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Why residual emissions matter right now

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Net-zero targets imply that continuing residual emissions will be balanced by carbon dioxide removal. However, residual emissions are typically not well defined, conceptually or quantitatively. We analysed governments' long-term strategies submitted to the UNFCCC to explore projections of residual emissions, including amounts and sectors. We found substantial levels of residual emissions at net-zero greenhouse gas emissions, on average 18% of current emissions for Annex I countries. The majority of strategies were imprecise about which sectors residual emissions would originate from, and few offered specific projections of how residual emissions could be balanced by carbon removal. Our findings indicate the need for a consistent definition of residual emissions, as well as processes that standardize and compare expectations about residual emissions across countries. This is necessary for two reasons: to avoid projections of excessive residuals and correspondent unsustainable or unfeasible carbon-removal levels and to send clearer signals about the temporality of fossil fuel use.

Nearly three-quarters of the world's global greenhouse gas emissions are covered by a net-zero law, policy or political pledge as of early 2022[1]. In its simplest form, net zero involves balancing some amount of remaining emissions with an equal amount of negative emissions through carbon dioxide removal. This idea of achieving a 'balance between anthropogenic emissions by sources and removals by sinks' was enshrined in Article 4.1 of the Paris Agreement and has become a prominent feature of recent IPCC assessments as well as country strategies. Net-zero targets are driven by science that indicates that to limit warming to 1.5 °C, the world must reach net-zero CO_2 emissions around 2050 and net-zero greenhouse gas emissions later in the century (2095–2100 with no or limited overshoot, 2070–2075 with high overshoot)[2].

With the advent of net zero as a concept, the category of 'residual emissions' has emerged to denote emissions that are regarded as hard to abate and will need to be compensated via carbon removal. In the integrated modelling literature, residual emissions may be defined as those whose abatement remains uneconomical or technically infeasible under the assumptions of a specific model and mitigation scenario[3]. From a governance or territorial standpoint, for example as stated in the city of San Francisco's climate plan, residual emissions are simply those "that remain due to limited existing options to eliminate or reduce them further".[4] For corporations, residual emissions may be defined in terms of the value chain; there may be emissions outside of the scope of the company's direct control.

Countries are currently detailing their strategies for how to reach net-zero goals, which presents an opportunity to understand how they see residual emissions at net zero. Specifically, governments are submitting long-term low-emissions development strategies (LT-LEDS) as invited under Article 4, paragraph 19 of the Paris Agreement. These strategies are intended as an evolving visioning exercise, with emphasis on process rather than the resulting document[5–7]. The idea was that this process could inform medium-term nationally determined contribution target setting[8]. Creating LT-LEDS is a highly political process, and nations have approached it in different ways, although most have employed both stakeholder engagement and modelling tools to create possible pathways.

Simply reading a plan does not give immediate insight into what sort of buy-in the plan has across different internal actors within the government or how involved external stakeholders in different sectors truly are, both of which bear on how seriously the country will be implementing the plan. Nations also have different levels of

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Table 1 | Summary of information in the long-term strategies (*N*=50)

Target framing		**Year of net-zero ambition**	
Net zero	31	2040	1
Carbon neutral	6	2045	2
Climate neutral	6	2050	31
Emissions reduction	5	2060	1
Reduction versus business as usual	1	2065	1
Other	1	Not specified	14
Considers natural negative emissions technologies?		**Considers technological carbon removal techniques?**	
Yes	36	Yes	25
No	4	No	12
Not specified	10	Not specified	13
Focus on territorial emissions only?		**Use of offsetting?**	
Includes consumption	7	Yes	25
Territorial only	20	No	13
Not specified	23	Not specified	12
Defines residual emissions?		**Quantifies residual emissions?**	
Yes	25	Yes	28
No or unclear	25	No	22

planning capacity—not just scientifically speaking in terms of having forecasting tools and data, but in terms of institutional and political possibilities to articulate a 2050 goal and explicate what would be needed to achieve it. Costa Rica's strategy, for example, states plainly that achieving the structural transformation requires new tools in terms of making political decisions and analysing what steps will be needed to see them succeed and that traditional approaches based on optimization models will not deliver[9]. It situates the LT-LEDS within a broader development planning process, led by the Ministry of National Planning and Economic Policy. For other countries, the LT-LEDS are not so well integrated into planning or sustainable development institutions. While in this paper we treat the outputs from these processes as comparable, it is important to understand that they are only facets of a deeply individual set of circumstances and processes.

