Promising Words, Evaluating Actions: Assessing Carbon Dioxide Removal in National Net Zero Plans

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In carrying out this research, I've been fortunate to travel across Europe and the United Kingdom (UK). In doing so, I've met many researchers whose work has inspired my own. The challenges posed by climate change are immense, but in undertaking this thesis, I've become convinced these challenges can be met.

This is evidenced, albeit inadvertently, by my own family. My parents met at Didcot A, a coal-fired power station, commissioned in 1970. I exist, in part, because of coal power. Didcot A closed on the 22nd March 2013, the year I turned 18 and attended university to study Environmental Science. My father, an apprentice turned engineer, then worked at Didcot B, the neighbouring combined cycle gas-fired power station, until his retirement in 2021. By spring of 2020, the six cooling towers and chimney of Didcot A had been demolished. Didcot is now more known for its train station, on the line to London Paddington, than its power stations. From the year I was born, 1995, to my father's retirement in 2021, annual coal power generation in the United Kingdom fell by 95% (DESNZ, 2024a). Much of this change happened after 2012, because of policy, just as I entered my adult years (Mayo, 2024). The closure of Didcot A itself in 2013 was a result of the European Union's Large Combustion Plant Directive, which set strict emission standards for air pollution (Mayo, 2024). Between 2012 and 2016 alone, coal power generation fell by 78% (DESNZ, 2024a).

Coal power generation was also overtaken by wind and solar in 2016 (DESNZ, 2024a), when I finished my first degree and entered the workplace for my first '*real job*' in climate policy. The following year renewables and nuclear generation combined surpassed all fossil fuel generation, the total of coal, gas, and oil (DESNZ, 2024a). The last coal power station in the UK, Ratcliffe-on-Soar, closed in September 2024 (Mayo, 2024). The United Kingdom now meets all its electricity demand without coal. My adult years and my father's retirement have witnessed the final days of coal power, in its industrial birthplace, and I hope that my career can be dedicated to ensuring all sectors are similarly transformed or otherwise abated.

A pessimist would note that this is one country, sector and technology, and such transformations are not guaranteed, certainly not at the planetary scale necessary. They would be right, but it is through a combination of climate policy and technological change that the average carbon footprint in the UK is not only half of my parents, when they were my age, but lower than even my grandparents (Ritchie, Rosado and Roser, 2024). It’s even more remarkable that all of this feels ordinary, happening in the background of daily life.

This thesis is dedicated to my family.

Abstract

Recent climate policy efforts are shaped by two connected trends, the rise of national net zero targets as the organising principle of climate policy, and the increasing recognition that Carbon Dioxide Removal (CDR) is unavoidable to reach the goals of the Paris Agreement, avoiding the worsts of climate change (Babiker et al., 2022). Net zero targets, by definition, require the deployment of CDR. National governments, however, have only recently engaged with the need for CDR to compensate for residual hard-to-abate emissions across their economies.

This thesis serves to address what is a key gap in climate policy research, the planning of national entities towards deploying CDR (Schenuit *et al.*, 2021). To address this gap, this thesis analyses one of the main reporting provisions in the Paris Agreement, long-term low emission development strategies (LT-LEDS) and similar long-term strategies (LTS). LT-LEDS are overlooked in climate policy research to date, given the more prominent role of the shorter-term Nationally Determined Contributions (NDCs) in the Paris Agreement, and the need to align NDCs with the 2030 benchmarks mainstreamed in the Intergovernmental Panel on Climate Change's (IPCC's) Assessment Reports (Den Elzen *et al.*, 2022). LT-LEDS, by contrast, given their focus on the mid-century, and the more prominent role of CDR to compensate for residual hard-to-abate emissions as a country approaches net zero, more readily communicate the role of CDR in decarbonisation. LT-LEDS, however, have only recently reached a critical mass, whereby they cover the majority of global emissions and global economic activity, with submissions from 74 countries.

Using a consistent methodology and inductive and deductive coding, this thesis analyses the contents of LT-LEDS and similar LTS, and the scenarios and pathways detailed therein. Assessing the inclusion of CDR methods in scenarios or pathways, and in text, across 41 strategies, reveals a reliance upon nature-based methods, notably forest and soil carbon sinks. National government's simultaneously stress the risks of relying upon these methods, such as the reversal risks to forests from wildfires, pests, and disease. Assessing the positive emissions that remain at the point of net zero, so called '*residual emissions*', across a larger sample of 71 LTS, reveals that residual emissions are considerable in size. As a proportion of peak emissions, residual emissions average 21% for Annex I countries, and upwards of 52% in specific cases. These emissions are commonly considered '*hard-to-abate*', stressing the technical and political complexities to their abatement, meaning they may be best indirectly mitigated through CDR, as opposed to directly abated at source (Babiker *et al.*, 2022). Residual emissions therefore serve as the basis for the deployment of CDR. High residual emission scenarios, show how some countries may retain or expand their fossil fuel production and use, using more CDR or international offsets to achieve net zero, substantiating concerns of mitigation deterrence. By sector, agriculture represents the largest contributor to total residual emissions and the sector with the least relative ambition compared with current emissions. The coding of supporting rationales, detailing why an emission source is considered hard-to-abate or residual, reveals many countries treat residual emissions as an inevitability, overlooking agriculture and emphasising emissions from industry.

LT-LEDS, however, provide a broad overview of climate policy efforts, not detailed policies. They reflect largely promises of decarbonisation, as opposed to concrete actions. This thesis therefore evaluates a national case study where a national strategy has led to advanced policies and plans for CDR, that of the United Kingdom (UK). Through 25 interviews with experts active in CDR policymaking, this thesis identifies a desire for greater government intervention, with calls for the UK government to take a more active role in stimulating market demand, overseeing the sector, and governing the standards through which projects are assessed and credited. Participants were sceptical of the voluntary carbon market (VCM), looking towards government to stimulate demand in addition to the government's current emphasis on ensuring supply. Participants welcomed greater government oversight, via, for example, the planned government monitoring, reporting and verification standard. These interviews demonstrate the challenge of CDR policymaking, including how concerns towards the role of CDR reflect wider debates in climate policy, such as the need for net-negative emission targets as an extension of net zero ambitions, given the seeming inevitability of temperature overshoot.

Combined this thesis demonstrates that CDR is no longer a debate limited to CDR's role in scenarios assessed by the IPCC (Fuss et al., 2014). Rather CDR has become an active part of the debate that animates climate policy, and a key feature of the visions of net zero laid out in LTS. In doing so CDR presents new challenges to national governments, such as the extent and reliance upon CDR, and the policies through which CDR is incentivised. CDR therefore brings new concepts to the forefront of climate governance, such as residual emissions.

This thesis ends by setting out future avenues for research, including the prospect of separate targets for CDR and emissions elsewhere in an economy, as a means to reduce the likelihood of high residual emission scenario. Research efforts should similarly be made to explore the means through which residual emissions in agriculture can be further reduced, given their emphasis in scenarios presented in LTS. Further case studies of CDR policymaking are also needed, particularly how government policies are incorporating early efforts to scale CDR through the VCM and the prospect of net-negative emissions.

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Acronyms & abbreviations

A/R	Afforestation and reforestation
AFOLU	Agriculture, Forestry, and Other Land Uses
AMC	Advanced market commitment
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
BECCS	Bioenergy with carbon capture and storage
CBDR-RC	Common but differentiated responsibilities and respective capabilities
CCC	Climate Change Committee
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture utilisation and storage
CDR	Carbon dioxide removal
CfD	Contracts for differences
CH_4	Methane
CI	Confidence interval
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
CO_2	Carbon Dioxide
CO_2e	CO_2 equivalent
COP	Conference of the Parties
CRCF	Carbon Removals and Carbon Farming
CRF	Common Reporting Format
CTU	Information to facilitate clarity, transparency and understanding
DACCS	Direct air carbon capture and storage
DESNZ	Department for Energy Security & Net Zero
ELM	Environmental Land Management
EU	European Union
EU LTS	European Union long-term strategy
F-gases	Fluorinated gases
GDP	Gross domestic product
GGR	Greenhouse gas removal
GHG	Greenhouse gas
Gt	Gigatonne
GWP	Global warming potential
IAMs	Integrated Assessment Models
IAS	International aviation and shipping
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IMO	International Maritime Organization

IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle analysis
LT-LEDS	Long-term Low Emission Development Strategy
LTS-SP	Long-term strategy scenarios and pathways
LULUCF	Land-use, land-use change, and forestry
MRV	Monitoring, reporting and verification
N_2O	Nitrous oxide
NDC	Nationally Determined Contribution
NETs	Negative emission technologies
NGHGI	National greenhouse gas inventory
OAE	Ocean alkalinity enhancement
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
SBTi	Science Based Targets Initiative
SCS	Soil carbon sequestration
TRL	Technological readiness level
UK	United Kingdom
UK ETS	UK Emissions Trading Scheme
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary carbon market
WCC	Woodland Carbon Code
WCU	Woodland Carbon Unit

1 Introduction Promising Words, Evaluating Actions

1.1 Introduction

With the adoption of the Paris Agreement in 2015, 195 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit global average temperatures to well below 2°C above pre-industrial levels, and pursue efforts to limit the increase to 1.5°C, avoiding the worsts of climate change [Article 2.1a of the Paris Agreement] (United Nations, 2016). Achieving the temperature goal of the Paris Agreement requires the rapid transformation of the global economy, notably to peak global greenhouse gas (GHG) emissions, rapidly reduce emissions thereafter, and achieve a balance of emissions from sources and removals by sinks in the second half of this century, or '*net zero*' [Article 4.1] (United Nations, 2016).

Scenarios from integrated assessment models (IAMs), energy-economy-climate models commonly used to assess pathways towards global temperature outcomes, reveal the extent and pace of the transformation necessary (Riahi *et al.*, 2022). Scenarios assessed in the Intergovernmental Panel on Climate Change (IPCC) Working Group III's 6th Assessment Report (AR6 WGIII), foresee that, to limit global average temperatures to below 1.5°C by the end of the century, with no or limited overshoot[1], global GHG emissions need to decline by 43% [34-60%, 90% confidence interval] by 2030, when compared to 2019 emissions, reaching net zero carbon dioxide (CO_2) emissions in 2050-2055[2] [2035-2070, 90% CI] (Riahi *et al.*, 2022).

Just over half (52%) of the below 1.5°C scenarios also reach net zero GHGs before the end of the century, whereby emissions of other prominent greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), are compensated by an equivalent removal of CO_2 from the atmosphere[3] (Riahi *et al.*, 2022). Scenarios that likely limit warming to below 2°C, are less demanding, but still require global GHG emissions to decline by 27% [13-45%, 90% CI] by 2030, when compared to 2019 emissions, reaching net zero CO_2 in 2070-2075 [2055-…, 90% CI][4] (Riahi *et al.*, 2022). Scenarios assessed by the IPCC are

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[1] These scenarios are category 'C1' in the IPCC's AR6 WGIII Report and AR6 Scenario Database. These scenarios represent mitigation pathways that limit warming to 1.5°C in 2100, with a likelihood of greater than 50% with no or limited overshoot. Likelihood, in this context, refers to the uncertainty of the warming response of the climate system to emissions. Limited overshoot refers to a peak of about 1.6°C for up to several decades, as stated in Table 3.1 of Chapter 3 of IPCC AR6 WGIII, cited as Riahi *et al.*, 2022.

[2] Scenarios in IPCC AR6 WGIII are reported in 5-year intervals. The median 5-year interval for the category 'C1' in the IPCC's AR6 WGIII Report and AR6 Scenario Database is presented.

[3] In IPCC AR6 WGIII, net zero GHGs corresponds to a balance of metric-weighted anthropogenic GHG emissions with metric-weighted anthropogenic removals, for a minimum of CO_2, CH_4 and N_2O, in CO_2-equivalents defined by the 100-year global warming potentials (GWP-100) (Riahi *et al.*, 2022). Global warming potentials measure the radiative forcing following an emission of a GHG, accumulated over a chosen time horizon (for example, a 100 years), relative to CO_2 (Matthews *et al.*, 2021).

[4] These scenarios are category 'C3a' in the IPCC's AR6 WGIII Report and AR6 Scenario Database. These scenarios represent mitigation pathways that limit peak warming to 2°C throughout the 21st century with a likelihood of >67%, with action starting in 2020. A second sub-category to C3 scenarios, 'C3b', includes emission reductions consistent with Nationally Determined

now commonly used as benchmarks to assess the ambition and performance of climate policy across countries and sectors (Lecocq and Winkler, 2024; Burgess and Dancer, 2025).

Since 2019, however, anthropogenic GHG emissions have continued to rise, albeit at a slowing rate, reaching 53.8 $GtCO_2e$ in 2023[5], 1.9% higher than levels in 2019, and 2.6% higher than levels in 2015, when the Paris Agreement was adopted (Jones *et al.*, 2024). The current ambition of climate policy adopted by parties, remains insufficient, leading to an estimated median rise of 2.7°C [2.2-3.4°C, 90% CI] by the end of the century (Climate Action Tracker, 2024)[6]. This outlook, however, has markedly improved since the adoption of the Paris Agreement, prior to which adopted policies were estimated to lead to a rise of 3.6°C [2.6-4.9°C, 90% CI] by 2100 (Climate Action Tracker, 2024).

Though absent globally, national examples of decarbonisation are many. To date, at least 37 countries (Figure 1) primarily in Europe, have decreased emissions whilst continuing to grow their economies, even when adjusting for the emissions embodied in trade, achieving '*green growth*'[7] (Hausfather, 2021; Fankhauser, 2024). Declines in the levelised cost of clean energy technologies have led to the transformation of the energy mix of many countries, with the combustion of coal, oil, and gas for electricity increasingly replaced by renewable generation, namely wind and solar photovoltaics (PV) (Ember, 2024). As a result, 118 countries are now past peak fossil fuel electricity generation[8] (Ember, 2024). Declines in the cost of batteries have similarly led to a rapid rise in the adoption of electric vehicles, outperforming the sales of petrol or diesel fuelled models in both Norway and Sweden, and projected to globally surpass 50% of all new car sales as early as 2030 (Andrew, 2024a; IEA, 2024). CO_2 emissions from land-use change have declined since the 1990s, consistent with declining decadal rates of deforestation (Ritchie, 2021; Friedlingstein *et al.*, 2024).

Contributions (NDCs) to 2030, short-term pledges made by Parties to the Paris Agreement. This requires stronger mitigation efforts post 2030 and is therefore commonly excluded from assessments of the ambition of climate policy. 91% of C3a scenarios reach net zero CO_2. Three dots (…) denotes net zero not reached for the 95th percentile.

[5] Using global warming potentials on a 100-year timescale (GWP100) from the IPCC AR6 WGI report.

[6] Using Climate Action Tracker's (CAT) 'policies & action' scenario, presented in their November 2024 update. This is typically based on projections of current policies adopted by governments, for example the 'With Existing Measures' or WEM scenarios found in reporting obligations submitted to the UNFCCC.

[7] There are multiple analyses of decoupling. These differ on the emissions accounting used, method, and definitions of decoupling. Figure 1 details cases of '*absolute*' decoupling, whereby economic growth is increasing, and emissions are decreasing. This is in contrast to '*relative*' decoupling, whereby the rate of economic growth exceeds the rate of emissions growth. Critics often suggest that decoupling should be defined according to a minimum rate of decoupling, or relative to historical emissions (see, for example, Tilsted *et al.*, 2021). This, however, makes decoupling a normative indicator, as opposed to an objective measure. Decoupling can occur for reasons beyond decarbonisation, such as structural change in an economy following a financial crisis (Bersalli, Tröndle and Lilliestam, 2023).

[8] Defined in Ember, 2024 as '*at least five years past a peak in electricity generation from fossil fuels*'.

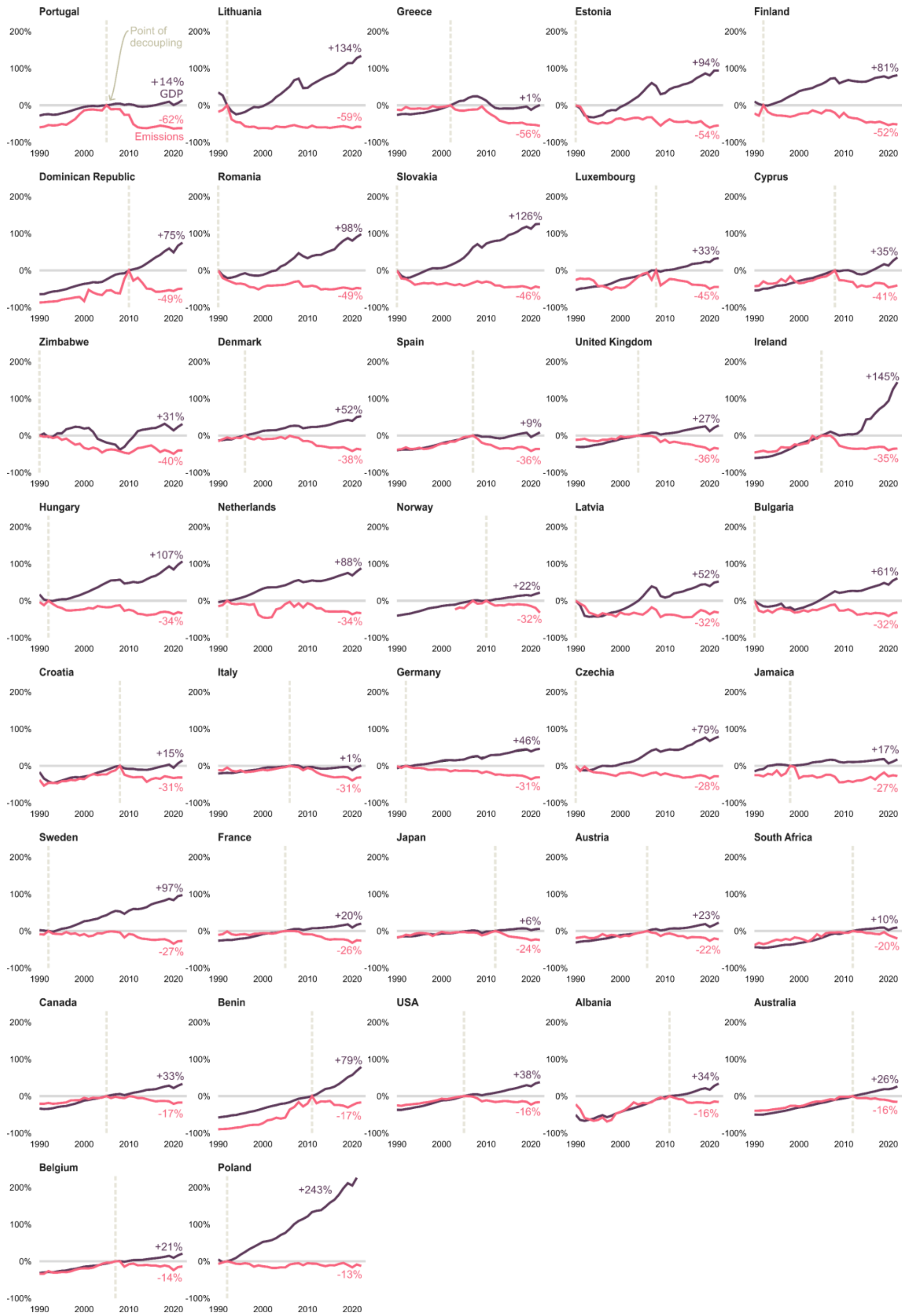

Figure 1. Absolute decoupling of gross domestic product (GDP) with consumption CO_2 emissions for 37 countries.

GDP (purple lines) shown on a purchasing power parity basis, using constant 2021 international $USD, sourced from the World Bank World Development Indicators Database (World Bank, 2024b). Ordered by percentage change in consumption CO_2 emissions from the point of decoupling (vertical line). Consumption CO_2 emissions (con. CO_2, red line) sourced from the Global Carbon Project, updated from Peters *et al.*, 2011. Consumption CO_2 emissions adjust for the emissions embodied in

trade. Decrease or increase in GDP and consumption CO_2 emissions shown relative to the point of decoupling and assessed according to linear regressions from the point of decoupling to the latest available year, 2022, using the methodology detailed in Hausfather, 2021. To be classified as a case of absolute decoupling, a country must have a negative regression coefficient for consumption CO_2 emissions between the point of decoupling and 2022, and a positive regression coefficient for GDP. Cases within the past ten years are excluded as too recent to allow for proper assessment.

Nevertheless, these positive trends must be accompanied by the reality that fossil fuels remain resilient across the global economy, with emissions rising year on year, irrespective of the rapidly diminishing remaining carbon budget for 1.5°C global average temperature rise stipulated in the Paris Agreement (Friedlingstein *et al.*, 2024). This does not necessarily mean climate policy has failed, policy efforts have already avoided several gigatonnes (Gt) of GHG emissions across the global economy, simply by reducing the rate of global emissions growth (Hoppe *et al.*, 2023). It does, however, reveal the tensions of climate policy research, that the global outlook for climate policy has largely improved on paper, but is yet to materialise as a peak in global emissions, with global emissions growth slowing, but continuing to be higher than predicted (Climate Action Tracker, 2024; Friedlingstein *et al.*, 2024).

Further impeding decarbonisation efforts, are areas of the economy where emissions are considered '*hard-to-abate*', owing to technical, economic, and socio-political dynamics to their abatement (Babiker *et al.*, 2022; Lund *et al.*, 2023). Hard-to-abate emissions include; the process emissions arising from the manufacturing of cement and steel, livestock and fertiliser emissions in agriculture, emissions from non-energy uses of fossil fuels in chemicals, emissions arising from combustion for high-temperature industrial heat, and emissions from the combustion of energy-dense fuels in aviation and shipping (Davis *et al.*, 2018; Brad, Haas and Schneider, 2024). Climate action therefore rests on accelerating the adoption of clean energy technologies, whilst resolving the barriers that remain elsewhere, or otherwise compensating for their continuing emissions by removing CO_2 from the atmosphere (Babiker *et al.*, 2022).

Net zero targets have rapidly become the organising principle of national climate policy (Coppenolle, Blondeel and Graaf, 2022; Green, Hale and Arceo, 2024). As of 2024, 147 countries have adopted a form of net zero or neutrality target, accounting for 87% of current global GHG emissions[9] (Net Zero Tracker, 2024b). These net zero targets, if fully implemented, are in reach of the Paris Agreement's

[9] Based on the Net Zero Stocktake 2024 of the Net Zero Tracker. Multiple data sources track national net zero targets, including the World Resource's Institute (WRI) Climate Watch platform and the International Energy Agency's (IEA) Climate Pledges Explorer. These data sources suggest that there may be less national net zero targets than stated. WRI's Climate Watch suggests there are 101 national net zero targets as of January 2024, whilst the IEA document 98 national net zero targets. The difference between the Net Zero Tracker and WRI and the IEA appears to be a list of countries published by the Climate Ambition Alliance at COP25, which the Net Zero Tracker treats as pledged. A figure of 147 national net zero targets covering 87% of global GHG emissions is consistent with the latest publication from the Net Zero Tracker. It is likely the emissions coverage is lower owing to the Net Zero Tracker not delineating between net zero CO_2 targets and net zero GHG targets.

temperature goal, leading to a rise in global temperature of 1.9°C [1.5-2.4°C] by the end of the century[10] (Climate Action Tracker, 2024).

Reaching net zero requires a means of balancing positive residual emissions with negative emissions (Fankhauser *et al.*, 2022). Essential to the concept of net zero, therefore, is carbon dioxide removal (CDR), a range of methods that remove and durably store CO_2 from the atmosphere, in a range of terrestrial, geological or ocean sinks, thereby producing negative emissions (Babiker *et al.*, 2022). CDR's conceptual role in mitigation has largely emerged through integrated assessment modelling, energy-economy-climate models that feature prominently in IPCC Assessment Reports (van Beek *et al.*, 2020). In IAM scenarios assessed by the IPCC, CDR compensates for continuing emissions from residual hard-to-abate sources across the global economy, enabling global net zero CO_2 to be reached, approximately stabilising global temperatures (Chen *et al.*, 2021).

CDR also enables a period of net-negative CO_2 emissions, whereby removals exceed anthropogenic CO_2 emissions (Chen *et al.*, 2021). Net-negative CO_2 emissions are a prerequisite to reaching net zero GHGs, whereby anthropogenic GHG emissions are balanced by an equivalent amount of CO_2 removal, which if sustained or exceeded, is expected to lead to a decline in global temperatures (Chen *et al.*, 2021). CDR is therefore central to the concept of net zero, and to the possibility of temperature overshoot, allowing for the temporary exceedance of global temperature limits such as the 1.5°C goal stipulated in the Paris Agreement (Schleussner *et al.*, 2024).

With the widespread adoption of national net zero targets, and increasing recognition of the likelihood of temporary temperature overshoot, CDR has now moved from a feature of scenario modelling towards real-world deployment, requiring new policies and means of governance (Green, Hale and Arceo, 2024; Peters, 2024; Schenuit *et al.*, 2024). Similarly, whilst the need for net zero conceptually emerges from climate science, namely earth-system models, it is practically enacted through national pledges, plans, and policies (Allen *et al.*, 2022; Fankhauser *et al.*, 2022). This thesis addresses the growing need to track CDR as a new consideration of national climate policy.

The rest of this chapter is as follows;

[10] Using CAT's 'Optimistic scenario', presented in their November 2024 update, which includes 'all announced targets including net zero targets, LTSs and NDCs'. Similar assessments of the temperature rise by 2100 including all announced targets, are produced by United Nations Environment Programme (UNEP), in their Emissions Gap Report. These largely agree with CAT's latest assessment, differing by 0.2°C, in the 2024 version of the Emissions Gap Report (1.7°C). These differences are well understood, and largely explained by differences in methodology, for example, CAT assesses warming in 2100, whereas the Emission Gap Report assesses peak warming during the century. There remains, however, disagreement as to how the temperature goals of the Paris Agreement translates into the calibrated uncertainty language used by the IPCC (Schleussner *et al.*, 2022). A general interpretation of 'below 2°C' corresponds to likelihood greater than 67% that peak warming is kept to below 2°C. A 50% likelihood is stated above but this estimate is nearly consistent with a 66% likelihood of limiting warming to 2°C (2.1°C in 2100 in CAT's assessment, 1.9°C peak warming in the 2024 Emissions Gap Report).

- Section 1.2 further defines CDR, details the range of CDR methods, delineates CDR from commonly conflated terms, and sets out the terminology used throughout this thesis.
- Section 1.3 details the role of CDR in climate action across multiple scales, with an emphasis on the national scale, the relevant scale to this thesis.
- Section 1.4 details the main data source for this thesis, formally known within the Paris Agreement as long-term low emission development strategies (LT-LEDS).
- Section 1.5 details the role of LT-LEDS within climate negotiations.
- Section 1.6 details the research to date on LT-LEDS.
- Section 1.8 details the structure of this thesis beyond this chapter, as well as this thesis's aims and sub-aims.

1.2 CDR methods and terminology

1.2.1 Definition of CDR

CDR represents a range of methods that remove CO_2 from the atmosphere, storing the carbon durably in geological, terrestrial and ocean carbon sinks (Babiker *et al.*, 2022). It excludes the uptake of CO_2 by terrestrial and ocean carbon sinks not directly due to anthropogenic activities, such as the indirect increase in CO_2 uptake owing to increased CO_2 fertilisation (Babiker *et al.*, 2022). CDR methods can produce net-negative emissions (or '*net CO_2-equivalent removal*')[11], where the CO_2 removed and durably stored exceeds the equivalent metric-weighted GHG emissions produced (Terlouw *et al.*, 2021; Nordahl *et al.*, 2024).

Practically this requires the certification of a series of measurements or modelled estimations across set boundaries, timescales, and metrics (Terlouw *et al.*, 2021; Nordahl *et al.*, 2024). These requirements are being developed by standards organisations, project developers, and scientific agencies, but disagreements remain as to the durability of the CO_2 stored, and therefore the storage period to be assessed, and whether avoided emissions should be certified (Terlouw *et al.*, 2021; Arcusa and Sprenkle-Hyppolite, 2022; Chiquier *et al.*, 2022). These requirements, collectively termed, '*Monitoring, Reporting & Verification*' (MRV), draw from prior practice in carbon markets and lifecycle analysis (LCA)[12].

[11] This thesis uses '*net-negative emissions*' and '*negative emissions*' largely interchangeably, as practiced elsewhere in climate policy research and within the IPCC. They are, however, terms distinguishable in the context of MRV, as net-negative implies the additional assessment of the equivalent metric-weighted GHG emissions produced, and negative emissions implies only the assessment of removals. 'Negative emissions', however, is also a more general term to describe the intended goal of CDR.
[12] MRV to establish net-negative emissions can differ from the LCAs commonly used to assess the impact on emissions of a product or service. LCAs are not necessarily structured to distinguish between emissions avoided and removals (Nordahl *et*

There are, however, a number of general principles that serve to define CDR. Tanzer and Ramírez, 2019 and Geden, Smith and Cowie (2024), together propose the following five general principles;

Principle 1. The CO_2 is removed, directly or indirectly, from the atmosphere,

Principle 2. The removed gases are stored out of the atmosphere in a manner intended to be permanent,

Principle 3. The removal must be a result of human intervention, additional to the Earth's natural processes,

Principle 4. Upstream and downstream greenhouse gas emissions associated with the removal and storage process, are comprehensively estimated, and included in the estimation of net-negative emissions,

Principle 5. The total quantity of atmospheric CO_2 removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere.

The first three principles form a minimum requirement for any method to be classified as a CDR method, and therefore capable of producing net-negative emissions. If the first three principles are met, MRV will be necessary to assess whether principles 4 and 5 are additionally met, thereby resulting in net-negative emissions. Without adequate MRV, the CDR method may not deliver any climate benefit (Babiker *et al.*, 2022).

1.2.2 CDR methods, categories, and feasibilities

There exists multiple methods of CDR. Methods differ according to their potential, their permanence, their economic costs, and the impacts of their deployment, which in turn may pose limits towards their feasibility (Fuss *et al.*, 2018; Prütz *et al.*, 2024). Given the number of methods, these are often grouped into different categories for ease of reference. These categories, and the more general terminology used across research and industry, are subject to substantial debate, with whole journal articles dedicated to debating the merits of different terminology (for example, see Renforth *et al.*, 2023).

In this thesis, two classes of method are used, nature-based and engineered methods. This split corresponds to a distinction widely used but roundly criticised in climate policy (Bellamy and Osaka, 2019; Bellamy and Raimi, 2023). For example, the '*natural*' framing of some methods may unduly

al., 2024). The type of LCA is also key. For example, attributional LCA can be used to quantify the emissions and removals associated with the carbon removal activity, which when summed may prove to be net-negative. However, for any climate benefit, it is necessary to establish the total system-wide change in emissions and removals caused by the activity, which is possible through consequential LCA (Brander, 2024). For example, if the activity uses resources that would have been used elsewhere, therefore stimulating new demand and therefore emissions, this would not be accounted for in an attributional LCA.

influence their social acceptance and negatively impact those by contrast deemed artificial (Bellamy and Osaka, 2019). There is also substantial ambiguity between these categories, as to what methods are sufficiently ‘*natural*’ (Bellamy and Raimi, 2023).

In light of these criticisms, researchers stress a need to emphasise the ‘*nature*’ in all CDR methods (Bellamy and Osaka, 2019), the ‘*technological*’ elements of nature-based methods (Markusson, 2022), or a need to dispense with categories altogether (Osaka, Bellamy and Castree, 2021). Others propose a further ‘*hybrid*’ category, or represent methods on a continuum (Morrow *et al.*, 2020). An increasingly common practice is to distinguish between novel and conventional methods, based on their current scales and levels of technological readiness (Smith *et al.*, 2023). These categories may reduce but not resolve the undue influence of framings first identified by Bellamy and Osaka, 2019, shifting the perceived positive framing towards those categorised as novel, considering novel is synonymous with '*advanced*' or '*state-of-the art*' (Flynn, 2007).

Regardless of the categories that eventually reach consensus or majority use in CDR research, it remains that a large contingent will continue to use ‘*natural*’ framings, such as those researching ‘*nature-based solutions*’, an ‘*umbrella concept*’ covering climate adaptation, biodiversity, and sustainable development, in addition to carbon sequestration (see, for example, Seddon, 2022). Resolving the undue influence of these framings is therefore beyond the researchers directly involved in CDR. Given this debate, this thesis sets aside what categories are sufficiently value-neutral and uses nature-based and engineered as the most widely used categories within climate policy, and a distinction used by multiple governments. For example, the UK government continue to use these categories within policy design (DESNZ, 2023d).

Under these categories, nature-based methods include afforestation and reforestation (A/R), soil carbon sequestration (SCS), peatland restoration, and ‘*blue carbon*’, means to enhance carbon sequestration in mangrove forests, seagrass meadows and tidal marshes (Griscom *et al.*, 2017; Macreadie *et al.*, 2021). Engineered methods include bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), biochar, enhanced weathering, ocean alkalinity enhancement (OAE) and ocean fertilisation. These methods and categories reflect the taxonomy of methods used in IPCC Assessment Reports and the categories used by the UK government (Babiker *et al.*, 2022; DESNZ, 2023d). It should be noted that this list is not exhaustive and further methods have been proposed since the IPCC taxonomy of methods was first produced in 2018 (Fuss *et al.*, 2018), for example, biomass burial (Yao, 2024) and direct ocean capture (DOC) (Yafiee *et al.*, 2024). Nevertheless, this list is sufficient for the aim of this thesis.

Methods differ widely when systematically assessed. Engineered methods are typically associated with higher removal potentials than nature-based methods, but are less mature in terms of their readiness to be deployed, and therefore more speculative (Fuss *et al.*, 2018; Babiker *et al.*, 2022). For example, in the IPCC's AR6 WGIII report, DACCS has a mitigation potential ranging from 5-40 $GtCO_2$/yr, substantially larger than the potential estimated for afforestation and reforestation, ranging from 0.5-10 $GtCO_2$/yr (Babiker *et al.*, 2022). DACCS however, has a lower technological readiness level (TRL) than afforestation and reforestation (6 compared to 8 on a 9-point scale), and is associated with minimal co-benefits, high current costs, and increases in energy demand (Babiker *et al.*, 2022). Nevertheless, DACCS remains a popular method owing to its modularity, and therefore advocates of the method point to the improvements in the cost and rate of deployment for solar PV, as a model that can be emulated for DACCS (Realmonte *et al.*, 2019; Malhotra and Schmidt, 2020).

Afforestation and reforestation, by comparison, is a proven method at lower cost, and with greater co-benefits, addressing multiple policy challenges simultaneously by, for example, improving biodiversity and mitigating climate change (Babiker *et al.*, 2022). Afforestation and reforestation, however, suffers from saturation, whereby the rate of carbon sequestration declines over time in the absence of active forest management, and the carbon is stored non-permanently, meaning the carbon is subject to greater risks of reversal in the event of forest fires or drought (Anderegg *et al.*, 2020; Babiker *et al.*, 2022; Mac Dowell, Reiner and Haszeldine, 2022). This is but one comparison between two archetypal methods and, using data collated in the IPCC AR6 WGIII report, further comparisons are shown in

Figure 2.

Potentials are heavily contested (Lewis *et al.*, 2019), and the '*feasible*' potential - the scales possible when constrained by environmental, socio-cultural, and institutional factors – is often greatly reduced when compared with the '*technical*' potential (Perkins *et al.*, 2023; Deprez *et al.*, 2024). This distinction has prompted calls to '*right-size*' CDR methods to prevent their abuse in climate policy (Field and Mach, 2017). Differences in costs, potentials, characteristics, and co-benefits, further suggest a need for a '*portfolio approach*' as a guide to CDR deployment, whereby multiple methods are deployed to limit the scale and impact of any individual method (Fuhrman *et al.*, 2023). The implication of this approach is that there is no ideal CDR method, and therefore no proven '*silver bullet*' to excuse the need for substantial emission reductions (Warszawski *et al.*, 2021; Dooley, Nicholls and Meinshausen, 2022). Despite the IPCC's assessment, there are limits to which global assessments can inform national climate policy, warranting further regional and national feasibility assessments, cognisant of national circumstances (Förster *et al.*, 2022).

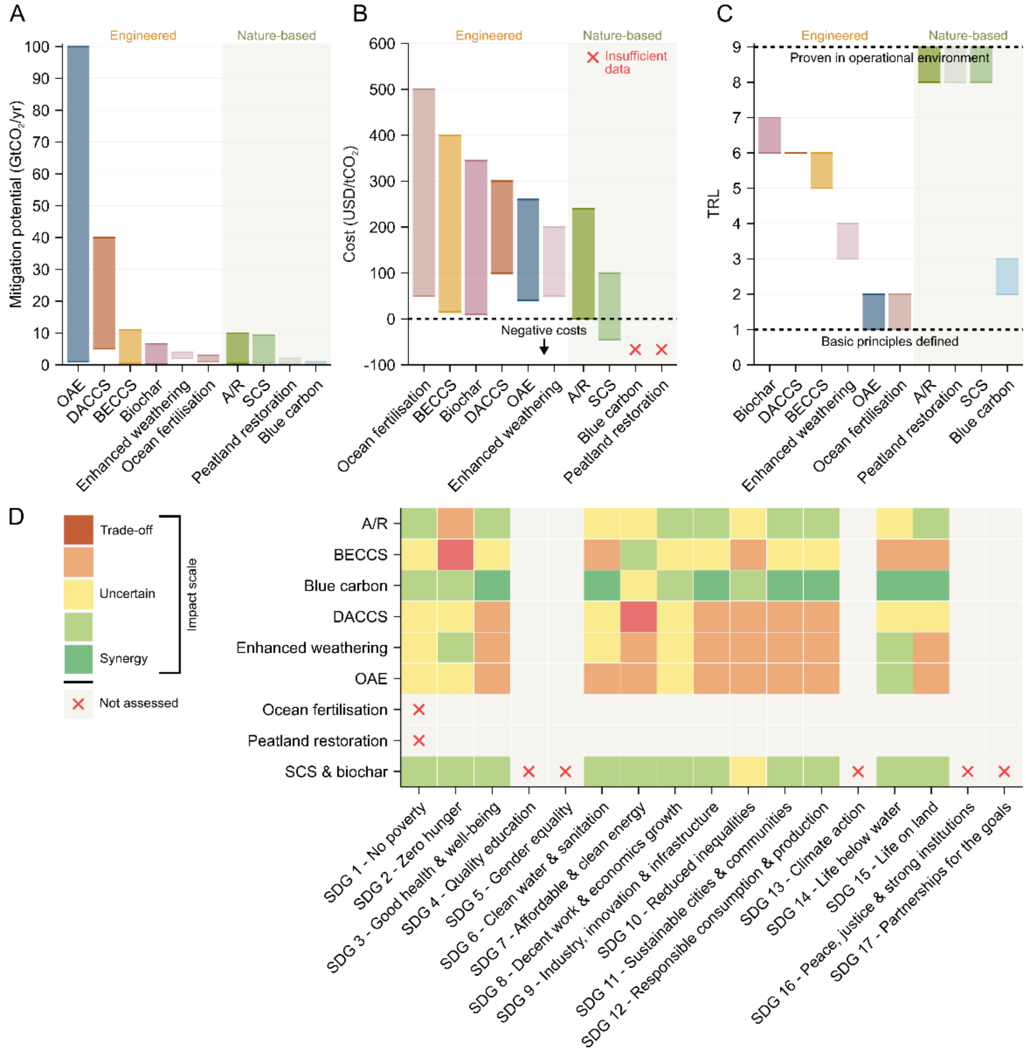

Figure 2. Comparison of CDR methods according to their potentials, costs, and technological readiness level (TRL).

Panel A details the mitigation potential of 10 different CDR methods from the IPCC AR6 WGIII Report, expressed in gigatonnes (Gt) of CO_2 removed annually, ordered from high to low and split into engineered and nature-based. Panel B details the costs of removal, expressed in US dollars (USD) per tonne of CO_2 removed (tCO_2). For blue carbon and peatland restoration, the IPCC conclude there is insufficient data to establish a cost range. Negative costs, as observed in the range for soil carbon sequestration (SCS) indicate a cost saving. Panel C details the technology readiness level (TRL) of each method on a 9-point scale, where 1 is low readiness (basic principles defined) and 9 is high readiness (proven in an operational environment). Data adapted from Table 12.6 of Chapter 12, IPCC AR6 WGIII, cited as Babiker *et al.*, 2022. Panel D details an assessment of 8 of the 10 methods assessed by the IPCC, according to their likely impact on the achievement of the Sustainable Development Goals (SDGs). SCS and biochar is assessed as a single method. Impact is assessed on a 5-point scale, ranging from -2 (trade-off) to 2 (synergy). Data in Panel D adapted from Fuhrman *et al.*, 2019.

1.2.3 Distinctions within carbon management

CDR is commonly subsumed under the larger umbrella of '*carbon management*', which includes, in addition to CDR, methods of point source carbon capture and storage, or '*CCS*', and carbon capture and utilisation (CCU). These terms are commonly conflated with CDR, and many terms are inaccurately used (Olfe-Kräutlein *et al.*, 2022).

CCU refers to the capture and use of CO_2 directly, or as a feedstock, in industrial or chemical processes to produce carbon-containing products, including; the production of synthetic fuels, synthesized from hydrogen and captured CO_2, the creation of plastics from captured CO_2, or the use of CO_2 as a curing agent in concrete (Hepburn *et al.*, 2019; Ravikumar *et al.*, 2021; Ueckerdt *et al.*, 2021; Bachmann *et al.*, 2023). These methods of CCU have widely different storage periods, for example, for synthetic fuels, the utilised captured CO_2 would be emitted upon combustion, typically being stored from days to weeks (Bruhn, Naims and Olfe-Kräutlein, 2016). The captured CO_2 utilised in plastics may be typically stored for a number of years, depending on their end-of-life, for example, combustion or landfill, whilst carbon in concrete may be stored for decades (Bruhn, Naims and Olfe-Kräutlein, 2016).

There exists limited overlap between CDR and CCU, the extent of which can be determined by applying the principles listed in Section 1.2.1. If the method of CCU fails Principle 1 and/or 2, that is, the source of the CO_2 is not from the atmosphere, and the means of storage is not intended to be permanent, it cannot be considered CDR, but the method may retain a climate benefit by displacing a more carbon intensive product or process, depending on the comparative assessment of lifecycle emissions and removals (Hepburn *et al.*, 2019; De Kleijne *et al.*, 2022). Only under very limited criteria can methods of CCU be considered CDR, such as the sequestration of biogenic or atmospheric CO_2 in long-lived products (De Kleijne *et al.*, 2022).

CCS refers to methods that capture CO_2 from industrial point sources, where the CO_2 is concentrated in flue gases, and its storage in geological sinks. Typically, in climate policy, this term is reserved to the application of CCS to capture and store CO_2 from fossil sources, that is, fossil fuels or minerals (Geden, Smith and Cowie, 2024). In this application, the CO_2 is not atmospheric and therefore fails Principle 1, despite being permanently stored in geological storage, fulfilling Principle 2. Confusion arises for select engineered methods, such as BECCS and DACCS, where CCS is a component of the method, applied to capture and store the CO_2 released from the treatment of biomass, or from the air, in which case the overall process would meet both Principle 1 and Principle 2, and be considered CDR. To avoid any conflation, within this thesis, CCS refers exclusively to fossil CCS.

Figure 3 serves to illustrate the principles listed in Section 1.2.1. Panel A describes a DACCS project, whereby Principle 1 and 2 are met, whereas Panel B depicts the utilisation of captured atmospheric CO_2 through direct air capture (DAC) in synthetic fuel, where it is soon re-released, failing to meet Principle 2. Panel C details a fossil CCS project, which fails Principle 1, by combusting fossil carbon, but meets Principle 2, through geological storage. Panel D depicts an afforestation project, where it is necessary to distinguish, as detailed in Section 1.2.1, between anthropogenic and natural processes, Principle 3. Across all panels, only Panel A and the activity indicated with a ✓ in Panel D can be considered CDR methods.

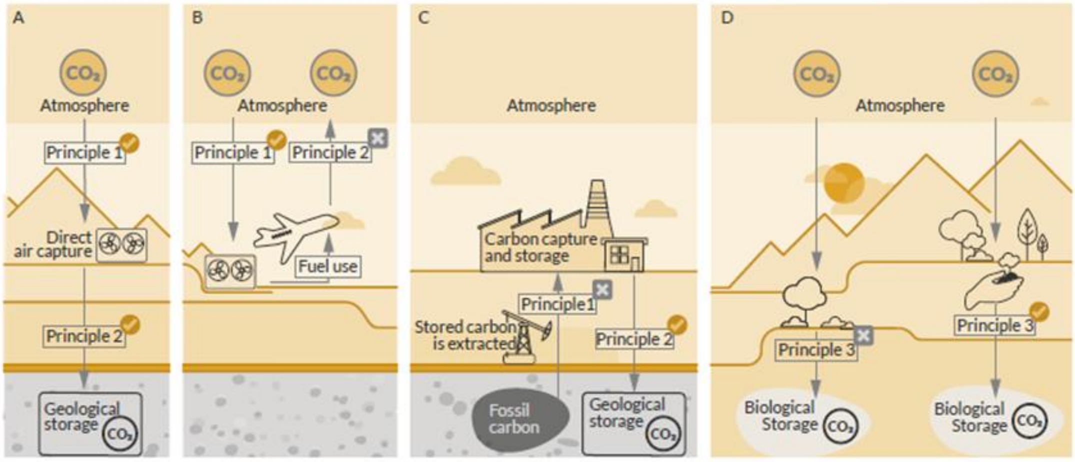

Figure 3. The first three principles that define CDR, illustrated with different methods across four panels.

Panel A details a DACCS project, which fulfils both Principle 1 and Principle 2. Panel B depicts the utilisation of captured atmospheric CO_2 through DAC in synthetic fuel, where it is soon re-released, failing to meet Principle 2. Panel C details a fossil CCS project, which fails Principle 1, by combusting fossil carbon, but meets Principle 2. Panel D depicts an afforestation project, where it is necessary to distinguish, between anthropogenic and natural processes, Principle 3. Source: Geden, Smith and Cowie, 2024.

1.2.4 Terminology

As the most popular and most widely held term, Carbon Dioxide Removal, or '*CDR*', is used throughout this thesis. However, across research and industry, many actors within CDR continue to use a range of wider terminology. For example, the UK Government uses '*Greenhouse Gas Removal*' (GGR), largely to allow for methods of removal beyond CO_2, such as methane removal (DESNZ, 2023d). Methods of methane removal, however, are less established in both policy and research, meaning the use of this term is largely pre-emptive (Jackson *et al.*, 2021). Negative Emission Technologies (NETs) remains a commonly used term, however there are limits to which CDR methods can be referred to as a technology (Markusson, 2022). Despite technical and connotative differences, GGR, NETs, and CDR are all currently used interchangeably in practice. We use CDR throughout this thesis and in published outputs. Other terms may be used in direct quotations, but largely denote the same set of methods, unless stated otherwise.

1.3 The role of CDR in climate action

1.3.1 Role at the global and national scales

CDR has multiple roles at multiple scales of climate governance. At the global and national scales, CDR fulfils three main roles, in the near-term, CDR can accelerate the rate of mitigation, in the medium term, CDR can compensate for residual hard-to-abate emissions to achieve net zero CO_2 or net zero GHGs, and in the longer-term, if deployed beyond the extent of residual hard-to-abate emissions, achieve net-negative CO_2 or GHG emissions (Babiker *et al.*, 2022).

These roles are sequential, that is, it is first necessary to reach net zero CO_2, prior to net zero GHGs, which necessitates reaching net-negative CO_2 emissions prior. However, achieving, for example, global net zero CO_2, does not necessitate all countries reaching this state simultaneously, but requires some countries to reach net-negative CO_2 or GHGs, allowing other countries to continue to net emit and more gradually decarbonise (Babiker *et al.*, 2022). This similarly applies to net zero GHGs, and net-negative CO_2 or GHG emissions.

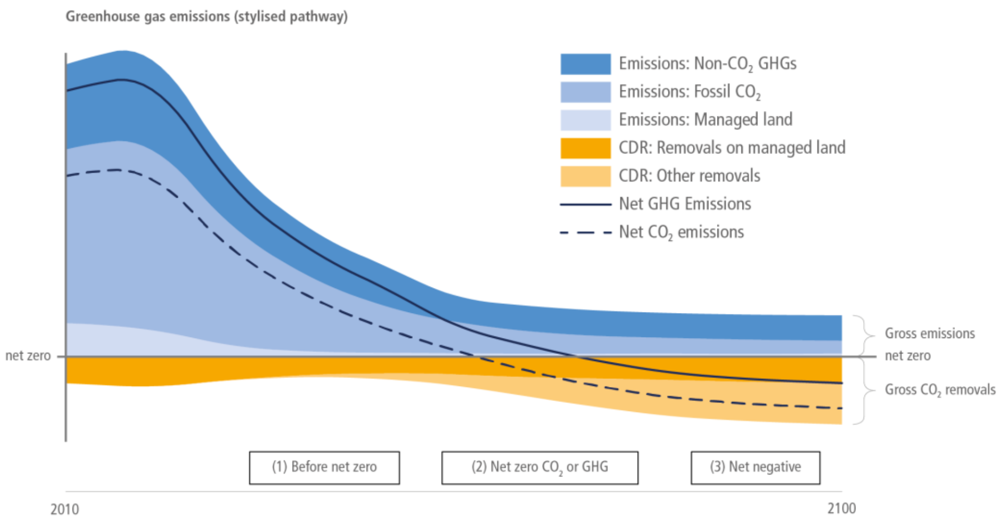

Figure 4. Stylised GHG pathway showing the sequential roles of CDR.

These roles are (1) further reducing net CO_2 or GHG emissions levels in the near-term; (2) counterbalancing residual emissions to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieving and sustaining net-negative CO_2 or GHG emissions in the long-term. Sourced from Chapter 12 of the IPCC WGIII AR6 Report, Cross-Chapter Box 8, Figure 2, cited as Babiker *et al.*, 2022.

Any acceleration in the rate of mitigation is conditional on the deployment of CDR being additional to the mitigation achieved through measures to reduce emissions. Academics, however, largely doubt whether this is possible in practice. For example, given that CDR methods such as DACCS require low-carbon or renewable electricity to maximise net-negative emissions, it remains that using this electricity to directly displace demand for any remaining fossil fuel generation may result in a greater net reduction emissions in the near-term than DACCS (Jacobson, 2019). Similar '*best use*' principles also apply to biomass (Patrizio *et al.*, 2021; Millinger *et al.*, 2025).

Similarly, academics and many environmental NGOs fear that CDR, by its inclusion in IAMs and mainstreaming through the IPCC, has resulted in mitigation deterrence, whereby the prospect of more stringent emission reductions are delayed or reduced, owing to the consideration of another climate intervention, in this case, CDR (McLaren, 2020; Church and Recupero, 2024). CDR, therefore, may have already resulted in the relaxation of otherwise necessary steeper near-term emission reductions (Larkin *et al.*, 2018). CDR is hence a '*false solution*', a distraction that should be excluded from the means of mitigation (Church and Recupero, 2024). This critique, however, relies on the assumption that, in the absence of CDR, climate policy would proceed on the basis of more stringent emission reduction measures, as opposed to climate targets being weakened or abandoned.

Despite these criticisms, IAMs suggest the contribution of CDR in this role is expected to be minimal, for example, a review of scenarios assessed in AR6 WGIII for categories C1-C3 revealed that 80% of net GHG emission reductions until reaching global net zero CO_2 comes from eliminating fossil fuel emissions and deforestation, independent of the climate target, that is, independent of whether the scenario targets 1.5°C (C1, C2) or 2°C (C3) (Ganti *et al.*, 2024). In short, the bulk of mitigation comes from emission reductions, regardless of the climate target, meaning, as far as evidenced by IAMs, mitigation deterrence is largely a matter of delay as opposed to substitution. Given the timing of current national net zero targets around the mid-century, alongside the scenarios assessed by the IPCC, near-term may be taken to refer to the decades prior to the mid-century, though some national net zero targets extend beyond 2050 (Hale *et al.*, 2021).

As noted in Section 1.1, CDR compensates for residual hard-to-abate emissions across the global economy to reach net zero CO_2, which, once reached, approximately stabilises global temperatures (Chen *et al.*, 2021). CDR also allows for net-negative CO_2 emissions, enabling net zero GHGs to be reached, allowing for the gradual decline of global temperatures (Chen *et al.*, 2021). Sustaining or exceeding this allows for a return to 1.5°C, or temporary temperature overshoot. Overshoot has been roundly criticised as entailing greater climate risks and climate damages compared to scenarios that limit overshoot (Drouet *et al.*, 2021; Wunderling *et al.*, 2023; Schleussner *et al.*, 2024). Beyond overshoot and residual hard-to-abate emissions, CDR may be necessary to hedge against uncertainties within the climate system, such as high climate sensitivity (Schaber *et al.*, 2024).

At the national scale, CDR similarly allows for countries to reach net zero CO_2 or GHGs by compensating for residual hard-to-abate emissions across an economy. Net-negative emissions at the national scale allows other countries to decarbonise more gradually, effectively expanding the carbon budget for these states (van Soest, den Elzen and van Vuuren, 2021). This follows the principle within the UNFCCC of '*common but differentiated responsibilities and respective capabilities*' (CBDR-RC), subsequently adopted in Article 2, paragraph 2, of the Paris Agreement. Greater mitigation efforts by developed nations have been seen as one means through which this principle is operationalised, which could extend to the need for net-negative targets (Mohan *et al.*, 2021; Schenuit, Geden and Peters, 2024).

The CBDR-RC principle, however, beyond a consensus that developed nations should go further than developing nations on mitigation and climate finance, does not prescribe who should do what by when (Mohan *et al.*, 2021). Nevertheless, the concept of '*carbon debt*', means of quantifying a country's cumulative historical contribution to climate change from an agreed starting date, has long been proposed in climate negotiations, and may need to be revisited as a means of advancing net-negative targets (Pickering and Barry, 2012; Mohan *et al.*, 2021; Hahn *et al.*, 2024).

1.3.2 Role at the sub-national scale

The Paris Agreement markedly mobilised sub-national actors towards climate action (Hale, 2016; Hsu *et al.*, 2020). Regions, cities, and corporates have introduced their own net zero targets, alongside a range of initiatives in climate governance to track progress against these commitments (Hale *et al.*, 2021; Seto *et al.*, 2021). Corporate actors have an interest in CDR to offset emissions from their own activities (Trouwloon *et al.*, 2023), but increasingly, in recognition of the limited supply, are actively governing CDR development and deployment, through their procurement of projects and purchase commitments (Battersby *et al.*, 2022).

CDR is desirable to corporate actors partly owing to the fact removals, notably from some methods, are more permanent and additional, offering less reputational risk than conventional carbon credits, which typically represent '*avoided*' emissions (Joppa *et al.*, 2021; Mistry *et al.*, 2023). Avoided emission credits have been subject to criticism, with multiple media reports criticising the practice, and academic studies suggesting many credit programmes to be inadvertently fraudulent. For example, a 2024 review found that 75% of all credits issued from avoided deforestation projects were non-existent (Probst *et al.*, 2024). CDR should therefore be viewed as a means of corporates demonstrating a more credible approach to offsetting, and a response to the integrity issues in the voluntary carbon market. This approach has now been internalised in corporate guidance. For example, the Oxford Offsetting Principles, one such set of corporate guidance, recommends a full transition away from both avoidance credits and removal credits with a 'higher risk of reversal', towards 'carbon removal to the geosphere', before 2050.

Given the diversity of corporates, and their interrelatedness through global supply chains, corporate claim action often frames the role of CDR beyond the roles outlined by the IPCC. For example, the use of CDR may extend to non-offsetting claims, such as ‘contribution’ approaches to global mitigation efforts (Trouwloon *et al.*, 2023). These are, however, conceptually similar to the first role outlined by the IPCC, to accelerate the rate of mitigation in the near-term. Cities and regions are similarly anticipated to require CDR to compensate for their own emissions, given their net zero targets largely precede national targets (Olsson *et al.*, 2024). Cities, however, have had limited engagement with CDR to date.

1.4 National net zero plans

This thesis sets out to analyse national net zero plans, regarding their inclusion and policy towards CDR. A range of reporting obligations could be regarded as these plans, however, there is no single widely supported reporting obligation that explicitly concerns net zero. Rather, there is a range of reporting provisions for Parties to the Paris Agreement, Parties to the UNFCCC, and European Union (EU) Member States, which can inform a range of reporting obligations found in national climate governance frameworks, such as climate laws (Evans *et al.*, 2021). Given this, it could be argued that reporting provisions such as NDCs form national plans, as do reports setting out policies for meeting set carbon budgets, as, for example, required of the UK Government by Section 14 of the UK’s Climate Law, the 2008 Climate Change Act. Many states therefore have climate governance frameworks that accommodate the requirements of both domestic and international reporting, with linkages between them. This thesis therefore analyses CDR in national net zero plans in two ways, firstly by analysing one of the main reporting provisions in the Paris Agreement, LT-LEDS, and secondly selecting a national case study where a national net zero plan has led to advanced policy plans for CDR.

LT-LEDS are chosen on the basis that their longer assessment period coincides with the year of many national net zero targets, forming the most readily available and comparable reporting provision to understand how parties plan to meet these targets (Lamb *et al.*, 2024). Given a focus on the mid-century, and the more prominent role of CDR to compensate for residual hard-to-abate emissions as a country approaches net zero, LT-LEDS may more readily communicate CDR, and are proposed as means to improve the governance of both net zero and CDR (Mace *et al.*, 2021; Rogelj *et al.*, 2023) .

A similar reporting obligation applies to EU Member States, namely the Regulation on the Governance of the Energy Union and Climate Action (EU/2018/1999), or the ‘*Governance Regulation*’. Article 15 of the Governance Regulation requires Member States to prepare and submit long-term strategies (EU LTS) analogous to LT-LEDS. These EU LTS can therefore be combined with LT-LEDS for those EU Member

States without a LT-LEDS. This thesis therefore describes this combined dataset as consisting of long-term national climate strategies, abbreviated to LTS. Where it is necessary to distinguish between LT-LEDS and EU LTS, either term is used directly.

