80% reduction by 2050	Canada*	×	✓	✓	×	—
	80% reduction by 2050	Czech Republic*	×	✓	✓	—	—
	80% reduction by 2050	Finland*	✓	✓	✓	—	×
	80% reduction by 2050	Estonia*	×	×	✓	—	—
	80–95% reduction by 2050	Germany*	×	×	✓	—	×
	80–95% reduction by 2050	Norway*	×	✓	✓	—	—
	95% emission reduction by 2050	Netherlands*	×	✓	✓	—	×
	72% emission reduction by 2050	North Macedonia*	✓	✓	✓	—	×
	50% emission reduction by 2050	Mexico*	×	✓	✓	—	—
	31–34% emission reduction by 2050	Ukraine*	✓	✓	✓	—	—
	33 $MtCO_{2e}$ in 2050, net-zero soon after	Singapore	×	✓	✓	×	×
	No long-term target	Tonga	×	✓	—	—	×

Grouped by target description, then listed by 2019 GHG emissions. Target details presented are either from statements made within the policy document or from the modelling data presented in text or graphical format in the policy document. *These countries have emission reduction targets relative to a base year. Most are set relative to 1990, except Canada and Mexico whose targets are set relative to a 2005 and 2000 base year respectively. Thailand has a dual target of net-zero in the second half of the century and carbon neutrality by 2065, our entry for 'All GHGs' reflects the latter target. Detail of the full analysis is provided in Supplementary Data 2 in Supplementary Data.

Table 2 Modelled quantification, qualitative consideration, or speculative consideration of Carbon Dioxide Removal (CDR) methods contained in long-term national climate strategies.

Country	Sink Status		Quantification or consideration of CDR in 2050 (values in MtCO_2)							
	Historic	Future	Nature-based CDR				CCUS	Engineered-CDR		
			Forests	Soils	Coastal Blue Carbon	Undefined		BECCS	DACCS	Undefined
China	-	-	✓	✓	✓		✓			
USA	↓	↓	✓	✓	✓	1000	✓	✓	✓	500
Japan	↓	-	✓	✓	—		✓	—	—	
Indonesia	↑	↓	390	160	—		✓	✓		
Germany	↓	-	✓	✓			✓			
Canada	-	-	✓	✓			23	—		
Mexico	↓	-	✓	✓			✓			
South Korea	↓	-	15		✓		✓			
Australia	↓	-	10	17	—		✓	38	—	
South Africa	↓	-	✓	✓	—		✓			
UK	↑	↑	✓	✓	✓		6	58	18	
France	↓	↓	56	11			6	10	—	
Thailand	↓	↓	✓			120	✓	✓		
Nigeria	↑	-	✓	✓						
Ukraine	↓	↓	50	✓			✓			
Netherlands	-	-	✓	✓			✓	—		
Czech Republic	↓	-	✓	✓						
Austria	↓	↓	3.9	✓			18			
New Zealand	↓	-	✓							
Norway	-	-	✓				✓	—		
Finland	-	-	22				✓	14		
Singapore	-	-	✓		✓		✓			
Sweden	↓	↓	✓	✓	✓	42	✓	✓		
Hungary	↓	↓	4.5	✓			✓	✓	—	
Portugal	↓	↓	15	0.69			—	—		
Nepal	↑	↓	✓	✓		9.2	✓			
Switzerland	-	-	✓	✓			5.1	1.9	4.9	
Slovakia	↓	↓	✓	✓		7	✓			
Denmark	↑	↑	✓	✓			✓	—		
Cambodia	↑	↓	50				✓			
Estonia	-	-	✓	✓						
Slovenia	↑	↓	✓	✓		2.5	✓			
Costa Rica	↓	↓	5.5		✓					
Latvia	↓	↑	✓	✓			—			
North Macedonia	↓	↓	✓	✓		3.8				
Iceland	↓	↓	✓	✓	—		✓			
Fiji	↑	↓	2.9		0.94					
Malta	-	-	—	—			—			
Tonga	↑	-	✓		✓					
Marshall Islands	-	-								
Andorra	↓	↓	✓	—		0.15				