The content of these strategies is more speculative than a definitive 'plan'. Most LT-LEDS present pathways—what-if explorations of different scenarios for reaching desired targets—created using a variety of methods. These scenarios and quantified projections inform the strategy but are meant to be illustrative of possible futures, not predictive or prescriptive[10]. This means that in this paper, when we discuss a country's estimation of residual emissions at mid-century, we are referring to the most ambitious scenario they have offered, not their preferred target or what they are necessarily planning for. Our sample reflects this diversity and is characterized by different approaches to offsetting, removal methods and target framing (Table 1).

While most countries submitted LT-LEDS in 2020 or 2021, some countries, such as Germany and Canada, submitted their LT-LEDS a few years ago (in 2016) and have enacted more ambitious policy since the first iteration of their plans. The Paris Agreement and Katowice Rulebook do not clearly specify whether LT-LEDS should be continuously updated, although at COP-26 in 2021, countries were encouraged to submit or update before COP-27. As of mid-2022, 51 long-term strategies have been submitted; 50 were examined for this Article, of which 28 include a quantified projection of residual emissions at net zero (in all but four cases, this is 2050). These countries are responsible for only about a fifth of current emissions and contain few large emitters. Because projections out to 2050 are generally not yet in updated official policy documents, the LT-LEDS remain the most accessible source of information on national expectations of amounts of residual emissions at mid-century. These countries are the first adopters of both LT-LEDS and net-zero targets, and their assessment and actions may set the tone for countries that follow.

In what follows, we analyse country LT-LEDS strategies to examine four key questions. (1) How are residual emissions defined? (2) What amounts are countries projecting? (3) How are residual emissions distributed among sectors? (4) What are the expectations around the land sector's ability to compensate for residual emissions?

Definition of residual emissions

Our analysis of the 50 LT-LEDS shows that there is no consistent definition or use of the concept of residual emissions. A majority of LT-LEDS do not explicitly mention the concept of residual emissions, despite having a net-zero target. Few countries provide an explicit definition or elaborate how residual emissions amounts are arrived at, explain what criteria were used to determine them or specify what greenhouse gases make up the residual emissions.

The examples in Table 2 illustrate the variance in how countries describe residual emissions in LT-LEDS. Countries such as Switzerland and Norway suggest an absolute limit on abatement options by describing residual emissions as those that 'cannot' be completely eliminated. By contrast, France and Nepal exemplify a more fluid understanding, where the need for residual emissions owes to 'the current state of knowledge' and with the expectation that technological advancement might change this. Sweden explicitly mentions the ambition to minimize residual emissions as much as possible, suggesting at least some political leverage over the amount of residual emissions allowed in LT-LEDS. Finally, some countries make explicit reference to economic considerations in their description of residual emissions.

We also examined the approach the countries took to projecting residual emissions. In theory, there are two main ways to estimate the amount of residual emissions at mid-century. The first is a top-down approach that starts with a specified national policy target (such as 85% or 90% of emissions from a baseline year) and either simply sets residual emissions equal to that or uses economy-wide or sector-specific modelling to figure out how to solve for it. The second is a bottom-up stakeholder-informed approach that estimates possible reductions in each sector then aggregates those sectoral estimates. In principle, a third approach is also possible—one that begins with negative emissions, with either a top-down approach that starts with a target sink capacity or a bottom-up approach that estimates the capacity for each source of carbon removals and then projects allowable residual emissions equal to that amount. However, countries are not at present using an approach that leads with negative emissions. In our sample of 50 LT-LEDS, around one-third of countries utilized a top-down approach, about 15% used a bottom-up approach, about 10% set residual emissions equal to the level of forest sinks and the rest used a combined approach or left the approach unspecified.

Amounts of residual emissions

The 18 LT-LEDS in our sample that include Annex I countries with a quantification of residual emissions together project residuals of 2.2 Gt yr^{-1} in 2050 in their most ambitious scenarios (Fig. 1). This corresponds to 17.9% of these countries' current emissions. Together, these countries are currently responsible for 18% of global emissions. Should the rest of the world make similar projections, the resulting residuals would be over 12 Gt yr^{-1} (if weighted by current emissions). This sets out a need for a substantial carbon-removal effort.