Beyond being the most readily available and comparable reporting provision of national plans to meet net zero, there are further supporting justifications for an emphasis on LTS. Firstly LT-LEDS, have largely been overlooked in climate policy research to date, which has tended to focus on the shorter-term NDCs, owing to the need to align climate ambitions with the 2030 benchmarks mainstreamed in IPCC Assessment Reports (den Elzen *et al.*, 2022). Prior research into NDCs and CDR have largely found these to be lacking in detail and principally focused on land-use (Fyson and Jeffery, 2019; Mcelwee, 2022). This is unsurprising given that NDCs are governed by rules developed in the Paris Rulebook, agreed in 2018, that guide the elements to be communicated[13]. NDCs are therefore ill-suited as a means of establishing, for example, a parties' perspective towards CDR conceptually, and there remains debate as to the extent they can be used to study elements in the global climate regime (see, for example, Leiter, 2024).

Secondly, LTS have reached a critical mass, whereby they cover the majority of global emissions and global economic activity. Prior research has largely focused on smaller samples owing to their time of publication (Thoni *et al.*, 2020; Buylova *et al.*, 2021). Thirdly LT-LEDS are flexible, with no direct guidance from the UNFCCC as to the elements to be communicated, meaning parties can develop a LT-LEDS according to their respective needs and emphasis. In doing so, they situate CDR within a wider political project of national decarbonisation or economic development. They are therefore instructive as to the emerging politics of CDR.

Across the duration of this thesis, research examining LT-LEDS has increased. This thesis, and its publications, have been part of this increase, serving to mainstream LT-LEDS as part of the apparatus to track climate commitments over time. In this manner, this thesis, and its publications, can be seen as an addition to the body of academic literature that tracks the reporting provisions of Parties to the UNFCCC and the Paris Agreement, as well as the literature evaluating CDR (Mace *et al.*, 2021).

1.5 LT-LEDS within climate negotiations

To assist in long-term planning, and to better frame the efforts towards the Paris Agreement's long-term temperature goal, Article 4, paragraph 19, of the Paris Agreement invites parties to '*strive to*

[13] Specifically Annex I of Decision 4/CMA.1 defines the information to be provided by parties on '*clarity, transparency and understanding*' (CTU) in NDCs. It includes specific provisions on removals occurring on managed land and harvested wood products.

formulate and communicate long-term low emission development strategies' (United Nations, 2016). LT-LEDS are strategies by national governments that integrate climate mitigation, climate adaptation, climate finance and economic development, through a long-term planning process informed by national circumstances (Rocha and Falduto, 2019; Cruanyes, Alcaraz and Sureda, 2024).

The concept of long-term strategies has a longer history in climate negotiations, preceding the Paris Agreement, and dating back to at least 15th session of the Conference of the Parties (COP15), held in Copenhagen in 2009. The Copenhagen Accord, reached at COP15, recognised '*that a low-emission development strategy is indispensable to sustainable development*' (Decision 2/CP.15, paragraph 2) but provided no definition as to what these strategies entail, nor any explicit calls for their development. The Cancun Agreements, reached the following year at COP16, improved upon COP15, by further deciding '*that developed countries should develop low-carbon development strategies or plans*' (Decision 1/CP.16, paragraph 45) and encouraging '*developing countries to develop low-carbon development strategies or plans in the context of sustainable development*' (Decision 1/CP.16, paragraph 65).

The 2015 Paris Agreement, adopted at COP21, formalised these efforts as LT-LEDS, inviting these strategies to be communicated to the UNFCCC by 2020, with a focus on the mid-century (Decision 1/CP.21, paragraph 35, '*Invites Parties to communicate, by 2020, to the secretariat mid-century, long-term low greenhouse gas emission development strategies in accordance with Article 4, paragraph 19, of the Agreement*'). LT-LEDS have been a consistent feature of the COP decisions that followed. The Katowice Climate Package agreed at COP24 held in 2018 (Decision 1/CP.24) reiterated the 2020 deadline, but many parties delayed their submissions owing to the COVID-19 Pandemic and the subsequent delay to COP26 (Ross *et al.*, 2021).

The Glasgow Climate Pact, agreed at COP26 in 2021, urged countries yet to submit their LT-LEDS to do so before the next COP, and called for submitted LT-LEDS to be updated according to the best available science and aligned with NDCs (Decision 1/CMA.3, paragraphs 32, 33, and 35)[14]. This same request was made in the Sharm el-Sheikh Implementation Plan, agreed at COP27 in 2022 (Decision 1/CMA.4, paragraphs 24 & 25) and the conclusion of the outcome of the first Global Stocktake at COP28 in 2023 (Decision 1/CMA.5, paragraphs 20, 40, and 42). Unlike NDCs, LT-LEDS are not mandatory[15], and there

[14] CMA referring to decisions from Parties to the Paris Agreement, the 'Conference of the Parties serving as the meeting of the Parties to the Paris Agreement', CP referring to decisions that apply to Parties to the UNFCCC.

[15] This is based on the qualified language used within the Paris Agreement and throughout the UNFCCC. Article 4.19 of the Paris Agreement details that parties '*should strive* to formulate and communicate' [*emphasis* added] LT-LEDS, as opposed to Article 4.2, which reads 'Each Party *shall* prepare, communicate and maintain successive' [*emphasis* added] NDCs. 'Shall' is seen as stronger language that 'should strive'. Similarly, whilst the content of NDCs are guided by COP decisions, such as Decision 4/CMA.1, Annex I, no COP decisions guide the content of LT-LEDS.

is no specific guidance from the UNFCCC on how they should be structured and what they should entail. COP22 in 2016, however, announced the 2050 Pathways Platform, an initiative intended to support the development of LT-LEDS, under which informal guidance is produced (UNFCCC, 2016a). Despite a lack of formal guidance, LT-LEDS are formally part of the input that informs the Global Stocktake within the Paris Agreement, the periodic process through which the collective progress of parties is assessed[16]. LT-LEDS, therefore, will likely continue to play a formative role within the UNFCCC, as parties update their NDCs ahead of February 2025 or prior to COP30[17].

According to the range of informal guidance produced, LT-LEDS serve national governments by identifying mitigation options with large potentials, or areas of the economy that are hard-to-abate, serving to sequence and prioritise mitigation over time (van Tilburg, Ochs and Lee, 2024). This may reduce the risk of stranded assets or the risk of locking-in high-emitting infrastructure, sending signals to the private sector to dissuade and redirect investment (Rocha and Falduto, 2019; Hans *et al.*, 2020; van Tilburg, Ochs and Lee, 2024). The quantification of mitigation options and resources further allows for the communication of what mitigation may be conditional on the receipt of climate finance, particularly for developing parties (Rocha and Falduto, 2019; Hans *et al.*, 2020; GGGI, 2022). It may also assist in integrating both mitigation and adaptation with national priorities (GGGI, 2022; van Tilburg, Ochs and Lee, 2024). Within the global climate regime, the communication of LT-LEDS can strengthen ambitions, as trust between states is enhanced and the credibility of international commitments improved (Rocha and Falduto, 2019; GGGI, 2022). Iterations of LT-LEDS can also be aligned with the update of NDCs so that resources can be pooled, coordinating modelling, stakeholder consultation and political approval (Hans *et al.*, 2020; Català *et al.*, 2024; Elliott, Fransen and Srouji, 2024).

Many benefits of LT-LEDS remain largely theoretical, given that the evaluation of, for example, the alignment of LT-LEDS with NDCs, was temporally constrained when NDCs were last updated in 2020, but may be more apparent as NDCs are now updated ahead of February 2025, given the greater number of LT-LEDS now published.

[16] Specifically through Decision 19/CMA.1, which sets out the modalities for undertaking the Global Stocktake. Paragraph 36 (a) of Decision 19/CMA.1 states that ‘The state of greenhouse gas emissions by sources and removals by sinks and mitigation efforts undertaken by Parties, including the information referred to in Article 13, paragraph 7(a), and Article 4, paragraphs 7, 15 and 19, of the Paris Agreement’.
[17] The February 2025 deadline is seen as an interpretation of Decision 1/CP.21 paragraph 25, which states that ‘… Parties shall submit to the secretariat their nationally determined contributions referred to in Article 4 of the Agreement at least 9 to 12 months in advance of the relevant session of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement…’. It is likely many parties may choose to ignore or miss this deadline.

1.6 Past research on LT-LEDS

Climate policy research has, to date, principally focused on NDCs, given their prominence within the Paris Agreement (den Elzen *et al.*, 2022; Meinshausen *et al.*, 2022). LT-LEDS, however, have recently gained momentum in climate policy research, given a more recent focus on implementation as opposed to agenda setting (Green and Reyes, 2023). This research suggests LT-LEDS are of value in three connected areas;

1. Their use to inform assessments of likely temperature outcomes based on the ambitions of national governments,

2. Their use to assess the plans of national governments towards certain low-carbon technologies or sectors,

3. Their use as a means to study the processes of national climate governance, specifically anticipatory governance, the future-oriented governance of climate change in the present (Muiderman *et al.*, 2020).

Meinshausen *et al.*, 2022 was amongst the first articles to integrate LT-LEDS into their assessment of the likely temperature outcomes of pledges made under the Paris Agreement. Meinshausen *et al.*, 2022 found that, with the inclusion of the long-term targets in LT-LEDS, for the first time, peak warming could be limited to 1.9–2.0 °C above the preindustrial [1.4-2.8 °C, 90% CI], if all NDCs and long-term targets are fully implemented. Rogelj *et al.*, 2023, evaluated cases where national net zero targets were supported by the publication of a LT-LEDS as part of an assessment towards their credibility. Assessing 35 major emitters, they assess that, if all NDCs and long-term targets are fully implemented, peak warming could be limited to 1.7°C [1.6 to 2.1°C]. Discounting those targets deemed not credible, however, raises peak warming to 2.4 °C [1.7 to 3.0°C].

Cruanyes, Alcaraz and Sureda (2024) use LT-LEDS to evaluate the remaining carbon budget for 1.5°C, the cumulative amount of allowable CO_2 emissions consistent with a 1.5°C temperature target: 400 $GtCO_2$ from 2020 onwards (67% likelihood) (Dickau, Matthews and Tokarska, 2022; Canadell *et al.*, 2023). They estimate, based on the timing of long-term targets within LT-LEDS, an exceedance of the 1.5°C carbon budget (67% likelihood) by 31 $GtCO_2$, though the large uncertainties entailed with the remaining carbon budget preclude a definitive assessment[18]. Notably, whilst these articles

[18] It should be noted that Cruanyes, Alcaraz and Sureda, 2024, does not differentiate between net zero CO_2, or carbon neutrality, and net zero GHGs, meaning their assessment of the remaining carbon budget is likely an overestimate given net zero CO_2 would be reached prior to net zero GHGs. Multiple uncertainties apply to the remaining carbon budget, notably, in relation to emissions, the mitigation of non-CO_2 emissions may cause the remaining carbon budget to vary by ±220 $GtCO_2$. Other uncertainties apply, as detailed in Table 5.8, Chapter 5, IPCC AR6 WGI report (Canadell *et al.*, 2023).

demonstrate the relevance of LT-LEDS to tracking climate commitments, none of these studies meaningfully engage with the content of LT-LEDS, nor the scenarios and pathways they contain, rather only the nature and timing of the long-term targets they communicate.

Beyond temperature outcomes, climate policy research has begun to focus on the contents of LT-LEDS. Jones *et al.* (2023) uses LT-LEDS to explore national government efforts to phase out fossil fuels across their economies. Alcalde, Johnson and Roberts, 2025 similarly use LT-LEDS to explore plans for geological storage in national climate policy. Several studies now examine the contents of LT-LEDS with respect to CDR. This range of studies is likely owing to the fact that LT-LEDS more readily feature CDR, given their emphasis on the mid-century and the more prominent role of CDR in compensating for residual hard-to-abate emissions at the point of net zero. Thoni *et al.*, 2020, were among the first to examine the contents of LT-LEDS regarding CDR, analysing 17 LT-LEDS submitted prior to September 2020, concluding that feasibility is primarily assessed, if at all, relative to biophysical and technical dimensions as opposed to the socio-cultural. Buylova *et al.*, 2021, reviewed 25 LTS submitted prior to the end of 2020, examining more generally the types of CDR, the barriers and opportunities to CDR deployment, and the possibility of international cooperation.

Jacobs, Gupta and Möller, 2023, reviewed 29 LT-LEDS submitted to the UNFCCC prior to March 2021, identifying a '*spiral of delay*', a dynamic by which the burden of mitigation is shifted away from near-term emission reductions, towards a set of CDR methods. When the trade-offs associated with these CDR methods become clearer, the burden of mitigation is further shifted to a more promissory CDR method with greater uncertainties. All three of these studies examine LT-LEDS and CDR as a means of studying different elements of their governance, whether feasibility, barriers and opportunities, or potential mitigation deterrence. All, however, introduce inconsistencies with how CDR is categorised, what methods are included, and what LTS are to be covered. Furthermore, none of these articles are clear regarding their documentation.

A final use in climate policy research is the use of LT-LEDS to examine the processes of national climate governance. Lecocq, Nadaï and Cassen, 2022, examine the '*modelling assemblages*' of the second French national low-carbon strategy in depth, alongside the US Mid-Century Strategy and the Swedish Zero Net Emission Strategy, all of which have been submitted to the UNFCCC as a LT-LEDS. '*Modelling assemblages*', in this case, refers to the use of multiple models informed by multiple stakeholders, ranging in technical expertise and degree of engagement. They argue the process of developing these strategies produces both '*numbers*' and '*shared visions*' of the future, attracting greater political support. The process may therefore lead to '*technical and institutional innovation*(s)', such as the introduction of new modelling tools to support national climate policy, or the creation of new working groups within or between government departments.

Buylova *et al.*, 2024 expands this effort by using topic modelling to quantitatively examine the contents of 50 LT-LEDS, finding that the majority analysed include language common to modelling and scenarios, and a lack of political language, indicating limited attention towards the political challenges posed by their implementation. Complimenting topic modelling with 11 interviews of experts involved in LT-LEDS development, Buylova *et al.*, 2024 further finds that interviewees contested the degree to which strategies could be practically implemented and whether they serve to politically provide '*nice sound bites*', given many strategies are aided by '*foreign consultancies*' that '*produce unrealistic models and projections*'.

Lecocq, Nadaï and Cassen, 2022 therefore emphasise that LT-LEDS are large undertakings for national governments, drawing on a wide range of models and stakeholders, providing opportunities for new institutional collaborations. Buylova *et al.*, 2024, by contrast, underline that LT-LEDS can be politically superficial and lacking in implementation. Such divergences are not surprising when considering the range of parties that have developed a LT-LEDS, and the varying levels of support and capacity these parties receive. Nevertheless, this research emphasises that, in contrast to the method employed in Rogelj et al., 2023, the publication of a LT-LEDS alone is not necessarily an indicator of the credibility of national climate action, and that due attention needs to be paid to the contents of LT-LEDS and the means through which they are developed.

1.7 Aims and sub-aims

This thesis serves to address what is a key knowledge gap in climate policy research, the planning of national entities towards developing and incentivising CDR (Schenuit et al., 2021). The primary aim of this thesis is to evaluate how countries are integrating CDR into national plans and policy to reach national net zero targets. To achieve this aim, three sub-aims were developed:

1. Establish the inclusion of CDR methods in national net zero plans, including the methods to be deployed and their extent relative to residual emissions.
2. Establish the nature of residual emissions in national net zero plans, and their justifications for compensation by negative emissions from CDR.
3. Evaluate how these national net zero plans translate into CDR policy, evaluating the policy plans of an advanced national case.

How each chapter addresses each sub-aim is detailed in Table 1.

Table 1. Chapters of this thesis according to their main data sources and the relevant thesis sub-aims.

Chapter	Main data source	Relevant thesis sub-aims
2	Document analysis: LTS (n= 41, published prior to 1st January 2022)	1 & 2
3	Document analysis: LTS (n= 71, published prior to 1st October 2023)	1
4	Document analysis: LTS (Add n=91, published prior to 22nd November 2024)	1 & 2
5	Primary data collection: Interviews (n=25, held between April and October 2024)	3

The research presented in this thesis has been published in peer-reviewed journals. The following chapters corresponds to the following publications;

- **Chapter 2** - Smith, H.B., Vaughan, N.E., and Forster, J. (2025), A dataset of emissions and removals from scenarios and pathways within long-term national climate strategies, *Scientific Data* 12, 485. https://doi.org/10.1038/s41597-025-04804-4
  Submitted 29th April 2024, Accepted 12th March 2025, Published 23rd March 2025.
- **Chapter 3** - Smith, H.B., Vaughan, N.E. & Forster, J. (2022) Long-term national climate strategies bet on forests and soils to reach net-zero. *Communications Earth & Environment* 3, 305. https://doi.org/10.1038/s43247-022-00636-x
  Submitted 11th July 2022, Accepted 17th November 2022, Published 7th December 2022.
- **Chapter 4** - Smith, H.B., Vaughan, N.E. & Forster, J. (2024) Residual emissions in long-term national climate strategies show limited climate ambition. *One Earth* 7, 5 P867-884. https://doi.org/10.1016/j.oneear.2024.04.009
  Submitted 18th December 2023, Accepted 18th April 2024, Published 9th May 2024.
- **Chapter 5** - Smith, H.B., Vaughan, N.E., and Forster, J. [Under review] (2025), Slow but Sure: Expert Perspectives on Carbon Dioxide Removal Policy in the United Kingdom, *Energy Research & Social Science.*
  Submitted 18th March 2025.

Other published work undertaken during this doctorate not directly included in this thesis include:

- Lamb, W.F., Gasser, T., Roman-Cuesta, R.M. et al. The carbon dioxide removal gap. *Nature Climate Change*. 14, 644–651 (2024). https://doi.org/10.1038/s41558-024-01984-6.

Contribution: I led the development of the LTS dataset, upon which part of the gap is assessed. Reviewed and commented on the manuscript.

- Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024). Contribution: I supported Chapter 9, The CDR Gap, as a chapter author. I also reviewed Chapter 5, Policymaking and governance, and Chapter 3, Demonstration and upscaling.
- Kinniburgh, F, Smith, H, Carton, W, et al. [Under review] (2025), Unpacking residual emissions in agriculture, *Nature Food*. Contribution: I led the production of the analysis, produced all four figures and led the results and methods sections. Submitted 25th February 2025

1.8 Thesis structure

Beyond this initial introductory chapter, this thesis is structured according to four main chapters, followed by a discussion and conclusion. The four main chapters that follow were authored at different times and are presented in a logical but not chronological order.

A challenge in climate policy research is its pace, particularly given this research, when focused on tracking and evaluating reporting by parties, is dynamic to climate negotiations and elections (see, for example,

Figure 5B, which details that many LT-LEDS are submitted in and around annual COPs). These cycles overlap with the duration of this thesis, meaning the total submissions of LT-LEDS have similarly changed across the same period, with many parties now revising their strategies. This thesis is therefore split into chapters which were published across the period the thesis was written, based on the number of LT-LEDS then available.

Figure 5 provides an overview of the LTS[19] submitted since the first LT-LEDS in 2016, marked with the cut-off and publication dates for the publications from each chapter. Key dates such as the start of this PhD project are also marked.

[19] As noted in Section 1.4, the EU has a similar reporting obligation to LT-LEDS, namely Article 15 of the Governance Regulation, which Member States to prepare and submit long-term strategies (EU LTS) analogous to LT-LEDS. These EU LTS are therefore combined with LT-LEDS for those EU Member States without a LT-LEDS, creating a combined dataset. I therefore describe the dataset as consisting of long-term national climate strategies, abbreviated to LTS throughout. Where it is necessary to distinguish between LT-LEDS and EU LTS, either term is used directly.

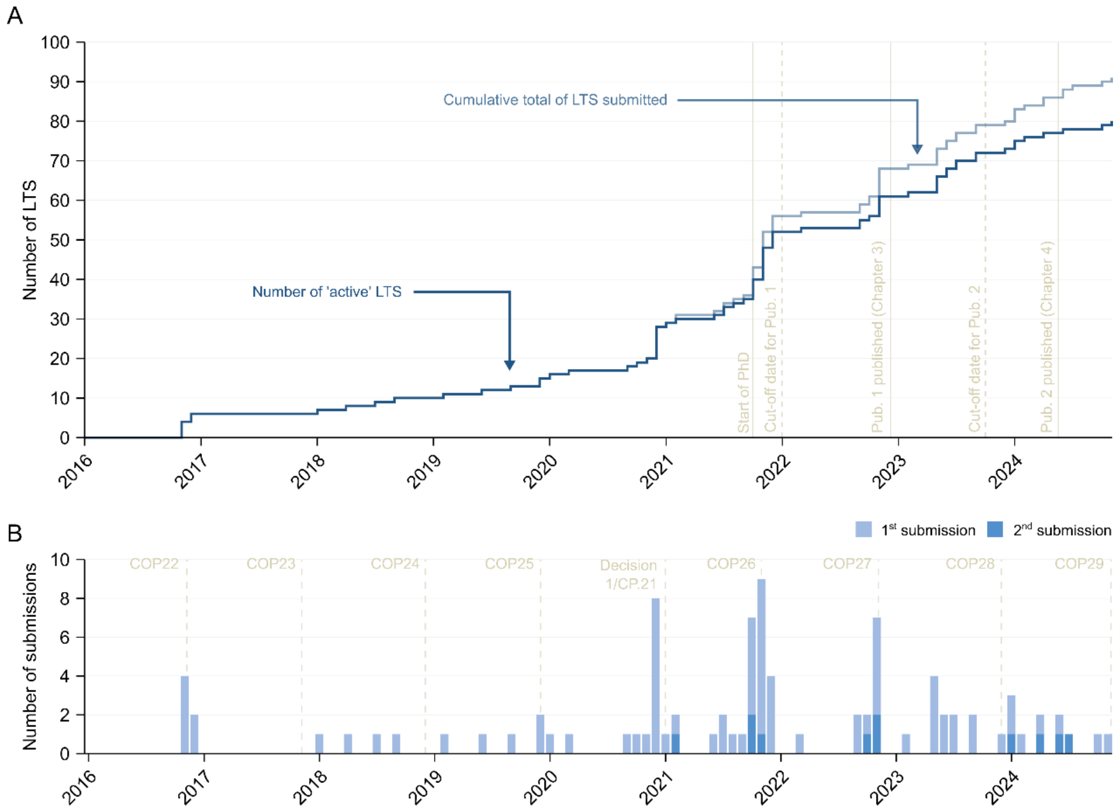

Figure 5. The number of LTS or LTS submissions over time.

Panel A details the number of active LTS over time, split by submission. Active refers to those LTS that have not been superseded by another LTS, such as a new submission from a country, retiring the previous strategy. Active therefore tracks the number of LTS that currently apply, as opposed to the total number of LTS submitted, which would include those superseded. Vertical lines denote cut-off and publication dates for publications affiliated with this thesis, alongside the chapters on which they are based. Panel B shows the number of submissions overtime. COPs are shown as vertical dashed lines. The month during which the meeting opened is shown. Some meetings span multiple months. Bars in Panel B are split by submission, split by 1st (lighter) and 2nd submission (darker). Decision 1/CP.21 refers to the 2020 deadline communicated in paragraph 35 of the decision. See Section 1.5 for further detail on paragraph 35, and its relevance in climate negotiations.

Chapter 2 presents the long-term strategies pathway and scenarios dataset (LTS-SP), a dataset covering emissions and removals from sectors and CDR methods found across the sample of LTS analysed within this thesis. This was written in response to interest in the publications from the works in this thesis, and the desire of others within the field to reuse the data within their own analyses. As a result, I and the supervisory team chose to detail the method used in prior publications as a full chapter, to allow for its reuse. The chapter was published as a '*data descriptor*' to the journal Scientific Data, a format aimed at helping others reuse data, rather than presenting new analysis. Details on the LTS covered can be found in the accompanying dataset to the chapter, accessible on Zenodo at 10.5281/zenodo.14943904 (ref. Smith, Vaughan and Forster, 2025).

Chapter 3 presents an analysis of CDR in LTS, assessing the inclusion or reference to CDR methods in scenarios or pathways, or in text. It similarly assesses the main concerns of states towards CDR using deductive and inductive coding. As the first work to be published (see

Figure 5A), this chapter features a smaller sample of LTS, reflecting the LTS then available. The countries assessed in this chapter can be seen in Figure 14.

Chapter 4 presents an analysis of residual emissions in LTS, quantifying the extent of residual emissions relative to peak emissions, their sectoral split, and their justifications where present. It provides one of the most detailed assessments of the concept to date. Similar to Chapter 3, the chapter is based on the sample of LTS then available. The countries assessed, alongside the LTS analysed, can be found in the accompanying dataset to the chapter, under the DOI 10.5281/zenodo.10972619 (ref. Smith, 2024).

Chapter 5 deviates from the focus on LTS by introducing a detailed national case study of the UK, based on interviews with policy experts and commercial actors. The chapter addresses a key need in climate policy research, that of detailed national case studies into CDR policymaking (Schenuit *et al.*, 2021).

Chapter 6 revisits the aims and sub-aims of this thesis, considering the main chapters, detailing the contribution of this thesis, and setting out a future research agenda.

2 A dataset of emissions and removals from scenarios and pathways within long-term national climate strategies – the LTS-SP dataset

This chapter was published as '*A dataset of emissions and removals from scenarios and pathways within long-term national climate strategies – the LTS-SP dataset*' in the journal Scientific Data in March 2025, accessible at: https://doi.org/10.1038/s41597-025-04804-4. Minor textual changes have been made to align with the format of this thesis.

2.1 Abstract

LT-LEDS, supported by Article 4, paragraph 19, of the Paris Agreement, present scenarios and pathways aligned with national long-term climate targets. There is a growing interest in understanding whether the collective effort of national climate plans align with the goals of the Paris Agreement, alongside the feasibility, sectoral focus, and the balance of emissions and removals seen in national scenarios. Here we introduce the long-term strategy scenarios and pathways (LTS-SP) dataset, a dataset presenting scenarios and pathways detailed within LT-LEDS or similar long-term strategies. We detail the level of total and sectoral GHG emissions in 2050, or the year in which net zero is achieved, alongside the emissions and removals within land-use, land-use change, and forestry (LULUCF) and removals from engineered CDR methods. We provide a comprehensive overview of our procedure and compare our dataset with current published estimates. We end by summarising several caveats to our dataset, detailing the limitations of LT-LEDS, and their use in climate policy research.

2.2 Background & Summary

Current national climate policies to address GHG emissions are insufficient to reach the goal of the Paris Agreement, to limit global average temperatures to well below 2°C above pre-industrial levels, pursuing efforts to limit the increase to 1.5°C (Climate Action Tracker, 2024). Despite the '*ambition gap*' that remains, the ratification of the Paris Agreement has led to a groundswell of national net zero targets (Green, Hale and Arceo, 2024), near-term climate pledges (UNFCCC Secretariat, 2024), and multilateral initiatives, aiming to further spur climate action (Forner and Julien Díaz, 2023). At the end of 2024, 147 countries have adopted a form of net zero or neutrality target (Net Zero Tracker, 2024b), 168 NDCs have been submitted (UNFCCC Secretariat, 2024), and international climate initiatives total over 500 (Forner and Waskow, 2023).

Climate change, however, is a '*long problem*', requiring, in turn, long-term policy-planning, coordinating policies across multiple sectors of an economy towards a long-term goal (Finnegan, 2022; Hale, 2024). Given the gradual diffusion of technologies and policies, this is an effort that must be sustained for multiple decades, suggesting a decisive role for national governments in climate action (Malhotra and Schmidt, 2020; Stern *et al.*, 2022). For national governments, long-term planning can involve creating strategies to guide policy and investment, setting out a strategic direction and anticipating future needs (Hale, 2024). Article 4, paragraph 19, of the Paris Agreement supports these efforts by inviting parties to '*strive to formulate and communicate long-term low emission development strategies*', strategies that integrate climate mitigation, climate adaptation, and economic development, through a long-term planning process, extending to the mid-century or beyond (Rocha and Falduto, 2019; Cruanyes, Alcaraz and Sureda, 2024). Concurrent with the rise of national net zero targets, therefore, has been a rise in the submission of LT-LEDS and similar long-term national climate strategies (LTS).

The concept of LTS in climate negotiations precedes the Paris Agreement, and dates to COP15, held in Copenhagen in 2009. The Copenhagen Accord, agreed at COP15, recognised '*that a low-emission development strategy is indispensable to sustainable development*' (Decision 2/CP.15, paragraph 2) but provided no definition as to what these strategies should entail, nor any explicit calls for their development. The Cancun Agreements, reached the following year at COP16, improved upon COP15, by further deciding '*that developed countries should develop low-carbon development strategies or plans*' (Decision 1/CP.16, paragraph 45) and encouraging *'developing countries to develop low-carbon development strategies or plans in the context of sustainable development*' (Decision 1/CP.16, paragraph 65).

The 2015 Paris Agreement, adopted at COP21, formalised these efforts as LT-LEDS, inviting these strategies to be communicated by 2020, with a focus on the mid-century, 2050 (Decision 1/CP.21, paragraph 35). LT-LEDS have routinely featured in the COP decisions that followed. The Katowice Climate Package agreed at COP24, in 2018, reiterated the 2020 deadline (Decision 1/CP.24, paragraph 21). The Glasgow Climate Pact, agreed at COP26 in 2021, urged countries yet to submit their LT-LEDS to do so before the next COP, and called for submitted LT-LEDS to be updated according to the best available science (Decision 1/CMA.3, paragraphs 34 & 35). This same request was made in the Sharm el-Sheikh Implementation Plan, agreed at COP27 (Decision 1/CMA.4, paragraphs 24 & 25), and the conclusion of the outcome of the first Global Stocktake at COP28 in 2023 (Decision 1/CMA.5, paragraphs 20, 40, and 42).

Unlike NDCs, LT-LEDS are not mandatory, and there is no specific guidance from the UNFCCC on how they should be structured and what they should entail. COP22 in 2016, however, announced the 2050 Pathways Platform, an initiative intended to support the development of LT-LEDS, under which informal guidance is produced (UNFCCC, 2016a). Despite a lack of formal guidance, LT-LEDS are formally part of the input that informs the Global Stocktake within the Paris Agreement, the process carried out every five years through which the collective progress of parties to the agreement is assessed (Decision 19/CMA.1, paragraph 36[a]). LT-LEDS, therefore, will likely continue to play a formative role within the UNFCCC, as parties update their NDCs for 2035, during 2025 (Decision 1/CP.21, paragraph 25).

Climate policy research has to date principally focused on NDCs, given their prominence within the Paris Agreement and the need to align climate ambitions with the 2030 benchmarks mainstreamed in IPCC Assessment Reports (Den Elzen *et al.*, 2022; Meinshausen *et al.*, 2022). LT-LEDS, however, have recently gained momentum in climate policy research. LT-LEDS have been used to; refine the projected global temperature outcomes of national pledges and targets (Meinshausen *et al.*, 2022), explore the credibility of national net zero targets (Rogelj *et al.*, 2023), and examine the remaining carbon budget (Cruanyes, Alcaraz and Sureda, 2024), demonstrating their relevance to assessing the ambition of climate policy. LT-LEDS have similarly proved valuable in assessing the plans of national governments towards certain climate technologies or sectors. LT-LEDS have been used to explore the degree to which domestic climate policy directly targets fossil fuel production (Jones *et al.*, 2021; N. Jones *et al.*, 2023) and to examine the role of geological storage (Alcalde, Johnson and Roberts, 2025). Multiple articles examine the role of CDR, largely owing to the more prominent role of CDR in compensating for residual hard-to-abate emissions at the point of net zero, coinciding with the focus of LT-LEDS on the mid-century (Buylova *et al.*, 2021; Babiker *et al.*, 2022; Buck *et al.*, 2023; Jacobs, Gupta and Möller, 2023).

Scenario or pathway data from LT-LEDS has been included in several prominent global assessments, including the 2023 United Nations Environment Programme (UNEP) Emissions Gap Report (United Nations Environment Programme, 2023), the 1st and 2nd edition of the State of Carbon Dioxide Removal Report (Smith *et al.*, 2023; W F Lamb *et al.*, 2024), and the UNFCCC LT-LEDS Synthesis Report (UNFCCC Secretariat, 2022, 2023), in addition to estimates across academic and grey literature (Buck *et al.*, 2023; Mooldijk *et al.*, 2023). This presents a need for a standard dataset supported by a common methodology. This dataset should be detailed in its coverage, methodology, and limitations, to aid reproducibility and serve as a resource for climate policy research.

This data descriptor serves as an initial effort, documenting in detail the methodology for producing a consistent dataset of GHG emissions and removals from scenarios and pathways contained within long-term strategies (LTS) – the long-term strategy scenarios and pathways (LTS-SP) dataset. The dataset assesses scenarios and pathways against long-term targets detailed within LTS, and details emissions and removals in 2050, and the date of net zero GHGs, using a consistent definition of sectors and categorisation of CDR methods. It concludes by validating the dataset against estimates in academic and grey literature.

2.3 Methods

The method has been developed to be reflexive to the detail presented across available LTS, based on our own previous analysis (Smith, Vaughan and Forster, 2022 [Chapter 3], 2024 [Chapter 4]). We first describe the source and nature of the strategies then we detail our procedure for analysing elements contained therein. We combine two sources of long-term strategies, LT-LEDS submitted to the UNFCCC Secretariat, and EU long-term strategies (EU LTS), submitted to the European Commission. The dataset will be updated periodically at the repository listed in '*Data Records*', as LT-LEDS or EU LTS are revised or newly published. At the time of writing, January 2025, we note several LT-LEDS in development, including strategies for Jamaica, Jordan, Kenya, Mozambique, and Pakistan (Carbon Counts, 2020; NDC Partnership, 2023c, 2023a, 2023b; United Nations Development Programme, 2023).

2.3.1 Long-term national climate strategies

The LTS-SP dataset contains 91 long-term national strategies in total, of which 11 have been superseded by revised submissions, leaving 80 '*active*' LTS. Of the 80, 74 are LT-LEDS submitted to the UNFCCC Secretariat and six are EU LTS submitted to the European Commission.

We analysed all 85 strategies made available by the Secretariat on the UNFCCC's long-term strategies portal, published prior to or during COP29, held in November 2024 (ref. UNFCCC Secretariat, 2025). The long-term strategies portal details all current submissions by parties available in a UN language

(Arabic, Chinese, English, French, Russian and Spanish), alongside previous submissions for countries that have since revised or updated their submission. Official and unofficial translations are also made available. Notably, LT-LEDS are far fewer than NDCs, with the latter submitted by all 195 parties (UNFCCC Secretariat, 2024).

LT-LEDS nevertheless cover a critical mass, with long-term strategies covering 74% of 2023 GHG emissions (including land-use) (Jones *et al.*, 2024) and 85% of global gross domestic product (GDP) (World Bank, 2024a). The 2023 LT-LEDS Synthesis Report estimates a similar coverage, assessing that LT-LEDS communicated by parties prior to 25th September 2023, cover 76% of total global greenhouse gas emissions in 2019 (excluding land-use), 87% of global GDP, and 68% of the global population (UNFCCC Secretariat, 2023).

There is substantial overlap between LT-LEDS and the EU LTS developed by EU Member States. 17 of the LT-LEDS submitted by EU Member States have dual status, serving also as the Member State's EU LTS. Given the dual role of these LT-LEDS, and their common purpose, it is reasonable to consider those Member State strategies that have not been submitted to the UNFCCC, but have been submitted to the European Commission, as equivalent to LT-LEDS.

EU LTS for Member States are made publicly available on the European Commission's portal for national long-term strategies (European Commission, 2024). Article 15 of the Regulation on the Governance of the Energy Union and Climate Action (EU/2018/1999) sets out a process for the Member States to prepare these strategies in a manner aligned with their commitments under the UNFCCC and the Paris Agreement. Both reporting exercises therefore share a common purpose. We include the EU LTS for six Member States within our dataset, leading to a total of 80 active strategies (excluding the strategy for the EU as a single entity). We further cross-check strategies for all Member States between the European Commission's portal for national long-term strategies and the UNFCCC's long-term strategies portal. In cases where differing strategies can be found on both portals, we prioritise the version found on the UNFCCC's portal. We exclude the LT-LEDS for the EU, on the basis that it is supranational in scope. For all strategies, we prioritise English translations if available for non-English strategies and machine translate remaining strategies using translation software. To indicate that our dataset contains strategies from multiple sources, we use the term long-term national climate strategies, abbreviated to LTS, throughout. We revert to using either LT-LEDS or EU LTS if referring to their reporting, or in reference to a specific national strategy.

Submissions to either portal were made around key dates, such as COPs or deadlines in legislation or COP decisions. The vast majority, 58 of the 80 active strategies, were recently published between 2021-2024. Geographically, the majority of the active strategies have been submitted by countries in Europe

(36) and Asia (17), with only nine from African states and four from South America. The 11 countries that have revised and updated their strategies tend to similarly be from Europe (4) and Asia (3). Nearly all active strategies (65) are published in English or otherwise have English translations readily available.

Once collated, we analyse each strategy according to two main elements, long-term targets, and scenarios or pathways. Of the 80 active strategies currently analysed, 73 contain a long-term target (Figure 6A). Of those 73 strategies, 59 detail at least one scenario or pathway extending beyond their NDC. Strategies often contain multiple scenario or pathways, meaning, for the 80 active strategies, the LTS-SP dataset details 153 scenarios or pathways from 59 countries (Figure 6C).

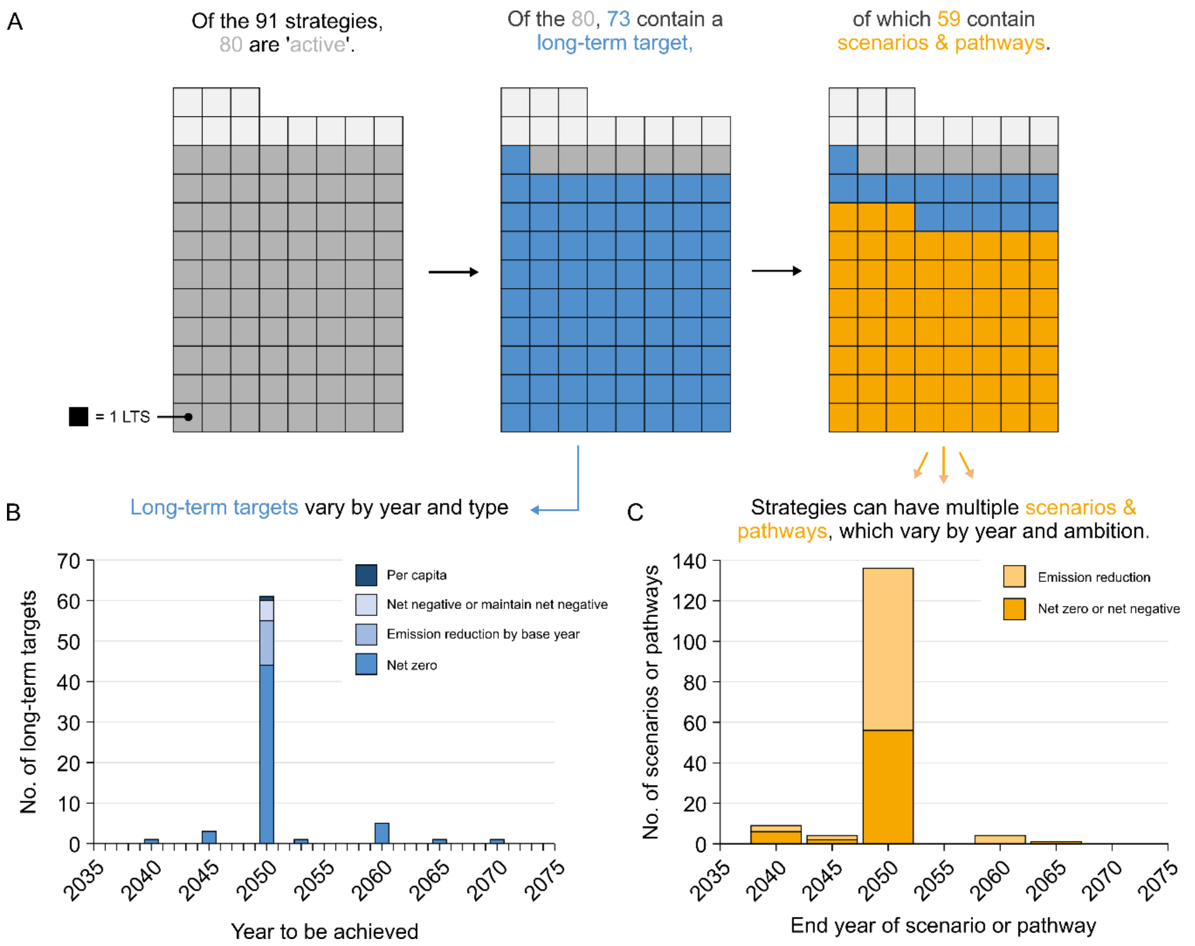

Figure 6. Explanatory figure detailing the contents of the LTS-SP dataset.

A) Plot series depicting the number of strategies that contain a long-term target (blue), or scenarios and pathways (yellow). Each block represents a long-term national climate strategy covered by the dataset (grey). B) Bar chart of long-term targets, by year to be achieved, for example, net zero GHGs by 2050. C) Bar chart detailing the number of scenarios or pathways, shown by end year. End year refers to the last available year within the strategy for which data is available.

2.3.2 Long-term targets

Long-term targets are those targets that extend beyond the time horizon communicated in NDCs, such as net zero targets in and around the mid-century. These targets are communicated within LT-LEDS but are often ambiguous in their design as to their precise coverage of sectors and GHGs. This is a widely recognised problem that adds undue uncertainty to the assessment of national pledges and targets (Jeudy-Hugo, Lo Re and Fadulto, 2021; Rogelj *et al.*, 2021; den Elzen *et al.*, 2025). Beyond metadata, such as the publication date of the strategy (see '*Metadata*' in Table 3, Data Records), long-term targets are the initial element extracted from LTS. We identify several elements that impact upon the definition of a long-term target, and therefore scenarios and pathways that meet these targets.

We differentiate between the '*headline target*', describing the target as it is written and referred to within the country's strategy, and a '*long-term target*', which we define as the headline target amended for its gas coverage. For example, a headline target of '*carbon neutrality*' that covers the main greenhouse gases (carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]), is best described as a long-term target of '*net zero GHGs*', as '*carbon neutrality*' implies the consideration of only CO_2 (Rogelj *et al.*, 2015). We identify the headline target within the strategy, alongside any description clearly stated. We then confirm the timing of the target, the gas and sector coverage, alongside any inclusion of emissions from international aviation and shipping (IAS) (IPCC, 2006a), either via the description stated or by a series of ordered indicative elements detailed in Figure 7. We define these terms in Table 2. Collating and understanding long-term targets are necessary for two related reasons, firstly to clarify the headline target, which may be miscommunicated if interpreted as written, and to prioritise scenarios and pathways that can be demonstrated to comply with the target.

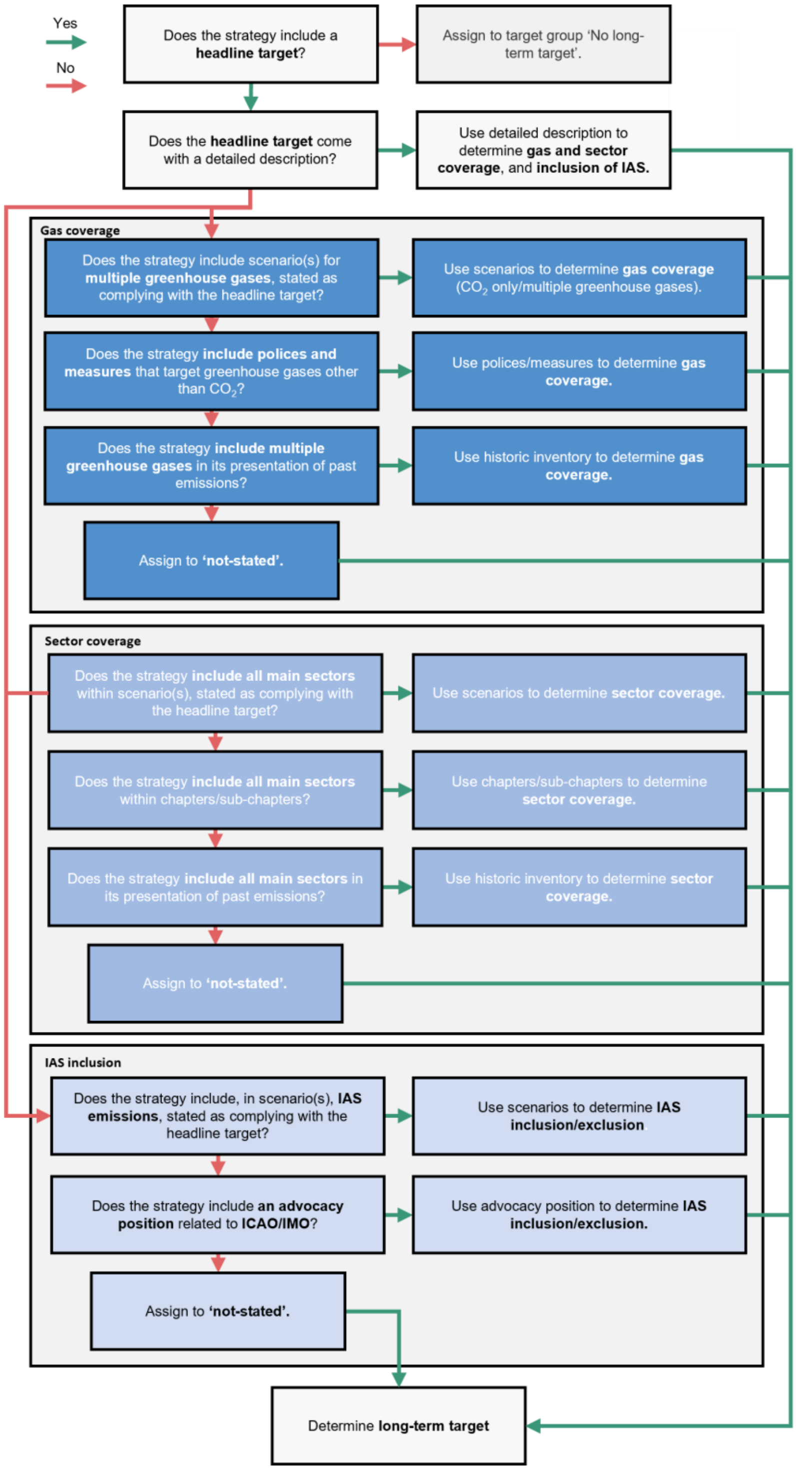

Figure 7. Analytical procedure for long-term targets.

Shown as a decision chart. IAS refers to international aviation and shipping. ICAO and IMO refer to the International Civil Aviation Organization and the International Maritime Organization respectively. If a target definition includes only one or two elements, for example, the gas coverage and the inclusion or exclusion of IAS, the outstanding element is determined by the relevant section of the decision chart, in this example, the sector coverage.

Table 2. Definitions of terms relevant to long-term targets.

Term	Definition
Headline target	The country's long-term target as it is written and referred to within the country's strategy.
Long-term target	The headline target amended for its *gas coverage*.
Gas coverage	The GHGs covered by the long-term target. For example, the target may include only carbon dioxide (CO_2) or include, in addition, the other two main greenhouse gases, methane (CH_4) and nitrous oxide (N_2O). Similarly, it may cover the '*Kyoto basket*' of gases covered by Annex A of the 1997 Kyoto Protocol, including the three main greenhouse gases, plus hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). It may also include, in addition, nitrogen trifluoride (NF_3), which was added in the 2012 Doha Amendment to the Kyoto Protocol. These seven gases continue to be reported under the Paris Agreement, see Decision 18/CMA.1, Annex, paragraph 48. We differentiate between the consideration of CO_2 only (for example, net zero CO_2), or the consideration of multiple greenhouse gases, implying coverage of at least CO_2, CH_4 and N_2O (for example, net zero GHGs).
Sector coverage	The sectors covered by the long-term target. Sector coverage refers to the inclusion or exclusion of all main sectors, including Energy, Transport [independently or as a subsector of Energy], Industry, Agriculture, Waste, and LULUCF, based upon the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (hereafter the 2006 IPCC Guidelines). This includes subsectors, sources, or combinations thereof, for example Agriculture, Forestry, and Other Land Uses (AFOLU).
IAS inclusion	The inclusion or exclusion of emissions attributable to the country from IAS. Domestic aviation and shipping, emissions from passenger or freight traffic that departs and arrives in the same country, is typically included in national greenhouse gas inventories and therefore long-term targets set, unless otherwise stated (IPCC, 2006c). IAS is typically estimated based on fuel sold, or based on '*bunker fuels*', but is excluded from national totals and reported separately within national greenhouse gas inventories, and therefore commonly excluded from long-term targets (IPCC, 2006c).

In Figure 7, the indicative elements are ordered in terms of priority. For example, a LTS may include a detailed definition of its headline target, following best practice (Cruanyes, Alcaraz and Sureda, 2024). If this definition provides the necessary detail to determine the coverage of the target, this is used. For example, the LT-LEDS for the United States, '*The Long-Term Strategy of the United States*', includes a detailed target description, specifying both the gas and sector coverage, as well as the exclusion of IAS and the current exclusion of the use of international offsets (see Figure 8A). Strategies, however, may not provide this necessary detail, for example Australia's LT-LEDS, simply describes its headline target as '*net zero by 2050*', without reference to coverage or inclusion (see Figure 8B). In these cases, it is necessary to discern coverage by other indicative elements (see Figure 7). Multiple indicative elements may be used to determine coverage for strategies that are unclear.

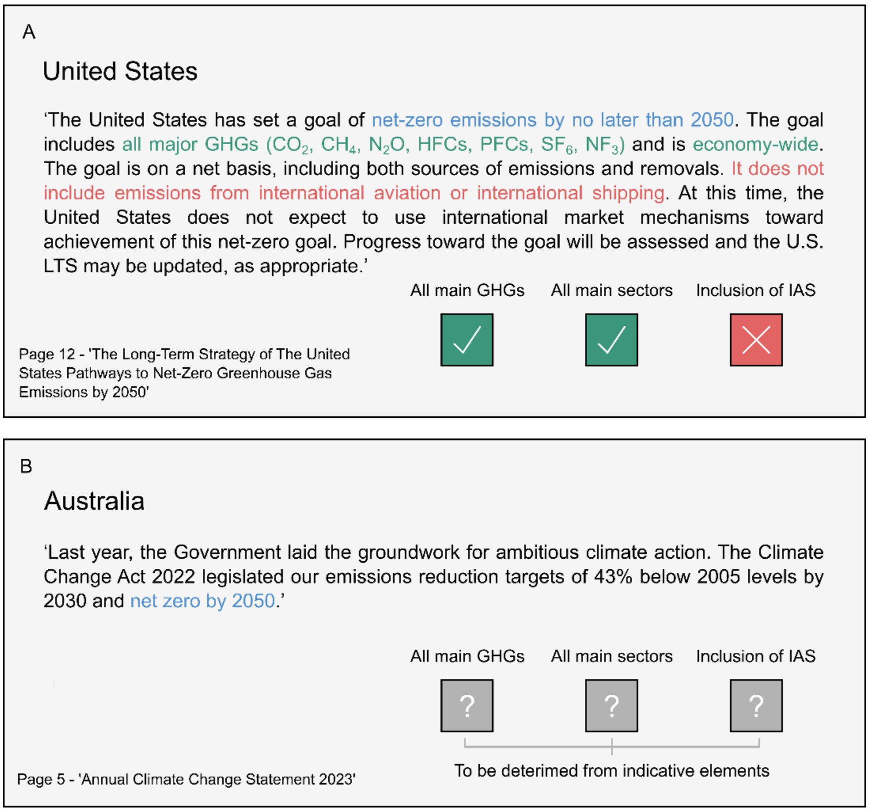

Figure 8. Examples of headline targets from strategies.

Panel A provides an example from the United States' LT-LEDS, detailing the headline target (blue) alongside a detailed description further specifying the gas coverage (green), sector coverage (green) and exclusion of IAS (red). Panel B provides an example from Australia's LT-LEDS, which provides only a headline target without a detailed description. As a result, the gas coverage, sectors coverage and inclusion of IAS are to be determined from indicative elements shown in Figure 7.

The 2006 IPCC Guidelines are the main reference for the development of National Greenhouse Gas Inventories (NGHGIs) - detailed national datasets of emissions by sources and removals by sinks (IPCC, 2006a). The guidelines provide the naming convention for emission sources and removals categorised into a nested structure of national sectors (IPCC, 2006a). NGHGIs are commonly the basis of scenarios and pathways included within strategies, as well as the basis for tracking trends in historical emissions, and therefore serve as the accounting logic for sectors, unless altered to better suit national circumstances. We take the approach advocated by the LT-LEDS Synthesis Report, analysing, if not explicitly specified in a target description or scenario or pathway modelling, the coverage of sectoral chapters as indicative of the sector coverage (UNFCCC Secretariat, 2023).

Caution should be exercised for non-Annex I countries, which submit NGHGIs only periodically as opposed to an annual basis (Umemiya and White, 2023). As a result, NGHGIs tend to be more limited for non-Annex I countries (Umemiya and White, 2023), meaning countries may be yet to source the necessary activity data to estimate emissions for a certain sector, impacting upon the inclusion of the sector within scenarios or pathways. This should not necessarily be considered as an omission of the sector from the long-term target, as improvements in inventory capacity may lead to the estimation of emissions in future NGHGI reporting or revisions to the LT-LEDS. Similarly, some sectors may not occur within an economy, for example, states with limited industry may not report industrial emissions (IPCC, 2006c). Sectors '*not occurring*' should not necessarily be seen as excluded from the long-term target.

For IAS, the inclusion of emissions attributed to a country may result in the need for increased removals or further emission reductions to achieve a set long-term target (for example, as observed in the UK LT-LEDS, HM Government, 2022). Typically, emissions from IAS are considered under international organisations, such as the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO). States participate in these organisations to multilaterally coordinate climate policy owing to the cross-border nature of emissions (Doelle and Chircop, 2019; Mithal and Rutherford, 2023). Nevertheless, NGHGIs typically estimate emissions from IAS on a '*bunker fuel*' basis, that is emissions from fuel sold during refuelling for international journeys (Committee on Climate Change, 2019). These emissions are, however, '*memo items*', excluded from national totals and therefore, by extension, commonly long-term targets (IPCC, 2006c; Committee on Climate Change, 2019). Select countries, such as the UK, include IAS emissions within their long-term target, net zero GHGs by 2050 (HM Government, 2022). Inclusion does not necessarily imply unilateral action on these emissions but can be complementary to international efforts, and a recognition that meeting the Paris Agreement for IAS will require new infrastructures and industries within national borders, such as engineered CDR and new synthetic fuels (Committee on Climate Change, 2019). The inclusion of IAS is therefore likely explicit, if a target description is included, or implied by supporting scenario or pathway modelling. As a last resort, the inclusion or exclusion of IAS can be inferred by the policy position, if stated, of the country towards the ICAO or IMO. In cases where no mention of IAS is found within the strategy, it is likely that the country follows existing practice, which is to exclude these emissions from scope.

2.3.3 Emissions & removals within scenarios and pathways

Once long-term targets are collated, we identify all instances of scenario and pathway modelling found within the strategies. This requires a reflexive approach, adaptive to the detail presented, as LTS can include no modelling, present only select results, such as total emissions, or present emission estimates across multiple sectors. We employ the following approach, we first identify whether the strategy includes scenarios or pathways that extend beyond the country's NDC (for example, 2030). If so, we collate total GHG emissions excluding LULUCF, any estimates of sectoral emissions, net LULUCF emissions, and any removals from engineered CDR methods, detailed in data tables, text, or legible graphs and figures (Figure 9). Scenarios are based on a key set of modelled assumptions made in a LTS, relating to, for example, the use of specific low-carbon technologies. Pathways, meanwhile, can take the form of a series of policy targets, prescribing a pathway for GHG emissions over time, or a range informed by multiple scenarios. Pathways tend to have a less direct connection to the assumptions underpinning them. If the strategy includes emissions by sector or by subsector or source, we collate these estimates, cross-checking the sum against total emissions excluding LULUCF (Figure 9).

We prioritise the year 2050, owing to its alignment with existing national net zero targets and its importance as a milestone within scenarios assessed by the IPCC (Riahi *et al.*, 2022). This is done mindful of the long-term target. For example, if the long-term target is net zero CO_2, scenarios and pathways may detail only CO_2 emissions, meaning it is necessary to make assumptions around the level of non-CO_2 emissions, unless otherwise specified. Similarly, if the long-term target extends beyond 2050, or is to be reached prior, we assess emissions and removals at the point net zero GHGs is achieved. Each step of this approach is shown in Figure 10.

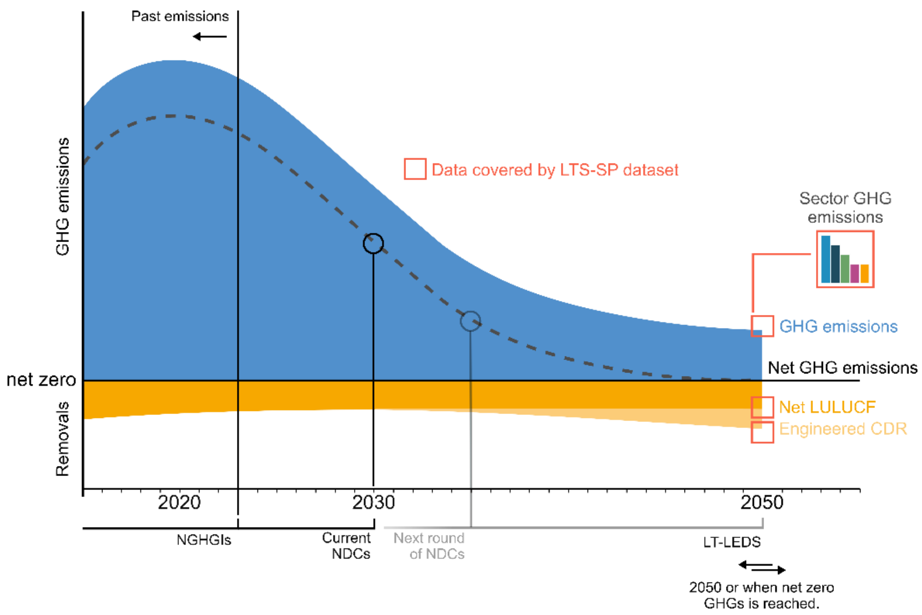

Figure 9. Stylised net zero pathway showing the data covered by the LTS-SP dataset.

