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Ratcheting of climate pledges needed to limit peak global warming

In the format provided by the authors and unedited

Supplementary Information: Ratcheting of climate pledges needed to limit peak global warming

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S1 Ratcheting ambition: Background and an overview of the literature

Parties to the United Nations Framework on Climate Change (UNFCCC) adopted the Paris Agreement in 2015[1]. As part of the Agreement, parties committed to *hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*. In preparation for the Agreement, parties communicated nationally determined contributions (NDCs), outlining emission reduction efforts through 2025 or 2030. Paragraph 17 of Decision 1/CP.21 of the Agreement acknowledged that the collective ambition suggested by the NDCs was insufficient and *do not fall within least-cost 2 ˚C scenarios and much greater emission reduction efforts will be required than those associated with the NDCs* to achieve the long-term goals of the Agreement articulated above[2]. With a goal to encourage countries to enhance ambition over time, Article 4 of the Agreement mandated that every 5 years, each Party must come forward with new NDCs that *represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition*. This requirement for ever-increasing ambition from countries is referred to as the "ratchet mechanism" or "ratcheting of ambition"[3].

The 26th Conference of Parties (COP26) held in Glasgow in November 2021 represented the first opportunity in the 5-year cycle since Paris for countries to revise and update their previous NDCs and submit new NDCs. In the run-up to and during COP-26, 151 countries submitted updated and new NDCs, official or unofficial long-term strategies (LTSs)[4], long-term objectives that outline emission reduction strategies through the mid-century[5], and net-zero emissions targets[6]. Multiple studies have examined the collective emissions and long-term temperature implications of the updated and new 2021 NDCs, LTSs and net-zero emissions targets and compared their global emissions and temperature impacts with the 2015 NDCs[7-14]. A key insight from these studies is that although the updated and new NDCs submitted until the end of COP26 suggest higher ambition compared to the 2015 Paris NDCs, achieving the long-term goals of the Paris Agreement will require countries to increase or ratchet ambition in 2030 and beyond. Consistent with these studies, Article IV of the Glasgow Climate Pact calls for countries to revisit and further strengthen the 2021 NDCs by the end of 2022[15].

Our study provides an *ex-ante* analysis to understand the long-term temperature and emissions implications of ratcheting ambition beyond the latest 2021 NDCs by exploring a range of emissions pathways that incorporate a combination of strategies that countries might employ to ratchet ambition. In doing so, the study provides a scientific underpinning to help decisionmakers design revised and more ambitious pledges in response to the calls made in the 2021 Glasgow Climate Pact.

Previous studies that have explored high ambition emissions pathways can be categorized into four groups. Our study extends analyses that have been conducted by studies in all of the groups and makes important contributions. The first group of studies have explored the long-term temperature implications of ratcheting ambition and strengthening of the 2015 NDCs. Holz et al.[16] used the 2015 NDCs as a starting point to explore high ambition pathways that result in 1.5°C warming by the end of the century under a range of constraints on the scale and type of CO2 removal (CDR). This study found that regardless of CDR assumptions, ratcheting of near-term ambition is required for any 1.5°C pathway. The study also showed that the rate of

reduction in gross CO_2 emissions by the middle of the century in pathways with constraints on CDR could increase to levels without historical precedence. An important insight from this study is that constraints on CDR deployment highlight tradeoffs with non-CO2 GHGs and the need to significantly ramp up efforts to reduce non-CO_2 GHGs. Bharadwaj & Brierley[17] explored high ambition pathways with the 2015 NDCs as a starting point in which: i.) countries increase emission reduction rates beyond the 2015 NDCs by 1% per year resulting in all countries peaking emissions by 2040, ii.) countries increase emission reduction rates beyond the 2015 NDCs resulting in all countries peaking emissions by 2030, and iii.) countries increase current emission reduction rates by 2% per year in addition to peaking emissions in 2030. Although the study showed that increasing ambition could result in economic savings that amount to US$100 trillion, none of the pathways result in a likely (>66%) chance of warming remaining below 2°C. While these studies use the 2015 NDCs as a starting point, our study begins with the 2021 NDCs and is thus a timely contribution in the run up to COP27 to be held in 2022.

The second group comprises studies that have explored the long-term temperature implications of ratcheting ambition and strengthening of the 2021 NDCs. A recent study by Grant[3] investigated high ambition pathways with the 2021 NDCs as a starting point. The study defines three ways to evaluate the strength of a ratchet and found that repeating the increased ambition between the 2021 and 2015 pledges every 5 years could result in median 2100 temperature change of 1.5°C and limit peak warming to <2°C with an 80% probability. The study also found that limiting peak warming to 1.5°C with >50% chance requires strengthening the ratchet mechanism 4-fold. A key distinction between our study and Grant[3] is that the latter begins with the *global* emissions impacts of the 2021 NDCs as assessed by Climate Action tracker and constructs high ambition emissions pathways that do not provide information about where and how emission reductions occur. By contrast, our study is a primary analysis that begins with country-level NDCs as submitted by the countries in the run-up to and during COP26 to UNFCCC and incorporates them into a well-established integrated assessment model with regional, sectoral, and technological detail. By doing so, our study accounts for multisectoral dynamics that influence and are influenced by countries' emissions reduction efforts. Thus, our study extends the study by Grant[3] and contributes to the literature by providing important insights related to the regional and sectoral implications of ratcheting ambition.

The third group of studies have explored least-cost pathways that result in 2°C or 1.5°C warming by the end of the century and suggest higher ambition than the 2015 or 2021 NDCs[8,18,19]. Such pathways assume equal marginal cost of abatement across regions and sectors and serve the purpose of highlighting the "emission gap" between the NDCs and idealized pathways that get to 2°C or 1.5°C warming by the end of the century. By contrast, the purpose and design of the high ambition pathways in our study are different. Our pathways are <u>not</u> least-cost in that they *do not* assume an equal marginal cost of abatement across regions. In other words, our high ambition pathways start with the latest 2021 NDCs, incorporate different ways in which countries might ratchet ambition beyond those NDCs, and do not embed a long-term temperature target in their design. Thus, temperature change is an outcome of our pathways rather than a goal to be achieved.

The fourth group of studies have examined pathways that suggest higher ambition compared to the 2015 NDCs to study how countries might close emission gaps compared to the least-cost

pathways explored in the studies described above by implementing nationally relevant and short-term policy measures[20-22]. While the present study is similar to the above studies in that they all explore pathways in which the stringency of the NDCs is increased in regionally differentiated ways based on best practices, ambition of existing NDCs, etc., a key difference is that our study focuses on century-wide temperature implications of high ambition pathways while other studies focus on 2030 and 2050 regional emissions and sectoral impacts of implementing "good practice" and "bridge" policies and measures. In that sense, the above studies complement our analysis by providing a reasonable benchmark to understand the challenges and political feasibilities of the high ambition pathways explored in our study.

S2 Mapping of the pathways explored in this study with IPCC's Sixth Assessment Report[23,24]

The recently released Sixth Assessment Report (AR6) of the IPCC categorized emissions scenarios in the literature into eight (categories C1-C8). The categories are defined in terms of the likelihood of the scenarios exceeding end-of-century and peak global temperature change levels. Since this study does not examine the likelihoods of emissions pathways exceeding end-of-century and peak global temperature change levels, the mapping of the pathways explored in this report with IPCC's 6th Assessment report is based on a qualitative assessment drawing from Table SPM.2 in the Summary for Policymakers. Table SPM.2 provides a summary of key emissions and temperature characteristics of the scenarios assessed in the report. For the purposes of this mapping exercise, we compared the following characteristics of the pathways explored in this study with the ranges provided in Table SPM.2: i.) cumulative CO2 emissions (2020 to year of net-zero CO2), ii.) Cumulative CO2 emissions (2020 to 2100), iii.) Peak temperature change, iii.) 2100 temperature change. Based on this comparison, the emissions pathways explored in this study can be mapped to categories C2, and C3 (Table S1). These categories are defined in the report as follows:

- Category C1 comprises scenarios that limit end-of-century warming to 1.5°C with a >50% chance, and reach or exceed 1.5°C warming with a likelihood of ≤67%. In the IPCC report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades.
- Category C2 comprises scenarios that limit warming to 1.5°C in 2100 with >50% chance, and exceed 1.5°C with >67% chance. In this report, these scenarios are referred to as scenarios that return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1-0.3°C for up to several decades.
- Category C3 comprises scenarios that limit peak warming to 2°C with a >67% chance. In this report, these scenarios are referred to as scenarios that limit warming to 2°C (>67%).

An important caveat of this mapping exercise is that the underlying socioeconomic and technological assumptions of our pathways may not be consistent with many of the individual scenarios from the IPCC report. For instance, most of the scenarios in the C1category in AR6 are based on socioeconomic development that is consistent with the Shared Socioeconomic Pathway 1 (SSP1). By contrast, the underlying socioeconomic assumptions in the pathways in our study are broadly consistent with SSP2. The goal of this simple mapping exercise is to provide readers with a sense for how our pathways might compare with the IPCC report in terms of some basic characteristics. A more detailed comparison is beyond the scope of this study.

S3 Sensitivity analyses

Since our results hinge on the methodology used to develop our high ambition pathways, we construct alternative high ambition pathways that are based on a simplified implementation of the "pragmatic apportionment" developed by Anderson et al. (2020) which is in turn based on the Human Development Index (HDI)[25]. The HDI reflects the overall development of a country that accounts for measures of health, education, and the quality of living[26]. Our alternative NDC+ cases assume that countries with HDI rating of "very high" (n=66) ratchet their ambition by reducing their emissions in 2030 by 30% below their current NDC. Our alternative NDC++ cases assume that countries with HDI rating of "very high" (n=66) and "high" (n=53) ratchet their ambition by reducing their emissions in 2030 by 30% below their current NDC. Countries with an HDI rating of "medium" (n=37) or "low" (n=33) are assumed to keep their current NDCs in all sensitivity scenarios. While the two methodologies lead to somewhat different GHG emission reductions in 2030 at the regional level in the NDC+ cases, they lead to similar reductions in the NDC++ cases (Table S7). Consequently, global emission pathways and temperature outcomes through the century under the two methodologies are similar (Figure S18, Table S8).

Supplementary Figures

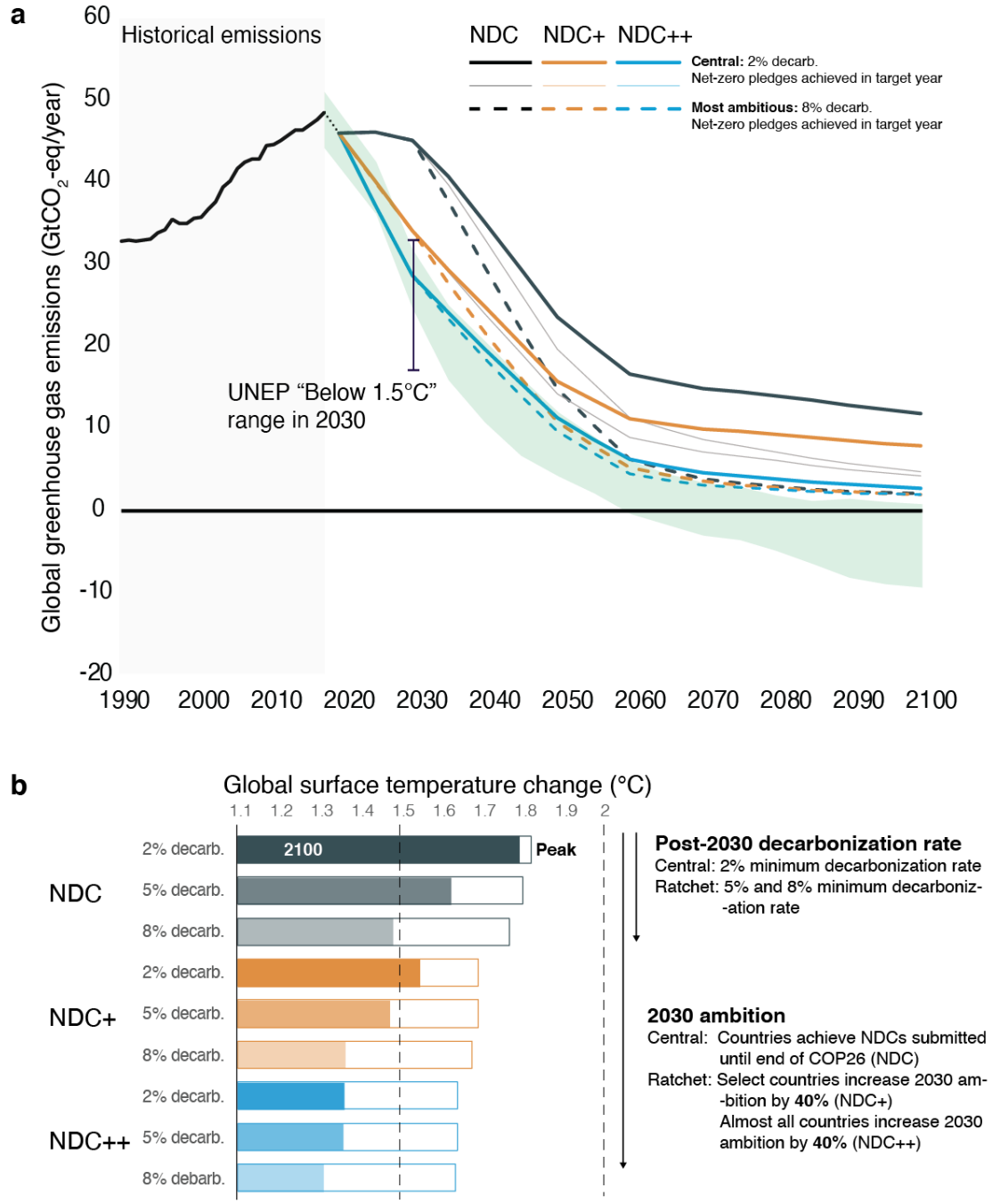

Figure S1 Emission and temperature outcomes for pathways with alternative degrees of ratcheting 2030 ambition. The alternative pathways explored in this figure vary across assumptions about 2030 ambition level (with increased ratcheting compared to the pathways explored in the main analysis as explained below) and post-2030 minimum decarbonization rate resulting in a total of 9 pathways. All pathways in this figure assume that countries will achieve net-zero pledges (if any) in the stated target years. In the NDC+ sensitivity, we assume that countries rated "Critically insufficient" and "Highly

insufficient" by CAT reduce their emissions by 40% below their current NDC – rather than 30% which is the assumption in the main analysis. In the NDC++ sensitivity, we assume that countries rated "Critically insufficient", "Highly insufficient", "Insufficient", and "not assessed" by CAT reduce their emissions by 40% below their current NDC. By contrast, the pathways explored in the main analysis assume a 30% reduction. The GHG emissions in 2030 in the NDC++ pathways in this figure fall within the range of 1.5°C pathways suggested by the UNEP GAP report[8]. The core qualitative insight from the main analysis – that ratcheting ambition *in the near-term* will be important to reduce temperature overshooting – remains unchanged.

