Supplementary Information

Paris targets within reach by aligning, broadening, and strengthening net-zero pledges

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Supplementary Notes

We use a set of scenarios that investigates a set of simple propositions to align the current national policies and pledges with global targets of the Paris Agreement. The key assumptions of the scenarios are indicated in Table 1 of the main text. The current policies (CurPol) and NDC scenarios function as reference scenarios to compare the impact of the net-zero targets. In the first net-zero (NZ) scenario, we assume that these pledges are implemented in combination with the current NDCs. The subsequent scenarios look at some ways to strengthen the net-zero targets. Firstly, we assume that the NDCs can be strengthened to be aligned with the NZ targets (NZ-Al scenario). Secondly, we broaden the NZ targets from the 75 countries that currently have made pledges to all countries (NZ-Br scenario). For this, we assume countries take on commitments in line with similar countries that have already pledged ambitions (based on income levels, see Supplementary Table 1 and Supplementary Figure 1). Subsequently, we strengthen the broadening of pledges (NZ-Str scenario) by assuming that all countries implement their respective net-zero target year five years earlier than the broadening step. We assume a rather conservative five-year acceleration of the net-zero target years due to our optimistic assumptions on countries with unclear commitments regarding CO_2 vs GHG neutrality (China, India, South Korea), as mentioned in the section “Scenario analysis to inform the global stocktake” of the main manuscript. Finally, for comparison, we use an existing cost-optimal IMAGE 1.5^{o}C scenario.

It is important to be noted that, apart from cheap natural gas prices driving the increase of emissions in our current policies scenario until 2080 before running in depletion issues, in our development of the scenario at the time (April-May 2022), we did not take into account several influential policies that had not been declared or signed fully into law yet. For example, the Inflation Reduction Act, which alone is projected to result in almost 1 Gt CO_2e emission reductions[1–3], and the Fit-for-55 package or REPowerEU plan are not included in our current policies scenario presented in this study. Additionally, we do not consider NDC targets and announcements as current policies, which means that China's coal peak or carbon intensity targets etc. are also not included in our current policies scenario. This, in combination with our current policies extension method of extending a nominal carbon tax beyond 2030 based on GDP growth but not necessarily keeping policies in place after 2030 but allowing the model to extrapolate based on the benefits incurred through their implementation until that time, can lead to slightly higher temperature results by the end of the century compared to more recent or constantly updated sources.

Supplementary Methods

We applied the IMAGE integrated assessment modelling framework, version 3.2, to explore the implications of environmental consequences of human activities worldwide[4–7]. IMAGE includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 major economies and world regions and most environmental parameters based on a geographical grid. The IMAGE modelling framework includes a detailed energy-system model (TIMER), a global climate policy model (FAIR), and a land-use model (IMAGE land).

The TIMER energy model of IMAGE has been developed to explore scenarios for the energy system[6,8]. TIMER describes 12 primary energy carriers in 26 world regions and analyses long-term energy demand and supply trends. It covers a wide range of mitigation options, including nuclear power, renewable energy (different solar and wind technologies, hydropower), bioenergy (first and second-generation), nuclear power and CCS technology[6]. The TIMER model dynamics are mainly determined by the substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive multinomial logit models that describe investments in new energy production and consumption capacity. The demand for new capacity is limited by assuming that capital goods are replaced not sooner than at the end of their economic lifetime (which is influenced by the carbon price). The long-term prices that drive the model are determined by resource depletion and technology development, which determine the long-term prices that drive the model. Resource depletion is represented by long-term cost-supply curves and technology development by endogenous learning curves or exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows by emission factors. A carbon price can be used to induce a dynamic response, such as the increased use of low- or zero-carbon technologies, energy efficiency improvements, and end-of-pipe emission reduction technologies.

The land-use model of IMAGE has been developed to explore scenarios for the land-use system. In terms of land-based mitigation options, IMAGE accounts for three general types of options: bio-energy production, REDD (avoided deforestation) and reforestation of degraded forests. Bio-energy demand is determined by TIMER based on bio-energy yield, the carbon price, dynamics in the energy system, and land availability, following a food-first principle[9].

