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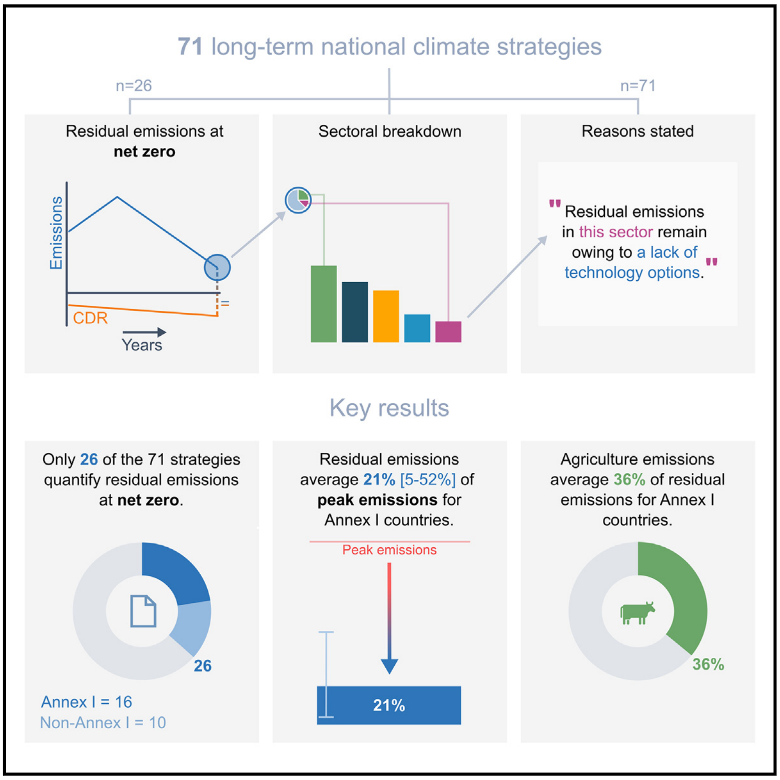
Residual emissions in long-term national climate strategies show limited climate ambition

Graphical abstract



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In brief

Net-zero targets are now the guiding principle of climate policy. The net element of these targets implies the need to remove carbon dioxide from the atmosphere to compensate for residual hard-to-abate emissions, which have specific barriers to their abatement. An analysis of 71 long-term national climate strategies found that the majority (41) fail to quantify these emissions. When they do, these emissions are on average one-fifth of developed countries' peak emissions and consist mainly of agricultural emissions.

Highlights

- Residual emissions average 21% of peak emissions for Annex I countries
- By sector, agriculture represents the largest contributor to residual emissions
- High-residual scenarios show how some countries may retain more fossil fuels

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Article

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

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SCIENCE FOR SOCIETY Net-zero targets are now the guiding principle of climate policy. The "net" of these targets implies the need to remove carbon dioxide from the atmosphere to compensate for a level of continuing emissions. These emissions are commonly called "residual emissions" and are expected to represent "hard-to-abate" sources, which have barriers to reducing their emissions. We explore 71 long-term national climate strategies to understand the level and distribution of residual emissions. We find that 41 do not include an estimate or include only short-term emissions modeling, meaning they do not estimate residual emissions. For strategies that do, these emissions are on average one-fifth of developed countries' peak emissions and mainly consist of emissions from agriculture. High-residual-emission scenarios show how some countries may retain or expand their fossil fuel production and use, using more carbon dioxide removal to achieve net zero.

SUMMARY

Net-zero targets imply a need to compensate for residual emissions through the deployment of carbon dioxide removal methods. Yet the extent of residual emissions within national climate plans, alongside their distribution, is largely unexplored. Here, we analyze 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% to 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 countries). 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.

INTRODUCTION

Net-zero targets have rapidly become the new norm of national climate policy. As of December 2023, 150 countries have adopted a form of net-zero or neutrality target, accounting for 82% of global greenhouse gas (GHG) emissions.[1,2] As targets are adopted, national governments have begun to develop policy plans, scenarios, and pathways, aimed toward the fulfillment of net zero.[3,4] Operationalizing net zero as a national target has led to increased attention toward 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 carbon dioxide removal (CDR).[3,5,6] CDR, a range of methods that remove carbon dioxide (CO_2) from the atmosphere, permanently storing carbon in terrestrial or geological sinks,[7] is therefore seen as a necessary and implicit element of reaching a national net zero target, legitimized by its connectedness to residual emissions.[8] Despite being central to the logic of net zero, to date there has been limited focus toward analyzing both the extent and distribution of residual emissions within national climate plans.

At the international level, nationally determined contributions (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 NDCs' 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.[9–11] In addition to NDCs, the Paris Agreement also supports the communication of long-term low-emission development strategies (LT-LEDS). These strategies are supported by scenario or pathway modeling to the mid-century or beyond, covering net-zero targets where set.[3] Given this longer-term focus on climate action, these strategies directly assess the extent and distribution of residual emissions, contextualizing 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,[5,6] meaning they are those emissions counterbalanced by negative emissions. Residual emissions, however, are commonly associated with emissions considered "hard to abate" or "difficult to decarbonize," implying a limit in efforts to reduce emissions.[5,6] Residual and hard-to-abate emissions are analytically distinct but commonly conflated concepts. 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. 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 modeling of future scenarios and policy projections.[12,13] 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 fertilizer application.[7,14–17] These sources are said to be hard to abate owing to the limits to available technologies for further reducing emissions or further emission reductions being prohibitively expensive.[18,19] This logic arises from integrated assessment models (IAMs), where residual emissions are said to be those emissions whose abatement remains infeasible or uneconomical under model and scenario designs.[20,21] 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.[22,23]