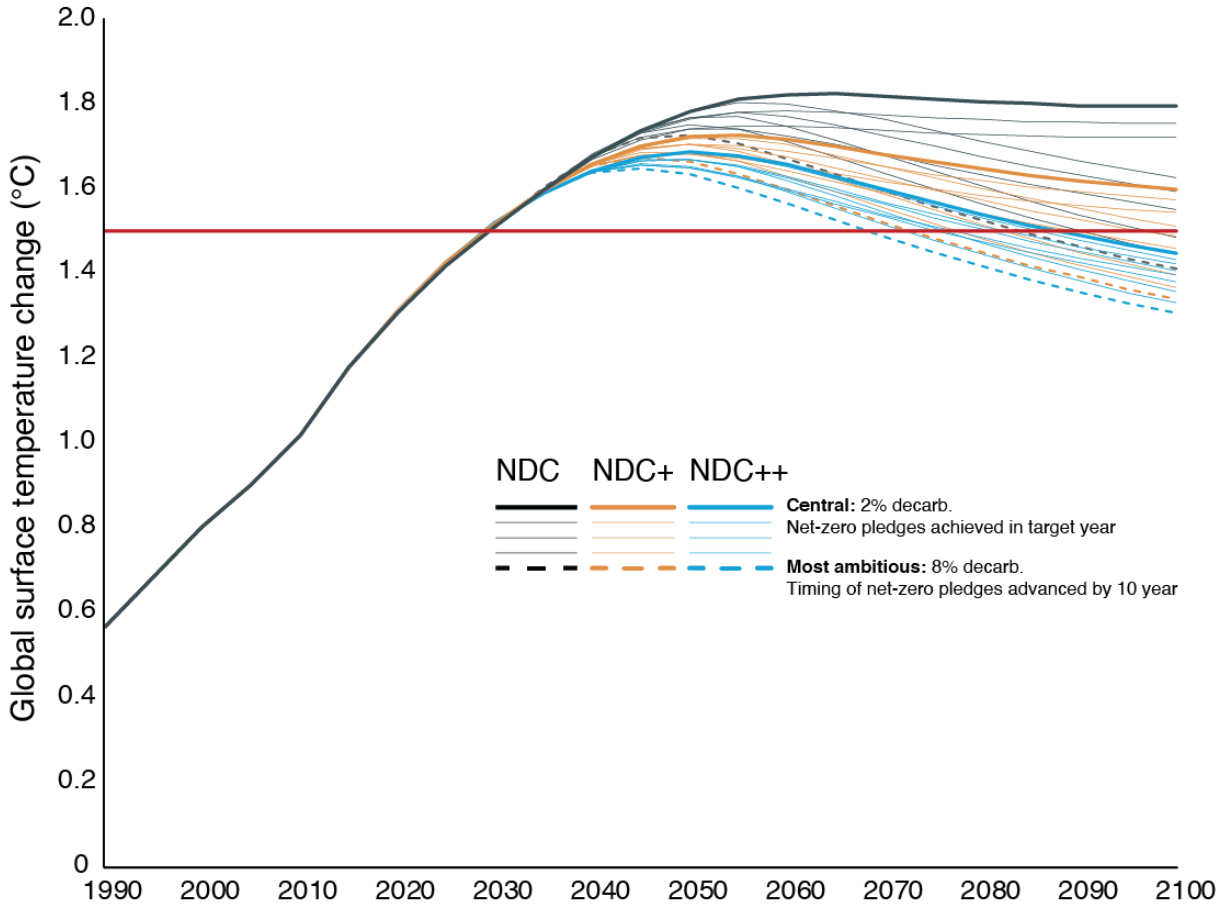

Figure S2 Temperature change outcomes over the 21st century in the main pathways explored in this study

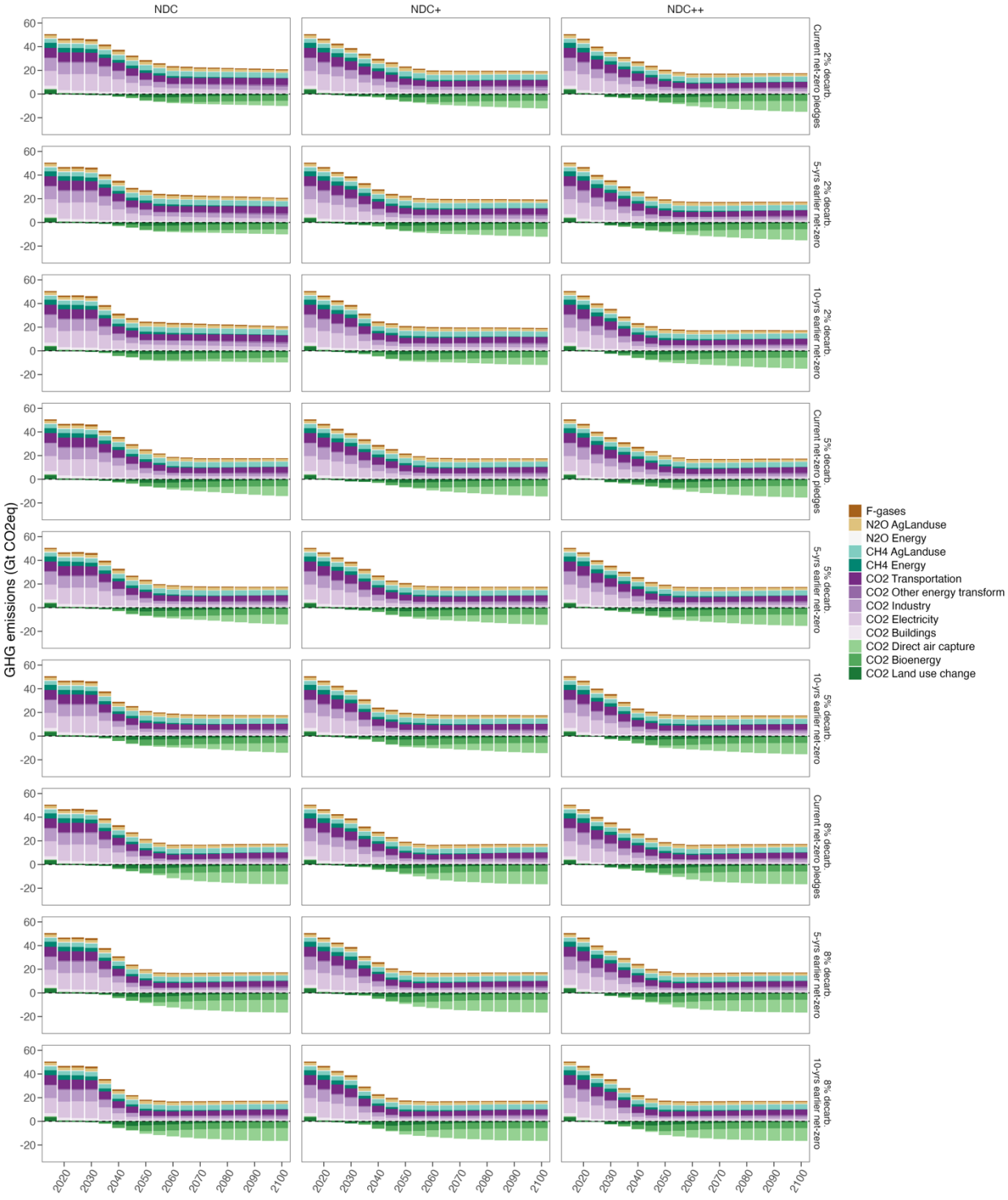

Figure S3 GHG emissions by sector and species in all pathways explored in this study

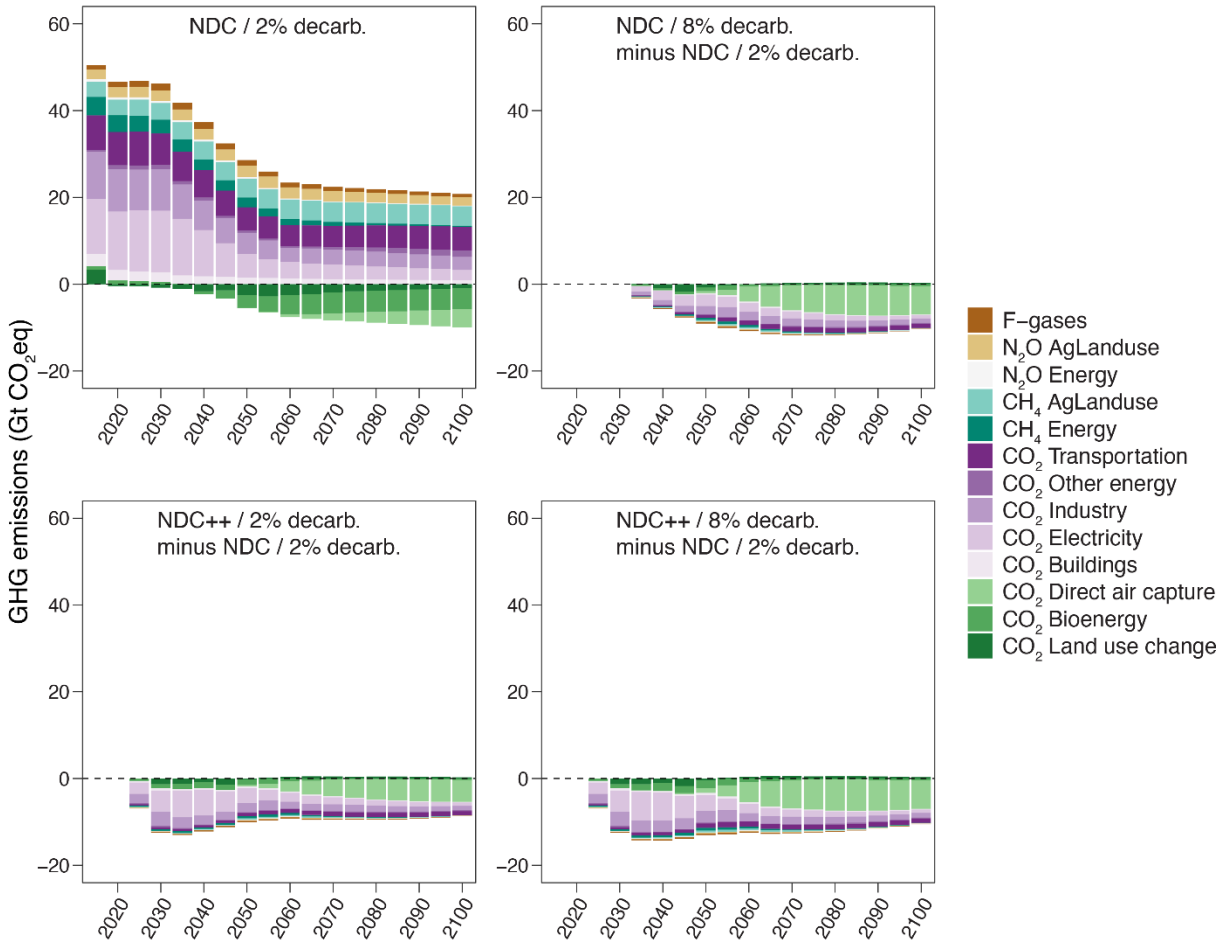

Figure S4 GHG emissions by sector and species under the NDC / 2% decarb. scenario, and changes in selected alternative scenarios relative to the NDC / 2% decarb. scenario.

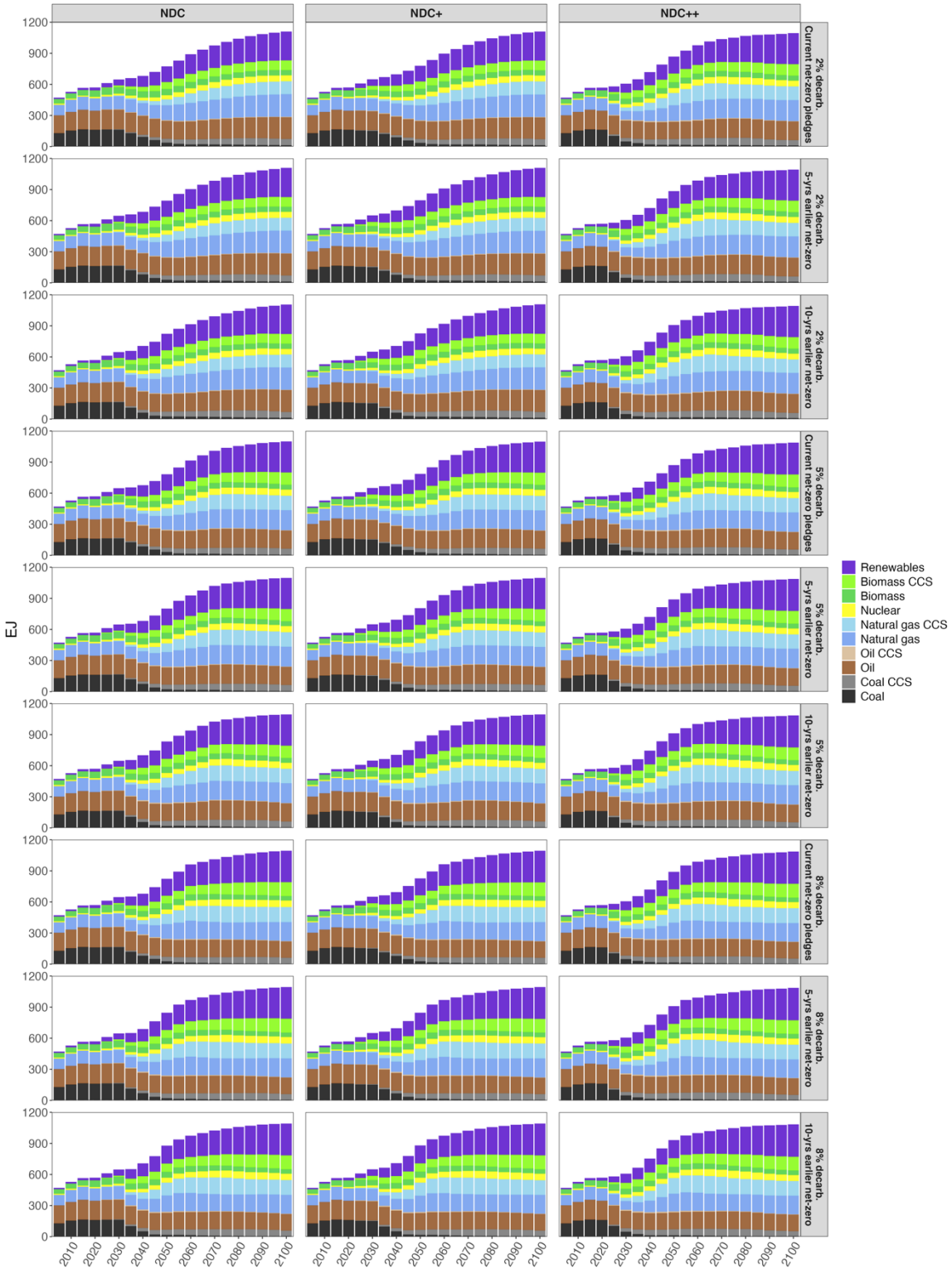

Figure S5 Global primary energy consumption in all pathways explored in this study.

