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Applying equity principles leads to higher carbon removal obligations in Canada

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Despite net-zero pledges, consensus on national responsibilities for carbon dioxide removal (CDR) strategies is lacking. Here, we use integrated assessment modeling to examine equity-informed estimates of Canada's remaining carbon budgets, exploring CDR's role at net-zero and beyond. Gigaton-scale CDR efforts post-2050 are needed to address Canada's carbon debt under various burden-sharing principles. Cumulative negative emissions (2050-2100) could increase from 7.5 $GtCO_2$ in the Net-Zero scenario to 20.3 $GtCO_2$ in equity-informed scenarios. By 2100, a CDR portfolio, including bioenergy with carbon capture and storage, direct air capture, and enhanced weathering could contribute up to ~500 $MtCO_2$/year of removals. The projected average CDR growth rates, 2.8%-16%/year, align with the historical adoption rates of ammonia synthesis and biomass consumption in Canada, underscoring the importance of drawing lessons from past successes. Socio-economic and technological sensitivity analysis highlights that, despite variations in the role of individual CDR technologies, CDR remains essential for Canada's post-net-zero commitments.

The Paris Agreement sets a goal to limit global average temperatures to well below 2 °C while pursuing efforts to limit the temperature increase to 1.5 °C[1]. The remaining carbon budget (RCB)—the permissible carbon dioxide (CO_2) emissions from a defined point in time that would limit global warming to agreed thresholds (e.g., 1.5 °C)—underscores the necessity of achieving and maintaining net-zero global CO_2 emissions as a cornerstone for meeting any climate target[2]. For two main purposes, carbon dioxide removal (CDR) methods are required to realize the 1.5 °C target. First, achieving net-zero emissions may require compensating for certain sectoral emissions that persist due to socio-economic or technological constraints, or a lack of mitigation strategies (e.g., in aviation). Second, exceeding the RCB results in a temperature overshoot that, in turn, necessitates CDR to reduce the concentration of CO_2 in the atmosphere to bring the temperature down to safe levels in subsequent years[3,4]. While overshooting the 1.5 °C target may be considered ethically and strategically problematic, especially in light of irreversible climate change effects[5–7] and uncertainties regarding the long-term efficacy of CDR methods[8,9], recent RCB estimates, the level of ambition of climate policies, and current global CO_2 emissions suggest the overshoot of 1.5 °C is highly probable[10].

The recognition that states will collectively exceed the RCB, leading to a form of carbon debt, has reignited calls for a transition to equity-driven national remaining carbon budgets (NRCB) in policy discussions[2]. Numerous studies have examined how to "fairly" share the RCBs associated with different temperature targets[11–18]. These studies draw on fairness principles that rely on different equity perspectives, such as the scale of countries' historical emissions and contribution to climate change (Responsibility), their ability to cut emissions and/or deploy CDR (Capability), equal emissions per-person (Equality) or mixed approaches[17].

Equity-based NRCBs, which would adjust a state's NRCB in light of fairness principles, provide a more ethically justifiable approach for states to determine the amount of CDR they may have to deliver to equitably contribute to achieving the Paris temperature goals. A broader set of implications flow from adopting equity-based NRCBs, particularly for states where the demands of fairness will increase the size of their carbon debt, resulting in increased responsibilities for CDR deployment. The policy choices concerning scaled-up CDR will influence other large-scale systems, such as energy and land use, and will increase infrastructure demands, such as geological storage. Integrated Assessment Models (IAMs) are essential tools for understanding the implications of interactions between socio-technological and economic sectors, thanks to their capacity for modeling these complex dynamics. IAMs and scenario analysis can guide state

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strategies, especially for developing emerging CDR technologies and supporting physical, social, and economic policies and regulatory frameworks.

This study focuses on Canada, recognized as one of the top ten countries worldwide in terms of per-capita emissions[19,20]. In 2022, Canada announced its Emissions Reduction Plan, outlining a framework of federal policies to reduce emissions to 40–45% below 2005 levels by 2030 and set a long-term target of reaching net-zero greenhouse gas emissions by 2050. Current Canadian policy is silent on the demand for negative emissions to address drawdown beyond the 2050 net-zero goal. Previous Canadian studies have mainly focused on pathways compatible with the net-zero goal for 2050, through integrated modeling studies where their CDR portfolio was predominantly limited to bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC)[21–24]. While previous research has calculated NRCB for various countries, including Canada[17,25–27], there has yet to be a study exploring the implications of these estimates to net-zero targets and the role of CDR beyond net zero that equity principles may mandate for Canada.

We incorporate the concepts of burden-sharing and NRCB within a technologically comprehensive IAM framework guided by the equity principles of equal per capita (EPC-Q) and per capita convergence (PCC-Q), where "Q" denotes qualified approaches as defined and modified by Williges et al.[17]. Incorporating equity into an IAM framework allows us to examine the impact of different approaches to equity on Canada's NRCB and the role of various CDR technologies in reversing the temperature overshoot by the year 2100. Through the application of a tailored version of the Global Change Analysis Model (GCAM), as developed by Fuhrman et al.[28], we model various CDR strategies, including DAC, BECCS, enhanced weathering (EW), biochar, and direct ocean carbon capture and storage (DOCCS). This study examines the potential of CDR technologies and considers their energy requirements and the CO_2 storage needs these strategies may entail. In addition to our primary scenarios, we examine scenarios under different techno-economic uncertainties, such as the varying costs and accessibility of CDR technologies, the potential of land use (through afforestation and reforestation) to serve as a carbon sink and alternative futures with a strong socio-technological change towards renewable energy and low energy demand. Another crucial aspect this study examines is the growth rates of various CDR methods under modeled scenarios, comparing them to historically adopted technologies in Canada using a global dataset on technology adoption[29]. Finally, this study concludes by reflecting on the value of incorporating equity-based NRCBs into planning and policy discussions. Key findings highlight the critical role of CDR for Canada to meet its post-net-zero obligations under various burden-sharing principles. Key technologies such as BECCS, DAC, and EW are essential for large-scale carbon removal. Historical technology adoption rates in Canada suggest that scaling CDR is feasible if lessons from past innovations are applied. While socio-technological uncertainties influence specific technologies and deployment levels, CDR remains indispensable for addressing Canada's carbon debt.

Results

We define our primary scenarios as follows: (1) No-Policy: A counterfactual baseline with no new climate policies and removal of all existing ones in Canada; (2) Net-Zero 2050: Canada achieves net-zero CO_2 emissions by 2050, maintaining this level thereafter; (3) EPC-Q 1.5 °C Scenario: Canada reaches net-zero by 2050 and compensates for a carbon debt of 16.4 $GtCO_2$ based on the EPC-Q equity principle; and (4) PCC-Q 1.5 °C Scenario: Canada attains net-zero by 2050 while addressing a carbon debt of 6.7 $GtCO_2$ following the PCC-Q equity principle. More information about different equity principles is available in the Section "Equity-based national remaining carbon budget (NRCB)". We explore emissions/removal pathways (Section "Emission pathways and the role of carbon dioxide removal methods"), primary and final energy demand (Section "Primary and final energy consumption pathways"), and potential geological CO_2 storage needs (Section "Potential need for geological storage"). Sections "CDR-related techno-economic uncertainties" and "Future energy pathway and the availability of natural-gas powered DAC" examine socio-economic and technological uncertainties affecting CDR deployment. Finally, the Section "Growth rates of CDR vs. historical technology adoption in Canada: uncertainties and challenges" compares modeled CDR growth rates with historical technology adoption and discusses associated challenges and barriers. Read more about the scenario design logic in the Section "Scenarios and their socio-technical assumptions" and Table 1.

Emission pathways and the role of carbon dioxide removal methods

As shown in Fig. 1, In the No-Policy scenario, Canadian emissions remain largely unchanged, reflecting the continuation of existing practices. Conversely, in the Net-Zero scenario, we see a marked decrease in emissions across all sectors by 2050 compared to 2010, with reductions amounting to 64%, 76%, 90%, and 96% in transportation, industry, electricity, and buildings, respectively. To achieve a net-zero balance by 2050, the model incorporates various CDR methods, primarily focusing on BECCS for electricity production (60.3 $MtCO_2$), BECCS for hydrogen (H_2) production (33 $MtCO_2$), and a smaller scale of DAC at 3.7 $MtCO_2$. Post-2050, the use of CDR extends to non-biomass techniques. The maturity and wider availability of additional CDR methods will increase residual emissions from 115 to 195 $MtCO_2$ by 2100. In the Net-Zero scenario, by 2100, emissions from the transportation sector drop to 84 MtCO2 per year—less than half of the 2022 levels (190 $MtCO_2$). However, these emissions still account for around 40% of the total positive residual emissions, making them notable. As shown in Supplementary Fig. 1, while road transportation—especially light-duty vehicles—undergoes substantial electrification, most of the remaining emissions come from hard-to-decarbonize sectors, such as heavy transport, large vehicles, trucks, and aviation. By the end of the century, DAC and EW contribute to removing approximately 63 and 12 $MtCO_2$, respectively.

Transitioning to the equity-based scenarios, illustrated in panels c and d of Fig. 1, a notable surge in total negative emissions is observed post-net-zero, peaking at the end of the century. In 2100, DAC and EW are projected to remove approximately 308 and 70 $MtCO_2$ under the EPC-Q scenario, and 184 and 38 $MtCO_2$ under the PCC-Q scenario. Deployment of other CDR strategies, such as biochar and DOCCS, are anticipated to be minimal at their peak. Examination of the cumulative deployment of various CDR methods suggests that BECCS for electricity, BECCS for H_2, DAC, EW, biochar, and DOCCS would be necessary within the ranges of 5700–6183, 1700–2318, 4000–8730, 598–1351, 107–110 and 0.01–0.02 $MtCO_2$, respectively, under different equity-based scenarios. Overall, cumulative negative emissions (2050–2100) increase by 12.8 $GtCO_2$, from 7.5 $GtCO_2$ in the Net-Zero scenario to 20.3 $GtCO_2$ in the ambitious EPC-Q 1.5 °C scenario.

Primary and final energy consumption pathways

Figure 2 illustrates the contributions to energy output of different technologies across different scenarios. In 2020, the primary energy sources were predominantly oil and gas, accounting for approximately 70% of total primary energy, followed by coal at 7.2%, biomass combustion (without CO_2 capture) at 5.8%, hydroelectric power at 11.5%, nuclear energy at 3.3%, and the remainder from solar, wind, and geothermal sources. Scenarios with climate policy introduce energy source variations. These include oil, gas, coal, and biomass combined with carbon capture and storage (CCS) technologies to neutralize their emissions. Specifically, in the Net-Zero 2050 scenario, there is a notable increase in the share of non-biomass renewable sources (reaching 30% of total primary energy by 2100), nuclear energy (12% by 2100), and biomass integrated with CCS (14% by 2100), coupled with a decrease in the contributions from coal, natural gas (without CCS), and biomass (without CCS). It is important to note that GCAM assumes CCS technologies will mature sufficiently later in the century to capture CO_2 at high rates. Supplementary Table 1 outlines the capture rates assumed for different technologies.