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.[14,16,24] 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.[25] Production also requires high-temperature heat, energy requirements that to date have been met through the combustion of fossil fuels.[26,27] While decarbonization can be aided through demand-side measures, such as material efficiency,[28,29] the production process itself must be directly abated, requiring fundamental changes and new means to meet heat requirements. Steel production can be decarbonized by remaking the steel-making process, reducing iron ore using green hydrogen as opposed to coke,[30] and by promoting circularity by greater rates of scrap recycling within electric arc furnaces powered by low-carbon electricity.[25,31] Similarly, conventional blast furnaces, currently used to produce most primary steel, can be retrofitted with carbon capture and storage (CCS), continuing to use fossil fuels or alternatively combusting biomass.[32] The use of green hydrogen and the retrofitting of plants with CCS is currently limited to pilot projects and company plans, and decarbonization of the sector depends on their commercialization alongside the retirement or replacement of conventional blast furnaces.[33–35]

Cement emissions may be reduced by replacing a proportion of the clinker with alternative materials,[36] the electrification of cement kilns, or the combustion of biomass for heat.[28,37] Owing to the ability to address both process and combustion emissions, retrofitting cement plants with CCS remains a prominent option.[25,37] In cases where emissions are captured and the use of conventional fossil fuels remains, residual emissions are likely due to limits to the capture rate, meaning 10%–20% of emissions may remain unabated.[24,38] The production of two chemicals, ammonia and methanol, accounts for 70% of emissions from the chemical sector.[39] Both require hydrogen, currently produced through steam methane reforming, a conversion of water and natural gas to hydrogen and carbon monoxide.[40] Gas feedstocks could be eliminated by using green hydrogen produced by electrolysis.[40]

Long-range transport, such as aviation and shipping, in existing modes of operation, requires energy-dense fuels, limiting the common strategy of the electrification of transport or the use of hydrogen.[14,41] Aviation emissions may be reduced by improvements in energy efficiency, while synthetic kerosene, synthesized from green hydrogen and captured CO_2, offers the best prospect of reducing or eliminating emissions from the sector.[41,42] Synthetic ammonia may offer a route to decarbonize global shipping, similarly reliant on the availability of green hydrogen.[43] Non-CO_2 emissions from agriculture originate from several biological sources, such as the nitrous oxide generated in soils from the application of nitrogen fertilizer or methane emissions from the fermentative digestion of livestock.[44] Connecting these sectors is the commonality that emissions can be reduced but not eliminated. Mitigation options to eliminate the remaining emissions, or enable deeper decarbonization, 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.[45–47]

Emission sources may also be hard to abate, owing to the arrangements, market dynamics, and expectations of certain sectors. Unlike the decarbonization of the power and road transport sectors, which benefit from the mass production and standardization of solar panels, wind turbines, and electric vehicles,[48] industry emissions are characterized by high design complexity, with technology configured for a wide array of emissive processes and end users.[49] 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.[32,41,50] Both aviation and industrial sectors are subject to growth in demand, with growth in passenger numbers and

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freight,[41,51] and increasing demand globally for industrial materials and chemicals.[16,52,53] 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.[32,54,55] Where carbon pricing has been introduced, for example, in the European Union (EU) Emission Trading System, free allowances have been granted to firms, limiting their need for abatement.[55] Decarbonizing these sectors therefore requires a shift in their governance through carbon border adjustment mechanisms or climate clubs, minimizing any losses to competitiveness.[56] Emission 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.[57,58] Similar strategic logic may deem emissions from the health sector or military as limited in terms of decarbonization.[5]

Residual hard-to-abate emissions, therefore, not only reflect the cost or the availability of abatement but also the technical and physical dynamics of emission sources, their complexity, lifetime, and demand, and policy priorities beyond climate mitigation.[14,16] These wider dynamics are analogous to carbon lock-in, whereby a combination of technology and norms collectively limit the extent of decarbonization.[59,60] Within the logic of net zero, residual emissions serve as the basis for the integration of CDR,[8,61] informing the near term regarding CDR's role and scale in climate policy.[62,63] 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.[64] Large requirements for CDR would place greater pressure on national resources, such as energy, land, and water,[65,66] and pose greater challenges in attaining public support.[67] It would risk later, more stringent mitigation to reach a certain temperature target if the required CDR failed to materialize.[68,69] Determining the appropriate scale of CDR, therefore, must account for the anticipated scale of residual emissions, pairing these within climate policy frameworks.