Boxes in red are data points covered by the LTS-SP dataset. Headers along the dateline show the years covered by different reporting obligations, including current NGHGIs (2022, soon 2023), current NDCs (2030), and new NDCs due in 2025 (2035). Figure based on Figure 2, Cross-Chapter Box 8, IPCC AR6 WGIII (ref. Babiker *et al.*, 2022). Figure depicts a stylised pathway that reaches net zero GHGs in 2050. Alternative pathways are possible and depend on the scenario or pathway design, long-term target, and timing.

Unlike reporting obligations within the UNFCCC and elsewhere in the Paris Agreement, LT-LEDS are not associated with guidance that recommends a specific scenario logic. Adopted guidelines within the UNFCCC, recommend a logic of three projections, (i) '*with measures*', (ii) '*with additional measures*' and

(iii) '*without measures*' or the '*baseline*' (for example, the annex of Decision 18/CMA.1). A '*with measures*' projection encompasses currently implemented and adopted policies and measures, whilst a '*with additional measures*' projection includes planned policies and measures yet to be adopted. This structure of projections is designed to identify the emission gap remaining between current or planned policy efforts and near-term climate targets, such as NDCs. Many LT-LEDS therefore adopt a similar structure for scenarios or pathways, but also include scenarios or pathways that seek to identify the conditions under which a long-term target may be met (Català *et al.*, 2024). Multiple scenarios or pathways may be included, designed to explore a range of technological options or policy approaches. Given the absence of guidelines for LT-LEDS, strategies may include multiple types of scenario, with only a select subset achieving the long-term target. We do not classify scenarios by the extent of adopted or additional policies and measures but by whether they achieve or exceed the long-term target set within the strategy.

The term '*residual emissions*' has recently emerged in climate governance to describe positive emissions remaining at the time of net zero (Buck *et al.*, 2023; Schenuit, Boettcher and Geden, 2023). This, however, is but one definition and use of the term, with the term used elsewhere to describe the emissions that remain after an emission reductions target is reached (DESNZ, 2023a), or the cumulative emissions that continue to be emitted across the century in modelled scenarios assessed by the IPCC (Luderer *et al.*, 2018). In these examples, '*residual emissions*' is used as a term irrespective of achieving net zero. Given the LTS-SP dataset covers a range of scenarios and pathways, targeting a range of mitigation outcomes, including those that focus only on reducing net emissions as opposed to achieving net zero, we do not universally use the term to describe the total or sectoral GHG emissions covered by the dataset, as this would combine multiple definitions. Residual emissions, within the LTS-SP dataset, are therefore only those total or sectoral GHG emission in scenarios or pathways that achieve a long-term target of net zero GHGs, adjusting for the timing of net zero GHGs, if achieved earlier than the long-term target itself.

With limited exceptions, LTS largely fail to specify the global warming potentials (GWPs) used when presenting GHG emissions on a CO_2-equivalent basis. It is likely that many use GWPs for a 100-year time horizon, based on Working Group 1 (WGI) of the IPCC's Fifth Assessment Report (or GWP100 AR5), consistent with existing practice for NGHGIs. The use of the GWPs for a 100-year time horizon from WGI of the IPCC's Fourth Assessment Report (AR4) may also be probable for those LT-LEDS published prior to 2019, before COP24 led to the adoption of GWP100 AR5 as the standard for parties (Decision 18/CMA.1, Annex, paragraph 37).

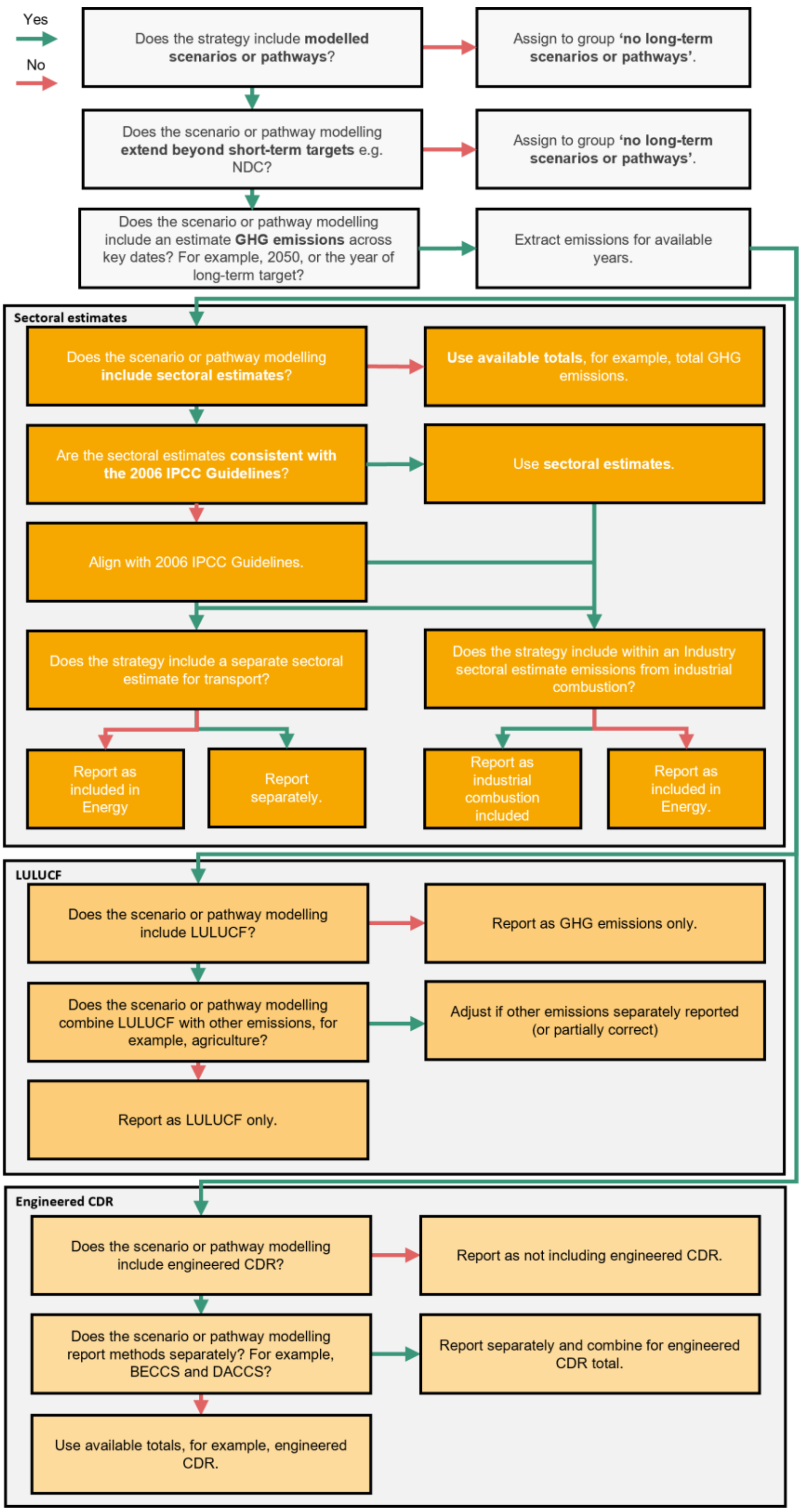

Figure 10. Analytical procedure for modelled scenarios or pathways.

Shown as a decision chart. We also include a check to verify whether the scenario or pathway complies with the long-term target from Figure 7.

2.3.4 Sectoral emissions

If the strategy includes emissions by sector or by subsector or source, we collate these estimates, cross-checking the sum against total emissions excluding LULUCF, if presented, or deriving a total if missing. Select strategies, such as Finland, detail emissions from their scenarios using the Common Reporting Format (CRF), the format of Annex I NGHGI submissions to the UNFCCC, meaning results can be directly mapped to sectors used in NGHGI reporting (UNFCCC, 2025). Many LTS refer to unconventional sectors, or a combination of sub-sectors and sources, meaning it is necessary to use their descriptions to assign to sectors. These sectors, or combinations thereof, are often inconsistent in the emissions they include, with country's devising a categorisation that better suits national circumstances, for example, the UK Net Zero Strategy's '*emission taxonomy*', which differs from the sectors used within the UK's NGHGI (UK Government, 2021). As with long-term targets, we include all main sectors, including Energy, Transport, Industry, Agriculture, Waste, and LULUCF, based upon the 2006 IPCC Guidelines. We use the reporting tables (Table 8.2, Volume 1, Chapter 8), found within the 2006 IPCC Guidelines, or otherwise the CRF, to align descriptions of sectors or sub-sectors and sources to these main sectors (IPCC, 2006c; UNFCCC, 2025)

Care is required in two cases, the inclusion of transport emissions within Energy and the inclusion of energy use emissions in addition to process emissions, within a wider Industry category (see Figure 10). This is owing to the changing focus of emissions as countries decarbonise and a need therefore to present sectors that are of interest towards the end of decarbonisation, as opposed to current NGHGI practice. Of recent interest are the so-called '*hard-to-abate*' sectors, typically used to describe emissions from long-range transport, such as aviation and shipping; heavy industries, such as steel, cement, and chemicals; and agriculture, for sources of non-CO_2 emissions, such as those emitted by livestock or by fertilisers (Babiker *et al.*, 2022). We similarly note a recent interest in the study of residual emissions (Buck *et al.*, 2023; Lund *et al.*, 2023). Though distinct from residual emissions, owing to their difficulty of abatement, emissions from hard-to-abate sources are likely to be residual and therefore indirectly mitigated through CDR, as opposed to directly abated at source (Babiker *et al.*, 2022). Creating a dataset that is of use to climate policy research should therefore seek to balance current practice with the likely direction of research. We therefore split, where specified, transport emissions from energy, owing to the tendency to describe aviation and shipping emissions as hard-to-abate and residual (Davis *et al.*, 2018).

Current practice in the 2006 IPCC Guidelines is to report emissions from transport in an overall Energy sector, owing to the use of national energy balances (IPCC, 2006c). Where not possible, for example, when a strategy fails to further disaggregate the Energy sector, we use the notation key '*included elsewhere*' or '*IE*', indicating where emissions are included (IPCC, 2006c). Notation keys are common across NGHGI reporting to indicate where emission categories may be incomplete, missing, or inconsistent with NGHGI practice (IPCC, 2006c).

The 2006 IPCC Guidelines also advocates the reporting of emissions from industrial fuel combustion within Energy, whereas select countries report this within an Industry sector. This may be desirable as decarbonising industry requires an approach that addresses the thermal heat required for industrial processes, conventionally supplied by the combustion of fossil fuels, in addition to addressing the emissions that arise from chemical reactions directly within the industrial process (Madeddu *et al.*, 2020; Rissman *et al.*, 2020). We adjust for this where possible, to ensure Industry consists of only emissions from industrial processes as opposed to combustion.

2.3.5 Engineered CDR

We identify estimates of removals from engineered CDR, specifying separate estimates for DACCS and BECCS, where available. The terminology surrounding CDR is still changing and CDR is commonly conflated with carbon capture utilisation and storage (CCUS) (Olfe-Kräutlein *et al.*, 2022). The overlap between engineered CDR and CCUS is limited in practice, given there are few means of CCUS that satisfy the criteria for CDR, that is, the CO_2 originates from the atmosphere, the CO_2 captured is permanently stored and not soon reemitted, and the net quantity of CO_2 removed is greater than the quantity of GHGs emitted (Tanzer and Ramírez, 2019; Geden, Smith and Cowie, 2024). Therefore, though commonly conflated, there is little justification for doing so. Owing to this ambiguity, we make several assumptions when engineered CDR is included, for example, if CCUS is presented as a removal within scenario or pathway modelling, it may be considered as engineered CDR unless otherwise specified as short-term utilisation. We are also alert to unconventional uses of terminology, for example, Finland's use of '*Bio-CCS*' as an equivalent term to BECCS. Given the current lack of guidance concerning the reporting of engineered CDR (Mace *et al.*, 2021), there are instances where removals from CDR methods are included as net emissions or removals within a sectoral total, for example, removals from BECCS are included within the total for the Energy sector. This follows the logic supported by the 2006 IPCC Guidelines, reporting emissions and removals within the sectors in which they occur (IPCC, 2006c). This may require assigning a main purpose. For example, the 2006 IPCC Guidelines advocate that, if waste is incinerated for the purposes of energy recovery it should be accounted for in the Energy sector as opposed to Waste (IPCC, 2006c). It is therefore logical that if biomass is combusted for energy purposes, it's removals should be similarly accounted for in Energy. We therefore adjust, where possible, cases where sectoral emissions and removals from engineered CDR are combined. Where not possible, we report what emissions are combined and whether this leads to an underestimate in sectoral or total emissions.

In select cases, only partial corrections are possible. For example, in a case where a sub-sector or sectoral total is net-negative owing to the inclusion of removals from engineered CDR, and the extent of removals from engineered CDR or the emissions excluding removals are not stated, we can infer a minimum bound for engineered CDR by the extent of net-negative emissions. It is likely that this would represent an underestimate. We document these cases as '*partial corrections*'. Similarly, if removals cannot be separated in this manner, for example, removals are included but the sector or subsector total is not net-negative, we document these instances.

2.3.6 Land-use, Land-use Change and Forestry

For LULUCF, current practice is to report the sectoral total on a net basis, without distinguishing between emissions and removals (IPCC, 2006c). Many strategies therefore report LULUCF according to current practice, obscuring the nature and direction of interventions within the land-use sector (for example, declining rates of deforestation or increasing rates of afforestation can both reduce net LULUCF emissions). We identify estimates of LULUCF, specifying net emissions or removals. As with engineered CDR methods, we adjust cases where emissions from other sectors and removals are combined. This is most common with '*AFOLU*', or '*Agriculture, Forestry and Other Land Use*', which combines emissions from agriculture with emissions and removals from LULUCF (IPCC, 2006c). Where separation is not possible, we report what emissions are combined and whether this leads to an underestimate. Note that LULUCF estimates within NGHGIs may be defined differently to that of the IPCC Assessment Reports (See Usage Notes, Section 2.6).

Once all necessary elements have been collated; total or the sum of sectoral emissions, LULUCF and any inclusion of removals from engineered CDR, we compare the net total to the long-term target, establishing whether the modelled scenario or pathway reaches the long-term target set. This is necessary to discern between scenarios, as typically long-term strategies contain multiple scenarios, differentiated by policy ambition or technology choice. These may or may not reach the long-term target set and cannot necessarily be inferred by the title of the scenario alone.

2.4 Data Records

The dataset can be accessed on Zenodo at 10.5281/zenodo.14943904 (ref. Smith, Vaughan and Forster, 2025). The dataset is available as a .xlsx file. The .xslx file contains three main tabs; '*Metadata*', '*Long-term targets*' and '*Emissions & removals*', detailed further in Table 3. At the Zenodo DOI, we maintain a change log, detailing additions, edits or corrections since January 2025 (Smith, Vaughan and Forster, 2025).

Table 3. A summary of the main tabs and contents of the dataset file.

Tab	Summary
Metadata	A table detailing the long-term strategies covered by the dataset, including their date of publication, name, submission, type, language, number of pages, and annex. Submission refers to whether the LTS serves as a countries 1st or 2nd submission to either the UNFCCC Secretariat or the European Commission. Type refers to whether the strategy is a LT-LEDS, EU LTS, or strategy with dual status, submitted as the EU Member State's EU LTS and LT-LEDS. Annex refers to whether the strategy is published by an Annex I or non-Annex I country, a division often used by the UNFCCC and is often indicative of the inclusion of scenario or pathway modelling. Annex I countries are required to submit national greenhouse gas inventories annually, and therefore should have the technical capacity for modelled scenarios and pathways.
Long-term targets	A table detailing the headline targets, coverage and resulting long-term targets detailed within LTS covered by the dataset. For each element, a page reference is included documenting the relevant source text, graphs, or tables.
Emissions & removals	A table detailing estimates of GHG emissions excluding LULUCF, sector GHG estimates, and emissions/removals from LULUCF and removals from engineered CDR, detailed within LTS covered by the dataset. For each element, a page reference is included documenting the relevant source text, graphs or tables. How non-conventional sectors, sub-sectors or sources have been assigned to the main sectors is also reported.

21 of the 80 active strategies, do not detail scenario or pathway modelling. 59 of the 80 active strategies contain quantified scenarios or pathways beyond the country's NDC. Our dataset, as of publication, therefore, covers this amount. 45 active strategies detail sectoral emission estimates and 49 strategies include estimates for LULUCF. Only 14 strategies include an estimate of engineered CDR. The inclusion of different elements by country is summarised in Table 4 below. Users of the dataset should refer to the change log found at the Zenodo address for the most recent assessment of elements included.

Table 4. The inclusion of different elements in active LTS by country.

Ticks (✓) refer to the inclusion of the element for at least one scenario. Crosses (×) refer to the element not being available within the strategy analysed. Dashes (-) are used for engineered CDR, owing to their recent introduction into national climate policy, meaning the inclusion of engineered CDR can not necessarily be anticipated for every country, unlike LULUCF.

Country	Total GHG emissions (excl. LULUCF)	Sectoral GHG emissions	LULUCF	Engineered CDR
Andorra	✓	×	✓	-
Argentina	×	×	×	-
Armenia	✓	✓	✓	-

Country	Total GHG emissions (excl. LULUCF)	Sectoral GHG emissions	LULUCF	Engineered CDR
Australia	×	×	×	×
Austria	✓	✓	✓	✓
Belgium	✓	✓	×	-
Belize	✓	✓	✓	-
Benin	×	×	×	-
Bhutan	✓	×	✓	-
Bosnia and Herzegovina	✓	✓	✓	-
Bulgaria	✓	✓	✓	✓
Cambodia	✓	✓	✓	-
Canada	✓	×	✓	✓
Chile	✓	×	✓	-
China	×	×	×	-
Colombia	✓	×	✓	-
Costa Rica	✓	✓	✓	-
Croatia	✓	×	✓	-
Cyprus	✓	✓	✓	-
Czechia	×	×	×	-
Denmark	×	×	×	-
Equatorial Guinea	×	×	×	-
Ethiopia	✓	✓	✓	-
Estonia	✓	✓	✓	-
Fiji	✓	✓	✓	-
Finland	✓	✓	✓	✓
France	✓	✓	✓	✓
Gambia	✓	✓	✓	-
Georgia	✓	✓	✓	-
Germany	×	×	×	-
Greece	✓	✓	×	✓
Guatemala	✓	✓	✓	-
Hungary	✓	✓	✓	✓
Iceland	✓	×	✓	-
India	×	×	×	-
Indonesia	✓	✓	✓	-
Ireland	✓	✓	×	✓
Italy	✓	✓	✓	✓
Japan	×	×	×	-
Kazakhstan	✓	×	✓	-
Latvia	✓	×	✓	-
Lithuania	×	×	×	-
Luxembourg	×	×	×	-
Malta	✓	×	×	-

Country	Total GHG emissions (excl. LULUCF)	Sectoral GHG emissions	LULUCF	Engineered CDR
Marshall Islands	✓	✓	×	-
Mexico	✓	×	✓	-
Morocco	×	×	×	-
Nepal	✓	✓	✓	-
Netherlands	×	×	×	-
New Zealand	×	×	×	-
Nigeria	✓	✓	✓	-
North Macedonia	✓	✓	✓	-
Norway	×	×	×	-
Oman	✓	✓	×	✓
Panama	✓	✓	✓	-
Portugal	✓	✓	✓	-
Romania	✓	✓	✓	-
Russia	✓	×	✓	-
Serbia	✓	✓	✓	-
Singapore	×	×	×	-
Slovakia	✓	✓	✓	-
Slovenia	✓	✓	✓	-
Solomon Islands	✓	✓	✓	-
South Africa	×	×	×	-
South Korea	×	×	×	-
Spain	✓	✓	✓	-
Sri Lanka	×	×	×	-
Sweden	✓	✓	✓	-
Switzerland	✓	✓	✓	✓
Thailand	✓	✓	✓	-
Tonga	×	×	×	-
Tunisia	✓	✓	✓	-
Turkey	×	×	×	-
Ukraine	✓	×	✓	-
United Arab Emirates	✓	✓	×	✓
United Kingdom	✓	✓	×	✓
United States	✓	×	✓	✓
Uruguay	✓	✓	✓	-
Vanuatu	✓	✓	✓	-
Zimbabwe	✓	✓	✓	-

2.5 Technical Validation

Three datasets are used to validate our results: the Net Zero Tracker (Net Zero Tracker, 2024b), the Supplementary Data of Buck *et al.*, 2023, and New Climate Institute's 2023 Assessment of the G20 Members' Long-term Strategies (cited as Mooldijk *et al.*, 2023). For long-term targets, we validate our dataset against the Net Zero Tracker, an online database tracking targets pledged by nations, states, cities, and companies (Net Zero Tracker, 2024b). The Net Zero Tracker tracks all Parties to the UNFCCC, using a range of submissions by parties, including LT-LEDS. Validating the LTS-SP dataset against the Net Zero Tracker has two purposes; firstly, to ensure the long-term targets are correctly coded, identifying disparities between the datasets, and secondly to provide an estimate as to the extent of which the LTS-SP may no longer reflect the latest long-term targets.

The Net Zero Tracker uses different codes to the LTS-SP dataset, representing the same or similar elements. For example, the Net Zero Tracker collates '*end targets*', which represent the country's own description of their target from a pre-determined list of codes (Net Zero Tracker, 2024a). This is analogous to the headline targets within the LTS-SP dataset. In contrast to the LTS-SP dataset, the Net Zero Tracker does not correct the end target for gas coverage, as we do for the headline target to produce the long-term target. We therefore produce a comparative long-term target by combining fields of the Net Zero Tracker dataset. We consulted the fields for '*end target*', '*end target year*', '*gasses coverage*', '*international aviation*', and '*international shipping*'. The Net Zero Tracker does not contain a field for sector coverage but does provide a summary of considerations not captured by other fields in the '*coverage notes*' field. Similarly, the Net Zero Tracker contains the '*target notes*' field, which provides further detail relating to the target not captured in other fields.

We compare the long-term targets within the LTS-SP dataset to the Net Zero Tracker, determining whether there are substantive differences between the coverage or nature of the target. For example, with the inclusion of IAS, if the Net Zero Tracker states that these emissions are included, whilst the LTS-SP details that these are excluded or not stated, this would constitute a substantive difference. The Net Zero Tracker stating these emissions are '*not specified*' and the LTS-SP dataset detailing that these emissions are excluded would not constitute a substantive difference. Similarly, disparities in the timing or '*end target year*', or the nature of the target would constitute as substantive, provided these are not modified by the '*gasses coverage*' field in the Net Zero Tracker. That is to say that an end target of '*carbon neutral(ity)*' in the Net Zero Tracker would be considered as functionally equivalent to a long-term target of '*net zero GHGs*' in the LTS-SP dataset, if the '*gasses coverage*' field in the Net Zero Tracker reads '*Carbon dioxide and other GHGs*'. If the '*gasses coverage*' reads '*Carbon Dioxide only*' this would be considered a substantive difference. In this manner we capture only key disparities, not simply differences in coding and method. We evaluate disparities across four elements: the nature of the target (for example, net zero GHGs versus an emission reduction target), target year, gas coverage, and the inclusion of IAS. Given the Net Zero Tracker provides no systematic assessment of sectors, we do not compare the datasets according to sector coverage.

We observe a large disparity between the datasets, with long-term targets for 35 of the 80 countries assessed not aligned on at least one or more of the four elements assessed (Figure 11A). For 22 countries, long-term targets differ according to the nature of the target (Figure 11B). We investigated all instances. In seven instances, we assess there is no headline target and therefore no long-term target to be assessed, whereas, in five of these cases, the Net Zero Tracker uses the wording of the NDC as the '*end target*'. In the remaining two cases, it is not clear how the Net Zero Tracker has arrived at a different target to the long-term target in the country's LT-LEDS. In six further instances, the long-term target appears to have been upgraded since the publication of the LTS, by for example, introducing a net zero target as opposed to an emission reduction target. In four instances, we determine the long-term target as a variation of a net-negative target, such as maintaining or increasing net-negativity for GHGs. In these cases, the Net Zero Tracker describes these as net zero. 13 countries differ on timing, similarly linked to cases where we assess there is no headline target and the Net Zero Tracker uses the wording of the NDC (five of the 13 cases).

Long-term targets for five countries differ according to their gas coverage. For example, for Nepal, the Net Zero Tracker lists a target of net zero applying to '*Carbon dioxide and other GHGs*', referencing Nepal's LT-LEDS as a source (Government of Nepal, 2021). We assess this long-term target to apply to only CO_2 based on the scenarios detailed in the LT-LEDS. In three of these cases, we document exemptions of certain gases, such as methane, from long-term targets, whereas the Net Zero Tracker does not differentiate these elements.

Long-term targets for five countries differ on the inclusion of IAS. In three cases the inclusion of IAS has been conflated with the mention of international targets. This is not comparative to the inclusion of IAS as defined in Table 2.

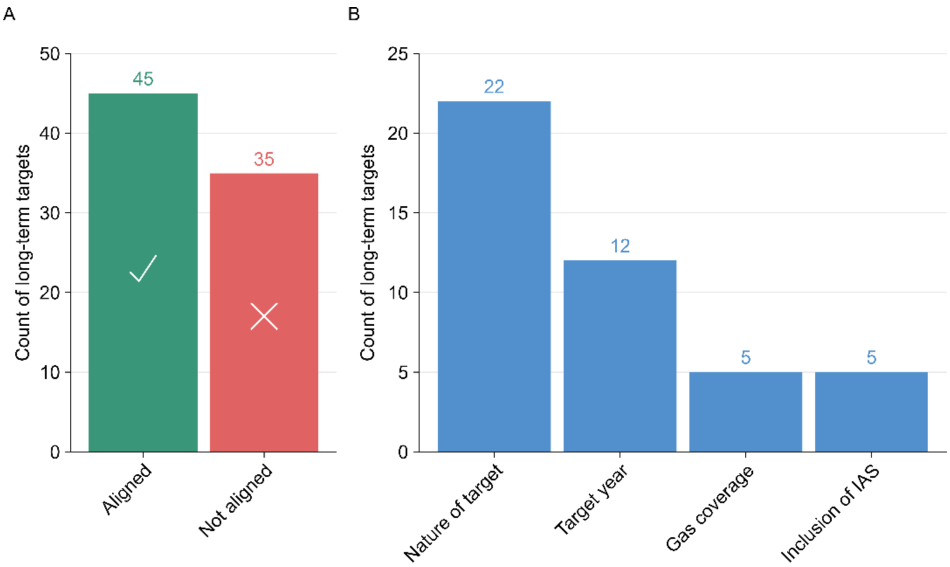

Figure 11. Comparison of long-term targets between the LTS-SP dataset and the Net Zero Tracker.

A) compares the alignment or misalignment between the datasets. If '*aligned*', the long-term target in the LTS-SP dataset is not substantively different from the combination of fields assessed in the Net Zero Tracker. If '*not aligned*', the long-term target in the LTS-SP dataset is substantively different on one or more of the four elements assessed in panel B.

For emissions and removals, we validate our dataset against the results available in the Supplementary Data of Buck *et al.*, 2023, '*Why residual emissions matter right now*'. This includes scenario data for 28 LT-LEDS, 18 from Annex I countries and 10 from non-Annex I countries, submitted to the UNFCCC Secretariat prior to mid-2022. Buck *et al.*, 2023 focuses on low residual scenarios, presenting the scenario with the lowest residual emissions where multiple scenarios are detailed within strategies, whereas our dataset includes all long-term scenarios found within LTS. We therefore compare the minimum residual emission scenario within our data to the data presented in Buck *et al.*, 2023. In select cases, Buck *et al.*, 2023 has prioritised those pathways that comply with a set long-term target. For example, if a net zero target is the headline target for the country, scenarios that fail to reach this target are dismissed. We therefore use the page references and target timing within Buck et al., 2023's Supplementary Data to determine how the total is reached and align the data with our own, comparing like with like scenarios where possible. Owing to the publication date of Buck *et al.*, 2023, scenarios are often sourced from LT-LEDS that have since been revised or superseded. Given that our intention is to validate the method through which estimates are reached, not compare how scenarios have changed between LT-LEDS, we compare scenarios from past LT-LEDS, even if since revised and superseded by a new submission.

We also compare our data to the data compiled for New Climate Institute's 2023, '*Assessment of the G20 Members' Long-term Strategies*' (Mooldijk *et al.*, 2023), which collates residual emissions, LULUCF and engineered CDR in 2050 for the G20 states. New Climate Institute's assessment includes both a maximum and a minimum for each element, for example, both maximum and minimum residual emissions. Here residual emissions are not necessarily those at the point of net zero, but rather remaining emissions in 2050 excluding LULUCF or engineered CDR methods. We therefore compare this data to the minimum and maximum found within our data, where a country presents multiple scenarios.

Figure 12A shows a comparison between the minimum emissions within the LTS-SP dataset and minimum residual emissions detailed in Buck *et al.*, 2023 and New Climate Institute's assessment of G20 strategies. The LTS-SP dataset shows good agreement with Buck *et al.*, 2023, with 17 of the 28 countries compared within ±5%. Several countries show wide disparities in estimates. We investigate all cases outside ±5%, correcting our dataset if necessary, or otherwise explaining the disparity in estimates in Table A 1, found in Annex I – Chapter 2. The LTS-SP dataset shows less agreement with New Climate Institute's assessment of G20 strategies, with only 3 of the 9 countries compared within a range of ±5%. As with Buck *et al.*, 2023, we investigate all cases outside ±5%, explaining disparities in estimates in Table A 1, Annex I – Chapter 2. We stress that disparities between estimates do not suggest errors, but rather different interpretations of the available data. Many disparities, for example, for Australia, Canada, Fiji, France, and Hungary, are explained by both Buck *et al.*, 2023 and New Climate Institute's assessment including removals, from engineered CDR or LULUCF, within larger sectoral totals. We use various methods and available data within the strategy to adjust for these cases.

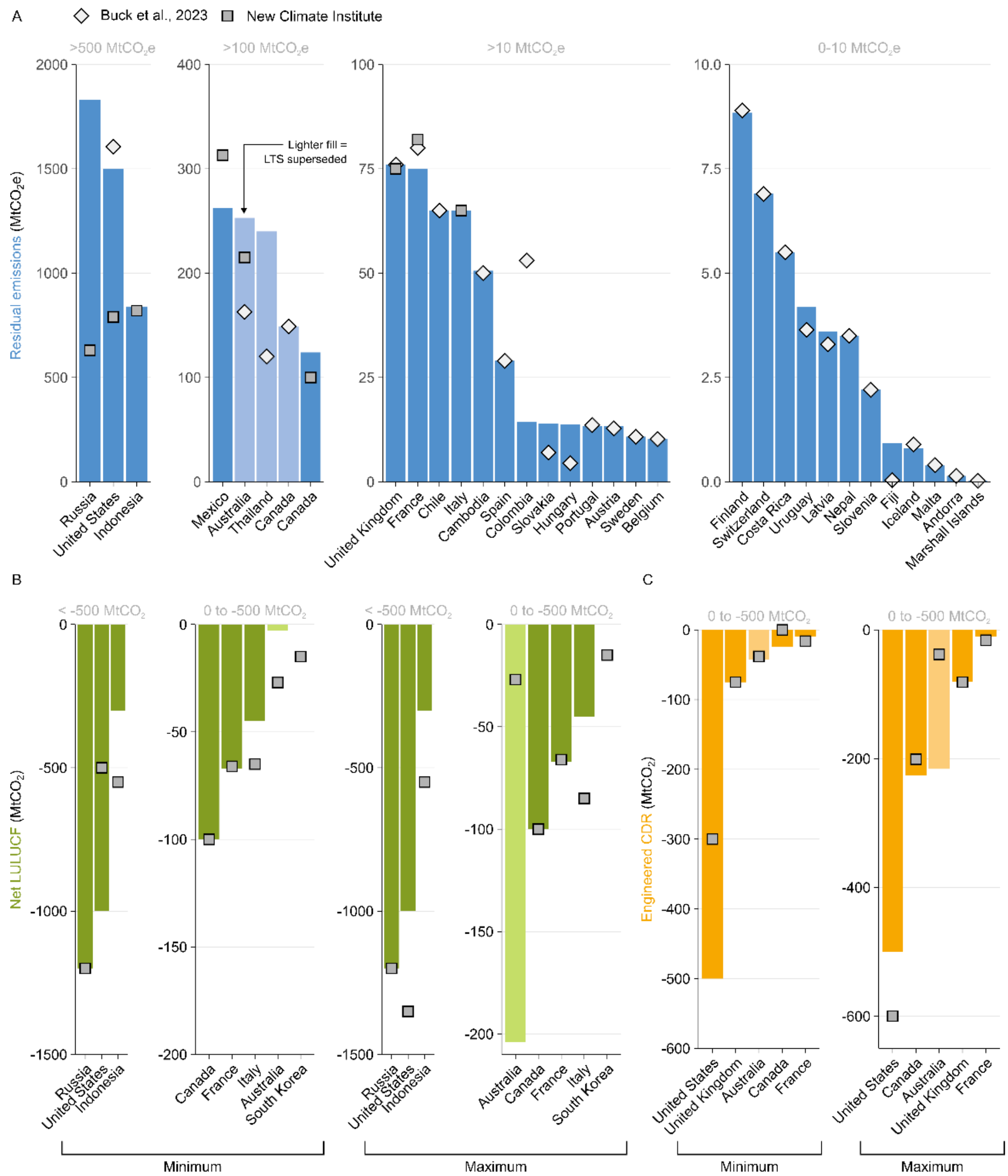

Figure 12. Comparisons between the LTS-SP dataset and Buck *et* al., 2023 and New Climate Institute's assessment of G20 strategies.

A) details residual emissions. Figure split into four size classes depending on the magnitude of minimum residual emissions. Buck *et al.*, 2023 depicted with a diamond, New Climate Institute's G20 data with a square. Bars in lighter shades are superseded LTS, that is, they are no longer the most recent LTS for the country detailed. B) details net LULUCF, split into minimum and maximum within New Climate Institute's G20 data and by size class. C) depicts removals from engineered CDR, split into minimum and maximum within New Climate Institute's G20 data and by size class.

Figure 12B shows a comparison between the minimum and maximum LULUCF for the LTS-SP dataset and the New Climate Institute's assessment of G20 strategies. For minimum LULUCF estimates, 3 of the 8 countries compared are within ±5%. The same applies for maximum LULUCF estimates. We explain disparities in Table A 2, Annex I – Chapter 2. Figure 12C details a comparison between the minimum and maximum engineered CDR removals for the same two datasets. For both minimum and maximum comparisons, only 1 country of the 5 compared is within ±5%, the UK. We explain all disparities in Table A 2, Annex I – Chapter 2. Many disparities, for example, for Canada, France, Indonesia, and Italy are explained by New Climate Institute's assessment including positive emissions within LULUCF or engineered CDR totals, or not differentiating between LULUCF and engineered CDR where this may be warranted.

2.6 Usage Notes

On the practical use of the LTS-SP dataset, we end with a caveat on the current challenges of estimating LULUCF, before detailing four factors that may alter either the status of a LT-LEDS or the relevance of the scenarios and pathways they present, namely; a change in political mandate, the upgrading of a long-term target, changes in models or modelling practice, and recalculations within NGHGIs - commonly used as input into scenario modelling. We illustrate each with examples.

Firstly, LULUCF estimates within the LTS-SP dataset are not adjusted to align with estimates used in IPCC Assessment Reports. LULUCF emissions and removals should represent only those arising from anthropogenic activities, not natural disturbances or indirect effects, such as increased CO_2 fertilisation or nitrogen deposition (IPCC, 2006d). Separating these in practice, however, remains a challenge (Grassi *et al.*, 2018; Schwingshackl *et al.*, 2022; Gidden *et al.*, 2023). Estimates within the LTS-SP dataset are likely based on the methodologies that support NGHGIs. In NGHGIs, the 2006 IPCC Guidelines estimate emissions and removals occurring on '*managed land*', which is used '*as a proxy for anthropogenic effects*' (IPCC, 2006d). This proxy means LULUCF estimates within NGHGIs capture, by definition, those emissions and removals arising from anthropogenic activities, but also natural and indirect effects (IPCC, 2006d). Whilst countries are not required to report emissions and removals on '*unmanaged land*', nearly all countries simply designate all land as managed, exacerbating these issues (Ogle *et al.*, 2018; Nabuurs *et al.*, 2023). Within IPCC Assessment Reports, bookkeeping models and dynamic global vegetation models are used to isolate anthropogenic activities from these wider effects (Gidden *et al.*, 2023). This leads to large disparities between global estimates. For the most recent decade for which data is available, 2010-2020, global LULUCF estimates as a mean of four bookkeeping models was a net source of 4.7 ± 5.1 (95% CI) $GtCO_2$/year (Friedlingstein *et al.*, 2024), whereas the combined global total from NGHGIs presents a net sink of -2.1 ± 0.8 $GtCO_2$/year (Grassi *et al.*, 2022) (see Figure 13). Both estimates of LULUCF are highly uncertain when compared to other emission sources. The LTS-SP dataset, therefore should not be directly compared to benchmarks within the IPCC Assessment Reports, such as those derived from scenarios assessed by the IPCC, without first adjusting estimates to reconcile these disparities, ensuring like-for-like comparisons (Gidden *et al.*, 2023).

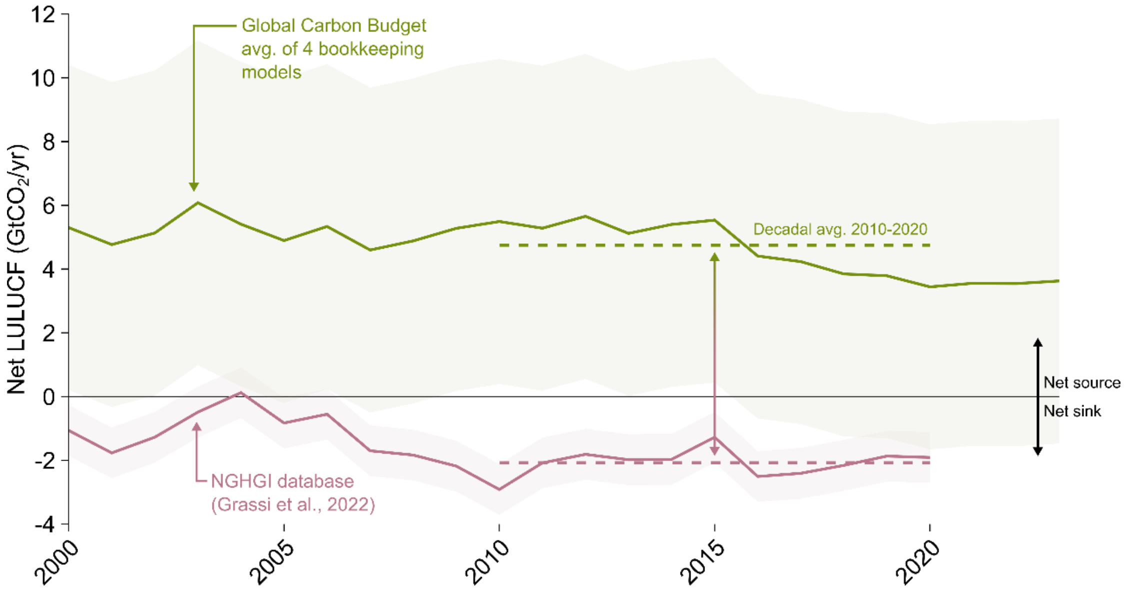

Figure 13. Comparison of net LULUCF emissions between the average of four bookkeeping models used by the Global Carbon Budget and the NGHGI database.

Shading indicates 95% confidence interval. Data from Grassi et al., 2022; Friedlingstein et al., 2024.

LT-LEDS are large undertakings for national governments and can take several years to produce (Lecocq, Nadaï and Cassen, 2022). Though most long-term national climate strategies within our sample are recent, 58 of the 80 strategies were published between 2021-2024, it is unlikely that the LTS-SP dataset will keep pace with political developments. Changes in government may alter a government's mandate towards climate action, meaning scenarios presented in the government's LT-LEDS may no longer be representative. For example, Australia's first LT-LEDS was published in 2021 under the then centre-right Morrison government (Australian Government, 2021a). The Morrison government was a notable laggard in climate policy (Crowley, 2021), which manifested in Australia's LT-LEDS through reducing the ambition of scenarios detailed within the strategy (Australian Government, 2021a). The main scenario presented, '*The Plan*', was purposefully limited to an 85% emission reduction upon 2005 GHG emissions, despite Australia's wider net zero GHG target and the modelling of four net zero scenarios excluded from the main text of the strategy (Australian Government, 2021a, 2021b). The remaining 15% of the necessary mitigation was to be met by '*further technology breakthroughs*', abdicating responsibility for these emissions (Australian Government, 2021a, 2021b). The Morrison government was replaced by the centre-left Albanese government in 2022. The Albanese government has since submitted the '*2023 Annual Climate Change Statement*' as a temporary LT-LEDS, with a fuller '*Net Zero Plan*' to be submitted (Bowen, 2024). The Annual Climate Change Statement represents a domestic reporting obligation laid out in Australia's 2022 Climate Change Act, to report on progress to the Australian Parliament, detailing near-term plans (Australian Government, 2024a). It therefore presents no scenarios to 2050, nor scenarios that model the needs of net zero. Nevertheless, the Albanese government has requested this document replace the 2021 LT-LEDS as the 2021 strategy '*reflected the approach of the previous government and is no longer aligned with the increased ambition of the Australian Government's legislated commitments and our extensive emission-reduction action*s' (Bowen, 2024). A renewed political mandate can therefore alter the relevance of a LT-LEDS despite no material change to the country's long-term target.

A renewed political mandate, however, can also be reflected by upgrading a long-term target. Changes to the long-term target can occur without requiring a country to revise its LT-LEDS, meaning, in the interim between strategies, scenarios may no longer be representative of long-term targets. For example, Thailand has submitted two LT-LEDS, the first in 2021, prior to COP26, and the second in 2022, during COP27 (Thai government, 2021; Ministry of Natural Resources and Environment, 2022). The first, the '*Mid-century, Long-term Low Greenhouse Gas Emission Development Strategy*' had a long-term target of net zero CO_2 in 2065, with multiple scenarios (Thai government, 2021). The second LT-LEDS, '*Thailand's Long-term Low Greenhouse Gas Emission Development Strategy*' increased Thailand's ambition by pledging to reach net zero GHGs in 2065, presenting revised scenario modelling (Ministry of Natural Resources and Environment, 2022). In this case, upgrades to the target were communicated within LT-LEDS, leaving no gap between announcements and revised scenarios, however, Parties to the Paris Agreement can communicate long-term targets by multiple means, including within NDCs. In these cases, the long-term target may be updated but the LT-LEDS not revised, reducing the relevance of any scenarios detailed therein.

Changes in models and modelling practice may also impact upon the relevance of scenarios. Canada's latest LT-LEDS, for example, includes four scenarios that all attain Canada's long-term target, net zero GHGs by 2050 (Environment and Climate Change Canada, 2022). Using three models, two integrated assessment models and one computable general equilibrium (CGE) model, the LT-LEDS provides ranges for sectoral emissions in 2050 (Environment and Climate Change Canada, 2022). Despite setting out a series of detailed technology assumptions, across all scenarios '*LULUCF was standardized to remove 100 $MtCO_2e$ by 2050*', allowing '*more residual emissions to appear across the economy in the modelling*' (Environment and Climate Change Canada, 2022). This is a contested assumption considering that bioenergy is also modelled, impacting upon emissions and removals in LULUCF if the necessary biomass is domestically sourced (Environment and Climate Change Canada, 2022). This assumption means that the modelling '*does not take into account changing pressures on the land base from other sectors and does not necessarily account for activities on the land base that will be necessary to support a pathway to net-zero emissions*', as acknowledged in the strategy (Environment and Climate Change Canada, 2022). Canada's LT-LEDS similarly acknowledges the need to develop new methodologies and modelling to account for this limitation (Environment and Climate Change Canada, 2022).

Many LT-LEDS use NGHGIs as base years for long-term targets or scenarios and pathways. NGHGIs, however, are recalculated across all historic years in each submission to the UNFCCC (IPCC, 2006a). Revisions may be necessary to incorporate methodological improvements or revisions to the activity data upon which emissions and removals are based (IPCC, 2006b). Recalculations pose the greatest challenge to non-Annex I countries, which typically have more limited institutional capacity and therefore lean more heavily on international support (Umemiya and White, 2023). NGHGIs for non-Annex I countries, therefore, frequently change with more limited documentation detailing recalculations. Whilst multiple historical emission datasets exist to provide estimates for non-Annex I countries using consistent methods (Crippa *et al.*, 2024), these estimates may differ to those used by the country within their LT-LEDS. Users of the dataset should therefore be cautious when comparing scenario and pathway estimates to historical emissions.

These four factors are not isolated to LTS, changes in political mandate and historical calculations both impact upon the relevance of reporting obligations such as NDCs. The challenges within LULUCF similarly impact upon the collective assessment of NDCs and their comparison to benchmarks in scenarios assessed by the IPCC. Nevertheless, these factors warrant attention when using the LTS-SP dataset. For example, the relevance of LT-LEDS can be determined by comparing the long-term targets to external sources, as demonstrated in the technical validation of this dataset. If using data for a single country or a small sub-sample, it should be possible to attain whether any changes in political mandate have occurred, though this can require detailed knowledge of domestic climate policy arrangements. Comparison to scenario benchmarks found in IPCC Assessment Reports warrant a need to adjust LULUCF. Despite these issues, LTS form the most readily available and comparable reporting provision to understand how countries plan to attain their long-term targets (Lamb *et al.*, 2024).

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

This chapter was published as ‘*Long-term national climate strategies bet on forests and soils to reach net-zero*’ in the journal Communication Earth & Environment in December 2022, accessible at: https://doi.org/10.1038/s43247-022-00636-x. Minor textual changes have been made to align with the format of this thesis. As noted in Chapter 1, Section 1.8, this chapter covers 41 LTS of the 50 then available. Unlike Chapter 4, which includes all scenarios that reach net zero GHGs, this chapter includes only what is determined as ‘*the main policy scenario*’ and assesses emissions in 2050 as opposed to the point of net zero GHGs.

3.1 Abstract

The deployment of CDR is essential to reach global and national net zero targets, but little attention has been paid to its practical deployment by countries. Here, we analyse how CDR methods are integrated into 41 of the 50 LT-LEDS submitted to the 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.

3.2 Introduction

As net zero becomes an organising principle of climate policy, countries are beginning to consider the practical and policy dimensions of deploying CDR and the implications for achieving national climate targets (Buylova *et al.*, 2021; Iyer *et al.*, 2021; Mace *et al.*, 2021; Schenuit *et al.*, 2021). 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[20] (Hale *et al.*, 2021; Fankhauser *et al.*, 2022). Despite being central to net zero ambitions, CDR is rarely made explicit in policy plans (Fuss *et al.*, 2020). We present a systematic analysis of CDR in 41 (of 50) long-term national climate strategies submitted to the UNFCCC before the start of 2022. These cover 58% of global 2019 GHG emissions (Minx *et al.*, 2022) and around 74% of global GDP (World Bank, 2023).

CDR has largely been analysed within global assessments, attracting debate regarding the credibility and sustainability of CDR methods if deployed at scale (Fuss *et al.*, 2014; Smith *et al.*, 2016). 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 (Peters and Geden, 2017; Honegger *et al.*, 2021). CDR methods are characterised by different potentials and limitations, including cost, readiness, energy requirements, permanence, and social and political acceptability (Fuss *et al.*, 2018; Fridahl *et al.*, 2020; Förster *et al.*, 2022). These may be implicit or arise from their national or local configuration and policy design (McLaren *et al.*, 2019; Honegger, Michaelowa and Roy, 2020). 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 (Meadowcroft, 2013; Honegger *et al.*, 2021). 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 (Nemet *et al.*, 2018).

CDR has a role in achieving global (or national) net zero by counterbalancing residual emissions from difficult to decarbonise sectors in the mid-century (Honegger *et al.*, 2021; Iyer *et al.*, 2021). 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 (Kachi *et al.*, 2019; Iyer *et al.*, 2021). There is a need, therefore, to consider the adoption of national net-negative targets as well as policy mechanisms to facilitate international transfers (Kachi *et al.*, 2019; Lee, Fyson and Schleussner, 2021; Mohan *et al.*, 2021). These

[20] This has since increased to 147 countries in the latest assessment from the Net Zero Tracker (Net Zero Tracker, 2024b).

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 (Buylova *et al.*, 2021; Schenuit *et al.*, 2021).

CDR methods remove CO_2 from the atmosphere and permanently store it in geological, terrestrial, or ocean reservoirs, or in products (IPCC, 2018). 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 (Tanzer and Ramírez, 2019). 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. BECCS and DACCS (Griscom *et al.*, 2017; Fuss *et al.*, 2018). 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 (Bellamy and Osaka, 2019; Woroniecki *et al.*, 2020; Osaka, Bellamy and Castree, 2021; Markusson, 2022). However, we use our two main groupings as it most accurately reflects the categorisations used within long-term national climate strategies.

Separately, we analyse CCS and 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 (Bruhn, Naims and Olfe-Kräutlein, 2016). 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 (De Kleijne *et al.*, 2022). 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 (De Kleijne *et al.*, 2022). 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 (Maher, 2018; Hepburn *et al.*, 2019). The role of CCUS in decarbonisation is contested (Mac Dowell *et al.*, 2017; De Kleijne *et al.*, 2022), 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.

3.2.1 Role and relevance of long-term national climate strategies

The Paris Agreement has two relevant reporting obligations towards national net zero planning: NDCs [Article 4, paragraph 2] and LT-LEDS [Article 4, paragraph 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 (Moe and S. Røttereng, 2018; Fyson and Jeffery, 2019; Mace *et al.*, 2021), whilst the consideration of engineered CDR is limited (Buylova *et al.*, 2021; Mcelwee, 2022). 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 (Honegger *et al.*, 2021). CDR may have a national role in accelerating near-term mitigation prior to a national net zero target (Fyson and Jeffery, 2019) and post, in achieving net-negative emissions (Honegger *et al.*, 2021). Compensating for residual emissions, however, appears to be the primary emphasis for national governments (Schenuit *et al.*, 2021).

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 the end of 2020 (UNFCCC, 2016b), referred to as the '*submission date*' in Figure 14. LT-LEDS have a longer-term focus allowing more detailed consideration of CDR methods, governance, and feasibility (Thoni *et al.*, 2020; Buylova *et al.*, 2021; Mace *et al.*, 2021). They are one of the few areas of reporting within the UNFCCC where CDR, conceptually, is explored (Thoni *et al.*, 2020; Buylova *et al.*, 2021; Honegger *et al.*, 2021; Förster *et al.*, 2022).

Considerable discretion is given to national governments about the design of LT-LEDS in comparison to NDCs. In practice LT-LEDS are highly varied 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 (Rocha and Falduto, 2019). 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 (Waisman *et al.*, 2019). Given the general absence of CDR within current policy processes (Peters and Geden, 2017), 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 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 (Buylova *et al.*, 2021), or the criteria of assessment used to discern their feasibility at the national level (Thoni *et al.*, 2020). We see a need, however, for an overview of CDR on the more recent and larger sample of LT-LEDS now available.

3.3 Materials & methods

3.3.1 Materials

We analysed all LT-LEDS published in English by the UNFCCC Secretariat before 1st January 2022, plus one EU LTS for Estonia (Figure 14). For each strategy, we analysed the full text (a total of 3,885 pages), using analytical categories based upon inductive and deductive coding (Azungah, 2018). Full detail of our approach can be found in the Methods section (Section 3.3.2). Most strategies were published in 2020 and 2021 (22/41 strategies) by countries in the Global North (Figure 14). 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 (Blicharska *et al.*, 2017). 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 GHG 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) (Rocha and Falduto, 2019; Jaber, Anderson and Nachtigall, 2020). 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 a 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 (Buylova *et al.*, 2021). 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 Figure 14.

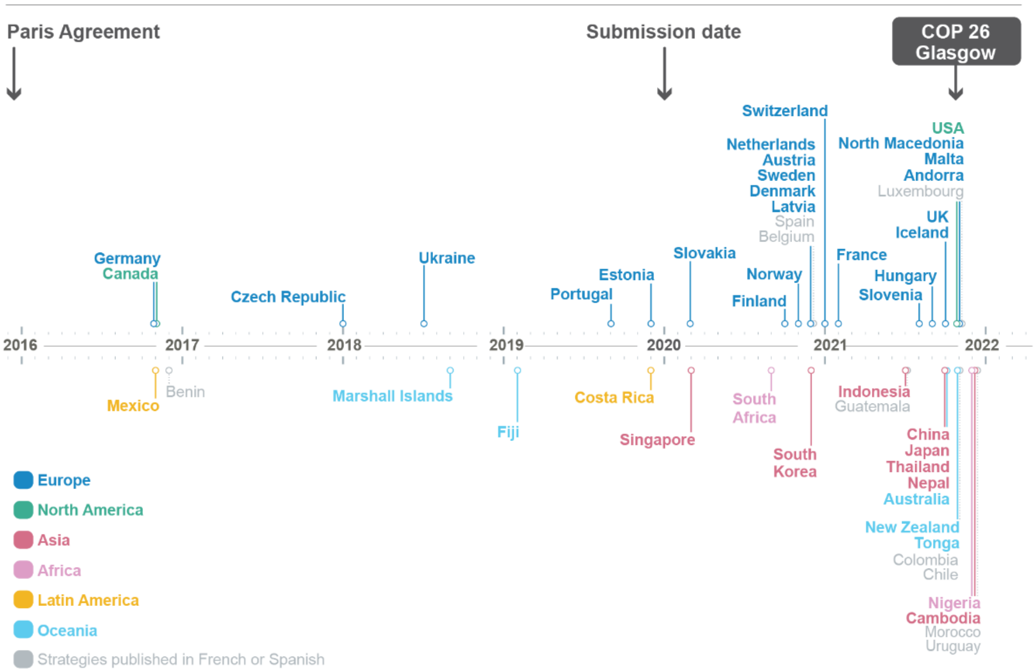

Figure 14. Timeline of submissions of Long-term national climate strategies to the UNFCCC Secretariat or European Commission, categorised by region.

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 UNFCCC, held in Glasgow, UK. '*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).

3.3.2 Methods

We use NVivo (Release 1.5.1), a computer-assisted software commonly used for qualitative data analysis (QSR International Pty Ltd, 2021), 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 (Azungah, 2018). 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), 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*' (Hennink, Kaiser and Marconi, 2017), 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 BECCS and 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 (Cox *et al.*, 2021), for example, ocean iron fertilization or OAE (Gattuso *et al.*, 2021). 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) (Dooley and Gupta, 2017). This nomenclature does not readily map to common categorisations of nature-based CDR, instead LULUCF 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 NGHGI '*memo*' items, such as the emissions nationally attributable from IAS. 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, 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 (Rogelj *et al.*, 2015) (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 (Jeffery *et al.*, 2018). 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 (Buylova *et al.*, 2021). 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 (Thoni *et al.*, 2020; Buylova *et al.*, 2021). 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 the Supplementary Data for the published output of this chapter, Smith, Vaughan and Forster, 2022.

3.4 Results

3.4.1 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 (Fyson and Jeffery, 2019; Kaya *et al.*, 2019; McLaren *et al.*, 2019). 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 5. 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, or the radiative impact of aerosols (Jeudy-Hugo, Lo Re and Fadulto, 2021). 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 IAS. Ten countries note the prospective or intended use of international offsets, or otherwise transferred mitigation outcomes, further complicating the extent of domestic emission reductions.

Table 5. Long-term targets stated in long-term national climate strategies.

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.

Target type	Stated target	Country	Negative emission quantification	All sectors	All GHGs	No international offsets	IAS 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	✓	✓	✓	✓	×
	Carbon neutrality by 2050	Cambodia	✓	✓	✓	–	–

Target type	Stated target	Country	Negative emission quantification	All sectors	All GHGs	No international offsets	IAS included
	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	×	✓	–	–	×

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 5). This could be explained by the target being achievable through emission reduction measures alone (for example, 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 (for example, the use or non-use of international offsets).

Ambiguity in targets is a common problem identified by literature (Rogelj *et al.*, 2015; Jeudy-Hugo, Lo Re and Fadulto, 2021), but in mobilising CDR, ambiguity has notable implications, as the target definition determines the extent of CDR required (Iyer *et al.*, 2021). 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 (Lomax *et al.*, 2015). '*Locking-out*' is also foreseeable with differences in sectoral coverage, such as the inclusion, or exclusion, of emissions from IAS. Emissions from IAS are typically considered under international bodies, such as the IMO, but are readily calculated by countries through national emission inventories, on a fuel basis (Selin *et al.*, 2021). A range of methods now support national allocation considering past failures to reduce emissions (Selin *et al.*, 2021), and the view that these emissions are hard-to-abate (Davis *et al.*, 2018). 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 (Kachi *et al.*, 2019). 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 (Mace *et al.*, 2021; Rogelj *et al.*, 2021).

3.4.2 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 6). This aligns with previous analyses of smaller samples of strategies (Thoni *et al.*, 2020; Buylova *et al.*, 2021). 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 6). 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 (Griscom *et al.*, 2017; Smith *et al.*, 2019) and their integration into prior policy mechanisms (Carton *et al.*, 2020). 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 in 2050 are quantified in 20 long-term national climate strategies (Figure 15). 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 (Figure 15). Other strategies also rely on forest carbon, but demonstrate a sizeable projected sink compared to residual emissions, such as Nepal and Fiji (Figure 15). 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 6) reports the net balance of the land-use carbon sink historically and in future projections. 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 further documented in the Supplementary Data for the published output of this chapter, Smith, Vaughan and Forster, 2022.