Table 1 | Defining scenarios, their underlying logic, and techno-economic assumptions

Scenario	Type	Burden-sharing principle	Scenario design elements and logic
No Policy	Primary	Not applicable.	The "No Policy" baseline scenario assumes the absence of climate policies and aligns with the "middle-of-the-road" shared socio-economic pathway, or SSP2[64]. In this scenario, all of Canada's climate and mitigation measures, including carbon pricing, are eliminated. Although this scenario is less likely given recent investments, it is included to reflect the considerable political uncertainty surrounding Canada's climate objectives. For example, Canada was the first country to withdraw from the Kyoto Protocol[65,66].
Net-Zero 2050			In this scenario, Canada meets its 2030 emissions target of 344 $MtCO_2$, reflecting a 40% reduction from the 2005 level of 575 $MtCO_2$. After 2030, emissions are reduced linearly to achieve net zero by 2050.
EPC-Q 1.5 °C		EPC NHB-qualified	After achieving the 2030 emissions reduction target and the 2050 net-zero goal, Canada is projected to incur a carbon debt of 16.4 $GtCO_2$ (Supplementary Note 3 provides the calculation steps), based on the EPC-Q burden-sharing principle. To address this debt, Canada will ramp up its negative emissions efforts, reaching a peak in 2100.
PCC-Q 1.5 °C		PCC NHB-qualified	Similar to the EPC-Q 1.5 °C scenario, but with the carbon debt calculated using the PCC-Q burden-sharing principle resulting in 6.7 $GtCO_2$ (calculation steps are provided in Supplementary Note 3).
Permitted biomass Import	Sensitivity analysis	Three variants with respect to Net-Zero 2050, EPC-Q 1.5 °C and PCC-Q 1.5 °C	In all of the primary scenarios, it is assumed that Canada cannot import biomass, to prevent shifting the negative externalities of logging activities to other countries[67]. This is particularly important given that Canada has abundant domestic biomass resources and acknowledges the distributional dimension of equity. In this scenario, however, we remove this constraint and enable biomass imports in GCAM to assess the impact of this change.
Limited Biomass			Since biomass played a dominant role in our primary scenarios but may have negative environmental and socio-economic impacts[61,68], "limited biomass" scenarios explore the effects of limiting total biomass usage. We analyze how these constraints affect emissions reductions and the deployment of other CDR methods. Specifically, we apply biomass constraints of 1.5, 2, and 4 EJ for primary energy production in the net-zero, PCC-Q 1.5 °C, and EPC-Q 1.5 °C scenarios
Limited carbon storage			The total cumulative geological storage capacity for CO_2 in Canada is limited to 30 $GtCO_2$, reduced from the default value of 105 $GtCO_2$. This adjustment is important given the potential regulatory and social challenges associated with large-scale CO_2 injection[32].
Limited DAC			DAC deployment upper limits increase linearly to 30 $MtCO_2$/year by 2050 and reach 100 $MtCO_2$/year by 2100. These constraints account for the socio-political and techno-economic uncertainties, such as material supply challenges, that DAC may encounter in the coming years[33,36,69].
Low-cost DAC			Baseline scenarios indicate a decrease in non-energy costs of DAC from 296-402 2015\$/tCO_2 (different technology variants) to 185-230 2015\$/tCO_2 by 2030. In low-cost scenarios, DAC costs could further decline to 78-137 2015\$/tCO_2 by 2030. These numbers are associated with SSP5 techno-economic assumptions of DAC modeled in GCAM[70]. This scenario accounts for the future uncertainties surrounding the cost of DAC as shown by various studies[69,71].
High-cost DAC			The high-cost scenario presupposes that DAC will not experience cost reductions, maintaining current levels of 296-402 2015\$/tCO_2. These figures align with the DAC techno-economic assumptions under SSP3[70]. The same scenario logic (exploring the uncertainties surrounding the cost of DAC) as the low-cost DAC scenario is applied here.
Limited EW			For EW potential, this analysis assumes half of the default values provided by GCAM. This limitation reflects various socio-technological barriers, including challenges related to scaling up the rock mining industry[48].
Negative Land-Use			We assume that land use will function as a CO_2 sink, with negative emissions from land use reaching -50 $MtCO_2$ by 2050 across all scenarios. In the EPC-Q and PCC-Q scenarios, this figure rises to -100 $MtCO_2$ in 2100 due to the stringency of the target. The assumption of -50 $MtCO_2$ by 2050 aligns with projections made in the Energy Future Canada report[22].
STC (Socio-technological change)		Three variants concerning Net-Zero 2050, EPC-Q 1.5 °C and PCC-Q 1.5 °C	In the STC scenario, which is adapted from the sectoral strengthening scenario of Fuhrman et al.[28], several assumptions from the SSP1 "Sustainable Development" storyline are incorporated. These include limited biomass availability, a stronger preference for renewable energy, improved efficiencies in buildings and industries, lower energy demand for industrial and consumer goods[40], and a limitation on the future growth of nuclear power generation. Achieving this scenario would require transformative changes in all aspects of societal life, moving toward a more sustainable future.
STC and No-HT-DAC-NG			This scenario builds upon the elements of the STC scenario while excluding a specific type of high-temperature DAC that relies on burning natural gas for

Table 1 (continued) | Defining scenarios, their underlying logic, and techno-economic assumptions

Scenario	Type	Burden-sharing principle	Scenario design elements and logic
			heat. This adjustment aims to further minimize dependence on fossil fuels, even when pursuing negative emissions.
EPC-Simple 1.5 °C		EPC simple	Under this approach, Canada incurs a carbon debt of 6.9 $GtCO_2$ based on NRCB calculated by Williges et al.[17] (See Supplementary Note 3 for an example of such calculations). Similar to EPC-Q 1.5 °C, negative emissions will be scaled up, peaking by 2100. The result is available in Supplementary Note 2 and Supplementary Fig. 12.
PCC-Simple 1.5 °C		PCC simple	Under this approach, Canada incurs a carbon debt of 79 $MtCO_2$. Similar to PCC-Q 1.5 °C, negative emissions will be scaled up, peaking by 2100. However, the 79 $MtCO_2$ carbon debt is negligible, essentially suggesting that by reducing emissions linearly to zero by 2050, there would be little to no need for negative emissions. This scenario, which is essentially based on pure grandfathering (allocating the remaining carbon budget according to current emission levels), raises ethical concerns, primarily because it fails to account for historical responsibility and capacity to mitigate. The result is available in Supplementary Note 2 and Supplementary Fig. 12.
Global 1.5 °C		Not applicable.	The remaining global carbon budget associated with the 1.5 °C target dictates the annual global emissions constraint. This involves a linear decrease in global emissions to reach the net-zero target by 2050, followed by a linear increase in negative emissions post-2050 to align with the budget, serving as the primary constraint for the model. The result is available in Supplementary Note 2 and Supplementary Fig. 12.

Similar trends are observed in the EPC-Q 1.5 °C and PCC-Q 1.5 °C scenarios, but the magnitude of change is more pronounced. For instance, in the EPC-Q 1.5 °C scenario, by 2100, biomass with CCS comprises 25% of the total primary energy, and the proportion of fossil fuel use equipped with CCS is approximately 24–35% of the total fossil fuel consumption. As shown in Fig. 2, despite the expansion of renewable energy production, fossil fuels (oil and gas) continue to play a substantial role, even by the end of the century. In the most ambitious EPC-Q 1.5 °C scenario, fossil fuels still account for 26% of the energy mix. In the Section "Future energy pathway and the availability of natural-gas powered DAC", we present sensitivity analysis scenarios that explore alternative energy futures and their implications for CDR and emissions.

Figure 3 illustrates the types of final energy consumption under the scenarios discussed. In all scenarios, including the No-Policy one, the role of electricity in the final energy mix increases, indicating that electrification is likely to occur in nearly all scenarios. However, the rate of electrification is considerably higher in scenarios involving climate policies. By 2100, electricity constitutes 55–59% of the total final energy, compared to approximately 23% in 2020. As shown in Fig. 3, refined liquids contribute noticeably to the final energy demand. A more detailed breakdown of the final energy demand supplied by refined liquids is provided in Supplementary Fig. 2, highlighting sectors such as transportation, construction, and other industries. To explore more ambitious deep decarbonization in these sectors, we conducted sensitivity analyses in the Section "Future energy pathway and the availability of natural-gas powered DAC" of the paper. Figure 3 also details the proportion of final energy allocated to DAC, an energy-intensive CDR method. As previously discussed, in 2100, DAC is expected to remove 63, 184, and 308 $MtCO_2$/year in the "Net-Zero 2050", "PCC-Q 1.5 °C", and "EPC-Q 1.5 °C" scenarios. The model projects 2%, 6%, and 9% of electricity and 15%, 31%, and 41% of natural gas will provide the electricity and heat necessary for DAC.

Potential need for geological storage

As illustrated in Figs. 1 and 2, numerous energy production pathways are integrated with CCS, alongside large deployments of CDR methods such as DAC and BECCS. The CO_2 captured by these diverse methods must be sequestered in stable mediums for extended periods. There are several options for CO_2 storage, but geological storage is the most promising because CO_2 can be securely contained for geological timescales. Geological storage is particularly viable in Canada due to the country's suitable geological characteristics and existing technical expertise derived from its oil and gas industry. Figure 4 outlines the annual rates of geological CO_2 storage required for Canada to meet its climate policy objectives through various implementations of DAC, BECCS, and CCS associated with fossil fuels and industry. By 2050, the model projects 315 $MtCO_2$ per year will need to be sequestered to meet the net-zero target, with this rate increasing to 853 $MtCO_2$ per year and 651 $MtCO_2$ per year by 2100 under the EPC-Q 1.5 °C and PCC-Q 1.5 °C scenarios, respectively. Canada is estimated to have the theoretical capacity for large-scale CO_2 storage, defined as the physical limit of CO_2 that the geological system can accept[30,31]. However, addressing social challenges, such as public acceptance and overcoming regulatory barriers, are critical prerequisites for realizing this potential[32]. The practical storage capacity, which accounts for geological, engineering, techno-economic, and socio-political constraints, represents only a fraction of the theoretical capacity [31]. Furthermore, since the locations of geological storage sites may not always align with potential CO_2 capture sites, scaling up CDR will necessitate major investment in CO_2 transportation infrastructure[33]. GCAM accounts for two main cost components in capture and storage technologies: capital and operating expenses, and region-specific CO_2 transport and storage costs based on updated supply curves from Dooley et al.[34].