The FAIR model of IMAGE calculates the impact of climate mitigation policy using carbon prices and marginal abatement cost curves (MACs) representing costs of mitigation actions to determine a cost-optimal emission pathway[5,10]. It captures the time- and pathway dependent dynamics of the underlying TIMER model by scaling the marginal abatement costs (MAC) curves based on the reduction effort from the previous years. The marginal abatement curves costs curves in FAIR are based on (1) the IMAGE energy model TIMER for energy-related CO_2 emissions[5] and (2) MACs for non-CO_2 GHG emissions as described in Harmsen et al.[11]. Some recent updates were made based on Harmsen et al.[11] and EPA[12]; see Hof et al.[4] for more detail. The non-CO_2 MAC curves are made consistent with the IMAGE scenarios. The MAC curves for energy-related CO_2 emissions were constructed to account for past efforts by imposing a wide range of carbon price pathways in the TIMER model and recording the induced reduction in CO_2 emissions[8].

In IMAGE, the main interaction with the earth system is by changes in energy, food and biofuel production that induce land-use changes and emissions of carbon dioxide and other GHGs. The calculated emissions of GHGs and air pollutants are used in IMAGE to derive changes in concentrations of GHGs, ozone precursors and species involved in aerosol formation on a global scale. Climatic change is calculated as global mean temperature change using a slightly adapted version of the MAGICC 6.0 climate model[13].

Our temperature outcomes for this work are estimated for global surface air temperature (GSAT) with the reduced-complexity carbon-cycle and climate model MAGICC 7.5.3[13,14] in a set up that captures the uncertainties in radiative forcing as well as climate and carbon-cycle response[15]. MAGICC's climate core is based on a 50-layer, hemispherically resolved upwelling-diffusion-entrainment ocean model coupled to a four-box (hemispheric land/ocean) spatial resolution for effective radiative forcing and as such includes enhanced representations of time-varying climate sensitivities, carbon cycle feedbacks, aerosol forcings and ocean heat uptake characteristics. The model runs on monthly timesteps, which improves its representation of the response to volcanic eruptions compared to an annual timestep. The key updates in the most recent version of MAGICC are the inclusion of a state-dependent climate feedback factor (previously it was only forcing-dependent) which has been calibrated to CMIP6 models, accounting for the effect of large historical anthropogenic biomass burning aerosol precursor emissions on aerosol effective radiative forcing, a nitrate aerosol forcing scheme which accounts for the sulfate competition for ammonia based on Hauglustaine et al.[16] and the inclusion of a non-ocean heat uptake parameterisation which represents land surface and cryosphere heat uptake in each hemisphere. In addition, it includes an updated effective radiative forcing parameterisations for CO_2, CH_4 and N_2O, while allowing for a wider range of input concentrations[13,14].

Supplementary Tables

Supplementary Table 1 presents the net-zero target years, the emission type each country or region covers in their pledge, and the status of their pledge for the various IMAGE regions and countries. The final net-zero target year as assumed in IMAGE is presented in the last column, based on the assumption that regions will achieve net-zero GHG emissions 15 years after achieving net zero CO_2 emissions, based on an assessment of cost-effective 1.5 °C and 2 °C scenarios from integrated assessment models of van Soest et al.[17], as well as the analysis of C1a and C2 category scenarios presented in the IPCC AR6 report[18]. Based on the percentage of scenarios that follow a net-zero pathway, CO_2 neutrality in C1a and C2 scenarios is achieved 10-20 years prior to GHG neutrality.

The selection of net-zero targets for each IMAGE region was based on both Net Zero Trackers (see Supplementary Table 1 notes). Most IMAGE regions contain more than one country, leading to complex calculations for net-zero targets when a dominant emitting country does not exist in the IMAGE region. Thus, for certain regions where only certain countries have a net-zero pledge, a net-zero target is assumed only when the country (or countries) with a target within the region is clearly dominant in terms of emissions (based on share of emissions in 2020). As such, regions like West Africa, where Nigeria is clearly the main emitter, or Southeast Asia where Thailand, Vietnam and Malaysia comprise 74% of the region's emissions, the whole region is assumed to have a net-zero target. All Member States of the EU27 and the United Kingdom are included in the IMAGE calculations as part of the Europe region, and in the main text we present the result for the EU28 (EU27 and the UK).