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 (Mace *et al.*, 2021).

Table 6. Modelled quantification, qualitative consideration, or speculative consideration of CDR methods contained in long-term national climate strategies.

'*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.

Country	Sink Status		Quantification or consideration of CDR in 2050 (values in $MtCO_2$)							
			Nature-based CDR				CCUS	Engineered CDR		
	Historic	Future	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	✓	✓		

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
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				

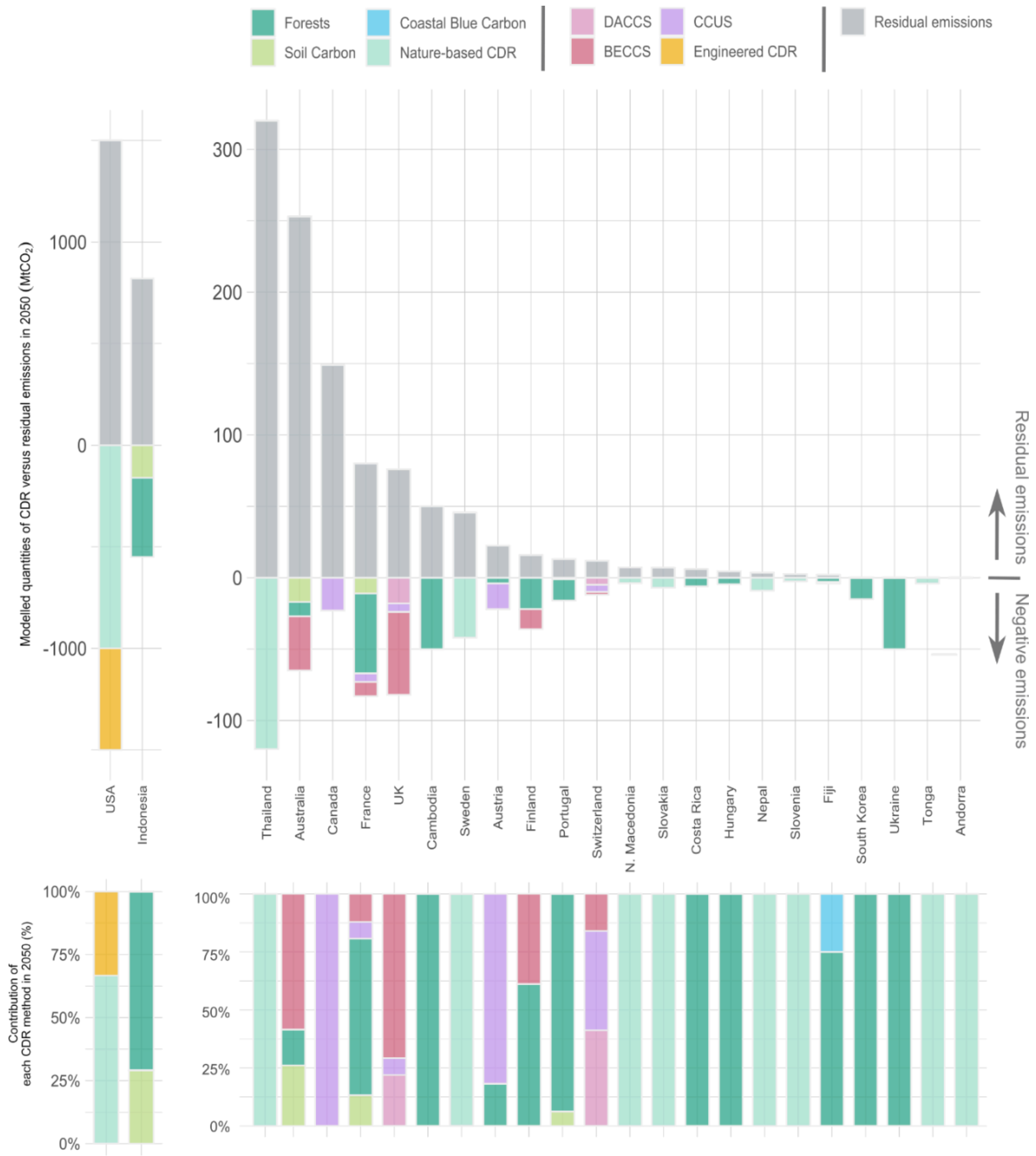

Figure 15. Long-term national climate strategies that quantify CDR and residual emissions in 2050.

'*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.

3.5 Emerging challenges

Our analysis reveals two major challenges within 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 (Thoni *et al.*, 2020; Waller *et al.*, 2020). Wider dimensions of feasibility, such as the socio-cultural, should be more widely explored (Thoni *et al.*, 2020; Waller *et al.*, 2020; Brutschin *et al.*, 2021).

3.5.1 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 (Smith, 2016; Bossio *et al.*, 2020), prone to disturbances (Anderegg *et al.*, 2020) and limited in the long-term owing to saturation (Smith, 2016; Bossio *et al.*, 2020). Historically, country estimates of carbon sinks in forests and soils have been limited by data availability and estimation methodologies, leading to large uncertainties (Grassi *et al.*, 2018; Fyson and Jeffery, 2019). 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 (for example, 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 (Nabuurs *et al.*, 2013; Anderegg *et al.*, 2020). 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 (Brack and King, 2021). 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 (Griscom *et al.*, 2017; Smith *et al.*, 2019). Engineered CDR similarly faces substantial challenges in deployment owing to the rates of infrastructure construction (Nemet *et al.*, 2018), the availability of low-carbon energy, and ultimately economic and accessible geologic storage (Fuss *et al.*, 2018).

National net zero is best characterised as a state to be attained and continued rather than a target momentarily achieved in a single year (Fankhauser *et al.*, 2022). National net-negative targets may be required in the case of overshooting Paris Agreement temperature targets (Boysen *et al.*, 2017; Fuss *et al.*, 2020), or from a justice perspective of allowing some countries to decarbonise more gradually (Lenzi *et al.*, 2021; Mohan *et al.*, 2021). In this context nature-based CDR may ultimately play a sequential role towards CDR methods able to deliver continual negative emissions (Energy Transitions Commission, 2022). 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.

3.5.2 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 (Geden and Schenuit, 2020).

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 (Kachi *et al.*, 2019; Maher and Symons, 2021). 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 (Kachi *et al.*, 2019). Net zero planning may therefore grow increasingly interconnected as CDR becomes a more prominent feature of climate policy.

3.6 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 5), 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 gas and sector coverage, treatment of IAS, 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 (Thoni *et al.*, 2020). 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 (Carton *et* *al.*, 2020). The importance of nature-based methods should not be readily dismissed, most notably, they are unique in helping to address multiple societal challenges (Seddon *et al.*, 2020). Namely the need to enhance biodiversity and the need to both adapt and mitigate climate change (Seddon *et al.*, 2020). 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 (Dooley, Nicholls and Meinshausen, 2022; Matthews *et al.*, 2022). 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 5). 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.

4 Residual emissions in long-term national climate strategies show limited climate ambition

This chapter was published as '*Residual emissions in long-term national climate strategies show limited climate ambition*' in the journal One Earth in May 2024, accessible at: https://doi.org/10.1016/j.oneear.2024.04.009. In January 2025, minor amendments were made to the article to align with the format of the thesis.

4.1 Abstract

Net zero targets imply a need to compensate for residual emissions through the deployment of CDR methods. Yet the extent of residual emissions within national climate plans, alongside their distribution, is largely unexplored. Here, we analyse 71 long-term national climate strategies to understand how national governments engage with residual emissions. Screening 139 scenarios, we determined that only 26 of the 71 strategies quantify residual emissions. Residual emissions are on average 21% of peak emissions for Annex I countries, ranging from 5-52% (excluding land-use). For non-Annex I countries, residual emissions are on average 34%. By sector, agriculture represents the largest contributor to total residual emissions (on average 36% for Annex I countries and 35% for non-Annex I). High residual emission scenarios, show how some countries may retain or expand their fossil fuel production and use, using more CDR or international offsets to achieve net zero.

4.2 Introduction

Net zero targets have rapidly become the new norm of national climate policy. As of December 2023, 150 countries[21] have adopted a form of net zero or neutrality target, accounting for 82% of global GHG emissions (M. W. Jones *et al.*, 2023; Net Zero Tracker, 2023). As targets are adopted, national governments have begun to develop policy plans, scenarios, and pathways, aimed towards the fulfilment of net zero (Buylova *et al.*, 2021). Operationalising net zero as a national target has led to increased attention towards residual emissions, an emerging concept in climate governance to describe emissions entering the atmosphere at the point of net zero, counterbalanced by negative emissions, necessitating the use of CDR (Buck *et al.*, 2023; Schenuit, Boettcher and Geden, 2023). CDR, a range of methods that remove carbon dioxide (CO_2) from the atmosphere, permanently storing carbon in terrestrial or geological sinks (Babiker *et al.*, 2022), is therefore seen as a necessary and implicit element of reaching a national net zero target, legitimised by its connectedness to residual emissions (Honegger *et al.*, 2022). Despite being central to the logic of net zero, to date, there has been limited focus towards analysing both the extent and distribution of residual emissions within national climate plans.

At the international level, NDCs describe the level of near-term climate policy ambition across countries. Given the timing of national net zero targets around the mid-century and NDC's near-term focus on climate action this decade, NDCs do not readily detail residual emissions, nor CDR, beyond the removals typically part of the land-use sector, a long-standing part of global climate policy (Fyson and Jeffery, 2019; Wiese *et al.*, 2021; Mcelwee, 2022). In addition to NDCs, the Paris Agreement also supports the communication of LT-LEDS. These strategies are supported by scenario or pathway modelling to the mid-century or beyond, covering net zero targets where set. Given this longer-term focus on climate action, these strategies directly assess the extent and distribution of residual emissions, contextualising the balance of emissions across an economy at the point of net zero.

From a governance perspective, residual emissions may be defined as gross emissions entering the atmosphere at the point of net zero (Buck *et al.*, 2023; Schenuit, Boettcher and Geden, 2023), meaning they are those emissions counterbalanced by negative emissions. Residual emissions, however, are commonly associated with emissions considered '*hard-to-abate*' or '*difficult to decarbonise*', implying a limit in efforts to reduce emissions (Buck *et al.*, 2023; Schenuit, Boettcher and Geden, 2023). Residual and hard-to-abate emissions are analytically distinct but commonly conflated concepts. Owing to their

[21] This has, since the publication of this chapter, been revised downward to 147 countries (Net Zero Tracker, 2024b). See footnote [9] for further discussions as to the national net zero targets and the data sources available.

difficulty of abatement, emissions from hard-to-abate sources are likely to be residual and therefore indirectly mitigated through CDR, as opposed to directly abated at source. Residual emissions describe emissions at the point of net zero irrespective of their difficulty of abatement. Turning a national net zero target into tangible policy measures requires the modelling of future scenarios and policy projections (Aro *et al.*, 2022; Green and Reyes, 2023). Defining residual emissions, in practice, therefore, involves projecting those emissions that are likely to be hard-to-abate, relative to the development of CDR, setting out a possible trajectory to net zero.

In literature, residual emissions are anticipated from; long-range transport, such as aviation and shipping; energy-intensive industries, such as steel, cement, and chemicals; and agriculture, particularly sources of non-CO_2 emissions, such as those emitted by livestock or fertiliser application (Davis *et al.*, 2018; Frank *et al.*, 2018; Bataille, 2020; Leahy, Clark and Reisinger, 2020; Babiker *et al.*, 2022). These sources are said to be hard-to-abate owing to limits to the available technologies for further reducing emissions, or further emission reductions being prohibitively expensive (Geden, Peters and Scott, 2018; Honegger *et al.*, 2021). This logic arises from IAMs, where residual emissions are said to be those emissions whose abatement remains infeasible or uneconomical under model and scenario designs (Luderer *et al.*, 2018; Hilaire *et al.*, 2019). IAMs are limited by their representation of sectors and mitigation options, meaning they are useful in outlining total emissions globally, or across an economy, but insufficient in understanding the precise nature of residual emissions (Bataille, Nilsson and Jotzo, 2021; Fritzeen *et al.*, 2023).

Bottom-up sectoral assessments are more specific as to why certain sources are considered hard-to-abate or residual. Several studies highlight the technical or physical dynamics of emissions sources (Davis *et al.*, 2018; Energy Transitions Commission, 2018; Bataille, 2020). Industrial sub-sectors, such as the production of steel, cement, and chemicals, lead to process emissions, directly tied to reactions within the production process, independent of the emissions released by the fuel combusted for energy (Rissman *et al.*, 2020). Production also requires high-temperature heat, energy requirements that to date have been met through the combustion of fossil fuels (Madeddu *et al.*, 2020; Thiel and Stark, 2021). Whilst decarbonisation can be aided through demand-side measures, such as material efficiency (Fennell *et al.*, 2022; Watari *et al.*, 2022), the production process itself must be directly abated, requiring fundamental changes and new means to meet heat requirements. Steel production can be decarbonised by remaking the steel-making process, reducing iron ore using green hydrogen, as opposed to coke (Vogl, Åhman and Nilsson, 2018), and by promoting circularity by greater rates of scrap recycling within electric arc furnaces, powered by low-carbon electricity (Bataille *et al.*, 2018; Rissman *et al.*, 2020). Similarly conventional blast furnaces, currently used to produce most primary steel, can be retrofitted with CCS, continuing to use fossil fuels or alternatively combusting biomass (Fan and Friedmann, 2021). The use of green hydrogen and the retrofitting of plants with CCS is currently limited to pilot projects and company plans, and decarbonisation of the sector depends on their commercialisation alongside the retirement or replacement of conventional blast furnaces (Vogl, Olsson and Nykvist, 2021; Mission Possible Partnership, 2022; de Villafranca Casas *et al.*, 2024).

Cement emissions may be reduced by replacing a proportion of the clinker with alternative materials (Napp *et al.*, 2014), the electrification of cement kilns or the combustion of biomass for heat (Fennell *et al.*, 2022; Marmier, 2023). Owing to the ability to address both process and combustion emissions, retrofitting cement plants with CCS remains a prominent option (Rissman *et al.*, 2020; Marmier, 2023). In cases where emissions are captured, and the use of conventional fossil fuels remains, residual emissions are likely owing to limits to the capture rate, meaning 10-20% of emissions may remain unabated (Energy Transitions Commission, 2018; Brandl *et al.*, 2021). The production of two chemicals, ammonia and methanol, accounts for 70% of emissions from the chemical sector (IEA, 2023a). Both require hydrogen, currently produced through steam methane reforming, a conversion of water and natural gas to hydrogen and carbon monoxide (Schiffer and Manthiram, 2017). Gas feedstocks could be eliminated by using green hydrogen produced by electrolysis (Schiffer and Manthiram, 2017).

Long-range transport, such as aviation and shipping, in existing modes of operation, require energy dense fuels, limiting the common strategy of the electrification of transport or the use of hydrogen (Davis *et al.*, 2018; Bergero *et al.*, 2023). Aviation emissions may be reduced by improvements in energy efficiency, whilst synthetic kerosene, synthesized from green hydrogen and captured CO_2 offers the best prospects of reducing or eliminating emissions from the sector (Bergero *et al.*, 2023; Sacchi *et al.*, 2023). Synthetic ammonia or methanol may offer a route to decarbonise global shipping, similarly reliant on the availability of green hydrogen (International Renewable Energy Agency, 2021). Non-CO_2 emissions from agriculture originate from several biological sources, such as the nitrous oxide generated in soils from the application of nitrogen fertiliser, or methane emissions from the fermentative digestion of livestock (Smith *et al.*, 2007). Connecting these sectors is the commonality that emissions can be reduced but not eliminated. Mitigation options to eliminate the remaining emissions, or enable deeper decarbonisation, are in the early phases of commercial development or policy support. Sources within transport and industry are notably dependent on the development of a new green hydrogen economy (International Renewable Energy Agency, 2020; Ueckerdt *et al.*, 2021; Odenweller *et al.*, 2022).

Emission sources may also be hard-to-abate, owing to the arrangements, market dynamics, and expectations of certain sectors. Unlike the decarbonisation of the power and road transport sectors, that benefit from the mass production and standardisation of solar panels, wind turbines and electric vehicles (Malhotra and Schmidt, 2020), industry emissions are characterised by high-design complexity, with technology configured for a wide array of emissive processes and end-users (Bergek *et al.*, 2023). Assets in aviation, shipping, and steel, also have high upfront capital costs and long asset lifetimes, limiting the rate of replacement or retirement within existing business models (Fan and Friedmann, 2021; Bullock, Mason and Larkin, 2022; Bergero *et al.*, 2023). Both aviation and industrial sectors are subject to growth in demand, with growth in passenger numbers and freight (Brazzola, Patt and Wohland, 2022; Bergero *et al.*, 2023), and increasing demand globally for industrial materials and chemicals (Bataille, 2020; Paltsev *et al.*, 2021; Tilsted *et al.*, 2023). Steel, cement, and chemicals are highly trade-exposed industries with slight operating margins, historically shielding firms from climate policy, owing to the risk of relocating to avoid carbon pricing (Åhman, Nilsson and Johansson, 2017; Fan and Friedmann, 2021; Oberthür, Khandekar and Wyns, 2021). Where carbon pricing has been introduced, for example, in the EU Emissions Trading System, free allowances have been granted to firms, limiting their need for abatement (Åhman, Nilsson and Johansson, 2017). Decarbonising these sectors therefore requires a shift in their governance, through carbon border adjustment mechanisms or climate clubs, minimising any losses to competitiveness (Hermwille *et al.*, 2022). Emissions sources may also be strategically important for priorities beyond climate mitigation. Food security is a common priority for national governments and stringently mitigating agricultural emissions may impact upon food availability, leading to a limited potential for emission reductions (Frank *et al.*, 2017; Fujimori *et al.*, 2022). Similar strategic logics may deem emissions from the health sector or military as limited in terms of decarbonisation (Schenuit, Boettcher and Geden, 2023).

Residual hard-to-abate emissions, therefore, not only reflect the cost or the availability of abatement, but also the technical and physical dynamics of emissions sources, their complexity, lifetime and demand, and policy priorities beyond climate mitigation (Davis *et al.*, 2018; Bataille, 2020). These wider dynamics are analogous to carbon lock-in, whereby a combination of technology and norms collectively limit the extent of decarbonisation (Erickson *et al.*, 2015; Seto *et al.*, 2016). Within the logic of net zero, residual emissions serve as the basis for the integration of CDR (Honegger *et al.*, 2021; Smith, 2021), informing the near-term regarding CDR's role and scale in climate policy (Fuss *et al.*, 2020; Iyer *et al.*, 2021). A country with high projected residual emissions, for example, would require a comparatively high level of CDR deployment, or acquire and transfer mitigation outcomes from other countries to reach a net zero target (Lee, Fyson and Schleussner, 2021). Large requirements for CDR would place greater pressure on national resources, such as energy, land, and water (Fuhrman *et al.*, 2023; Deprez *et al.*, 2024) and pose greater challenges in attaining public support (Waller, Cox and Bellamy, 2024). It would risk later, more stringent mitigation, to reach a certain temperature target, if the required CDR fails to materialise (Larkin *et al.*, 2018; Grant *et al.*, 2021). Determining the appropriate scale of CDR, therefore, must account for the anticipated scale of residual emissions, pairing these within climate policy frameworks.

LT-LEDS are national reports that address principally climate mitigation, but often integrate a focus on macroeconomic development and climate adaptation, forming a holistic strategy (UNFCCC Secretariat, 2023; Cruanyes, Alcaraz and Sureda, 2024). Under Article 4, paragraph 19 of the Paris Agreement, parties must strive to formulate and communicate LT-LEDS. These are intended to inform the ambition of NDCs, with the NDCs acting as intermediate targets along the long-term pathway set out in LT-LEDS (Hans *et al.*, 2020). Given their focus on the mid-century or beyond and on quantified mitigation pathways, they are not only contrasted against NDCs but unique in their focus amongst other reporting obligations under the UNFCCC, such as Biennial Reports and National Communications. Unlike NDCs, however, LT-LEDS are not mandatory. For many countries, LT-LEDS serve mainly as illustrative documents, rather than prescriptive plans, leaving the extent of their influence on national climate policy unclear. Nevertheless LT-LEDS are among the few reference points available for the mid-century. The conclusion of the first Global Stocktake at COP28, held in the United Arab Emirates, further encouraged Parties to the UNFCCC to revise or communicate LT-LEDS prior to COP29, aligning strategies with their newly strengthened NDCs. LT-LEDS may therefore increasingly play a formative role within the UNFCCC.

LT-LEDS have previously been used to explore national expectations towards CDR and residual emissions (Thoni *et al.*, 2020; Buylova *et al.*, 2021; Buck *et al.*, 2023; Jacobs, Gupta and Möller, 2023). Analyses directed towards CDR have focused on the conceptual role of CDR within national climate policy (Buylova *et al.*, 2021), the criteria used to discern their feasibility (Thoni *et al.*, 2020), and the prominence of nature-based CDR methods within strategies (Jacobs, Gupta and Möller, 2023). A previous analysis of residual emissions analysed only low residual emissions scenarios within LT-LEDS, using an inconsistent mapping of sectors across countries (Buck *et al.*, 2023). Given the long-held concern that CDR may reduce emission reduction efforts (Carton *et al.*, 2023), so called '*mitigation deterrence*', this criterion may limit our understanding towards the national expectations of CDR deployment, given mitigation deterrence may be more evident in high residual scenarios. Nor are these residual emissions compared to peak emissions, a measure commonly used to compare decarbonisation efforts across countries (Lamb *et al.*, 2022; Bersalli, Tröndle and Lilliestam, 2023). Similarly, there is a need to understand what residual emissions relate to, both in terms of the sub-sectors and sources contained within sectors, in addition to what may motivate a certain emission to be considered residual (Brad, Haas and Schneider, 2024). Expanding upon previous analysis using the more recent and larger sample of strategies now available, we address this gap, showing that residual emissions represent a sizeable proportion of peak emissions, with an average 21% of peak emissions for Annex I countries, ranging from 5-52% (excluding land-use). High residual emission scenarios, show how some countries may retain or expand their fossil fuel production and use, using more carbon dioxide removal or international offsets to achieve net zero. We show that agriculture represents the single largest sector as a proportion of residual emissions, contributing on average 36% to total residual emissions for Annex I countries and 35% for non-Annex I. Agriculture also represents the sector in which the least progress is anticipated, with a reduction on average of only 37% for Annex I countries compared to 2021 GHG emissions. Despite agriculture's large contribution to residual emission totals, Industry, notably emissions from the production of steel and cement, and the use of fluorinated gases, are largely the focus of textual statements concerning residual or hard-to-abate emissions. We end by outlining three ways in which residual emissions may be addressed in future climate policy efforts.

4.3 Results

4.3.1 Methods summary

We analysed all 67 national LT-LEDS submitted to the UNFCCC before the start of October 2023. The European Union (EU) mandates the creation of national long-term strategies (EU LTS) for Member States, meaning many strategies have a dual status, serving as a country's submission to the UNFCCC, as a LT-LEDS, and a submission to the European Commission, as an EU LTS. We therefore include the EU LTS for Croatia, Estonia, Italy, and Greece within our sample, mirroring the 16 strategies with dual status for other EU Member States. We exclude the submission to the UNFCCC from the EU, as this is supranational in scope and superseded by strategies from Member States (European Commission, 2020), which within our sample cover 23 Member States of the EU27. In total, our sample covers long-term national climate strategies for 71 countries.

We read and coded over 6,600 pages, across the 71 strategies within our sample, screening a total of 139 national scenarios and pathways. We screened scenarios to collate estimates of total and sectoral residual emissions, which we define as gross emissions entering the atmosphere at the point of net zero greenhouse gases, excluding net emissions or removals from LULUCF, and removals from engineered CDR methods. Engineered CDR refers to those methods that are currently deployed at small scales compared to the scale of removals in the LULUCF sector (Nemet *et al.*, 2023). For the purposes of this analysis, engineered CDR refers to BECCS and DACCS. We then compare total residual emissions to peak emissions within the historical timeseries for each country, as a measure of the climate ambition implied by scenario or pathway modelling.

Strategies typically detail sectoral residual emissions according to their own sectoral classifications. To allow for comparison across countries, we allocated sectoral emissions to a consistent sectoral split, based upon the logic of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (hereafter '*IPCC NGHGI Guidelines*'), detailing emissions from Energy, Industry, Transport, Agriculture, and Waste. We determine the proportion of residual emissions from each sector, by comparing sectoral to total residual emissions, and determine the level of mitigation implied, comparing sectorial residual emissions to 2021 GHG emissions. To further contextualise residual emission estimates, we read and inductively coded all statements relating to residual or hard-to-abate emissions, developing a series of '*rationales*', as to why a certain emission may be residual or hard-to-abate, and a typology of sources and sub-sectors considered residual or hard-to-abate.

Combined our sample accounts for the majority of economic activity and global emissions, covering 87% of global gross domestic product in 2021 (World Bank, 2023) and 71% of GHG emissions (M. W. Jones *et al.*, 2023). The vast majority, 49 of the 71 strategies, were recently published between 2021-2023. Geographically, the majority of the strategies analysed are from Europe and Asia (45), with only eight from African states and four from South America. A full list of LT-LEDS analysed, including the title, status, and translation, can be found in the dataset accompanying this chapter, detailed in Experimental Procedures, Section 4.6. See Section 4.6, for further detail regarding our methodology.

4.3.2 Total residual emissions

41 strategies, the majority of our sample, fail to quantify residual emissions, either through a lack of modelling of scenarios or pathways, or limitations to the modelling itself. This includes major emitters such as China, India, and Russia. China and India present no scenario or pathway modelling, but have a net zero target, implying residual emissions. Russia presents two scenarios up to and including 2050, stopping short of Russia's net zero by 2060 target. Four countries are net-negative according to their recent assessment of national emissions, including Belize, Bhutan, the Solomon Islands and Vanuatu. These countries therefore put forward pathways in their LT-LEDS that further reduce gross emissions

whilst ensuring economic development. Given that this pathway poses a fundamentally different challenge to a net zero pathway, reducing emissions to align with existing or enhanced carbon sinks, we do not consider these estimates as residual.

26 LT-LEDS produce an estimate of residual emissions, with 16 estimates from Annex I countries and 10 from non-Annex I countries (Figure 16). For 13 Annex I countries, scenarios reach net zero GHGs in 2050, whilst Finland and Iceland include scenarios for 2040. Eight non-Annex I countries reach net zero GHGs in 2050, whilst Thailand includes a scenario reaching net zero GHGs in 2065. Mean residual emissions for Annex I countries are 21% relative to peak emissions, or 23% when excluding partial residual emission estimates (Figure 16). Residual emissions are, on average, 25% of 2021 GHG emissions for Annex I countries, with a range of 10% (UK, Spain) to 55% (Australia).

Mean residual emissions for non-Annex I countries are 34% relative to peak emissions (Figure 17A), excluding Cambodia, which increases its emissions above its 2021 level but reaches net zero GHGs by transforming its LULUCF sector (termed ‘FOLU’ for forestry and other land-use, in Cambodia’s strategy) from a net-source to a large net-sink. Residual emissions are, on average, 41% of current GHG emissions for non-Annex I countries, excluding Cambodia, with a range of 6% (Oman) to 96% (Ethiopia). Eight countries present multiple scenarios for residual emissions. Countries such as Australia and Canada, show a range of residual emissions depending on the scenario, with Australia ranging from 36-52% of peak emissions and Canada 17-44%. Scenarios with a high proportion of residual emissions tend to rely more heavily on the scaling-up of engineered CDR methods. In the case of Australia, we observe a large reliance on the procurement of international offsets to reach net zero, with these offsets compensating up to 55% of the residual emission total. The majority of Annex I countries, have residual emissions within the range of 5-15% of peak emissions, or 10-24% when compared to 2021 GHG emissions.

The extent of past decarbonisation is also captured, for example, the UK has similar levels of both current and residual emissions to France, but has decarbonised further than France considering peak emissions, with 2021 emissions 47% lower than peak emissions in 1991, compared to just 26% for France. In absolute terms, both LT-LEDS exhibit similar levels of ambition in reducing further emissions (Figure 17B).

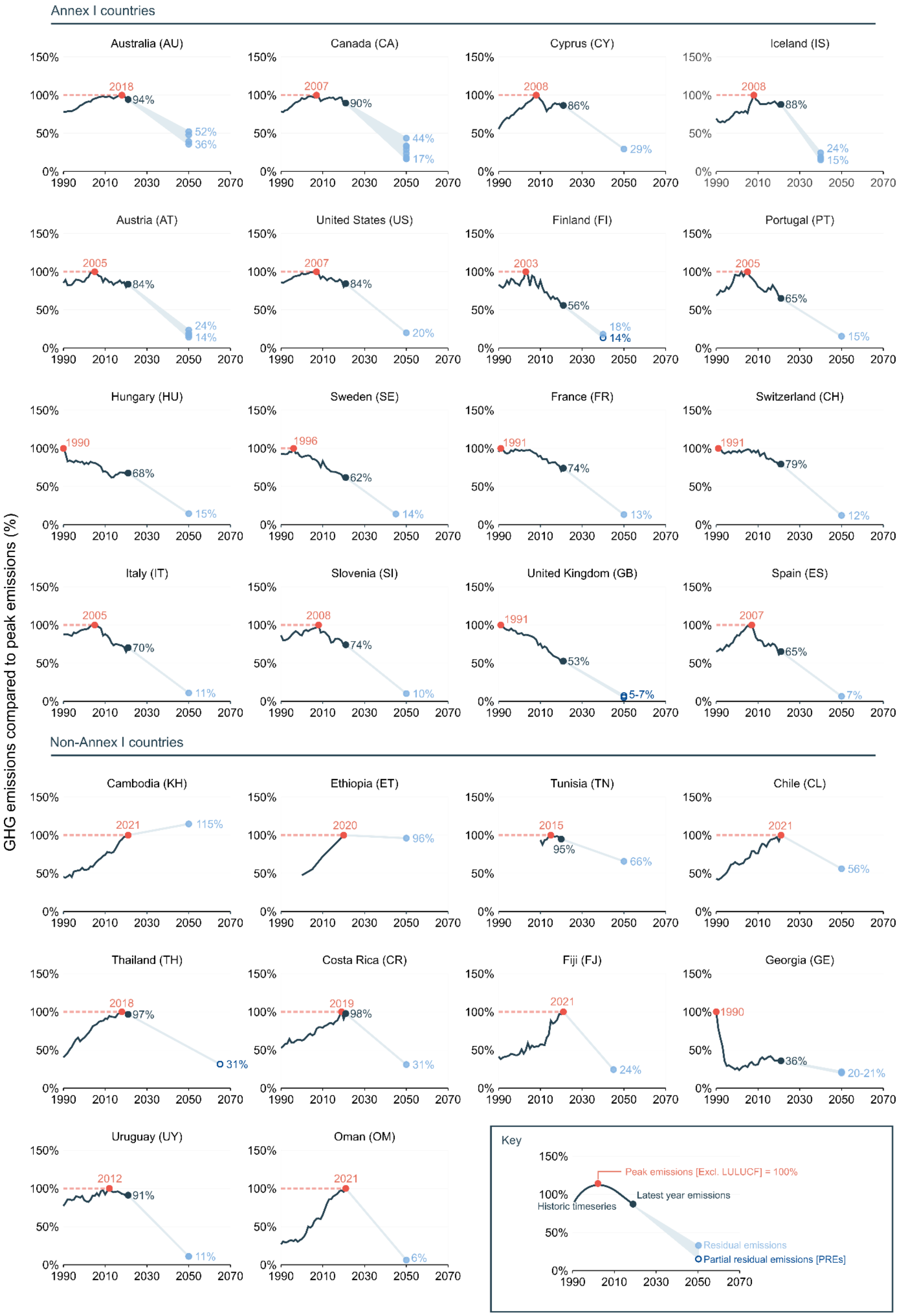

Figure 16. Residual emissions compared to current and peak emissions.

Points in red refer to peak emissions excluding land use, land-use change, and forestry (LULUCF). Dark-blue lines detail the historic time series excluding LULUCF. Dark-blue points represent emissions in 2021, or, for Ethiopia and Tunisia, 2020.

Residual emissions are displayed in light blue. Light-blue shading represents a linear trajectory from 2021 or 2020 to residual emissions estimates at the year of net zero greenhouse gases. This is indicative only and not representative of the modelled scenario or pathway. Percentages are relative to peak emissions, with peak emissions equal to 100%. Partial residual emissions are shown using a white point with blue outline. These are estimates that include a limitation in determining residual emissions, such as the combination of negative emissions from carbon dioxide removal (CDR) with positive emissions, where this practice is not already established (as is the case with LULUCF)—for example, bioenergy with carbon capture and storage (BECCS) in the electricity sector. In these cases, the precise level of residual emissions is obscured by the presentation of the data within the strategy. Countries ordered by percentage residual emissions, for both Annex I and non-Annex I categories.

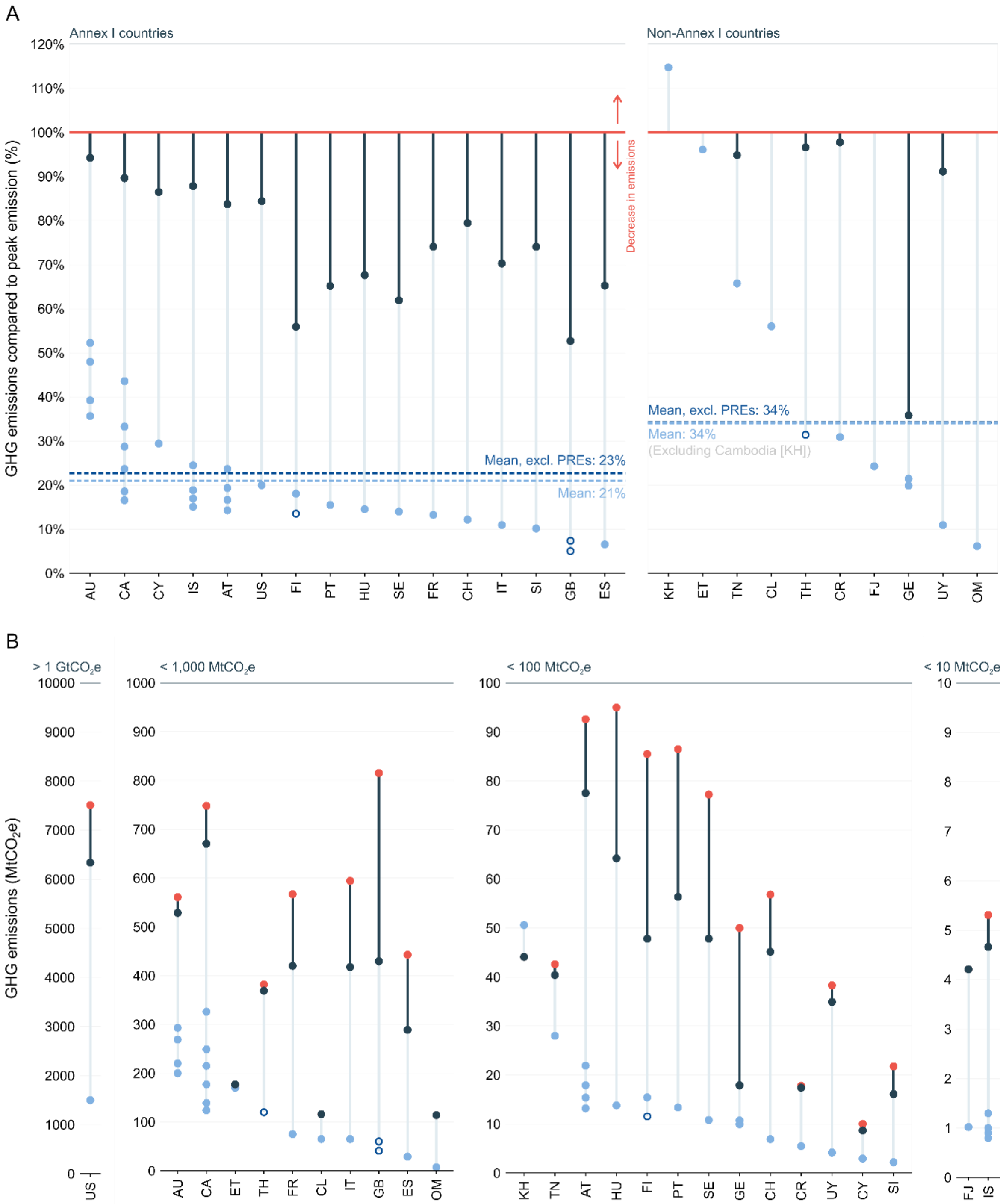

Figure 17. Residual emissions compared to current and peak emissions in absolute relative terms.

(A) Details of current and residual emissions relative to peak emissions, with peak emissions = 100% (red line). Dark-blue points represent emissions in 2021, or, for Ethiopia and Tunisia, 2020. Residual emissions are displayed in light blue. Partial residual emissions are shown using a white point with blue outline. These are estimates that include a limitation in determining residual emissions, such as the combination of negative emissions from CDR with positive emissions, where this practice is not already established (as is the case with LULUCF)—for example, BECCS in the electricity sector. Two means are produced, a mean including all residual emission estimates, shown as a light-blue dashed line, and a mean excluding partial residual emissions, shown in darker blue. Residual emissions relate to different dates for net zero greenhouse gases across countries, ranging from 2040 to 2065. (B) Residual, current, and peak emissions in absolute terms, categorized by four classes based on peak emissions: >1 $GtCO_2e$, <1,000 $MtCO_2e$, <100 $MtCO_2e$, and <10 $MtCO_2e$. Points in red refer to peak emissions excluding LULUCF. Dark-blue line details the historic time series excluding LULUCF. Dark-blue points represent emissions in 2021, or, for Ethiopia and Tunisia, 2020. Residual emissions are displayed in light blue. Partial residual emissions are shown using a white point with blue outline. Countries are shown according to their alpha-2 country code, defined in ISO 3166. See Figure 16 for reference between country codes and official names. Countries ordered by percentage residual emissions, for both Annex I and non-Annex I categories.

4.3.3 Sectoral residual emissions

Figure 18 details residual emissions by sector (See Figure A 2, Annex II – Chapter 4, for detail on what each sector covers). Across all scenarios, agriculture tends to be the largest single sector as a proportion of total residual emissions, contributing, on average, 36% for Annex I countries and 35% for non-Annex I. For countries such as Fiji, Ethiopia, Switzerland, Spain, France, Slovenia, and Sweden, agricultural emissions represent the majority of residual emissions, upwards or equal to 50% (Figure 18). The energy sector contributes, on average, 26% of residual emissions for Annex I countries, and 16% for non-Annex I. Energy, however, is a large category inclusive of many sources beyond electricity generation, notably residential combustion. Where further disaggregation is possible, as is the case for France, Slovenia, Sweden, Switzerland and the UK, emissions from 'buildings' are between 18-71% of energy-related residual emissions. Several countries, including Austria, Cambodia, Costa Rica, Thailand, Tunisia, and Uruguay specify only energy and transport as a single total. We therefore include in Figure 18 an estimation of the proportion of residual emissions where both sectors are combined, inclusive of those countries that specify only this combined total. Energy and transport combined total, on average, 37% of residual emissions for Annex I countries and 45% for non-Annex I. Residual emissions in transport are, on average, only 10% of total residual emissions for Annex I countries and 11% for non-Annex I. This excludes international aviation and shipping. Industry contributes, on average, 19% for Annex I countries, and 18% for non-Annex I. This average includes cases of industrial combustion and process emissions combined, highlighted in Figure 18, but principally includes emissions from industrial processes and fluorinated gases (f-gases). Waste represents a small but persistent contribution to residual emissions, averaging around 9% for Annex I countries and 6% for non-Annex I.

Agriculture represents the sector in which the least progress is anticipated, with a reduction on average of only 37% for Annex I countries relative to 2021 emissions (Figure 19). Similarly, only a modest reduction is seen for agriculture in non-Annex I countries, with a reduction on average of 51%. The energy sector, by the time of net zero GHGs, has largely been decarbonised relative to 2021 emissions, with an 84% reduction on average for Annex I countries. Transport has been decarbonised to a similar extent, with an 83% reduction on average for Annex I countries. Non-Annex I countries, as with Figure 18, tend to report energy and transport as a single total. Similarly, the PRIMAP dataset (the dataset used for historic emissions for non-Annex I countries, see Experimental Procedures, Section 4.6), owing to limitations in data granularity, does not present transport as a separate total for the historic timeseries. We therefore assess for non-Annex I countries the reduction in the combined total. When combined, emissions from energy and transport are reduced, on average, by 65% relative to current emissions. Not shown in Figure 19, is the combined total for Cambodia. Cambodia doubles its emissions by 2050 for energy and transport, enabled by a large transformation in LULUCF from a net source to a net sink. Increases in emissions are not considered when calculating mean reductions. Industrial emissions for Annex I countries are reduced by 70%, on average, when compared to 2021 emissions, or by only 45% for non-Annex I countries. Australia, in select scenarios, increases its industrial emissions relative to 2021. Ethiopia, similarly, increases its emissions by a factor of eight, starting from a low industrial base. Waste emissions are reduced by 71%, on average, when compared to 2021 emissions for Annex I countries, or by 65% for non-Annex I countries.

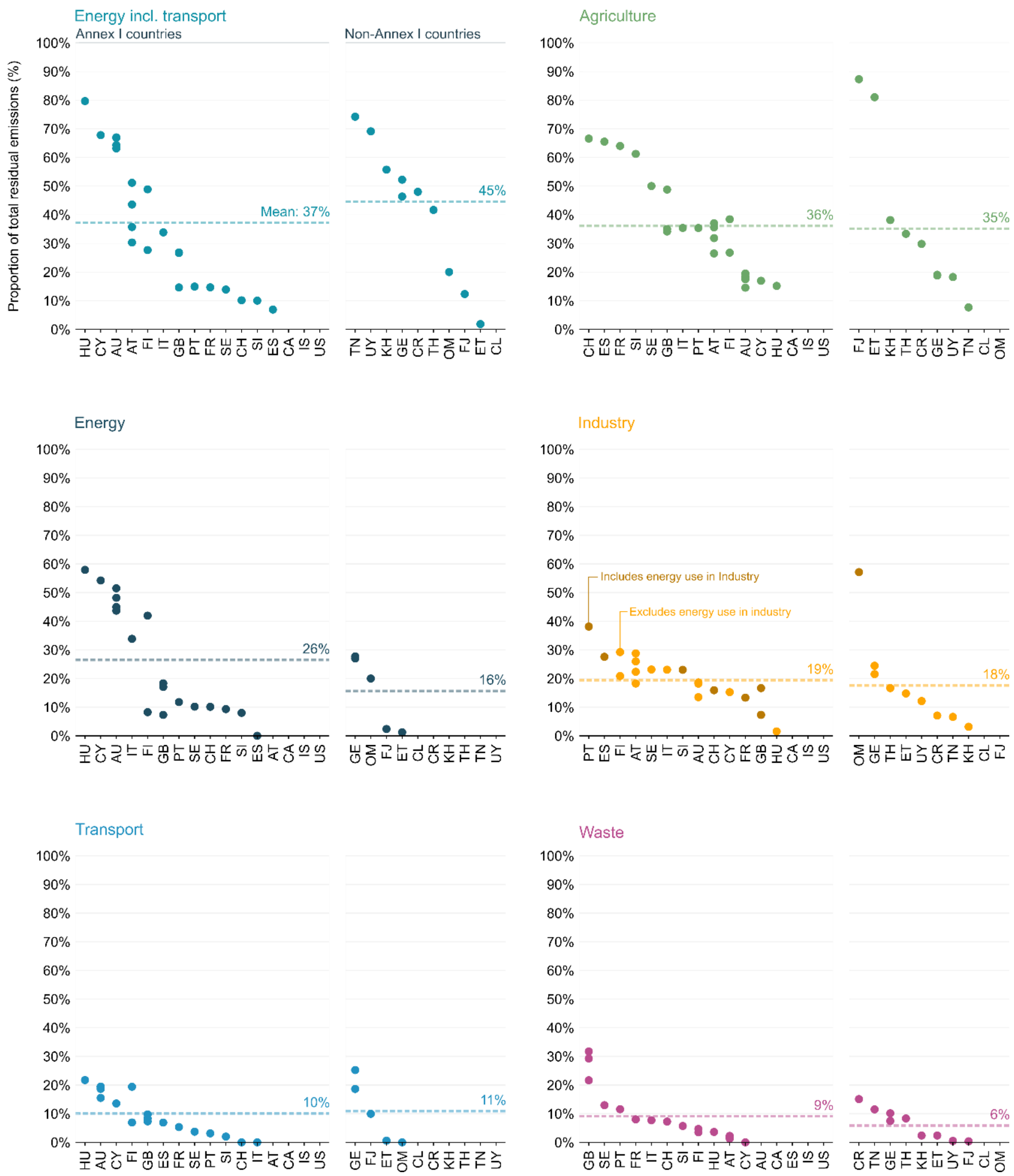

Figure 18. Proportion of residual emissions by sector.

The proportion of total residual emissions for each sectoral total. Points represent results for individual scenarios. Horizontal dashed lines represent the mean for Annex I and non-Annex I countries. Countries with no points are cases where no sectoral data are supplied for the specified sector. Not shown are ‘*other*’ or unlabelled residual emissions and, when included, ‘international aviation and shipping’. Data for these sectors can be found in the dataset accompanying this chapter, accessible through Section 4.6. Countries are shown according to their alpha-2 country code, defined in ISO 3166. See Figure 16 for reference between country codes and official names. Countries ordered within each sector by proportion of total residual emissions, for both Annex I and non-Annex I categories. See Figure A 2, Annex II – Chapter 4, for detail on what each sector covers.

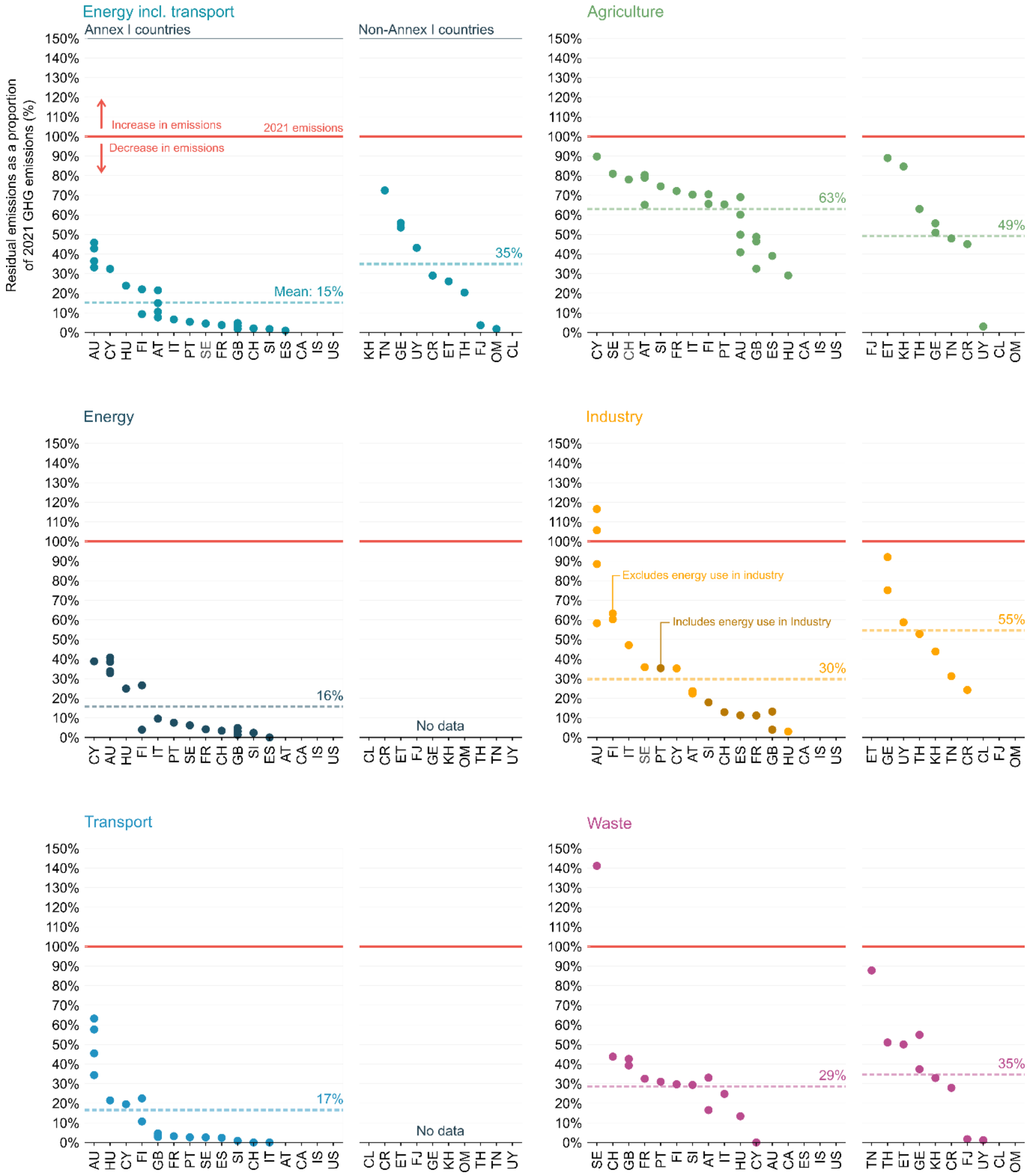

Figure 19. Residual emissions by sector as a percentage of current emissions.

Current emissions represent GHG emissions in 2021 or, for Ethiopia, emissions for 2020. Current emissions equal 100%. Less than 100% represents a decrease in emissions, with greater than 100% representing an increase. Horizontal dashed lines represent the mean for Annex I and non-Annex I countries, excluding scenarios that increase emissions. Not shown are cases where increases in emissions are greater than 150%, applying to Cambodia, for energy including transport, Fiji, for agriculture, and Ethiopia, for industry. Data for these cases can be found in the dataset accompanying this chapter, accessible through Section 4.6. Not shown are 'other' or unlabelled residual emissions and, when included, '*international aviation and shipping*'. Data for these sectors can be found in the dataset accompanying this chapter, accessible through Section 4.6. Countries are shown according to their alpha-2 country code, defined in ISO 3166. See Figure 16 for reference between country codes and official names. Countries ordered within each sector by residual emissions as a proportion of 2021 emissions, for both Annex I and non-Annex I categories. See Figure A 2, Annex II – Chapter 4, for detail on what each sector covers.

4.3.4 Residual emissions rationales

We identified 357 statements within our sample of LT-LEDS relating to residual or hard-to-abate emissions. Many of these statements describe specific sources or sub-sectors, in addition to a supporting rationale or proposed policy solution. A complete and consistent mapping of policy solutions, however, is limited by the lack of detail presented in many strategies and common inaccuracies in the use of terminology (Olfe-Kräutlein *et al.*, 2022).

Figure 20 details these statements by sub-sector and source. Unlike the trend observed in Figure 18, where agriculture is the primary sector concerning residual emissions, Industry is the focus of Figure 20, with a total of 232 statements. 109 statements, nearly half, are associated with three main sub-sectors, cement production (48), fluorinated gases ['*F-gases*'] (36), and steel production (25). Transport (140 statements) primarily concerns emissions from aviation (50), heavy road transport (38), alongside shipping (29). Agriculture (72 statements) is, by contrast, rarely discussed, nor detailed in relation to sources and sub-sectors, with only eight mentions of livestock. Energy (65 statements), although highly decarbonised in residual emission scenarios compared to current emissions (Figure 19), is associated with a range of residual emission sources, including fossil fuel production and combustion. This may reflect the use of CCS within electricity generation or the combustion of fuels for industrial heat. A prominent source within Energy is buildings (19), corroborating albeit limited evidence found in the scenarios.

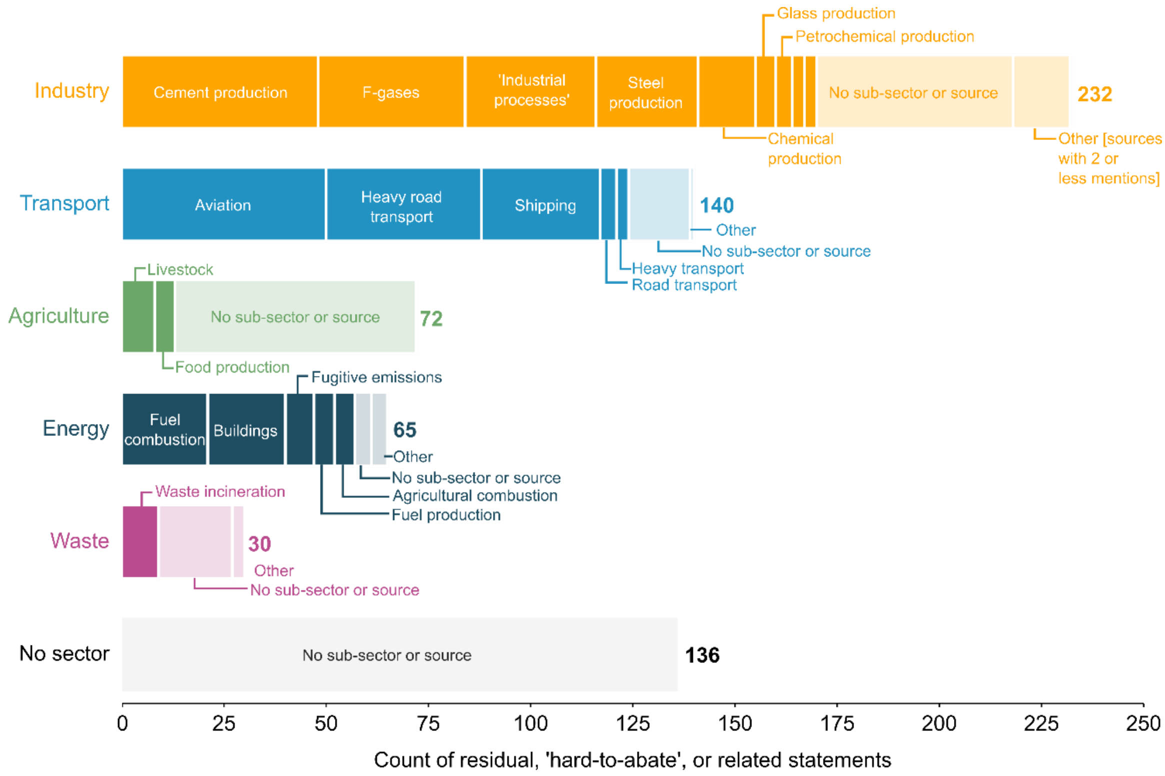

Figure 20. Count of residual, 'hard-to-abate', or related statements by sub-sector or source.

The figure is divided into main sectors. Waste incineration is assigned to waste; however, if waste is combusted to generate electricity or heat, this would be treated as energy under the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC NGHGI guidelines). A single statement can include one or more sources or sub-sectors. '*No sector*' describes those statements without a specific sector or sub-sector/source. '*No sub-sector or source*' describes statements that are attributable to a main sector but provide no attributable detail as to the sub-sector or emission source. '*Other*' contains all sub-sectors and sources with two or fewer mentions across our sample.

Table 7 details seven '*residual emission rationales*', analytical categories based on the coding of statements concerning residual or '*hard-to-abate*' emissions. Figure 21 details counts of these rationales by sector. For industry, residual or hard-to-abate emissions are justified by stressing the further need for research, development and demonstration of mitigation options that enable deep decarbonisation ('*limited innovation*' 50 statements). For example, both Spain and Italy stress the need for further innovations in decarbonising steel production through hydrogen. Industry sources are similarly supported by the rationale that mitigation options have been exhausted, yet some level of emissions remain ('*limited further abatement*', 49 statements). For example, Ireland claims that 'there is no known way to deliver complete decarbonisation in some industry sub-sectors, such as cement', meaning the sub-sector [*emphasis* added] 'will need to *reduce emissions as much as possible* and use negative emissions to offset these remaining emissions'. Transport is similarly supported by technical or physical limitations to decarbonisation (54 statements), with countries detailing the limited possibilities of electrification of long-range or heavy transport modes, necessitating the need to develop synthetic or biomass-based fuels, or the continued use of conventional fuels, such as fossil kerosene in aviation. Residual or hard-to-abate emissions in agriculture are principally supported by the rationale of '*limited further abatement*' (27 statements). The United States, for example, claim [*emphasis* added] 'the agriculture sector, cannot be abated in the 2050 timeframe *even after applying all available mitigation technologies*, and will have to be offset by negative CO_2 emissions'. Cost is commonly cited as justification for residual or hard-to-abate emissions but is not the primary rationale for any sector. Countries envisage a decrease in costs through technological learning, meaning currently expensive abatement options will become progressively more cost-effective over time.

Several rationales are indicative of an approach beyond innovation, technology, or cost. Demand is rarely used to justify residual emissions, for example, it is the fourth most common rationale in agriculture, yet where used demonstrates policy priorities beyond climate mitigation. Switzerland, for example, notes that 'some agricultural emissions are likely to remain even after 2045 [the date of Switzerland's net zero target]' owing to the introduction of a national food strategy, mandating the increase of domestic food production. South Korea highlights the need for a more gradual transition in the building sector owing to the [*emphasis* added] 'city gas used…for heating and cooking has a *nationwide distribution network of pipelines already in place*, which makes it *difficult to fully decarbonize*', implying a path dependency in gas infrastructure. Spain details a concern regarding f-gases, given their use in applications with long lifetimes (15-50 years in Spain, depending on the application). Spain therefore anticipates remaining emissions in 2050, owing to the limited rate at which these applications could be replaced, even if alternative blends with lower global warming potentials are developed. In all sectors '*no specific rationale*', describing cases where residual or hard-to-abate emissions are simply stated without a supporting rationale, is notably common.

Table 7. Residual emission rationales.

The example column details national examples from our coding, with bold added to emphasise key phrasing. Examples have been lifted from each country's respective LT-LEDS. Full detail of each LT-LEDS, alongside detail as to how these can be accessed, can be found in the dataset accompanying this chapter, detailed in Experimental Procedures, Section 4.6. The full coding of residual emission rationales, including the examples detailed in Table 7, can also be found in the accompanying dataset.