However, this figure of 12 Gt yr^{-1} probably underestimates the global residual emissions that countries will be planning for. We say this for three reasons. First, most countries included between two and four low-carbon scenarios. For all these countries, we chose the

Table 2 | Selected references to residual emissions in long-term strategies

Country	Description
Examples of references to residual emissions with varying degrees of certainty	
Costa Rica	"Today, the great imperative in Costa Rica ... would be to transform the emissions pattern of the economy into a net-zero emissions, or negative emissions (i.e., removals) society, in sectors where it is possible - and very low emissions **where it is not possible** to reach zero. In practice, this means that each sector will be transformed toward zero emissions, yet at different speeds."[9]
Switzerland	"The emission of greenhouse gases **cannot be completely eliminated in some sectors**. From a current perspective, this includes agricultural food production, some industrial processes, such as cement manufacture, and waste incineration. To achieve the net-zero goal, these remaining emissions must be balanced by the use of technologies or processes that remove CO_2 from the atmosphere and store it permanently."[26]
Iceland	"The goal of climate neutrality will not be reached without using removals of carbon from the atmosphere to compensate for emissions that are **unlikely to be eliminated**."[27]
Japan	"Despite the progress in energy efficiency and decarbonization in each sector, there are some sectors where CO_2 emissions are **unavoidable**. CO_2 from those sectors can be removed by specific measures such as Direct Air Carbon Capture and Storage (DACCS), Bio-Energy with Carbon Capture and Storage (BECCS), and forest sink measures."[28]
Examples of residual emissions constrained by current state of technological knowledge	
France	Glossary entry: "Near-total decarbonisation: maximum reduction of greenhouse gas emissions, the residual emissions, which are **unavoidable according to the current state of knowledge**, being mainly due to agriculture, and to a lesser extent to industrial processes, waste, domestic air transport and gas leaks (biogas, hydrogen, fluorinated gases)."[12,29]
Nepal	"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**."[13,30]
Examples of residual emissions delimited politically	
Sweden	"[S]ome agricultural emissions are likely to remain even after 2045. These remaining emissions will need to be compensated for with supplementary measures. It is nevertheless **essential to work to ensure that these remaining emissions are as small as possible**."[31]
United Kingdom	"We are clear that the purpose of greenhouse gas removals is to balance the residual emissions from sectors that are unlikely to achieve full decarbonisation by 2050, **whilst not substituting for ambitious mitigation to achieve net zero**. GGRs must not be pursued as a substitute for decisive action across the economy to reduce emissions, often referred to as mitigation deterrence."[32]
Examples of residual emissions defined partly in economic terms	
Australia	"Additional direct emissions reductions could be enabled through a more aggressive approach to technology. Informed by the Technology Investment Roadmap and annual LETS, Australia could focus on **bringing down the costs of currently very expensive abatement opportunities in hard-to-abate sectors** like industry and agriculture."[33]
United States	"In the three decades to 2050, our emissions from energy production can be brought close to zero, but certain emissions such as non-CO_2 from agriculture will be difficult to decarbonize completely by mid-century ... **While mitigation opportunities exist for many sources of non-CO_2 GHG emissions, costs and applicability vary**. Because it is challenging to eliminate all of these sources, some remaining non-CO_2 emissions will need to be offset in 2050 by net-negative CO_2 emissions."[34]

Bold text indicates authors' emphasis.

scenario with the smallest number of residual emissions for this calculation. Second, most countries do not include international aviation and shipping in their projections, both of which are commonly seen as hard-to-abate sectors. They could represent substantial sources of residual emissions: the International Energy Agency's Net Zero by 2050 scenario includes 210 $MtCO_2$ from aviation and 120 $MtCO^2$ from shipping, while also making strong assumptions about behavioural change and demand reductions in aviation[11]. Finally, and crucially, this calculation is derived from projections from wealthy Annex I countries, and poorer countries may claim higher shares of residual emissions as well as later net-zero dates. This would be in accordance with the principle of common but differentiated responsibilities and respective capacities[12]. In other words, extrapolating from the most ambitious current projections of the world's richest countries still gives a baseline indication of residual emissions in the double digits.

Expectations of carbon removal via LULUCF

We examined the projected role of land use, land-use change and forestry (LULUCF) for the 18 Annex I countries that offer estimations of residual emissions at net zero to understand whether countries projected that this sector would compensate for residual emissions. The plans for future LULUCF vary in their concreteness and detail; some include several scenarios specifying amounts of future LULUCF while others offer only vague ideas about future mitigation through LULUCF.