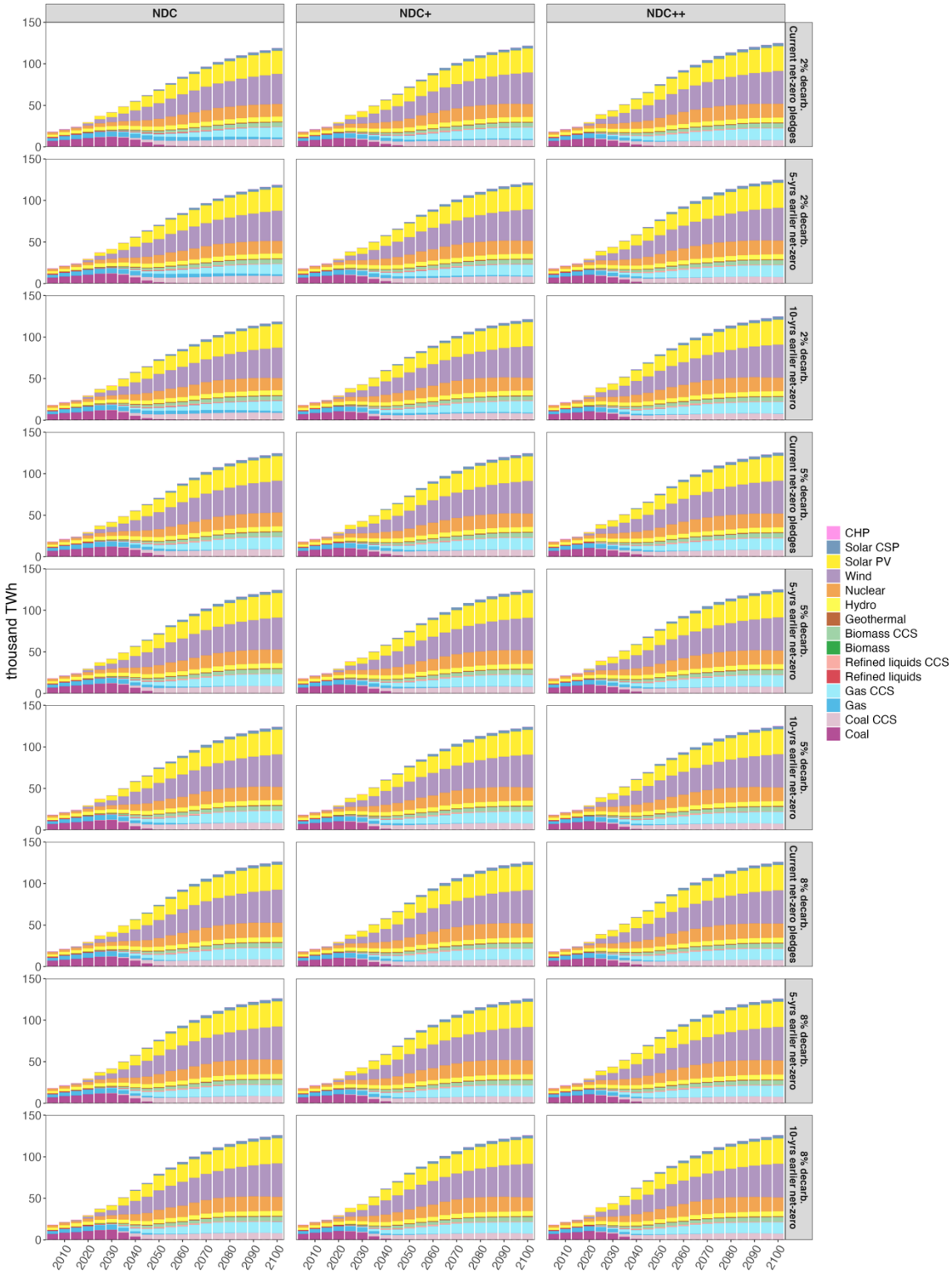

Figure S6 Global electricity generation in all pathways explored in this study.

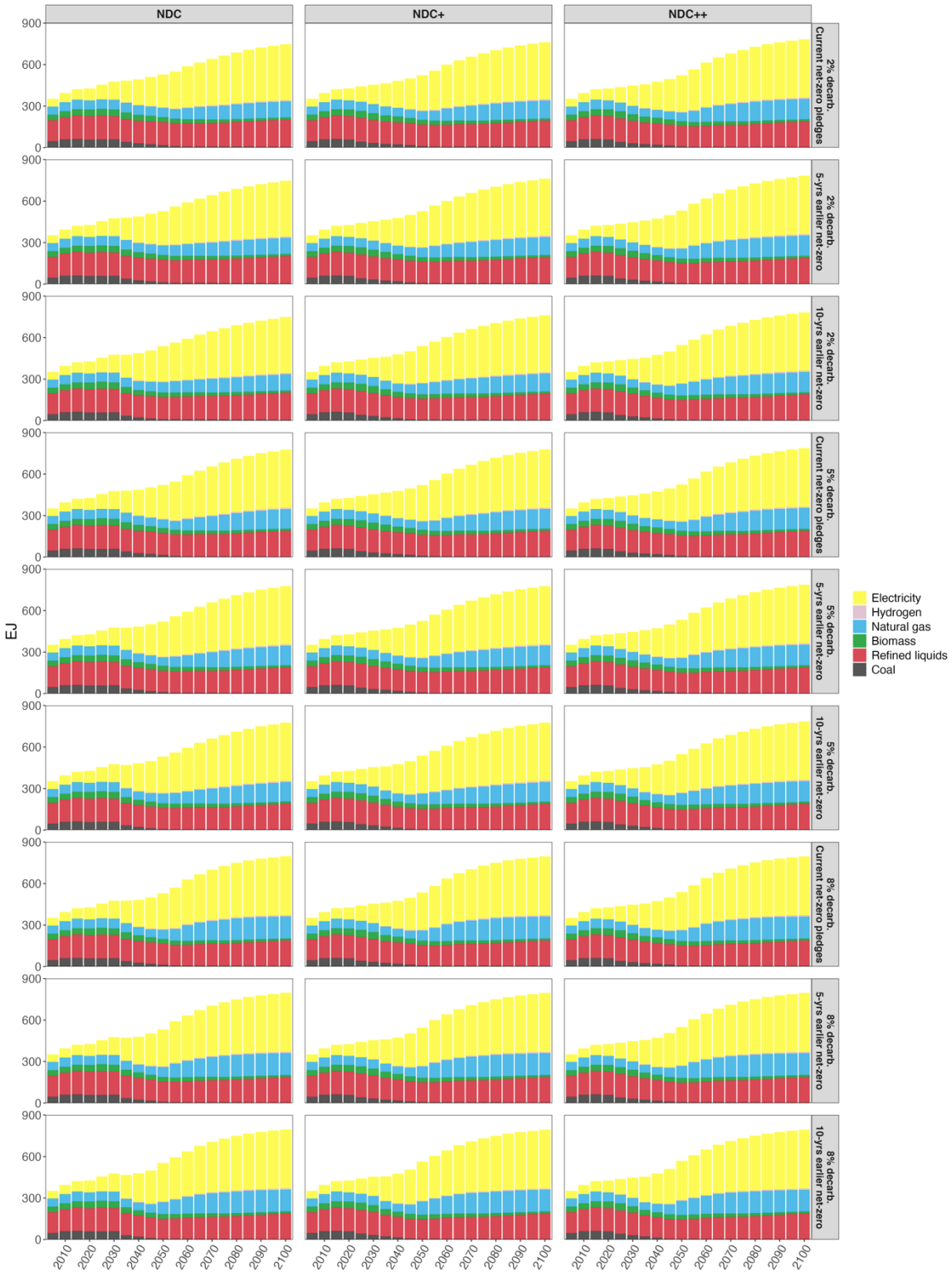

Figure S7 Global final energy consumption in all pathways explored in this study.

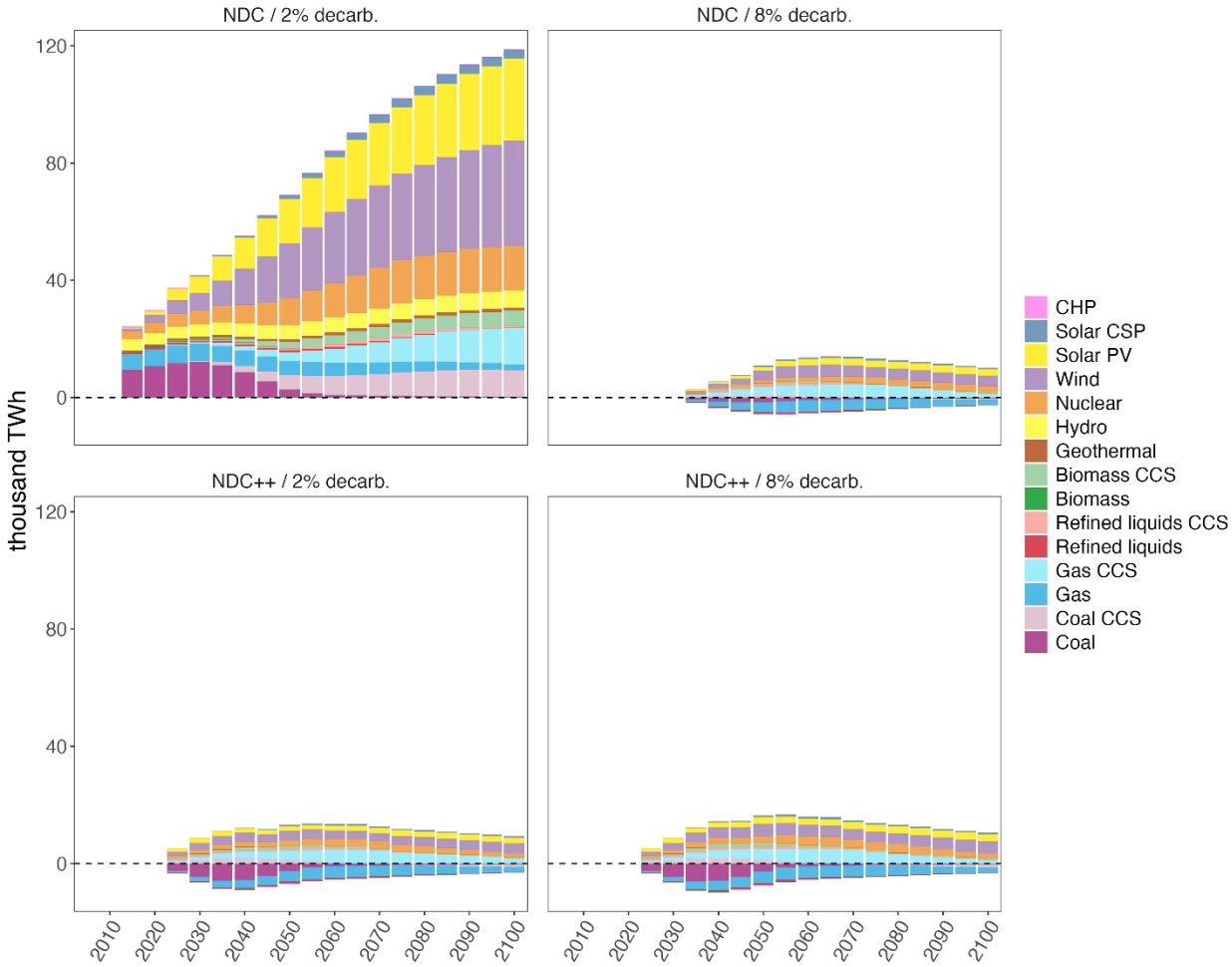

Figure S8 Electricity generation by fuel and technology under the NDC / 2% decarb. scenario, and changes in selected alternative scenarios relative to the NDC / 2% decarb. scenario.

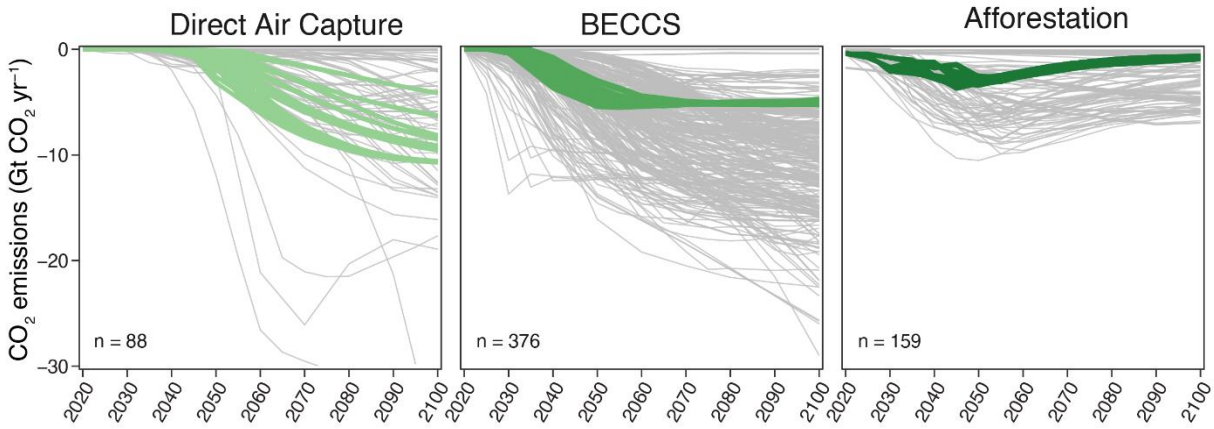

Figure S9 Deployment of various CDR options (DAC, BECCS, and afforestation) in the 27 central pathways explored in this study (in green) compared with scenarios in IPCC AR6[23] (faint gray lines).