Residual emission rationale	Description	Example
Lack of low-cost abatement	Low-cost abatement technologies do not yet exist to abate a certain emission source.	*'**Low-cost abatement technologies do not yet exist** for hard-to-abate sectors like steel, chemicals and cement.'* (Australia, p.76, Australia's Long-Term Emissions Reduction Plan)
Limited further abatement	A level of emissions remain either after all technologies or policy options for direct abatement are exhausted.	*'While waste emissions can be reduced through recycling and landfill improvements, they cannot be eliminated entirely **due to the limitations of current technologies and policy options**'* (Marshall

Residual emission rationale	Description	Example
		Islands, p.14, Tile Til Eo - 2050 Climate Strategy 'Lighting the Way')
Gradual transition	Legacy infrastructure, assets, or the pace of social and structural change result in a need for a more gradual transition within a specific sector.	*'Some transportation segments, such as aviation,* ***will likely remain difficult to electrify and some legacy vehicles will continue to be necessary in the near term****, both of which would require alternate sources of low-carbon fuels that have yet to be deployed at the necessary scale.'* (United States, p.35, The Long-Term Strategy of The United States)
Demand	The sector producing emissions is foundational to a certain economy or subject to demand growth, limiting abatement.	*'Steel, chemicals, and cement are the industries with the highest GHG emissions within the industrial sector.* ***At the same time, they produce essential basic materials for German industry****. Technical negative emissions will be necessary to offset unavoidable residual emissions and ensure the attainment of the climate targets after 2045.'* (Germany, p.5-6, Update to the long-term strategy for climate action of the Federal Republic of Germany)
Technical/physical limitation	A specific technical or physical limitation to a certain emission process limits abatement.	***'GHG emissions from the farming sector mostly come from the biological reactions taking place from food production processes****. Therefore, it is impossible to remove the sector's entire GHG emissions, but still there are many mitigation technologies available for use.'* (South Korea, p.11, 2050 Carbon Neutral Strategy of The Republic of Korea)
Limited Innovation	Further innovations in new technologies are required in order to abate a certain emission.	*'Due to the limited capacity of current technologies, there are still emissions from energy and IPPU.* ***However, with future technological advancements, this can be avoided and reduced****.'* (Nepal, p.12, Nepal's Long-term Strategy for Net-zero Emissions)
Trade-off	Progress in reducing emissions from a specific sector, reduce the need for emission reductions in other areas.	*'With lower residual emissions in aviation and improvement in capture or negative emission potential,* ***end use sectors such as transport, buildings, agriculture and industrial dispersed sites can decarbonise to a lesser extent****.'* (United Kingdom, p.73, UK Net Zero Strategy)

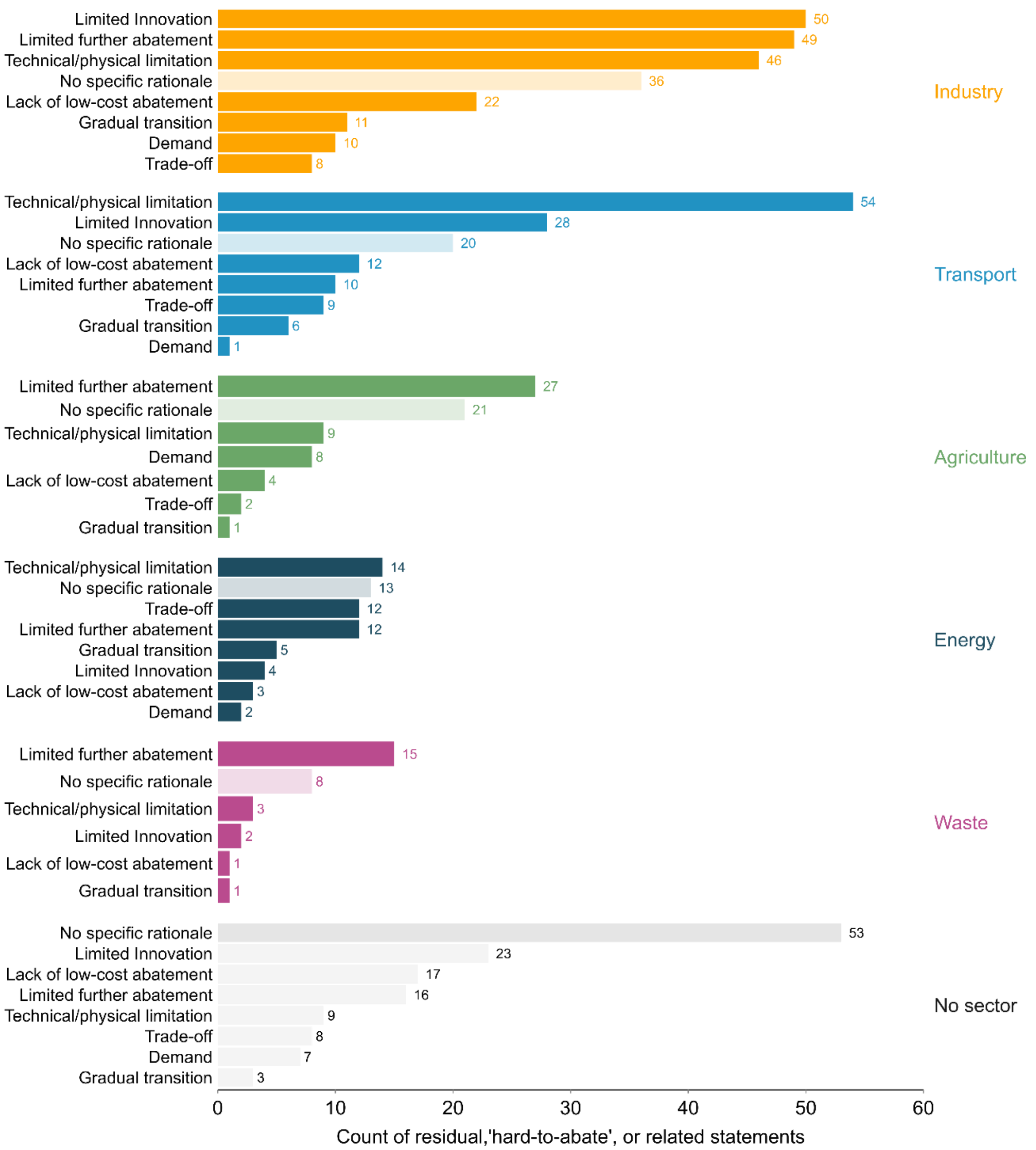

Figure 21. Count of residual, '*hard-to-abate*', or related statements by sector and rationale.

Waste incineration is assigned to waste; however, if waste is combusted to generate electricity or heat, this would be treated as energy under the IPCC NGHGI guidelines. A single statement can include one or more rationales. Rationales ordered from high to low for each sector.

4.4 Discussion

Net zero is now well-established as the goal of global climate policy, strongly supported by climate science (Allen *et al.*, 2022). Net zero as a national target, however, raises new and difficult questions for national governments (Elliott *et al.*, 2023; Green and Reyes, 2023) - questions such as what the balance of emission reductions and CDR should be, both at the national level and across different economic sectors. At the national level, residual emissions are treated as technical, political, and economic choices about sources or sectors where governments shift the effort of reducing emissions elsewhere. In our analysis of national scenarios, this shift of effort often falls to changes to land management, the development and deployment of engineered CDR methods, or to other countries, in the form of international offsets. Strategies with high residual emission scenarios, show how some countries may attempt to retain or expand their fossil fuel production and use, by using more CDR to achieve net zero. Given the known limits of CDR methods, this risks the credibility of their target and risks a failure to meet national and global net zero (Mace *et al.*, 2021; Rogelj *et al.*, 2023).

Our analysis underlines that residual emissions within national scenarios represent a sizeable proportion of peak and current emissions. Our results are comparable to Buck *et al.*, 2023, which details an analysis of only low residual emission scenarios from LT-LEDS for 18 Annex I countries, with a mean of 18% of 2019 GHG emissions. We present an updated analysis, inclusive of new strategies published or revised since mid-2022 and inclusive of all scenarios. Our estimates are markedly higher owing to the range of scenarios presented by Canada and Australia, with a mean of 25% of 2021 GHG emissions for Annex I countries, ranging from 10-55%.

In the case of Canada, differences in scenarios reflect divergent approaches to decarbonisation, with the '*High Use of Engineered CO_2 Removal Technologies*' scenario representing the highest level of residual emissions. Reaching net zero GHGs, in this scenario, is contingent upon the potential that [*emphasis* added] 'if CO_2 removal technologies are deployed rapidly and at a large scale, *fossil fuel production and consumption could remain higher than in other scenarios.*' Australia's scenario logic concerns the prevalence of international carbon markets, as opposed to technology choice, but similarly shows the same dynamic, with the highest residual emissions occurring in the scenario that retains the highest absolute level of energy-related emissions, compensated by the procurement of international offsets. Cambodia's scenario increases energy-related emissions compared to 2021, advocating for increased investment in natural gas combustion and only limited renewable energy penetration, compensated by the reversal of deforestation and transformation of Cambodia's LULUCF sector into a substantial net sink. These, albeit limited examples, substantiate the long-held concern that expanding CDR may lead to reduced ambition in the phase-out of fossil fuels (Asayama, 2021; Carton *et al.*, 2023).

Climate policy frameworks should guard against reduced ambition by introducing separate targets, separating between the LULUCF sector, removals from engineered CDR methods, and emissions reductions elsewhere in an economy, reducing substitution (McLaren *et al.*, 2019; Geden and Schenuit, 2020; Carton, Lund and Dooley, 2021). Figure 22 depicts a comparison between a low residual emission scenario, based upon separate targets, versus a high residual scenario that allows for greater substitution of emission reductions with CDR from both LULUCF and engineered methods. Figure 22A depicts Portugal's Framework Climate Law, which requires a 90% emission reduction in emissions by 2050 relative to 2005, excluding LULUCF, with a separate target for LULUCF, on a net basis, of 13 $MtCO_2$/year, representing the maintenance of the existing carbon sink and the remaining mitigation. Canada's '*High Use of Engineered CO_2 Removal Technologies*' scenario (Figure 22B) similarly maintains net LULUCF at historic levels, but greatly expands engineered CDR to 113 times the current global capacity of 2 $MtCO_2$/year (Powis *et al.*, 2023), to retain a higher level of fossil fuel production and use. Real world examples of separate targets are already evident in the policy frameworks of Portugal, Lithuania, and Sweden, suggesting real world applicability. For countries with an existing LULUCF net sink, this serves as an entry point to separate targets, which, if treated as a minimum bound, can preserve the integrity of emission reductions, with any additional deployment of CDR or offsets beyond this bound used to enhance ambition, by achieving net zero or net-negative sooner (Geden and Schenuit, 2020).

Similarly, developing a norm on the use of CDR may help further differentiate between what may be seen as legitimate and illegitimate use. Switzerland detail within their LT-LEDS, that CDR, in relation to Switzerland's emissions, should 'only be used on the condition that no greenhouse gases from fossil energies which could be avoided through technical measures will be emitted by 2050 at the latest'. Phase-out norms, such as coal phase-out dates, have grown in popularity within UNFCCC negotiations and national climate policy (van Asselt and Green, 2023). For engineered CDR, '*phase-in*' norms, prescribing the ultimate and legitimate use may further consolidate the role of CDR within domestic and international climate policy. The IPCC provides an initial starting point, by defining the role of CDR in net zero to '*counterbalance residual emissions from hard-to-transition sectors*' within the 2022 AR6 WGIII report (Babiker *et al.*, 2022). Operationalising this role requires an understanding of what emission sources are hard-to-transition.

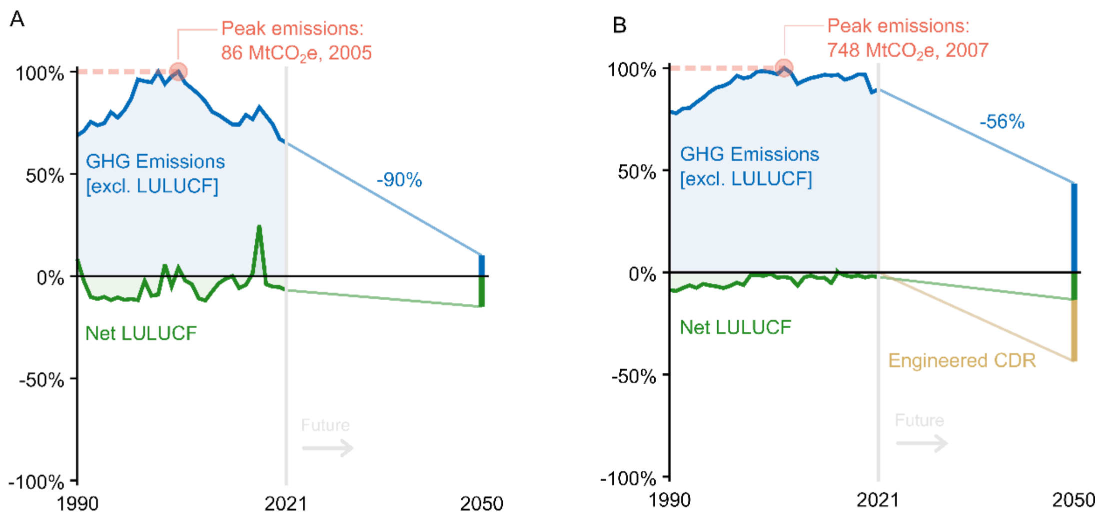

Figure 22. Comparison of a low-residual scenario and a high-residual scenario.

(A) Portugal's pathway to net zero greenhouse gases, based on Portugal's Framework Climate Law no. 98/2021, informed by the modelling contained within Portugal's long-term low-emission development strategy (LT-LEDS). This includes a 90% reduction, excluding LULUCF, relative to the 2005 peak, with a separate target for LULUCF. Under this framework, Portugal would achieve net zero GHGs in 2045–2050. (B) Canada's '*high use of engineered CO_2 removal technologies*' scenario from Canada's LT-LEDS. Here a 56% reduction upon peak emissions is modelled relative to 2007, excluding LULUCF. Historical data for greenhouse gas (GHG) emissions is from UNFCCC national GHG inventories for 1990–2021. The peak year equates to 100%, with the rest of the data normalized to this level. Both Portugal and Canada have similar timing in terms of peak emissions and maintain LULUCF to 2050 at a level similar to their historical inventory. Engineered CDR, in the case of Canada, refers to bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

Sectoral analysis suggests residual emissions from agriculture are underrepresented as a focus relative to agriculture's contribution to residual emissions and the limited abatement observed in scenarios. Industry, notably emissions from the production of steel and cement, and the use of f-gases, are largely the focus by comparison. Statements concerning residual and hard-to-abate emissions are typically used to delineate between more certain and known abatement options and what are considered '*technological bets*', subject to further research, development, and deployment. Countries stress the uncertainty of these options, for example, Japan's LT-LEDS notes the difficulty of estimating '*the outcome of the technology development or innovation to fulfil the 2050 goal*'. Expectations towards the deployment of low-carbon technologies are continually revised, meaning what may be considered hard-to-abate is dynamic according to emerging research, technological developments, and progress in deployment (Malhotra and Schmidt, 2020; Thiel and Stark, 2021; Perdana *et al.*, 2023). An iterative approach to residual emissions, therefore, appears necessary. In cases where residual emissions are supported by rationales that present a path dependency, requiring a more gradual transition, changes to business models and asset management may be needed. For example, by aligning innovation and investment cycles, ensuring that low-carbon options prove commercially viable before the need for further investment in a carbon intensive asset (Vogl, Olsson and Nykvist, 2021).

Whilst countries detail the prospect of innovations further reducing residual emissions, our analysis suggests many treat the inevitability of residual emissions as a foregone conclusion. For many strategies '*no specific rationale*', describing cases where residual or hard-to-abate emissions are simply stated without a supporting rationale, is common across all sectors. Treating residual emissions as an inevitability risk de-emphasising these emissions, further locking-in high emitting activities and infrastructure, and locking-out alternative means of mitigation (Peeters *et al.*, 2016; Buck *et al.*, 2023). Further decarbonisation of residual hard-to-abate emissions may be possible if demand reduction is considered a viable or necessary policy prescription to pursue beyond the technological options available, by, for example, reducing meat consumption or modal shifts away from aviation (Sharmina *et al.*, 2021; Ivanovich *et al.*, 2023; Sacchi *et al.*, 2023). The extent to which the scenarios and strategies assess demand reduction, beyond efficiencies, is uncertain. There are, however, explicit cases of residual emissions being defined relative to demand. Switzerland defines '*difficult-to-avoid*' emissions as those that 'cannot be prevented with technical measures alone'. Compensating for these emissions via CDR is conditional on the basis that [*emphasis* added] 'these emissions *cannot be reduced by using alternatives or through avoidance'*. Italy similarly notes that residual emissions may be further reduced, not only by new technologies, but by '*disruptive changes*' in citizens' habits, including a '*change in the diet that would affect the agricultural sector*'. This recontextualises residual emissions as constructed on claims of what activities are socially necessary and what actions are possible or compatible with national priorities (Lund *et al.*, 2023). Further unpacking these assumptions can lead to a change in national approach whereby demand-side transformations are more readily explored in strategies and policies (Sharmina *et al.*, 2021).

Moving from target setting to implementation requires national governments to identify, design, and implement the necessary policies to transform their economy, all within a matter of decades (Waisman *et al.*, 2019; Buck *et al.*, 2023). LT-LEDS have been proposed as a means of adding credibility to this transformation (Rogelj *et al.*, 2023). Our analysis, however, suggests this opportunity is largely missed, with most countries within our sample, either failing to include scenario modelling or pathways, or including pathways that are limited by timing or design, precluding an assessment of the quantitative aspects of net zero targets. Given the gap between the expectation within guidance, that scenarios are key features within LT-LEDS (Rocha and Falduto, 2019; Jaber, Anderson and Nachtigall, 2020), and their lack in practice, LT-LEDS need further guidance or requirements under the UNFCCC. Past studies have called for standardising an understanding of residual emissions within LT-LEDS (Buck *et al.*, 2023), or the transition of LT-LEDS from an optional to compulsory obligation, to inform debates around the role and extent of CDR within national climate policy (the published output of Chapter 3).

4.5 Conclusion

National governments now face the challenge of moving from target to practice (Green and Reyes, 2023). Our analysis of 71 long-term national climate strategies suggests residual emissions, though central to the logic of net zero, remain largely unexplored. In the limited cases where residual emissions are quantified, our analysis suggests residual emissions may constitute a sizeable proportion of peak and current emissions, and in select cases represent limited sectoral decarbonisation and the retention or expansion of fossil fuels. We observe a mismatch between the sectoral contribution of agricultural emissions to residual emissions in scenario modelling and pathways, and the focus of strategies towards industrial emissions as residual and hard-to-abate. Different sectors are similarly supported by different rationales, yet there is a tendency to treat residual emissions as an inevitability. Strengthening guidance and reporting requirements for LT-LEDS will further improve engagement with residual emissions, offering greater transparency towards national net zero targets. We offer three ways forward. Firstly, separate targets for emission reductions and removals can ward against high residual fossil-fuel scenarios by reducing the substitution of emission reductions with CDR. Secondly, treating residual emissions as a focus of innovation efforts, iterating according to progress in research, development, and deployment. Thirdly, recontextualise residual emissions as activities that are perceived as necessary and limited by what is deemed possible or compatible with national priorities, allowing for the exploration of alternative means of mitigation beyond technology, such as the role of demand-side transformations.

4.6 Experimental procedures

All data extracted from long-term national climate strategies is available at Zenodo, under the DOI 10.5281/zenodo.10972619 (ref. Smith, 2024). This dataset contains a full list of LT-LEDS analysed, including the title, status, and translation, alongside the underlying residual emission data extracted from strategies, and the coded statements relating to residual or hard-to-abate sources. This chapter also analyses existing publicly available data. The PRIMAP dataset is publicly available at Zenodo under the DOI 10.5281/zenodo.4479171 (ref. Gütschow and Pflüger, 2023). UNFCCC greenhouse gas data for Annex I countries available from the following URL, https://di.unfccc.int/time_series.

We examined all instances of scenario or pathway modelling across our sample of 71 long-term national climate strategies. Following the definition of residual emissions as emissions entering the atmosphere at the point of net zero, we screen scenarios to collate estimates of total and sectoral residual emissions. Residual emissions may be defined at the point of carbon neutrality, or net zero CO_2, or climate neutrality, referring to net zero GHGs. Owing to the commonality of the net zero GHG target, for example, 99 of the 150 national net zero targets currently set include multiple greenhouse gases (Net Zero Tracker, 2023), we focus on net zero GHGs in our definition of residual emissions. This also captures non-CO_2 residual emissions from agriculture (Hilaire *et al.*, 2019). Given that the date of national net zero targets within our sample ranges from 2040 (Iceland) to 2070 (India), these estimates describe emissions entering the atmosphere at different points in time. In select cases, residual emission estimates differ in scope, by, for example, including emissions from international aviation and shipping or by combining negative emissions from engineered methods of CDR, such as BECCS, with positive emissions in sectoral totals.

Emissions from IAS are treated as '*memo items*' within the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (hereafter '*IPCC NGHGI Guidelines*'), meaning they are excluded from the estimates of national emissions reported to the UNFCCC (IPCC, 2006c) and commonly excluded from the scope of national net zero targets (Net Zero Tracker, 2023). Owing to their cross-border nature, emissions are managed by international bodies, though countries such as the United Kingdom have since included IAS within their net zero target (Committee on Climate Change, 2019). Given current practice is to exclude these emissions, we similarly exclude these emissions from our assessment when otherwise included. Similarly, though the accounting of negative emissions within sectoral totals follows the logic of the current IPCC NGHGI Guidelines, accounting for emissions and removals in the sectors in which they occur (IPCC, 2006c), doing so obscures the extent of, and reliance upon, CDR methods (Köhnke *et al.*, 2023). We therefore remove from estimates of residual emissions the inclusion of negative emissions from engineered CDR methods. Where not possible, we apply partial corrections, by, for example, subtracting the minimum extent of negative emissions if a sectoral total is net-negative. We highlight these instances within the main results as '*partial residual estimates*'. With limited exceptions, LT-LEDS largely fail to specify the global warming potentials (GWPs) used when presenting residual emissions on a CO_2-equivalent basis. We assume many follow existing practice for reporting GHG emissions to the UNFCCC, using GWPs for a 100-year time horizon, based on Working Group 1 of the IPCC's Fifth Assessment Report (or GWP100 AR5).

The LULUCF sector, can act as a net-source or net-sink of CO_2 at the national scale, and current national plans suggest most countries intend to retain or expand net-sinks, or transition from a net-source to a net-sink prior to reaching net zero (Buck *et al.*, 2023). Current convention in national reporting is to report the sectoral total without distinguishing between emissions and removals (IPCC, 2006c; Mackey *et al.*, 2022). Many strategies therefore report LULUCF on a net basis. We therefore exclude LULUCF from our definition of residual emissions, even though any land-use emissions will enter the atmosphere at the point of net zero and therefore constitute as residual under proposed definitions (Schenuit, Boettcher and Geden, 2023). Our analysis, therefore, uses gross emissions entering the atmosphere at the point of net zero GHGs excluding LULUCF, engineered CDR, and IAS, as a measure of residual emissions. Whilst this comes with limitations, this measure is readily accessible and broadly comparable across the strategies, informing upon the ambition of emission reductions relative to the deployment of CDR methods. Figure A 1, in Annex II – Chapter 4, visually depicts this definition and contrasts this definition to alternative variations.

Further complicating LULUCF is the definition of '*managed land*' used within NGHGIs. Net zero should be attained through a balance of anthropogenic emissions and removals (Fankhauser *et al.*, 2022), but the methodologies for LULUCF within the IPCC NGHGI Guidelines use an area-based definition, meaning it is not possible to discern between anthropogenic and natural factors that determine emissions and removals (IPCC, 2006a; Gidden *et al.*, 2023). This differs from the bookkeeping models and dynamic global vegetation models used within the IPCC that are more able to discern between factors, isolating only anthropogenic effects (Grassi *et al.*, 2021; Gidden *et al.*, 2023). In addition, these models use a more precise definition of managed land, accounting for land-use change, harvest, and regrowth, as opposed to areas that perform '*production, ecological or social functions*', as per the IPCC NGHGI guidelines (IPCC, 2006a; Grassi *et al.*, 2021; Gidden *et al.*, 2023). Given many instances of scenario or pathway modelling within our sample use national GHG inventories as a basis, it is likely that net zero, in terms of a balance between LULUCF and residual emissions, would include net removals that would be considered natural by common practice within the IPCC. Resolving this misalignment requires reforms in IPCC modelling and UNFCCC reporting, beyond the scope of LT-LEDS (Gidden *et al.*, 2023). Our estimates for residual emissions therefore pertain to existing reporting practice within the UNFCCC.

Long-term national climate strategies typically detail sectoral emissions according to their own sectoral classifications. To allow for comparison across countries, we allocated sectoral emissions to a consistent sectoral split, based upon the logic of the IPCC NGHGI Guidelines, detailing emissions from Energy, Industry, Transport, Agriculture, and Waste (IPCC, 2006c) (see Figure A 2, Annex II – Chapter 4). We compare total residual emissions to peak emissions within the historical timeseries, as a measure of the climate ambition implied by scenario or pathway modelling. '*Peak emissions*' describes the year emissions peaked in a countries' historical national GHG inventory timeseries, excluding LULUCF. Peak emissions have commonly been used to assess the relative performance of decarbonisation efforts between countries (Lamb *et al.*, 2022; Bersalli, Tröndle and Lilliestam, 2023). For sectoral residual emissions, we determine the proportion of residual emissions from each sector, by comparing sectoral to total residual emissions, and determine the level of mitigation implied by scenarios or pathways, by comparing sectorial residual emissions to 2021 GHG emissions for the same sector. For Annex I countries, we use official national GHG inventories submitted to the UNFCCC in 2023, covering the years 1990-2021. National GHG inventories from the UNFCCC reflect the GWPs used by Parties in their submission. Current reporting practice uses GWP100 AR5. Non-Annex I countries are not required to submit national GHG inventories on an annual basis. We therefore use the PRIMAP-hist dataset, a composite dataset of the Kyoto basket of GHGs, that combines periodic country reported data with third-party data (Gütschow *et al.*, 2016). We use the '*HistCR*' scenario, which prioritises data reported by countries over third-party data. For PRIMAP, we use GHG emissions expressed in GWP100 AR5. To ensure use of this data does not impact our analysis of residual emissions, we validate the PRIMAP-hist dataset against available data reported within the LT-LEDS, deferring to data in the LT-LEDS if substantially diverging from PRIMAP-hist. Further detail regarding scenarios is provided in Annex II – Chapter 4 with the underlying data accessible through the dataset accompanying this chapter, ref. Smith, 2024.

To further contextualise residual emission estimates, we read and inductively coded each strategy to identify statements concerning residual or hard-to-abate emissions. We developed analytical categories based upon these statements regarding '*rationales*' as to why a certain emission or sector may be residual or hard-to-abate. We then use these analytical categories to repeat the coding of our sample, until '*code saturation*', where a full range of analytical categories are developed (Hennink, Kaiser and Marconi, 2017). We subsequently organised these categories and statements into insights as to how residual emissions is conceptually treated within LT-LEDS. All coding was completed in NVivo, a computer-assisted software commonly used for qualitative data analysis. For LT-LEDS published in non-English (13), we machine translated the strategy using translation software, repeating the same coding procedure. Statements from these strategies were then verified against the English translation with a native language speaker for strategies published in French, Greek, Italian and Spanish. The full range of rationales is detailed in Table 7. Multiple rationales may be expressed in a single statement. In select cases, rationales may appear conceptually similar and be harder to differentiate, representing different framings of the same perceived limitation or barrier to abatement. To provide transparency, we include all coded statements in the dataset accompanying this chapter, ref. Smith, 2024, and further detail the procedure in Annex II – Chapter 4.

5 Slow but Sure: Expert Perspectives on Carbon Dioxide Removal Policy in the United Kingdom

This chapter was submitted in March 2025 as '*Slow but Sure: Expert Perspectives on Carbon Dioxide Removal Policy in the United Kingdom'* to the journal Energy Research & Social Science and is currently under review. Minor textual changes have been made to align with the format of this thesis.

5.1 Abstract

CDR methods are essential to meeting national net zero targets, yet governments have only recently engaged with the need for CDR policymaking. The UK government is amongst the most active, introducing explicit targets and dedicated policies for CDR deployment. To assess how both commercial and policy actors view these policy developments, we conduct semi-structured interviews with 25 experts active in UK CDR policymaking, with expertise spanning all relevant CDR methods. Through inductive coding, we identify and detail several key themes and policy recommendations. Firstly, a scepticism towards the voluntary carbon market, reflecting a need for the government to stimulate near-term demand for CDR. Secondly, a need to implement credible monitoring, reporting, and verification through a government standard, standardising how differences in the permanence of CDR methods are managed. Thirdly, a need to improve state capacity, to be met by a new cross-government body tasked with overseeing CDR. Fourth, a need for '*net-negative ready*' policy, ensuring that the proposed integration of CDR within the UK Emissions Trading Scheme continues to provide long-term demand, given the likelihood of temporary temperature overshoot and net-negative emission targets, as the next necessary extension of climate policy.

5.2 Introduction

With net zero targets as the guiding principle of national climate governance, governments now face the challenge of turning pledges into plans and policies, transforming multiple sectors of their economies within a matter of decades (Green, Hale and Arceo, 2024). Reaching a national net zero target requires a means of balancing positive residual emissions with negative emissions, either directly within policy design or within national accounts (Fankhauser *et al.*, 2022; Pahle *et al.*, 2025). An essential component of reaching national net zero targets is therefore CDR; a term used to describe methods of removing CO_2 from the atmosphere and durably storing the carbon in terrestrial, ocean, or geological sinks, thereby producing (net) negative emissions (Babiker *et al.*, 2022). CDR is both an established area of climate policy and a nascent early-stage industry, depending on the method (Powis *et al.*, 2023). Nature-based methods of CDR[22], that enhance the uptake of CO_2 in land, are a long-standing element of global climate policy since the 1997 Kyoto Protocol, the predecessor to the 2015 Paris Agreement (Dooley and Gupta, 2017; Carton *et al.*, 2020). Since the emergence of net zero as a guiding concept in climate science and climate policy, the land's ability to store carbon has taken on a new importance as a means to compensate for residual hard-to-abate emissions elsewhere in an economy (Rogelj *et al.*, 2015; Dooley, 2024; Green, Hale and Arceo, 2024).

Engineered methods of CDR, such as BECCS and DACCS, are a recent addition to climate policy, gaining traction from their prominent role in IAMs – energy-economy-climate models influential in IPCC Assessment Reports (Fuss *et al.*, 2014; van Beek *et al.*, 2020; Gusheva, Pfenninger and Lilliestam, 2024). Engineered CDR methods are at an early stage of policy support, with many governments supporting companies undertaking pilot plants, field trials, or exploring the feasibility of retrofits to existing sites (Ricardo, 2023; Nemet *et al.*, 2024). Engineered methods of CDR, following the trajectory common to

[22] In this chapter we refer to two categories of CDR: nature-based and engineered. This mirrors the distinction made by the UK government. 'Nature-based approaches', in UK government communications, refer to CDR methods such as afforestation, forest management, and soil carbon sequestration, whereas 'engineering-based approaches' refer to methods such as Direct Air Carbon Capture and Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), wood in construction, biochar, and enhanced weathering (HM Government, 2021). Notably, many engineered methods rely on land to provide the means of capture and/or storage of carbon, for example, BECCS, enhanced weathering and biochar (Bellamy and Osaka, 2019). Further sub-categories are also used, for example, more recent policy announcements distinguish between 'CCUS-enabled' and 'non-CCUS' approaches, with the former describing BECCS and DACCS, and the latter, biochar and enhanced weathering (DESNZ, 2023d). These sub-categories delineate between methods that rely principally on geological storage, given the policies developed to support offshore geological storage by pipeline transport (DESNZ, 2023d). Whilst in this chapter we use CDR as the umbrella terms to describe all methods, irrespective of categories or sub-categories, UK climate policy commonly uses 'greenhouse gas removal', or 'GGR', to allow for methods that remove other greenhouse gases, such as methane (The Royal Society, 2018; HM Government, 2021). We use CDR as the most widely accepted term in academia and international climate policy (Renforth et al., 2023).

many low-carbon technologies, are said to be in the '*formative phase*', between the first commercial projects and widespread commercial adoption (Nemet *et al.*, 2023).

The UK has been an early advocate of CDR, the UK Government has funded research programmes into CDR since at least 2017, and has consulted academics on the concept as early as 2009 (Lezaun *et al.*, 2021). CDR features prominently in scenarios published by the UK Government and the Climate Change Committee (CCC), the independent statutory climate advisory body (CCC, 2020b; HM Government, 2022). For the CCC, the Balanced Net Zero Pathway, used by the committee to benchmark the progress and policies of the UK government, features 36 $MtCO_2$ of engineered removals in 2050 (CCC, 2025). Whilst the removals from LULUCF amount to 44$MtCO_2$ in 2050 (CCC, 2025).

The UK Government's Net Zero Strategy, published in 2021, features 75-81 $MtCO_2$ of engineered removals in 2050, 39-45 $MtCO_2$ more than the CCC's Balanced Pathway in Carbon Budget 7, the CCC's latest modelling (HM Government, 2022; CCC, 2025). Based on these scenarios, and the latest estimates of the UK's greenhouse gas emission inventory, LULUCF and engineered removals combined may amount to 20% of the required mitigation between 2022 and 2050, the vast majority delivered by engineered removals (DESNZ, 2024b). Based on the trajectory set out in the strategy, the government has set ambitions for engineered removals, deploying 5 $MtCO_2$ by 2030, and 23 $MtCO_2$ by 2035, alongside targets for woodland creation and peatland restoration (HM Government, 2022; DESNZ, 2023b). Estimates for engineered removals, however, in modelled net zero scenarios for the UK, have declined since the publication of the strategy, driven primarily by a reduced use of BECCS in these scenarios (Figure 23). For example, in the CCC's latest modelling, engineered removals reaches 36 $MtCO_2$/yr in 2050, 62% lower than the Royal Society's original estimate published in 2018 (Royal Society, 2018; CCC, 2025).

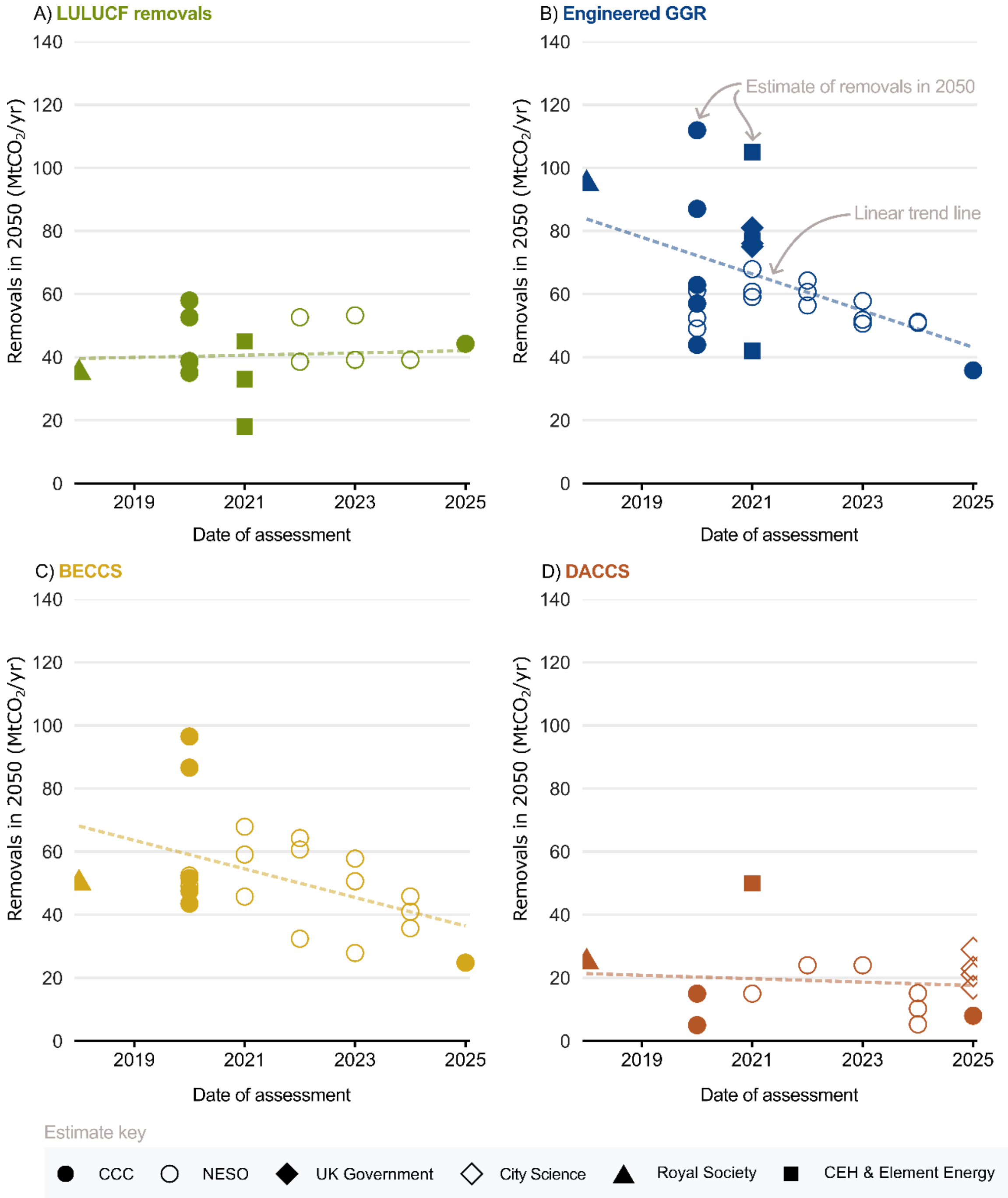

Figure 23. Estimates of UK CDR estimates in modelled net zero scenarios by date of assessment.

'Date of assessment' refers to the year the assessment was published in the public domain. 'Engineered GGR' refers to BECCS, DACCS, and other methods typically classed as engineered in UK policy, such as enhanced weathering, if modelled. 'LULUCF removals' refers gross removals. All subplots use the same key, detailing the source of the estimate.

The UK government have been lauded as '*policy entrepreneurs*', developing dedicated policies for CDR (Schenuit *et al.*, 2021; Schenuit, Geden and Peters, 2024). Criticisms, however, have been levelled by industry and the CCC that the necessary policy commitments have not kept pace, and these efforts are now overshadowed by policy developments in the United States and the EU (Schenuit *et al.*, 2021;

CCSA, 2023; CCC, 2024). As with engineered removals, CDR policymaking itself may be described as in a similar '*formative phase*', as interest groups seek to shape policy formation and the surrounding policy discourse (Boettcher, Schenuit and Geden, 2023).

The UK government has been amongst the most active in designing CDR policy, financing supply, through grants or contract for differences (CfDs), and ensuring longer-term demand, by proposing to integrate removals into the UK Emissions Trading Scheme (the UK ETS) (DESNZ, 2023d; UK Government *et al.*, 2024). This reflects a policy sequence common to climate policy, transitioning from research and development, to incentives for deployment, to integration into carbon pricing (Linsenmeier, Mohommad and Schwerhoff, 2022). Further transitions are envisaged within this sequence, such as a transition from voluntary to compliance markets, and a transition from public to private finance (DESNZ, 2023d). This sequence is similar to the sequence common to technology development, moving from '*supply-push*' to '*demand-pull*' policies, inducing innovation through deployment, lowering costs by '*learning-by-doing*' and economies of scale (Nemet, 2009; Malhotra and Schmidt, 2020).

Whilst this sequence has accelerated the deployment of many low-carbon technologies, most prominently wind power, solar, and electric vehicles (Malhotra and Schmidt, 2020), CDR methods differ in their readiness, cost, potential, and permanence (Fuss *et al.*, 2018; Borchers *et al.*, 2024). Given these differences, advocates of CDR commonly recommend governments adopt a portfolio of methods, whilst simultaneously maintaining emission reductions and balancing multiple further policy objectives, such as restoring biodiversity (Honegger *et al.*, 2022; Dooley, Pelz and Norton, 2024). CDR policy, though informed by these sequences, is likely markedly more complex in practice. Given the number of policy developments, and the prominent role of CDR in national scenarios, the UK serves as a valuable example for governments similarly exploring the integration of CDR within their own plans and policies.

Addressing the need for detailed national case-studies to compliment comparative assessments across countries (Schenuit *et al.*, 2021), and building on prior practice in stakeholder-led studies (Forster *et al.*, 2020; Yang *et al.*, 2024), we carry out semi-structured interviews with 25 participants, spanning commercial actors and policy advocacy organisations, active in UK CDR policymaking. We consider engineered and nature-based removals, covering the majority of methods, including those with limited policy support in the UK, such as enhanced weathering and biochar (DESNZ, 2023d). We provide a summary of the main CDR policy developments in the UK, detail our methodology, and then explore themes emerging from the qualitative coding of our interviews.

5.2.1 A summary of CDR policy developments in the UK

Through multiple consultations, the UK government has refined it's approach, setting out a broad policy sequence familiar to climate policy, beginning with government support for research and development, prior to dedicated incentives, followed by wider integration into existing carbon pricing schemes, such as the UK ETS (Figure 24) (Schenuit *et al.*, 2024). We address each part of this sequence, in turn, delineating between supply and demand. For engineered CDR methods, government support for research and development, though preceded by smaller academic programmes (UKRI, 2010, 2023), began in 2020, with the Direct Air Capture and other Greenhouse Gas Removal technologies Competition, a two-phase competition for project developers totalling £70 million in announced government grants (BEIS, 2020, 2021). Phase two of the competition saw £54.4 million allocated across 15 pilot projects, including for methods; BECCS, DACCS and biochar (BEIS, 2022b).

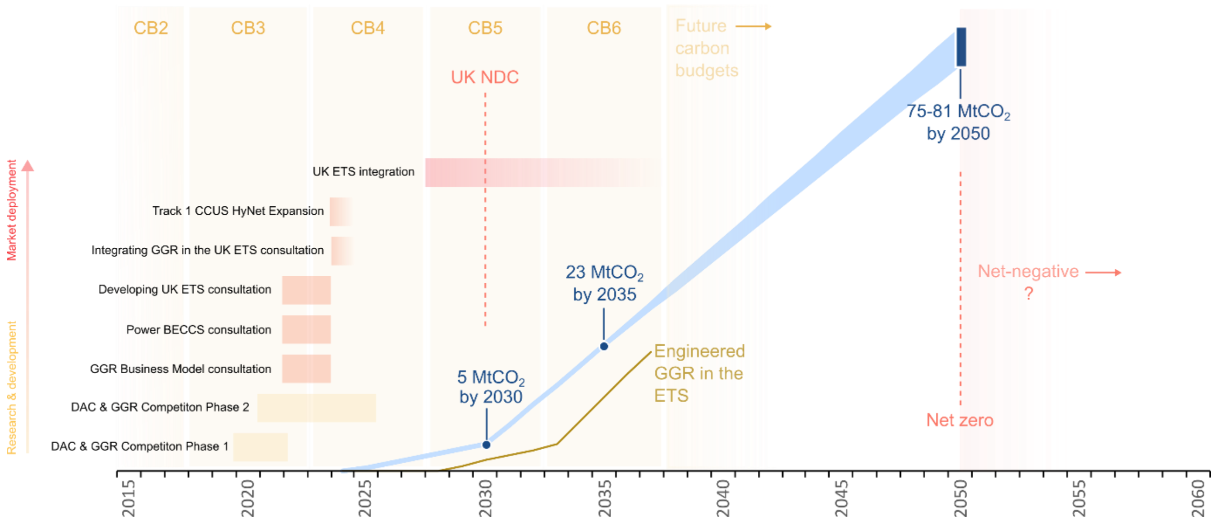

Figure 24. Progress in UK CDR policy developments over time.

Figure depicts a transition from research and development towards integration into the UK ETS, and wider market deployment. Consultation lengths taken from relevant consultation documents, and include the period of opening up until the publication of the government's response. Ambitions for engineered removals from the 2021 UK Net Zero Strategy shown in blue.

To bridge the investment risks of early engineered projects, the UK government plans to introduce a CfD scheme for project developers, also known as the '*GGR Business Model*', building on the success of the CfD introduced for offshore wind (BEIS, 2022a; Watson and Bolton, 2024). In the scheme, a fixed '*strike price*' per tonne removed (£/tCO_2) is negotiated between the government and the project developer, based on costs and investment returns (DESNZ, 2023d). The project developer then sells the project's removal credits into either the voluntary carbon market (VCM) or a compliance market, with the difference between the '*market price*' and the strike price paid by the government to the developer if negative, or by the project developer to the government if positive, guaranteeing a set revenue for the project developer (DESNZ, 2023d). CfDs will also be supported by a government monitoring, reporting and verification (MRV) standard, setting out the requirements projects must meet to receive government support (DESNZ, 2023e, 2024c). Demand for removal credits is anticipated to initially come from the VCM, given the rise in corporate climate action and removal credit purchases from technology companies, such as Microsoft, Meta, and Google (DESNZ, 2023e).

In the longer-term, from 2028 or later, demand may come from substituting removals for allowances in the UK ETS, a cap-and-trade scheme established in 2021 after the UK's exit from the EU's Emission Trading System (UK Government *et al.*, 2024). These policies are complimented by policies that may induce spillover effects that benefit removal projects, such as the UK's Sustainable Aviation Fuel Mandate, which supports the utilisation of CO_2 from direct air capture to produce fuels, or policies that incidentally produce negative emissions, such as the Industrial Carbon Capture (ICC) Business Model and Waste ICC Business Model, which supports negative emissions from BECCS by combusting biomass for energy and heat, capturing and storing the resulting CO_2 (DESNZ, 2023c, 2024d; DfT, 2024).

Geological storage for BECCS and DACCS projects is supported by shared CO_2 storage and transport networks in the UK's industrial clusters, areas of concentrated industrial emissions that receive dedicated government support to decarbonise (Sovacool, Geels and Iskandarova, 2022; DESNZ, 2023e). Engineered removals, notably BECCS and DACCS, are therefore tied to the wider decarbonisation of both industry and aviation, the success of the industrial clusters, and the use of carbon markets to drive demand. Biochar and enhanced weathering, beyond their inclusion in academic trials, have comparatively limited government support (UKRI, 2022; DESNZ, 2023e; Welsh Government, 2024a).

Policies to incentivise the supply and demand of nature-based removals are most established for woodlands and peatlands. Since 2011, the government has supported the Woodland Carbon Code (WCC), a standard for woodland carbon projects, allowing private landowners to generate removal credits or, under the standard, '*woodland carbon units*' (WCUs), sold to private buyers through a dedicated registry (West, 2019). WCC operates alongside the Woodland Carbon Guarantee, a £50 million scheme that allows landowners generating WCUs to sell these periodically to the UK government for a guaranteed price (Forestry Commission, 2019). Longer-term, WCUs may be integrated in the UK ETS (UK Government *et al.*, 2024). Supply is supported by a series of grants across the UK's devolved governments, paying for the capital costs of tree-planting and annual payments for their maintenance (Scottish Forestry, 2019; Forestry Commission, 2021).

This policy approach has been mirrored for peatland projects, establishing in 2015 the Peatland Code, a standard supporting private investment into peatland restoration, with grants available across the devolved governments (Natural England and Defra, 2021; IUCN, 2024; NatureScot, 2024). Similar codes are under development for saltmarshes and soil carbon (Environment Agency, Defra, and Natural England, 2021). Despite these efforts, targets for woodland creation and peatland restoration set before COP26 are likely to be missed (CCC, 2024).

Grants are to be expanded in England through the Environmental Land Management (ELM) schemes, which will pay landowners for actions that increase carbon sequestration in soils, peatlands and woodlands, replacing the payments paid to landowners under the EU's Common Agricultural Policy (HM Government, 2018). Similar '*agri-climate*' schemes have been launched by the devolved governments (Scottish Government, 2024; Welsh Government, 2024b). To support greater private funding, the UK government plans to establish new nature markets, building on the example of biodiversity net-gain in England, whereby housing developers are obliged to purchase biodiversity units to compensate for the biodiversity lost through development (Defra, 2023). In these markets, the co-benefits of a carbon project can be '*stacked*' or '*bundled*' together, explicitly trading, for example, the biodiversity and carbon benefits as separate credits or as a singular '*bundle*' (Defra, 2023). Nature-based removals, therefore, whilst a more established policy area, are similarly reliant on markets to drive demand.

5.3 Method

CDR, as an active and growing area of climate policy (Lück, Mohn and Lamb, 2024), is rarely static, and our interview period encompasses several policy developments that may have informed how our participants respond in interview. Notably, the government's consultation into integrating removals into the UK ETS, running from May to August of 2024, overlapping with our interview period of April to October (UK Government *et al.*, 2024).

Participants were selected by consulting publicly available lists (for example, the MRV Task & Finish Group, Phase 1 reports of the Direct Air Capture and other Greenhouse Gas Removal technologies competition), the registry of the WCC and Peatland Code, and organisations who have released publicly available documents in response to public consultations. In cases where an organisation, not an individual, was invited to interview, we requested the organisation nominate an individual with knowledge of the relevant policy context or direct involvement in acquiring relevant policy incentives, such as grants. In total, semi-structured interviews were held with 25 participants. All participants signed consent forms detailing how their interview will be used. The research design for this chapter was approved by UEA's Faculty of Science Research Ethics Subcommittee, Application ID: ETH2324-0863.

Participants were asked to self-select prior to interview the role of their organisation from a pre-defined list, later recategorized to produce a split between commercial actors and policy organisations. Commercial actors include not only project developers but also market platforms, registries, certifiers, and standard organisations, actors essential to a functioning commercial market (IEAGHG, 2024). Policy organisations include think tanks, the civil service, and specialist consultancies. We therefore consult participants involved directly in shaping UK CDR policy or those with experience of the relevant policy incentives. In doing so, we inevitably overlook other actors, such as investors (Yang *et al.*, 2024). In the following results section, we label participants according to their organisation's recategorized self-selected role, with '*C*' for commercial actors and '*P*', for policy organisations. Each participant is assigned a number and label, for example, P1. Interviews were held online from April to October 2024, lasting between 30 to 90 minutes. Interviews were transcribed and the transcripts checked against recordings.

We asked participants to describe those CDR methods they have expertise or familiarity with, using a figure providing an overview of CDR methods, sourced from the IPCC AR6 Report (Babiker *et al.*, 2022). Based on participants' responses, we allocate two levels of expertise, '*familiar*', suggesting a degree of knowledge of, or familiarity with, a method, and '*expert*', suggesting practical involvement in projects or a specialism within a specific method. Based on these allocations we further allocate each participant to an '*engineered*' or '*nature-based*' category, aiming to ensure a near-even balance between categories and across relevant methods. The results of these allocations are shown in Figure 25.

Interviews followed a semi-structured script with seven questions, three of which covered; the role of CDR in meeting UK climate commitments, what is working well, and what barriers remain. The remaining four questions followed either a '*nature-based*' or '*engineered*' removals script, depending on the participants' familiarity or expertise with certain CDR methods, in response to the opening question. These scripts contain similar questions but differ according to phrasing and prompts. Each script ended by asking participants to detail what they would like to see introduced or changed regarding new or existing policy. A copy of the semi-structured interview script can be found in Annex III – Chapter 5.

Transcripts were inductively coded in NVivo 14, a software tool commonly used for qualitative data analysis. Codes were created relating to themes within the textual data, iteratively clustered and aggregated across multiple rounds of review, until '*code saturation*' is reached, whereby a full range of codes, describing all themes found in the textual data, are developed (Hennink, Kaiser and Marconi, 2017). These themes were then organised into the main themes and sub-themes used to structure our results.

To focus our results, we prioritise only those sub-themes and themes mentioned by at least 6 of our participants. This, largely arbitrary, cut-off, focuses the results on the most commonly expressed themes and sub-themes, reducing the number of themes then explored in the results section, Section

5.4, to a manageable level. A cut-off of five generates 44 sub-themes, as opposed to the 30 sub-themes explored in Section 5.4. In total, 161 sub-themes were identified.

5.3.1 Participant summary

Figure 25A shows participants' responses when asked to describe their expertise and familiarity with CDR methods. Participants have a range of knowledge and expertise, covering those methods directly subject to policy support in the UK, or demand within the VCM. More of our participants are primarily experts in engineered methods (14), with 11 classed as experts in nature-based methods.

Woodlands are the most common method amongst our participants, both in terms of the depth of expertise (11 participants consider themselves experts) and overall familiarity (16 considered themselves expert or familiar with the method). BECCS and DACCS similarly score highly, with a high level of expertise (9 for both methods) and familiarity. Despite limited government support for biochar, our participants were largely familiar with the method. No participants regarded themselves as experts in ocean alkalinity enhancement (OAE), however, OAE is of limited relevance to UK climate policy. The UK Government considers OAE in a third '*ocean-based*' category, subject to early-stage development and legal risks (HM Government, 2021; DESNZ, 2023d). Figure 25B shows participants by type of organisation. Our participants predominantly hold commercial roles (15), with 10 participants coming from policy organisations.

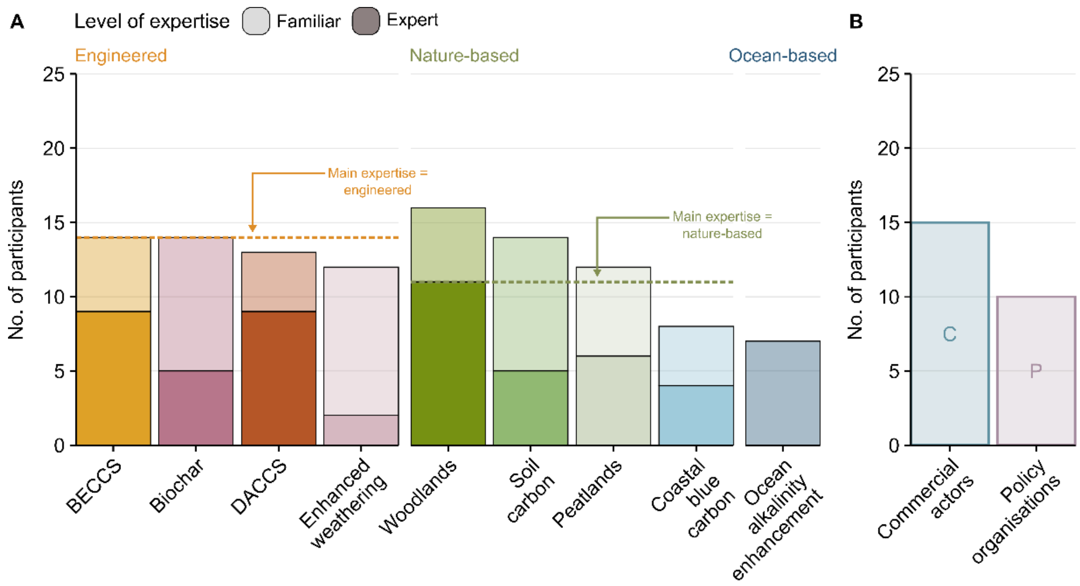

Figure 25. Participants classed by expertise in CDR methods and organisation.

Panel A details participants classed by expertise in CDR methods. '*Familiar*' describes statements made that suggest a degree of knowledge, whereas '*expert*' describes statements made that detail practical involvement in projects of that method, or specialism within that method. '*Coastal blue carbon*' includes coastal wetlands. BECCS stands for bioenergy with carbon capture and storage. DACCS stands for direct air carbon capture and storage. Most participants have expertise across more than one method. Panel B details participants by organisation, classified into '*commercial actors*' and '*policy organisations*'.

5.4 Results

Figure 26 summarises the main themes and sub-themes identified through inductive coding, classed by type of organisation. As seen in Figure 26, the themes of commercial actors and policy organisations largely overlap. Selected quotes from these themes are detailed in Table 8, and the main themes further elaborated in dedicated sub-sections. We address the main themes '*Near-term demand, the VCM & corporate climate action*', '*Monitoring, Reporting and Verification (MRV)*', and '*Long-term demand*' as dedicated sub-sections prior to combining many of the main themes with fewer sub-themes into a single section, entitled '*policy approach*'. Though essential to the successful deployment of CDR, we omit '*Feasibility constraints*' from our results, given that feasibility may be better addressed through dedicated feasibility assessments (for example, Förster *et al.*, 2022 and Borchers *et al.*, 2024). We note, however, that many of the most prominent sub-themes for feasibility constraints mirror the main constraints detailed in previous government commissioned assessments of CDR methods (Element Energy and CEH, 2021).