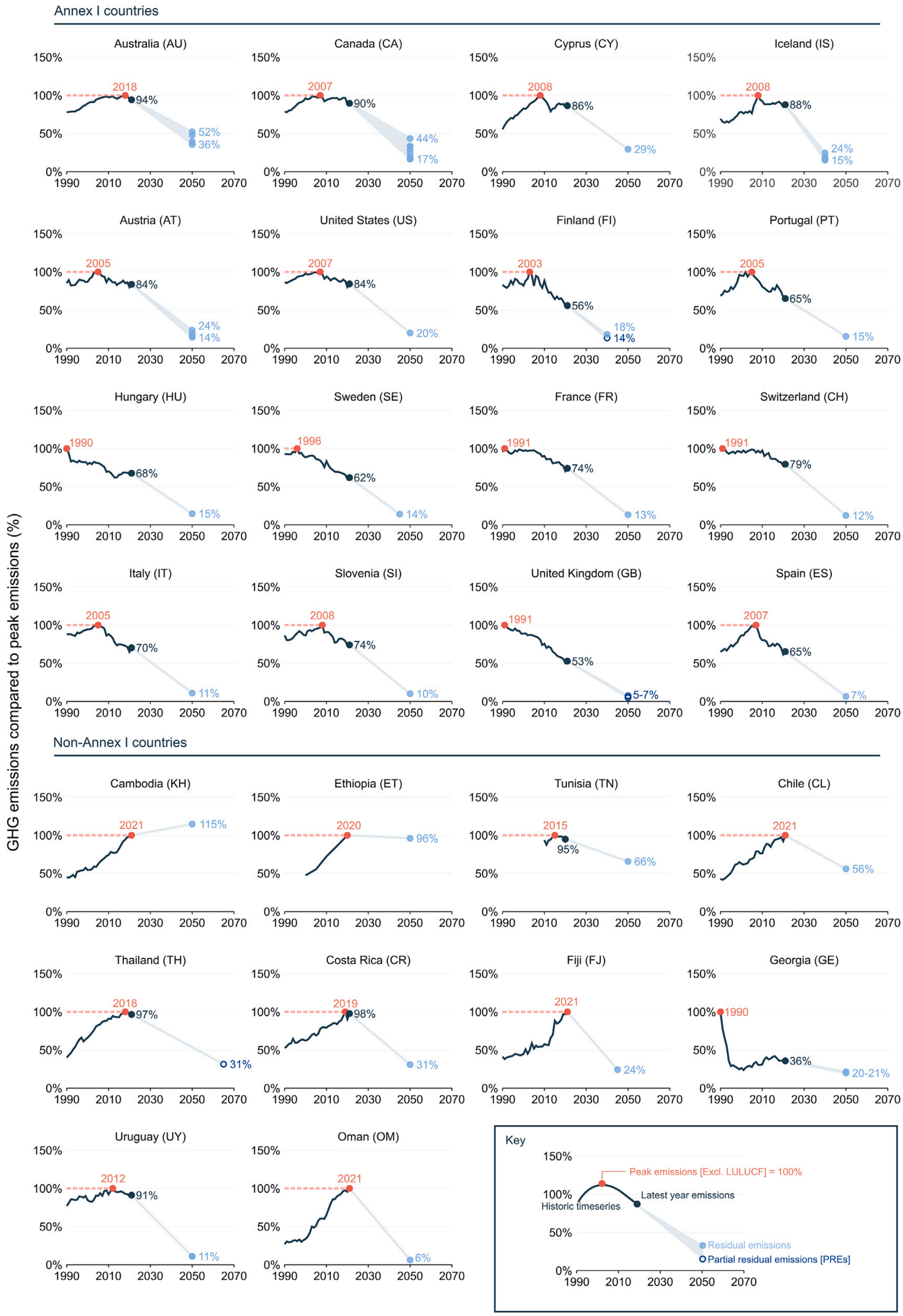
LT-LEDS are national reports that address principally climate mitigation but often integrate a focus on macroeconomic development and climate adaptation, forming a holistic strategy.[70,71] Under Article 4.19 of the Paris Agreement, parties must strive to formulate and communicate LT-LEDS. These are intended to inform the ambition of NDCs, with the NDCs acting as intermediate targets along the long-term pathway set out in LT-LEDS.[72] 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 among other reporting obligations under the United Nations Framework Convention on Climate Change (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 stock take 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 toward CDR and residual emissions.[3,4,6,73,74] Analyses directed toward CDR have focused on the conceptual role of CDR within national climate policy,[4] the criteria used to discern their feasibility,[73] and the prominence of nature-based CDR methods within strategies.[3] A previous analysis of residual emissions analyzed only low-residual emission scenarios within LT-LEDS, using an inconsistent mapping of sectors across countries.[6] Given the long-held concern that CDR may reduce emission reduction efforts,[75] so called "mitigation deterrence," this criterion may limit our understanding toward the national expectations of CDR deployment, given that mitigation deterrence may be more evident in high-residual emission scenarios. Nor are these residual emissions compared to peak emissions, a measure commonly used to compare decarbonization efforts across countries.[76,77] Similarly, there is a need to understand what residual emissions relate to in terms of both the sub-sectors and sources contained within sectors, in addition to what may motivate a certain emission to be considered residual.[78] 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 sizable proportion of peak emissions, with an average 21% of peak emissions for Annex I countries, ranging from 5% to 52% (excluding land use). High-residual-emission scenarios show how some countries may retain or expand their fossil fuel production and use, utilizing more CDR 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 countries. 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.

RESULTS

Methods summary

We analyzed all 67 national LT-LEDS submitted to the UNFCCC before the start of October 2023. The EU mandates the creation of 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 an 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,[79] which within our sample



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cover 23 of the 27 EU member states. 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 GHGs, excluding net emissions or removals from the land-use, land-use change, and forestry (LULUCF) sector, and removals from novel CDR methods. Novel CDR refers to those methods that are currently deployed at small scales compared to the scale of removals in the LULUCF sector.[80] For the purposes of this analysis, novel CDR refers to bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). We then compare total residual emissions to peak emissions within the historical time series for each country as a measure of the climate ambition implied by scenario or pathway modeling.

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 on the logic of the 2006 Intergovernmental Panel on Climate Change (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, comparing sectoral to total residual emissions, and determine the level of mitigation implied, comparing sectoral residual emissions to 2021 GHG emissions. To further contextualize 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[81] and 71% of GHG emissions.[1] The vast majority, 49 of the 71 strategies, were recently published between 2021 and 2023. Geographically, the majority of the strategies analyzed are from Europe and Asia (45), with only eight from African states and four from South America. A full list of the strategies analyzed, including the title, status, and translation, can be found in the dataset accompanying this article, available in the data and code availability section. See experimental procedures for further detail regarding our methodology.

Total residual emissions

Forty-one strategies, the majority of our sample, fail to quantify residual emissions, either through a lack of modeling of scenarios or pathways or limitations to the modeling itself. This includes major emitters such as China, India, and Russia. China and India present no scenario or pathway modeling 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 while 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 strategies as providing a quantification of residual emissions.

Twenty-six LT-LEDS produce an estimate of residual emissions, with 16 estimates from Annex I countries and 10 from non-Annex I countries (Figure 1). For 13 Annex I countries, scenarios reach net-zero GHGs in 2050, while Finland and Iceland include scenarios for 2040. Eight non-Annex I countries reach net-zero GHGs in 2050, while 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 2A). Residual emissions are, on average, 25% of 2021 GHG emissions for Annex I countries, with a range of 10% (United Kingdom [UK] and Spain) to 55% (Australia).

Mean residual emissions for non-Annex I countries are 34% relative to peak emissions (Figure 2A), excluding Cambodia, which increases its emissions above its 2021 level but reaches net-zero GHGs by transforming its LULUCF (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% to 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 novel 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 decarbonization is also captured; for example, the UK has levels of both current and residual emissions similar to those of France but has decarbonized further

Figure 1. 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 modeled 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. For access to the underlying data, see data and code availability.