CDR-related techno-economic uncertainties

Here, we explore how various sources of CDR-related uncertainties influence both the cumulative deployment throughout the century and the annual deployment in 2100, as illustrated in Fig. 5. As shown in Table 1, our primary scenarios prohibit biomass imports to avoid shifting biomass production's negative externalities abroad, given Canada's substantial biomass resources. For comparison, we include a scenario allowing imports. In these scenarios, the cumulative deployment of BECCS increases compared to the baseline, leading to reduced reliance on DAC and EW for both achieving net-zero emissions by 2050 (to offset residual emissions) and generating negative emissions thereafter. Specifically, cumulative DAC deployment declines from 1.5, 3.9, and 8.7 $GtCO_2$ in the baseline scenarios (where biomass import is not permitted) to 1.1, 2.4, and 4.5 $GtCO_2$ under the Net-Zero, PCC-Q 1.5 °C, and EPC-Q 1.5 °C scenarios, respectively. Similarly, cumulative EW deployment decreases from 140-1350 $MtCO_2$ in the baseline scenarios to 62–822 $MtCO_2$ under scenarios with permitted biomass import. Since our primary scenarios rely heavily on BECCS, despite limited biomass imports, we explored how reduced biomass availability would affect the deployment of other CDR methods. In these scenarios, the cumulative deployment of DAC ranges from 3.8 to 9.6 $GtCO_2$, while EW

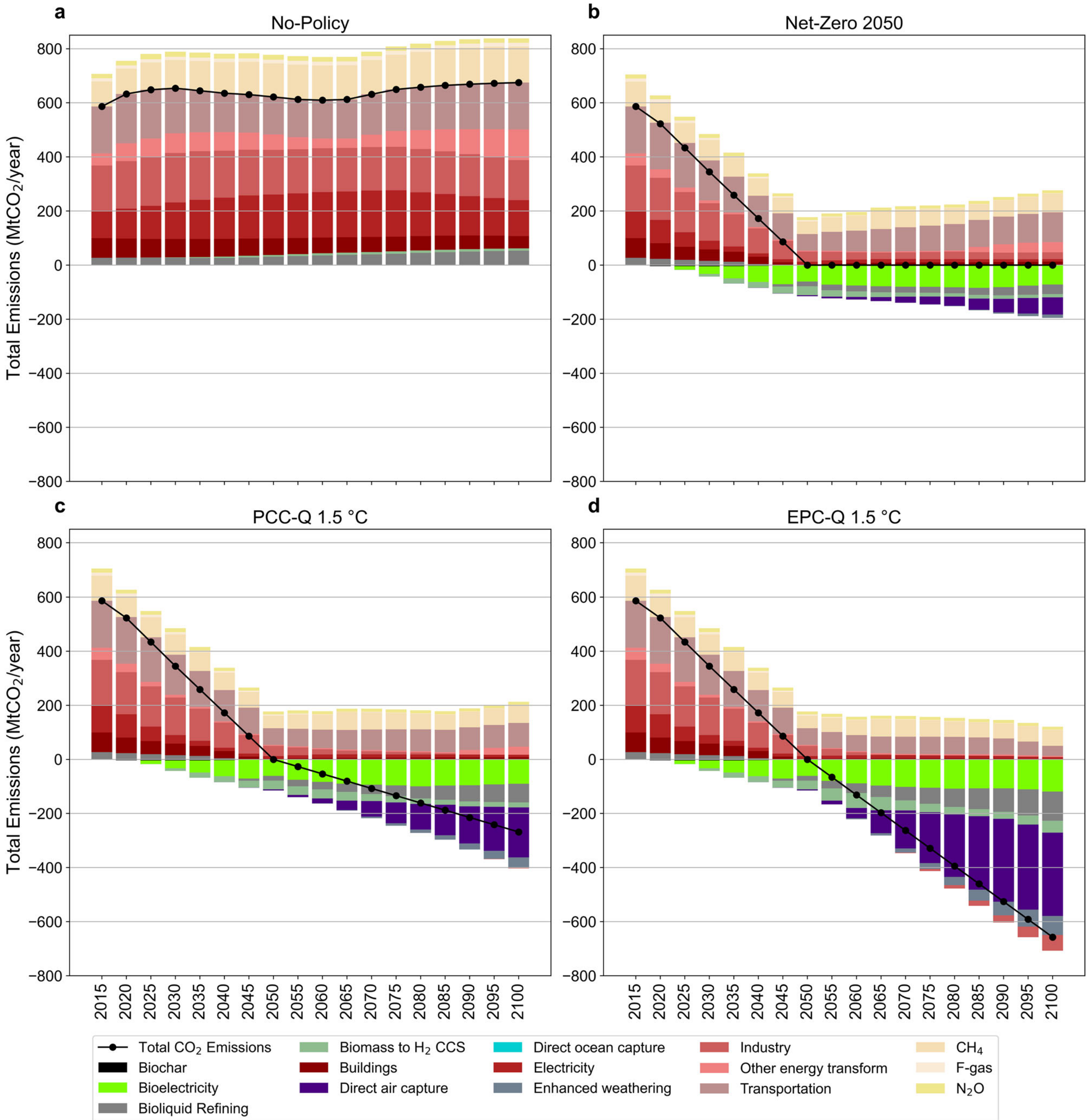

Fig. 1 | Emissions and removals by sector in Canada. **a** CO_2 and non-CO_2 emissions by sector in the No-Policy counterfactual baseline scenario, which assumes no mitigation measures (e.g., carbon tax) are implemented. **b** CO_2 and non-CO_2 emissions, along with CO_2 removal by sector, for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **c**, **d** Sectoral emissions and removals under equity-based scenarios PCC-Q 1.5 °C and EPC-Q 1.5 °C, respectively (details provided in the "Methods" section). Different sectors are represented by distinct colors, and the black line indicates the total CO_2 emissions across all sectors.

increases from 400 to 1600 $MtCO_2$, depending on the scenarios. The yearly sectoral emissions/removals in these two scenarios are shown in Supplementary Figs. 3 and 4. In scenarios constrained by limited carbon storage capacity, the cumulative contribution of DAC is reduced by approximately 16–30%, varying with the equity principle applied. The yearly sectoral CO_2 emissions and removals in the limited carbon storage scenario are presented in Supplementary Fig. 5.

In limited DAC scenarios, where a cap was set on its yearly deployment—reaching 30 $MtCO_2$ by 2050 and 100 $MtCO_2$ by 2100 (more information on the scenario logic is available in Table 1)—we observe a reduction in the role of DAC (25–29%) and an increase in the roles of BECCS (7–15%) and EW (55–80%) for the equity-based scenarios. In scenarios with a low-cost trajectory for DAC, we observe a substantial increase in its cumulative deployment, with figures ranging from 5.5 (from 1.5) to 8.7 (from 6.4) $GtCO_2$, influenced by the chosen equity principle. By 2100, the annual deployment of DAC peaks at 261 and 344 $MtCO_2$ for the PCC-Q and EPC-Q 1.5 °C scenarios, respectively. In contrast, a high-cost trajectory, assuming constant costs throughout the century, reduces DAC's cumulative deployment to just 2.2 $MtCO_2$ and 38 $MtCO_2$ for the Net-Zero and PCC-Q 1.5 °C scenarios, respectively. However, in the EPC-Q 1.5 °C scenario, our most

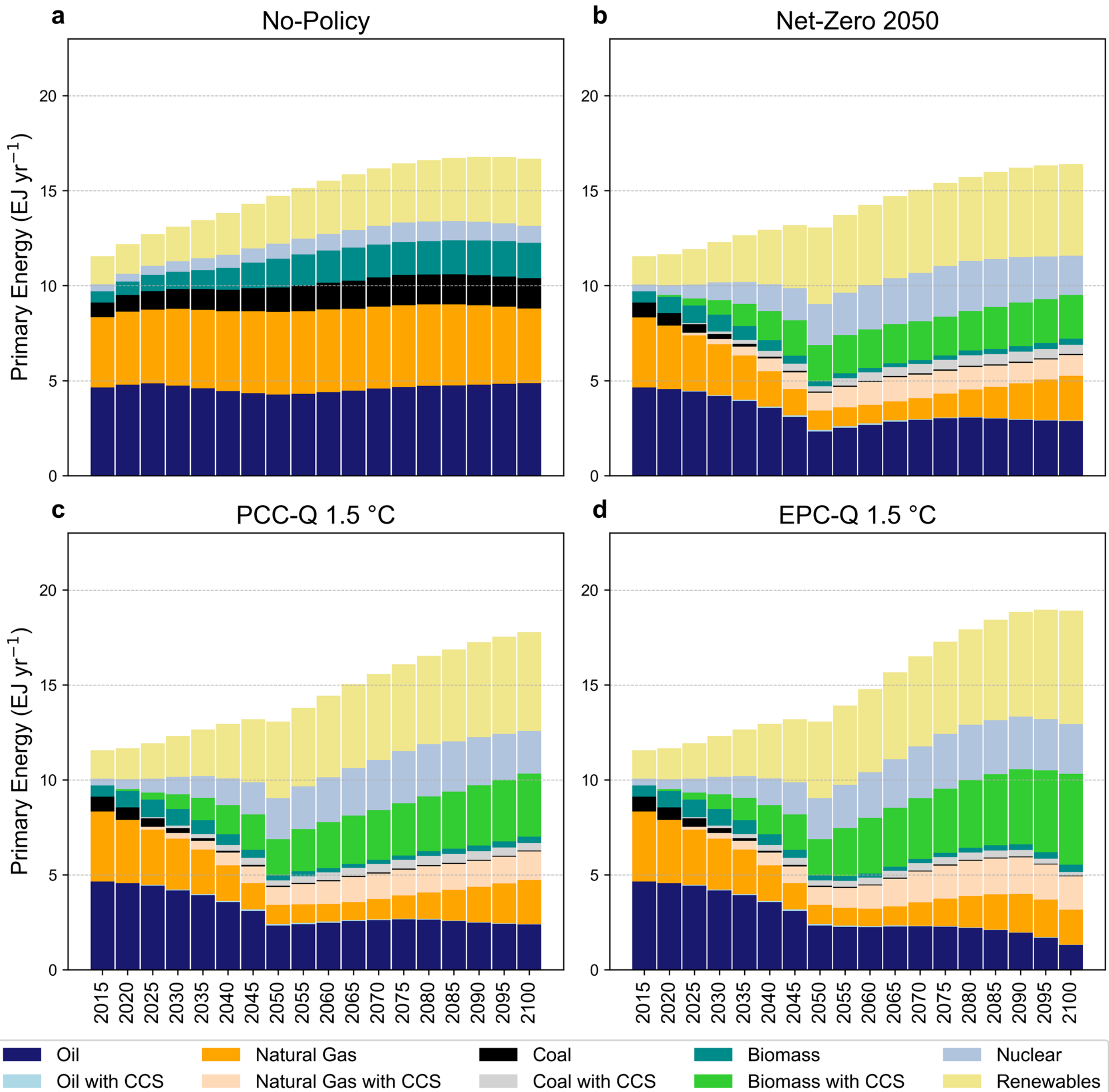

Fig. 2 | Primary energy production in Canada. **a** Primary energy production by sector in the No-Policy counterfactual baseline scenario, which assumes no mitigation measures (e.g., carbon tax) are implemented. **b** Primary energy production for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **c**, **d** Primary energy production under equity-based scenarios PCC-Q 1.5 °C and EPC-Q 1.5 °C, respectively (details provided in the "Methods" section). Different energy technologies are depicted in distinct colors. For certain technologies, such as oil, variants with carbon capture and storage (CCS) are included and labeled "with CCS".