'BECCS' refers to biomass energy with carbon capture and storage. 'DACCS' refers to direct air carbon capture and storage. 'CCUS' refers to carbon capture utilisation and/or storage. Countries listed in order of 2019 GHG emissions. 'Sink Status' is the net balance of the land-use carbon sink historically (i.e., the latest available historic year of the national emission inventory) and in modelled scenarios (i.e., 2050) presented within the strategies. ↓ is a net sink, ↑ a net source, - no information. ✓ indicates qualitative consideration of the CDR method (i.e., existing, or planned policy mechanisms). – indicates speculative consideration of the CDR method (i.e., noting potential use of the method in the future). Values were taken from the scenario that best reflects the national position. This could be the scenario that is modelled to achieve the long-term target of the strategy, or the scenario that is explicitly expressed within the strategy as the national government's policy position or preferred scenario. Not shown, the USA and UK speculatively consider the use of enhanced weathering. Full details are provided in Supplementary Data 3 in Supplementary Data.

Critically, most strategies do not quantify residual emissions from decarbonisation which limits evaluation. The lack of quantification and limited breadth of CDR suggests countries are struggling to integrate CDR into their modelled scenarios, many of which use national GHG inventories as a foundation, and current inventory guidelines are not specifically designed to cover CDR[3].

Emerging challenges. Our analysis reveals two major challenges within the strategies towards national CDR deployment: the limitations of forests to act as substantial or long-term stable carbon sinks, and the limited national geological storage capacity for engineered-CDR. Understanding these feasibility challenges highlights what constraints to deployment countries envisage. Feasibility, within this analysis, mainly concerns the technological and biogeophysical dimensions of CDR, as these dimensions are the focus of feasibility in discussions of CDR, and within long-term national climate strategies, as identified by previous studies[40,55]. Wider dimensions of