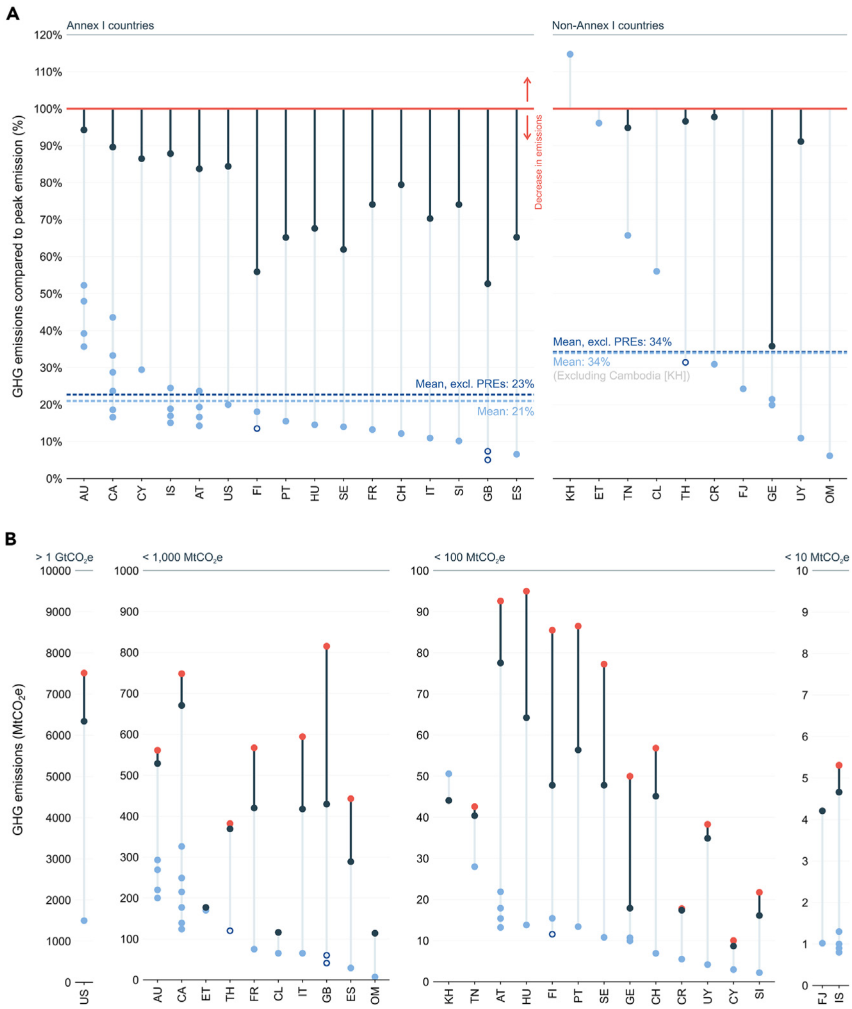

Figure 2. Residual emissions compared to current and peak emissions

(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 1 for reference between country codes and official names. For access to the underlying data, see data and code availability.

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 2B).

Sectoral residual emissions

Figure 3 details residual emissions by sector. 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 countries. For countries such as Fiji, Ethiopia, Switzerland, Spain, France, Slovenia, and Sweden, agricultural emissions represent the majority of residual emissions, upward of or equal to 50% (Figure 3). The energy sector contributes, on average, 26% of residual emissions for Annex I countries and 16% for non-Annex I countries. 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% and 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 3 an estimation of the proportion of residual emissions where both sectors are combined, inclusive of those countries that specify only this combined total. The energy and transport combined total is, on average, 37% of residual emissions for Annex I countries and 45% for non-Annex I countries. Residual emissions in transport are, on average, only 10% of total residual emissions for Annex I countries and 11% for non-Annex I countries. This excludes international aviation and shipping. Industry contributes, on average, 19% for Annex I countries and 18% for non-Annex I countries. This average includes cases of industrial combustion and process emissions combined, highlighted in Figure 3, 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 countries.

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 4). Similarly, only a modest reduction is seen for agriculture in non-Annex I countries, with a reduction on average of 51%. The energy