Supplementary Table 1: Net-zero target years per IMAGE region. Net-zero GHG or CO_2 target year for the IMAGE regions based on official submissions and documents (as of August 2022), and the net-zero GHG target years as assumed in the scenarios of this study. The fifth column presents the assigned net-zero GHG emissions year for the NZ-Br scenario.

IMAGE region	Official net-zero target year	Emission type	Net-zero GHG target year	Assigned net-zero GHG target year	Net-zero status of the main emitting country within the region*	Region classification
Canada	2050	GHG	2050	-	Canada: In law	OECD
USA	2050	GHG	2050	-	USA: In policy document	
Mexico	N.A.	N.A.	N.A.	2062	No net zero target	
Western Europe	2050	GHG	2050	-	EU27, UK: In law	
Central Europe	2050	GHG	2050	-	EU27: In law	
Turkey	2053	CO_2	2068**	-	Turkey: In policy document	
Japan	2050	GHG	2050	-	Japan: In law	
Republic of Kore	2050	GHG[5]	2050	-	Republic of Korea: In law (coverage not specified, but here assumed all GHGs)	
Oceania	2050	GHG	2050	-	Australia: Pledge	
Brazil	2050	GHG	2050	-	Brazil: Declaration/pledge	Non-OECD (with net-zero target)
China	2060	GHG[5]	2060	-	China: In policy document (coverage not specified, but here assumed all GHGs)	
India	2070	GHG[5]	2070	-	India: Declaration/pledge (coverage not specified, but here assumed all GHGs)	
Indonesia	2060	GHG	2060	-	Indonesia: Proposed/in discussion	
Russia	2060	CO_2	2075**	-	Russian Federation: Pledge (coverage not specified)	
South Africa	2050	CO_2	2065**	-	South Africa: Declaration/pledge	
Southeast Asia	2050	CO_2	2065**	-	Malaysia, Thailand, Vietnam: Declaration/pledge[6]	
Central Asia	2060	CO_2	2075**	-	Kazakhstan: Pledge (coverage not specified)	
Western Africa	2060	CO_2	2075**	-	Nigeria: Declaration/pledge[3]	
Ukraine	2060	GHG	2060	-	Ukraine: In policy document	

Rest of Central America	N.A.	N.A.	N.A.	2065	N.A.: two countries of the region[1]	Non-OECD (without net-zero target)
Eastern Africa	N.A.	N.A.	N.A.	2072	N.A.	
Rest of South America	N.A.	N.A.	N.A.	2065	N.A.: only four countries[2]	
Northern Africa	N.A.	N.A.	N.A.	2068	N.A.	
Middle East	N.A.	N.A.	N.A.	2060	N.A.: three countries[4]	
Rest of South Asia	N.A.	N.A.	N.A.	2070	N.A.: one country[7]	
Rest of South Africa	N.A.	N.A.	N.A.	2070	N.A.	

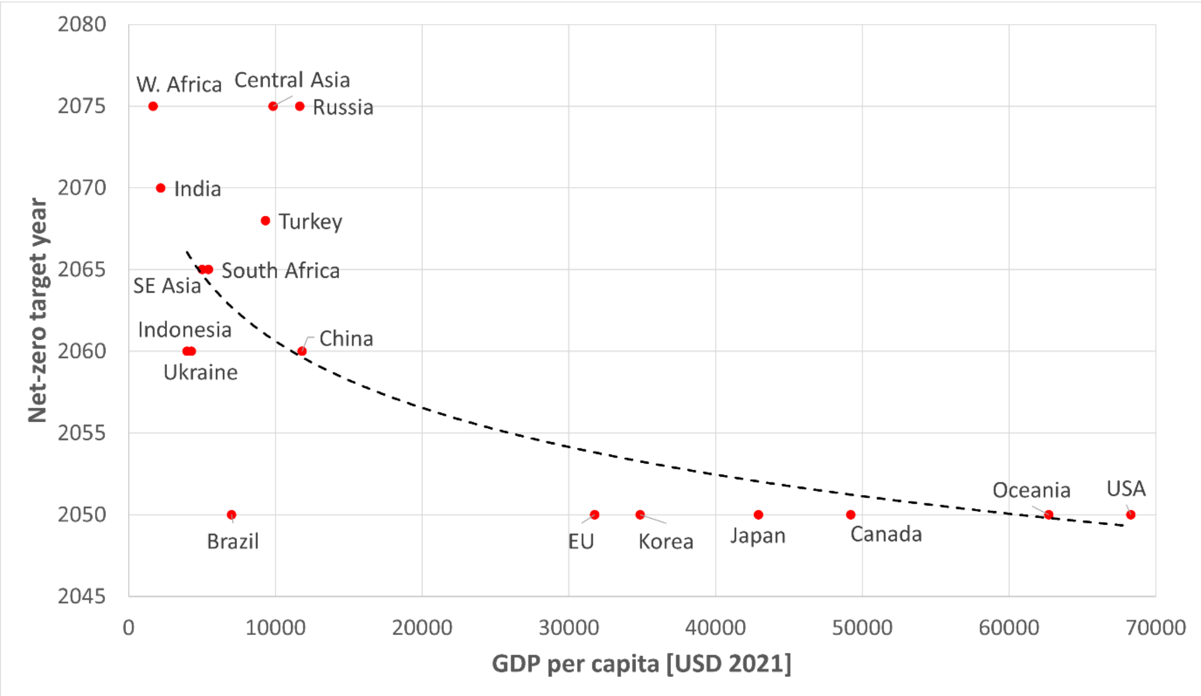
* Source: Net Zero Tracker[19]; Climate Watch Net zero tracker[20] ** based on the assumption that the region will achieve net-zero GHG emissions 15 years after achieving net zero CO2 emissions.