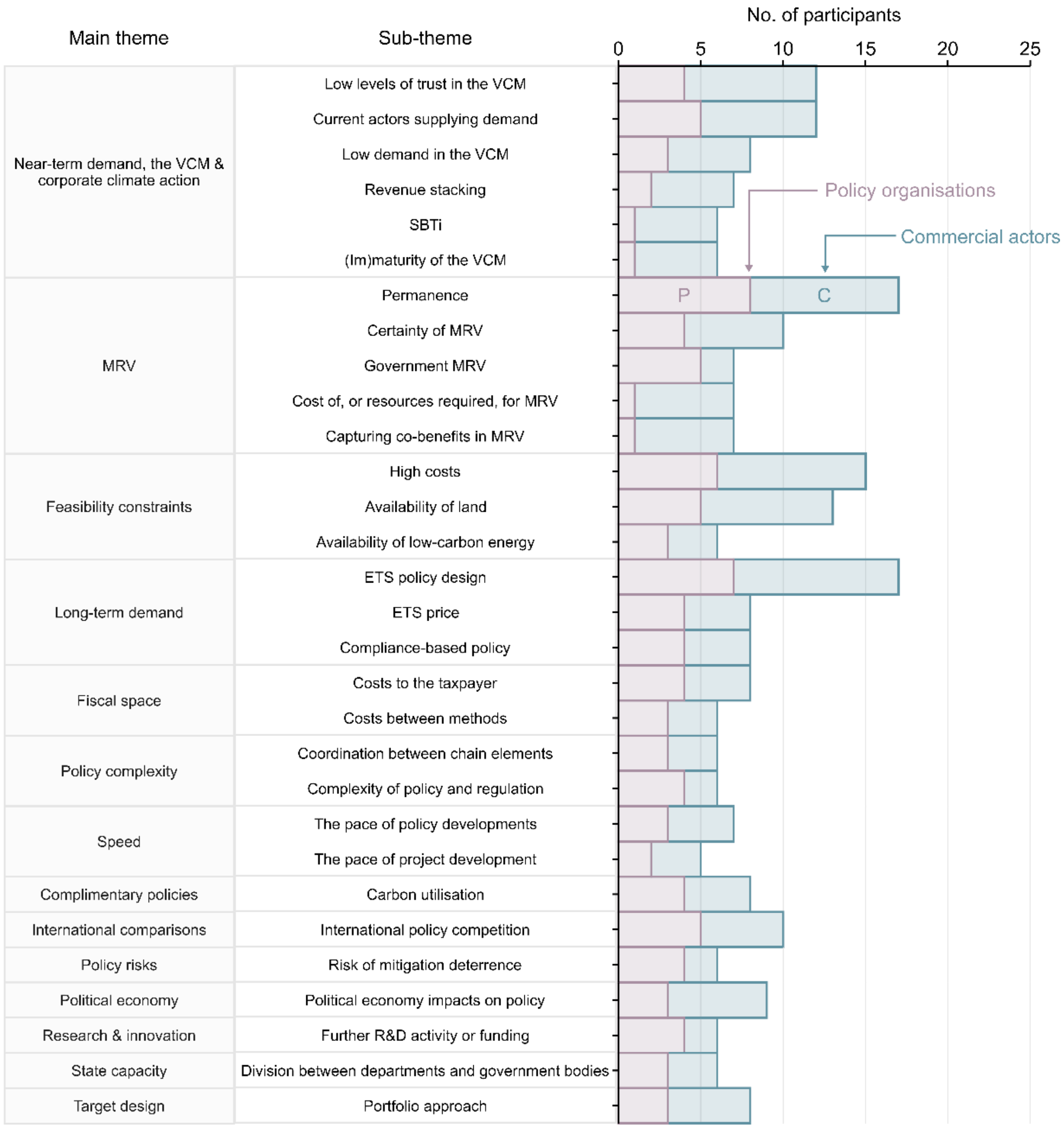

Figure 26. Count of main themes and sub-themes discussed by participants.

Participants classed by type of organisation. Only those sub-themes and main themes discussed at least 6 participants are presented. VCM stands for voluntary carbon market. MRV stands for monitoring, reporting and verification. ETS stands for the UK emission trading scheme.

Table 8. Main themes and sub-themes identified through inductive coding of interviews.

For each main theme, we present select sub-themes. 'Participant count' is the number of participants that made statements pertaining to a sub-theme, not the total instances statements pertain to that sub-theme were mentioned.

Main theme	Sub-theme (participant count)	Barrier/enabler	Selected quotes
Near-term demand, the VCM & corporate climate action	Low levels of trust in the VCM (12)	Barrier	'*The VCM, I have no trust in the VCM right now.*' [P4]
	Current actors supplying demand (12)	Barrier	'*Tech companies and banks are providing the stimulus for CDR at the moment, and that's maybe ok, if they reduce costs in the short term for everybody else*' [P5]
	Low demand in the VCM (8)	Barrier	'*Yeah, I think, as important as the VCM is I think there is a risk of hedging all your bets that it will continue growing, like, we saw in the last two years It shrunk.*' [P1]
	Revenue stacking (7)	Enabler	'*One of the positives we see from our technology in the sense that you're not pinning your hopes on a single revenue stream.*' [C7]
	Science Based Targets initiative (SBTi) (6)	Barrier	'*Demand is not really growing at the moment because of what's gone on with the likes of SBTi's recent announcements and the kind of hesitancy around, well, are credits going to be used* [to offset emissions]?' [C15]
	(Im)maturity of the VCM (6)	Barrier/enabler	'*The voluntary carbon market, I think that that is kind of the natural growth area for carbon removal for the moment, which is unfortunate because it's not the most mature market which makes it very hard to get any projects into bankability*' [C4]
MRV	Permanence (17)	Enabler	'*So, the benefits are that you'll be able to more easily track and confidently state against carbon budgets a true removal as an engineered because of their enhanced durability. So that gives governments, scientific advisors, and even the academic world a bit more confidence when we say what our removals are*' [P2]
	Certainty of MRV (10)	Barrier/enabler	'*The second point is we're mostly scientists and engineers and we like very clear permanent solutions, and don't necessarily like dealing with the complexity of nature-based removals, which have a lot of co-benefits that we don't know how to quantify, but also the removal elements seem to be a bit more vague.*' [P10]
	Government MRV (7)	Enabler	'*I think it needs to start with, at least in the short term, the government needs to set all the guardrails. So, I would have a regulator, the government set the guardrails, which is what they're doing, eventually, they are in the process of setting minimum standards which companies can adhere, as long as they adhere to those minimum standards, that's fine.*' [P5]
	Cost of, or resources	Barrier	'*So again, the number one philosophy on our MRV, which is really important, is that MRV is critical, but it has to be cost effective, not to kill the thing it's trying to MRV*' [C1]

Main theme	Sub-theme (participant count)	Barrier/enabler	Selected quotes
	required for MRV (7)		
	Capturing co-benefits in MRV (7)	Enabler	*'So, if we're going to optimise for the time value of storage, we lose a lot of the co-benefits that a lot of these methods might have, whether that's ecosystem restoration, air quality benefits, water quality benefits, whatever it might be, there is a danger that we lose a lot of that.'* [P5]
Feasibility constraints	High costs (15)	Barrier	*'So…there's the fundamental problem, which is the cost of achieving removals is very high, the world is used to a place where they think they can buy, that £20 buys them a negative tonne of emissions, whereas the engineered world is looking at £1000, £500 a tonne.'* [C2]
	Availability of land (13)	Barrier	*'Afforestation is limited by the land that's available in the UK, there's just not that much in the UK and there's large demand for it.'* [C14]
	Availability of low-carbon energy (6)	Barrier	*'If we can resolve for green electrons, make them accessible and at a decent price, I mean, the prices we see in the UK at the moment are ludicrous.'* [C4]
Long-term demand	ETS policy design (17)	Barrier/enabler	*'Obviously there is a clear preference in government to go down a market route, so for example, bringing it into the ETS, for example. Again, I think that's fine, as long as there are safeguards against it effectively being a lifting of the CAP in the ETS system, because if you don't have a cap in a cap-and-trade system, then the whole system kind of falls apart.'* [P6]
	ETS price (8)	Barrier	*'Market prices in the ETS are too low for many methods, so we need a prior phase of subsidies to bring those costs down, so that, when integrated into the ETS, those prices do really incentivize technologies.'* [P5]
	Compliance-based policy (8)	Enabler	*'I do think that there should be a compliance-based kind of requirement for, for purchasing GGR or for financing it. I'm agnostic as to whether that should be a compliance market like the ETS or whether it should be…a removal obligation on certain sectors, …setting a trajectory for how much removal should be financed by them.'* [P3]
Fiscal space	Costs to the taxpayer (8)	Barrier	*'We often overcomplicate our policy design. Trying to ring out the most cost and benefit for the taxpayer and that we have a preoccupation with that, and it often can slow down efforts.'* [P5]
	Costs between methods (6)	Barrier	*'The challenges of that is obviously scalability and expense that nature based at the moment are vastly more scalable and vastly cheaper, than engineered.'* [P2]
Policy complexity	Coordination between chain elements (6)	Barrier	*'So, I think, when you, when you look at DACCS and BECCS, I can't help but sense that we need to look at the full chain of activities and think of them as a package, not just as GGR versus fossil carbon, because I think there's generic challenges to building transport systems and there's certain generic challenges to developing storage sites.'* [P8]
	Complexity of policy and regulation (6)	Barrier	*'It's* [The GGR business model] *certainly proving complicated and to the point where there's only really a handful of people who seem to understand what's going on there*?' [P8]

Main theme	Sub-theme (participant count)	Barrier/enabler	Selected quotes
Speed	The pace of policy developments (7)	Barrier	‘*So, these business models are usually seen as a success. But one of their weaknesses seem to be the slow rollout, because they're being perfected. The specific design is being perfected before anything launches.*’ [P10]
	The pace of project development (6)	Barrier	‘*The challenge is that we are relying quite a bit on engineered ones and those take time and money to be able to implement a true sector.*’ [P2]
Complimentary policies	Carbon utilisation (8)	Enabler	‘*We're focusing more on utilization for the short to medium term and waiting for that mass market to come before then really getting stuck into removals themselves.*’ [C4]
International comparisons	International policy competition (10)	Barrier	‘*Why would you move to the UK? if you, if you're carbon engineering and you've got cheap hydro in BC and a big tax credit, you know that that's more compelling than coming to the UK and having to bid into an auction.*’ [P5]
Policy risks	Risk of mitigation deterrence (6)	Barrier	‘*Limiting GGR financing to residual emissions and not, kind of, overall increasing the window of emissions that are allowed, because more are being reduced, because we know that we've got finite capacity for GGRs, or that's our present understanding.*’ [P3]
Political economy	Political economy impacts on policy (9)	Barrier	‘*I think we need to make sure that we have our vested interests clearly in check when it comes to BECCS*’ [C11]
Research & innovation	Further R&D activity or funding (6)	Enabler	‘*I'm sure the ambition of innovation funding could be scaled up*’ [P9]
State capacity	Division between departments and government bodies (6)	Barrier	‘*I think the departmental division between Defra and DESNZ is particularly unhelpful*’ [P3]
Target design	Portfolio approach (8)	Barrier/enabler	‘*An understanding about the need to develop a diverse portfolio of solutions and providing funding and same levels of support to explore that. I think direct air capture and bioenergy carbon capture and storage are two very well understood…relatively simple to understand technologies. But there are other methods that have a lot of scalability potential and will be required, to be able to meet our targets, such as enhanced weathering or biochar, and I think these need to be, the support for these needs to be expanded and included as well.*’ [C5]

5.4.1 Near-term demand, the VCM & corporate climate action

The VCM was raised by 16 of our participants, and was central to discussions of how near-term demand for CDR can be met, and by extension, the role of corporates in providing demand. To government, the VCM provides the near-term demand for both nature-based and engineered removals, prior to their integration into compliance markets, such as the UK ETS (DESNZ, 2023e). Yet participants cite dampened demand (n=8 [C=5,P=3]) owing to low levels of trust in the market (n=12 [C=8,P=4]), creating a need for greater government engagement or a need for policy alternatives (see Figure 26 for a further breakdown of sub-themes by type of organisation).

Low levels of trust are seen by participants as stemming from negative publicity, following a series of public scandals concerning offset projects, as explained by one policy professional '*nobody wants another article written about them about junk credits they've purchased*' [P2]. Yet for credit buyers, the reputational risk of junk credits has pushed buyers to seek out quality projects, benefitting project developers who claim to adhere to stricter standards on additionality and permanence, as common with engineered removals. As one participant explained '*so, what it's done with carbon credit buyers is that they're much more sceptical of all carbon credits, but it also means they also want the best.*' [C1]. This creates, in the view of select participants, a welcome differentiation between the '*carbon removal space*' [C1] and the wider VCM.

Yet the VCM is not a single global market, but a patchwork of smaller marketplaces and standards, and negative publicity may have dampened the enthusiasm of landowners towards the WCC, the UK's own domestic voluntary market for woodland projects. A commercial actor explained that '*anecdotally it appears to be farmers and landowners thinking the carbon markets are kind of a busted flush* [something that began successfully but later fails]', leading to '*a dip in the number of new woodland creation projects coming forward*' [C3]. This, in their view, is unwarranted given that scandals were owing to '*REDD+ projects in the tropics, yet it's tainting this market with the same brush*' [C3]. This publicity may have also dampened the enthusiasm to participate in general in the VCM, as argued by one policy professional; '*I think you're seeing that right now with how the previous iteration of the voluntary carbon market was operated, that the challenges in how credits are viewed, issued, and delivered is actually putting a cooling effect* [across the market]' [P2]. For commercial actors, public scandals are not the fundamental explanation of low demand, as explained by one participant, commenting on the WCC, '*we're not having any difficulties where they're citing the Guardian article from early 2023, and the concerns that that created*', rather low demand is best explained by the tightening of corporate finances [C6].

For engineered removals, the actors currently supplying demand through corporate offtake agreements, primarily technology or financial companies, are seen as unique in their high-willingness to pay but disconnected from the residual hard-to-abate emissions that should ideally be mitigated through CDR. They have, in short, '*low emissions and large pockets*' [C8], resulting in *'high-profit philanthropy*' [C13]. These actors, therefore, are among the few that can afford the higher costs associated with engineered projects, though limited in the demand they can ultimately provide. As remarked by one participant '*I don't think the current market scales and the voluntary carbon market starts to fall apart once you exhaust philanthropy effectively*' [C4]. As a result, their role in supplying demand may be none the less useful but time limited, as remarked by one participant '*tech companies and banks are providing the stimulus for CDR at the moment, and that's maybe ok, if they reduce costs in the short term for everybody else*' [P5].

A range of corporate standards guide how corporations should measure their emissions, prioritise mitigation measures and set climate targets (Becker *et al.*, 2024). Amongst the most popular is the Science Based Targets Initiative's (SBTi) Net Zero Standard, which, amongst other aspects, limits the extent to which carbon credits may be counted against corporate climate targets (SBTi, 2024). Many participants praised the stricter requirements of SBTi, for example, its exclusion of avoided emissions [C6], the accounting of credits only for residual emissions [P6], or their use for '*beyond value chain mitigation*', voluntary mitigation that goes beyond near-term emission reduction targets (SBTi, 2024). Others viewed the approach taken by SBTi to be too restrictive. By limiting the role of credits to only residual emissions, SBTi provides no clear incentive to engage with the VCM, and by extension, the need to procure removal credits. This results in limited engagement, as argued by one participant, commenting from the view of corporates '*we don't need to have that removals conversation, because all of our efforts are on our priority to decarbonise* [reduce emissions]*, and that's been the mentality across the private sector for years*' [C13]. Similarly, turmoil in April 2024 within SBTi, related to whether the Net-Zero Standard could be altered to allow for the use of credits to abate scope 3 emissions, was seen as creating hesitancy as to whether corporates should or shouldn't engage with the VCM. As explained by one participant '*demand is not really growing at the moment because of what's gone on with the likes of SBTI's recent announcements and the kind of hesitancy around, well are credits going to be used* [against targets in the Net-Zero Standard]*?*' [C15].

5.4.2 Monitoring, Reporting and Verification (MRV)

The need for credible project MRV was discussed by 20 of our participants. Of particular interest was the issue of permanence (n=17 [C=9,P=8]). Engineered methods, such as BECCS and DACCS, owing to their use of geological storage, are seen as more permanent than nature-based removals, meaning that, in the view of participants, these methods carry less risk regarding reversals and greater certainty in MRV (see Figure 26 for a further breakdown of sub-themes by type of organisation). This greater degree of permanence has implications for policy. For example, prioritising engineered methods means '*you'll be able to more easily track and confidently state against carbon budgets… because of their enhanced durability*' [P2]. For others, the permanence of the method dictates whether removal credits should enter carbon markets, particularly if compensating for long-lived fossil CO_2 emissions. As remarked by one policy professional '*anything less permanent or less durable* [than BECCS or DACCS] *makes me very nervous*' [P5]. Others advocated for a broader like-for-like principle within policy, meaning that policies should aim to '*compensate for a source of CO_2…with a removal that has the same type of permanence*' [P4]. Corporate purchases should also be governed by the same principle [C13]. Yet others contested whether permanence should be the premise of policy design. For example, perhaps an overriding principle could be '*whether you can accept a long-term losses or impermanence, as we all strive to reduce emissions in the near term*' [P7].

For select participants, the relative impermanence of nature-based removals can be managed through MRV (n=2). Multiple measures can ensure the effective permanence of nature-based removals, for example, creating buffer pools, or enforcing liability measures for reversals (Burke and Schenuit, 2024). Many participants doubt the effectiveness of these measures, notably those that rely on enforcement. For example, one commercial actor claims that for reversals '*it comes back to the monitoring and compliance. It's a massive issue, "we're permanent, because everybody has to restock* [a woodland]*", if you're not enforcing that, you're not monitoring that*' [C10]. Others doubt whether such measures are practically possible given the length of monitoring periods implied by the permanence. For example, in the view of one policy professional, commenting on biochar, '*some people say this is permanent for thousands of years, other people question how do you track or account for that? Will you keep going back to the farms and monitor them for hundreds of years*?' [P10]. For woodland projects certified under the WCC, the monitoring period can last up to a 100 years (Woodland Carbon Code, 2022). This brings further challenges to monitoring and enforcement, as claimed by one participant '*when you think about the time scales that these projects exist on, that's only going to get murkier and murkier as land changes hands* [ownership]' [C10]. Given the practicalities of monitoring and enforcement, some participants advocate to integrate permanence into the pricing of removal credits, meaning a greater number of credits may need to be purchased to equate to a single permanent credit (n=3).

Permanence is not the only factor impacting upon MRV, participants' concerns also extend to the measurability of the removal, and the costs and resources required. On measurability, participants point to scientific uncertainties, still to be resolved, such as the permanence of biochar (n=2), or to the open properties of a CDR method. For example, as raised by one policy professional '*but the biggest barrier that I can see is that of monitoring, reporting and verification, especially for some greenhouse gas removal methods like enhanced weathering, for example, where you do not have a set amount of carbon dioxide at the end that you can hold in your hand* [quantify accurately] *and then store geologically*' [P9].

On the costs and resources required, participants highlighted a need for a pragmatic balance in MRV between '*creating a really stringent strict standard, but also not again killing* [making uneconomic] *the* [CDR] *industry, because it's so intensive that you need a 10-man team just to get through the standard*' [C1]. Participants highlighted the need to understand the costs of MRV, with the notion that certain methods may be penalised if MRV costs are not covered by policies, for example, in the payments made to CDR project developers under the CfD [P5]. Projects may similarly be penalised if MRV standards are too costly or onerous to comply with compared to the scale and resources of the project (n=3). Similarly, there is a need to reduce the risks that the costs of MRV may change, for example, with increasing costs for verification across the monitoring period of the project (n=2).

With the creation of multiple private standards, participants are keen to see governments intervene, to develop a standard that represents the '*government stamp of approval*' [P2], or to regulate existing private standards, ensuring that project developers are not '*self-certifying whether a code is fit for purpose*' [P7]. This, arguably, would also help address the lack of trust in the VCM, by providing regulatory oversight through the standard [P1]. It may also provide the opportunity for the government to develop its own registry to, for example, provide transparency as to what projects are receiving government subsidies [P2], or to allow for the accounting of all removals within the national greenhouse gas inventory [P9], given their current absence within IPCC guidelines [P10].

5.4.3 Long-term demand

Many participants set out how CDR policy should be viewed in the longer-term, as the UK decarbonises and approaches its net zero target. For government, the main policy supplying this longer-term demand is the planned integration into the UK ETS (UK Government *et al.*, 2024). The UK ETS is seen as an '*established policy framework*' [P10], familiar to companies [P3]. Integration provides '*a guarantee of longer-term demand*' [P2], whilst pairing removals with '*residual emissions we're unable to abate, which may be from installations in the ETS*' [P2]. Yet integration isn't without its risks, and participants cite concerns spanning the price of allowances and the scheme's design, warranting close attention to how removals will be integrated.

On price, many participants share the view that the current UK ETS price of auctioned allowances, corresponding to the right to emit 1 tonne of carbon dioxide equivalents (tCO_2e) under the emissions cap, is currently too low (n=8 [C=4,P=4]). UK ETS allowances in 2023, averaged an auction price of £53 t/CO_2e, far below the cost of many CDR methods, though higher than the historic price for WCUs (Element Energy and CEH, 2021; CCC, 2024; Woodland Carbon Code, 2024). A connected concern is the volatility of the price of allowances, and the need for a sufficiently predictable price to incentivise removals (n=4). Combined, the UK ETS price may not be sufficient to allow for investment in many engineered projects, without the continued support of policies like a CfD. As explained by one policy professional '*market prices in the ETS are too low for many methods, so we need a prior phase of subsidies to bring those costs down so that when integrated into the ETS, those prices do really incentivize technologies*' [P5]. Given the scales necessary and the long lead time of projects, '*we need so much* [engineered removal] *capacity that we need to start building in the 2030s, and the ETS price is not going to be high enough at that point and it's probably not going to be predictable enough*' [P4].

Seventeen of our participants raised concerns around the design of the UK ETS, and how this may impact the demand for CDR. Select participants regard removals as a '*separate use case*' to the UK ETS [P1], which should be principally focused on preventing emissions (n=3). Views are therefore mixed as to whether removals should be integrated to allow fungibility with allowances (n=3) or whether a separate parallel removal trading system may be necessary (n=3). For WCUs, participants remarked that the WCC's current practice of first crediting '*pending issuance units*', representing potential removal credits, then validating projects with WCUs as the woodland grows, poorly aligns with the fungibility of allowances and the timescales in the UK ETS (n=2). In the view of one commercial actor '*you are talking about really small volumes entering the market in 15 and 25 years* [time]' [C15].

Many participants detailed what has been described by researchers as the '*ETS endgame*', that is, as the emissions cap declines, allowances become increasingly scarce (Pahle *et al.*, 2025). As sites decarbonise in response to fewer allowances and higher UK ETS prices, fewer sites remain in the market, lowering the liquidity, the ease with which allowances can be bought and sold (UK Government *et al.*, 2024; Pahle *et al.*, 2025). As a result '*the ETS should evolve into a trading scheme where you've got net zero as the output, and your cost of emitting is equal to your cost of abating, and then then you'll reach an economy where those two things are in balance*' [C2]. Yet participants anticipate a need for net-negative emissions in the UK (n=5), given the expectations of developing nations towards historic emitters, to extend climate ambitions beyond net zero (Schenuit, Geden and Peters, 2024). The implications of a net-negative economy may mean the UK ETS needs to extend beyond the polluter pays principle upon which it is currently based, so that '*some companies have to pay for much more removals than…their emissions are equivalent to*' [P4]. In a net-negative economy, therefore, demand for removals must go beyond compensating for current emissions, by, for example, extending compliance to past emissions [P6], or otherwise expanding the UK ETS to new sectors with likely residual emissions (n=2). The progression to a net-negative economy is thought to be more viable with a separate removal trading system, as a separate system needn't rely on the polluter pays principle [P3]. A separate system leaves open how demand can be met, though three participants favoured the use of mandates levied on specific sectors, such as a Carbon Takeback Obligation, as explored in Jenkins *et al.*, 2021.

For nature-based removals, there remains debate as to whether integration into the UK ETS would be a positive step (n=6). Some participants speculate as to whether the proposal to integrate WCUs into the UK ETS is principally political, given that the government has missed its near-term woodland targets, meaning '*they* [the government] *see the* [UK] *ETS as a way of channelling finance to those technologies or methods, regardless of whether that's actually an optimal approach for incentivizing their deployment*' [P5]. Other participants are concerned by the prospect that current government grants may end, transitioning towards a greater reliance on private finance through markets (n=2), leading one participant to suggest that nature-based removals may need to retain public funding in perpetuity, '*personally, I think it's always going to be a need for the public sector to step in to, to continue to create the interest in the market*' [C3]. The long-term outlook for nature-based removals, therefore, seems less clear. Eight participants, however, are united in the view that long-term demand should be met by compliance-based policies, obligating actors to purchase removals and ensuring demand. This entails a transition from voluntary to compliance policies. As explained by one policy professional '*that transition from VCM to compliance market has to happen, the timing of it is the critical question*' [P5].

5.4.4 Policy approach

Our interviews often went beyond the discussion of discrete areas of policy, towards discussion of the government's wider policy approach, addressing the government's overall strategy towards CDR policymaking. Participants, for example, viewed the UK government's policy approach as slow and overly bureaucratic (n=7 [C=4,P=3], see Figure 26 for a further breakdown of sub-themes by type of organisation). Policies, particularly for engineered removals, are seen as not progressing at the necessary pace. For example, as remarked by one participant '*the biggest issue of the policy, in my view, is it's not moving quickly enough*' [C2]. Another stated '*if we really want to get this stuff off the ground, we need to see it moving a lot faster*' [P1]. The business models developed by the government, such as the CfD, are viewed as adding bureaucracy, requiring the government to initially negotiate individual agreements with project developers, leading to longer lead times to establish the first projects (n=2). Their greater complexity means there are more elements to be designed in consultation, adding to the perceived slow pace of policy development. For example, one policy professional stated that, when commenting on engineered removals, '*these business models are usually seen as a success, but one of their weaknesses seems to be the slow rollout, because they're being perfected, the specific design is* *being perfected before anything launches*' [P10]. Nevertheless, the speed of policies may, in part, be deliberate. As explained by one policy professional, '*we're* [the UK] *doing things slowly, but we're doing it right*' [P2]. The slower pace allows for fuller engagement from government, learning from the scandals that have reputationally damaged the VCM. For example, '*by going slower and sure, we can create a stable long-term footing for projects to bank off of*' [P2].

To participants, the slow pace is explained by the government's desire to ensure the efficient use of public money. For example, '*we* [the UK] *often overcomplicate our policy design, trying to ring out the most cost and benefit for the taxpayer, we have a preoccupation with that, and it often can slow down efforts*' [P5]. Many participants draw comparisons between the government's CfD and policies abroad, such as Canada's 60% tax credit on capital invested in carbon capture utilisation and storage, or the United States' 45Q tax credit, both of which include eligibility for DACCS (n=4). These policies are viewed as both simpler to administer and more immediate to the financing needs of project developers, addressing the financing gap between pilot and commercial scales, such as the scales eligible for the government's business models. Without addressing this financing gap, participants believe the UK may not be competitive, with the policy framework seen as more demanding than rewarding for project developers. As remarked by one participant commenting on the prospect of reverse auctions to award CfDs; '*You know, why would you move to the UK? if you, if you're Carbon Engineering* [a direct air capture technology developer] *and you've got cheap hydro* [hydroelectricity] *in BC* [British Columbia, Canada] *and a big tax credit, you know, that's more compelling than coming to the UK and having to bid into an auction*' [Po5].

No one solution is offered to address this gap. Rather participants propose that the gap could be addressed by; direct grants from government for specific methods (n=2), government support in arranging corporate offtake agreements [P1], or greater coordination between pilot plants and eligibility for support under the business models [P10]. These efforts should seek to improve the ability of companies to secure more conventional means of finance, such as debt financing, as opposed to venture capital, improving a project's '*bankability*' (n=5).

Policy design in the UK is made markedly more complex by the need to balance the utilisation of CO_2 with the need for removals. Commercial actors may therefore pursue a strategy that leverages policy incentives for both utilisation and removals (n=3). For example, one company's strategy is to focus '*more on utilization for the short to medium term and waiting for that mass market to come before then really getting stuck into removals themselves*' [C4]. For others, projects are to be designed to utilise multiple revenue streams, flexibly changing between removals and utilisation, or combining them into a single project (n=3). This strengthens the financial security of the project by spreading the risk of low prices across multiple markets, but complicates both the MRV of the project and its eligibility within government policies, given the government's business models use set thresholds for eligibility (DESNZ, 2024d).

For nature-based removals, pace remains a concern, but as the policy incentives are more established, concerns focus on the pace of projects as opposed to policy developments (n=2). Like engineered removals, participants cite concerns over the complexity of the current policy approach, for example, the creation of multiple carbon codes, such as the WCC, Peatland Code, and the similar codes for saltmarshes and soil carbon currently in development (n=6). These are argued to complicate engagement with both credit buyers and landowners. For credit buyers, it can create barriers to access, given each scheme uses its own terminology, reflecting differences in design. As explained by one participant '*What's validation? What's verification? What's a PIU* [pending issuance unit]*? What's a WCU? and if they're having to do that, for every single standard that they're engaging with, you know, it's really going to put companies off…buying different carbon credits from different standards*' [C6].

For landowners, multiple standards can create greater bureaucracy, particularly given that many land holdings may have multiple habitat types, each targeted by a separate code, creating, for example, the need for multiple validations. For example; '*You've got a separate woodland carbon code administered in one way, peatland another. Well, there's land ownerships that have woodland and peatland, and there's agricultural holdings that are woodlands and peatlands, and it actually needs simplification*' [C3]. This, it is argued, could be resolved by merging multiple codes into a single UK standard, administered by a single entity, therefore standardising procedures, such as eligibility, additionality, and validation (n=2). The standard may still include methodologies for each habitat type, but these would be treated as methodologies under a single standard, as opposed to separate standards, as currently practiced [C3].

Many participants raised the issue of state capacity, reflecting the government's own capacity to implement its desired policy approach (n=6). Participants cite a lack of expertise within government (n=4), or unhelpful divisions between government departments (n=6). For nature-based removals, resolving divisions between departments, or fostering means of collaborating, is a necessity owing to the multiple policy objectives to be achieved through land management, spanning biodiversity, flood alleviation, and climate mitigation (n=3). Participants highlighted that, given the variety of methods, and their interaction across multiple domains, CDR largely falls between government departments and regulatory bodies (n=3). Though the Department for Energy Security & Net Zero (DESNZ) considers, within its remit, engineered removals, no single government entity has the specific remit of CDR (n=3).

Participants argue this could be resolved by creating, for example, '*a joint unit between Defra and DESNZ*' [P3], or by facilitating greater collaboration between departments [C4].

5.5 Discussion

The UK is not alone in implementing CDR policy, nor alone in its explicit policy support for engineered removals (Meissner, 2024). Many countries are now introducing subsidies for engineered projects, ranging from tax credits in Canada and the US, grants in Norway, tenders in Denmark, and reverse auctions in Sweden (Hickey *et al.*, 2023; Fridahl *et al.*, 2024; Meissner, 2024). Both the EU and Japan are exploring the integration of CDR within their own emission trading schemes (CDR.fyi, 2024b; Pahle *et al.*, 2025). Similarly, nearly all countries have an interest in maintaining or enhancing the uptake of CO_2 by land, ensuring that land-use remains a focal point in climate policy (Fyson and Jeffery, 2019; Dooley, 2024). Increasingly, therefore, there exists a need to examine CDR policymaking. To date, research examining CDR policies have been few, and national case studies, where carried out, have largely focused on potential policy design, rather than evaluating the policies introduced (Zetterberg, Johnsson and Möllersten, 2021; Hickey *et al.*, 2023). Our case study into the UK, a country with advanced policy plans for CDR, helps address this research gap.

Our 25 interviews reveal several themes and policy recommendations. Firstly, participants had little trust that the VCM can provide the necessary demand to scale CDR in the near-term, presenting a need for the government to stimulate demand more directly. Criticism of the VCM is common across academia, many of the scandals that have reputationally damaged the VCM originate in academic research that attempts to externally validate the carbon credit claims of projects (Probst *et al.*, 2024). Researchers differ, however, on whether the VCM can be reformed in time to serve the goals of the Paris Agreement (Cullenward, Badgley and Chay, 2023; Kreibich, 2024). To some, scandals reflect flawed incentives that can be readily addressed through market reforms (Reinhard, Planavsky and Khan, 2023; Swinfield *et al.*, 2024). Whilst for others, scandals are evidence of a wider '*identity crisis*' in the VCM, reflecting the priorities of climate policy prior to the Paris Agreement, of reducing the economic burden of achieving only modest emission cuts (Cullenward, Badgley and Chay, 2023; Kreibich, 2024). The VCM is therefore a market in search of a purpose.

The approach taken by the government attempts, in part, to address these criticisms, by, for example, seeking to develop its own government standard for MRV. A development largely supported by our participants. Yet the government's policy approach reflects '*a clear preference in government to go down a market route*' [P6]. The success of the government's CfD for engineered removals, for example, is tied to securing demand through voluntary corporate offtake agreements (DESNZ, 2023e). Similarly, nature-based removals are tied to the success of new nature markets (Swinfield *et al.*, 2024). Our participants suggest this preference reflects the government's desire to protect the taxpayer by mobilising private finance. This is similarly reflected in government communications, consultations on the design of the CfD frequently reference a need to '*maximise value for money*' and reduce '*government support over time*' (DESNZ, 2023e, 2023d). Yet, without demand, the government may be forced to act as a '*buyer of last resort*', and the government is currently exploring whether a '*government offtake backstop*' is required in the CfD, to mitigate '*volume risks*' to project developers, when a shortfall occurs in market demand (DESNZ, 2023e). For the WCC, the woodland carbon guarantee has acted as a similar backstop (Forestry Commission, 2019).

Participants propose multiple means to stimulate near-term demand. A common proposal for engineered projects is to introduce tax credits similar to the US and Canada, replacing the proposed CfD. This may not guarantee demand, but a more generous subsidy may lead to higher deployment (Element Energy, E4tech, and Cambridge Econometrics, 2022). Participants, however, highlight a need to improve the pace of projects and policy development, whilst improving state capacity. Given the government's prior experience with CfDs, and relative inexperience with tax credits, both the pace of projects and the government's capacity to deliver on its policies may be best served by the continuation of the CfD. For example, the government can leverage existing institutional capacity through the Low Carbon Contracts Company, a private company owned by DESNZ, that currently administers CfDs for renewable energy.

There are, however, proposals that more directly target demand. The government, could, for example, procure removal credits directly, as explored in the US Department for Energy $35 million CDR Purchase Pilot Prize and Canada's $10 million Low-Carbon Fuel Procurement Program (TBS, 2024; US DOE, 2024). This, however, may further delay the introduction of the CfD, as the government cannot both stimulate supply and provide demand simultaneously whilst retaining a CfD. As raised by participants, the government could also facilitate corporate offtake agreements, expanding the voluntary purchase of engineered removals beyond the technology companies that currently dominate purchases (Joppa *et al.*, 2021; CDR.fyi, 2024a). The government should therefore consider ways to stimulate near-term demand for CDR, across both engineered and nature-based removals. Given the future integration with the UK ETS, funds for public procurement or direct grants could come from the revenues generated from the auction of UK ETS allowances, which currently accrue to the general budget, unlike the EU ETS, which uses revenues to fund grants to low carbon technologies through the EU Innovation Fund (EEA, 2024). UK ETS allowances contribute only 0.6% (2023/24) to total government revenue, rerouting less than 1% of this contribution could exceed the procurement programmes of the US and Canada combined (IFS, 2023).

Secondly, the government should implement credible MRV, introducing its own government standard and MRV regulator. This offers the opportunity to build upon existing standards such as the WCC and the Peatland Code, introducing a standard covering all main methods, standardising the means through which permanence is managed. The government has already explored, in past consultations, fungibility measures to address differences in permanence between methods, if multiple CDR methods are integrated into the UK ETS. For example, methods '*that store carbon for shorter periods of time*' could be awarded fewer allowances than methods '*that store carbon for longer periods of time and with greater security*' (UK Government *et al.*, 2024). The government, however, should assess the impact of these measures on near-term demand. For example, announcing that multiple nature-based removal credits may be needed to be fungible with allowances could be interpreted as a standard that should apply also in the VCM, effectively increasing the price.

The development of a government MRV standard also suggests a need for a regulator to ensure compliance with the standard, offering the opportunity to improve state capacity, a third key theme. Participants highlighted a need for a new cross-government body to oversee the CDR sector. This body should include DESNZ and Defra, given the nature of both engineered and nature-based removals, and, given the role of CO_2 utilisation in, for example, synthetic transport fuels, the Department for Transport (DfT, 2024). This body should aim to build the necessary expertise to regulate the sector.

Finally, participants highlighted a need to set a clear policy direction towards a net-negative economy, ensuring the UK ETS is '*net-negative ready*' (Schenuit, Geden and Peters, 2024). The need for net-negative emissions targets will likely animate climate negotiations as the world approaches the 1.5°C limit stipulated in the Paris Agreement (Mohan *et al.*, 2021; Betts *et al.*, 2023). Multiple countries have articulated an ambition to go net-negative after net zero greenhouse gases, including Germany, Finland and Denmark (Dunne, 2024). In scenarios assessed by the IPCC, net-negative emissions are necessary to reverse the temporary overshoot of 1.5°C (Schleussner *et al.*, 2024). The implications of net-negative emissions for climate policy are less clear, though net-negative necessarily entails more removals than emissions. This has implications towards the UK ETS. For example, as the cap declines, the current proposal to substitute allowances with removal credits becomes increasingly untenable, reaching a point where the UK ETS ceases to provide additional demand (UK Government *et al.*, 2024). The government therefore needs to ensure that the '*ETS endgame*' is not the end of the UK's climate ambitions, by providing a pathway to a net-negative ETS.

5.6 Conclusion

The UK government serves as a useful example for countries aiming to integrate CDR within their climate policy frameworks. Policies and plans in the UK, though still under development, are advanced reflecting multiple rounds of consultation. Through 25 interviews with experts active in UK CDR policymaking, we identify several key themes. Firstly, a scepticism towards the VCM, reflecting a need to stimulate near-term demand. Secondly, a need to implement credible MRV, standardising differences in the permanence of CDR methods. Thirdly, a need to improve state capacity, to be met by a new cross-government body tasked with overseeing the CDR sector. Fourth, a need for '*net-negative ready*' policy, ensuring that the UK ETS provides long-term demand for CDR, given the likelihood of temporary temperature overshoot and net-negative emission targets as the next necessary development of climate policy.

Whilst governments elsewhere may differ in their policy approach, these needs may also apply beyond the UK. For example, the VCM is not limited to the UK, and government's with different policy designs similarly need to consider interactions between the VCM and government incentives. The EU has since adopted, in 2024, the Carbon Removals and Carbon Farming (CRCF) Regulation (EU/2024/3012), a voluntary framework for certifying carbon removals, and similarly requires further state capacity in order to manage certification. Lastly, the need for net-negative policy applies to many developed countries, who will face similar pressures to move beyond net zero.

It remains to be seen whether '*going slower and sure*' [P2] will successfully scale CDR. This approach aims to provide stability for the CDR sector, allowing for fuller government engagement. Our interviews, however, suggest even greater engagement and oversight is necessary to ensure this approach continues to support the UK's climate ambitions.

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6 Discussion & conclusion

6.1 Introduction

This thesis addresses what is a key knowledge gap in climate policy research, the planning of national entities towards developing and incentivising CDR (Schenuit *et al.*, 2021). CDR remains an essential part of mitigating climate change, albeit one contested in scale, impact and feasibility (Förster *et al.*, 2022; Deprez *et al.*, 2024). This thesis demonstrates that CDR is no longer a debate limited to CDR's role in scenarios assessed by the IPCC (Fuss *et al.*, 2014), but has become an active part of the debate that animates climate policy, and a key feature of LTS and their visions of net zero. In doing so CDR poses new challenges to national governments, such as the policies and markets through which CDR is incentivised, and brings new concepts to the fore of climate governance, such as the residual emissions indirectly mitigated by CDR.

This chapter considers the contributions of this thesis against the three sub-aims set out in the introduction, Section 1.8. Section 6.2 details progress against these aims, whilst Section 6.3 details the implications of this research towards climate policy and climate governance. Section 6.3 also sets out multiple avenues for future research. Finally, Section 6.4, concludes.

6.2 Research contribution

To address the primary aim of this thesis, three sub-aims were developed, each addressed in one or more chapters.

6.2.1 Sub-aim 1

Sub-aim 1 was to '*establish the inclusion of CDR methods in national net zero plans, including the methods to be deployed and their extent relative to residual emissions*'. Chapters 2, 3 and 4 serve to evidence progress against this sub-aim. Chapter 3 established, through an analysis of 41 of the 50 LTS then available, that enhancing forest and soil carbon sinks were the most advocated CDR methods across this sample. The inclusion of engineered CDR methods was limited to a handful of Global North states, predominantly European. This trend continues in the extended dataset detailed in Chapter 2. Chapter 4 serves to address residual emissions, focusing on their extent relative to peak and current emissions across 71 LTS. Residual emissions were found to be substantial, on average 25% of 2021 GHG emissions for Annex I countries, and, in select cases, up to 55%. For select countries the extent of residual emissions may be justified, for example, states with large agricultural sectors and limited emissions from other sectors may legitimately claim a need for high relative residual emissions. Concerningly, however, many of the scenarios with high residual emissions reflect a desire to minimise disruption to the energy and industry sectors, retaining a greater share of their emissions and minimising the need for sectoral mitigation (for example, as seen in the scenarios for Australia and Canada).

Further research is necessary to explore the extent to which residual emissions can be further reduced, and how policy design may help avoid high residual emission scenarios. As explored in Chapter 4, separate targets for LULUCF, engineered CDR and emissions elsewhere in an economy, may limit cases where high residual emissions are compensated by the large scale deployment of CDR. This proposal is further explored, as a future research area, in Section 6.3.3. How residual emissions may be further reduced, is explored in Section 6.3.2.

6.2.2 Sub-aim 2

Sub-aim 2 was to '*establish the nature of residual emissions in national net zero plans, and their justifications for compensation by negative emissions from CDR*'. Analysing the extent of residual emissions reveals their political nature, alongside what may be understood as current technical limitations in their abatement. Chapter 4 serves to understand both the nature of residual emissions and their justification, as an insight into their emerging politics. Chapter 4 examines sectoral residual emissions, establishing agriculture as the largest contributor on average across net zero GHG scenarios detailed within LTS, contributing, on average, 36% for Annex I countries. Chapter 4 also establishes agriculture as the sector with the least relative ambition, with a reduction on average of only 37% for Annex I countries relative to 2021 emissions, compared to upwards of 70% in all other sectors.

Scenarios within LTS tend to detail emissions in broad sectors, which need to be aligned to a common framework, as undertaken in Chapter 4, limiting the resolution at which residual emissions can be compared. Chapter 4 therefore mapped 357 statements concerning specific sources or sub-sectors to the main sectors analysed, revealing the extent to which specific sources or sub-sectors may contribute to residual emissions within the sector. This analysis largely agreed with prior analyses of residual hard-to-abate emissions, highlighting the challenges of mitigation in cement, steel and chemical production under industry and the difficulties of fuel-switching in aviation and shipping under transport (Davis *et al.*, 2018; Babiker *et al.*, 2022; Fennell *et al.*, 2022). Agriculture was notably absent from the discussion of residual or hard-to-abate emissions within LTS, despite the sector's prominence within scenarios. Analysing these statements as to whether they establish a rationale, justifying a sector, sub-sector or source as residual or hard-to-abate, revealed seven rationales, which differed in frequency across the main sectors. Industry, for example, was viewed as justified owing to the further need for innovation in the technologies that enable deeper decarbonisation. Industry is therefore a sector where further innovation efforts may alter the extent of residual emissions in further LTS scenarios, as national governments grow increasingly confident in the feasibility and deployment of new technologies, such as direct reduction of iron using green hydrogen. Residual emissions in agriculture, meanwhile, were viewed as simply an inevitability, with limited prospects for improvement.

The prospect of residual emissions in agriculture, therefore, should be prioritised as a future area of research, given this differs to how residual emissions in industry are commonly characterised. Here, demand-side dietary shifts may play an important role in further mitigating agricultural emissions. Demand-side policies, however, are more challenging to integrate into the modelling approaches that commonly underpin the scenarios explored in LTS (Sharmina *et al.*, 2021). Further reducing agricultural residual emissions, is explored in Section 6.3.2.

6.2.3 Sub-aim 3

Sub-aim 3 was to '*evaluate how these national net zero plans translate into CDR policy, evaluating the policy plans of an advanced national case*'. Chapter 5 addresses this sub-aim through a case study of the UK. The UK's LT-LEDS, the UK Net Zero Strategy, largely mobilised a series of consultations and policy plans to scale CDR in the UK, alongside setting out, through scenario modelling, the ambition for the scale of the CDR sector and its contribution to net zero (HM Government, 2022). These advanced policy plans create a sizeable expert community, engaged in CDR policymaking via consultations, task and finish groups, or via the receipt of policy incentives. We interviewed 25 participants, active in CDR policymaking, revealing a desire for greater government intervention. Participants were sceptical of the VCM, looking towards government to stimulate demand in addition to the government's current emphasis on supply. Participants similarly welcomed greater government oversight, via, for example, the planned government MRV standard (DESNZ, 2023e). Participants similarly viewed the government's policy approach as preoccupied with ensuring taxpayer value-for-money, overly concerned with mobilising private finance and demand. Participants recognised that greater public investment may be necessary, particularly given the lack of near-term demand and the need to finance removals beyond the limits of the polluter-pays principle that currently guides climate policy, as would be necessary for net-negative emissions.

The ongoing debate regarding the integration of CDR into the UK ETS revealed the wider tensions within UK climate policy, concerning the UK's leadership in climate action, given the likelihood of temporary temperature overshoot and the subsequent need for net-negative targets, as an extension of net zero. Overall, the chapter addresses a direct need for national case studies, evaluating existing policy plans as opposed to potential policy designs (Schenuit *et al.*, 2021, 2024).

Further research is necessary to explore further policy contexts, given that many countries are beginning to further incentivise CDR through climate policy. The role of the VCM and large corporates, in incentivising CDR, should also be further explored, given this became the predominant focus of expert interviews. Large corporates, in the absence of governments, have largely acted to govern CDR through the voluntary market, and may now act as a crucial lobby in the design of policies being introduced by governments. Large corporates as a focus of future research is explored further in Section 6.3.4.

6.3 Policy implications and avenues for future research

This thesis, by analysing both LT-LEDS and expert interviews, contributes to the literature that tracks the reporting provisions of Parties to the UNFCCC and the Paris Agreement, as well as the rapidly growing literature on CDR policy and governance (Lück, Mohn and Lamb, 2024). This thesis's implications towards climate policy therefore span both these areas, yielding several avenues for future research.

6.3.1 Clarifying and mandating LT-LEDS reporting

Chapters 3 and 4 both conclude by advocating for stronger reporting requirements towards LT-LEDS, by, for example, making their development and submission to the UNFCCC mandatory. This policy recommendation is based upon observations within these chapters as to the contents of LT-LEDS, for example, their value in identifying long-term challenges to the feasibility of CDR, or the value of the scenarios and pathways they contain in informing a country's ambition across sectors. Chapter 2, meanwhile, documents the contents of LT-LEDS, revealing many omit scenario or pathway modelling, opting to communicate more qualitative '*visions*'. There exists, therefore, a large difference in the quality of LT-LEDS.

LT-LEDS represent a lost opportunity for many states to strengthen their own understanding of climate action, providing insight towards enacting their long-term targets. Owing to their optionality within the Paris Agreement, LT-LEDS are unlikely to reach the level of reporting seen for NDCs and other obligated reporting elements, such as Biennial Transparency Reports (BTRs). Mandatory reporting would in turn strengthen our understanding of CDR, given CDR's more prominent role in decarbonisation towards net zero and the longer-term focus of LT-LEDS (Mace *et al.*, 2021). Yet mandatory reporting would require, practically speaking, for the UNFCCC to revisit in negotiations the implementation of the Paris Agreement, which was largely formalised at COP24 in 2018, as the '*Paris Rulebook*'. It may also require greater capacity building for non-Annex I parties, efforts which may be better directed to informing NDCs, NGHGIs and BTRs (Umemiya and White, 2023). An emphasis on these elements alone, however, greatly reduces the Paris Agreement's time horizon, given there are no other reporting elements which extend beyond 15 years into the future[23]. There exists, therefore, a need to balance the near and long-term elements of the Paris Agreement. This need is made more pressing given that nearly all Parties to the Paris Agreement have declared long-term targets towards the mid-century, yet lack a formal reporting obligation through which parties can communicate these same targets (Net Zero Tracker, 2024b). Instead, many parties appear to make do by using other existing reporting elements, like NDCs (Meinshausen *et al.*, 2022). Formalising LT-LEDS as a mandatory reporting obligation, introducing guidance detailing best practice for the reporting of long-term targets, can fulfil this gap.

The submission of LT-LEDS may strengthen the global climate regime through multiple means (Rocha and Falduto, 2019). For example, submitting LT-LEDS signals credibility to other states within the regime, improving trust between parties (Rocha and Falduto, 2019; Rogelj *et al.*, 2023). Many of the theorised benefits of LT-LEDS, however, lack evidence in practice. For example, within informal guidance, LT-LEDS and NDCs are to be aligned, informing the ambition of one another (Català *et al.*, 2024). Yet, according to the most recent LT-LEDS Synthesis Report, only 10% of the LT-LEDS analysed are said to be aligned with NDCs (UNFCCC Secretariat, 2023). 47% of the LT-LEDS analysed provided no information on how they relate to NDCs (UNFCCC Secretariat, 2023). There exists, therefore, a need for further research into the benefits of LT-LEDS in practice, given the greater number now submitted.

NDCs meanwhile have been extensively studied, varying from the formulation of 2030 targets, to the extensive topic modelling of their contents (King and van den Bergh, 2019; Mills-Novoa and Liverman, 2019; Savin, King and van den Bergh, 2025). NDCs, however, may not be an appropriate focus of research owing to guidance that formalises their contents, the '*Information to facilitate clarity, transparency and understanding of nationally determined contributions*' (CTU), found within the Paris Rulebook (Decision 4/CMA.1, Annex I). The most recent NDC Synthesis Report suggests that parties largely adhere to this guidance, with a reported 95% of parties providing the '*the information necessary to facilitate clarity, transparency and understanding of their NDCs*' (UNFCCC Secretariat, 2024). Given that this guidance prescribes the elements to be included in the NDC, it serves that NDCs are unlikely to provide insight towards certain elements within the global climate regime not otherwise covered by this guidance (Leiter, 2024). For example, NDCs can be used to assess how governments frame their NDC in relation to '*fair and ambitious*' considerations within the Paris Agreement (Decision 4/CMA.1, Annex I, paragraph 6), an element explicitly covered by guidance, but may be limited in setting out a government's position towards CDR, given its absence from this same guidance.

[23] 15 years being the required minimum for emission projections, according to the modalities, procedures and guidelines (MPGs) for BTRs (annex to Decision 18/CMA.1, paragraph 95).

There are more consequential reporting elements within the Paris Agreement for many concepts, such as Adaptation Communications for climate adaptation (Article 7, paragraphs 10 and 11 of the Paris Agreement). It could be argued, therefore, that researchers should become more acquainted with the range of reporting elements within the Paris Agreement, including, amongst others, LT-LEDS, diversifying away from NDCs (Leiter, 2024). However, it remains the case that many countries treat NDCs as an opportunity to communicate beyond the elements in guidance. For example, the most recent assessment of the content of NDCs using topic modelling found that the largest theme, covering a quarter of all NDC content, concerns '*sustainable, economic or rural development*' (Savin, King and van den Bergh, 2025). This is larger than the total textual content in NDCs devoted to communicating near-term targets (20%), the overarching purpose of NDCs (Savin, King and van den Bergh, 2025). The development theme was communicated primarily by developing countries, whilst high-income countries, as referred to within the analysis, primarily use NDCs to communicate targets and the necessary information for CTU (Savin, King and van den Bergh, 2025). It therefore seems necessary for parties to similarly diversify beyond NDCs before researchers do so. Since 2024, parties now adhere to the Paris Agreement's Enhanced Transparency Framework (ETF), which requires more of non-Annex I parties than previously required for reporting under the convention (UNFCCC, 2023). Capacity within these countries may therefore improve, meaning information more suited to LT-LEDS or Adaptation Communications can be reported through these provisions.

The credibility of current climate commitments could be strengthened by developing CTU guidance for LT-LEDS, clarifying the role of LT-LEDS versus NDCs and wider reporting elements, ensuring parties communicate the necessary information to evaluate, for example, long-term targets. It could also be strengthened by a requirement to submit a LT-LEDS ahead of 2030 or prior to the submission of every other NDC. These changes would introduce a decadal cycle to compliment the 5-year ambition cycle within the Paris Agreement (Grant, 2022), aligning with the Governance Regulation in the EU which mandates EU Member States produce similar long-term strategies. Flexibility for, for example, least developed countries and small Island developing states can be retained as practiced elsewhere within the Paris Agreement[24]. CTU guidance for LT-LEDS should build on best practice, incorporating the range of informal guidance already published (van Tilburg, Ochs and Lee, 2024). Guidance should require a '*backcasting*' approach to scenarios, working backwards to identify the policies and actions needed in the present to fulfil a long-term target, thereby making clear the gap between these scenarios and the country's NDC (Dolphin *et al.*, 2023; Català *et al.*, 2024).

[24] For example, least developed countries and small Island developing states can submit a BTR at their discretion in accordance with the annex to Decision 18/CMA.1, paragraph 11.

6.3.2 The social and political nature of residual emissions

Chapter 4 establishes agriculture as the main source of residual emissions, as well as the sector with the least relative ambition in reducing emissions when compared to current levels. Such a result is to be anticipated, given the decarbonisation strategies of many countries resemble the broad sequential logic found within IAM scenarios assessed by the IPCC, starting with decarbonisation in the energy sector, transitioning to a largely renewable energy system, before electrifying other parts of the economy, including residential heating, road transport, and subsections of industry, such as low temperature industrial heat (Riahi *et al.*, 2022; Fankhauser, 2024). For industrial processes that cannot be electrified, further emissions reductions are achieved through both fuels switching and the use of CCS (Bataille *et al.*, 2018; Riahi *et al.*, 2022). Agricultural emissions, specifically sources of CH_4 and N_2O, as assessed in Chapter 4, are only modestly reduced in these scenarios (Riahi *et al.*, 2022).

Figure 27 compares the scenarios detailed within LTS to the most ambitious of group of IAM scenarios found within AR6, the '*C1*' scenarios, which limit global average temperatures to below 1.5°C by the end of the century, with no or limited overshoot (Riahi *et al.*, 2022). To allow for a more direct comparison, we use only those scenarios that also reach net zero GHGs across the century, or the '*C1a*' scenarios (Riahi *et al.*, 2022). Figure 27A depicts the relative ambition of C1a and LTS scenarios between 2021 and the year net zero GHGs is reached. As seen, the relative ambition is similar for agriculture, indicating that, though the emissions reductions modelled for agriculture within the LTS are modest compared to other sectors, they are aligned with the extent of ambition seen within scenarios assessed by the IPCC. LTS scenarios differ on the timing, however, as seen in Figure 27C, with LTS scenarios achieving net zero GHGs largely by 2050, whereas, for C1a scenarios, the median year net zero GHGs is reached is 2070. Figure 27B details the same analysis but for industry. For industry, a clear gap is evident, though there are limits to which this comparison applies given industrial emissions are highly concentrated in select countries. For example, 45% of all cement emissions in 2023 originate from China (Andrew, 2024b).

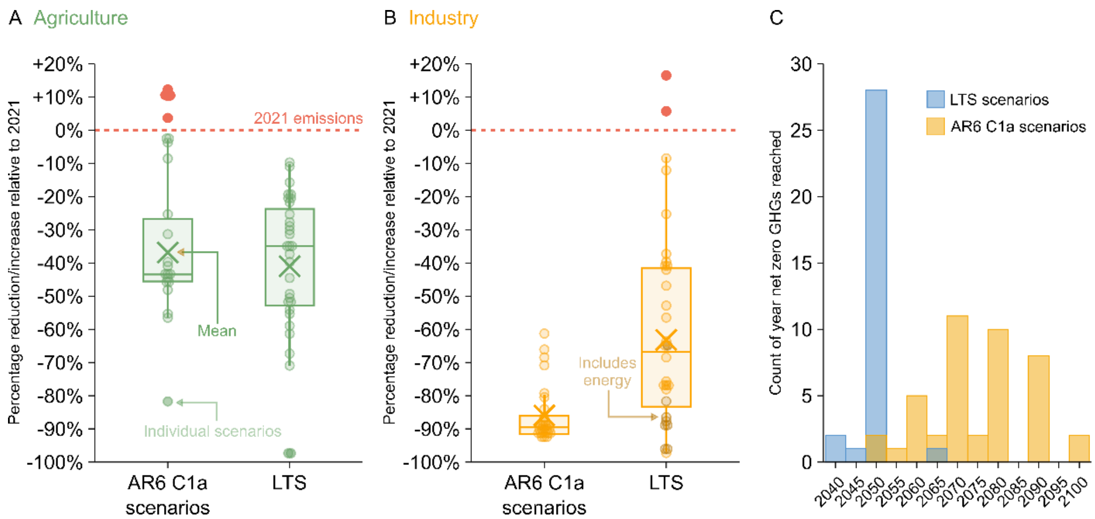

Figure 27. Comparison of AR6 C1a scenarios to LTS scenarios showing the change in GHG emissions from 2021 and the year of net zero GHGs.

Panel A compares C1a scenarios from the AR6 database for agriculture, to scenarios detailed within LTS and explored in Chapter 4. Panel A depicts the percentage reductions in agriculture between 2021 and the year net zero GHGs is reached. Panel B compares C1a scenarios from the AR6 database for industry to the scenarios detailed within LTS. Gold points indicate the inclusion of energy use in industry, owing to the presentation of scenarios in LTS. Panel C compares the year net zero GHGs is reached in C1a scenarios compared to the scenarios detailed within LTS. C1 scenarios are taken from the AR6 Scenarios Database hosted by IIASA (Byers *et al.*, 2022). Red points indicate scenarios that have an increase in emissions relative to 2021 values.

Integrated assessment modelling since AR6 has revealed that it is possible to reduce residual emissions further, through assumptions regarding large behavioural changes, including dietary shifts away from animal agriculture (Edelenbosch *et al.*, 2024; Fuhrman *et al.*, 2024; Humpenöder *et al.*, 2024). Further reducing residual emissions reduces the need for CDR in these scenarios, though the land released from animal agriculture also allows for negative emissions via BECCS or afforestation and reforestation, further contributing to mitigation (Hayek *et al.*, 2021; Rueda *et al.*, 2024). A substantial literature now exists on demand-side mitigation, detailing how changes to the patterns of consumption can support climate action (Creutzig *et al.*, 2016; Creutzig, Roy and Minx, 2024). Further research is necessary to attain the feasibility of large behavioural changes, including how they can be enacted in climate policy (Brutschin *et al.*, 2021).

