DOI: 10.1111/nyas.14970

ORIGINAL ARTICLE

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Achieving net-zero emissions targets: An analysis of long-term scenarios using an integrated assessment model

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Funding information
European Union's Horizon 2020 research and innovation program, Grant/Award Numbers: 821471-ENGAGE, 821124-NAVIGATE

Abstract

More than 100 countries have communicated or adopted new Nationally Determined Contributions (NDCs) and net-zero target pledges. We investigate the impact on global, national, sectoral, and individual greenhouse gas emissions projections under different scenarios based on the announced NDCs and net-zero pledges using the IMAGE integrated assessment model. Our results show that while the net-zero pledges, if implemented, could be an important step forward, they are still not enough to achieve the Paris Agreement goals of well below 2°C and preferably 1.5°C by the end of the century. Still, our net-zero scenarios project significant all-sector decarbonization, in particular, electricity; however, certain sectors like industry and transport prove hard to completely abate.

KEYWORDS
carbon neutrality, climate change, NDC, net zero, Paris Agreement

INTRODUCTION

The Parties to the Paris Agreement (adopted by nearly all countries) pledged to limit global warming to well below 2°C and preferably to 1.5°C, compared to preindustrial levels.[1] In addition, the Parties further agreed to achieve a balance between anthropogenic emissions and removals by sinks. Parties need to implement these goals via national policies and climate strategies, communicated via Nationally Determined Contribution (NDC) plans submitted to UNFCCC every 5 years.[1] At the moment, about 150 Parties have submitted new NDC targets,[2] representing about 85% of global greenhouse gas (GHG) emissions in 2019, including land use emissions.[3,4] Under the Agreement, countries are also invited to communicate "mid-century long-term low greenhouse gas emissions development strategies" (long-term strategies, or LTSs), and 46 Parties have submitted LTSs (60% of global GHG emissions in 2019).[5] At the same time, about 75 parties communicated the ambition to reach net zero early in the second half of the century (either in NDCs, LTSs, domestic law, policy, or political announcements).[6]

Among the countries that have communicated net-zero emissions targets are the United States, the EU, China, India, Brazil, and Russia. However, the ambition, scope, status, and elaboration in terms of concrete implementation strategies differ substantially across countries.[7,8] More specifically, the EU's climate neutrality target by 2050 is confirmed in the European Climate law,[9] while the net-zero targets of Brazil, China, and the United States are communicated in an NDC and/or LTS,[2,5] but they are still not enshrined in legislation. India and Russia have announced a net-zero target, but not yet institutionalized that pledge in any way. Respective to specific long-term strategies, the EU and the United States have presented a detailed model analysis of transition pathways to their respective net-zero emissions targets,[10,11] while Brazil and India have not yet formulated LTSs. China has not complemented its LTS with a detailed analysis of its long-term strategy; the LTS document states that China "intends to achieve carbon neutrality by 2060."[2,5] For net-zero targets to be credible, they need to be accompanied with detailed and transparent plans for achieving said targets.[8] In addition, they need to be supported by near-term actions for delivery.[12]

In 2021, numerous studies were published, analyzing the impacts of countries' NDCs and net-zero targets. Höhne et al.,[13] Ou et al.,[14] and Meinshausen et al.[15] provided an analysis of updated mitigation pledges for 2030 and net-zero pledges, as of May, September, and November 2021, respectively, concluding that while net-zero pledges could significantly lower projected global warming compared to currently implemented policies or the pledges submitted to the Paris Agreement, more effort is needed to implement these commitments. Several technical reports and policy briefs have also analyzed the pledges in the second half of 2021, emphasizing the global temperature projections as well as showing that progress has been made in reducing the projected global emissions projection by 2030, but it is not enough to achieve the Paris climate goals.[12,16–20] While the above analyses provide a thorough look into the impacts of NDCs and net-zero targets, only a few studies[21–23] provided a scenario analysis of the transition in the sectoral emissions for the G20 economies toward the NDC and net-zero targets.

Therefore, this study aims to analyze the transition of the world and six major emitting countries (China, the EU, India, Brazil, Russia, and the United States) toward achieving the NDCs and net-zero pledges, including all announcements made until the closing of COP26. We assess the global, national, sectoral, and individual greenhouse gas emissions under five different scenarios. These scenarios comprise: current policies; the latest NDCs; announced mitigation pledges (NDCs and net-zero targets); pathways meeting net-zero targets (starting from 2021 emissions); and a least-cost pathway consistent with the 1.5°C climate targets. These scenarios have been developed using the IMAGE integrated assessment model.[24] We analyze the difference between the global and national emission pathways expected under the current policies and those needed to meet the NDC (in both cases, extrapolating these into the future based on a constant effort) and net-zero targets. We also analyze the difference between these scenarios and the cost-effective emissions pathway for holding global warming below 1.5°C. We use the current policies scenario of IMAGE as a starting point for our cost-effective implementation of abatement options that bring emissions toward the NDC and net-zero target pledges, and finally the 1.5°C target, as described below in the section "Model implementation of the scenarios."