ambitious pathway, DAC still plays a crucial role in achieving the necessary level of negative emissions, though its deployment decreases from 8.7 $GtCO_2$ in the primary scenario to 3.7 $GtCO_2$. This stark difference underscores DAC's sensitivity to cost and its competitive standing compared to other CDR strategies. The yearly sectoral emissions/removals in limited DAC, low-cost, and high-cost DAC scenarios are shown in Supplementary Figs. 6–8, respectively. In scenarios with limited EW availability, DAC's role increases slightly (up to 4% in equity-based scenarios) to offset the reduced contribution of EW. However, due to EW's overall smaller deployment compared to DAC, this increase is less significant. Yearly sectoral emissions/removals for the limited EW scenario are shown in Supplementary Fig. 9.

In our primary scenarios, we do not account for emissions or removals from land use/cover within the emissions constraints. We prevent excessive dependence on carbon removal through traditional land management for several reasons: (1) The land-use sector in Canada alternates between acting as a carbon sink and a source of emissions; (2) There's an observed increase in wildfire occurrences, with 23% of total wildfire emissions in 2023 attributed to Canada[35]; (3) To prevent the model from heavily relying on land-use changes to achieve negative emissions—a strategy that GCAM often favors for its cost-effectiveness[36]. There are also a few factors that might inhibit a high level of carbon sink, such as (1) elevated management costs, some of which are coming from monitoring, validation, and regulation of the land carbon sequestration projects to ensure additionality[37], (2) the risk of reversal, where carbon is released back into the atmosphere either intentionally through land-use decisions

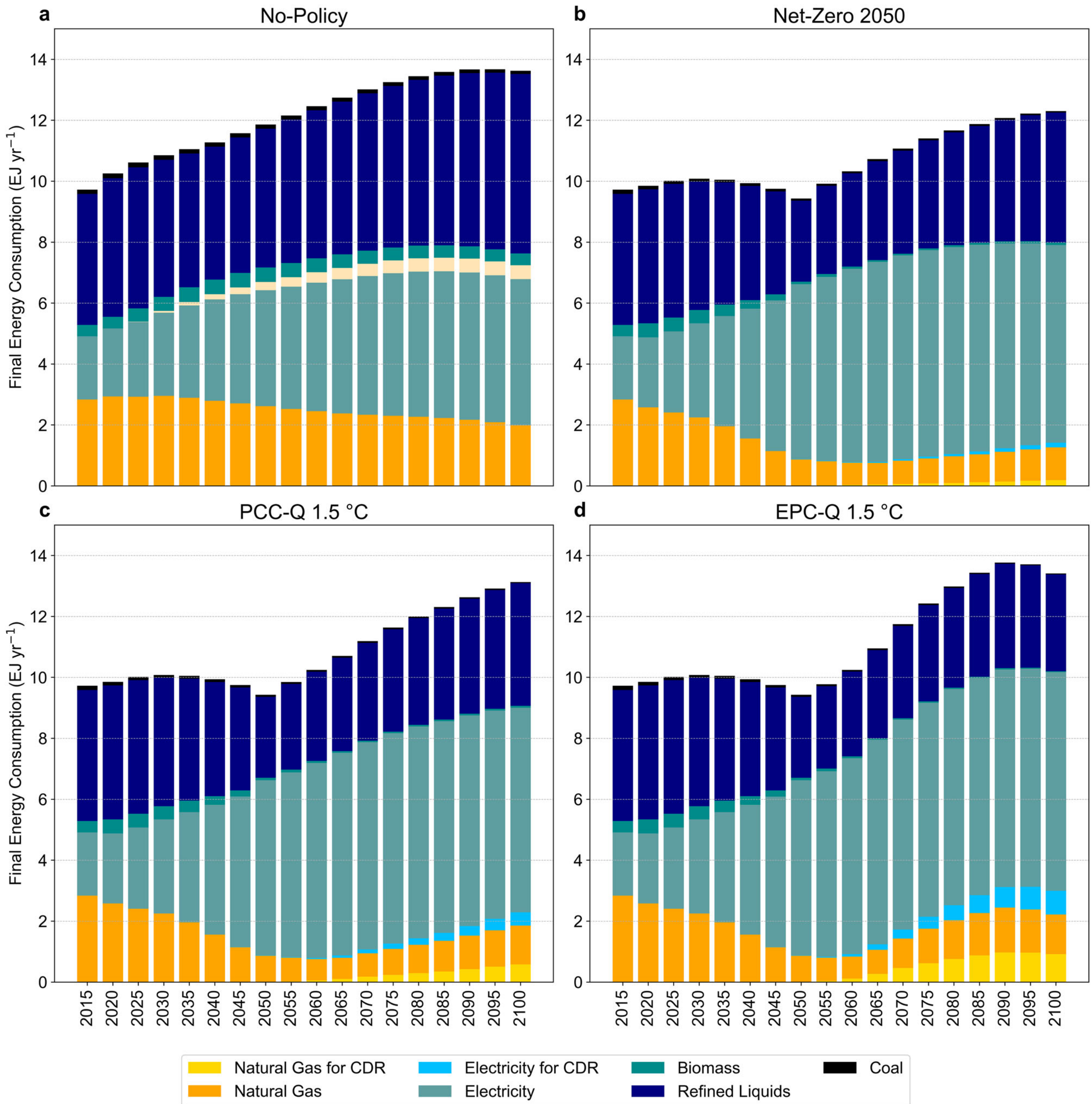

Fig. 3 | Final energy consumption by modes in Canada. a Final energy consumption by mode in the No-Policy counterfactual baseline scenario, which assumes no mitigation measures (e.g., carbon tax) are implemented. **b** Final energy consumption for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **c, d** Final energy consumption under equity-based scenarios PCC-Q 1.5 °C and EPC-Q 1.5 °C, respectively (details provided in the "Methods" section). Different energy consumption modes are represented by distinct colors. The natural gas and electricity required for carbon dioxide removal methods are labeled "for CDR".

or unintentionally due to climate-related extreme weather events such as storms and wildfires[38]. Although these challenges led us to exclude land-based carbon removal from our primary scenarios, in this section, we explore the implications of effectively addressing them. We assume Canada implements a successful land-management strategy capable of removing 50 $MtCO_2$ by 2050, a figure consistent with current literature and the recent Energy Future Report[22]. This is particularly important given that in IPCC scenarios, land-based carbon removal (through afforestation and reforestation) methods play a crucial role in the near term, while novel CDR methods are projected to have a marked impact later in the century, helping to balance residual emissions and reverse temperature overshoot[39].

For the ambitious EPC-Q and PCC-Q 1.5 °C scenarios, we anticipate an increase in land removals to 100 $MtCO_2$ by 2100. In scenarios where land use acts as a carbon sink, there's an observable increase in residual positive emissions for 2050—approximately 14% higher than in baseline scenarios. A closer examination of cumulative negative emissions reveals the pivotal role of land-use carbon removal, contributing 3.4–4.7 $GtCO_2$ across various scenarios. This also corresponds with a decrease in the cumulative deployment of other CDR methods, including a 12–28% reduction for DAC, 18–65% for EW, 12–14% for BECCS for electricity, and 17–23% for hydrogen production from biomass. The yearly sectoral emissions/removals in a scenario with land-based CDR are shown in Supplementary Fig. 10.