Chapter 4, by assessing the rationales supporting residual or hard-to-abate emissions, found that, though many countries detail technical limitations to further abatement, many also cite social and political rationales, defining residual or hard-to-abate emissions as those emissions that cannot be abated through technical measures alone. This recontextualizes residual emissions as constructed on claims of which activities are socially necessary and which measures are possible or compatible with national priorities. Chapter 4 therefore recommends the creation of a norm within climate policy, prescribing CDR's legitimate use, warning against CDR's use to extend fossil fuel infrastructure. Whilst a broad social norm, analogous the norm against new fossil fuel projects, could be established (van Asselt and Green, 2023; Green *et al.*, 2024), there are likely limits to how detailed a norm can become. For example, Lund *et al.*, 2023, advocate for a wider debate on what can reasonably be justified as a necessity, thereby what emissions, beyond technical measures, can be considered legitimate. Citizens assemblies could provide a forum where the legitimacy of emissions can be debated. Lage *et al.*, 2023, however, compares the policy mix advocated in citizens assemblies with the mix detailed in National Energy and Climate Plans (NECPs) for 11 EU Member States, finding that citizens assemblies heavily emphasise '*sufficiency*' measures enforced by regulations, such as bans, when compared to NECPs. This, they argue, supports a '*sufficiency turn and a regulatory turn in climate mitigation*'. From this perspective, the behavioural changes entailed to further reduce residual emissions appear feasible, limiting their social necessity. Yet there may be limits to which lifestyle change and restrictive measures can be pursued (Brutschin *et al.*, 2021).

6.3.3 Separate targets and geological net zero

Chapter 4 raises the need for separate long-term targets, separating LULUCF, removals from engineered CDR, and emission reductions elsewhere in an economy, reducing their substitution with one another. This follows a recommendation commonly made in literature[25] (McLaren *et al.*, 2019, 2023; Geden and Schenuit, 2020; Becker *et al.*, 2024; Koponen *et al.*, 2024). Separate targets are also widely advocated in policy campaigns directed at national governments (CarbonGap, 2025; Carbon Market Watch, 2025). Chapter 4 references this literature but contributes by demonstrating the relevance of separate targets using existing climate policy frameworks and LTS scenarios. The chapter demonstrates that separate targets are already in place for many states, including for Portugal, Lithuania, and Sweden. It serves, therefore, that the uptake of separate targets within climate governance may be best progressed by surveying those countries where separation has already been enacted. Further research is necessary in this regard.

Elsewhere in literature, separate targets are viewed as enhancing the credibility of climate commitments, reducing the incentive for mitigation deterrence by stipulating the contribution of CDR (McLaren *et al.*, 2019). Failing to separate emissions from removals, it is argued, would create undue lock-in of high-emitting technologies and infrastructure, owing to the use of CDR as offsets (McLaren *et al.*, 2019). Yet, in practice, separate targets are not necessarily a complete solution to mitigation deterrence. Lock-in is not a dynamic limited to CDR, but extends to many technologies, infrastructures, institutions, and behaviours (Seto *et al.*, 2016). Lock-in is complex and context-specific, requiring greater attention in climate policy than attained through separate targets (Smith, 2021).

CDR is often described as '*unproven at the scale implied by modelling*', raising the prospect that these scales may fail to materialise, substituting for the emission reduction otherwise required, thereby creating lock-in (McLaren, 2020). The notion that CDR is '*unproven*', however is paradoxical, if CDR were proven at the gigatonne scales implied by modelling, the goals of Paris Agreement would be easier to attain, and concerns over mitigation deterrence largely resolved. Until then, CDR is nominally '*unproven*'. Yet many low-carbon technologies are unproven at the scales required (Kazlou, Cherp and

[25] McLaren et al., 2019 is among the most cited literature with respect to separate targets, but cite Peters and Geden, 2017, as the first to call for the separation of '*gross-, and net-negative emissions*'. Peters and Geden, 2017, however, does not call directly for separation but for the volumes of CDR in net zero pathways to be a focus of negotiations. A general separation between gross emissions and net-negative emissions is infeasible, given that net-negative emissions entail a combination of gross positive and negative emissions resulting in a net-negative emissions balance, however the gross positive emissions would already be accounted for in the now separated gross emissions. Separating gross positive from gross negative emissions is possible. The fact that the most cited article is incorrect on the matter demonstrates the complexity in practice of what is an intuitively simple recommendation.

Jewell, 2024; Odenweller and Ueckerdt, 2025). Innovation and deployment are also dynamics analysts and modellers struggle to accurately forecast and represent (Perdana *et al.*, 2023; Lopez, Pourjamal and Breyer, 2025). For example, in 2021 the International Energy Agency (IEA) estimated, in its net zero scenario for the global energy-system, that half of the CO_2 emissions reductions between 2020 and 2050 are to come from '*technologies at either demonstration or prototype stage*', yet to reach commercial scales (IEA, 2021). In the IEA's 2023 update of the same scenario, this had fallen to 35% in less than 2 years (IEA, 2023b). Encouragingly, the IEA has proved to be largely conservative in its forecasts of technology, severely underestimating the rate of renewable energy deployment (Lopez, Pourjamal and Breyer, 2025). Separate targets thereby presume that mitigation deterrence is largely unique to CDR and presume greater knowledge of the path to net zero than we may otherwise have.

Similarly, separate targets are largely irrelevant if a country's climate policy continues to allow for the substitution of emissions reductions and removals within policy design. For example, if a country was to allow the entry of removal credits into its emission trading system without preserving an emissions cap (Burke and Gambhir, 2022). Mitigation deterrence in policy design may therefore be more important than separate targets. Efforts to explore mitigation deterrence in policy, however, are nascent (Brad and Schneider, 2023). Similarly, not all substitution constitutes mitigation deterrence, for example, under the UK's plans to integrate CDR into the UK ETS, emission allowances are substituted for removals (UK Government *et al.*, 2024). The total mitigation provided by the UK ETS, however, is maintained by enforcing the emission cap (UK Government *et al.*, 2024). Nevertheless, separate targets may still be beneficial in providing much needed visibility to CDR, signalling the extent of the investments necessary (CarbonGap, 2025).

The motivation for many researchers, in advocating separate targets, is to limit the role of CDR within climate policy in favour of other means of mitigation (Markusson *et al.*, 2022). CDR has, to these researchers, '*enabled the avoidance of transformative social, economic and political change, and therefore delayed decarbonisation*' (Markusson *et al.*, 2022). This contrasts with other accounts which claim, '*the broader public is largely unaware that CDR will be necessary to meet the objectives of the Paris Agreement*' (Geden, Peters and Scott, 2018). The two are reconcilable, it is possible that the broader public is unaware of the implications of the Paris Agreement, and that modellers may have prioritised technological over social or political change (Stephenson and Allwood, 2023; Slameršak *et al.*, 2024). Yet many of the policy programmes advocated by the same researchers, are themselves unproven, with limited evidence base, such as degrowth, a deliberate contraction of the global economy (Lund *et al.*, 2023; Savin, King and van den Bergh, 2025). Mitigation deterrence therefore carries with it an implicit assumption, that transformative social and political change would inevitably follow in the absence of CDR. This requires research to establish.

Separate targets therefore serve as an entry point to '*right size*' CDR, relative to emissions reductions elsewhere in the economy (Field and Mach, 2017), raising the salience of CDR in climate policy, but achieving little else. Further research is necessary to establish whether substitution in policy design constitutes mitigation deterrence, alongside the practicalities of implementing separate targets. Separate targets, however, are not the only proposals to reform net zero. Researchers are increasingly calling for '*geological net zero*', whereby '*any remaining fossil-origin CO_2 production is balanced by CO_2 capture or recapture and geological-timescale storage*' (Allen *et al.*, 2024). The corollary is that net zero requires balancing emissions of a set residence time in the atmosphere with removals of a similar storage period, or the '*like-for-like principle*' (Brunner, Hausfather and Knutti, 2024).

Both geological net zero and the like-for-like principle require governing according to the permanence of CDR, a theme raised by participants in Chapter 5 (Allen *et al.*, 2024; Brunner, Hausfather and Knutti, 2024). Both concepts can be seen as an attempt to address the managed land problem detailed in Chapter 2, by reducing the ability of the LULUCF sector to compensate for fossil emissions elsewhere in the economy, whilst also claiming net zero (Allen *et al.*, 2024; Brunner, Hausfather and Knutti, 2024). Both similarly reflect concerns made in Chapter 3, regarding the integrity of the biosphere under increasing climate change (Allen *et al.*, 2024; Brunner, Hausfather and Knutti, 2024). Chapter 3, however, surveys the CDR methods included in LTS, identifying measures in the LULUCF sector as the most common strategy for removals. Chapter 2 extends the dataset in Chapter 3, revealing this as a trend that continues in more recent LTS submissions. Both geological net zero and the like-for-like principle, therefore, could be disruptive to the current strategies of the Parties to the Paris Agreement, if enacted as the new measure of net zero[26]. For example, it is unlikely that parties with large land-use sinks would willingly accept a diminished role for LULUCF within their climate policy framework (Dooley and Gupta, 2017).

This is further evidenced by scenarios and pathways detailed within LTS. For example, in Chapter 5, Cambodia was identified as the only country with a net zero GHG scenario within their LT-LEDS that increased GHG emissions, excluding LULUCF, across their economy relative to 2021 levels. Cambodia achieves this by simultaneously transforming its land-use sector from a net source to a sizeable net sink, reversing deforestation. A strict interpretation of the like-for-like principle would largely invalidate this strategy.

Sweden, by comparison, discounts it's LULUCF sector from its long-term target, despite the sector acting as a large and persistent net sink. Instead, Sweden's climate policy framework requires GHG

[26] I make a similar argument in a media article responding to Allen *et* al., 2024, published in the New Scientist, accessible at: https://www.newscientist.com/article/2456548-countries-are-cheating-their-way-to-net-zero-by-overrelying-on-forests/

emissions excluding LULUCF to be reduced by 85% compared with 1990, with the remaining 15% addressed through '*supplementary measures*', including increased net removals in LULUCF, BECCS, or internationally transferred mitigation outcomes under Article 6 of the Paris Agreement. Sweden's climate policy framework therefore includes separate targets, albeit with flexibility regarding supplementary measures. In the interim, till 2030, net removals from LULUCF are to increase to fulfil Sweden's contribution to the EU's LULUCF Regulation, meaning LULUCF is not simply omitted from Sweden's climate policy. Through this framework, Sweden has amongst the most ambitious long-term targets globally. If we were to reframe Sweden's long-term target as an emission reduction target, using the same accounting rules that apply within NGHGIs, the target would equate to a reduction of 212% in net GHG emissions compared to 1990 levels. Sweden's climate policy framework, however, is largely enabled by Sweden's extensive bioeconomy and historic land-use change (Christiansen and Carton, 2021). Whether this same framework can be replicated in other countries will determine whether geological net zero or the like-for-like principle can become the new standard for net zero.

The simplicity of net zero is arguably its greatest strength as a long-term target, every country's emissions have to first peak, then decline, and eventually reach a balance of sources and sinks (Geden, 2016). This formulation is direct, transparent and easy to evaluate, resulting in the concept's popularity (Geden, 2016; Green, Hale and Arceo, 2024). Researchers should therefore be cautious in their proposals for reform. Further research is needed to explore the implications of these changes towards national climate action. This research should focus on the practicalities of these proposals in addition to their likely politics. Allen *et* al., 2024, for example, propose that countries may use accounting rules to their advantage, reducing the need for emissions reductions, by deeming more land as managed or expanding the reach of NGHGIs to include the carbon uptake in the oceans.

Little evidence exists to suggest such practices, but prior technocratic debates on accounting rules have spilled over into climate politics. For example, GWP*, a method that relates emission rate changes of short-lived GHGs like methane to emissions of CO_2, has been proposed by Allen *et* al., 2018 as a more accurate metric to replace GWP100, used in the Paris Rulebook. However, GWP* introduces too much variability when used to aggregate multiple GHGs into a single timeseries (Meinshausen and Nicholls, 2022). This limits it's practical use as a metric in climate policy, given the main use of GWP metrics is to allow a country to assess whether it is on track to meet its climate targets, a goal ill-suited to a metric which amplifies variability (Meinshausen and Nicholls, 2022). Whilst GWP* performs better than GWP100 at relating emissions to global mean temperatures, it is largely destabilising to the global climate regime (Schleussner *et al.*, 2019; Meinshausen and Nicholls, 2022). Since this debate, multiple studies have claimed that climate neutrality could be reached for agriculture with minimal methane reductions, based upon the GWP* metric (Donnison and Murphy-Bokern, 2023). Lobbying by the livestock sector, for government to adopt the metric, has also grown since (NFU, 2023). Attempts to reform net zero may have similar political ramifications. Geological net zero, for example, centres upon geological storage, benefiting engineered removals from DACCS and BECCS, alongside CCS, the roles of which are already heavily contested in climate politics (Center for International Environmental Law, 2023).

6.3.4 The corporate governance of CDR

Chapter 5 goes beyond Chapter 2 to 4's emphasis on LTS, as a means of data, by introducing expert interviews. In doing so, Chapter 5 highlights further actors in CDR policymaking beyond national governments. Namely, Chapter 5 highlighted the centrality of the VCM and corporate climate action to current efforts to scale CDR projects. Whilst participants viewed the VCM as a market to be circumvented, or at least strengthened by government interventions to drive demand, the vast majority of engineered CDR removals is sold through the VCM (CDR.fyi, 2025). Forecasts anticipate substantial market growth, driven, in part by increased voluntary corporate climate action and increased adherence to corporate standards (McKinsey Sustainability, 2023; BCG, 2024).

Similarly, Chapter 3 highlighted the interest of countries towards Article 6, as a means to internationally cooperate on the trading of removals. Article 6 includes the Paris Agreement Crediting Mechanism, Article 6.4. Article 6.4 establishes a new international carbon market, leveraging the current VCM, to enable carbon market activities to be traded between companies and countries, applying '*corresponding adjustments*' to NDCs to account for the mitigation traded (La Hoz Theuer, Schneider and Broekhoff, 2019). The VCM, therefore, will likely remain a key market for CDR and a contentious element of the Paris Agreement.

Academic research has largely focused on evaluating forestry projects within the VCM, developing new methodologies to evaluate projects that aim to, for example, reduce or avoid deforestation and the resulting land-use change emissions (West *et al.*, 2020, 2023; Guizar-Coutiño *et al.*, 2022). This research has revealed pervasive over-crediting linked to limited additionality, owing to exaggerated baselines and substantial leakage, where, for example, deforestation shifts to another area outside of the project, cancelling out the project's supposed impact (Guizar-Coutiño *et al.*, 2022; Haya *et al.*, 2023). A recent systematic review of a fifth of all credits issued to date (972 $MtCO_2$) found that 84% likely constitute no real emissions reduction (Probst *et al.*, 2024). 75% of all credits issued from avoided deforestation projects covered by the review were found to be non-existent (Probst *et al.*, 2024). Furthermore, studies that identify over-crediting often disagree on how many credits should have been issued for the same project, given studies differ in their method of evaluation (Probst *et al.*, 2024). There exists, therefore, no quick methodological fix.

Researchers argue the tendency within the market to over-credit is largely owing to the market's current structure, given these projects are financed ex ante, based on their projected impact, in order to finance the activity itself (Swinfield *et al.*, 2024). Similarly, elements of project design are often entrusted to project developers, allowing developers to choose favourable data and choose amongst the most favourable (often lower) standards (Haya *et al.*, 2023; West *et al.*, 2023). Certifiers and standard organisations similarly have an incentive to look past these practices given many receive their revenue from project certification (Reinhard, Planavsky and Khan, 2023). Furthermore, demand for carbon credits by corporates is concentrated amongst the cheapest offsets of often low quality. Another recent review, examining demand in the VCM by the top 20 corporates, found that 87% of the credits purchased '*carry a high risk of not providing real and additional emissions reductions*' (Trencher *et al.*, 2024). In short, the VCM is characterised by misaligned incentives and often outright fraud. As a result, the VCM has channelled cheap '*hot air*' to corporates with dubious offsetting schemes, ranging from carbon neutral liquid natural gas to carbon neutral flights for frequent flyers (Probst *et al.*, 2024; Trencher *et al.*, 2024).

The recent history of the VCM is crucial context for CDR, given mounting pressure to reform the market has generated new enthusiasm for removal credits from CDR projects, supplanting the '*avoidance*' credits that currently make up nearly all but 3% of credits issued in 2024 (Haya *et al.*, 2024). Corporate guidelines and standards, intended to inform corporate climate action, have largely converged on the principle of transitioning from avoidance credits towards permanent removal credits (Becker *et al.*, 2024). Though these same guidelines and standards differ on how permanence is defined and enforced (Becker *et al.*, 2024). The view, therefore, that removal credits are inherently higher quality than avoidance credits has become increasingly common (Mitchard *et al.*, 2024; Möllersten *et al.*, 2024). Little research exists on the implications of this convergence. For example, the Oxford Offsetting Principles, one such set of corporate guidance, recommends a full transition away from both avoidance credits and removal credits with a '*higher risk of reversal*', towards '*carbon removal to the geosphere*', before 2050. An approach which, if widely adopted, would entail finding alternative means to finance nature-based removals and similar forestry projects (Blanchard *et al.*, 2024). A move likely to be resisted (Mitchard *et al.*, 2024; Möllersten *et al.*, 2024). However, by signalling a transition away from cheaper offsets, the principles may engender greater climate action by corporates, by necessitating greater measures to reduce emissions within their scope.

Chapter 5 also reveals the concerns towards the current actors supplying demand, namely the technology and financial companies that currently dominate the engineered removal market. Again, little research exists on the impact of their involvement. Battersby *et al.*, 2022, suggest these companies, in the absence of national governments, '*de facto govern*' CDR, shaping the sector through research, advocacy, investments and offtake agreements. They are unique in their high willingness to pay, and high profit-to-emissions ratio (CarbonGap, 2022). Stripe, a payments company, and an originator in the engineered removal market, has a distinct approach to CDR, based on advance market commitments (AMCs), used previously for vaccines (Stripe, 2022). Stripe has since joined Frontier, a joint AMC with Google, Meta and Shopify (Frontier, 2022). Together they are the third largest purchaser of engineered removals in 2024 (CDR.fyi, 2025). Microsoft vastly leads the market, purchasing 63% of all removal credits in 2024 (CDR.fyi, 2025). The impact of these trends on the policies of national governments is largely unknown, but in the UK, there is evidence to suggest these trends have already impacted policy design. For example, the UK government cites both Frontier and Microsoft in its consultations, citing the '*rapid growth in voluntary demand for high-durability carbon removal credits*' as validation of its focus on supply-side policy (DESNZ, 2023e).

6.3.5 MRV and state capacity

The need for credible MRV featured strongly in the expert interviews in Chapter 5. These findings also identified a need to improve government oversight of CDR, improving state capacity by introducing a government body or regulator, in part to regulate MRV. The government's efforts to introduce a government standard is world-leading in this respect. Since the UK's government's announcement in 2023, the EU adopted, in 2024, the Carbon Removals and Carbon Farming (CRCF) Regulation (EU/2024/3012), a voluntary framework for certifying carbon removals under which certification methodologies for specific CDR methods are to be developed. Multiple articles reviewed the regulation, highlighting flaws in its accounting, for example, the regulation allows for the certification of '*soil emission reductions*', conflating the certification of removals with avoided emissions (Schenuit *et al.*, 2023; Štrubelj *et al.*, 2023). The CRCF similarly sidestepped disagreements, for example, despite delineating between a '*permanent carbon removal unit*' and a '*carbon farming sequestration unit*' representing only a '*temporary net carbon removal benefit*', the regulation treats the two as fungible, without adjusting for the more temporary nature of the latter (Schenuit *et al.*, 2023; Štrubelj *et al.*, 2023). Both limitations were argued to be a result of lobbying by the EU's agricultural sector (Schenuit *et al.*, 2023). The CRCF, however, was successful with respect to standardising the principles of certification. The UK government standard offers an opportunity to resolve outstanding issues and avoid the errors of the CRCF.

MRV to date has largely been led by the private sector, given the need for standards within the VCM (Arcusa and Sprenkle-Hyppolite, 2022; Mercer and Burke, 2023). There exists, therefore, vastly more experience in the private sector than within government. The growth of methodologies for engineered removals within the private sector has delayed the government standard, as the government has decided to first introduce '*Minimum Quality Thresholds*' for BECCS and DACCS projects, defining the minimum criteria to be covered, allowing projects to progress with existing privately developed methodologies (DESNZ, 2024c). The increased government interest in developing methodologies and creating standards raises questions as to how the private sector may adapt, as well as the expertise and capacity required in government to enforce the eventual government standard. State capacity is widely regarded in research as limiting the ability of governments to enforce '*policy sticks*', such as carbon taxes (Meckling and Benkler, 2024). In the case of incentives or subsidies, however, state capacity also limits the ability of the government to ensure their efficient use. Without proper MRV, the climate benefit of a CDR project cannot be established, and by extension the proper use of a subsidy, for example, in the case of the UK, the appropriate level of payment to a project under the CfD for BECCS and DACCS projects.

Future research into the appropriate governance structures for CDR is needed, drawing on experience elsewhere. For example, multiple countries have experience in developing methodologies, primarily for forestry projects (Li and Zhang, 2024). Australia, for example, has extensive experience through its Safeguard Mechanism, Australia's domestic compliance market for large industrial facilities (Clean Energy Regulator, 2024b). Facilities can comply with the mechanism by purchasing Australian Carbon Credit Units (ACCUs), administered by Australia's Clean Energy Regulator, an independent statutory authority which also governs the Safeguard Mechanism (Clean Energy Regulator, 2024a). An independent assessment of ACCUs, however, has established that forestry regeneration projects credited under the scheme were '*non-existent, non-additional and potentially impermanent*', using methods used to evaluate forestry projects in the VCM (Macintosh, Butler, *et al.*, 2024; Macintosh, Evans, *et al.*, 2024). Whilst this points to some of the unique challenges posed by forestry projects, the scandal also highlights the importance of regulatory oversight, transparency, and accountability. In this case, the Clean Energy Regulator was responsible for both crediting projects and administering the government purchase of ACCUs, resulting in a profound conflict of interest (Australian Government, 2024b). Research into the appropriate governance structures in climate policy is nascent (Meckling and Benkler, 2024), but progress can be made by reviewing the governance structures already in place for existing schemes and avoiding past errors.

Permanence was a central theme in Chapter 5. Chapter 3 similarly raises permanence as a concern given the reliance on LULUCF in LTS. Permanence is also central to MRV, given MRV can involve measures to ensure effective permanence, such as buffer pools, or measures to create fungibility between methods based upon their storage period, such as equivalence ratios (Burke and Schenuit, 2024). The UK government is also exploring such measures as part of its integration of CDR into the UK ETS (UK Government *et al.*, 2024). Permanence is similarly central to concepts such as geological net zero and the like-for-like principle, detailed in Section 6.3.2. Further research, however, is needed on the impact of these measures upon policies and wider markets, as raised as a recommendation to government in Chapter 5. To provide one example, the government proposes equivalence ratios based upon Groom and Venmans, 2023, which calculates the social value of carbon stored temporarily, estimating that carbon stored for a 100 years, then released, equates to 66-70% of permanent storage. Prado and Mac Dowell, 2023, also cited by the UK government in proposals for the UK ETS, by comparison, estimate a '*climate repair value*' of just 7.5% compared to permanent storage. Applying these equivalences to the WCC, implies that, if WCUs were to enter the UK ETS, 1.4 - 13.3 WCUs would equate to 1 UK ETS allowance. Based on existing average prices for WCUs (£23 for 2023, reduced to £19 to account for the 20% of WCUs allocated to the buffer pool, Woodland Carbon Code, 2024), this would raise the price to £27 to £249/tCO_2. Large increases in price could impact upon existing markets, limiting who can afford CDR. The application of the climate repair value, for example, means '*almost all forms of permanent removal will emerge as economically preferable*' (Prado and Mac Dowell, 2023).

For government, MRV extends beyond the project level to national MRV, such as NGHGIs, which track and report emissions and removals over time (IEAGHG, 2024; Lebling, Riedl and Leslie-Bole, 2024). Project level MRV and the national MRV in NGHGIs are largely distinct. Project level MRV uses carbon accounting methods to establish the net-negativity of the project. In practice this requires accounting for a range of emissions occurring across a set system boundary (Tanzer and Ramírez, 2019). For example, a BECCS project would account for emissions emitted from the transport of the biomass feedstock in addition to removals transferred from the atmospheric CO_2 sequestered within the biomass to geological storage (García-Freites, Gough and Röder, 2021). NGHGIs, by contrast, are concerned with consistently and accurately estimating emissions and removals within a territory (IPCC, 2006a). Beyond allocating emissions and removals to sectors, NGHGIs are not concerned with attributing emission to specific entities, meaning transport emissions would be reported as unaffiliated from the BECCS project, in this example. Similarly, as the sequestration of CO_2 in the biomass would be reported as a removal within LULUCF, to report the same removal at the point of geological storage would result in double-counting (IPCC, 2024). In addition, NGHGIs, given their national focus, may use methods and data sources suited to estimating national emissions, such as methodologies detailed within the IPCC 2006 Guidelines (IPCC, 2006a). Whilst project level MRV, given its much reduced scale, can use data sources and methods specific to the carbon removal activity (IEAGHG, 2024). This results in a reduced ability for the NGHGI to '*see*' the climate benefit of the project (IEAGHG, 2024). This is a known problem within climate governance, termed '*inventory visibility*' (Schneider *et al.*, 2022). There may be significant asymmetries between what is '*MRV'd*' and credited for the project and what is visible in the inventory (IEAGHG, 2024). Projects with lower net-negativity, projects with a net-negative emissions balance but higher relative positive emissions occurring within the system boundary, may lead to greater asymmetries.

This is exacerbated by the fact that many CDR methods are not covered by existing IPCC guidelines that support NGHGIs (IEAGHG, 2024). Those methods that are covered are rarely covered explicitly, nor made visible in the categories of sources and sinks that are reported to the UNFCCC (Köhnke *et al.*, 2023). Work is underway within the IPCC to correct this, namely through a '*Methodology Report on Carbon Dioxide Removal Technologies, Carbon Capture Utilisation and Storage activities*', to be published as part of the IPCC's AR7 cycle (IPCC, 2024). Chapters 2 and 3 are instructive to this work, by indicating what methods are to be incentivised and the conditions of their deployment. BECCS projects within the UK, for example, plan to source biomass feedstocks from North America, meaning emissions and removals occur in two separate NGHGIs, leading to a need for adjustments to credit the removal to one country (Mace *et al.*, 2021; Drax and Stockholm Exergi, 2023). Switzerland's LT-LEDS similarly anticipates the deployment of DACCS abroad, with the removals credited to Switzerland. Further research is needed to inform the IPCC's work on this matter. This is not helped by the conflation of project level MRV and national MRV. For example, Lefvert and Grönkvist, 2024, conflate the two, leading them to wrongly conclude the EU's CRCF regulation is unnecessary and even counterproductive to the deployment of BECCS.

6.3.6 CDR in a world of temperature overshoot

Chapter 5 highlighted a need for '*net-negative ready*' policy, as participants look towards the need for net-negative targets as the next necessary extension of climate policy. This informs their ideal policy design in the present, by, for example, advocating for a separate removals trading system as opposed to integration with the UK ETS. Governments should take a similar approach, ensuring they consider the need for net-negative emissions within their policy designs. Chapter 2 similarly highlights several countries with net-negative targets. Net-negative targets are necessary owing to temperature overshoot, given many scenarios assessed by the IPCC (notably the so-called '*C2*' scenarios) temporarily exceed 1.5°C before returning below 1.5°C, through a period of sustained net-negative CO_2 or GHG emissions (Riahi *et al.*, 2022). Temperature overshoot is relatively understudied in climate policy research, despite the inevitability of soon reaching the 1.5°C goal stipulated in the Paris Agreement (Betts *et al.*, 2023; Bevacqua, Schleussner and Zscheischler, 2025). To the extent to which overshoot has been studied, research has been limited to assessing the physical climate risks and economic damages entailed (Drouet *et al.*, 2021; Schleussner *et al.*, 2024).

Others claim that '*even if the world exceeds 1.5°C of global warming, this changes very little to the focus of mitigation policy*', at least in the near-term (Rogelj, 2023). This is true, even in a world of temperature overshoot, the challenge of mitigation remains largely unchanged, emissions still must peak, then decline, and eventually reach net zero. However, net-negative targets, as now additionally required, may prove uniquely challenging. The existing proposals to operationalise net-negative policies, such as an ETS with the temporal trading of carbon debt (Bednar *et al.*, 2021), would likely prove politically challenging, given carbon debt would require the acceptance of responsibility for historical emissions (Matthews, 2016; Fyson *et al.*, 2020). The notion that historical emissions can inform the burden of mitigation has long been part of climate negotiations. For example, in 1997, in the run-up to the Kyoto Protocol, the Brazilian government proposed distributing the burden of mitigation for Annex I countries according to each country's relative responsibility for global temperature rise (Cole, 2012). The '*Brazilian Proposal*', as it became known, was rejected and along with it the notion of historical emissions, with the Kyoto Protocol instead adopting a 1990 baseline and targets largely reflective of political negotiations, as opposed to any real method (Liverman, 2009). The Paris Agreement arguably deviates further from this notion given the pledge and review structure of the agreement provides substantial discretion to governments (Keohane and Oppenheimer, 2016). Nevertheless, many journal articles continue to be dedicated to the idea (Höhne, den Elzen and Escalante, 2014; Hahn *et al.*, 2024). Temperature overshoot will likely cause many parties to revisit the notion in the UNFCCC (Mohan *et al.*, 2021).

Given the likely political challenges of historical emissions, future research should explore how net-negative targets may progress in the global climate regime, and how CDR may be financed in a net-negative economy. For example, given the resistance of oil and gas majors to climate policy, it is morally justified that these majors should finance CDR to reduce the damages caused by their emissions, yet this too may be politically challenging, given many oil and gas majors are state-owned ventures (Climate Analytics, 2023; Grasso and Heede, 2023). Similarly, any funds generated can have multiple claims (Climate Analytics, 2023). Should an oil major, for example, fund CDR, to compensate for its past emissions, or fund loss and damage, to compensate for present harms?

6.3.7 A summary of policy implications and future research

Table 9 summarises the policy recommendations and avenues for future research detailed in this chapter, for ease of reference. Policy recommendations span multiple audiences, including the UNFCCC, national government and civil society, highlighted in blue.

Table 9. Policy recommendations and avenues for future research raised in Chapter 6.

Sub-section	Policy recommendation (target audience)	Avenues for future research
6.3.1 Clarifying and mandating LT-LEDS reporting	- Require the development and submission of LT-LEDS to the UNFCCC Secretariat to be mandatory, integrating LT-LEDS into the Paris Agreement's ambition cycle on at least a decadal basis. (UNFCCC) - Introduce guidance to facilitate the clarity, transparency and understanding of LT-LEDS, analogous to the CTU guidance that currently informs the reporting of NDCs. (UNFCCC)	- Evaluate the theorised governance benefits of LT-LEDS, determining their benefit in practice. For example, research the reasons behind the (mis)alignment of NDCs and LT-LEDS. - Diversify away from NDCs to research the number of reporting elements within the Paris Agreement, including LT-LEDS, BTRs, and Adaptation Communications, given the implementation of the Paris Agreement's ETF.
6.3.2 The social and political nature of residual emissions	- Introduce a norm within climate policy, prescribing CDR's legitimate use, warning against CDR's use to extend fossil fuel infrastructure. (UNFCCC, civil society)	- Research the feasibility of large behavioural changes, including how they can be enacted in climate policy, in the context of reducing residual emissions, particularly in agriculture.
6.3.3 Separate targets and geological net zero	- Implement separate targets for LULUCF, removals from engineered CDR, and emission reductions elsewhere in an economy, reducing their substitution with one another. (national governments)	- Research the prospect of mitigation deterrence in policy design. - Research into the practical implementation of separate targets, utilising existing climate policy frameworks. - Research the implications of geological net zero and the like-for-like principle on national climate plans.
6.3.4 The corporate governance of CDR		- Research the implications of the VCM transitioning towards an emphasis on engineered CDR methods. - Research the influence of trends in the VCM towards the policies of national governments, including the influence of large corporates.
6.3.5 MRV and state capacity	- Introduce government-led MRV standards with government oversight via a new regulator of body. (national governments)	- Research the appropriate governance structures for CDR, drawing on the experience of statutory authorities elsewhere. - Research into how project-level MRV and national MRV may differ.
6.3.6 CDR in a world of temperature overshoot	- Introduce 'net-negative ready' policies to incentivise CDR. (national governments)	- Future research exploring how net-negative targets may progress in the global climate regime, and how CDR may be financed in a net-negative economy.

6.4 Conclusion

CDR is essential for national governments to achieve their national net zero targets, reach the goal of the Paris Agreement, and avoid the worsts of climate change. National governments, however, have only recently engaged with the need for CDR to compensate for residual emissions across their economies. This thesis serves to address what is a key knowledge gap in climate policy research, the planning of national entities towards CDR (Schenuit *et al.*, 2021). It addresses this gap by analysing LT-LEDS and similar LTS submitted by countries, serving to raise the prominence of LT-LEDS in climate policy research.

This thesis reveals the inclusion of CDR in these strategies is largely limited to nature-based methods, which predominantly serve to compensate for residual emissions from agriculture, such as emissions from ruminants. Where engineered CDR is included in scenarios and pathways, greater deployment can allow for the greater retention of fossil fuels, substantiating concerns about mitigation deterrence. Separate targets may reduce but not resolve this concern. This thesis similarly reveals the limited engagement of countries with LT-LEDS, given the omission of scenario and pathway modelling in many strategies. Strengthening LT-LEDS as the key long-term planning provision of the Paris Agreement may lead to greater engagement, serving to improve the credibility of climate policy efforts, building trust in the global climate regime.

To provide an understanding of how CDR in national net zero plans translate into policies, interviews with 25 experts active in UK CDR policymaking are carried out - evaluating the UK as a country with advanced plans for CDR. Expert interviews reveal a desire for greater government intervention, with the UK government tasked with stimulating demand, overseeing the sector, and designing the standards to be met by project developers. These interviews demonstrate the challenges raised by CDR towards national governments, such as the extent and reliance upon CDR, the policies and markets through which CDR is incentivised, and the nature of residual emissions to be abated. These challenges, however, map onto wider debates in climate policy, ranging from the role of corporate climate action to the fate of net zero, as currently conceptualised in climate governance.

Many continue to decry CDR as a '*false solution*', a distraction that should be excluded from the means of mitigation (Church and Recupero, 2024). Yet this thesis illustrates that CDR is now a key feature of LTS and their visions of net zero, and an active part of national climate policy. Given the likelihood of temperature overshoot and the necessity of net-negative emissions targets, CDR is set to become an even greater focus in climate action. Getting the right policies, and the right governance frameworks in place, will become only ever more pressing in the years ahead.

7 References

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Annex I – Chapter 2

Table A 1. Assessment of the difference between minimum residual emission estimates between LTS-SP dataset and prior published data.

Percentage difference from LTS-SP dataset shown.

Country	Difference	Explanation
Australia	LTS-SP dataset: 253 $MtCO_2e$ Buck et al., 2023: 163 $MtCO_2e$ (36% lower) New Climate Institute: 215 $MtCO_2e$ (15% lower)	Buck et al., 2023 uses 2005 values for the historic GHG inventory, found in Figure 1.4, Page 30. This is combined with the maximum reduction potentials from 2005-2050 shown in Figure 1.7, Page 36, for all totals shown in Figure 1.4, excluding LULUCF. Table 6, Page 59 of Australia's LT-LEDS Modelling and Analysis annex, shows the emissions prior to BECCS, DACCS, land-use and the inclusion of any international offsets for all scenarios. The minimum residual emissions at the point of net zero GHGs, is 200 $MtCO_2e$, shown for the 'NZE 100%' scenario. This is different to 'The Plan' scenario, which appears to be the basis of Figure ES.2, Page 15 (as it maintains a 15% gap prior to reaching net zero GHGs, as detailed in Table 5, Page 58 of Australia's LT-LEDS Modelling and Analysis annex). This poses a problem as to whether the main scenario, as presented in the strategy, should be used, despite the scenario failing to meet Australia's long-term target, or whether scenarios that do reach this target but are deprioritised and shown only in additional documents, should be used instead. Given Buck et al., 2023 intends to examine 'residual emissions at net zero', 'The Plan' scenario falls short of this definition. Nevertheless, Table 6 of the Annex suggests the residual emissions in 2050 excluding sources of removals or international offsets, for 'The Plan' scenario totals 253 $MtCO_2e$, substantially higher than the estimate derived from Figure 1.4 and Figure 1.7. New Climate Institute's assessment of G20 strategies appears to use numbers for 'The Plan' scenario, detailed in Table 6, Page 59, but use the row 'Emissions before offsets' as opposed to 'gross emissions' within the LTS-SP dataset. 'Emissions before offsets' already incorporates 38 $MtCO_2$ of removals from BECCS, as noted in the 'Negative emissions (BECCS)' row of Table 6. We exclude removals from BECCS from our calculation of residual emissions. Note that we compare the 2021 LT-LEDS, now superseded by the more recent LT-LEDS in January 2024.
Canada	LTS-SP dataset: 124 $MtCO_2e$ New Climate Institute: 100 $MtCO_2e$ (19% lower)	The LTS-SP dataset uses Canada's 'Exploring Approaches for Canada's Transition to Net-Zero Emissions', published as a LT-LEDS in October 2022. We use values for all scenarios presented in Figure 1, Figure 4, Figure 7 and Figure 10, corresponding to the scenarios detailed in Table 4, Page 34. As Table 4 combines removals from BECCS in within Electricity and Industry sector totals, we use the ranges stated on Pages 22, 25, 28 and 31 to determine residual emissions, excluding BECCS, DACCS and LULUCF, leading to a minimum of 124 $MtCO_2e$ (Page 25 and Page 28, for the High Electrification Scenario and the High Use of Renewable and Alternative Fuels Scenario respectively). New Climate Institute's assessment of G20 strategies appears to use the totals found in Table 4, Page 34 of the 2022 strategy. Here the row 'Total (excluding DAC and LULUCF)' includes, as noted above, removals from BECCS. We exclude removals from BECCS from our calculation of residual emissions by using the ranges stated on Pages 22, 25, 28 and 31.
Colombia	LTS-SP dataset: 14 $MtCO_2e$ Buck et al., 2023: 53 $MtCO_2e$ (268% higher)	Colombia has a goal of becoming 'a carbon neutral country by 2050', as stated on Page 19. Page 30 states that 'To comply with what is required by science (1.5 to 2 °C), by 2050 Colombia needs to reduce GHG emissions by around 90% compared to 2015 emissions and balance the remaining 10% with proportional national absorptions (10%), to achieve a net zero balance between emissions and absorptions of greenhouse gases (carbon equivalents) from the year 2050' [translation]. This implies a 90% trajectory for emissions reductions. This is similarly supported by Figure 20, Page 121, and the text shown on Page 120, which details that 'Regarding the emission trajectories of the modelled scenarios, the grey area

Country	Difference	Explanation
		corresponds to a space of emissions that would allow Colombia to become carbon neutral, and for multiple scenarios it is necessary to achieve additional compensation to those already considered in 2050 (figure twenty). In particular, the scenarios lead to 90% decarbonization relative to 2015 levels and a substantial reduction in non-CO_2 GHGs.' [translation]. Figure 20, Page 121, indicates a residual emission in 2050 of around 20 $MtCO_2$eq. Table 4, Page 128, alongside Page 129, Figure 23, indicates that for the 'carbon neutrality scenario' 12 $MtCO_2$ is anticipated from the energy sector. Other scenarios presented in Table 4 and Figure 23 pertain to the 'National Energy Plan' or 'PEN', representing different energy technologies seen in Table 3, Page 114. Figure 24, Page 130, indicates that emissions from electricity generation could be as low as approximately 0.5 $MtCO_2$. Section 4.3.4, Page 131, describes 'Options for increasing greenhouse gas absorptions by 2050', including 'non-AFOLU' options. These, however, pertain to enhanced oil recovery or post combustion CCS, options that typically reduce emissions, not provide negative emissions. Table 5, Page 131, appears to analyse the potential of these options as opposed to their inclusion within a modelled scenario. Table 7, Page 136, details a series of three scenarios to increase absorptions or avoid emissions in the AFOLU sector. For rows labelled absorptions, these total -54.79 $MtCO_2$/yr in 2050 for Scenario 1, -164.8 $MtCO_2$/yr in 2050 for Scenario 2, and -507.3 $MtCO_2$/yr in 2050 for Scenario 3. Considering that Page 68 details that 'Total absorptions' in 2014 total -22.66 $MtCO_2$, these scenarios represent at least double current absorptions, to upwards of 20 times. It is unclear whether these are part of modelled scenarios. Page 135 notes that 'According to the results of the decarbonization scenarios for 2050, it would be necessary to capture from 14.4 to 31.5 $MtCO_2$eq, depending on the levels of GHG emissions reduction achieved at the national level'. Overall, our assessment of available data within Colombia's LT-LEDS adds considerable ambiguity to our attempt to quantify residual emissions. Using values for 2014, found on Page 68, net emissions total 236.97 $MtCO_2$e. a 90% reduction of this total would lead to a level of 23.7 $MtCO_2$e, roughly in line with Figure 20. This value, however, includes emissions from land-use and excludes absorptions. This would, however, align with the current extent of absorptions from land-use, of around -22.66 $MtCO_2$, reaching near net zero GHGs if this level is maintained. Excluding land-use emissions and applying the same 90% reduction would lead to a value of 15.8 $MtCO_2$e remaining in 2050. Both values are within the range detailed on Page 135. Crucially, both values, alongside the range presented on Page 135 are greatly exceeded by the values for AFOLU absorption measures found in Table 7, Page 136. Given the ambiguity presented in the LT-LEDS, we use the range noted in Page 135 as indicative of residual emissions, leading to a minimum of 14.4 $MtCO_2$e. Buck et al., 2023 appears to use the 'PEN disruption' scenario from Table 4, Page 128 and shown in Figure 23, Page 129 (and first shown on Page 115, as detailed in Buck et al., 2023 Supplementary Data). This would appear to be a scenario in which the long-term target is not reached, as noted in Figure 20, Page 121, and Figure 23, Page 129.
Fiji	LTS-SP dataset: 0.93 $MtCO_2$e Buck et al., 2023: 0.04 $MtCO_2$e (95% lower)	Buck et al., 2023 uses 2050 values found in Table 3, Pages 36-37, for the 'Very High Ambition' Scenario. As seen In Figure 7, Page 39 of Fiji's LT-LEDS, this is the only scenario that reaches net zero GHGs prior to 2050, as per Fiji's long-term target. Buck et al., 2023 sums the total for 'Electricity and Other Energy Use', 'Domestic Air Transport' and 'Waste', reaching 43,619 tCO_2e in 2050, and excluding AFOLU. The categorisation of AFOLU, however, combines agricultural emissions with land-use emissions and removals. AFOLU can be separated into agriculture and land-use via Table 35, Page 136. The LTS-SP dataset therefore separates and combines agricultural emissions for the scenario with the remaining totals in Table 3, in order to be consistent with other values.
France	LTS-SP dataset: 75 $MtCO_2$e Buck et al., 2023: 80 $MtCO_2$e (7% higher)	Both studies appear to use the figure shown on Page 18 and replicated on Page 168, showing 'Sinks and greenhouse gas emissions in France in 2050 according to the baseline scenario' (Page 168). We adjust for the avoided emissions from CCS, using the 6 $MtCO_2$/year stated on Page 170, that appears to be represented as part of the 'GHG sinks' of the Figure on Page 168. This appears not to represent BECCS, unlike the remaining 10

Country	Difference	Explanation
	New Climate Institute: 82 $MtCO_2e$ (9% higher)	$MtCO_2$/year which is also detailed on Page 170 as BECCS and therefore thought to represent removals. New Climate Institute's assessment of G20 strategies appears to also use the figure first shown on Page 18, estimating the GHG sinks column as 82 $MtCO_2e$. We make the same estimation but adjust for the avoidance of emissions from CCS on Page 170, as above.
Hungary	LTS-SP dataset: 13.8 $MtCO_2e$ Buck et al., 2023: 4.5 $MtCO_2e$ (67% lower)	Buck et al., 2023 uses 2050 values found on Page 10, and graphically shown in Figure 2, Page 10. Here it is noted that 'Natural sink capacities will be expanded to balance out the remaining emissions in 2050. It is forecasted in the EA and LA scenarios that 4.5 million tons of CO_2eq/year will be naturally absorbed, mainly due to the increasing forest coverage'. Given Figure 2 shows only LULUCF as a net sink, it is reasonable to assume that the residual emissions shown for Energy, Agriculture and Waste management, shown on the positive y-axis, as an equivalent emission. Figure 19, Page 41, however, details the balance of emissions within Energy, indicating around 10 $MtCO_2$ is removed by 'CCUS – Electricity Generation' and 'CCUS – Industry' combined. Owing to their representation on the negative y-axis, and later reference to the use of biomass (for example, Page 43), we assume these categories represent removals from engineered CDR methods, such as BECCS. We therefore adjust the Energy sector total accordingly.
Iceland	LTS-SP dataset: 0.8 $MtCO_2e$ Buck et al., 2023: 0.9 $MtCO_2e$ (13% higher)	Both datasets use Figure 10, Page 47, to determine residual emissions. We note that Scenario E is slightly lower than Scenarios A and C. We therefore estimate this as a 100 $ktCO_2e$ lower than A and C. Given the legibility of Figure 10, it is reasonable to anticipate a difference of this magnitude.
Latvia	LTS-SP dataset: 3.6 $MtCO_2e$ Buck et al., 2023: 3.3 $MtCO_2e$ (8% lower)	Latvia present a single 'With current measures' scenario, which considers only current policy and measures and the scenario only provides for the currently available commercial technologies (as shown in Figure 5, Page 26). It is not clear, however, if alternative trajectories have been produced, for example, on Page 26 it is noted that 'According to the initial indicative projections, the specified quantity of GHG emissions which will have to be compensated with removals in 2050 is approximately 3.6 million tCO_2 eq'. This value would appear to be linked to modelling by an external and separate organisation. This differs from the level residual emissions shown in Figure 5 directly above this text, with a level well over 10 million t CO_2 eq, including LULUCF as a net source. The trajectory depicted in red would appear to be a linear projection between targets for 2030 and 2040 and therefore is not a meaningful projection. In lieu of multiple scenarios, we use 3.6 $MtCO_2e$ as indicative of residual emissions. Buck et al., 2023 uses the same reference seen on Page 26, but appears to note this as 3.3 $MtCO_2e$ as opposed to 3.6 $MtCO_2e$ as written.
Mexico	LTS-SP dataset: 262 $MtCO_2e$ New Climate Institute: 313 $MtCO_2e$ (19% higher).	Mexico presents a series of scenarios in relation to GHG emissions in Figure 21, Page 73. New Climate Institute's assessment of G20 strategies uses the value shown for the 'NDC more ambitious' and 'NDC policy' scenario shown in the figure, for the year 2050. The LTS-SP dataset adjusts for the land-use CO_2 emissions [labelled 'CO2 Land Use Change'] included within this total, seen in Figure 22.
Russia	LTS-SP dataset: 1830 $MtCO_2e$ New Climate Institute: 630 $MtCO_2e$ (66% lower).	Russia's LT-LEDS presents two scenarios; the 'inertial scenario' and 'target (intensive) scenario'. The 'target (intensive) scenario' is the preferred scenario, as stated on Page 33 'As a basis for the implementation of the Strategy, it is proposed to use the target (intensive) scenario' and Page 15 'In view of the above, the inertial scenario is not considered as the main one. In order to fulfil the task set in the address of the President of the Russian Federation to the Federal Assembly of the Russian Federation dated April 21, 2021, and to minimize these risks, it is proposed to consider the target (intensive) scenario as the main one'. The 'target (intensive) scenario' is thought to represent an 'additional policy' scenario, owing to the inclusion of 'additional emission reduction measures' (Page 15).

Country	Difference	Explanation
		The results of each modelled scenario, in terms of the emissions for 2030 and 2050, can be found in the table on Page 34 (ANNEX). The results available, however, are not presented according to sectors, but only gross emissions, the net balance of 'adsorption', and the combined net emission balance. New Climate Institute's assessment of G20 strategies appears to use the 'net emissions' row of the table shown on Page 34, which includes the 'absorption', thought to represent LULUCF. We use the gross emissions excluding LULUCF, labelled as 'Greenhouse gas emissions'.
Slovakia	LTS-SP dataset: 14 $MtCO_2e$ Buck et al., 2023: 7 $MtCO_2e$ (50% lower)	Buck et al., 2023 uses the 'target emission gap' referred to on Page 18 of Slovakia's LT-LEDS. Modelled scenarios, however, detail that this gap is what remains after LULUCF removals are taken into account, leading to a 14 $MtCO_2e$ gap prior to accounting for removals (Page 15 & Figure 2, Page 15). Slovakia, however, notes that 7 $MtCO_2e$ represents a target to be reached, as this is the 'amount that can potentially be eliminated through removals (the LULUCF sector)' (Page 18), specifically via further policy measures (labelled as 'NEUTRAL' throughout sectoral chapters), that go beyond the modelled measures included in the WEM (with existing measures) and WAM (with additional measures) scenarios. We prioritise the use of modelled scenarios to determine residual emissions, however it is also reasonable to use the target emission gap given this is stated as an objective to be reached.
Thailand	LTS-SP dataset: 240 $MtCO_2e$ (for the purpose of comparison) Buck et al., 2023: 120 $MtCO_2e$ (50% lower)	Buck et al., 2023 appears to use the figures found on Page 44 of Thailand's 2021 LT-LEDS, detailing trajectories for 'carbon neutrality' in 2065 or 2070. These trajectories, however, are for CO_2 only. The LTS-SP dataset uses 'Thailand's long-term low greenhouse gas emission scenario' presented in 'Figure 3-6' on Page 38. This reaches net zero GHGs in 2090, but for comparison, we compare the emissions in 2065 to align with the timing of carbon neutrality seen on Page 44, and therefore the relevant reference for Buck et al., 2023. Note that we compare the 2021 LT-LEDS, now superseded by the more recent LT-LEDS in November 2022.
United States	LTS-SP dataset: 1500 $MtCO_2e$, Buck et al., 2023: 1605 $MtCO_2e$ (7% higher) New Climate Institute: 790 $MtCO_2e$ (47% lower).	The USA's LT-LEDS presents a total of 12 modelled scenarios across a range of technological assumptions. These are detailed in Table 1 on Page 22. Figure 3 presents a stepwise 'representative' emission reduction pathway with 7 alternative pathways explored. The representative pathways 'provides a rough approximation for reaching net-zero emissions using contributions from all sectors', as detailed on Page 22. The results of modelled pathways serve as modelled ranges across a series of figure supporting sector level analysis in Chapters 4-6. Figure 3's presentation, however, means residual emissions at the time of the net zero target cannot be determined. Figure 17, on Page 45, provides a means of estimating residual emissions, however, only by approximation from the figure itself. Nor are specific values cited elsewhere within the text. Some limited detail of residual emissions in 2050 by gas, including fluorinated gases, can be found in Figure 12 and 13, Pages 36 and 37 respectively. These, however, do not appear to show differing levels, with Figure 13 implying residuals for nitrous oxide comparative to methane, however nitrous oxide is visibly lower in Figure 12. These estimates, therefore, cannot be used with accuracy to determine residual emissions. We therefore approximate residual emissions from the Figure 17 itself, using the central line within the ranges presented. Buck et al., 2023 appears to also use Figure 17, Page 45, to estimate residual emissions, but also notes the 'energy sector and non-CO_2 GHG figure captions'. We take this to refer to Figure 13 and Figure 12, which are subject to the issues we outline above. We are unclear as to how the specific value has been reached, but note that a difference of a 100 $MtCO_2e$ is reasonable considering the legibility of Figure 17. New Climate Institute's assessment of G20 strategies appears to use the range presented in Figure 18, Page 48 for LULUCF, which is estimated to range between -500 to -1350 $MtCO_2e$ in 2050, where -500 $MtCO_2e$ is the upper range of the BAU scenario and -1350 $MtCO_2e$ the lower bound of the 'NCS Action Range'. CDR (here referring to engineered CDR) is estimated to be -300 to -600 $MtCO_2e$ in 2050,

Country	Difference	Explanation
		leading to a total range of 800 $MtCO_2e$. We believe this to be too low judging from Figure 17, perhaps owing to the inclusion of the BAU range in Figure 18, whereas LULUCF in Figure 17 may refer to the 'NCS Action Range' shown in Figure 18. Given the legibility of Figure 17, and the incorporation of ranges, such a difference in estimates should be anticipated.
Uruguay	LTS-SP dataset: 4.19 $MtCO_2e$ Buck et al., 2023: 3.64 $MtCO_2e$ (13% lower)	Buck et al., 2023 uses Table 04, Page 55. This details only CO_2 emissions from energy and industrial processes. For methane and nitrous oxide, Uruguay's LT-LEDS explores scenarios which stabilise emissions prior to 2050, detailed on Pages 62-70. We combine these same estimates with Table 04 to determine total GHG emissions in 2050.

Table A 2. Assessment of the difference between LULUCF and engineered CDR between the LTS-SP dataset and New Climate Institute's assessment of G20 strategies.

Percentage difference from LTS-SP dataset shown.

Country	Element	Difference	Explanation
Australia	LULUCF	LTS-SP dataset: Max -204 $MtCO_2$, Min -3 $MtCO_2$, New Climate Institute: -27 $MtCO_2$	Table 6, Page 59 of Australia's LT-LEDS Modelling and Analysis annex, shows the emissions prior to BECCS, DACCS, land-use and the inclusion of any international offsets. The minimum LULUCF at the point of net zero GHGs, is -3 $MtCO_2e$, shown for the 'NZE no offsets' scenario. The maximum engineered CDR at the point of net zero GHGs, is -204 $MtCO_2e$, shown for the 'NZE no trade' scenario, referring to the row 'Domestic offsets: Land sector'. New Climate Institute's assessment of G20 strategies appears also to use Table 6, Page 59, but for 'The Plan' scenario, which incorporates 27 $MtCO_2$ of removals from the 'Land sector', as noted in Table 6. We note that 'The Plan' scenario does not reach net zero GHGs, as per the 'NZE' scenarios in Table 6. We therefore use the NZE scenarios as representative of Australia's LULUCF. Note that we compare the 2021 LT-LEDS, now superseded by the more recent LT-LEDS in January 2024.
Indonesia	LULUCF	LTS-SP dataset: -300 $MtCO_2$, New Climate Institute: -550 $MtCO_2$	New Climate Institute's assessment appears to use Figure 6, Page 37, to determine LULUCF, estimating the amount of removals by the extent of the negative y-axis for LCCP scenario in 2050. Figure 6 details emissions for AFOLU under both 'CPOS and 'LCCP' scenarios and includes not only positive emissions from agriculture on the positive y-axis, but similarly emissions from land-use. When combined to reach a net total, the net FOLU total in 2050 is near -300 $MtCO_2$, as seen in Figure 5, Page 34. We therefore use Figure 5 to determine the contribution from FOLU.
Italy	LULUCF	LTS-SP dataset: -45 $MtCO_2$, New Climate Institute: Min -65 $MtCO_2$ Max -85 $MtCO_2$	New Climate Institute's assessment appears to use the range stated on Page 19 'These reduction dynamics, however intense, leave a quantity of emissions to be compensated of approximately 65-85 Mton CO_2 eq.' [translated]. It is then thought to be assumed that this amount is compensated by LULUCF, however, Page 19 also notes that 'the absorption capacity of the LULUCF sector must be considered which, with adequate policies to fight fires and sustainable soil management, can be brought back to an all-time high (equal to 45 Mton CO_2 eq)' [translation], and therefore doesn't appear to compensate for the total extent of residual emissions. This is confirmed by Figure 3.5.4, Page 83. We note that Page 19 also details the potential use of BECCS, similarly included in Figure 2.2.4, Page 35. If residual emissions equate to at least 65 $MtCO_2eq$, as stated on Page 19, then emissions from known sectors stand at 50 $MtCO_2eq$ (22

Country	Element	Difference	Explanation
			$MtCO_2e$ [Industry, including combustion, text on Page 49 and Figure 3.1.6] + 23 $MtCO_2e$ [Agriculture, Figure 3.4.3, Page 76] + approximately 5 $MtCO_2eq$ [Waste, Figure 1.3.2, Page 19]). Subtracting the maximum extent of LULUCF, stated on Page 19 and displayed Figure 3.5.4, Page 83, of 45 $MtCO_2eq$, leaves 5 $MtCO_2eq$ remaining. Given that Figure 1.3.2, Page 19, shows that 'energy industries [Industrie energetiche]' to be net-negative at approximately -5 $MtCO_2e$ [a similar extent to Waste judging by the Figure 1.3.2], it serves that, if BECCS was deployed at a scale of -20 $MtCO_2eq$, as implied by Page 19, positive emissions for the 'energy industries' would equate to 15 MtCO2eq, approximately the extent seen in Figure 2.2.4, Page 35. We therefore use 15 $MtCO_2eq$ as our estimate for 'energy industries'. This would then total 65 $MtCO_2e$. It is unclear how the 85 $MtCO_2e$, detailed on Page 19, can be reached using data presented within the strategy. We therefore discount a scenario with a residual of this amount. We assume this amount is exclusive of avoided emissions from carbon capture and storage, as implied on Page 19.
South Korea	LULUCF	LTS-SP dataset: Not provided, New Climate Institute: -15$MtCO_2$.	New Climate Institute's assessment appears to use Figure 4-30, Page 99, to determine LULUCF. This shows a decline in removals from forests through to 2050. This appears to reflect only removals not emissions and removals combined, as Figure 4-31, Page 98, details removals at '45.7 million ton CO_2eq' in 2017, whereas Table 2-1, Page 30 and 31, details total LULUCF as -41.6 $MtCO_2$. Figure 4-30 appears to show a forward-looking projection of the same variable as Figure 4-31. This projection represents existing policy, a trend which South Korea seeks to reverse via the policies outline in Section 7.2, beginning on Page 99. We therefore view this projection as partial, excluding emissions, and representative of business as usual, as opposed to the policies proposed. As a result, we do not recommending using this figure to determine LULUCF.
Australia	Engineered CDR	LTS-SP dataset: Max -216 $MtCO_2$, Min -43 $MtCO_2$, New Climate Institute: -38 $MtCO_2$ (12-82% higher).	Table 6, Page 59 of Australia's LT-LEDS Modelling and Analysis annex, shows the emissions prior to BECCS, DACCS, land-use and the inclusion of any international offsets. The minimum engineered CDR at the point of net zero GHGs, is -43 $MtCO_2e$, shown for the 'NZE 100%' scenario. The maximum engineered CDR at the point of net zero GHGs, is -216 $MtCO_2e$, shown for the 'NZE no offsets' scenario, combining rows for 'Negative emissions (BECCS)' and 'Negative emissions (DAC)'. We assume DAC represents permanent removals and not the use of direct air capture for CO_2 utilisation that results in short-term storage. New Climate Institute's assessment of G20 strategies appears also to use Table 6, Page 59, but for 'The Plan' scenario, which incorporates 38 $MtCO_2$ of removals from BECCS, as noted in the 'Negative emissions (BECCS)' row of Table 6. We note that 'The Plan' scenario does not reach net zero GHGs, as per the 'NZE' scenarios in Table 6. We therefore use the NZE scenarios as representative of Australia's engineered CDR. 'The Plan' scenario, appears to be the basis of the figure depicting the main scenario, Figure ES.2, Page 15 of Australia's LT-LEDS (as it maintains a 15% gap prior to reaching net zero GHGs, as detailed in Table 5, Page 58 of Australia's LT-LEDS Modelling and Analysis annex). This poses a problem as to whether the main scenario, as presented in the strategy, should be used, despite the scenario failing to meet Australia's long-term target, or whether scenarios that do reach this target but are deprioritised and shown only in additional documents.
Canada	Engineered CDR	LTS-SP dataset: Max -226 $MtCO_2$, Min -24 $MtCO_2$,	New Climate Institute's assessment of G20 strategies appears to use the totals found in Table 4, Page 34 for 'DAC', ranging from 0 to -201 $MtCO_2$. This excludes removals from BECCS which are combined within Electricity and Industry sector totals within Table 4. We calculate a engineered CDR total for the scenarios in Table 4 by using the ranges

Country	Element	Difference	Explanation
		New Climate Institute: Max -201 $MtCO_2$, Min 0 Mt CO_2 (11-100% higher).	stated on Pages 22, 25, 28 and 31, which are inclusive of 'LULUCF, BECCS, and DAC'. As the contribution from LULUCF remains constant across the scenarios, as noted on Page 19 ('Across all scenarios, the modelling approach for Canada's LTS assumes a contribution of -100 Mt from LULUCF'), the contribution from engineered CDR can be determined by subtracting this contribution from the ranges detailed.
France	Engineered CDR	LTS-SP dataset: -10 $MtCO_2$, New Climate Institute: -16 $MtCO_2$ (60% lower).	New Climate Institute's assessment of G20 strategies appears to use the figure shown on Page 18 and Page 168, estimating the GHG sinks column as 82 $MtCO_2$, with a contribution of 16 $MtCO_2$ from 'Carbon Capture and Storage', labelled by New Climate Institute as 'tech CDR'. We make the same estimation, but adjust for the avoided emissions from CCS, using the 6$MtCO_2$/year stated on Page 170, that appears to be represented as part of the 'GHG sinks' of the Figure on Page 168. This appears not to represent BECCS, unlike the remaining 10 $MtCO_2$/year which is also detailed on Page 170 as BECCS and therefore thought to represent removals.
USA	Engineered CDR	LTS-SP dataset: Max -1500 $MtCO_2$, Min -1500 $MtCO_2$, New Climate Institute: Max -300 $MtCO_2$, Min -600 Mt CO_2 (40% lower – 20% higher).	New Climate Institute's assessment appears to use the range presented in Figure 17, Page 45 estimating the range seen for 'CDR' to be -300 to -600 $MtCO_2$ in 2050. We approximate the contribution from CDR similarly from Figure 17 but use the central line within the ranges presented. Given the legibility of Figure 17, and the incorporation of ranges, such a difference in estimates should be anticipated.