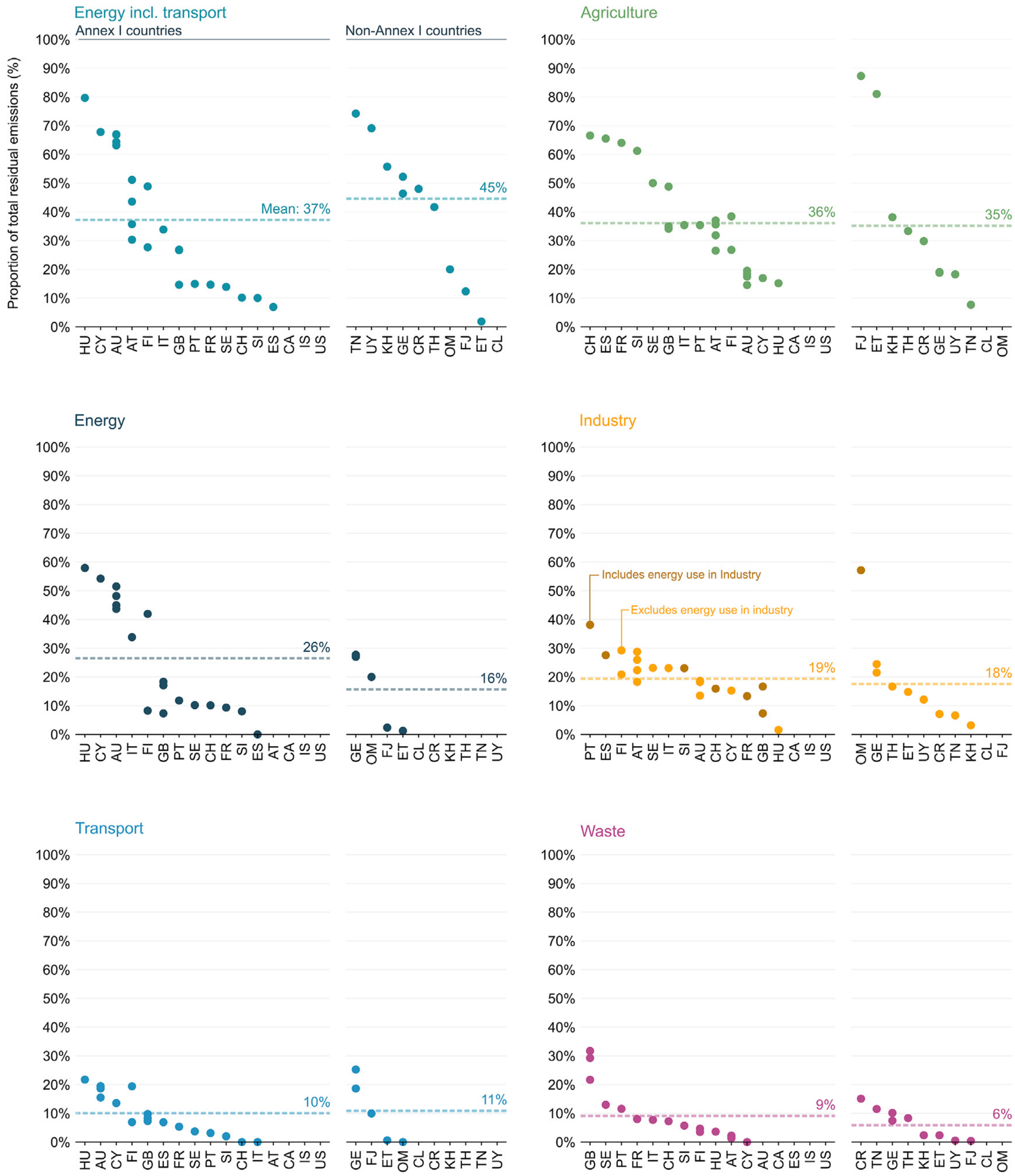

Figure 3. Proportion of residual emissions by sector

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 unlabeled residual emissions and, when included, "international aviation and shipping." Data for these sectors can be found in the dataset accompanying this article, accessible through the data and code availability section. Countries are shown according to their alpha-2 country code, defined in ISO 3166. See Figure 1 for reference between country codes and official names.

sector, by the time of net-zero GHGs, has largely been decarbonized relative to 2021 emissions, with an 84% reduction on average for Annex I countries. Transport has been decarbonized to a similar extent, with an 83% reduction on average for Annex I countries. Non-Annex I countries, as with Figure 3, 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), owing to limitations in data granularity, does not present transport as a separate total for the historic time series. 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 4 is the combined total for Cambodia.

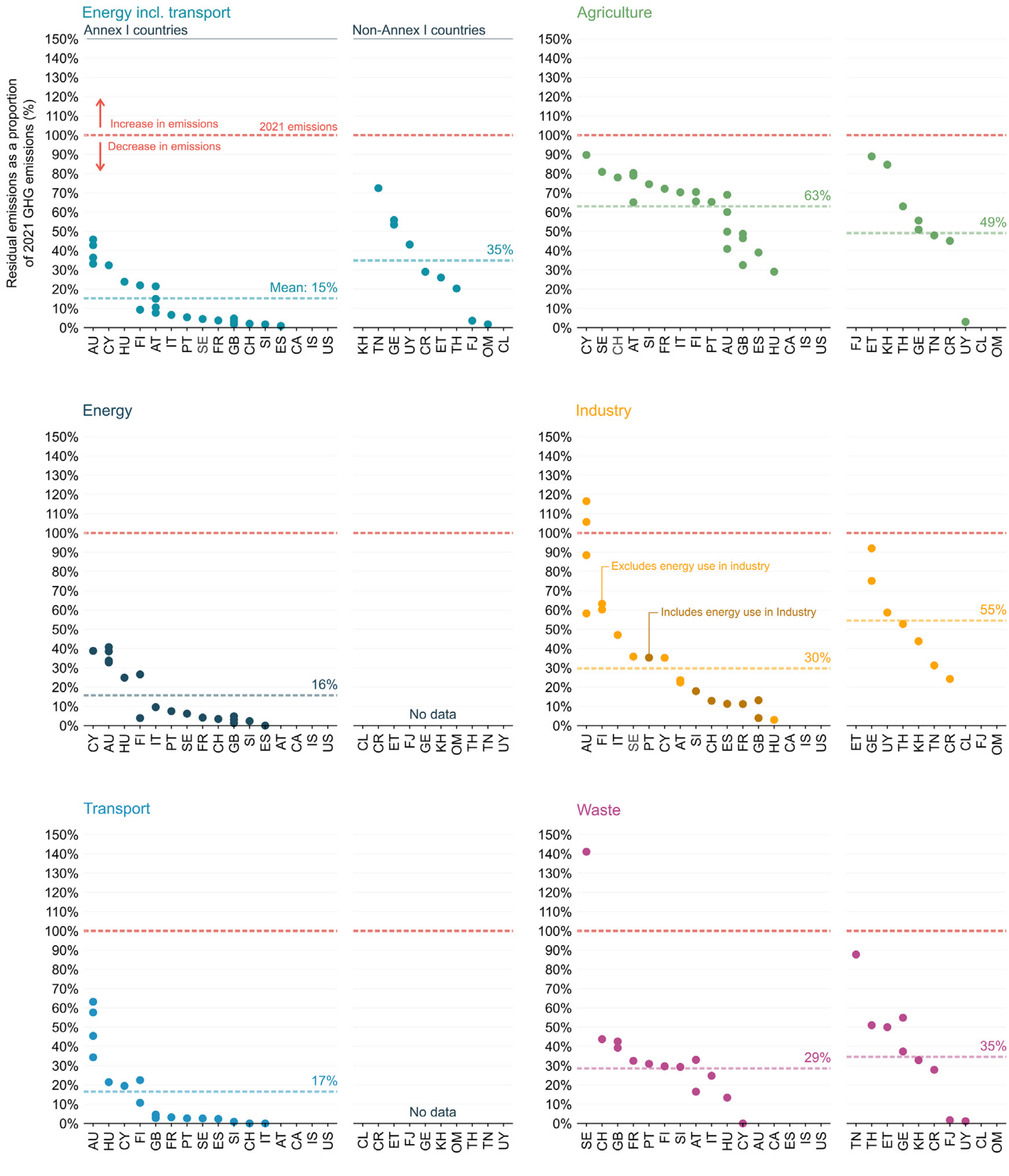

Figure 4. Residual emissions by sector as a percentage of current emissions

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 article, accessible through the data and code availability section. Not shown are "other" or unlabeled residual emissions and, when included, "international aviation and shipping." Data for these sectors can be found in the dataset accompanying this article, accessible through the data and code availability section. Countries are shown according to their alpha-2 country code, defined in ISO 3166. See Figure 1 for reference between country codes and official names.