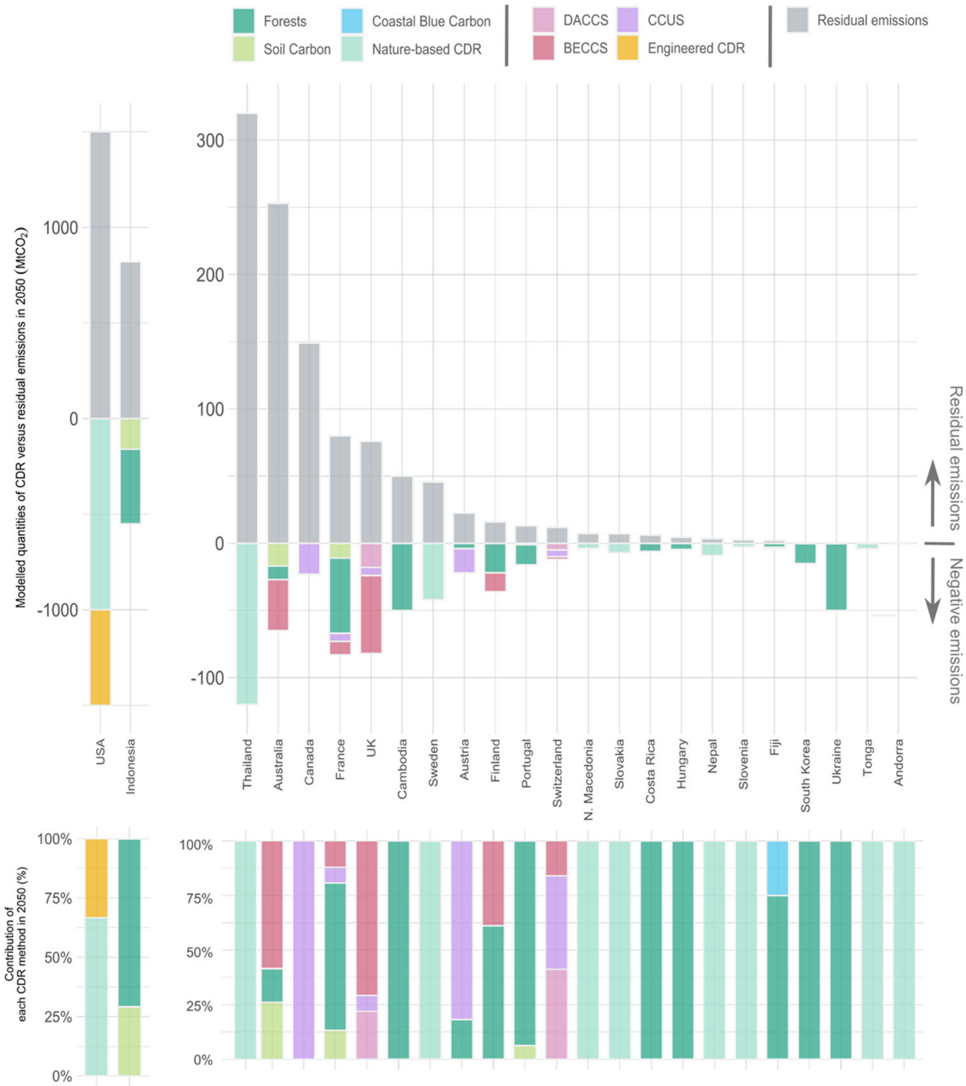

Fig. 2 Long-term national climate strategies that quantify Carbon Dioxide Removal (CDR) and residual emissions in 2050. 'BECCS' refers to biomass energy with carbon capture and storage. 'DACCS' refers to direct air carbon capture and storage. 'CCUS' refers to carbon capture utilisation and/or storage. The top panel details residual emissions (positive values) and negative emissions achieved by CDR (negative values), adapted from the strategies themselves. Larger CDR values than residual emissions indicate a country where negative emissions through CDR is modelled to exceed residual emissions in 2050. Larger residual emissions than CDR indicates modelled domestic CDR does not compensate for residual emissions in 2050. We exclude any quantification of international offsets or transfers from the above. Similarly, the exact level of negative emissions also depends on the presentation of the land-use sink, which is often coupled with positive emissions from land-use or the agriculture sector when presented, obscuring the level of removals within the sector. As such, the total quantity of negative emissions achieved by CDR may be higher than shown. We present CCUS on the negative y-axis despite the fact CCUS does not generate negative emissions, as many countries present the abatement potential in relation to residual emissions (e.g., Switzerland). Twenty long-term national climate strategies include the quantification of residual emissions and CDR. South Korea, Ukraine, Tonga, and Andorra have not quantified residual emissions within their long-term national climate strategies. For select countries (e.g., Thailand), long-term targets are to be achieved at a date later than 2050. The bottom panel details the percentage contribution in 2050 of each CDR methods relative to the total amount of CDR quantified. More detail is provided in Supplementary Data 3 in Supplementary Data.

feasibility, such as the socio-cultural, should be more widely explored[40,55,56].

CDR limited by geology and land-use. Many national strategies 'bet' on the increase of carbon sinks in forests and soils as a means of achieving long-term targets. Such reliance on forests and soils creates risks for both national and global net-zero, as these methods of CDR are reversible[57,58], prone to disturbances[59], and limited in the long-term owing to saturation[11,58]. Historically, country estimates of carbon sinks in forests and soils have been limited by data availability and estimation methodologies, leading to large uncertainties[36,60]. These risks are readily acknowledged by countries in our sample. Several strategies emphasise the limited potential of carbon sinks in forests, with the increasing age of forest stands gradually tapering the magnitude of removals possible until effective equilibrium (e.g., France). South Korea, Slovakia, Ukraine, Hungary, and Finland anticipate a limited contribution from forests carbon sinks towards long-term targets, owing to the age of existing stands or limited additional area for new forests. Portugal, Sweden, and Slovenia note the vulnerability of forests to natural hazards, such as wildfires and increased natural mortality from disease or pests. These risks can impact the carbon stored within forests, requiring continuous active management[59,61]. France notes the gradual saturation of soil carbon and the risk of reversal from changes in land-use or land-use conditions, alongside natural hazards. Malta similarly notes the impact that climate change may have in reducing the effectiveness of soil to store carbon. Removal estimates from forests tend to be associated with higher uncertainties than emissions from other economic sectors, as noted by Sweden and Finland, or subject to methodological difficulties, as noted by Germany.