[1] Only Costa Rica, Panama in policy document, representing 11% of the CO_2 emissions of the region; [2] Only Chile, Ecuador, Peru, Uruguay in policy document, representing 22.4% of the emissions of the region; [3] Only Nigeria declaration/pledge, representing 58% of the CO_2 emissions of the region. [4] Only Saudi Arabia, Israel, UAE declaration/pledge, representing 38.3% of the CO_2 emissions of the region. [5] For this study we asses that the net-zero target for China, India and Republic of Korea refers to all GHGs, similar as assumed in Höhne et al. and Meinshausen et al.[21,22]; [6] Thailand, Viet Nam, Malaysia in policy document (net-zero targets for CO_2 by 2050), representing 74% of the CO_2 emissions of the region; [7] Only Sri Lanka in policy document, representing 5.5% of the CO_2 emissions of the region.

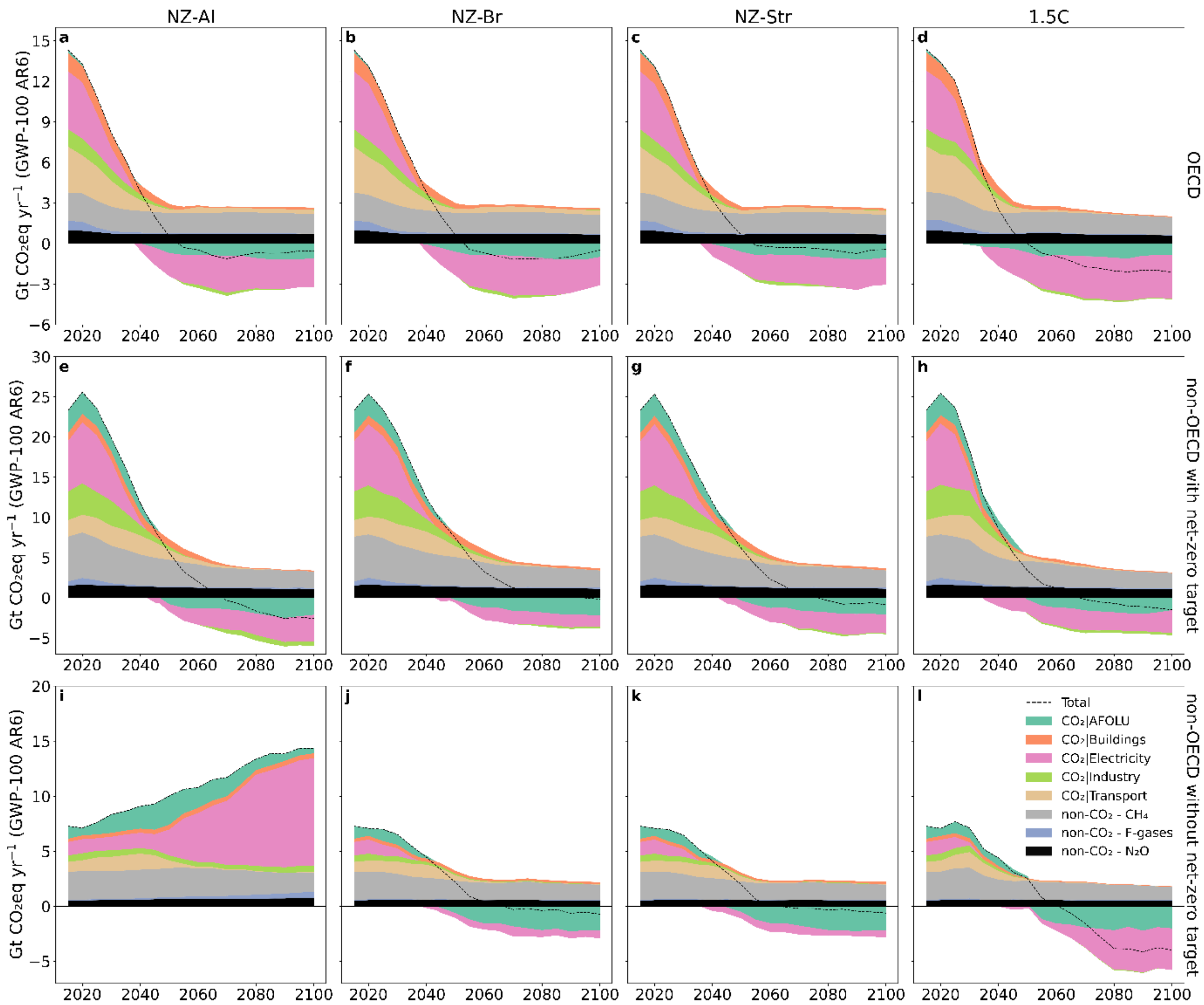