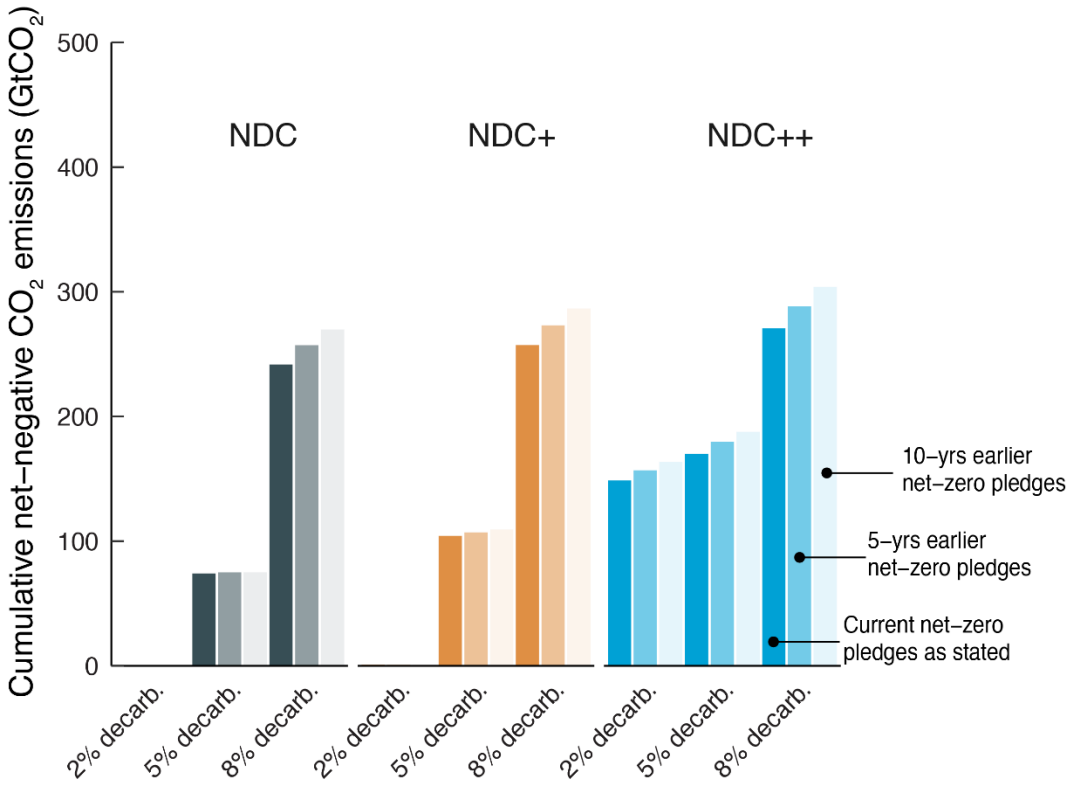

Figure S10 Cumulative net-negative CO_2 emissions ($GtCO_2$) in 2020-2100 for all the main pathways explored in this study. For comparison, a recent study reported a range of 0-500 Gt of cumulative net-negative emissions for scenarios consistent with a temperature change in 2100 of 1.5°C using an end-of-century budget design[27].

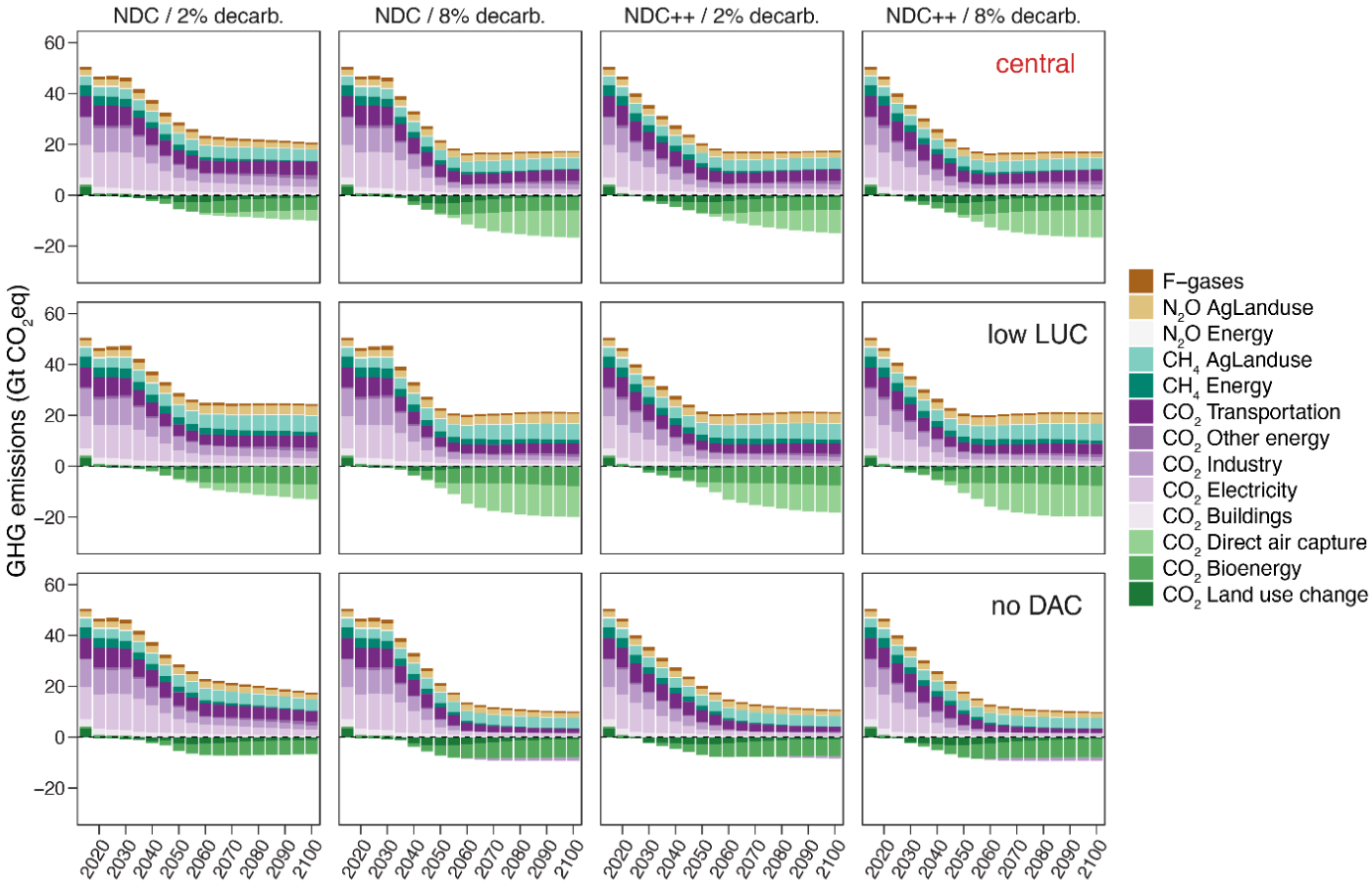

Figure S11 GHG emission by sector and species in a subset of the pathways explored in this study, under alternative CDR assumptions. The "low LUC" case assumes limited afforestation, leading to greater deployment of DAC and BECCS. The "no DAC" case assumes that DAC technology is unavailable, resulting in reduced CDR overall as well as higher reductions of CO2 emissions from energy and industrial sectors and non-CO2 emissions (see Figure S12 below).

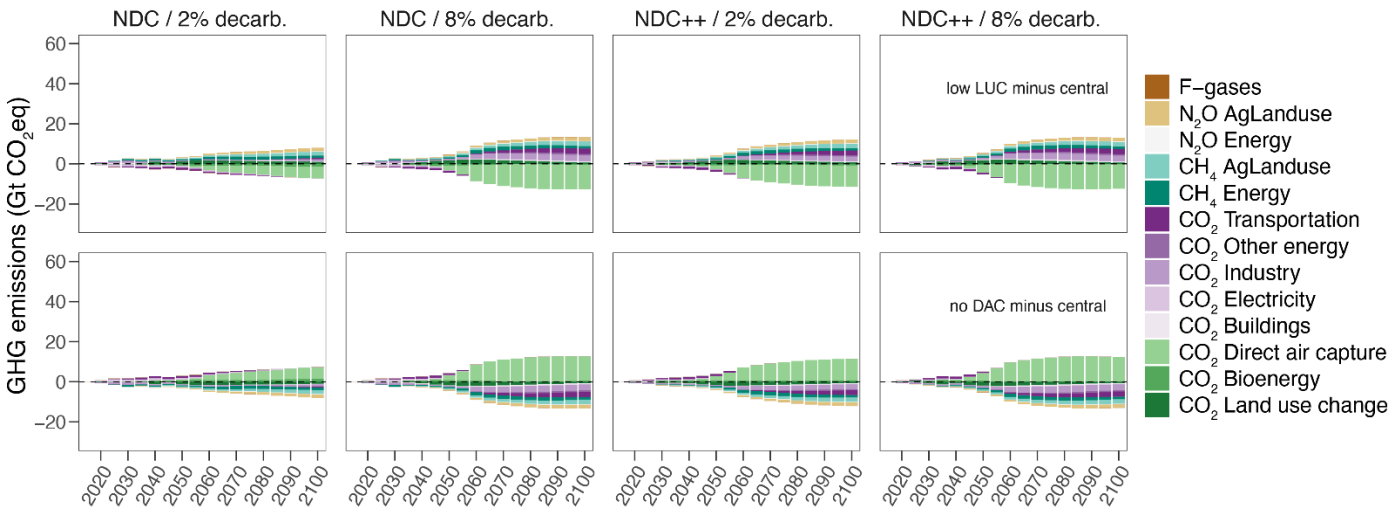

Figure S12 GHG emission by sector and species in a subset of the pathways explored in this study, under alternative CDR assumptions. The figure shows differences in the "low LUC" and "no DAC" cases relative to the "central" cases shown in Figure S11.

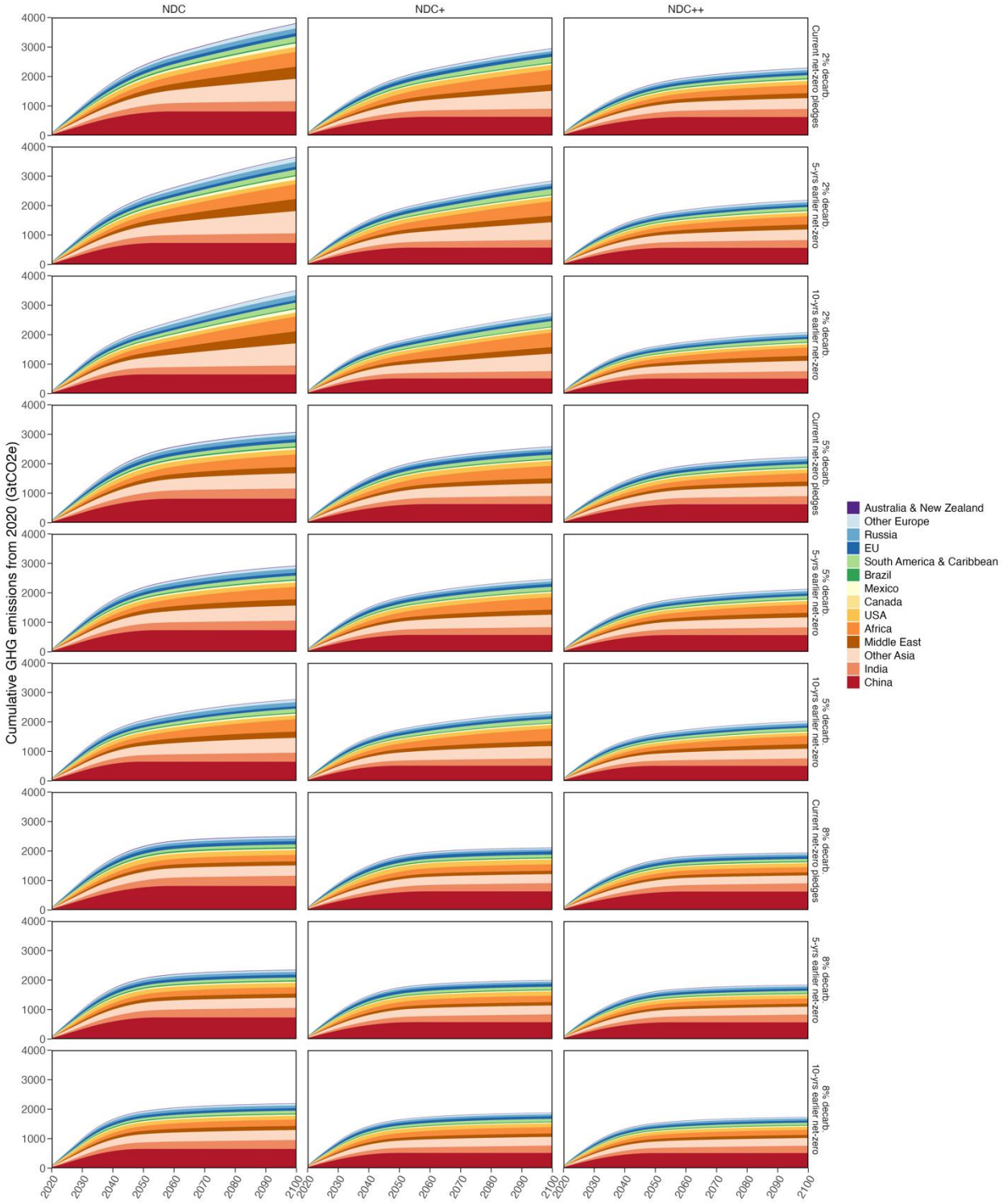

Figure S13 GHG emissions by region in the pathways explored in this study.