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.

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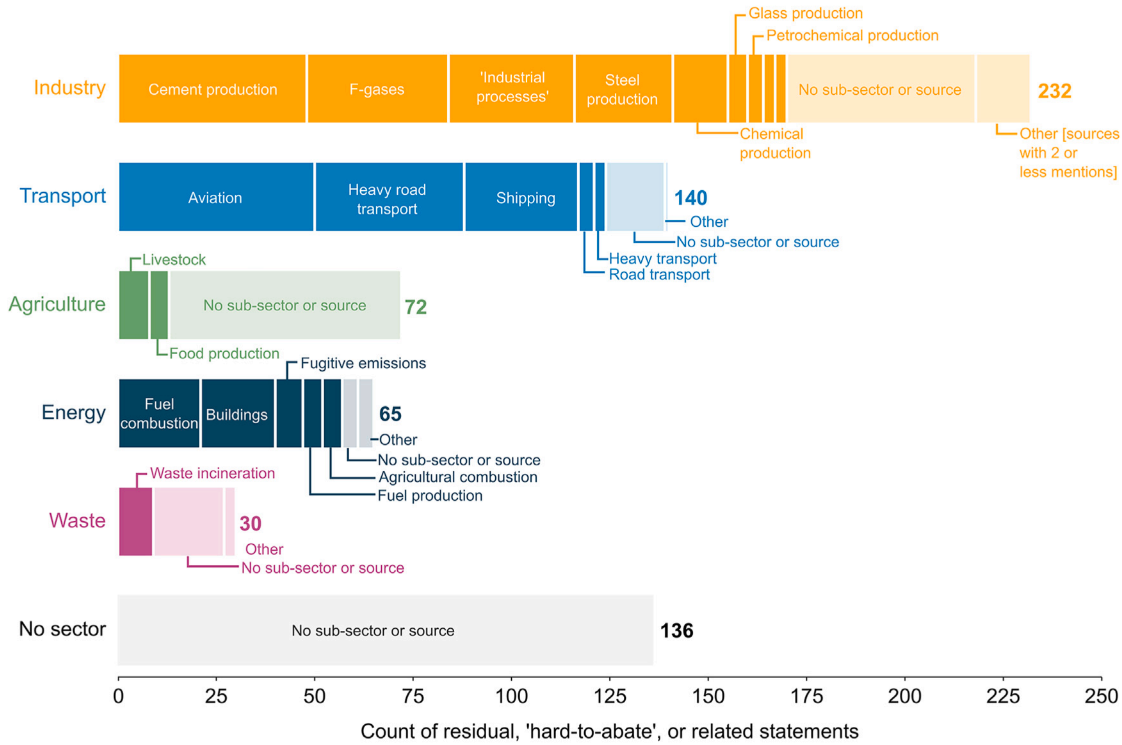

Figure 5. Count of residual, "hard-to-abate," or related statements by sub-sector or source

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.

Residual emission 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.[82]

Figure 5 details these statements by sub-sector and source. Unlike the trend observed in Figure 3, where agriculture is the primary sector concerning residual emissions, industry is the focus of Figure 5, with a total of 232 statements. Nearly half (109) of these statements are associated with three main sub-sectors, cement production (48), F-gases (36), and steel production (25). Transport (140 statements) primarily concerns emissions from aviation (50) and 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 decarbonized in residual emission scenarios compared to current emissions (Figure 4), 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.

Table 1 details seven "residual emission rationales," analytical categories based on the coding of statements concerning residual or hard-to-abate emissions. Figure 6 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 decarbonization ("limited innovation," 50 statements). For example, both Spain and Italy stress the need for further innovations in decarbonizing steel production through hydrogen. Industry sources are similarly supported by the rationale that mitigation options have been exhausted, yet some level of emissions remains ("limited further abatement," 49 statements). For example, Ireland claims that "there is no known way to deliver complete decarbonization in some industry sub-sectors, such as cement," meaning the sub-sector (italics added for emphasis) "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 decarbonization (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 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 (italics added for

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Table 1. Residual emission rationales

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 remains after either 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 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 decarbonize to a lesser extent*." (United Kingdom, p. 73, UK Net Zero Strategy)

The "example" column details national examples from our coding, with italics added to emphasize key phrasing. Examples have been lifted from each country's respective LT-LEDS. Full details of each LT-LEDS, alongside details as to how these can be accessed, can be found in the dataset accompanying this article, available in the data and code availability section. The full coding of residual emission rationales, including the examples detailed here, can also be found in the accompanying dataset.