Supplementary Table 2: GHG emission reductions (in %) for all IMAGE regions compared to their NDC scenario, for the year 2030. The NZ scenario is not shown in this Table as by default all regions meet their NDC targets in 2030 first, and then follow a pathway to their respective net-zero targets.

	NZ-Al	NZ-Br	NZ-Str	Region classification
Canada	-7	-8	-12	OECD
USA	-1	1	1	
Mexico	-13	-12	-4	
Western Europe	5	0	0	
Central Europe	5	4	2	
Turkey	-6	-2	-4	
Japan	-15	-14	-20	
Republic of Korea	-6	-6	-17	
Oceania	-49	-11	-10	
Brazil	-55	-28	-25	Non-OECD (with net-zero target)
China	-39	-38	-45	
India	-4	-4	-4	
Indonesia	-22	-22	-28	
Russia	1	-1	-1	
South Africa	15	-5	-5	
Southeast Asia	-40	-25	-20	
Central Asia	-11	-11	-10	
Western Africa	-50	-45	-44	
Ukraine	-33	-35	-32	
Rest of Central America	-2	-13	-12	Non-OECD (without net-zero target)
Eastern Africa	-4	-5	-5	
Rest of South America	-12	-24	-23	
Northern Africa	-8	-9	-9	
Middle East	-2	-45	-47	
Rest of South Asia	0	-2	-2	
Rest of South Africa	-2	-49	-34	