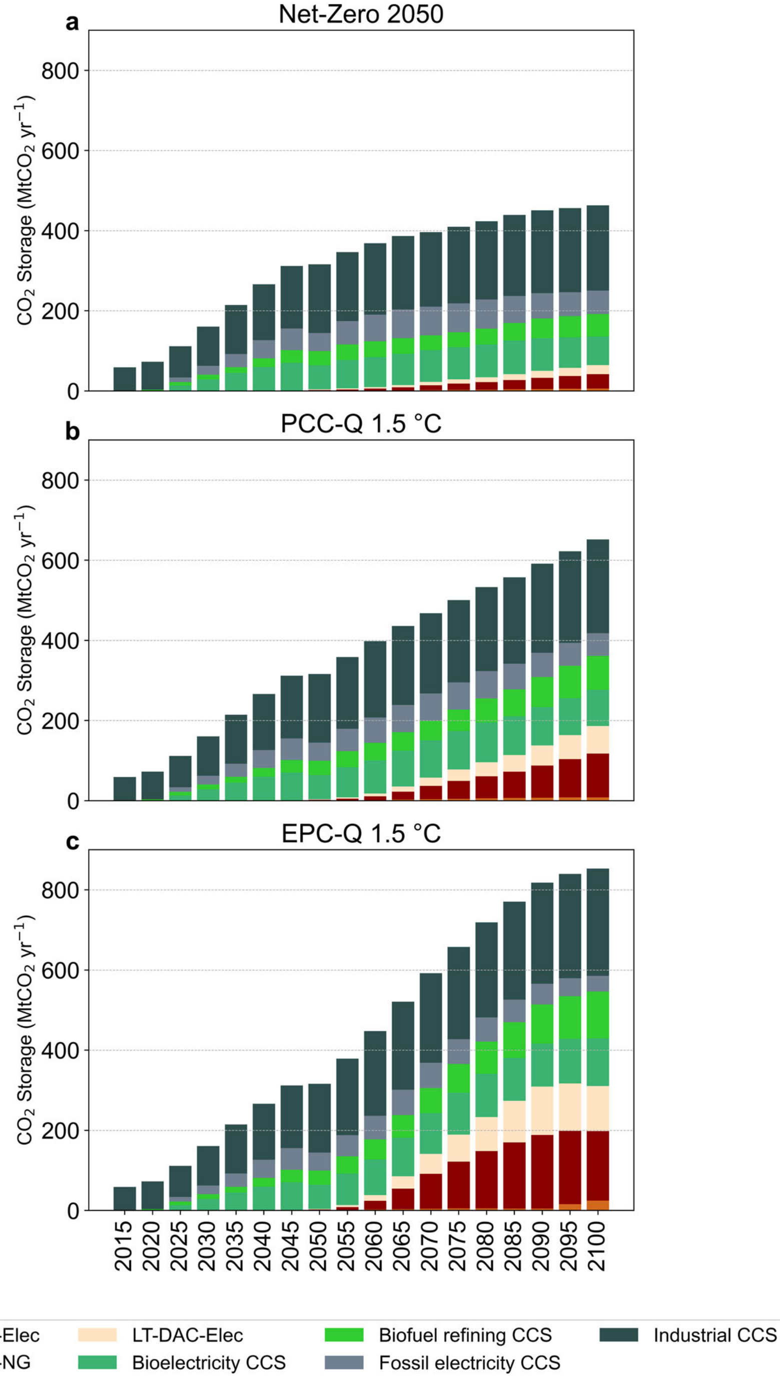

Fig. 4 | Required carbon storage in net-zero and equity-based scenarios in Canada. **a** Required carbon storage for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **b**, **c** Required carbon storage under equity-based scenarios PCC-Q 1.5 °C and EPC-Q 1.5 °C, respectively (details provided in the "Methods" section). Different CO_2 sources requiring storage are represented by distinct colors. For Direct Air Capture (DAC), the legend includes three technological variants: (1) high-temperature DAC with heat supplied by electricity (HT-DAC-Elec), (2) high-temperature DAC with heat supplied by natural gas (HT-DAC-NG), and (3) low-temperature DAC with heat supplied by electricity (LT-DAC-Elec).

Future energy pathway and the availability of natural-gas powered DAC

This section explores how an alternative future with considerable socio-technological change (STC) impacts energy use, emissions, and CDR deployment. The STC scenario, based on the SSP1 "Sustainable Development" storyline, emphasizes renewable energy, reduced biomass reliance, improved efficiency, lower energy demand, deep transportation decarbonization[28,40], and limited nuclear growth. A variant, "STC with No HT-DAC-NG," excludes natural gas-powered DAC to further reduce fossil fuel reliance. We compare these scenarios' energy characteristics, emission pathways, and CDR deployment with our primary scenarios.

As shown in Fig. 6a, nuclear energy in STC scenarios drops significantly to 1–2% by 2100, compared to 12% in baseline scenarios. Fossil fuel energy production declines to 13% in the EPC-Q 1.5 °C STC scenario (26% in the baseline scenario) and further to 9% when HT-DAC-NG is excluded. Final energy demand (shown in Fig. 6b) also decreases markedly, with electrification rising to 62–77% and natural gas reliance falling to 2–10%. In the EPC-Q 1.5 °C scenario, DAC electricity use increases from 5.8% to 8.4% under STC, reaching 10.4% when HT-DAC-NG is excluded. Meanwhile, natural gas use for DAC drops from 6.8% to 3.7% and to zero when HT-DAC-NG is unavailable, underscoring a clear shift away from fossil fuels in STC scenarios.

The reduction in final energy demand, combined with Canada's cleaner energy mix in the STC and STC without HT-DAC-NG scenarios, significantly lowers residual emissions by 2100, reducing reliance on CDR. As shown in Fig. 7b, STC scenarios have shorter bars above the year axis

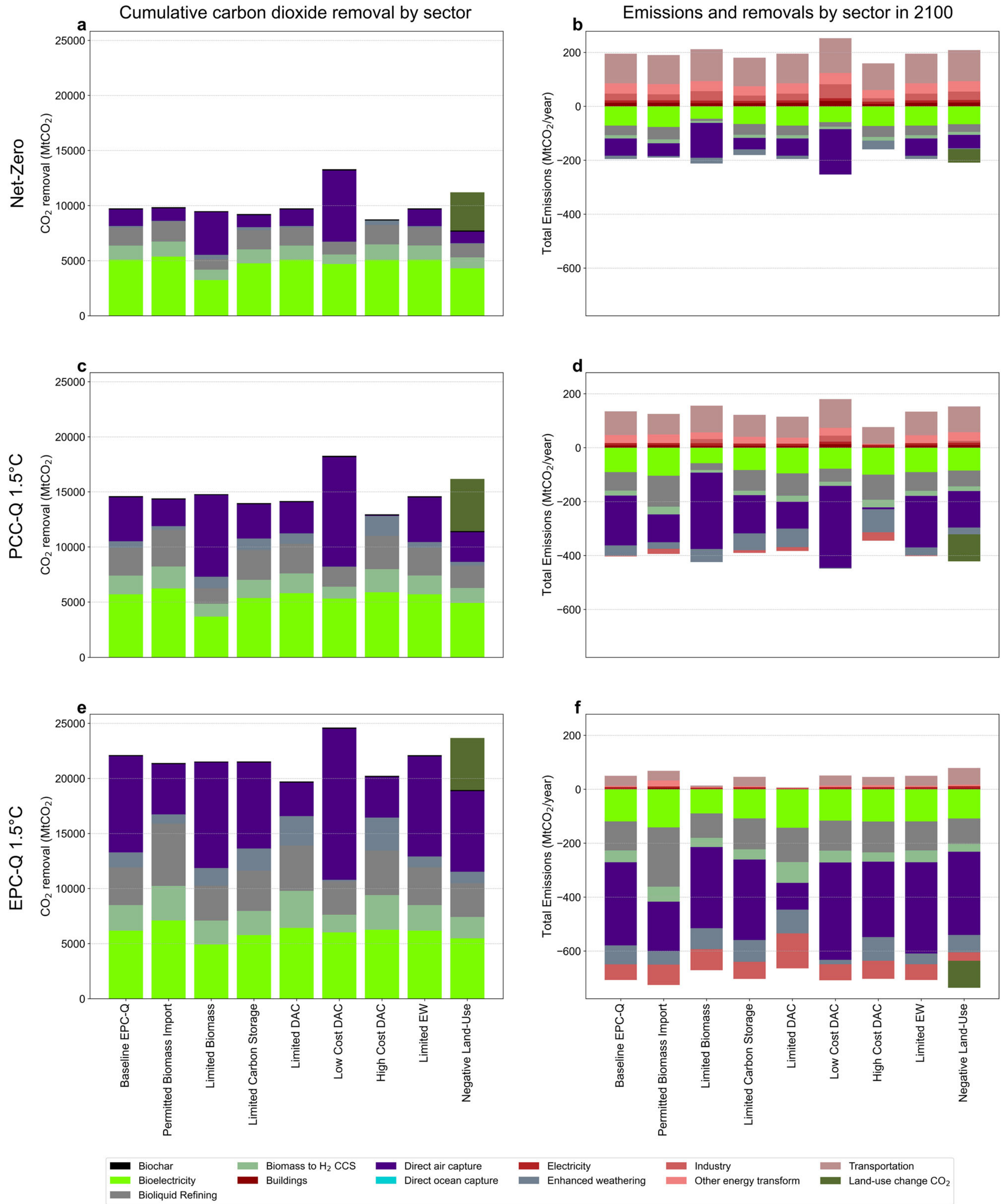

Fig. 5 | CO_2 Emissions and removals under different techno-economic uncertainties in Canada. a, c, e Cumulative CO_2 removal by different technologies across sensitivity analysis scenarios (detailed on the *x*-axis, with further information in Table 1) for the net-zero (**a**), PCC-Q 1.5 °C (**c**), and EPC-Q 1.5 °C (**e**) scenarios. **b, d, f** CO_2 emissions and removals in 2100 by different technologies across sensitivity analysis scenarios for the net-zero (**b**), PCC-Q 1.5 °C (**d**), and EPC-Q 1.5 °C (**f**) scenarios. Different sources of emissions and removals are represented using distinct colors.

compared to the baseline, reflecting lower residual emissions. For example, residual CO_2 drops from 195 $MtCO_2$ in the baseline Net-Zero scenario to 94 $MtCO_2$ in 2100. In the most ambitious scenario, EPC-Q 1.5 °C, emissions decrease further from 50 to 7.5 $MtCO_2$ in the "STC and No HT-DAC-NG scenario." This substantial reduction is largely driven by the transportation sector, which sees lower emissions due to reduced demand and stronger decarbonization efforts. Detailed comparisons are provided in Supplementary Note 1 and Figs. 1, 2, and 11.