Some countries address the feasibility of CDR methods in relation to national geological storage capacity. Austria and Switzerland note a limited geological storage capacity, whilst Singapore has no geological formations suitable for CO_2 storage. Cambodia identifies issues with location, seeing a need to identify land isolated from urban or industrial areas. France, comparatively, presents an initial assessment of up to 1.5 $GtCO_2$ in geological storage capacity, with suitable co-location of emissions sources and geological storage sites, although the strategy notes social acceptability may mean offshore sites are prioritised. National geology will provide a comparative advantage for those able to pursue it for engineered-CDR.

Engineered-CDR, such as BECCS and DACCS, can deliver continual negative emissions. France outlines this possibility and advocates for BECCS within its strategy, owing to its potential to generate negative emissions in the very long term. This is contrasted to nature-based CDR, such as enhancing the carbon stored in forests and soils, which are limited by saturation and risky owing to reversals[62]. This does not diminish their importance, there are many reasons to pursue nature-based CDR beyond carbon, such as the possible co-benefits for biodiversity and other ecosystem services[26,53]. Engineered-CDR similarly faces substantial challenges in deployment owing to the rates of infrastructure construction[20], the availability of low-carbon energy, and ultimately economic and accessible geologic storage[14].

National net-zero is best characterised as a state to be attained and continued rather than a target momentarily achieved in a single year[6]. National net-negative targets may be required in the case of overshooting Paris Agreement temperature targets[7,63], or from a justice perspective of allowing some countries to decarbonise more gradually[22,64]. In this context nature-based CDR may ultimately play a sequential role towards CDR methods able to deliver continual negative emissions[65]. Seen from this perspective, the reliance on forests and soils in long-term national climate strategies is problematic for the viability of national net-zero, even though for select countries enhancing the carbon stored in forests and soils may be sufficient to achieve long-term targets. Focusing solely on forests and soils, may obscure from what will be needed beyond the achievement of national net-zero, and detract from an imperative to engage with engineered-CDR methods.

Cooperation between countries is needed for CDR and net-zero. Several strategies emphasise a need for cooperation in deploying CDR and achieving long-term targets. These have physical, biophysical, or economic rationales. For example, the Netherlands calls for EU countries to shape CDR around their respective physical circumstances and common interests, noting the limited additional space it has for afforestation but the potential for bilateral partnerships for CO_2 storage under the North Sea. Switzerland has limited geological CO_2 storage and propose implementing DACCS abroad to minimise storage and transport costs (e.g., the North Sea), with domestic storage reserved for CCS on industrial sources. Understanding CDR resources and potentials within a country can facilitate the joint coordination of strategies. Coordination within the EU is more likely given the overarching EU objective of climate neutrality and existing EU policies that assign emission reduction targets by country and sector. Partnerships towards CDR may be the next necessary extension of EU climate policy[66].

Australia calls for international cooperation to create international carbon markets, such as a proposed 'high integrity carbon offset scheme in the Indo-Pacific' to attract private sector investment in 'nature-based solutions'. Removals via enhancing soil carbon in Australia is presented as a means of generating these offsets, although the strategy maintains flexibility towards whether these are internationally traded or supplied to a domestic market. Australia's strategy also envisages the ability to reach its long-term target via international offsets in addition, or as a substitute, to removals via soil carbon. Australia may therefore seek to mobilise on both the supply and purchase of offsets, presenting CDR as an extension of existing offsetting regimes. Latvia similarly notes the potential of a domestic emissions trading scheme in forestry, with eventual integration into a single international market mechanism under the Paris Agreement.

These countries foresee partnerships for CO_2 storage or deployment of CDR beyond national borders, with removals transferred. Such partnerships and transfers would require strong institutions, policy, and governance, with precise rules and accounting frameworks to avoid double-counting. Both bilateral partnerships and international markets for removals are foreseeable under the provisions of Article 6 of the Paris Agreement, which allows for 'internationally transferred mitigation outcomes'. These transfers, however, would also stretch the meaning of a domestic net-zero target when contingent on the deployment of CDR in other countries[21,67]. Similarly, issues surrounding the permanence and uncertainties of nature-based CDR may make them unamenable to international markets, whilst engineered-CDR, by contrast, more amenable to the carbon accounting necessary for their transferal[21]. Net-zero planning may therefore grow increasingly interconnected as CDR becomes a more prominent feature of climate policy.