Most countries expect to enhance or maintain the removal capacity of the LULUCF sector (Table 3). For many of the countries that plan for enhanced removals from the LULUCF sector, these removals will equal or surpass their expected residual emissions by the point of net zero. This is the case for, among others, Finland, Iceland, Hungary, Latvia, Portugal, Slovakia, Spain and Sweden. However, for the biggest emitters in the sample, expected LULUCF removals fall far short of residuals. This is the case for Australia, Canada, France, Switzerland, the United Kingdom and the United States. Taken together, these six countries comprise 96% of the total residuals of the sample. As these countries comprise the majority of residuals, their plans will be decisive for the overall amount of residuals that will have to be removed through means other than the LULUCF sector.

Sources of residual emissions

Of the countries with quantitative projections of residual emissions, 15 Annex I countries provide a quantitative sectoral breakdown, shown in Fig. 2. Notably, across these countries, electricity is not responsible for many residual emissions, aligning with common expectations that electricity is feasible to decarbonize. Agriculture and industry represent the largest residual emissions. The prominence of agriculture brings up the question of whether residual emissions are expected to be CO_2 or other greenhouse gases, which is unspecified in most strategies. Only the United Kingdom includes aviation in its accounting of residual emissions, amounting to nearly half of its total. Notably, these figures are mainly from Organisation for Economic Co-operation and Development countries, and many of the non-Annex I countries indicated that they would have residual emissions from energy.