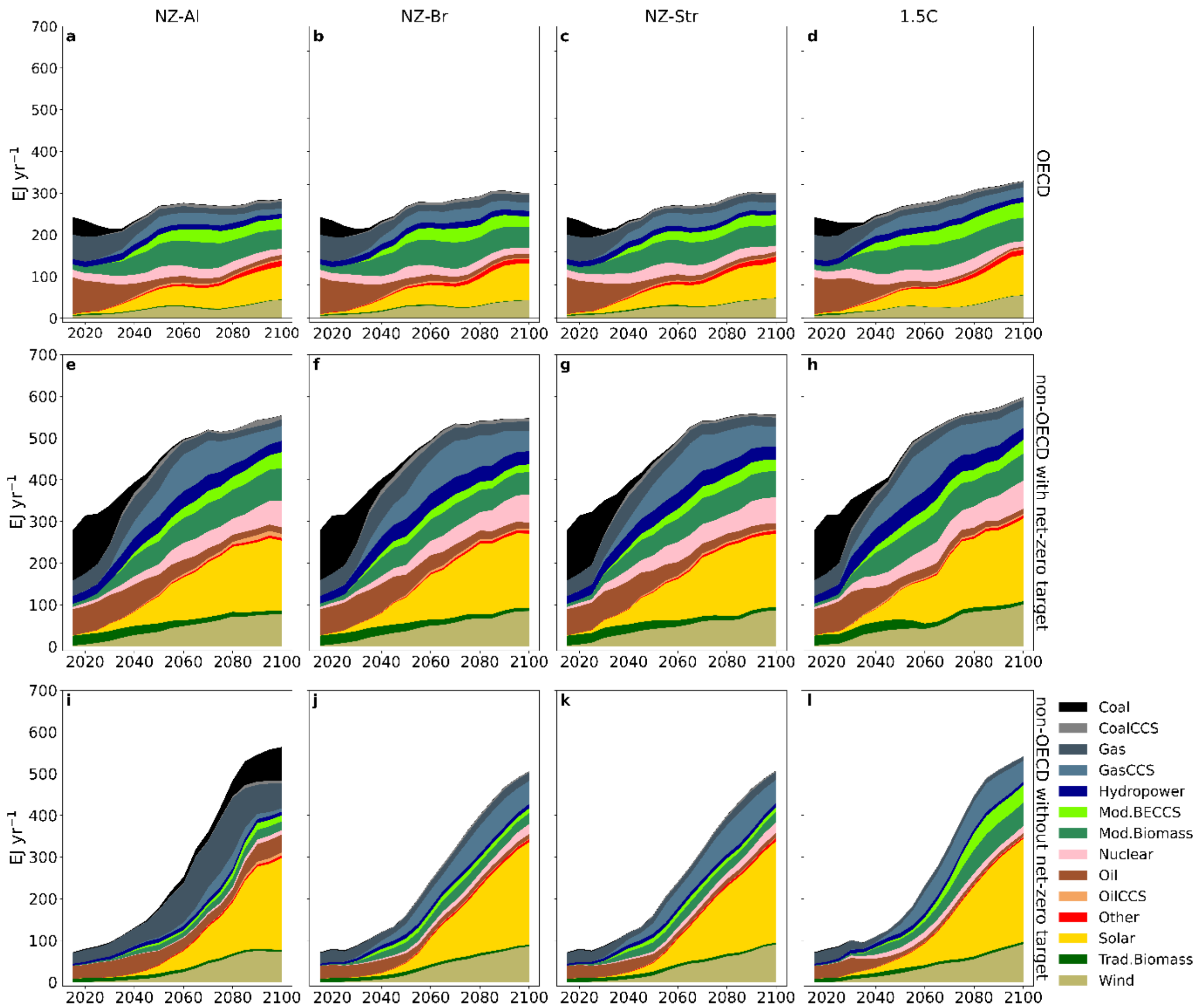
Supplementary Figures



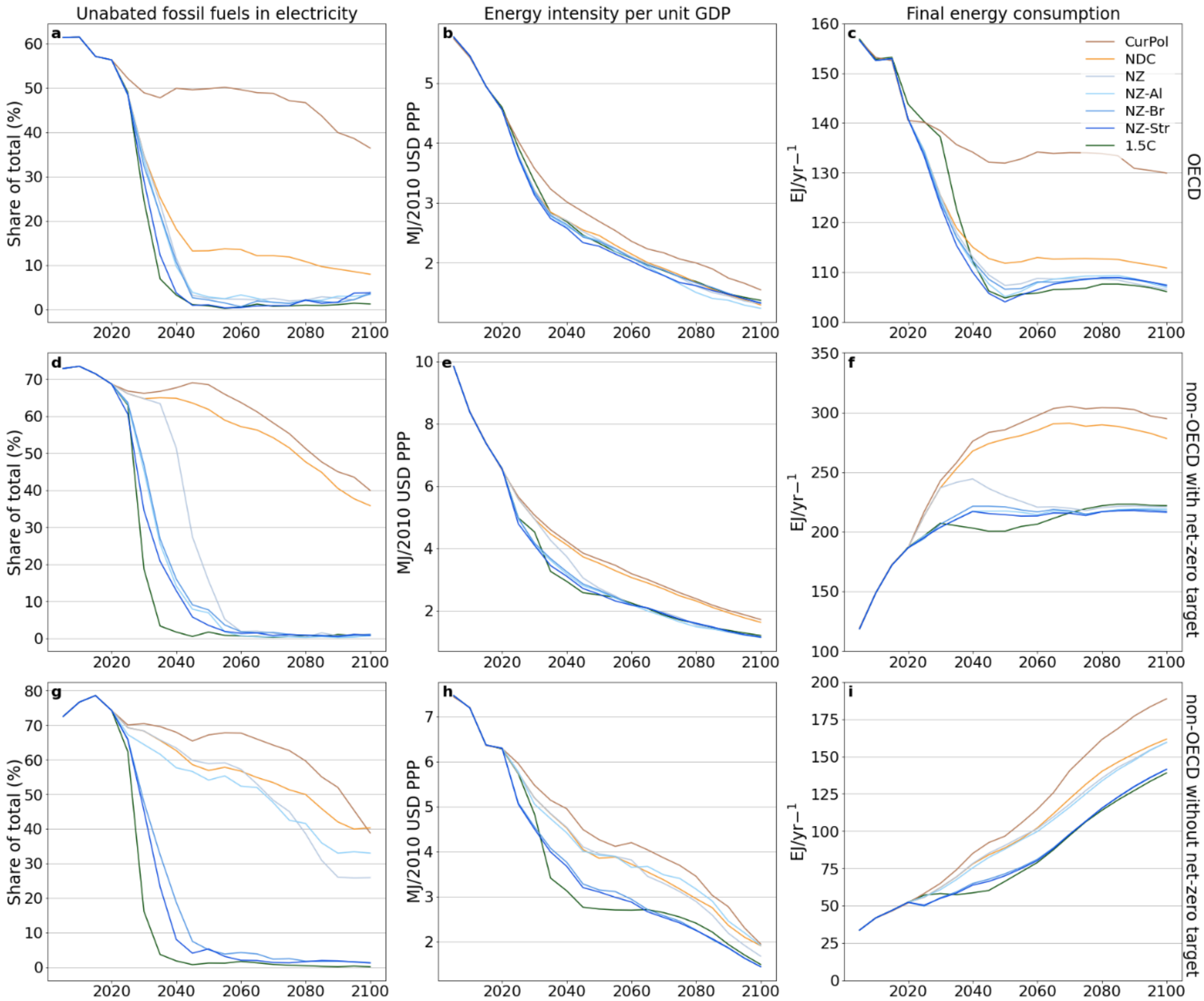
Supplementary Figure 1: GDP per capita vs net-zero target year for IMAGE regions. Income along the x-axis; net-zero year for GHGs along the y-axis. Countries/regions with current pledges are plotted against their GDP per capita income – resulting in a relationship as seen here. Based on the ensuing fitted trendline, the rest of the regions/countries are assigned an assumed net-zero emissions year based on their GDP per capita levels as shown in Supplementary Table 1



Supplementary Figure 2: GHG emission projections per sector and gas for all regions. Development of GHG emission projections over time by sector, for OECD (**a-d**), non-OECD with a net-zero target (**e-h**) and non-OECD without a net-zero target (**i-l**) regions, for the aligned, broadened, strengthened and 1.5°C scenarios explored in this study



Supplementary Figure 3: Primary energy consumption by source. Development of substituted primary energy consumption projections over time, for OECD (**a-d**), non-OECD with a net-zero target (**e-h**) and non-OECD without a net-zero target (**i-l**) regions, for the aligned, broadened, strengthened and 1.5°C scenarios explored in this study. Trad.Biomass (traditional biomass) in the IMAGE model includes charcoal, fuelwood, crop residue and dung. Mod.Biomass (modern biomass) includes all liquid biofuels (ethanol, diesel, methanol), as well as wood pellets



Supplementary Figure 4: Key energy indicators. Unabated fossil fuel use in electricity, energy intensity per unit GDP and final energy consumption for OECD (**a-c**), non-OECD with a net-zero target (**d-f**) and non-OECD without a net-zero target (**g-i**) regions, for all scenarios explored in this study

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