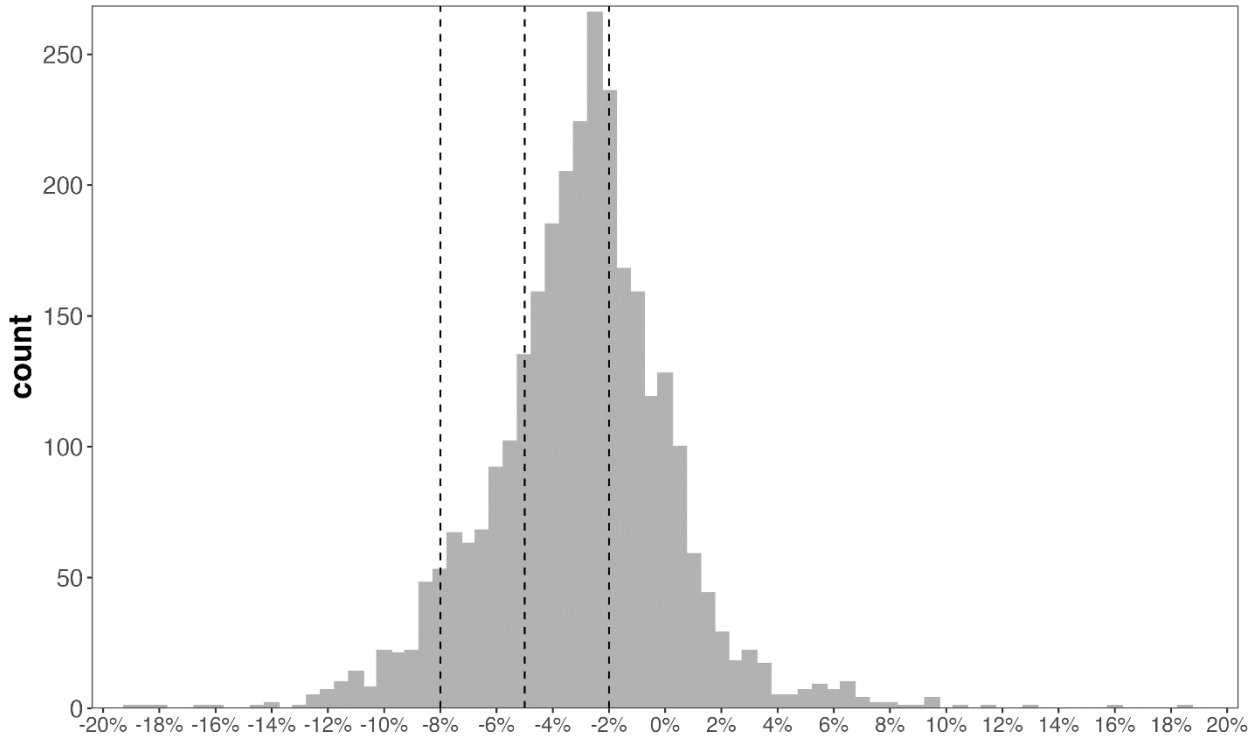

Figure S14 Historical distribution of 10 year running average of country level rates of change in GHG/GDP (1990-2018). Negative rates of change are referred to as "decarbonization rates". GHG data source: World Resources Institute [28]; GDP data source: Bolt and Zanden [29]

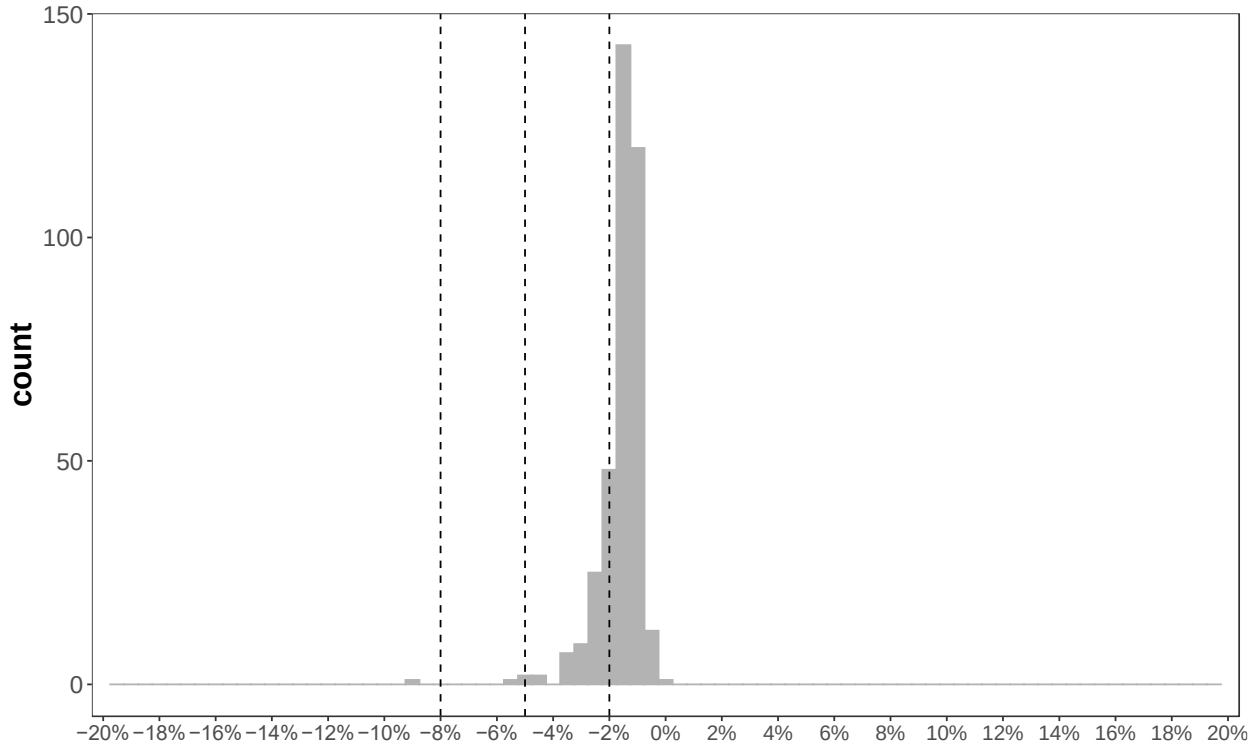

Figure S15 Distribution of 10-year running average of global rates of change in GHG/GDP (change in global GHG/global GDP) from 2010 to 2100 in baseline scenarios (that is, scenarios with no new GHG mitigation policies) from the IPCC's SR1.5 report[18]. Negative rates of change are referred to as "decarbonization rates". GDP data source: Bolt and Zanden [29]

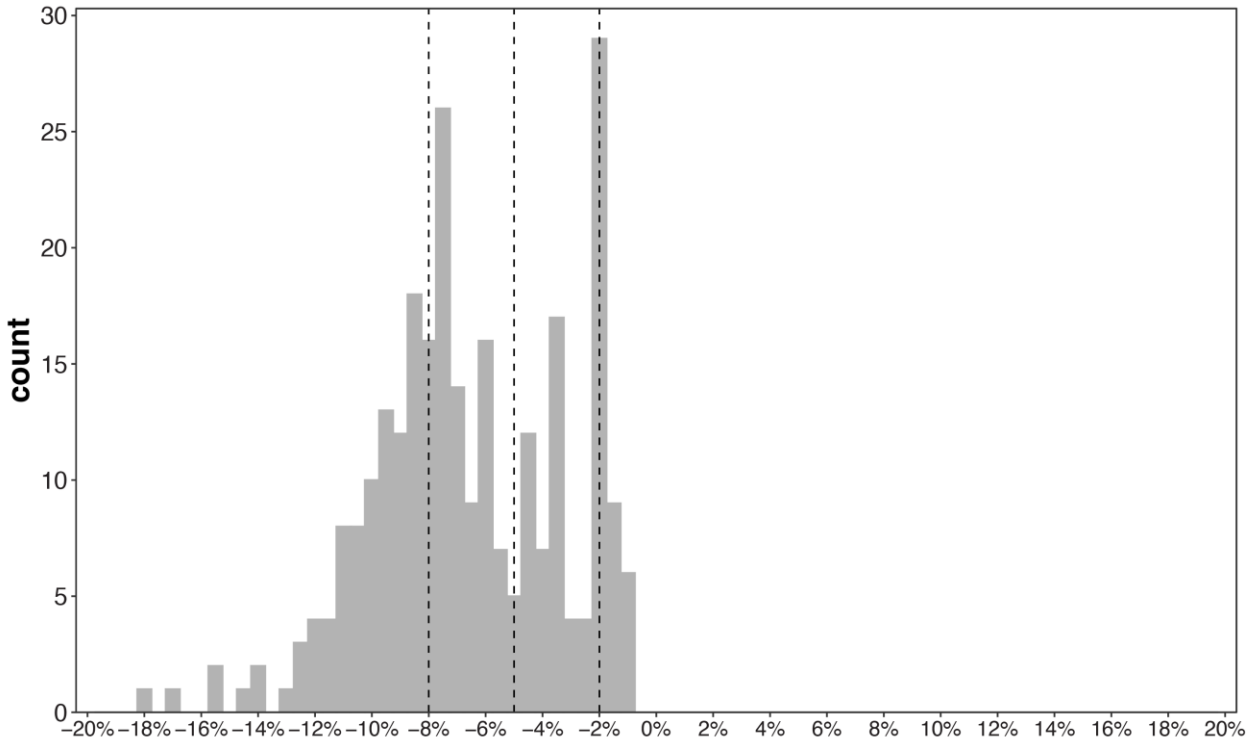

Figure S16 Distribution of 10-year running average of global rates of change in GHG/GDP (change in global GHG/global GDP) from 2010 until the year of net-zero CO2 emissions in 1.5°C-consistent scenarios (including pathways with no overshoot, with limited (low) overshoot, and with high overshoot) from the IPCC's SR1.5 report[18]. Negative rates of change are referred to as "decarbonization rates". GDP data source: Bolt and Zanden [29]

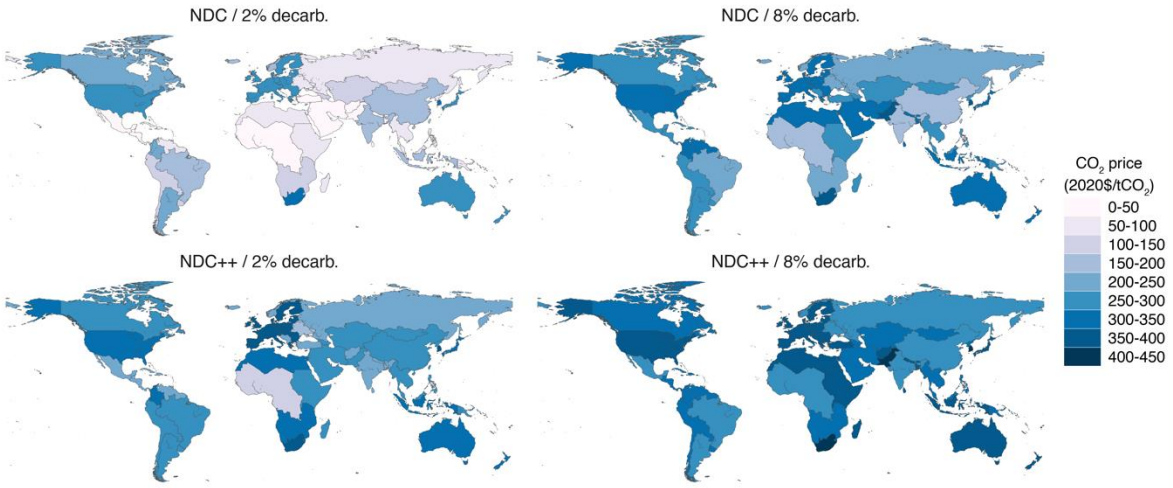

Figure S17 2050 CO_2 price (2020$/t$CO_2$) in a subset of the main pathways explored in the study. The pathways presented in this figure are the same as those in Figures 3-5 in the main analysis.

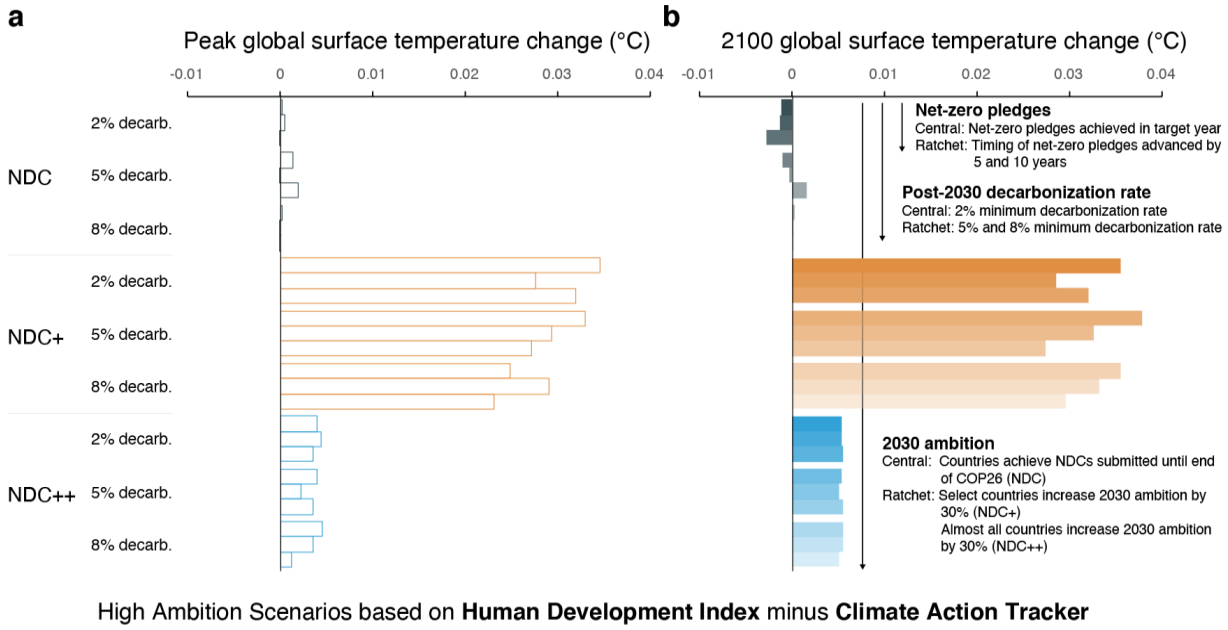

Figure S18 ***Difference in global surface temperature change outcomes of emissions pathways based on the Human Development Index method from outcomes of pathways based on Climate Action Tracker.***