Policy and governance implications. Long-term national climate strategies, such as LT-LEDS, provide an essential policy context for countries to consider the long-term implications of net-zero or other targets, and therefore CDR. Our study identifies the limits of current national approaches, including; the dependence of CDR upon the precise definition of long-term targets, the reliance on forests or other nature-based CDR to compensate for residual emissions, and a lack of quantifying residual emissions in some strategies. Strategies that do quantify residual emissions and CDR, acknowledge the challenges of nature-based CDR relative to national constraints, ranging from limited land availability for afforestation, the maturity of existing forests attenuating removal potential, and the risk of reversals from fires, pests, or disease. Strategies that advocate engineered-CDR note concerns over geological storage. Taken together, these findings highlight the challenge and complexity CDR poses to national governments.

Such findings have notable implications towards the current state of national net-zero planning and climate policy. Firstly, our study underlines both the value and limitations of long-term national climate strategies in addressing CDR at the national level. Analysing long-term national climate strategies, such as LT-LEDS, provides for a means of comparing national approaches to CDR currently absent from other policy processes. Given the need for CDR to counterbalance residual emissions to reach net-zero, and the date of many net-zero targets (Table 1), supporting the development and revision of LT-LEDS may help bring long-term needs of net-zero into the near-term purview of national climate policy, mobilising CDR and more ambitious emissions reductions. The optionality of LT-LEDS and lack of specific requirements, however, leads to either a lack of reporting, as reflected by the size of our sample, or substantial limitations that obscure any comparison, such as the ambiguity in long-term targets, a lack of residual emission quantification, or the varied national constraints to CDR.

The UNFCCC should consider requiring LT-LEDS, or similar long-term national climate strategies, as a compulsory reporting obligation with detailed formal guidance on format and contents. This guidance should make explicit a shared definition of national net-zero, which can be used as a benchmark to communicate national long-term targets. Long-term targets should specify the greenhouse gas and sectoral coverage, treatment of international aviation and shipping, and the intended use of international offsets, all of which are adjacent considerations to CDR affecting the extent of CDR required. Long-term targets should be supported by the modelling of scenarios or pathways that makes explicit the extent of CDR necessary to compensate for residual emissions, alongside the CDR methods used, considering their different characteristics with respect to national circumstances. Such pathways could inform detailed national feasibility assessments, providing the basis for domestic policy and public engagement[40]. Quantification in modelled scenarios or pathways, alongside feasibility assessments, should be accompanied by efforts to incentivise CDR in the near-term, for example, by separate targets for negative emissions in NDCs. Near-term targets are a feature of some long-term national climate strategies, the UK notes an ambition for 5 $MtCO_2$/year in engineered-CDR by 2030, and Switzerland propose targets for CDR in 2040. Recognising these targets in NDCs, however, can signal political commitment and help differentiate between those strategies that integrate CDR but fail to incentivise CDR in the near-term.

Secondly, our study reveals the 'betting' of long-term national climate strategies on forests and soils in compensating for residual emissions. The dominance of forests and soils is to be anticipated given the legacy of forest and land management, and their integration into prior policy mechanisms[54]. The importance of nature-based methods should not be readily dismissed, most notably, they are unique in helping to address multiple societal challenges[68]. Namely the need to enhance biodiversity and the need to both adapt and mitigate climate change[68]. Recent studies, however, point to the risks of solely pursuing nature-based CDR, given their limited capacity and permanence to compensate for an absence of steep global emission reductions[69,70]. Wholly relying on these methods to compensate for residual emissions, therefore, may prove similarly risky, considering the national constraints and uncertainties in estimation, readily acknowledged within our sample of long-term national climate strategies. We argue that the long-term viability of net-zero as a national target relies on acknowledging net-zero as a state to be achieved and maintained, not a target of a single year that is momentarily attained. National net-zero may also serve as a transitional phase towards a net-negative state, as anticipated in the long-term targets for Sweden and Iceland (Table 1). Doing so refocuses attention on the need for steep and sustained emissions reductions in the immediate decades ahead and the unique role of engineered-CDR, such as BECCS and DACCS, to provide continual negative emissions in the long-term. Long-term national climate strategies should reflect this understanding, further engaging with engineered-CDR, or the potential of Article 6, in the case of limited domestic geological storage capacity.