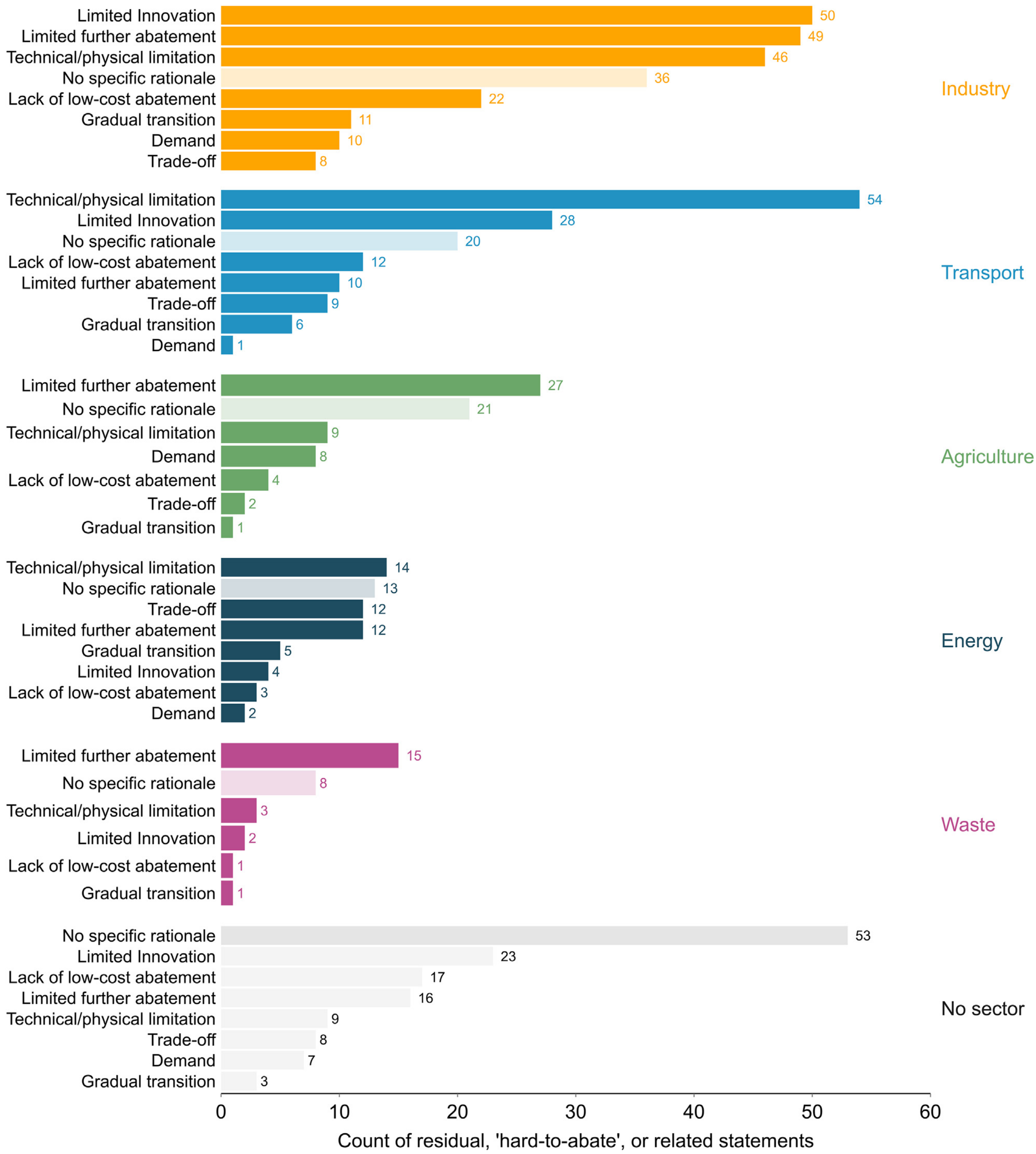

Figure 6. Figure 6. Count of residual, “hard-to-abate,” or related statements by sector and rationale
Waste incineration is assigned to waste; however, if waste is combusted to generate electricity or heat, this would be treated as energy under the IPCC NGHGI guidelines. A single statement can include one or more rationales.

emphasis) “the agriculture sector, cannot be abated in the 2050 time frame *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 instance, 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 (italics added for emphasis) "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.

DISCUSSION

Net zero is now well established as the goal of global climate policy, strongly supported by climate science.[83] Net zero as a national target, however, raises new and difficult questions for national governments [13,84]—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 in land management, to the development and deployment of novel 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.[85,86]

Our analysis underlines that residual emissions within national scenarios represent a sizable proportion of peak and current emissions. Our results are comparable to those of Buck et al.,[6] 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% to 55%.

In the case of Canada, differences in scenarios reflect divergent approaches to decarbonization, 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 (italics added for emphasis) "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.[75,88]

Climate policy frameworks should guard against reduced ambition by introducing separate targets, separating out the LULUCF sector, removals from novel CDR methods, and emission reductions elsewhere in an economy, thus reducing substitution.[89–91] Figure 7 depicts a comparison between a low-residual emission scenario, based on separate targets, versus a high-residual-emission scenario that allows for greater substitution of emission reductions with CDR from both LULUCF and novel methods. Figure 7A 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 5B) similarly maintains net LULUCF at historic levels but greatly expands novel CDR to 113 times the current global capacity of 2 $MtCO_2$/year [92] 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.[90]

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 GHGs 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.[93] For novel 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.[7] Operationalizing this role requires an understanding of which emission sources are hard to transition.

Sectoral analysis suggests that residual emissions from agriculture are under-represented as a focus relative to agriculture's

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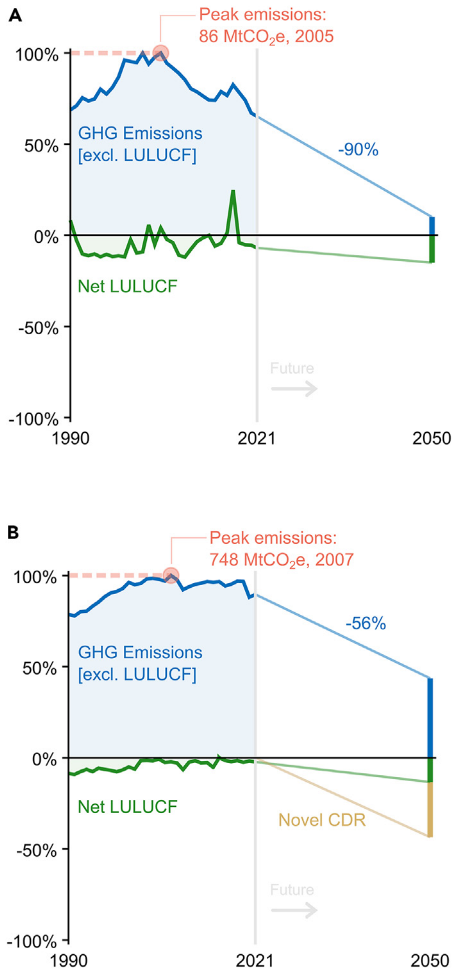