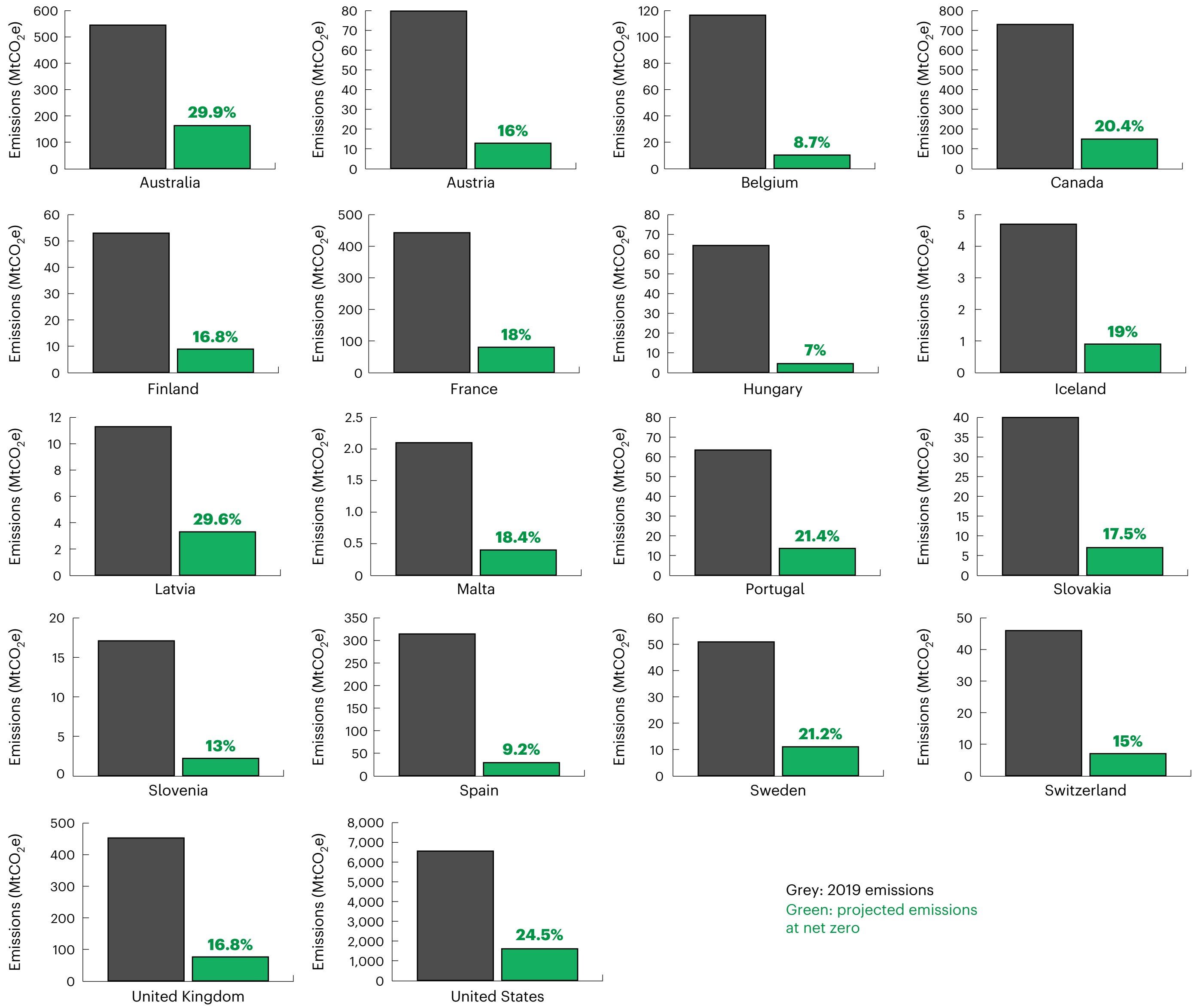

Fig. 1 | Residual emissions versus 2019 emissions, Annex I countries. The 2019 emissions are from UNFCCC inventories; total GHG emissions without LULUCF. CO_2e, CO_2-equivalent.

The projections in country strategies cohere largely with the sectoral breakdown of residual emissions one can find in the literature, although countries may be projecting larger amounts than in the literature. The International Energy Agency's Net Zero by 2050 scenario describes a largely decarbonized power sector. Out of 1.5 Gt of residual emissions in this scenario, 40% is from heavy industries, mainly in developing economies (chemicals, steel, cement), and 33% is from aviation, shipping and trucks; notably, this scenario is focused only on energy, not land.

Scenario studies analysed in the IPCC Sixth Assessment Report (AR6)[2] similarly highlight residual emissions from non-electric energy, particularly in transport and industry (2.7.3). The AR6 also presents estimations of residual GHG emissions at net zero from illustrative mitigation pathways (IMPs) (fig. SPM.5). The pathways compatible with below 1.5 °C with limited or no overshoot have residuals of 6.79 Gt ('shifting development pathways', IMP-SP), 8.73 Gt ('low demand', IMP-LD) and 11.87 Gt ('high renewables', IMP-Ren), with half to two-thirds of these from non-CO_2 emissions[13]. In other words, analysis of net-zero and 1.5 °C compatible pathways from the scientific literature also anticipates that the majority of residual emissions will be from agriculture, with some residual emissions from industry and transport. Yet estimations of total amounts vary widely depending on scenario, and regional analysis is limited.

Discussion

Our analysis of the LT-LEDS submitted to the UNFCCC so far shows that (1) residual emissions do not have a standard conceptual definition; (2) countries' projected residual emissions are a substantial percentage of current emissions, averaging around 18% for Annex I countries in the most ambitious scenarios; (3) while most residual emissions in ambitious scenarios are indicated to come from agriculture, industry and mobility, few countries specify sectoral breakdowns; (4) for countries analysed, LULUCF sinks by 2050 cannot balance out all residual emissions.

As countries look towards submitting or updating LT-LEDS in advance of future UNFCCC events, researchers, policymakers and civil society should work towards standardizing expectations on residual emissions. Right now, state and non-state actors alike can self-define,

Table 3 | Overview of countries' residuals, recent and current LULUCF[35] and long-term LULUCF outlook

Country	Residuals ($MtCO_2e$)	2020 LULUCF ($MtCO_2$)	Average 2000–2020 LULUCF ($MtCO_2$)	Long-term LULUCF outlook
Australia	139	−43	17	Enhance
Austria	13	−5	−7	Ambiguous
Belgium	10	−1	−2	Maintain or enhance
Canada	149	9	−8	Enhance
Finland	9	−17	−22	Maintain or enhance
France	80	−35	−40	Enhance
Hungary	5	−6	−4	Maintain
Iceland	1	6	6	Enhance
Latvia	4	−3	−6	Enhance
Malta	0	0	0	Maintain
Portugal	9	−8	−7	Enhance
Slovakia	7	−6	−7	Maintain
Slovenia	2	0	−5	Enhance
Spain	29	−38	−39	Maintain
Sweden	11	−37	−39	Enhance
Switzerland	68	−2	−2	Ambiguous
United Kingdom	76	−1	0	Enhance
United States of America	1,605	−813	−818	Enhance

and claim, various amounts of residual emissions. The gift of the Paris Agreement framework is its flexibility in exactly how countries choose to balance sources and sinks of emissions. However, specifying residual emissions will mitigate against the risk that governments put things that are expensive or politically inconvenient to abate into the 'residual box', thus increasing the amount of residual emissions—and thereby creating pressures for an even larger carbon-removal infrastructure.