Supplementary Tables

Table S1 Key characteristics of the main pathways explored in this paper and mapping of those pathways with the IPCC's Sixth Assessment Report[23,24]

2030 ambition	Post-2030 min. decarbonization rate	Timing of net-zero pledges	2030 GHG emissions (GtCO2e)	Cumulative CO2 emissions (2020 to year of net-zero CO2 globally, GtCO2)	Cumulative CO2 emissions (2020 to 2100, GtCO2)	Year of net-zero CO2 emissions globally	Peak temperature change (°C)	2100 temperature change (°C)	Number of years of overshoot before returning to 1.5°C this century	IPCC Sixth Assessment Report Scenario Category
NDC	2%	As stated	45	1114	1114	NA	1.8	1.8	NA	C3
		5-yr earlier	45	1042	1042	NA	1.8	1.8	NA	C3
		10-yr earlier	45	970	970	NA	1.7	1.7	NA	C3
	5%	As stated	45	853	779	2066	1.8	1.6	NA	C3
		5-yr earlier	45	782	707	2064	1.8	1.6	NA	C3
		10-yr earlier	45	710	635	2064	1.7	1.6	NA	C3
	8%	As stated	45	756	514	2056	1.8	1.5	67	C2
		5-yr earlier	45	699	442	2052	1.7	1.4	60	C2
		10-yr earlier	45	639	369	2049	1.7	1.4	54	C2
NDC+	2%	As stated	37	721	720	2095	1.7	1.6	NA	C3
		5-yr earlier	37	666	665	2095	1.7	1.6	NA	C3
		10-yr earlier	37	611	610	2095	1.7	1.5	NA	C3
	5%	As stated	37	653	549	2060	1.7	1.5	72	C3
		5-yr earlier	37	601	494	2057	1.7	1.5	67	C2
		10-yr earlier	37	548	439	2055	1.7	1.5	60	C2
	8%	As stated	37	590	332	2053	1.7	1.4	52	C2
		5-yr earlier	37	550	277	2050	1.7	1.4	48	C2
		10-yr earlier	37	508	222	2047	1.7	1.3	43	C2
NDC++	2%	As stated	33	570	422	2057	1.7	1.4	58	C2
		5-yr earlier	33	529	372	2053	1.7	1.4	53	C2
		10-yr earlier	33	486	322	2049	1.7	1.4	47	C2
	5%	As stated	33	564	394	2056	1.7	1.4	56	C2
		5-yr earlier	33	524	345	2053	1.7	1.4	51	C2
		10-yr earlier	33	482	295	2049	1.7	1.4	46	C2
	8%	As stated	33	526	255	2052	1.7	1.4	47	C2
		5-yr earlier	33	493	205	2049	1.7	1.3	43	C2
		10-yr earlier	33	459	155	2046	1.6	1.3	39	C2

Table S2 Representation of net-zero pledges for major countries in GCAM

Country	Description
Argentina	Net-zero CO_2 emission by 2050
Australia	Net-zero GHG emission by 2050
Brazil	Net-zero GHG emission by 2050
Canada	Net-zero GHG emission by 2050
China	Net-zero GHG emission by 2060
EU	Net-zero GHG emission by 2050
India	Net-zero CO_2 emissions by 2070
Japan	Net-zero GHG emission by 2050
South Africa	Net-zero CO_2 emission by 2050
South Korea	Net-zero CO_2 emission by 2050
USA	Net-zero net GHG emission by 2050

Table S3 Year of net-zero CO_2 for all GCAM regions and ratcheting pathways. (NA indicates CO_2 emissions do not reach net-zero before 2100)

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC/2% decarb.	Africa_Eastern	2098	2098	2098
NDC/2% decarb.	Africa_Northern	NA	NA	NA
NDC/2% decarb.	Africa_Southern	2046	2048	2050
NDC/2% decarb.	Africa_Western	NA	NA	NA
NDC/2% decarb.	Argentina	2050	2045	2040
NDC/2% decarb.	Australia_NZ	2045	2042	2038
NDC/2% decarb.	Brazil	2041	2038	2036
NDC/2% decarb.	Canada	2044	2041	2037
NDC/2% decarb.	Central America and Caribbean	NA	NA	NA
NDC/2% decarb.	Central Asia	2091	2091	2091
NDC/2% decarb.	China	2058	2053	2049
NDC/2% decarb.	Colombia	2052	2052	2052
NDC/2% decarb.	EU	2046	2042	2038
NDC/2% decarb.	Europe_Eastern	NA	NA	NA
NDC/2% decarb.	Europe_Non_EU	NA	NA	NA
NDC/2% decarb.	European Free Trade Association	2057	2058	2058
NDC/2% decarb.	India	2070	2065	2060
NDC/2% decarb.	Indonesia	2091	2091	2091
NDC/2% decarb.	Japan	2049	2045	2040
NDC/2% decarb.	Mexico	NA	NA	NA
NDC/2% decarb.	Middle East	NA	NA	NA
NDC/2% decarb.	Pakistan	NA	NA	NA
NDC/2% decarb.	Russia	NA	NA	NA
NDC/2% decarb.	South Africa	2050	2045	2040
NDC/2% decarb.	South America_Northern	NA	NA	NA
NDC/2% decarb.	South America_Southern	2099	2099	2099
NDC/2% decarb.	South Asia	NA	NA	NA
NDC/2% decarb.	South Korea	2050	2045	2040
NDC/2% decarb.	Southeast Asia	NA	NA	NA
NDC/2% decarb.	USA	2046	2042	2038
NDC/5% decarb.	Africa_Eastern	2078	2078	2078
NDC/5% decarb.	Africa_Northern	2096	2096	2096

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC/5% decarb.	Africa_Southern	2045	2045	2046
NDC/5% decarb.	Africa_Western	NA	NA	NA
NDC/5% decarb.	Argentina	2050	2045	2040
NDC/5% decarb.	Australia_NZ	2045	2041	2038
NDC/5% decarb.	Brazil	2041	2038	2036
NDC/5% decarb.	Canada	2044	2041	2037
NDC/5% decarb.	Central America and Caribbean	NA	NA	NA
NDC/5% decarb.	Central Asia	2080	2080	2080
NDC/5% decarb.	China	2058	2053	2049
NDC/5% decarb.	Colombia	2048	2048	2048
NDC/5% decarb.	EU	2046	2042	2038
NDC/5% decarb.	Europe_Eastern	2089	2089	2089
NDC/5% decarb.	Europe_Non_EU	2086	2086	2086
NDC/5% decarb.	European Free Trade Association	2057	2057	2057
NDC/5% decarb.	India	2070	2065	2060
NDC/5% decarb.	Indonesia	2091	2091	2091
NDC/5% decarb.	Japan	2049	2045	2040
NDC/5% decarb.	Mexico	2085	2085	2085
NDC/5% decarb.	Middle East	NA	NA	NA
NDC/5% decarb.	Pakistan	2078	2078	2078
NDC/5% decarb.	Russia	2088	2088	2088
NDC/5% decarb.	South Africa	2050	2045	2040
NDC/5% decarb.	South America_Northern	2059	2058	2058
NDC/5% decarb.	South America_Southern	2080	2080	2080
NDC/5% decarb.	South Asia	2082	2082	2082
NDC/5% decarb.	South Korea	2050	2045	2040
NDC/5% decarb.	Southeast Asia	NA	NA	NA
NDC/5% decarb.	USA	2046	2042	2038
NDC/8% decarb.	Africa_Eastern	2041	2041	2042
NDC/8% decarb.	Africa_Northern	2060	2060	2060
NDC/8% decarb.	Africa_Southern	2039	2039	2039
NDC/8% decarb.	Africa_Western	2044	2045	2045
NDC/8% decarb.	Argentina	2050	2045	2040
NDC/8% decarb.	Australia_NZ	2045	2041	2038
NDC/8% decarb.	Brazil	2041	2038	2036

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC/8% decarb.	Canada	2044	2041	2037
NDC/8% decarb.	Central America and Caribbean	2058	2058	2058
NDC/8% decarb.	Central Asia	2054	2054	2054
NDC/8% decarb.	China	2058	2053	2049
NDC/8% decarb.	Colombia	2039	2039	2039
NDC/8% decarb.	EU	2046	2042	2038
NDC/8% decarb.	Europe_Eastern	2057	2057	2057
NDC/8% decarb.	Europe_Non_EU	2061	2061	2061
NDC/8% decarb.	European Free Trade Association	2049	2049	2049
NDC/8% decarb.	India	2070	2065	2060
NDC/8% decarb.	Indonesia	2069	2069	2069
NDC/8% decarb.	Japan	2049	2045	2040
NDC/8% decarb.	Mexico	2057	2058	2058
NDC/8% decarb.	Middle East	2068	2068	2068
NDC/8% decarb.	Pakistan	2049	2049	2049
NDC/8% decarb.	Russia	2052	2052	2053
NDC/8% decarb.	South Africa	2050	2045	2040
NDC/8% decarb.	South America_Northern	2043	2043	2044
NDC/8% decarb.	South America_Southern	2049	2049	2049
NDC/8% decarb.	South Asia	2051	2051	2052
NDC/8% decarb.	South Korea	2050	2045	2040
NDC/8% decarb.	Southeast Asia	2066	2066	2066
NDC/8% decarb.	USA	2046	2042	2038
NDC+/2% decarb.	Africa_Eastern	2091	2091	2091
NDC+/2% decarb.	Africa_Northern	NA	NA	NA
NDC+/2% decarb.	Africa_Southern	2047	2048	2049
NDC+/2% decarb.	Africa_Western	NA	NA	NA
NDC+/2% decarb.	Argentina	2049	2044	2039
NDC+/2% decarb.	Australia_NZ	2043	2040	2037
NDC+/2% decarb.	Brazil	2037	2035	2034
NDC+/2% decarb.	Canada	2042	2039	2036
NDC+/2% decarb.	Central America and Caribbean	NA	NA	NA
NDC+/2% decarb.	Central Asia	2068	2068	2068
NDC+/2% decarb.	China	2057	2052	2048
NDC+/2% decarb.	Colombia	2052	2052	2052

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC+/2% decarb.	EU	2046	2042	2038
NDC+/2% decarb.	Europe_Eastern	2090	2090	2090
NDC+/2% decarb.	Europe_Non_EU	NA	NA	NA
NDC+/2% decarb.	European Free Trade Association	2057	2057	2057
NDC+/2% decarb.	India	2070	2065	2060
NDC+/2% decarb.	Indonesia	2063	2063	2063
NDC+/2% decarb.	Japan	2049	2045	2040
NDC+/2% decarb.	Mexico	2088	2088	2088
NDC+/2% decarb.	Middle East	NA	NA	NA
NDC+/2% decarb.	Pakistan	NA	NA	NA
NDC+/2% decarb.	Russia	2053	2054	2054
NDC+/2% decarb.	South Africa	2050	2045	2040
NDC+/2% decarb.	South America_Northern	NA	NA	NA
NDC+/2% decarb.	South America_Southern	2099	2099	2099
NDC+/2% decarb.	South Asia	NA	NA	NA
NDC+/2% decarb.	South Korea	2050	2045	2040
NDC+/2% decarb.	Southeast Asia	2097	2097	2097
NDC+/2% decarb.	USA	2046	2042	2038
NDC+/5% decarb.	Africa_Eastern	2077	2077	2077
NDC+/5% decarb.	Africa_Northern	2096	2096	2096
NDC+/5% decarb.	Africa_Southern	2045	2045	2046
NDC+/5% decarb.	Africa_Western	NA	NA	NA
NDC+/5% decarb.	Argentina	2049	2044	2039
NDC+/5% decarb.	Australia_NZ	2042	2039	2037
NDC+/5% decarb.	Brazil	2037	2035	2034
NDC+/5% decarb.	Canada	2042	2039	2036
NDC+/5% decarb.	Central America and Caribbean	NA	NA	NA
NDC+/5% decarb.	Central Asia	2068	2068	2068
NDC+/5% decarb.	China	2057	2052	2048
NDC+/5% decarb.	Colombia	2048	2048	2048
NDC+/5% decarb.	EU	2046	2042	2038
NDC+/5% decarb.	Europe_Eastern	2080	2080	2080
NDC+/5% decarb.	Europe_Non_EU	2081	2081	2081
NDC+/5% decarb.	European Free Trade Association	2057	2057	2057
NDC+/5% decarb.	India	2070	2065	2060

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC+/5% decarb.	Indonesia	2063	2063	2063
NDC+/5% decarb.	Japan	2049	2045	2040
NDC+/5% decarb.	Mexico	2074	2074	2074
NDC+/5% decarb.	Middle East	2100	2100	2100
NDC+/5% decarb.	Pakistan	2078	2078	2078
NDC+/5% decarb.	Russia	2053	2054	2055
NDC+/5% decarb.	South Africa	2050	2045	2040
NDC+/5% decarb.	South America_Northern	2058	2057	2057
NDC+/5% decarb.	South America_Southern	2080	2080	2080
NDC+/5% decarb.	South Asia	2082	2082	2082
NDC+/5% decarb.	South Korea	2050	2045	2040
NDC+/5% decarb.	Southeast Asia	2096	2096	2096
NDC+/5% decarb.	USA	2046	2042	2038
NDC+/8% decarb.	Africa_Eastern	2040	2040	2041
NDC+/8% decarb.	Africa_Northern	2060	2060	2060
NDC+/8% decarb.	Africa_Southern	2039	2039	2039
NDC+/8% decarb.	Africa_Western	2045	2045	2045
NDC+/8% decarb.	Argentina	2049	2044	2039
NDC+/8% decarb.	Australia_NZ	2042	2039	2036
NDC+/8% decarb.	Brazil	2037	2035	2034
NDC+/8% decarb.	Canada	2042	2039	2036
NDC+/8% decarb.	Central America and Caribbean	2058	2058	2058
NDC+/8% decarb.	Central Asia	2051	2051	2051
NDC+/8% decarb.	China	2057	2052	2048
NDC+/8% decarb.	Colombia	2039	2039	2039
NDC+/8% decarb.	EU	2046	2042	2038
NDC+/8% decarb.	Europe_Eastern	2052	2052	2052
NDC+/8% decarb.	Europe_Non_EU	2058	2058	2058
NDC+/8% decarb.	European Free Trade Association	2049	2049	2049
NDC+/8% decarb.	India	2070	2065	2060
NDC+/8% decarb.	Indonesia	2063	2063	2063
NDC+/8% decarb.	Japan	2049	2045	2040
NDC+/8% decarb.	Mexico	2050	2051	2051
NDC+/8% decarb.	Middle East	2064	2064	2064
NDC+/8% decarb.	Pakistan	2049	2049	2049