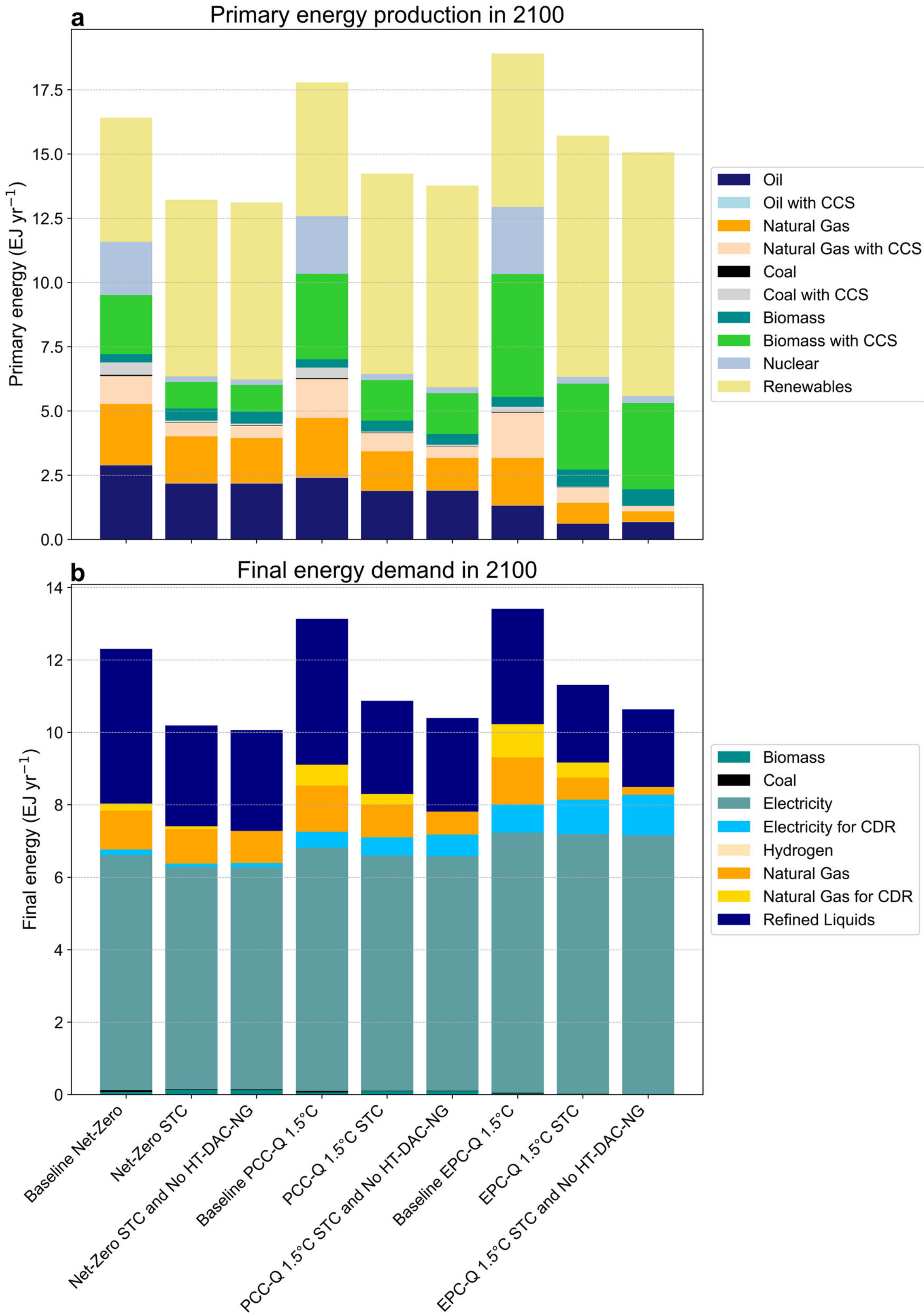

Fig. 6 | Future energy characteristics under alternative socio-technological pathways in Canada. **a** Primary energy production in 2100 by different sources under baseline and alternative socio-technological scenarios. **b** Final energy consumption by mode in 2100 under baseline and alternative socio-technological scenarios. Baseline scenarios are labeled with "baseline" at the beginning of the name, while alternative socio-technological pathways are labeled with "STC" (socio-technological change) and "STC and No HT-DAC-NG," which excludes high-temperature DAC technology where heat is supplied by natural gas from the model's technology portfolio. Further details on scenario logic can be found in Table 1.

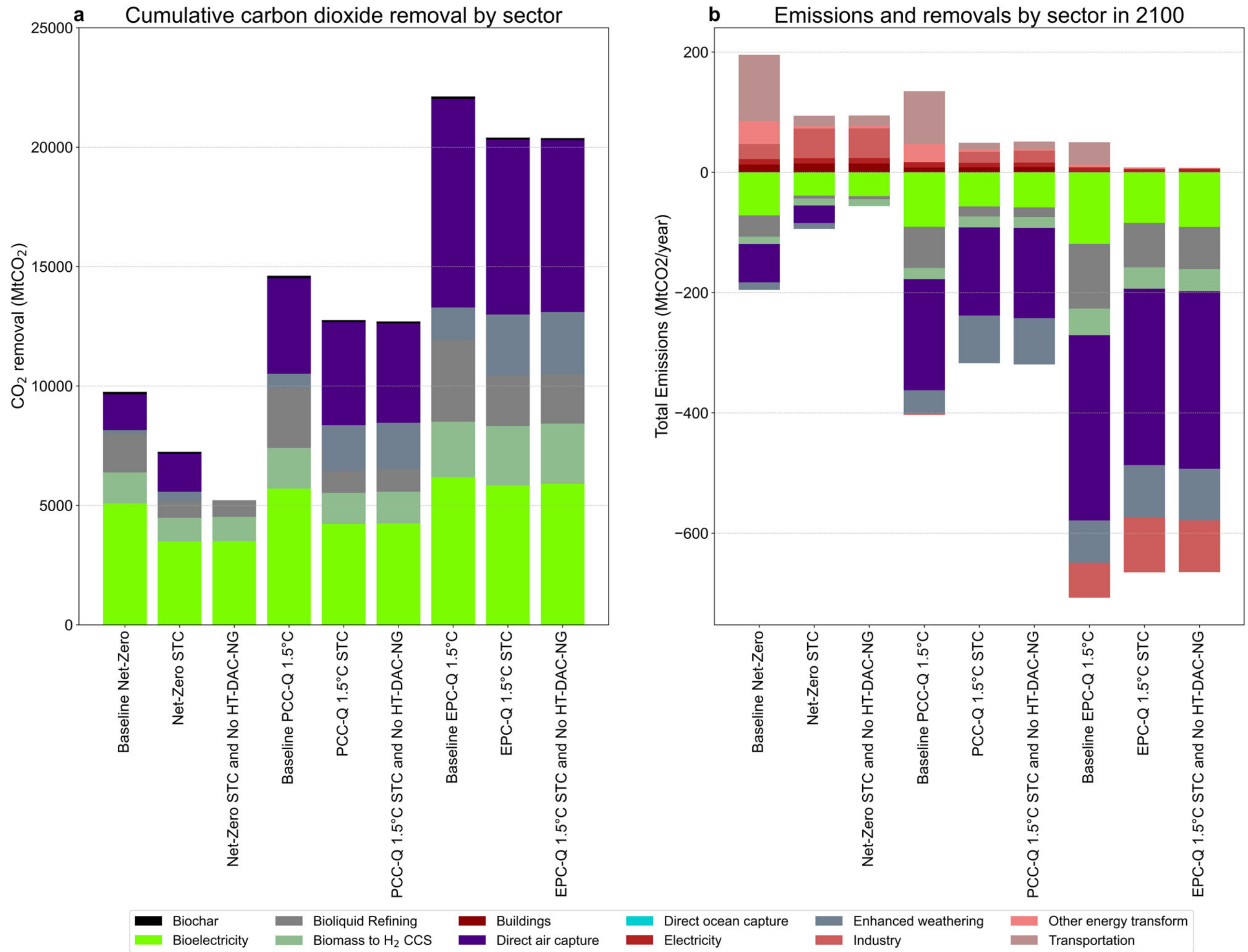

Fig. 7 | CO_2 Emissions and removals under alternative socio-technological pathways in Canada. a Cumulative CO_2 removal by different technologies under baseline and alternative socio-technological scenarios. **b** CO_2 emissions and removals in 2100 by different technologies across alternative socio-technological scenarios. Baseline scenarios are labeled with "baseline" at the beginning of the name, while alternative socio-technological pathways are labeled with "STC" (socio-technological change) and "STC and No HT-DAC-NG," which excludes high-temperature DAC technology where heat is supplied by natural gas from the model's technology portfolio. Further details on scenario logic can be found in Table 1.

In our scenarios, CDR plays two primary roles: (1) compensating for residual emissions and (2) achieving negative emissions to meet equity-driven targets. In the STC scenarios, the need for CDR to address the first goal is dramatically reduced due to stringent emissions reductions and minimized residual emissions. However, as shown in Fig. 7a, in our equity-focused scenarios, EPC-Q and PCC-Q 1.5 °C, CDR still plays a pivotal role. Various methods such as BECCS for electricity (4.2–5.9 $GtCO_2$), BECCS for hydrogen (1.3–2.5 $GtCO_2$), DAC (4.1–7.3 $GtCO_2$), and enhanced weathering (1.8–2.6 $GtCO_2$) remain crucial, despite a slight decrease due to the reduction in residual emissions.

Growth rates of CDR vs. historical technology adoption in Canada: uncertainties and challenges

CDR technologies are crucial for meeting policy targets, especially by century's end in EPC-Q and PCC-Q scenarios. Currently, non-land-based methods like DAC are in their early stages, with minimal deployment, high risks, and limited resources. Nemet et al.[41] examined global scenarios aligning with Paris Agreement temperature goals, concluding that novel CDR technologies must be developed within the next 15 years to move past the formative stage and achieve dramatic scaling post-formation. The formative phase is crucial in determining the trajectory of a technology during its subsequent expansion; however, overcoming barriers during the scale-up phase is equally critical. Based on the literature on the early stages of technology development[29,42], the formative phase is considered complete when technology reaches 2.5% of its eventual saturation.

In this section, we are interested in comparing the growth rate in CDR technologies as projected by our model to historical rates. To do this, we calculated both the average and maximum growth rates of various CDR technologies from the end of the formative phase to full saturation. These rates were compared with the historical average and maximum growth rates of 20 pathways associated with the adoption of energy and chemical materials in Canada, as recorded in the Historical Adoption of TeCHnologies (HATCH) dataset[29,43]. These technologies were classified into two categories: (1) energy (e.g., nuclear power) and (2) chemicals and material productions (e.g., ammonia synthesis), with a comprehensive classification presented in Supplementary Table 2.

Figure 8 illustrates the comparative analysis of the average and maximum growth rates for technology adoptions across different scenarios. The growth rates are detailed for different CDR methods including BECCS for electricity and hydrogen production, EW, and three variants of DAC. In our primary scenarios, BECCS for electricity and H_2 production exhibit average growth rates of 2.8–3.8% and 11.6–16.1% per year, with maximum growth rates of 18% and 68% per year, respectively. EW demonstrates an average growth rate of 7.6–9.6% per year and a maximum of 22–27% per year between 2058 and 2086, varying by scenario. DAC technology variants typically require an average growth rate of 7–8.1% per year from the end of