Concerns about the feasibility, sustainability and societal impacts of carbon removal at several gigatons per year[14,15] have led to calls to moderate expectations of future carbon removal[16]. This is because terrestrial carbon removal at the scales indicated in this Article would require vast amounts of land and entail severe risks for food production and/or biosphere functioning[17,18] as well as the land rights and livelihoods of rural communities and Indigenous peoples[19]. While some industrial carbon-removal techniques such as direct air carbon capture and storage have a much smaller direct land footprint, this approach comes with large energy requirements[20], which could divert energy, and critical minerals and the associated land for renewables, from other societal needs. Ultimately, the idea that some emissions are hard to abate must be examined in light of these risks and challenges with scaling carbon removal.

Many actors have called for greater clarity in net-zero targets and plans, regarding carbon removal but also around pathways in general[12,21–23]. Norms are evolving about how to develop net-zero pathways, as set forth in the UN Race to Zero campaign or the Science-Based Targets Initiative. The latter sets out cross-sector and sector-specific pathways that include a 90% reduction by 2050, with pathways that reach a 'low–medium' global level of carbon removal of 1–4 Gt yr^{-1} in 2050[24]. This could be an effort that sets global norms around corporate residual emissions. While we applaud the business community and NGOs for attempting to set norms, we see a much clearer role for governments in this area, even while acknowledging that governments will face difficulties in this space. There is political advantage in leaving residual emissions strategically ambiguous as governments need to accommodate the interests of different sectors and regions. At the same time, both industries and communities can benefit from certainty in planning, and better setting out clarity and expectations around residual emissions also has political and economic benefits.

We make the following three recommendations for policymakers developing long-term strategies. These recommendations are also important for the researchers and NGOs supporting their work, who have a critical role in supporting international policymaking (Box 1).

First, include clear projections for (1) the amount of residual emissions, (2) where they originate sectorally and spatially and (3) the types of greenhouse gas. Scenarios and the graphical user interfaces used to explore them can be made more user friendly, allowing broader engagement with these key issues in climate policy. Multiscalar datasets linking broader analysis of residual emissions to regional or facility-level data would enable critical debates about infrastructure and enable planning for just transitions.

Second, the policy and research communities should suggest defined criteria by which 'hard to abate' should be judged. While sectors such as aviation, steel and agriculture are commonly understood as difficult to decarbonize, terms such as difficult, unavoidable, hard to abate, impossible to eliminate and so on carry value judgements about what kind of activities a society should or should not engage in and what costs are reasonable. This normativity is unavoidable. However, greater transparency around how emissions come to be considered residual is critical for the legitimacy of decarbonization efforts. Defining criteria would allow for comparison and negotiation and the development of international norms on how to determine difficulty of abatement. This is particularly important given that what is hard to abate changes along with technological developments, such as green hydrogen and low-carbon aviation. Thus, assumptions and norms around hard-to-abate emissions must be constantly revised.

The scientific community has a key role in supporting society in defining these criteria, in terms of both creating tools and producing research. Researchers can also produce analysis to answer the following key questions. What processes and sectors lack technological options for fully eliminating emissions? Are there technologies that would become options under different policy scenarios? Where are there opportunities for demand-side options to lower residual emissions further, and what social factors enable and constrain those options? These questions require interdisciplinary research, and governments should support this research, directly funding and coordinating it as well as being receptive to existing efforts and incorporating them into programmes.

Third, be explicit about whether residual emissions—and net zero as a goal—are a temporary stopgap towards a further state of decarbonization or a state to maintain in perpetuity. Clarity on whether residual emissions are a temporary condition or a permanent state is important, both for calibrating expectations for the future of the fossil fuel sector and for understanding the intended role for carbon removal. If negative-emission capacity is being used to compensate for residual emissions domestically or in another country, it is not available for legacy carbon removal or coping with overshoot. Although the AR6[2] frames these roles of carbon removal as complementary, they may be in conflict if we assume carbon-removal potential will be limited for social and sustainability reasons. Clarity on the temporality of residual emissions is also important because strategies such as soil carbon sequestration have apparently high mid-century technical potential, but these sinks saturate after ~20 years and require ongoing maintenance[14]. Land-based sinks already accounted for may saturate over time, as may carbon stored in products. Net zero needs to be a durable state[22], not something that might be achieved and then be lost again. The timing of various carbon-removal strategies needs to be better planned for, and the ability to do so hinges on understanding