Figure 7. Comparison of a low-residual scenario and a high-residual scenario

(A) Portugal's pathway to net-zero greenhouse gases, based on Portugal's Framework Climate Law no. 98/2021, informed by the modeling 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 modeled 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. Novel CDR, in the case of Canada, refers to bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

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 fulfill the 2050 goal [net zero]." Expectations toward 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.[27,48,94] 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.[34]

While 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 inevitable risks de-emphasizing these emissions, further locking in high-emitting activities and infrastructure and locking out alternative means of mitigation.[6,95] Further decarbonization 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.[42,96,97] 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 (italics added for emphasis) "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 recontextualizes residual emissions as constructed on claims of which activities are socially necessary and which actions are possible or compatible with national priorities.[98] Further unpacking these assumptions can lead to a change in national approach whereby demand-side transformations are more readily explored in strategies and policies.[96]

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.[87,99] LT-LEDS have been proposed as a means of adding credibility to this transformation.[85,100] Our analysis, however, suggests that this opportunity is largely missed, with most countries within our sample either failing to include scenario modeling 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,[101,102] and their lack in practice, LT-LEDS need further guidance or requirements under the UNFCCC. Past studies have called for standardizing an understanding of residual emissions within LT-LEDS,[6] 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.[3]

Conclusion

National governments now face the challenge of moving from target to practice.[13] Our analysis of 71 long-term national climate strategies suggests that residual emissions, though central to the logic of net zero, remain largely unexplored. In the limited number of cases where residual emissions are quantified, our analysis suggests that residual emissions may constitute a sizable proportion of peak and current emissions and in select cases represent limited sectoral decarbonization and the retention or expansion of fossil fuels. We observe a mismatch between the sectoral contribution of agricultural emissions to residual emissions in scenario modeling and pathways and the focus of strategies toward 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 inevitable. Strengthening guidance and reporting requirements for LT-LEDS will further improve engagement with residual emissions, offering greater transparency toward national net-zero targets. We offer three ways forward. First, separate targets for emission reductions and removals can ward against high residual fossil fuel scenarios by reducing the substitution of emission reductions with CDR. Second, residual emissions should be treated as a focus of innovation efforts, iterating according to progress in research, development, and deployment. Third, residual emissions should be recontextualized 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.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

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Materials availability

This study did not generate new unique materials.

Data and code availability

All data extracted from long-term national climate strategies is available at Zenodo: https://doi.org/10.5281/zenodo.10972619. This dataset contains a full list of LT-LEDS analyzed, 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 study also analyzes existing publicly available data. The PRIMAP dataset is publicly available at Zenodo: https://doi.org/10.5281/zenodo.4479171 (https://zenodo.org/records/10006301). UNFCCC GHG data for Annex I countries are available from https://di.unfccc.int/time_series.

We examined all instances of scenario or pathway modeling 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 GHGs,[2] we focus on net-zero GHGs in our definition of residual emissions. This also captures non-CO_2 residual emissions from agriculture.[21] 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 novel methods of CDR, such as BECCS, with positive emissions in sectoral totals.

Emissions from international aviation and shipping (IAS) are treated as "memo items" within the 2006 IPCC NGHGI guidelines, meaning they are excluded from the estimates of national emissions reported to the UNFCCC[103] and commonly excluded from the scope of national net-zero targets.[2] Owing to their cross-border nature, emissions are managed by international bodies, although countries such as the UK have since included IAS within their net-zero target.[104] Given that current practice is to exclude these emissions, we similarly exclude these emissions from our assessment when otherwise included. Similarly, although 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,[103] doing so obscures the extent of, and reliance upon, CDR methods.[105] We therefore remove from estimates of residual emissions the inclusion of negative emissions from novel 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.[3,6] Current convention in national reporting is to report the sectoral total without distinguishing between emissions and removals.[103,106] 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.[5] Our analysis, therefore, uses gross emissions entering the atmosphere at the point of net-zero GHGs excluding LULUCF, novel CDR, and IAS, as a measure of residual emissions. While 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 S1 visually depicts this definition and contrasts this definition to alternative variations.

Further complicating LULUCF is the definition of "managed land" used within national GHG inventories. Net zero should be attained through a balance of anthropogenic emissions and removals,[107] 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.[108,109] 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.[108,110] 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.[108–110] Given that many instances of scenario or pathway modeling 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 modeling and UNFCCC reporting beyond the scope of LT-LEDS.[108] 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 on the logic of the IPCC NGHGI guidelines, detailing emissions from energy, industry, transport, agriculture, and waste[103] (see Figure S2). We compare total residual emissions to peak emissions within the historical time series as a measure of the climate ambition implied by scenario or pathway modeling. "Peak emissions" describes the year emissions peaked in countries' historical national GHG inventory time series, excluding LULUCF. Peak emissions have commonly been used to assess the relative performance of decarbonization efforts between countries.[76,77] 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 sectoral 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, which combines periodic country reported data with third-party data.[111] We use the "HistCR" scenario, which prioritizes data reported by countries over third-party data. For PRIMAP, we use GHG emissions expressed in GWP100 AR5. To ensure that use of these 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 supplemental experimental procedures, with the underlying data accessible through the dataset accompanying this article in the data and code availability section.

To further contextualize 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 on 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.[112] We subsequently organized these categories and statements into insights as to how residual emissions are conceptually treated within LT-LEDS. All coding was completed in NVivo, a computer-assisted software tool 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 1. 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 article, available in the data and code availability section, and further detail the procedure in supplemental experimental procedures.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.04.009.

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AUTHOR CONTRIBUTIONS

H.B.S.: conceptualization, methodology, formal analysis, writing – original draft, visualization. N.E.V.: conceptualization, writing – review & editing, supervision. J.F.: conceptualization, writing – review & editing, supervision.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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