Thirdly, we outline the emerging cooperation between countries regarding CDR, as well as the contingency of CDR on international policy mechanisms such as Article 6. Long-term national climate strategies provide a means for national governments to position themselves relative to this mechanism, either as suppliers or buyers of transferred removals. It also establishes a rationale of the mechanisms use, such as national constraints on geological storage or space for afforestation, or the economic flexibility provided by international markets. The development of a long-term national climate strategy may therefore serve as a useful precondition in engaging with Article 6 mechanisms, to ensure this engagement is supportive of a national project of decarbonisation. The UNFCCC should consider these changes to deepen discussions of CDR in climate policy, ensuring CDR becomes a critical element of national net-zero planning.

Methods

We use NVivo (Release 1.5.1), a computer-assisted software commonly used for qualitative data analysis[71], to process and analyse our sample of long-term national climate strategies. We developed analytical categories based upon inductive coding of our sample and deductive coding from previous literature on CDR[43]. Such flexibility is necessary owing to the wide differences in terminology, structure, and depth of analysis presented across the strategies. Owing to this heterogeneity, we read and coded the full strategy document (a total of 3,885 pages analysed) (Supplementary Data 1, Supplementary Data), as many do not include a specific section on CDR, as common with other concepts in the UNFCCC, such as climate adaptation. Coding was conducted by one author [HS], with the coding then subsequently crosschecked and discussed with the two remaining authors [NV, JF]. This ensured that the coding was accurate and thorough, but also unbiased by individual perception. Our first round of coding generated a wide array of detailed categories that were then aggregated into broader themes. We then reviewed the literature relating to the induced codes, using this literature to deduce further refined codes, iteratively repeating this process until 'code saturation'[72], whereby a full range of categories were identified. Once collated a second stage in our analysis systematised these categories into insights regarding CDR in national net-zero planning.

Categories were developed for several CDR methods, four 'nature-based CDR' methods; forests, soils, coastal blue carbon, and enhanced weathering, and two 'engineered-CDR' methods, biomass energy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). By 'soils' we refer to CO_2 removals within agricultural land or grassland, including the application of biochar. By 'coastal blue carbon' we refer to CO_2 removals within a range of coastal ecosystems, including mangroves, sea grasses, tidal marshes, and wetlands. We use 'coastal' to differentiate between these methods and a range of emerging methods proposed for the deep ocean[73], for example, ocean iron fertilization or ocean alkalinity enhancement[74]. Ocean-based CDR does not feature within our sample of LT-LEDS, with the exception of the USA's LT-LEDS, which notes 'ocean-based CDR' as a focus of further research and development.

One of the issues presented is that the categorisation of CDR methods, in terms of terminology, is not consistent across strategies. For the same CDR method, different terms made be used relative to the national context. Similarly, whilst BECCS and DACCS may be relatively new technologies, and therefore new considerations for national governments, forests and soils have a long policy legacy, with its own nomenclature (e.g., in the case of national emission inventories, which are commonly the empirical basis of long-term national climate strategies, the 'common reporting format' supported by the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention)[75]. This nomenclature does not readily map to common categorisations of nature-based CDR, instead LULUCF (land-use, land-use change and forestry) activities may be referenced. LULUCF excludes consideration of non-CO_2 agricultural activities (such as emissions from livestock) but includes both CO_2 emissions and removals from forests and soil carbon. It therefore can be presented in a variety of ways, both on a net basis for certain land-cover types and as an aggregate sector, without differentiating between forest and soil components. In the case of the latter, we characterise this as undefined 'nature-based CDR'. In the case of the former, we prioritise the gross removals from forests or soil carbon, only presenting a net basis if gross removals are not detailed within the long-term national climate strategy.