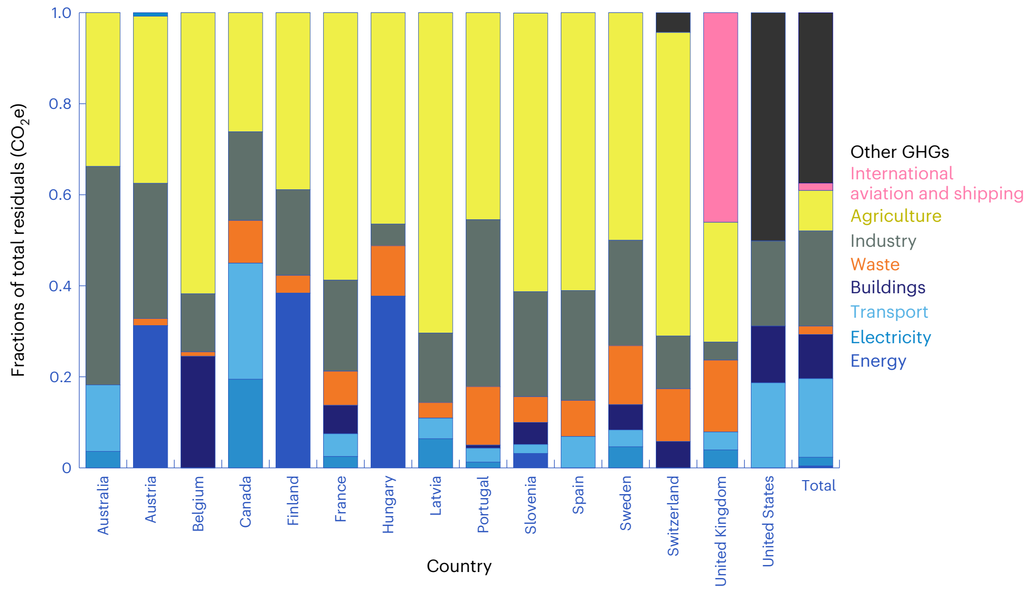

Fig. 2 | Sectoral breakdowns of residual emissions at mid-century in the most ambitious scenarios. Data are for Annex I countries that featured projections with quantified sectoral breakdowns. Year depicted is 2050 for all countries besides Sweden, which has projections for 2045 when it reaches net zero. Finland has a target of net zero at 2035 but includes projections for 2050. Note that some countries group electricity and transport into energy, and the United States does not report agriculture but rather CO_2 and other GHGs.

BOX 1

Emerging research areas for international net-zero policy

International policy efforts are needed to solve multiple problems that underlie the net-zero framework. One problem is how residual emissions and removals can be matched. Carbon-removal-focused international cooperation efforts are absent or poorly described in LT-LEDS, even though cross-country efforts might be the most cost effective[36,37]. Some countries indicate that they may need to procure carbon removal from abroad (Switzerland, Australia), yet no countries indicated that they intended to produce surplus removals for global markets. The challenge here has typically been read as (1) the need to work out issues with market mechanisms, as Article 6 negotiations are tackling, and (2) the need for better monitoring, reporting and verification to make exchangeable removals credible[38–42]. Both of these are serious challenges.

However, there is another pressing international policy need to create safeguards against dynamics where countries expect to acquire removals in developing countries, creating rushes—for land, terrestrial carbon storage, space for ocean carbon removal, geological sequestration capacity or renewable resources to power carbon-removal technologies, such as direct air capture.

A second problem is that the evolving carbon marketplaces have no way of making sure that removals are in fact compensating for emissions from sectors and activities that are truly hard to abate. Alternative frameworks might have nations with similar socioeconomic capacities striving for the same amount of ambition in terms of decarbonizing each sector or dividing residual emissions according to luxury and subsistence emissions[43].

A third policy challenge is that from a climate-justice perspective, wealthy countries with historical responsibility, such as the United States, should deliver net-negative emissions sooner to allow poorer countries some net residual emissions post 2050. However, if such wealthy countries decide to use their capacity for carbon removal to balance residuals in expensive but possible-to-reduce sectors to lower the costs of meeting net-zero goals, this adds further pressure on other countries. Moreover, the geopolitics of carbon removal are such that some countries have greater capacity for land-based and geologic sinks. Countries with large sinks might seek to use them to give competitive advantages to their industrial or agricultural sectors, with a risk of less-stringent policies for decarbonizing those sectors. In other words, if carbon removal is a natural resource with finite capacity, the choices a country makes in allocating that resource have global-justice dimensions. Thus, residual emissions can be seen as an emerging, important focal point for climate justice and the UNFCCC negotiations, alongside emissions reductions goals, loss and damage, and climate finance. Researchers have an important role to play in producing a robust foundation for those discussions.

whether net zero is a stopgap or permanent state. While governments will have a challenging time being explicit about this, given their need to address multiple domestic actors, the research institutions and NGOs working in policy have more flexibility to be explicit about this in their analyses and can spell out the implications of treating residual emissions as continuing versus temporary.