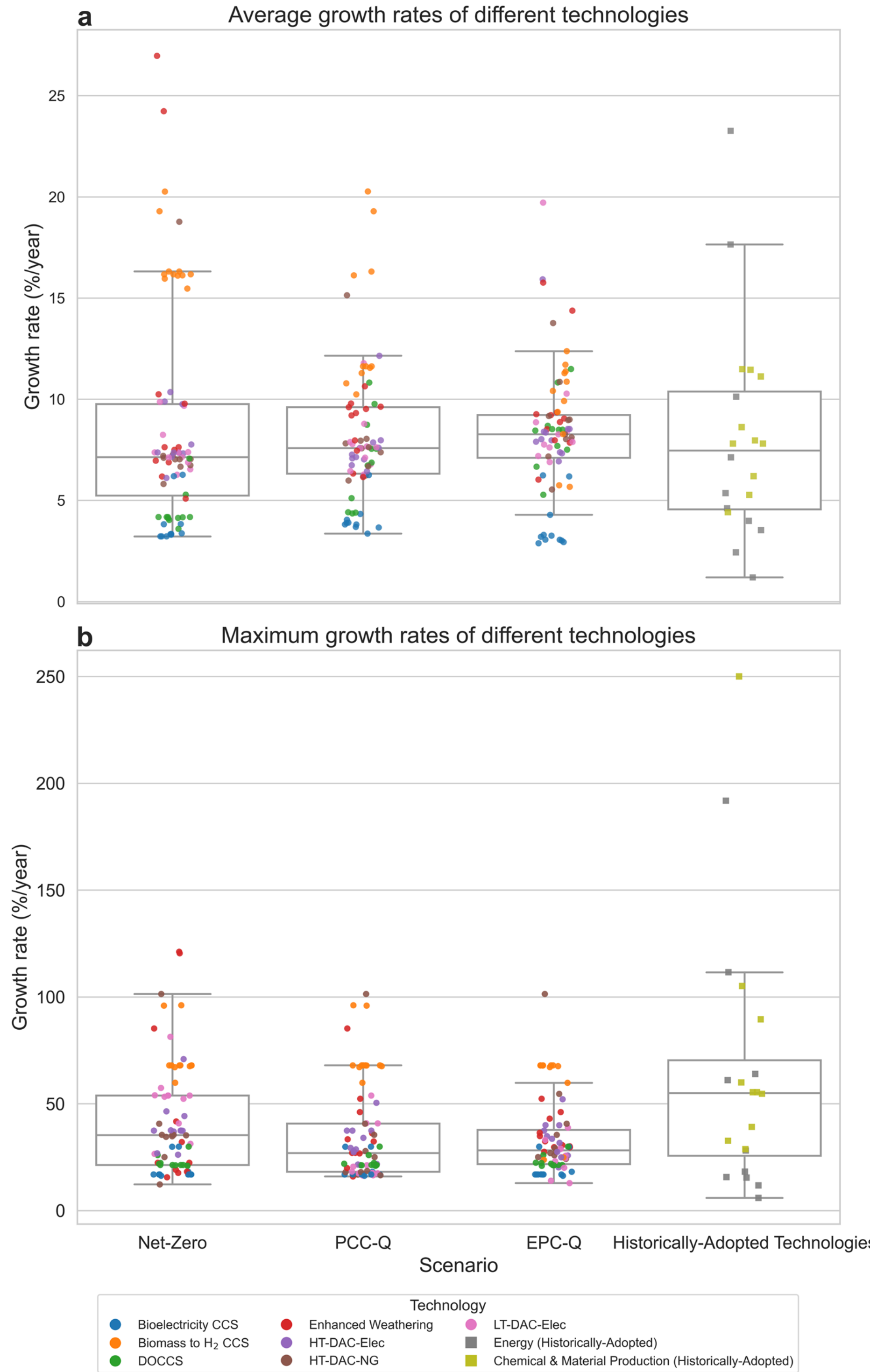

Fig. 8 | Comparative analysis of growth rates for carbon dioxide removal technologies and historically adopted technologies in Canada. **a** Average yearly growth rate (%/year) of various carbon dioxide removal (CDR) technologies under the Net-Zero and equity-based scenario families, including EPC-Q 1.5 °C and PCC-Q 1.5 °C, across all primary and sensitivity scenarios listed in Table 1. The plot also includes two categories of historically adopted technologies[43] in Canada, grouped under 'Historically Adopted Technologies.' These technologies are classified into: (1) energy and (2) chemical and material production. **b** Maximum yearly growth rate (%/year) is for the same scenarios and technologies. Box plots illustrate the distribution of average growth rates (top chart) and maximum growth rates (bottom chart) across the CDR technologies and historically adopted technologies. Box plots illustrate the distribution of growth rates across technologies, excluding outliers (data points falling below Q1 − 1.5× IQR or above Q3 + 1.5× IQR. Here, Q1 is the first quartile (25th percentile), Q3 is the third quartile (75th percentile), and IQR (interquartile range) is the difference between Q3 and Q1. Strip plots overlay individual data points, with circles representing current scenarios and squares representing historically adopted technologies. Colors indicate different technologies. Classification of historically adopted technologies is provided in Supplementary Table 2.

their formative phase until they achieve maximum capacity by 2100. The peak growth rate for DAC occurs between 2048 and 2060, depending on the technology variant and specific scenario. In scenarios where DAC deploys at a greater scale—either due to limited biomass supply or relatively lower costs—the average and maximum growth rates can escalate to as high as 9.7% per year and 44% per year, respectively.

When comparing these rates to historically adopted technologies in Canada after their formative phases, the projected growth rates for CDR technologies are notable yet not unprecedented. For instance, the production of biofuels in Canada, post its formative phase in 1999, maintained an average growth rate of 23.2% per year, peaking in the 2006-2007 period with a nearly threefold increase (191%). Similarly, ammonia synthesis, after its formative phase in 1961, experienced an average growth rate of 7.8%, with a peak of 55% in 1975–1976, reaching its zenith in 1999. A key point about this example is that the literature highlights ammonia synthesis, an energy-intensive chemical technology for processing atmospheric gases, as an analogous technology to high-temperature DAC. Both ammonia synthesis and DAC are processes characterized by their high energy intensity. Historically, ammonia synthesis was expanded during the world wars and the Green Revolution, demonstrating how industrial technologies can be scaled up in response to global needs. Similarly, DAC could be expanded as an emergency response to the climate crisis[44]. Furthermore, ammonia synthesis intervenes in the nitrogen cycle by industrially converting nitrogen to ammonia, while DAC intervenes in the carbon cycle by capturing atmospheric carbon dioxide[41,45]. The Canadian DAC growth rate projection (7–8.1%) is very close to how Canada has historically expanded ammonia synthesis.

Although reducing emissions and approaching net zero is the primary and most critical step, Canada's carbon debt can only be addressed through CDR, whether by domestic deployment or future participation in international CDR markets. While Fig. 8 shows that the growth rates projected for BECCS, EW, and DAC are comparable to those achieved by other technologies in Canada, scaling up these methods presents critical challenges.

For example, the most pressing problem for scaling up BECCS is the rising demand for land, water, and fertilizers, which can directly compete with food production and put pressure on already limited world resources. When expanded to fulfill climate targets, the land and water footprint of BECCS may have a detrimental impact on environmental goals like ecosystem services and biodiversity protection. Logistical problems further hinder BECCS implementation. Large-scale biomass agriculture raises the need for agricultural water and nitrogen fertilizers, both of which are resource-intensive and can cause environmental deterioration[46]. Although technical solutions such as employing agricultural leftovers or algal biomass can alleviate part of the land-use demand, these approaches still challenge scalability and resource availability limitations[47].

Similarly, with EW, a major worry is the possible release of harmful components from industrial wastes used in EW, which might pollute soil and endanger food safety[48]. Furthermore, the energy required for mining, crushing, and transporting rock powder may jeopardize the process's long-term viability if it is not fueled by renewable energy[49].

DAC is frequently regarded as a more flexible CDR option due to its lower land-use requirements when compared to other methods. However, its high energy intensity poses a challenge. Unless DAC systems are powered by low-carbon energy sources, their overall carbon removal potential may be limited[50,51]. In addition to energy demands, DAC technologies have large material requirements. While the input requirements for chemical sorbents do not limit the scalability of DAC, material efficiency improvements are required to reduce environmental impacts and optimize resource use, as well as to ensure the technology's viability and social acceptability [51]. The economic feasibility of DAC presents an evident challenge, with costs varying from \$30 to \$600 per tonne of CO_2 captured, rendering it economically impractical without substantial policy intervention, including carbon pricing or subsidies[52]. Concerns exist regarding the potential burden on local infrastructure, especially in economically disadvantaged communities. In California, for instance, there are fears that DAC facilities could lead to increased energy costs for ratepayers, especially in low-income areas already burdened by other waste-processing infrastructure[53]. Additionally, logistical challenges related to CO_2 transport and storage, along with the need for extensive renewable energy infrastructure, further complicate the large-scale deployment of DAC.

Discussion

In this study, we explored the potential roles of various CDR methods at the point of achieving net-zero and the potential evolution of their roles beyond the net-zero year under two burden-sharing frameworks, which are EPC-Q and PCC-Q, incorporating historical emissions, benefits derived from those emissions, and countries' capabilities to undertake mitigation actions[41]. We also examined how the role of CDR might shift under principles that disregard these equity dimensions, as discussed in Supplementary Note 2 and illustrated in Supplementary Fig. 12.

In addition to the quantitative results of CDR methods deployment, we offer insights into the different dimensions related to national and global equity, CDR, and decision-making. The discussion of equity in the context of the Paris Agreement is not just a policy preference but an international legal commitment, as outlined in Article 2[1]. Beginning to apply a quantitative framework to the varying definitions of equity in modeling exercises can help inform actionable CDR policies for decision-makers. This study provides deeper insights into the scale of CDR required at the national level to meet fairness commitments, specifically for Canada.

Implementing equity is not just about doing more in terms of reductions and removals; different approaches to equity lead to drastically different national-level mitigation portfolios. This is evident in the increased requirements for EW and DAC in the EPC-Q 1.5 °C scenario and the varying energy, land use, and geological storage needs associated with scaled-up levels of CDR. Understanding the broader system requirements of equity-driven climate policy is crucial for long-term planning decisions within national polities. Equity-consistent decisions must be made in the medium term (next 10–15 years). The study suggests several low-regret policy choices that are necessary across various scenarios, such as increased use of land-based carbon sinks, development of geological storage infrastructure, and a diversified energy supply. The study also highlights the tension between global and local equity demands. The equity-based approaches modeled reflect global considerations of fairness in burden distribution among states. However, local inequities may arise at the national level, particularly in land-use decisions driven by technologies such as BECCS, which may impose localized burdens. Similarly, fixed geological storage opportunities can lead to localized burdens. Substantial national-level investment is needed for global equity, but this may revive earlier debates on burden-sharing that were set aside with the Paris Agreement framework.

Finally, the study identifies potential constraints on realizing equitable outcomes. Technology adoption rates are one such constraint, and comparing the needed rates with other historically adopted technologies in Canada reveals the potential feasibility of CDR deployment at scale. Conditions enabling rapid technological scaling and their applicability to CDR require deeper investigation. Our models assumed that Canada would implement all CDR methods domestically. However, the development of an integrated international CDR market may prompt countries to invest in CDR deployment abroad, particularly when facing feasibility challenges domestically[13,54]. Differences between NRCB-based and global modeling may highlight cost-effective opportunities outside Canada that can be pursued through technology transfer and international trading, in alignment with equity principles.

Moving forward, there are areas where future studies could build upon our work. One recommendation is to incorporate non-CO_2 greenhouse gas emissions more explicitly. In this study, NRCBs were calculated based solely on CO_2 budgets, as carbon removal methods are primarily focused on CO_2 emissions. However, between 2050 and 2100, non-CO_2 emissions are projected to range from 60 to 80 $MtCO_2$-equivalent (Fig. 1), which suggests that CDR methods might play an additional role in offsetting these emissions if no specific policies are enacted to reduce them. It is important to note that nearly all our scenarios depend on substantial decarbonization across various sectors, partly facilitated by CCS technologies. GCAM assumes these technologies will reach high capture rates once they are fully mature. However, current real-world capture rates may be considerably lower than GCAM's assumptions[55], underscoring the need for a more detailed sensitivity analysis of varying capture rates.