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC+/8% decarb.	Russia	2047	2047	2047
NDC+/8% decarb.	South Africa	2050	2045	2040
NDC+/8% decarb.	South America_Northern	2043	2043	2044
NDC+/8% decarb.	South America_Southern	2048	2048	2048
NDC+/8% decarb.	South Asia	2051	2051	2052
NDC+/8% decarb.	South Korea	2050	2045	2040
NDC+/8% decarb.	Southeast Asia	2062	2062	2062
NDC+/8% decarb.	USA	2046	2042	2038
NDC++/2% decarb.	Africa_Eastern	2042	2043	2044
NDC++/2% decarb.	Africa_Northern	2087	2087	2087
NDC++/2% decarb.	Africa_Southern	2031	2031	2031
NDC++/2% decarb.	Africa_Western	2082	2082	2082
NDC++/2% decarb.	Argentina	2049	2044	2039
NDC++/2% decarb.	Australia_NZ	2042	2039	2036
NDC++/2% decarb.	Brazil	2037	2035	2034
NDC++/2% decarb.	Canada	2042	2039	2036
NDC++/2% decarb.	Central America and Caribbean	NA	NA	NA
NDC++/2% decarb.	Central Asia	2054	2054	2054
NDC++/2% decarb.	China	2057	2052	2048
NDC++/2% decarb.	Colombia	2033	2033	2033
NDC++/2% decarb.	EU	2044	2041	2037
NDC++/2% decarb.	Europe_Eastern	2078	2078	2078
NDC++/2% decarb.	Europe_Non_EU	2083	2083	2082
NDC++/2% decarb.	European Free Trade Association	2043	2043	2043
NDC++/2% decarb.	India	2070	2065	2060
NDC++/2% decarb.	Indonesia	2063	2063	2063
NDC++/2% decarb.	Japan	2049	2044	2040
NDC++/2% decarb.	Mexico	2087	2087	2087
NDC++/2% decarb.	Middle East	NA	NA	NA
NDC++/2% decarb.	Pakistan	2090	2090	2090
NDC++/2% decarb.	Russia	2054	2054	2055
NDC++/2% decarb.	South Africa	2050	2045	2040
NDC++/2% decarb.	South America_Northern	NA	NA	NA
NDC++/2% decarb.	South America_Southern	2048	2048	2048

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC++/2% decarb.	South Asia	2086	2086	2086
NDC++/2% decarb.	South Korea	2050	2045	2040
NDC++/2% decarb.	Southeast Asia	2079	2079	2079
NDC++/2% decarb.	USA	2044	2040	2037
NDC++/5% decarb.	Africa_Eastern	2042	2043	2044
NDC++/5% decarb.	Africa_Northern	2087	2087	2087
NDC++/5% decarb.	Africa_Southern	2031	2031	2031
NDC++/5% decarb.	Africa_Western	2082	2082	2082
NDC++/5% decarb.	Argentina	2049	2044	2039
NDC++/5% decarb.	Australia_NZ	2042	2039	2036
NDC++/5% decarb.	Brazil	2037	2035	2034
NDC++/5% decarb.	Canada	2042	2039	2036
NDC++/5% decarb.	Central America and Caribbean	2093	2093	2093
NDC++/5% decarb.	Central Asia	2054	2054	2054
NDC++/5% decarb.	China	2057	2052	2048
NDC++/5% decarb.	Colombia	2033	2033	2033
NDC++/5% decarb.	EU	2044	2041	2037
NDC++/5% decarb.	Europe_Eastern	2078	2078	2078
NDC++/5% decarb.	Europe_Non_EU	2077	2077	2077
NDC++/5% decarb.	European Free Trade Association	2043	2043	2043
NDC++/5% decarb.	India	2070	2065	2060
NDC++/5% decarb.	Indonesia	2063	2063	2063
NDC++/5% decarb.	Japan	2049	2044	2040
NDC++/5% decarb.	Mexico	2074	2074	2074
NDC++/5% decarb.	Middle East	2097	2097	2097
NDC++/5% decarb.	Pakistan	2064	2064	2064
NDC++/5% decarb.	Russia	2054	2054	2055
NDC++/5% decarb.	South Africa	2050	2045	2040
NDC++/5% decarb.	South America_Northern	2045	2046	2046
NDC++/5% decarb.	South America_Southern	2048	2048	2048
NDC++/5% decarb.	South Asia	2070	2070	2070
NDC++/5% decarb.	South Korea	2050	2045	2040
NDC++/5% decarb.	Southeast Asia	2079	2079	2079
NDC++/5% decarb.	USA	2044	2040	2037
NDC++/8% decarb.	Africa_Eastern	2035	2035	2035

Pathway	GCAM region	Net-zero pledges in stated target year	5-yrs earlier net-zero pledges	10-yrs earlier net-zero pledges
NDC++/8% decarb.	Africa_Northern	2054	2054	2054
NDC++/8% decarb.	Africa_Southern	2031	2031	2031
NDC++/8% decarb.	Africa_Western	2041	2041	2042
NDC++/8% decarb.	Argentina	2049	2044	2039
NDC++/8% decarb.	Australia_NZ	2042	2039	2036
NDC++/8% decarb.	Brazil	2037	2035	2034
NDC++/8% decarb.	Canada	2042	2039	2036
NDC++/8% decarb.	Central America and Caribbean	2049	2049	2049
NDC++/8% decarb.	Central Asia	2048	2048	2048
NDC++/8% decarb.	China	2057	2052	2048
NDC++/8% decarb.	Colombia	2033	2033	2033
NDC++/8% decarb.	EU	2044	2041	2037
NDC++/8% decarb.	Europe_Eastern	2051	2051	2051
NDC++/8% decarb.	Europe_Non_EU	2055	2055	2056
NDC++/8% decarb.	European Free Trade Association	2043	2043	2043
NDC++/8% decarb.	India	2070	2065	2060
NDC++/8% decarb.	Indonesia	2063	2063	2063
NDC++/8% decarb.	Japan	2049	2044	2040
NDC++/8% decarb.	Mexico	2051	2051	2051
NDC++/8% decarb.	Middle East	2062	2062	2062
NDC++/8% decarb.	Pakistan	2042	2042	2042
NDC++/8% decarb.	Russia	2047	2047	2047
NDC++/8% decarb.	South Africa	2050	2045	2040
NDC++/8% decarb.	South America_Northern	2038	2038	2038
NDC++/8% decarb.	South America_Southern	2043	2043	2043
NDC++/8% decarb.	South Asia	2045	2045	2045
NDC++/8% decarb.	South Korea	2050	2045	2040
NDC++/8% decarb.	Southeast Asia	2059	2059	2059
NDC++/8% decarb.	USA	2044	2040	2037

Table S4: Cost and Energy Input assumptions for DACCS. More details can be found in Fuhrman et al. (2021)[30]. Detailed sensitivity analyses on various cost assumptions are documented in Fuhrman et al. (2021)[30]. Cost declines over time are applied to capital, variable and fixed O&M costs. Non-energy costs (that include the total of capital, variable and fixed O&M costs) decline by 40% linearly from 2020 to 2050 and are held constant beyond 2050.

	Capex	**Lifetime**	**CRF**	**Capex**	**Opex**	**Electricity demand**	**Heat/fuel demand**	**Heat pump cost**	**Cost reported (total)**	**Recalculated GCAM Non-Energy Cost**
	$/tCO2$-a	*years*	*%*	*$/tCO2*	*$/tCO2*	*GJ/tCO2*	*GJ/tCO2*	*$/tCO$_2$*	*$/tCO2*	
HT aqueous		20	9.40%						$500	
HT aqueous			-						$343	
HT aqueous	$2,105	20	9.40%		$84	1.8	8.1		$411	
HT aqueous	$2,774	20	9.40%		$111	1.8	8.1		$525	
HT aqueous			-				6.6		$ 376-399	
HT aqueous			-			5.4			$ 100-150	
HT aqueous	$1,146	25	8.60%		$42		8.8		$ 168-232	
HT aqueous	$793	25	8.60%		$30		8.8		$ 127-170	
HT aqueous	$694	25	8.60%		$26	1.3	5.3		$ 122-163	
HT aqueous	$609	25	8.60%		$23	0.3	5.3		$ 94-97	
HT aqueous	$905	25	8.60%		$33	6	-			
HT aqueous	$2,060		11%		$76	1.8	8.1		-	
HT aqueous	$1,146		11%		$42	1.3	5.3		-	

HT aqueous	$700		11%		$27	1.3	5.3		-	
HT aqueous (natural gas)	$1,763		13%	$220	$76	1.8	8.1			$296
HT aqueous (fully electric)	$2,300		13%	$299	$85	6.5	-			$384
LT solid sorbent	$1,623	25				2.5	7.5			
LT solid sorbent	$971	25				2.5	7.5			
LT solid sorbent						0.5-0.9	4.2-5.0		$113	
LT solid sorbent						0.5-0.10	4.2-5.0		$ 11-38	
LT solid sorbent		20				0.72-1.1	5.4-7.2			
LT solid sorbent									$83	
LT solid sorbent	$810	20	9.40%	$76	$32	0.9	6.3			$109
LT solid sorbent	$750	15	12%	$89	$260	1.1	7.2			$349
LT solid sorbent	$430	15	12%	$51	$150	0.6	4.4			$201
LT solid sorbent	$110	15	12%	$13	$37	0.6	4.4			$50
LT solid sorbent		20-Dec				1.4	5.8			
LT solid sorbent						1.8	9		$600	
LT solid sorbent							7		$200	

LT solid sorbent (heat pump)		20	13%	$89	$260	5.5	-		$53	$402

Table S5 Representation of NDCs. NDC refers to the Nationally Determined Contributions. BAU refers to the "business-as-usual" scenario. Our representation includes countries with ratified, quantifiable, unconditional NDC commitments, including absolute emissions limit, percentage emission reductions from a given reference level, and emission intensity targets. Action-based targets for individual sectors are not included. Unless otherwise specified, the targets listed below are objectives in 2030. All NDCs are obtained from UNFCCC NDC Entry as of Nov 12, 2021 (end of COP26). Countries with shaded areas are new submissions not included in Ou & Iyer et al.[7]. "% of GHG" refers to the share of total GHG emissions in the respective GCAM region in 2019[31].

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
Africa_Eastern	Burundi	1.4%	3% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2018-01-17
	Djibouti	0.2%	40% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC	2016-11-11
	Eritrea	1.2%	39.2% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2018-06-19
	Ethiopia	33.0%	14% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-23
	Kenya	13.2%	32% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-12-28
	Mauritius	1.2%	30% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-05
	Rwanda	1.3%	16% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-05-20
Africa_Northern	Algeria	37.0%	13% reduction in all GHG (including LUC) below BAU	BAU based on GCAM Reference scenario	First NDC	2016-10-20
	Morocco	11.9%	18.3% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-06-22
	Tunisia	5.0%	27% reduction in carbon intensity below 2010	BAU and NDC target emissions based on NDC submission	First NDC	2021-10-10
Africa_Southern	Angola	18.5%	14% reduction in all GHG (including LUC) below BAU in 2025	BAU based on NDC submission	First NDC (updated submission)	2021-05-31
	Botswana	7.6%	15% reduction in all GHG below BAU	BAU based on NDC submission	First NDC	2016-11-11

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
	Eswatini	<0.1%	5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
	Lesotho	<0.1%	10% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2018-06-22
	Malawi	2.8%	6% reduction in all GHG (including LUC) below BAU in 2040	BAU based on NDC submission	First NDC (updated submission)	2021-07-30
	Namibia	3.1%	9% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-30
	Tanzania, United Republic of	22.4%	30-35% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-30
	Zambia	13.2%	25% reduction in all GHG (excluding AFOLU) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-30
Africa_Western	Benin	1.5%	3.5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2018-09-09
	Burkina Faso	3.2%	19.6% reduction in all GHG (including LUC) from BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-09
	Cabo Verde	<0.1%	18% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-04-02
	Chad	6.1%	0.5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-19
	Congo	1.7%	21% reduction in all GHG (excluding LUC) below 2017	Historical emissions based on NDC submission	First NDC (updated submission)	2021-08-02
	Cote dIvoire	3.0%	28% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC	2016-10-26
	Gabon	1.1%	50% reduction in all GHG (including LUC) below BAU in 2025	BAU based on NDC submission	First NDC	2016-02-11
	Gambia	0.2%	2.6% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	Second NDC	2021-09-12
	Ghana	0.7%	24.6 MtCO2e reduction in GHG compared to the 2020-2030 cumulative emission in BAU	BAU based on GCAM Reference scenario	First NDC (updated submission)	2021-11-04

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
	Guinea Bissau	0.2%	10% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
	Liberia	0.9%	10% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-08-04
	Mali	2.5%	Reductions of 31.2 MtCO2e in all GHG (including LUC) from BAU	Emissions reductions from BAU based on NDC submission	First NDC	2016-09-23
	Mauritania	0.8%	9% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
	Niger	2.5%	3.5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2016-09-21
	Nigeria	20.4%	20% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-30
	Senegal	1.9%	5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2020-12-29
	Togo	0.5%	20.51% reduction of all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
Argentina	Argentina	100.0%	A maximum emissions limit target of 349 MtCO2e net GHG emissions	2030 NDC target based on NDC submission	Second NDC (updated submission)	2021-11-02
Australia_NZ	Australia	89.3%	26% reduction in all GHG (including LUC) below 2005	Historical emissions based on Climate Action Tracker	First NDC (updated submission)	2021-10-28
	New Zealand	10.7%	50% reduction in all GHG (including LUC) below 2005	Historical emissions based on NDC submission	First NDC (updated submission)	2021-11-03
Brazil	Brazil	100.0%	37% reduction in 2025 and 43% reduction in 2030 in all GHG (including LUC) below 2005	BAU based on NDC submission	First NDC (updated submission)	2020-09-12
Canada	Canada	100.0%	40-45% reduction in all GHG (including LUC) below 2005	Historical emissions based on NDC submission	First NDC (updated submission)	2021-07-11
Central America and Caribbean	Barbados	1.3%	35% reduction in all GHG (including LUC) below 2008	Historical emissions based on NDC submission	First NDC (updated submission)	2021-07-30