Annex II – Chapter 4

This section further details our methodology, beyond what is presented within Chapter 4. It further describes our procedure, in addition to some of the limitations and caveats to our methods.

Residual emission definition

As noted in Chapter 4, our definition of residual emissions is based upon available data across our sample of long-term national climate strategies and existing conventions in UNFCCC reporting and net zero targets. Different configurations of emissions and removals may lead to different residual emission estimates, either by extensions in scope or by further delineating between removals and emissions. Three of these configurations are detailed in Figure A 1 below. In Figure A 1A, LULUCF emissions and removals are delineated, with emissions added to the gross emissions from all other sectors (transport, industry, etc.). This follows a proposed definition within Schenuit, Boettcher and Geden, 2023 where residual emissions are '*a quantity that simply describes which emissions actually enter the atmosphere in and after the net-zero year*'. Any emissions from LULUCF at the point of net zero would continue to enter the atmosphere, therefore counting as residual under this definition. Existing convention within the reporting of national greenhouse gas inventories to the UNFCCC is to report LULUCF on a net basis, combining emissions and removals, but as noted by Mackey *et al.*, 2022, net accounting obscures the importance of measures to increase or maintain removals. It may also grow increasingly problematic in attempts to further define residual emissions.

In Figure A 1B, emissions from IAS are added to national totals excluding LULUCF. Existing reporting convention is to report emissions from IAS as a '*memo item*', with emissions calculated on a bunker fuel basis, that is, fuel sold. If included, as proposed in some net zero targets (for example, the United Kingdom's), this would require a greater level of CDR to attain net zero. This may not necessarily be taken as unilateral action to address what are deemed international emissions, but may rather reflect the need for infrastructure, such as the manufacturing of synthetic fuels or the generation of offsets through DACCS, within national territories (Committee on Climate Change, 2019; Mithal and Rutherford, 2023). Figure A 1C depicts accounting where engineered CDR is included within sectoral totals. This follows the existing convention of reporting emissions and removals within the sectors they occur (IPCC, 2006a). In our example, this would appear as a reduction in the gross emissions from other sectors excluding LULUCF. This however would limit our understanding of residual emissions as emissions entering the atmosphere at the point of net zero (Schenuit, Boettcher and Geden, 2023). We therefore caveat our main analysis as conditional on a specific definition of residual emissions, as gross

GHG emissions entering the atmosphere at the point of net zero excluding LULUCF, engineered CDR, and IAS.

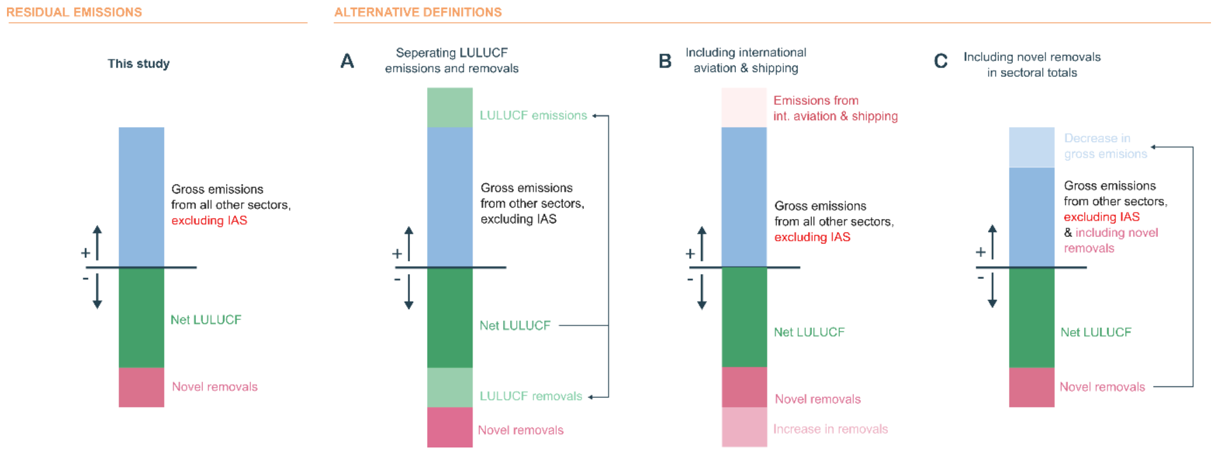


Figure A 1. The definition of residual emissions used within this study versus three alternative definitions.

Sizes of removals and emissions bars are indicative only, not representative of any specific national example.

We review all scenarios and pathways within our sample according to this definition, assessing whether net zero GHGs is reached when including LULUCF and engineered CDR (within a bound of +0.5 $MtCO_2e$ to account for rounding). An exception is Sweden, where we use the climate policy framework specific to Sweden, detailed in Section 2.1.2, Page 10, of Sweden's LT-LEDS. This is taken to discount the existing LULUCF sink detailed in Figure 7 of the strategy, instead requiring additional removals in forest lands or alternative supplementary measures including international offsets or removals from bioenergy with carbon capture and storage (BECCS). The scenario data used, found in Annex 1, Page 86 of Sweden's LT-LEDS, is taken to comply with this policy framework.

Sectoral residual emission estimates

Residual emission estimates across the strategies follow no standard format, and whilst guidance exists recommending the information to be detailed, practice varies widely (Cruanyes, Alcaraz and Sureda, 2024). Further complicating matters, the representation of emission sources and sectors are not consistent between strategies, with countries either failing to disclose necessary detail or designing their own sectoral classification that better suits their national climate policy framework. For example, the United Kingdom, for their LT-LEDS, the 2021 UK Net Zero Strategy, designed an emission taxonomy that differs from their national GHG inventory (UK Government, 2021).

The 2006 IPCC Guidelines for NGHGIs governs the classification of emissions sources and sinks into national sectors. These guidelines, whilst suited to the development of national GHG inventories, are ill-suited to assess residual emissions, largely owing to two issues. Firstly, residual emissions pertain to specific sources within and across sectors. Decarbonising an industry sub-sector such as cement would require addressing the emissions arising from fuel combustion and the process emissions arising from calcination reactions (Rissman *et al.*, 2020), emissions represented within Energy (1A2f) and the '*industrial processes and product use*' or IPPU sector (2A1) respectively. Across strategies, countries have opted to include fuel combustion within industry directly within an '*industry*' sector, whereas others have opted to include fuel combustion within industry within the energy sector, as per the IPCC guidelines. We therefore map the inclusion of emission sources across sectors according to information presented within the strategy. We similarly split out transport, conventionally included within the guidelines under energy, as a separate sector, as emissions from aviation and shipping are also considered hard-to-abate and residual (Babiker *et al.*, 2022). Where inconsistency between sectors occur, which cannot be corrected, such as the inclusion of a sector's emissions within another, we use the notation key '*IE*' for '*included elsewhere*' in the dataset accompanying Chapter 4, indicating where emissions are included. We term these '*sectoral adjustments*'. The dataset accompanying Chapter 4 is detailed in Experimental Procedures, Section 4.6, and details sectoral adjustments.

A second issue is the inclusion of negative emissions within sectors. Countries may report emissions for the '*Agriculture, Forestry and Other Land Use*' or '*AFOLU*' sector, combining hard-to-abate emissions from livestock and fertilisers with net-negative emissions from forestry (Babiker *et al.*, 2022). If these emissions cannot be disaggregated, this obscures the extent of residual emissions. Similarly, though the guidelines do not include nomenclature of engineered CDR, such as DACCS and BECCS, multiple strategies include these methods and may choose to account for these negative emissions within the sectors they occur. This would similarly obscure the extent of residual emissions. Proposals exist on reforming these guidelines to clarify how these methods are to be accounted for (Mace *et al.*, 2021; Köhnke *et al.*, 2023). We present engineered CDR separately within our emission logic. Where the disaggregation of negative emissions from a sectoral total is not possible, we highlight these within Figure 16 and Figure 17 of Chapter 4 as '*partial residual emissions*' (PREs). We also use information within the strategy to identify whether this inclusion leads to an under or overestimate. Partial residual emissions and sectoral adjustments are further explored in the sections and tables below.

We allocated sectoral emissions to a consistent sectoral split, based upon the logic of the IPCC NGHGI Guidelines and the common reporting format for Annex I countries (CRF), detailing emissions from Energy, Industry, Transport, Agriculture and Waste. Where the description of a source or sub-sector is unclear, referring to a country's own classification, we refer to our expert judgement. Our emission logic is detailed in Figure A 2 below. This provides examples of the sources/sub-sectors contained within our main categories alongside their category code, mapping onto the IPCC NGHGI Guidelines or CRF.

Figure A 2. The emissions logic to assign sources/sub-sectors to main sectors.

Sources/subsectors are described according to their official name in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories or Annex I Common Reporting Format. Sources/sectors not exhaustive. See the accompanying dataset for further detail on sources/sub-sectors to sector mapping. The dataset accompanying Chapter 4 is detailed in Experimental Procedures, Section 4.6.

Partial residual emissions

Partial residual emissions describe cases where the disaggregation of negative emissions from a sectoral total is not possible. Partial corrections can be made, for example, by subtracting the minimum extent of negative emissions if a sectoral total is net-negative. We describe partial residual emissions in the table below, alongside the direction of their effect (overestimate/underestimate).

Table A 3. Partial residual emission estimates.

'*Sector(s) affected*' details the sector(s) which is primarily impacted, noting that partial estimates have an impact on the overall balance of residual emissions.

Country	Scenario(s)	Correction	Likely over/underestimate	Sector(s) affected
Finland	Savings	Row '1A1 Energy Industries' of Annex 2, Page 3, is negative in 2040, the earliest timestep during which Finland reaches net zero when including LULUCF. Page 9 of the main text indicates this is through 'bio-CCS', which we take as referring to BECCS. We therefore assign to BECCS a minimum amount equal to the extent of the net-negative emissions within 1A1. This is to assume, for example, that emissions in 1A1 excluding BECCS is equal to 0. It is likely that the amount is higher, if judged by the category 'CO_2 from energy sector' in Figure 1, Page 9. If 'Net emission' is assumed to represent BECCS (as is likely owing to the absence of the category within the 'Continuous Growth' scenario and the detail on Page 9 that this scenario excludes CCS and therefore likely 'bio-CCS') then BECCS is around 6 $MtCO_2$ and emissions from the energy sector around 5 $MtCO_2$. Energy emissions can be estimated by summing the remaining rows excluding 1A1 and '1A3 Transport' equalling 956 kilotonnes CO_2eq. As this likely includes non-CO_2 emissions it is therefore not comparable to the category 'CO2 from energy sector' in Figure 1. It is, however, indicative of the extent of the underestimate given that emissions from the energy sector tend to be dominated by CO_2 (98% of the energy sector total according to UNFCCC data for Finland for 2021), giving a likely underestimate of the energy sector by around 4$MtCO_2$. We defer to data presented for the scenario on Annex 2, Page 3, given the greater detail by sector provided compared to Figure 1, but note this as a likely underestimate.	Likely underestimate	Energy
Thailand	Thailand's Net Zero GHG Emission Pathway	Only LULUCF is shown as compensating for residual emissions. The statement made on Page 14, however, implies BECCS and DACCS may be included in the energy sector: 'Coal phase-out and negative emission technologies in the energy sector, e.g., Bioenergy with CCS (BECCS) or direct air capture and storage, will be necessary in Thailand's net zero GHG emission pathway.' If this is the case, the 'true' level of residual emissions is likely higher.	Likely underestimate	Energy
United Kingdom	High electrification, High resource & High innovation	Table 4, Page 318, uses the category 'Agriculture and LULUCF'. This combines commonly considered residual emissions (for example, livestock emissions) with emissions/removals associated with land-use. This obscures the extent of emissions in agriculture and the level of LULUCF.	Likely underestimate	Agriculture

Sectoral adjustments

Sectoral adjustments represent cases where the presentation of the scenario data within the strategy prevents direct allocation to the sectoral split. For example, if emissions for a specific sector were combined with another sector, and no information was available within the strategy to differentiate these emissions from one another, this would be noted as a sectoral adjustment within dataset accompanying Chapter 4. The dataset accompanying Chapter 4 is detailed in Experimental Procedures, Section 4.6. Within this dataset we use notation keys (e.g. '*IE*' for included elsewhere), as with inventory reporting (IPCC, 2006a). In the case of Figure 19, we modify the 2021 or current emissions baseline to match the scope of the sectoral adjustment, to ensure we are comparing like with like. Sectoral adjustments, unlike partial residual emission estimates, do not affect the extent of residual emissions, only the allocation between sectors.

Table A 4. Sectoral adjustments.

Country	Sectors affected	Adjustment
Australia	Waste & Industry	Waste is included in 'Industrial emissions' (see footnote associated with Table 6, Page 59, 'Modelling & Analysis' Annex), allocated to 'Industry'. Industry, therefore, is anticipated to include emissions from both waste and industrial processes and product use. Waste is therefore given the notation key 'IE' for 'included elsewhere'.
Austria	Transport & Energy	Transport is not specifically defined in the figures presented for Pathways A-D, Section 6.1.2, beginning on Page 83, except for international aviation and shipping (or 'Int. air traffic and shipping'). These figures instead use the category 'fuel consumption'. As this could be inclusive of any remaining transport emissions, for example, in road transport, and this is allocated broadly to 'Energy', we give Transport the notation key 'IE' for 'included elsewhere'.
Cambodia	Transport & Energy	Transport is thought to be included within Energy. This is supported by the statement made on Page 7 that 'Energy sector emissions are largely determined by the power mix, road transportation and the level of vehicle electrification'. Similarly Figure 10, Page 12, depicts emission 'Savings from transport' within the total abatement for the energy sector. Transport is therefore given the notation key 'IE' for 'included elsewhere'.
Costa Rica	Transport & Energy	Transport is thought to be included within Energy. This is supported by the description of the scenarios found on Page 26, alongside the description of the energy sector found on Page 11 onwards. Transport is therefore given the notation key 'IE' for 'included elsewhere'.
Oman	Agriculture, Waste & Other	Agriculture and waste are considered 'out of scope' according to 'Exhibit 5', Page 19, detailing Oman's 'Orderly transition' pathway. This is not taken to refer to the fact they are not estimated, but rather out of scope of the emission reduction initiatives subjected to other sectors, such as industry and transport (see table within Exhibit 5). This would be supported by the trend seen for 'other', containing emissions from these sectors, in Exhibit 5. Agriculture and Waste is therefore given the notation key 'IE' for 'included elsewhere' and the emissions thought to be associated with these sources allocated to 'Other'.
Thailand	Transport & Energy	Transport is thought to be included within Energy. This is supported by Figure 3-3, Page 14, which details only 'Energy'. This is similarly supported by the '2018 Emission Profile' detailed on Page 10, which includes transport emissions under the 'ENERGY' heading. It is thought this same logic is used for scenarios and pathways. Transport is therefore given the notation key 'IE' for 'included elsewhere'.
United Kingdom	Waste & Industry	Table 4, Page 318, uses the category 'Waste and F-gases'. F-gases would typically be considered under industry, as per the logic of the IPCC 2006 Guidelines on National GHG Inventories. In this case, no correction can be made to differentiate f-gases from waste emissions. As only a proportion of the emissions typically considered within 'Industry' are

Country	Sectors affected	Adjustment
		instead allocated to 'Waste', not one sector wholly contained within the other, 'IE' for 'included elsewhere' is not applicable.
Spain	Agriculture & Waste	Table E.1, Page 136, of Spain's LT-LEDS Annex details emissions for the ELP scenario but uses the category 'Agriculture and waste'. It is thought that the total (19 $MtCO_2e$) for 'Agriculture and waste' primarily pertains to agriculture. Page 44 of Spain's LT-LEDS details that agricultural emissions are '53% compared to the reference year 1990' within the ELP scenario, whereas Page 45 notes that waste and wastewater emissions are 'reduced by 81% in 2050 compared to 2015'. Given agriculture emissions are higher in 1990 than waste emissions in 2015 (according to UNFCCC data for the 1990-2021 inventory), this would suggest this is mostly emissions from agriculture. Though this data could be used to split the two categories, we avoid this as this uses data external to the LT-LEDS. Waste is therefore given the notation key 'IE' for 'included elsewhere'.
Tunisia	Transport & Energy	Figure 37, Page 66 of Tunisia's LT-LEDS details emissions in the energy sector for the 'BaC' scenario. This is thought to include transport emissions owing to the description found on Page 65, relating to energy and the electrification of transport as part of the mitigation under consideration, 'Tunisia should therefore strongly promote the electrification of uses, in particular through the transition to electric transport, thus allowing the share of electricity to increase from 20% of the final energy mix in 2020 to around 25% in 2030 and 43% in 2050'. Transport is therefore given the notation key 'IE' for 'included elsewhere'.

Residual emission rationales

To further contextualise residual emission estimates, we read and inductively coded each strategy to identify statements concerning residual or hard-to-abate emissions. Though we note within Chapter 4 that these are best handled as distinct concepts, the terms are commonly conflated. Inductive coding is necessary as we are principally interested in the suite of rationales used by national governments, not the identification of existing rationales in literature within the strategies, as would be the case using deductive coding. Statements relating to hard-to-abate and residual emissions were identified across our sample. We subsequently iterated multiple reviews of these statements, before arriving at a final set of codes or '*code saturation*' (Hennink, Kaiser and Marconi, 2017). For similar sources/subsectors we merged phrasings into a single category. For example, '*air traffic*' and '*aviation*' would be combined into a category for '*aviation*'. We then assigned these to the emission logic seen in Figure A 2, to align these codes with the main sectors. For example, aviation would be considered under '*Transport*'. For rationales, we produced a range of supporting rationales evidenced by examples in Table 7 of Chapter 4. Multiple rationales and sources/sub-sectors may be contained within a single statement, meaning our total of statements analysed (357) does not reflect the sum of rationales seen in Figure 20 and Figure 21. An example of our coding is detailed below. All our codes, alongside page references to their position within their respective strategy, are detailed in the dataset accompanying the chapter, accessible through Section 4.6.

UK Net Zero Strategy, Page 39 [highlight added] 'Government is committed to ambitious decarbonisation measures across society. However, we know that this does not mean emissions will drop to absolute zero by 2050 – we acknowledge that sectors such as industry, agriculture, and aviation are difficult to decarbonise completely. Greenhouse gas removals (GGR), like trees and carbon capture and storage technology, are therefore essential to compensate for the residual emissions arising from these hard to decarbonise sectors, so we can reach net zero by 2050.'
Procedure
We note two sectors and one sub-sector contained in the above statement. For sectors we note 'industry' and 'agriculture'. The sub-sector is 'aviation' which would, according to our emissions logic, be included under 'Transport'. Three codes are therefore generated with respect to sectors and sub-sectors, with two codes relating to industry and agriculture. These have no source or sub-sector detailed, only the main sector, and so appears in Figure 20 of Chapter 4 as 'no sub-sector or source'. The third code relates to 'aviation' as the sub-sector/source and 'Transport' as the main sector. This code would appear in the aviation portion of the transport section of Figure 20. Each of these three codes would be associated with the same rationale, of 'limited further abatement', as it is implied that a limit to further possible abatement has been reached. That is, these sectors can not be decarbonised 'completely' and so must be compensated by GGR. These codes would appear in the rows for 'limited further abatement' in Figure 21, across the three sectors of industry, agriculture, and transport.

Non-Annex I historic data validation

In Chapter 4, we note that for non-Annex I countries the annual reporting of greenhouse gas (GHG) inventories is not required. Instead, these countries are required to report GHG inventories in a range of national reports including National Communications (NCs) and Biennial Update Report (BURs). NCs are submitted every four years with BURs submitted every two, combining the two reports when required to be reported in the same year. Both NCs and BURs contain information as to their national GHG inventories. For Annex I countries, we used the official national GHG inventory submitted to the UNFCCC. For non-Annex I countries we use PRIMAP v2.5 dataset (ref. Gütschow and Pflüger, 2023), which combines published datasets into a comprehensive set of country data for almost all Parties to the UNFCCC (Gütschow *et al.*, 2016). We use the '*HISTCR*' scenario which prioritises country-reported data over third-party data, such as those from BP, FAO, or EDGAR (Gütschow and Pflüger, 2023). This is consistent with our use of official GHG inventory data for Annex I, as our interest is in understanding residual emissions from the perspective of national governments, as opposed to differences between published datasets.

For non-Annex I LT-LEDS, countries may utilise the national GHG inventory produced for a recent BUR/NC or update the inventory within the publication of the LT-LEDS. We therefore compare the available timeseries within the LT-LEDS to the PRIMAP dataset, deferring to the LT-LEDS timeseries where estimates substantially diverge. The table below details, for non-Annex I countries with residual emission estimates, the source data for the historic timeseries between PRIMAP and the LT-LEDS

(Gütschow and Pflüger, 2023). For Cambodia and Georgia, both PRIMAP and the LT-LEDS appear to use the same data source, whereas for the remaining non-Annex I countries, data sources differ.

Table A 5. Differences between GHG inventory sources between PRIMAP and LT-LEDS for Non-Annex I countries.

BUR1 would refer to the country's first biennial update report, BUR2 the second report, etc. The same logic applies to NCs, for example, NC3 would be the country's third national communication.

Country	PRIMAP source	LT-LEDS GHG inventory source	Assessment
Cambodia	BUR1 – Published in 2020. Link: https://unfccc.int/documents/232019	BUR1 (see footnote 7, Page 6 of Cambodia's LT-LEDS – Page 8 similarly notes a base year of 2016, coinciding with the latest year of the inventory for BUR1).	Matching data source
Chile	BUR5 – Published in 2022. Link: https://unfccc.int/documents/624735	BUR4 – Published in 2021. Link: https://unfccc.int/documents/267936 (see Table 1, Page 17).	Differing data source
Costa Rica	NIR (National Inventory Report).	National Inventory of Greenhouses Gases and Carbon Absorption 2012 (see Page 10, and Table 4 – Page 25).	Differing data source
Ethiopia	UNFCCC DI data for 1990-2014.	GHG Inventory 2000-2020 (see Table 31, Page 21 of Ethiopia's LT-LEDS).	Differing data source
Fiji	NC3 combined with data from UNFCCC DI – NC3 published in 2020. Link: https://unfccc.int/documents/226599	GHG inventory for the LT-LEDS, with base year varying by sector/source.	Differing data source
Georgia	NC4 combined with data from UNFCCC DI – NC4 published in 2021. Link: https://unfccc.int/documents/271341	NC4 (see, for example, Page 32 of Georgia's LT-LEDS, which detail historic emissions estimates from the GHG inventory in NC4, and Page 174, which details this has been used for scenario projections).	Matching data source
Oman	No country reported data used, combined estimates from BP, FAO, and EDGAR.	Emissions estimates for 2021.	Differing data source
Thailand	BUR4 – Published in 2022. Link: https://unfccc.int/documents/624750	NC4 – Published in 2022. Link: https://unfccc.int/documents/624738 (see also Page 9 of the Thailand's LT-LEDS).	Differing data source
Tunisia	NC3 combined with data from UNFCCC DI – NC3 published in 2019. Link: https://unfccc.int/documents/196836	2010-2020 GHG inventory (see Page 19 of Tunisia's LT-LEDS).	Differing data source
Uruguay	BUR2 combined with data from UNFCCC DI – BUR2 published in 2017. Link: https://unfccc.int/documents/39887	BUR3 – Published in 2020. Link: https://unfccc.int/documents/208390 (see Page 19 of Uruguay's LT-LEDS).	Differing data source

To assess the impact of using PRIMAP for non-Annex I countries, we collate available historic estimates detailed within the LT-LEDS for the same non-Annex I countries. Using the data available within the LT-LEDS, we produce a timeseries of available years for total GHG emissions excluding LULUCF. We then compare this to '*M.0.EL*', the '*Total emissions excluding LULUCF*' in PRIMAP. For Cambodia, no historic data is detailed and so we default to PRIMAP. Fiji similarly uses a variety of base years per sector, as opposed to a consistent historic dataset, such as a past inventory (for example, Page 51 of Fiji's LT-LEDS details 2013 as the base year for the energy sector, whereas Page 129 details 2015 as the base year for agriculture). We therefore also default to PRIMAP. Uruguay similarly presents no data comparative to GHG emissions excluding LULUCF. Chile present a GHG inventory for the years 1990, 2000, 2010, 2013, 2016, 2017 and 2018 in Table 1, Page 17. Costa Rica presents data for a single year, 2012, in Table 4, Page 25. Ethiopia present a GHG inventory for the years 2000, 2005, 2010, 2015, and 2020 on Page 21, Table 3.3. Georgia presents data for 1990, 1995, 2000, 2005, 2010-2017, in Table 1.2.1, Page 16. Oman presents a single estimate for 2021 in Exhibit 1, Page 13. Notably, this may include some LULUCF emissions within '*Other*'. Thailand presents two data points, 2000 and 2018, found in Figure 2-4, Page 9, though Figure 2-3, Page 9, shows the full timeseries, from 2000-2018, but includes no labels and so cannot be read with accuracy. Finally, Tunisia includes an inventory from 2010-2020, in Table 1, Page 19, which can be adjusted to remove LULUCF components of the total by using Table 3, Page 22.

Our analysis can be found in the below. As seen, Chile's LT-LEDS data tracks closely to PRIMAP, despite PRIMAP using BUR5 as opposed to BUR4. Costa Rica shows a large difference in 2012, with the LT-LEDS lower by 1.4 $MtCO_2e$, or 9.6%. Ethiopia shows a trend that deviates from PRIMAP from 2000 onwards, with emissions 31 $MtCO_2e$ higher in 2020, or 21%. Georgia tracks lower than PRIMAP across the years available, with emissions 9.4% lower in 2017. Oman's emissions in 2021 are 24 $MtCO_2e$ lower than PRIMAP for the same year, or 21% lower. Thailand's data is similar to PRIMAP, with emissions in the LT-LEDS 2.5% lower in 2018. Tunisia's emissions peak in both datasets in 2015, but the LT-LEDS data is 4 $MtCO_2e$ lower than PRIMAP, a difference of 9%.

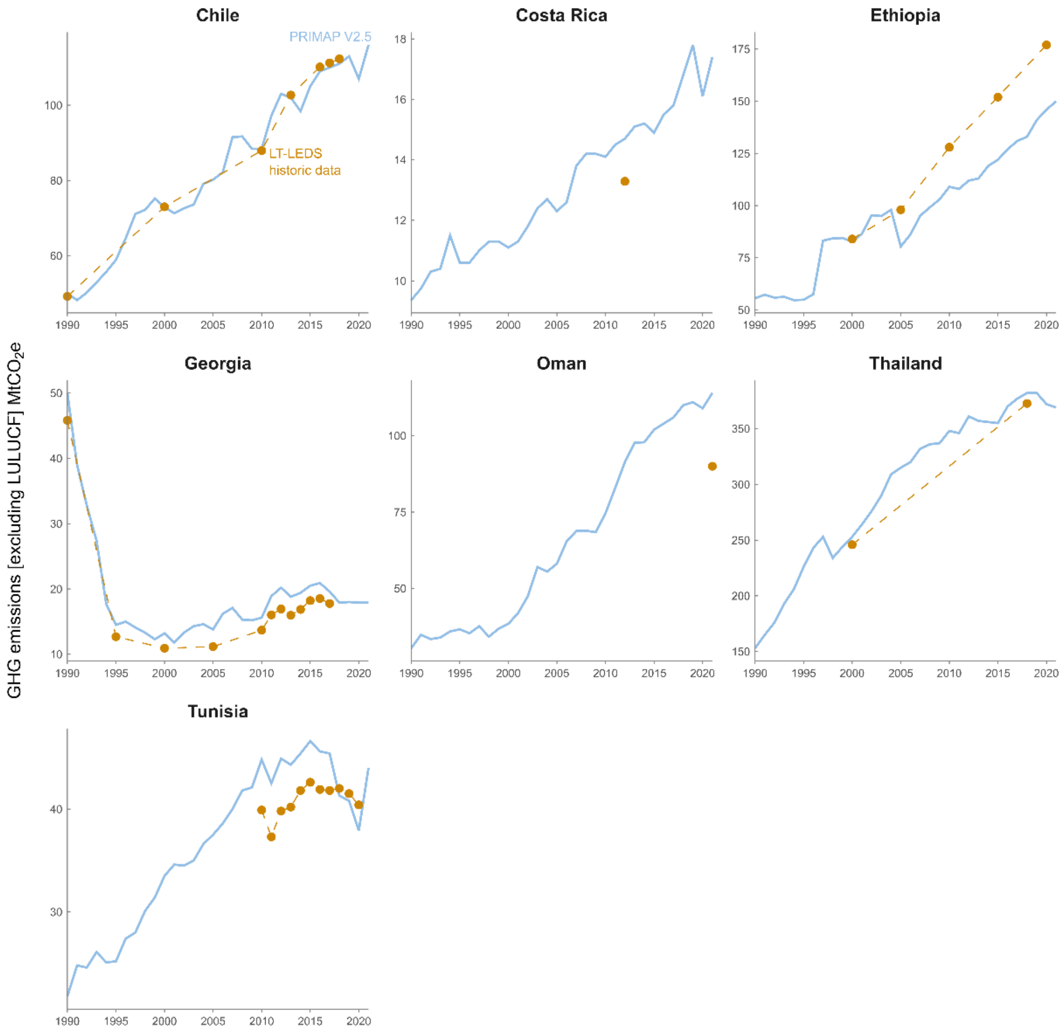


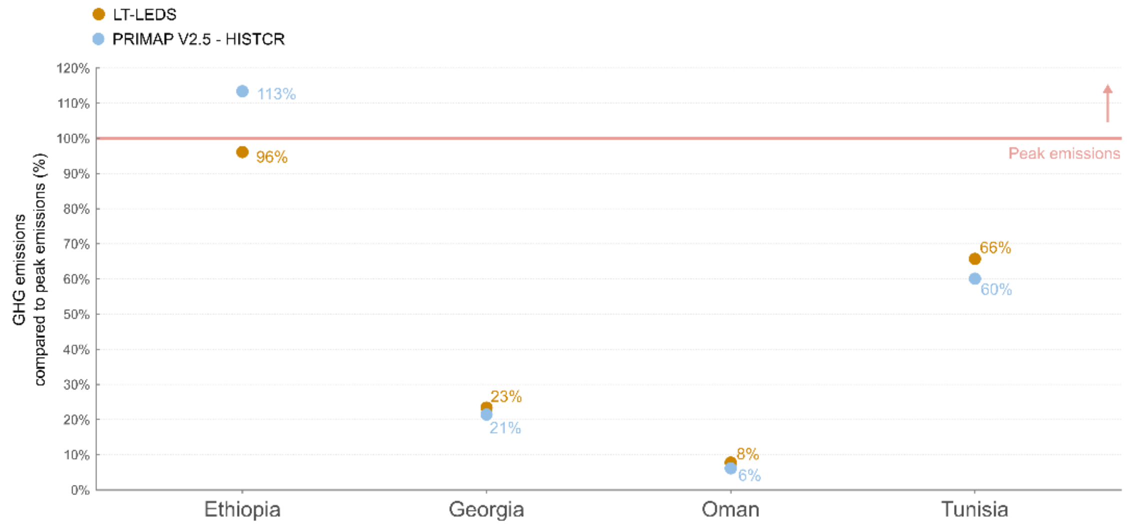
Figure A 3. The difference between the PRIMAP dataset and LT-LEDS data for selected non-Annex I countries.

PRIMAP V2.5 is represented in light blue. LT-LEDS data is depicted in gold. The number of points for the LT-LEDS data represents the data for the years available. All emissions are excluding LULUCF.

We therefore consider PRIMAP sufficient for Chile and Thailand. We are also limited on choice for Costa Rica, given the trend increases from 2012 in PRIMAP and our analysis uses peak year to assess residual emissions. For Ethiopia, Georgia, Oman, and Tunisia, we assess the impact of using LT-LEDS data over PRIMAP. For Georgia and Oman, switching from PRIMAP to LT-LEDS data leads to a 2% difference. We therefore continue to use PRIMAP, owing to the greater availability of data and minimal impact. For Ethiopia, using LT-LEDS data results in residual emissions in 2050 being 96% of peak year emissions, compared to 113% using PRIMAP. We therefore use LT-LEDS data for Ethiopia. Using LT-LEDS data for Tunisia results in residual emissions in 2050 being 66% of peak year emissions, compared to 60% when using PRIMAP. We therefore use LT-LEDS data for Tunisia.

Figure A 4. Residual emissions as the percentage of peak emissions for select non-Annex I countries.

PRIMAP V2.5 is represented in light blue. LT-LEDS data is depicted in gold.



Unlike Annex I countries, which, out of those assessed, have already peaked emissions, non-Annex I countries are likely to follow a peak and decline trajectory, increasing emissions in the near term, even when considering the targets set out in NDCs (Kuramochi *et al.*, 2021). In these cases, it may be more logical to use the future peak in our comparison of residual emissions. We evaluate non-Annex I country projections of emissions excluding LULUCF against PRIMAP data or historical emissions from the LT-LEDS. We examine all instances where a future peak in emissions excluding LULUCF is identified, using information on scenarios and pathways presented within non-Annex I LT-LEDS.

We find that for Chile, Costa Rica, Fiji, Georgia, Tunisia and Uruguay, there is sufficient evidence to indicate a peak in the historical timeseries. For Ethiopia, Oman, and Thailand, there is the possibility of a future peak. Here we seek to balance the availability of a timeseries in PRIMAP versus the minimal data in LT-LEDS. We, therefore, as with Figure A 4, change the peak emissions in the historical timeseries to the future peak, assessing the impact on residual emissions as the percentage of peak emissions. For Oman, we substitute peak emissions according to the PRIMAP dataset with the peak observed in the mid-2020s in Oman's '*Orderly transition*' pathway. The difference of residual emissions as the percentage of peak emissions is less than 1%. For Thailand we substitute peak emissions within the PRIMAP dataset with a peak shown in '*Thailand's Net Zero GHG Emission Pathway*' for 2025. The difference of residual emissions as the percentage of peak emissions is less than 0.5%. For Ethiopia, a future peak in emissions could not be established owing to the presentation of the Ethiopia's '*NZE*' scenarios, though it would appear likely that historical emissions without land-use, presented in the LT-

LEDS, and used within Chapter 4, are indicative of a likely peak in emissions. We therefore retain the use of historical emissions as peak emissions, given the minimal impact on key results.

Table A 6. Assessment of future peak emissions in non-Annex I countries.

Country	LT-LEDS projection reference	Assessment
Cambodia	Figure 7, Page 10	Figure 7, Page 10, of Cambodia's LT-LEDS indicates that emissions from Agriculture, Energy, IPPU, and Waste all increase from 2020 onwards. This increase in emissions from these sectors is enabled by the transformation of 'FOLU' from a net source to a net-sink, allowing net zero GHGs to be reached in 2050, Cambodia's long-term target.
Chile	Figure 10, Page 65	Figure 10, Page 65, indicates emissions without the 'forestry sector'. This indicates a peak, labelled accordingly, in 2025, as also detailed within the text on Page 56. Figure 10 also indicates previous peak of 112 $MtCO_2e$, in 2015, which is lower than the proposed future peak in 2025. Owing to a more complete timeseries we use the PRIMAP dataset for Chile, which indicates that emissions have continued to grow past the 2015 peak shown in Figure 10, to a peak of 116 $MtCO_2e$ in 2021. From this data it would appear likely that emissions peaked historically despite the peak and decline trajectory within Chile's LT-LEDS.
Costa Rica	Figure 10, Page 26	Figure 10, Page 25 shows the declining emissions from Energy, Industrial processes, Agriculture and Waste combined, declining from the year 2020 to 2050, in 5-year intervals. Combined emissions from these sectors decline year on year. For Costa Rica, we use PRIMAP as opposed to data presented in the LT-LEDS, owing to the more complete timeseries available (Figure S3). Emissions in 2020, shown in Figure 10, are much lower than emissions seen in PRIMAP for the same combination of sectors, indicating a likely historical peak.
Ethiopia	Figure 4.1, Page 30 & Figure 4.17, Page 51	Figure 4.1, Page 30, details all four scenarios in Ethiopia's LT-LEDS, detailing that all mitigation scenarios; 'Late Action', 'NDC Aligned' and 'Maximum ambition', decline from a peak of 2018-2020. Figure 4.1, however, details net GHG emissions, inclusive of forest removals detailed in Section 4.5, beginning on Page 56. Ethiopia's LT-LEDS does not present scenario emissions from sectors excluding forests. We therefore evaluate the trajectory of the largest single sector, agriculture, shown in Figure 4.17, Page 51. Owing to the significant deviation in historical emissions between PRIMAP and data contained in the LT-LEDS (see Figure S3 & S4), we opt to use data contained in the LT-LEDS, indicate a peak of 177 $MtCO_2e$ in 2020, the latest available year. Figure 4.17 indicate that in two scenarios 'NDC 2030' and 'Late Action', emissions from agriculture may exceed this historical peak, however this would need to be combined with other sectoral figures to ensure that this a future peak inclusive of mitigation in other sectors, such as Energy. Similar it is unclear if the highest of these scenarios, 'Late Action' should be used as this fails to meet Ethiopia's NDC, despite reaching net zero in 2050, Ethiopia's long-term target. We therefore use the historic data presented in the LT-LEDS in lieu of any clear assessment across the relevant sectors as to the

Country	LT-LEDS projection reference	Assessment
		evolution of emissions and mitigation. We believe that 177 $MtCO_2e$ is indicative level of the likely peak.
Fiji	Table 3, Pages 36-37, combined with Table 35, Page 136, for the 'Very High Ambition' scenario	Fiji combines agriculture emissions with emissions/removals from land-use, into a combined category 'AFOLU'. We separate this category using Table 35, Page 136, for the year 2020, observing in Table 3 and Table 35, that emissions decrease from 2020 onwards for all sectors, including agriculture. For Fiji, we use PRIMAP owing to the use of multiple base years in the LT-LEDS, meaning emissions for a historic year cannot be produced. PRIMAP data is notably higher in the historic timeseries than the 2020 data contained in Table 3 combined with Table 35. From this data it would appear likely that emissions peaked historically.
Georgia	Table 2.2.4, Page 65, and Table 2.2.5, Page 66, for the 'WAM Optimistic' and 'WAM Pessimistic' scenarios	Georgia's LT-LEDS presents six scenarios, Without Measures (WOM), With Existing Measures (WEM), and With Additional Measures (WAM), each with pessimistic and optimistic versions. As noted from Section 2.2, Page 62 onwards, only two scenarios, WaM Optimistic and WaM Pessimistic, reach net zero GHGs. The results for these scenarios can be found in Tables 2.2.4 and Table 2.2.5, Pages 64-65. Emissions are shown for 2016, and 2020-2050, in 5-year intervals. Emissions in the WAM Optimistic scenario, for the years shown, peak in 2020, for the measure 'Total excluding LULUCF', whereas the WAM Pessimistic scenario peaks in 2016 for the years shown. Historical emissions detailed within the LT-LEDS show good agreement with PRIMAP, and so we use PRIMAP owing to greater data availability. Both datasets show a historical peak in the 1990s, much higher than the 2016 or 2020 peaks observed for the two scenarios considered.
Oman	Exhibit 5, Page 19, 'Orderly transition pathway'	Oman's 'Orderly transition' pathway, used throughout it's LT-LEDS reaches peak emissions for the data provided in the mid-2020s, as shown in Exhibit 5, at around 100 $MtCO_2e$. Oman's historical data within it's LT-LEDS is limited, and we use PRIMAP owing to greater data availability. This dataset details that for 2021, emissions are estimated to be 114 $MtCO_2e$, higher than the mid-2020s peak observed for the pathway. Using the estimate for the pathway instead of 2021 data as peak emissions results in a 1% difference between results (residual emissions/peak emissions as a percentage). We therefore opt to retain the peak seen in the historic timeseries within PRIMAP.
Thailand	Figure 3-3, Page 14, for 'Thailand's Net Zero GHG Emission Pathway'	Thailand's Net Zero GHG Emissions Pathway, shown in Figure 3-3, Page 14, indicates that emissions from Energy, IPPU, Agriculture and Waste combined peak in 2025 at 388 $MtCO_2e$. For Thailand, we use PRIMAP, owing to the greater data availability, which indicates a peak of 382 $MtCO_2e$ in 2018. Using the estimate for the pathway instead of the 2018 data as peak leads to a 0.5% difference between results (residual emissions/peak emissions as a percentage). We therefore opt to retain the peak seen in the historic timeseries within PRIMAP.

Country	LT-LEDS projection reference	Assessment
Tunisia	Figure 31, Page 59 for the 'BaC Scenario'	Figure 31, Page 59 indicates that emissions likely peaked in the historic timeseries presented in the LT-LEDS, which we use instead of PRIMAP data owing to discrepancies between the datasets, impacting upon the results (see Figure S3 & S4). We adjust for the inclusion of 3A within the 'AFAT' sector, viewed as equivalent to 'AFOLU'.
Uruguay	Figure 18, Page 49	Figure 18, Page 49, details the projections of emissions from energy and industry. This indicates a past peak for these two sectors in 2012. For methane and nitrous oxide, Uruguay's LT-LEDS explores scenario which stabilise emissions prior to 2050, first noted on Page 14, later detailed on Pages 62-70. This section indicates an intention to maintain current levels of methane and nitrous oxide. We use PRIMAP for Uruguay, owing to the absence of a complete set of historical emissions, except for Figure 18. PRIMAP similarly indicates a peak in emissions for all sectors excluding land-use in 2012. From this it would appear likely that Uruguay's emissions peak historically.

Annex I data historic validation

For Annex I countries, annual GHG inventories are submitted to the UNFCCC each year, covering the timeseries from 1990 through to two years prior to the reporting year. For example, the national GHG inventory submitted in 2023 would cover years 1990-2021. This may differ from the inventory used within the LT-LEDS, which is likely based on previous versions of the same inventory. National GHG inventories for Annex I countries are recalculated for the full time series each year, meaning emissions in historic years may change, owing to, for example, methodological improvements or the addition and identification of new emission sources. We therefore gather the latest year within the LT-LEDS to ascertain the GHG inventory upon which it is based, using available information contained within the strategy. This is detailed in the table below.

Table A 7. GHG inventory version used within the LT-LEDS for Annex I countries.

Country	Latest inventory year	Latest year reference	Inventory version (and link to CRF [common reporting format])
Australia	2019	Section 1.4 and Figure 1.4, Page 30	1990-2019 (submitted in 2021), Link: https://unfccc.int/documents/273475
Austria	2017	Page 45 suggests 2017 as the most recent year for which greenhouse gas data was available. Page 16 and Page 82 suggest 2017 is the base year of the	1990-2017 (submitted in 2019), Link: https://unfccc.int/documents/194890

Country	Latest inventory year	Latest year reference	Inventory version (and link to CRF [common reporting format])
		'transition scenario', however it is not clear if this also applies to Pathways A-D (described on Pages 17-18). It is thought likely owing to the timing (2019, as detailed on Page 17)	
Canada	2019	Figure found on Page 7 suggests 2020 as the latest inventory year. Table 1 and text below Table 1, Page 13, suggests 2019 as the latest inventory year for 2030 projections. Page 46 suggests this may differ for the modelled scenarios, with 2015 as the base year, though calibrated against more recent data published in 2022 (Environment and Climate Change Canada's E3MC reference case), suggesting data up until and including 2020.	1990-2020 (submitted in 2022), Link: https://unfccc.int/documents/461923
Cyprus	2018	Figure 2.1, Page 9, notes that '"NIR2020" are the GHG historical emissions according to the latest GHG inventory report available (May 2020 submission to the UNFCCC secretariat);', suggesting 2018 as the latest available year.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/227988
Finland	2017	No clear date is provided, projections often use 2010 and 2015 as base years, but scenarios do diverge from 2020 onwards, suggesting latest available data is a prior year. Page 7 suggests 2017, owing to the timing of the studies used to support the scenario modelling. This would appear to be supported by descriptions of historical emissions throughout sectoral chapters, for example, Page 30. Model descriptions for data, found in Appendix 3, similarly coincide with 2017. The 1990-2017 inventory, similarly, is the inventory referenced on Page 13, Appendix 3.	1990-2017 (submitted in 2019), Link: https://unfccc.int/documents/194632
France	2017	Figure on Page 8 and text below figure suggest 2017 is the latest available year.	1990-2017 (submitted in 2019), Link: https://unfccc.int/documents/194492
Hungary	2018	Page 24 notes 2018 as 'the latest available data', though Table 2 suggests Hungary use Eurostat data as the data source, as opposed to their own inventory. Typically, Eurostat refers to data from the European Environment Agency submitted by EU Member States based on their official inventories.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/267417
Iceland	2019	Figure 3, Page 21, and text above Figure 3, suggest 2019 as the latest available year. This is further noted as originating from the '2021 National Inventory Report (NIR)'.	1990-2019 (submitted in 2021), Link: https://unfccc.int/documents/273422
Italy	2018	Page 5 notes and cites the national inventory report for the 1990-2018 inventory, suggesting 2018 is the latest available year.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/223564
Portugal	2017	Page 10, Figure 1, suggests 2017 as the latest available year.	1990-2017 (submitted in 2019), Link: https://unfccc.int/documents/194483

Country	Latest inventory year	Latest year reference	Inventory version (and link to CRF [common reporting format])
Slovenia	2018	Table 1 and Figure 7, Pages 15 and 16 respectively, suggest 2018 as the latest available year.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/223665
Spain	2018	References to 2018 as the current situation, throughout Spain's LT-LEDS Annexes suggest 2018 is the latest inventory year.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/216423
Sweden	2018	Section 3.2, beginning on Page 17, suggest 2018 as the latest available year.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/224121
Switzerland	2018	Section 3.2, beginning on Page 11, suggest 2018 as the latest available year.	1990-2018 (submitted in 2020), Link: https://unfccc.int/documents/224854
United Kingdom	2019	Table 4, Page 318, alongside references to 1990-2019 inventory throughout, suggest 2019 as the latest available year.	1990-2019 (submitted in 2021), Link: https://unfccc.int/documents/273497
United States	2019	Figure ES-1, Page 4, notes that 'the historical trajectory of U.S. net GHG emissions from 1990 to 2019', suggesting 2019 as the latest available year.	1990-2019 (submitted in 2021), Link: https://unfccc.int/documents/272414

We extract the timeseries for the inventory version referenced in the LT-LEDS from the country's CRF reporting, or the '*date aligned inventory*', linked in the table above. We then extract the '*Total CO_2 equivalent emissions without land use, land-use change and forestry*' across the available years found in Table 10s1 of the CRF. We then identify peak emissions in the date aligned inventory and calculate residual emissions as the percentage of peak emissions in both the date aligned inventory and the latest inventory used within Chapter 4, submitted in 2023. We find the impact of inventory version upon Annex I results to be minimal, and at most a difference of 1.1%. We therefore use the 1990-2021 GHG inventories within our analysis, as seen in Figure 16 and Figure 17 of Chapter 4.

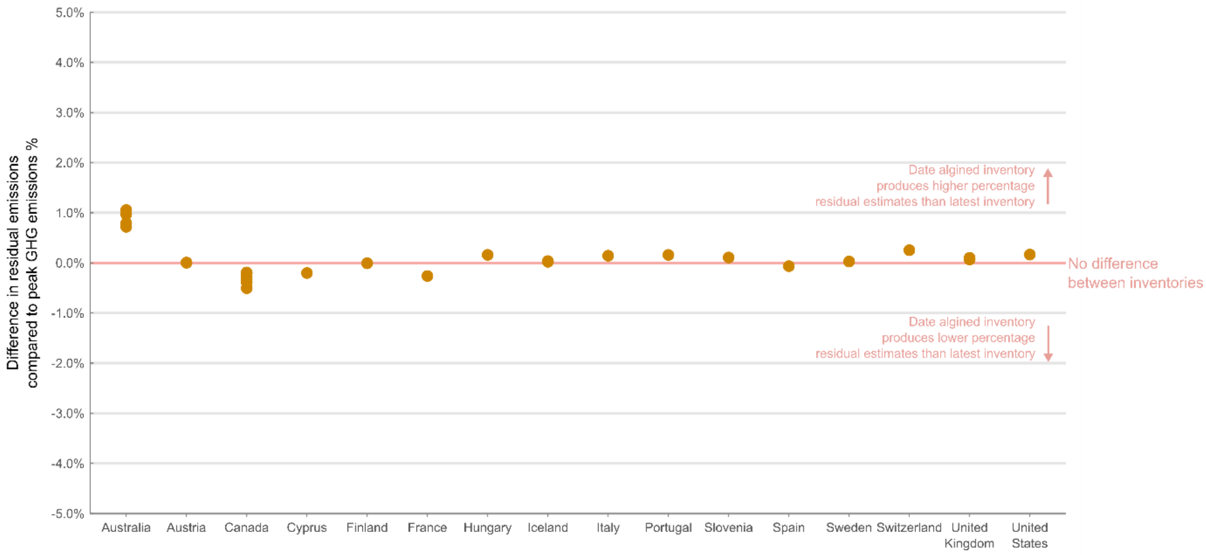


Figure A 5. Difference in residual emissions as the percentage of peak emissions for Annex I countries.

An increase represents cases where the date aligned inventory produces a higher estimate than the latest inventory. A decrease represents the opposite case.

Supplemental Figures

Per capita residual emissions

In addition to the main analysis, we produced a comparison of per capita residual emissions, combining residual emissions from our sample of LT-LEDS with 2022 UN population projections for the medium fertility variant (United Nations, 2022). We combine estimates of residual emissions with population data according to the date of net zero, meaning that, for example, population projections for Thailand refer to the date of Thailand's net zero target in 2065, not 2050. 18 of the 26 countries for which estimates of residual emissions are available are below 2 tCO_2e/person. Those countries with high per capita residual emissions tend to also be those countries with high absolute residual emissions, such as Australia and Canada.

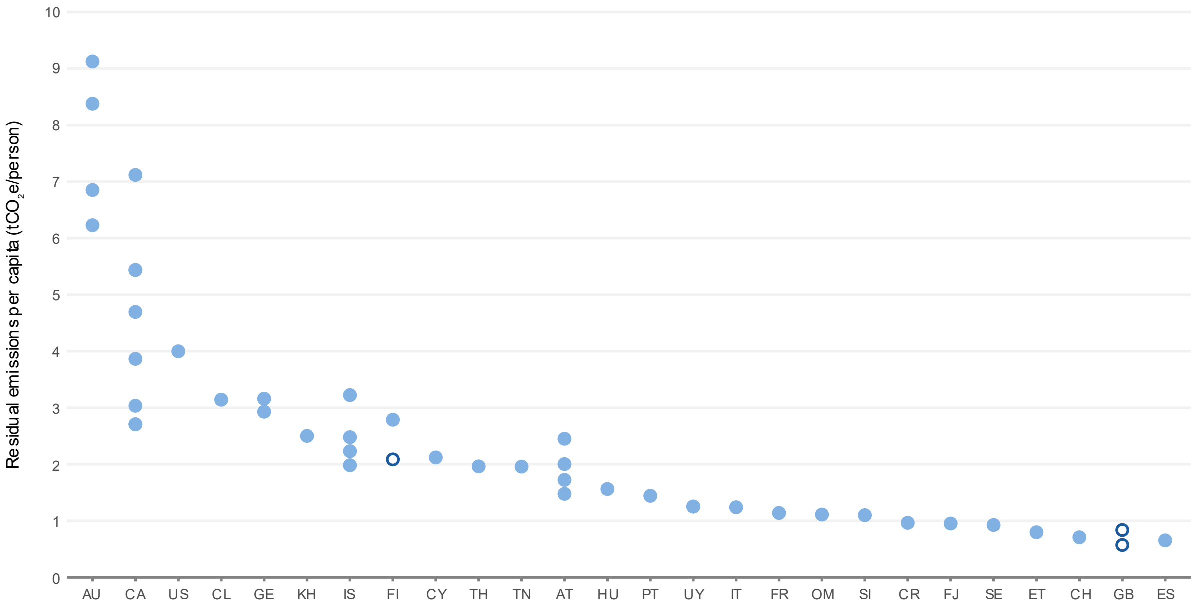


Figure A 6. Difference in residual emissions as the percentage of peak emissions for Annex I countries

Residual emissions are displayed in light blue. Partial residual emissions are shown using a white point with blue outline. Countries are shown according to their alpha-2 country code, defined in ISO 3166. See Figure 16 of Chapter 4 for reference between country codes and official names.

Annex III – Chapter 5

This section further details our interview transcript used in Chapter 5, and referred to in Section 5.3.

Prior to interview:

Participants will be invited to identify, ahead of the interview or prior to questioning, the GGR methods they have expertise or familiarity with. This will be through a version of the methods figure (IPCC AR6 WGIII, Chapter 12, Cross-Chapter Box 8, Figure 1). Miro, or a similar system, will be used to visually portray the UK GGR 'policy system' and how 'policy elements' interrelate. This will be used as a visual aid throughout the main interview. The interviewer will maintain a note of all the areas discussed.

Questions below are intended to be open, non-leading but cognisant of the existing structure of UK CDR policy. The question list is separated into questions asked of all participants and two 'tracks' separated by method class.

Questions asked of all participants:

These questions will be asked of all participants:

1. 'What is the role of CDR in reaching the UK's Net Zero target?'
2. 'What is working well within the UK's CDR policy system?'
3. 'What are the main barriers or risks to the UK's CDR policy system?'

Based on response to methods proceed based on track:

Nature-based removals track	Engineered removals track
1. In current UK plans, the UK government intends to rely less on nature-based methods than engineered methods, what are some of the benefits and risks to this approach?	1. In current UK plans, the UK government intends to rely more heavily on engineered methods than nature-based, what are some of the benefits and risks to this approach?
2. How might policies and plans in other connected areas affect UK efforts to incentivise nature-based methods? For example, biodiversity policy or demand for biomass?	2. How might policies and plans in other connected areas affect UK efforts to scale engineered methods? For example, carbon capture and storage projects, CO_2 pipeline networks, or other aspects of industrial decarbonisation?
3. How should nature-based methods be incentivised in the long-term?	3. How should engineered methods be incentivised in the long-term?

4. What changes would you recommend be introduced to help reduce the risks or attain the benefits you've identified?	4. What changes would you recommend be introduced to help reduce the risks or attain the benefits you've identified?