Methods

Equity-based national remaining carbon budget (NRCB)

The allocation of NRCBs will be determined by the definition of fairness used[56] and other modeling assumptions[57]. This allocation, in turn, determines how the transition costs and burdens of climate policy are distributed across countries. There have been multiple studies in the burden-sharing literature that address sharing the remaining carbon budget[17,25,27,58,59] or global CDR deployments[11,13,14] that are required for meeting climate targets. Two of the burden-sharing approaches for conducting such analysis include equal per capita (EPC) and per capita convergence (PCC). EPC and PCC methods offer contrasting strategies for distributing the remaining carbon budget, rooted in different justice philosophies[17]. EPC promotes an

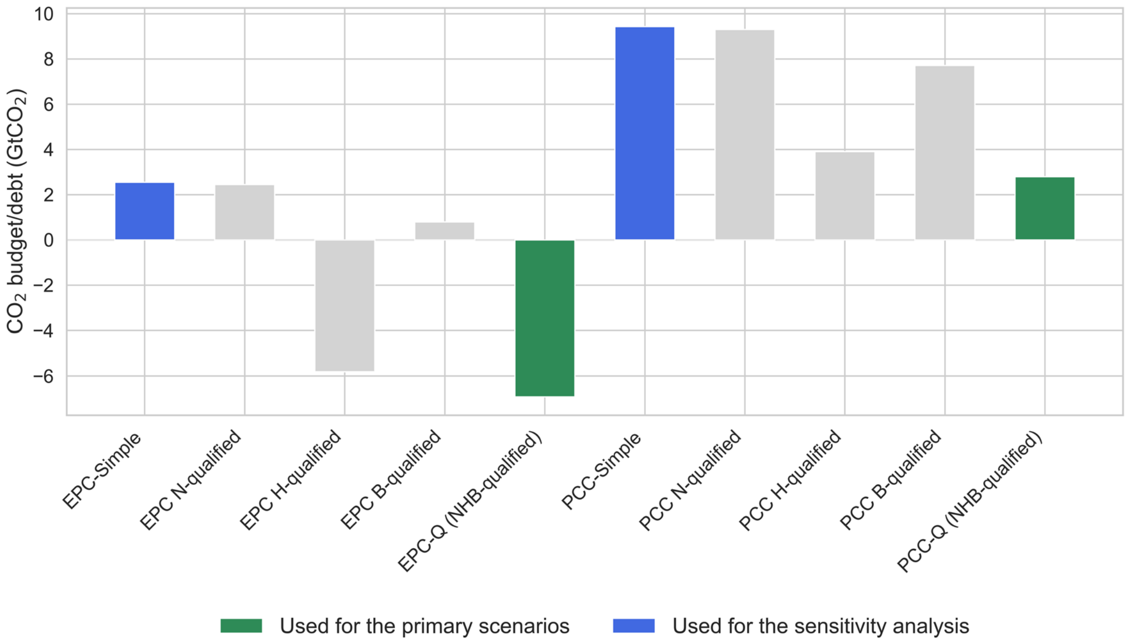

Fig. 9 | Remaining carbon budgets for Canada under different equity principles. This figure presents the remaining carbon budgets for Canada starting in 2017, calculated based on various burden-sharing principles as quantified by Williges et al.[17]. The budgets highlighted in green, EPC-Q and PCC-Q (both NHB-qualified), represent the primary scenario estimates, while those in blue, EPC and PCC-simple, are used for sensitivity analysis. Details are provided in Supplementary Note 2, with results shown in Supplementary Fig. 12.

egalitarian principle by allocating equal emission rights to every individual from the present until a set future date, such as 2050. This approach underscores an equitable distribution from the outset, disregarding the existing disparities in emissions among nations. Conversely, PCC acknowledges these current disparities by starting with the unequal levels of emissions and population shares, and it aims for a gradual shift towards equal per capita emissions by the end of the budget period. This transition reflects a more pragmatic approach, allowing for a phased reduction in emissions, particularly benefiting wealthier, higher-emitting countries during the initial phase. While PCC seeks to address the practical challenges of global emission reduction by accommodating existing inequalities, it faces criticism for initially favoring nations that have historically emitted more[17]. In particular, PCC incorporates a form of grandfathering, which Rajamani et al.[56] have indicated is not supported by international legal principles. However, PCC does reflect the incremental approach to mitigation ambition seen in many developed states' Nationally Determined Contributions.

Williges et al.[17], amended the EPC and PCC models to better align with fairness principles in three ways:

1) N-qualified: Implementing a basic needs threshold using the Human Development Index to determine initial CO_2 allocations, ensuring that countries below this threshold are supported to meet basic living standards before a standard emission distribution is applied.
2) H-qualified: Adjusting the historical accounting start date to 1995, recognizing countries' awareness of climate impacts by then, and incorporating this into their emission responsibilities.
3) B-qualified: Accounting for the benefits derived from emissions prior to 1995, deducting these from the emission shares of benefiting countries, to reflect the long-term effects of their past activities.

In applying equity principles to Canada's NRCB, we adopt these approaches (as opposed to, for example, ones based solely on historical emissions) with all three modifications (EPC NHB-qualified and PCC NHB-qualified) since these provide, in our view, a compelling and multi-dimensional approach to equity. Both equity principles take into account the basic needs of countries, historical emissions (from 1995), and benefits derived from past emissions[17]. In Fig. 9, we show different estimates of NRCB starting in 2017 based on EPC NHB-qualified and PCC NHB-qualified for the 1.5 °C target. For this paper, we will refer to EPC NHB-qualified and PCC NHB-qualified as EPC-Q and PCC-Q, respectively, where "Q" stands for "Qualified." In Supplementary Note 2, we also examine EPC Simple and PCC Simple to assess the potential implications of these approaches for Canada's post-net-zero carbon removal strategies. However, since EPC Simple and PCC Simple do not consider historical emissions, the basic needs of nations, or the advantages certain countries have gained from their past emissions, they are misaligned with several key equity principles. Further details on the equations and methodology used to quantify these principles can be found in Williges et al.[17].

GCAM and CDR representation

GCAM is a comprehensive integrated assessment tool that simulates interactions between energy, water, land, economy, and climate systems across 32 global regions. It finds the market equilibriums from 1990 to 2100 with updates every five years. By integrating these systems within its core rather than treating them as separate modules, GCAM provides insights into macroeconomic trends, energy supply and demand, agriculture and land use changes, and water usage, underpinned by population and productivity projections[60]. Since the primary objective of this study is to investigate the role of CDR methods in achieving net-zero and post-net-zero scenarios, we have chosen to utilize a specific version of the GCAM 5.4, as developed by Fuhrman et al.[28]. This version was selected for its enhanced capability to integrate various CDR approaches:

- Direct air capture (DAC): DAC involves several technologies aimed at extracting dilute CO_2 directly from the atmosphere[61]. In GCAM, DAC includes high-temperature solvent-based processes (HT-DAC), powered by either electricity or natural gas, and low-temperature (LT-DAC) options powered by electricity, each evolving in efficiency and cost[62].
- Direct ocean carbon capture and storage (DOCCS): DOCCS utilizes the ocean's higher CO_2 concentration, over 120 times that of the atmosphere, to capture CO_2 through electrochemical processes. This captured CO_2 is then geologically stored, allowing the ocean to absorb more atmospheric CO_2. In GCAM, this is modeled through stand-alone

and integrated desalination technologies[28].

- Bioenergy with carbon capture and storage (BECCS): BECCS combines bioenergy production from biomass with CO_2 capture and storage, aiming for negative emissions by balancing the CO_2 absorbed by biomass growth with that released during energy conversion[61]. GCAM models BECCS across multiple sectors to assess its impact on land, water, and emissions[28].
- Enhanced weathering (EW): EW accelerates natural weathering processes to increase CO_2 sequestration by treating rocks to increase their reactive surface area. This method is aimed at transforming weathering from a geological to a human timescale[61]. In GCAM, EW is represented by the application of crushed basalt on lands, with considerations for cost, land use, and environmental impacts[28].
- Biochar: Biochar is produced through the pyrolysis of organic materials in an oxygen-limited environment, resulting in a stable form of carbon that can enhance soil properties when applied to land[61]. In GCAM, biochar is modeled as a soil amendment that competes with the direct use of biomass feedstock for energy (i.e., BECCS) impacting soil carbon stocks. It can also possibly improve agricultural crop yields[28].

Scenarios and their socio-technical assumptions

We integrated Canada's commitment to reducing greenhouse gas emissions by 40–45% by 2030, aiming for net-zero emissions by 2050[63] as constraints within our GCAM model. Since the primary focus of this study is on the implications of the burden-sharing mechanism on the national deployment of CDR methods, and the remaining carbon budgets are calculated specifically for CO_2, we make a simplifying assumption that the government's targets apply exclusively to CO_2 emissions rather than all greenhouse gases. The model iteratively seeks market equilibrium across various Canadian sectors, ensuring alignment with the specified emission reductions. We then calculate cumulative emissions from 2017 to 2050. By comparing these cumulative emissions to the NRCBs starting from 2017 (as shown in Fig. 9), we assess Canada's carbon budget or deficit by 2050. This assessment is conducted under both the EPC-Q and PCC-Q equity principles, in the context of limiting warming to 1.5 °C targets. This assessment informs the emission constraints for every subsequent five-year period up to 2100, to utilize any remaining budget or address any carbon debt.

Canada faces a carbon debt (see the results section) under all assessed equity principles and temperature targets, indicating the necessity for net-negative emissions post-2050. Using GCAM, we project how these negative emissions could be realized through various CDR methods in the years following 2050. From the net-zero year through to 2100, a linear ramp-up of negative emissions reaches a peak in 2100. A detailed example of such a calculation is available in Supplementary Note 3 along with Supplementary Figs. 13 and 14. In our analysis, we conducted several scenarios to explore various sources of socio-technical uncertainties. Table 1 outlines these scenarios and provides their descriptions. To streamline the presentation of our results, we categorized these scenarios into two groups: primary scenarios, which are discussed thoroughly in the "Results" section, and others, which are examined in the context of sensitivity analysis. Given that the primary scenarios are subject to numerous sources of uncertainty, sensitivity analysis is employed to provide further insights into the impact of key variables. These latter scenarios differ in terms of the inclusion of removals from the land-use sector, temperature targets, and the techno-economic assumptions and constraints associated with different CDR methods, thereby offering a comprehensive understanding of potential outcomes.

Data availability

All model output data for this study are available in a public repository accessible at https://doi.org/10.5281/zenodo.14550600

Code availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. The particular version of GCAM is available at https://doi.org/10.5281/zenodo.7492895. Configuration files and codes used for generating the figures shown in this study are available at https://doi.org/10.5281/zenodo.14550600.

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The authors declare no competing interests.

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