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
	Costa Rica	2.8%	A maximum emissions limit target of 9.37 MtCO2e net GHG emissions	2030 NDC target based on NDC submission	First NDC (updated submission)	2020-12-29
	Dominican Republic	13.3%	27% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-12-29
	Grenada	0.8%	40% reduction in all GHG (including LUC) below 2010	Historical emissions based on NDC submission	Second NDC	2020-12-01
	Guatemala	12.9%	11.2% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2017-01-25
	Haiti	3.7%	5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2017-07-31
	Jamaica	3.4%	25.4% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-07-01
	Saint Vincent and the Grenadines	0.1%	22% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2016-06-29
	Trinidad and Tobago	9.5%	30% reduction in GHG in public transportation sector below BAU	BAU based on NDC submission	First NDC	2018-02-22
Central Asia	Armenia	1.3%	40% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2020-05-05
	Azerbaijan	6.7%	35% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC	2017-01-09
	Georgia	2.2%	35% reduction in all GHG (excluding LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2021-05-05
	Kazakhstan	34.6%	15% reduction in all GHG (including LUC) below 1990	Historical emissions based on UNFCCC statistics	First NDC	2016-12-06
	Kyrgyzstan	1.7%	15.97% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-09
	Mongolia	7.5%	22.7% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-10-13
	Tajikistan	2.2%	30% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2021-10-12

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
China	China	100.0%	Peak in CO2 emissions from fossil fuels and industry in 2030; Lower carbon dioxide emissions per unit of GDP by 65% from the 2005 level	2030 NDC target based on UNFCCC statistics and Climate Action Tracker assessment	First NDC (updated submission)	2021-10-28
Colombia	Colombia	100.0%	51% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-12-30
EU	EU-12, EU-15	100.0%	55% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2020-12-18
Europe_Eastern	Belarus	21.8%	35% reduction in all GHG (excluding LUC) below 1990	BAU based on NDC submission	First NDC (updated submission)	2021-10-11
	Moldova, Republic of	4.5%	70% reduction in all GHG (including LUC) below 1990	BAU based on NDC submission	First NDC (updated submission)	2020-03-04
	Ukraine	73.7%	65% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2021-07-31
Europe_Non_EU	Albania	1.5%	20.9% (3.17 MtCO2e) in in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
	Bosnia and Herzegovina	4.2%	33.2% reduction in all GHG (excluding LUC) below 1990	Historical emissions based on NDC submission	First NDC	2021-04-20
	Montenegro	10.6%	35% reduction in all GHG (excluding LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2021-06-15
	Republic of North Macedonia	1.9%	51% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2021-04-16
	Serbia	10.6%	9.8% reduction in all GHG (including LUC) below 1990	Historical emissions based on UNFCCC statistics	First NDC	2017-07-25
European Free Trade Association	Iceland	3.7%	55% reduction in all GHG (including LUC) below 1990	Historical emissions based on UNFCCC statistics	First NDC (updated submission)	2021-02-18
	Liechtenstein	<0.1%	40% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC	2017-09-20
	Norway	36.5%	50% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2020-02-07

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
	Switzerland	59.8%	50% reduction in all GHG (excluding LUC) below 1990	Historical emissions based on NDC submission	First NDC (updated submission)	2020-12-09
India	India	100.0%	Reduce the emissions intensity of its GDP by 33-35% by 2030 from 2005 level	2030 NDC target based on UNFCCC statistics and Climate Action Tracker assessment	First NDC	2016-10-02
Indonesia	Indonesia	100.0%	29% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-22
Japan	Japan	100.0%	46% reduction in all GHG (excluding LUC) below 2013	BAU based on NDC submission	First NDC (updated submission)	2021-10-22
Mexico	Mexico	100.0%	22% reduction in all GHG (including LUC) below BAU	2030 NDC target based on NDC submission	First NDC (updated submission)	2020-12-30
Middle East	Israel	3.1%	27% reduction in all GHG (including LUC) below 2015	2030 NDC target on all GHG (including LUC) based on NDC submission	First NDC (updated submission)	2021-07-29
	Jordan	1.3%	5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
	Kuwait	4.8%	7.4% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-12
	Lebanon	1.2%	20% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-03-16
	Oman	3.6%	7% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	Second NDC	2021-07-29
	Qatar	4.1%	25% reduction in all GHG (excluding LUC) below BAU	BAU based on GCAM Reference scenario	First NDC (updated submission)	2021-08-24
	United Arab Emirates	8.6%	23.5% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	Second NDC	2020-12-29
Pakistan	Pakistan	100.0%	15% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-10-21
Russia	Russia	100.0%	25-30% reduction in all GHG (including LUC) below 1990	Historical emissions based on NDC submission	First NDC	2020-11-25

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
South Africa	South Africa	100.0%	Emissions constraint of 420 MtCO2e on all GHG (including LUC)	BAU based on 2000: National Communication; NDC emissions in 2030 based on average of range in INDC submission (398-614 MtCO2e)	First NDC (updated submission)	2021-09-27
South America_Southern	Chile	9.0%	A maximum emissions limit target of 95 MtCO2e GHG emissions (excluding LUC)	2030 NDC target based on NDC submission and Climate Action Tracker assessment	First NDC (updated submission)	2020-04-09
	Ecuador	16.1%	20.4% reduction in all GHG (excluding LUC) below BAU in 2025	2030 NDC target based on BAU projection of GCAM Reference and NDC partnership assessment	First NDC	2019-03-29
	Paraguay	15.7%	10% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-16
	Peru	31.0%	30% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-12-18
South Asia	Bangladesh	66.8%	6.73% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-08-26
	Lao Peoples Democratic Republic	1.8%	60% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-05-11
	Samoa	0.0%	26% reduction in all GHG (including LUC) below 2007	BAU based on NDC submission	Second NDC	2021-07-30
	Sri Lanka	10.7%	4% reduction in all GHG (excluding LUC) below BAU in the energy sector	BAU based on GCAM Reference scenario and NDC submission	First NDC (updated submission)	2021-07-30
South Korea	South Korea	100.0%	24.4% reduction in all GHG (excluding LUC) below 2017	Historical emissions based on NDC submission	First NDC (updated submission)	2020-12-30
Southeast Asia	Brunei Darussalam	<0.1%	20% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC	2020-12-31
	Cambodia	3.4%	41.7% reduction in all GHG (including LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-12-31
	Fiji	<0.1%	10% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-12-31

GCAM Region	Country/Region	% of GHG	Representation of NDCs	Source of Historical/BAU emissions	NDC status	Latest submission date
	Kiribati	<0.1%	12.8% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC	2016-09-21
	Malaysia	18.6%	45% reduction in GHG (including LUC) emissions intensity of GDP below 2005	2030 NDC target based on ADVANCE	First NDC (updated submission)	2021-07-30
	Marshall Islands	<0.1%	45% reduction in all GHG (excluding LUC) below 2010	Historical emissions based on NDC submission	Second NDC	2020-12-31
	Philippines	11.1%	2.71% reduction of cumulative GHG (excluding LUC) below BAU between 2020 and 2030	2030 NDC target based on Climate Action Tracker assessment	First NDC	2021-04-15
	Seychelles	<0.1%	26.4% reduction in all CO2, CH4, and HFCs (excluding LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2021-07-30
	Singapore	3.2%	A maximum emissions limit target of 65 MtCO2e GHG emissions (including LUC)	2030 NDC target based on NDC submission	First NDC (updated submission)	2020-03-31
	Solomon Islands	2.2%	14% and 33% reduction in CO2 below 2015 in 2025 and 2030, respectively	BAU based on NDC submission	First NDC (updated submission)	2021-07-21
	Thailand	20.5%	20% reduction in all GHG (excluding LUC) below BAU	BAU based on NDC submission	First NDC (updated submission)	2020-10-26
	Tuvalu	<0.1%	60% reduction in all GHG (excluding LUC) below 2010 in 2025	Historical emissions based on NDC submission	First NDC	2016-04-22
	Viet Nam	20.5%	7.3% and 9% reduction in all GHG (including LUC) below BAU in 2025 and 2030, respectively	BAU based on NDC submission	First NDC (updated submission)	2020-09-11
USA	USA	100.0%	50% reduction in all GHG (including LUC) below 2005	Historical emissions based on EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks	First NDC (after rejoining the Paris Agreement)	2021-04-22

Table S6 Decarbonization rate (annual rate of decrease in GHG emissions per unit of GDP) between 2015 and 2030 under the NDC, NDC+, and NDC++ cases in the central pathways explored in this study

GCAM Region	NDC	NDC+	NDC++
Africa_Eastern	4.60%	4.80%	6.00%
Africa_Northern	3.00%	3.00%	5.00%
Africa_Southern	6.60%	6.60%	8.80%
Africa_Western	4.80%	4.80%	5.60%
Argentina	4.50%	6.80%	6.80%
Australia_NZ	3.80%	6.10%	6.10%
Brazil	5.00%	7.20%	7.20%
Canada	6.10%	8.30%	8.30%
Central America and Caribbean	2.40%	2.40%	4.50%
Central Asia	4.40%	5.30%	6.60%
China	3.60%	5.80%	5.90%
Colombia	4.50%	4.50%	6.70%
EU	4.90%	4.90%	7.10%
Europe_Eastern	2.70%	4.50%	5.00%
Europe_Non_EU	2.30%	3.80%	4.60%
European Free Trade Association	6.20%	6.20%	8.40%
India	2.10%	4.40%	4.40%
Indonesia	5.80%	8.00%	8.00%
Japan	4.10%	4.10%	6.40%
Mexico	2.00%	4.30%	4.30%
Middle East	2.30%	3.80%	4.60%
Pakistan	1.60%	1.60%	3.90%
Russia	4.00%	6.30%	6.30%
South Africa	4.50%	4.50%	6.70%
South America_Northern	-3.20%	-3.20%	-0.80%
South America_Southern	4.10%	4.10%	6.40%
South Asia	2.00%	2.00%	4.20%
South Korea	4.50%	6.80%	6.80%
Southeast Asia	3.80%	5.10%	5.90%
USA	5.60%	5.60%	7.80%

Table S7 GHG emission reductions in 2030 relative to the current NDC level for GCAM regions under "Climate Action Tracker" and "Human Development Index" grouping methods.

	Climate Action Tracker			Human Development Index		
	NDC	NDC+	NDC++	NDC	NDC+	NDC++
Africa_Eastern	0%	0%	17%	0%	3%	5%
Africa_Northern	0%	0%	27%	0%	0%	27%
Africa_Southern	0%	0%	30%	0%	0%	3%
Africa_Western	0%	0%	13%	0%	0%	2%
Argentina	0%	30%	30%	0%	30%	30%
Australia_NZ	0%	30%	30%	0%	30%	30%
Brazil	0%	30%	30%	0%	0%	30%
Canada	0%	30%	30%	0%	30%	30%
Central America and Caribbean	0%	0%	29%	0%	3%	24%
Central Asia	0%	14%	30%	0%	15%	29%
China	0%	29%	30%	0%	0%	30%
Colombia	0%	0%	30%	0%	0%	30%
EU	0%	0%	30%	0%	30%	30%
Europe_Eastern	0%	25%	30%	0%	5%	30%
Europe_Non_EU	0%	21%	30%	0%	27%	30%
European Free Trade Association	0%	0%	30%	0%	30%	30%
India	0%	30%	30%	0%	0%	0%
Indonesia	0%	30%	30%	0%	0%	30%
Japan	0%	0%	30%	0%	30%	30%
Mexico	0%	30%	30%	0%	0%	30%
Middle East	0%	21%	30%	0%	16%	27%
Pakistan	0%	0%	30%	0%	0%	0%
Russia	0%	30%	30%	0%	30%	30%
South Africa	0%	0%	30%	0%	0%	30%
South America_Northern	0%	0%	30%	0%	0%	30%
South America_Southern	0%	0%	30%	0%	13%	30%
South Asia	0%	0%	28%	0%	0%	5%
South Korea	0%	30%	30%	0%	30%	30%
Southeast Asia	0%	18%	28%	0%	11%	29%
USA	0%	0%	30%	0%	30%	30%

Table S8 Comparison of emissions and global net-zero CO_2 years between outcomes based on Human Development Index (HDI) and Climate Action Tracker (CAT) for all emissions pathways explored in this study

2030 ambition	Post-2030 min. decarb. rate	Timing of net-zero pledges	2030 GHG emissions (Gt)		Cumulative CO2 emissions (2020 to year of net-zero CO2 globally or 2100 if not reaching net-zero before 2100)		Year of net-zero CO2 emissions globally (NA indicates not reaching net-zero before 2100)	
			CAT	HDI	CAT	HDI	CAT	HDI
NDC	2%	As stated	45.4	45.4	1114	1114	NA	NA
		5-yr earlier	45.4	45.4	1042	1042	NA	NA
		10-yr earlier	45.4	45.4	970	970	NA	NA
	5%	As stated	45.4	45.4	853	853	2066	2066
		5-yr earlier	45.4	45.4	782	782	2064	2064
		10-yr earlier	45.4	45.4	710	710	2064	2064
	8%	As stated	45.4	45.4	756	756	2056	2056
		5-yr earlier	45.4	45.4	699	699	2052	2052
		10-yr earlier	45.4	45.4	639	639	2049	2049
NDC+	2%	As stated	37.1	41.4	721	799	2095	2095
		5-yr earlier	37.1	41.4	666	737	2095	2095
		10-yr earlier	37.1	41.4	611	674	2095	2095
	5%	As stated	37.1	41.4	653	731	2060	2060
		5-yr earlier	37.1	41.4	601	672	2057	2057
		10-yr earlier	37.1	41.4	548	611	2055	2055
	8%	As stated	37.1	41.4	590	665	2053	2054
		5-yr earlier	37.1	41.4	550	619	2050	2051
		10-yr earlier	37.1	41.4	508	571	2047	2048
NDC++	2%	As stated	32.9	34.8	570	583	2057	2057
		5-yr earlier	32.9	34.8	529	542	2053	2053
		10-yr earlier	32.9	34.8	486	499	2049	2049
	5%	As stated	32.9	34.8	564	577	2056	2056
		5-yr earlier	32.9	34.8	524	538	2053	2053
		10-yr earlier	32.9	34.8	482	496	2049	2049
	8%	As stated	32.9	34.8	526	512	2052	2052
		5-yr earlier	32.9	34.8	493	482	2049	2049
		10-yr earlier	32.9	34.8	459	450	2046	2046

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