Residual emissions need to be openly analysed in both science and politics because the stakes of continuing to treat residual emissions as a technocratic matter are high. Large and unsubstantiated claims on residual emissions will undermine mitigation. Moreover, failing to decide and agree on residual emissions, and instead allocating them according to simple market logics, means that more-powerful actors (countries, sectors, companies) will claim remaining residual emissions and corresponding negative emissions capacity, leaving less-powerful or less-well-organized actors unable to operate or, more likely, to continue to operate illegally. Further, the ambiguity of residual emissions—as a temporary measure while zero-carbon technologies are developed versus residual emissions as a long-term feature of the energy system—risks not just confusing publics and stakeholders, but decreasing support for net-zero targets more broadly.

These questions may seem like far-off matters in a world where emissions have not even peaked. But 2050 is not so distant, and the science is clear that fossil fuel production must rapidly be curtailed and most fossil fuel reserves must remain unextracted to meet a 1.5 °C temperature goal[25]. Publics, investors, planners and other decision makers need greater clarity on the longer-term aims of net zero to guide decisions around fossil fuel phaseout as well as what sort of removal efforts to invest in. Future expectations act in the present: our expectations of 2050 inform choices made today. Many actors may see net zero as a temporary state towards a net-negative society, but this vision is not yet evident in national strategies.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01592-2.

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Methods

Country long-term strategies were downloaded from the UNFCCC and were qualitatively coded in a spreadsheet by two independent coders, a research assistant and a member of the research team, for the following information:

(1) Type of target (for example, carbon neutrality, net zero or other)
(2) Coverage of target (GHGs or CO_2)
(3) Year of net zero, for countries with net-zero or carbon-neutral targets
(4) Whether there is a definition of residual emissions or hard-to-abate/remaining emissions and, if so, how it is introduced
(5) Whether there is a quantitative projection of residual emissions at net zero and, if so, what the amount is
(6) Sectoral breakdowns of residual emissions
(7) The source and process of generating the projections (which approaches were used; whether they appeared to be top-down or bottom-up; which particular models were used to generate them)
(8) Mentions of public or stakeholder consultation or engagement

In a few cases, other government documents or sources were also used for reference, including technical annexes for government strategies.

Percentages of current country emissions were derived from the World Resources Institute's Climate Watch platform at https://www.climatewatchdata.org/ (ref. [1]).

Current-year emissions were derived from the 2019 emissions listed in UNFCCC inventories for total GHG emissions without LULUCF, at https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc.

Recent and current LULUCF data are from (ref. [35]).

The coded data was used to generate the tables and figures in the Article. The analysis is straightforward; the work was simply in extracting the amounts of residual emissions and sectoral breakdowns because these are not presented in a standard form across the documents, and in some cases they appear in charts but are not well explicated in the main text of the reports.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data analysed in the current study are provided in Supplementary Data 1. The majority of the relevant data was extracted from publicly available documents available from the UNFCCC at https://unfccc.int/process/the-paris-agreement/long-term-strategies. Percentages of current country emissions were derived from the World Resources Institute's Climate Watch platform at https://www.climatewatchdata.org. Current-year emissions were derived from the 2019 emissions listed in UNFCCC inventories for total GHG emissions without LULUCF, at https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc. Recent and current LULUCF data are from (ref. [35]).

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Author contributions

H.J.B. conceived the idea for the paper and led the analysis and writing. W.C., J.F.L. and N.M. contributed to the analysis and development of the argument. All authors contributed to drafting, reviewing and editing the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Research sample	The data was extracted from long-term low-emissions development strategies submitted to the UNFCCC under the Paris Agreement. These were used because this is the first body of policy documents to consistently include projections and discussion of mid-century climate goals.
Sampling strategy	All the long-term climate strategies were analyzed; most analysis focused on coutnries with net-zero by 2050 goals.
Data collection	This was a document analysis with no human subjects.
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