We recorded information on the headline long-term target (e.g. net-zero by 2050), as described by the long-term national climate strategy itself, and further coded for detail denoting the sectoral coverage, the coverage of greenhouse gases, the prospective use of international offsets or otherwise traded outcomes, and the inclusion of national emission inventory 'memo' items, such as the emissions nationally attributable from international aviation and shipping. Where these are not explicitly stated as a characteristic of the target itself (i.e. net-zero by 2050 without using international offsets), we examine the criteria of any pathways or scenario modelling present within the strategy that achieves the long-term target (e.g. modelling that supports the use of international offsets). We also coded for the quantification of CDR within pathways or scenario modelling, regardless of the specific CDR method.

To allow comparison between countries, we also coded for the quantification of CDR methods in 2050, based upon pathways or scenario modelling presented within the strategy. Where quantification is contingent upon choice of scenario, the quantification supporting the scenario that reflects the position of the national strategy was chosen. This could be the scenario that is modelled to achieve the long-term target of the strategy, or the scenario that is expressed within the strategy as the national government's chosen policy position or preferred scenario. We also capture, where possible, the extent of residual emissions in 2050. Discussion of CDR methods within the strategies were not limited to their quantification within pathway or scenario modelling, and therefore we also coded for any qualitative consideration of a specific CDR method, such as the statement of policies to incentivise a specific method or discussions of national circumstances intended towards deployment. We also include a 'speculative' category, for statements that note the potential deployment of a specific CDR method, should conditions or national circumstances change. To describe these instances, we use the term 'advocated', denoting a CDR methods qualitative consideration.

In recognition of the contestation between the common categorisations of nature-based CDR and the IPCC nomenclature used in national emission inventories, we recorded the historic and future status of the terrestrial sink, or 'sink status', that is, the net balance for the LULUCF sector according to the data presented within the strategy itself. We determined the historic status according to the latest available year of the national emission inventory included within the strategy and determined the future status according to pathways or scenario modelling presented. The overall net balance of the sector determines the potential of the sector to compensate for residual emissions in other sectors of the economy and can therefore be considered a key determination for national governments. LULUCF can also be presented in aggregate with non-CO_2 emissions from agriculture, or AFOLU (Agriculture, Forestry and Other Land Use), as per the sectors and categories in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. This poses a potential problem as it pairs what is commonly considered as residual emissions[48] (e.g. non-CO_2 emissions from livestock) with removals from activities in the LULUCF sector, obscuring the true extent of the LULUCF sector. For many countries, agricultural emissions can be sizeable compared to the sink provided by the LULUCF sector, in some cases changing the overall net balance to a gross emission when presented as AFOLU[76]. Nevertheless, in the few cases where only AFOLU is presented within the long-term national climate strategy, we recorded the status in the same manner as LULUCF, as a net sink for the sector still offers the potential to compensate for residual emissions in other economic sectors.

Our iterative rounds of deductive and inductive coding accounted for a range of governance considerations that inform CDR at the national scale, such as calls for international cooperation, national considerations of feasibility, policies targeting CDR, mentions of mitigation deterrence, the institutional arrangements for CDR, and commentary regarding residual emissions or hard-to-abate sectors. As with previous studies, we found the treatment of policy too limited across our sample to provide for meaningful categories, or to discern between general policies and those specifically targeting CDR[2]. As a result, we opted to exclude policy from this study. We then examined which categories were common across many strategies, choosing to focus on calls for international cooperation and national considerations of feasibility owing to their commonality across the sample and their inclusion in prior studies[2,40]. For transparency and reproducibility, further detail regarding each analytical element (e.g. long-term targets or quantification of CDR) across our sample of strategies can be found in Supplementary Data 2 and Supplementary Data 3, found within Supplementary Data.

Data availability

The data analysed and discussed in this article are included in Supplementary Data.

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Author contributions

All designed the research; HBS performed the analysis and wrote the manuscript. N.E.V. & J.F. supervised the analysis and writing. All authors discussed the results and commented on the manuscript at all stages.

Competing interests

The authors declare no competing interests.

Additional information

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