METHODOLOGY

Scenarios

Description of scenarios

We use a set of scenarios that investigates a set of simple propositions to align the current national policies and pledges with the global targets of the Paris Agreement. The key assumptions of the scenarios are indicated below. The current policies and NDC scenarios function as reference scenarios to compare the impact of the net-zero targets. In the first net-zero 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. In the first scenario, we first assume that the NDCs can be strengthened to be aligned with the NZ targets. For comparison, we use an existing cost-effective IMAGE 1.5°C scenario.

The current policies (CurPol) scenario includes currently implemented national climate policies updated to reflect climate mitigation policies adopted and implemented as of April 2022, up to 2030. Apart from the most recent literature research, input by the NewClimate Institute, based on their Climate Policy Database, and a country expert review of the national policies were also used in the development of this scenario.[25,26] It is important to note that the Fit-for-55 package for the EU and the Inflation Reduction Act for the United States are not included in our current policy scenario. For consistency reasons, we only include policies that have already been enshrined in law, and while the package was approved in July 2021, by the time this work was completed, the vote in the European Parliament had not yet taken place, so the package was considered a "planned policy" and thus excluded from quantification in our scenario. The Inflation Reduction Act was passed at a later stage, beyond our policy cut-off date, so it is not included in our scenarios.

The NDC scenario assumes full achievement of both conditional and unconditional NDC targets (including the new and updated NDCs) by 2030 (cut-off date: December 31, 2021).[27,28] The scenario assumes the CurPol scenario is implemented first.

Our first net-zero scenario is based on the NDC scenario until 2030 (NDC-NZ). After 2030, it is assumed that countries/regions that have already announced or adopted a net-zero target implement emissions reductions toward their adopted or announced net-zero targets. It is assumed that the reduction linearly increases in time until the net-zero target is reached. All other countries with no announced net-zero targets follow the NDC scenario. It should be noted that while we are aiming for a linear pathway to the target year for each region in our NDC-NZ and NZ scenarios, due to the dynamics of the response of the resulting carbon price in the energy system, the final calculated emission pathways might differ slightly from a directly linear one. More specifically, the foresight in the IMAGE model (anticipating the carbon price developments) as well as the induced benefits in the energy system from increased technology learning and reduced technology costs imply that the final calculated emission pathways slightly overachieve a linear pathway.

Our second net-zero scenario (NZ) assumes full achievement of each region's announced net-zero target, but with immediate implementation of its target (thus not implementing the NDC targets in 2030).[a] However, in our approach to better reflect equity principles and to support the Paris Agreement's principle of common-but-differentiated responsibilities and respective capabilities, we assume for the low and lower-middle income countries a minimum transition period of 40 years to reach net zero, meaning that countries with a net-zero target year in 2070, for example, like India, are still allowed to increase emissions until 2030—basically follow their NDC scenario. This assumption is based on the observation of high-income countries like the United States, Canada, and Japan, which all witnessed peak emissions around 2005–2010 and have a net-zero target by 2050.

[a] The emissions reduction profile follows a path, which is in between a linear pathway from 2020 levels to net-zero targets and a pathway that first meets the NDC targets in 2030, and then meets the net-zero targets at their respective year.

Finally, our 1.5°C scenario assumes a cost-effective achievement of a radiative forcing target of 1.9 W/m^2 by 2100 via a global uniform carbon price applied from 2021 onward.[29]

Net-zero GHG targets

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 26 IMAGE regions.[b] 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.[30]

The selection of net-zero targets for each IMAGE region was based on both Net Zero Trackers[6,31] (see Table 1 notes). For certain countries where coverage of emissions is unclear or not specified, we assume coverage of emission types as follows: for China, we assume a GHG net-zero target by 2060, similar to other (inter)national studies.[13,15,32,33] For India, published studies vary between a conservative approach of interpreting the country's 2070 target as covering CO_2 emissions only,[15] and all GHGs.[21] We apply the more ambitious assumption covering all GHGs, in order to be consistent with the rest of the major emitters presented here as well. For South Korea, we assume coverage of all GHGs similar to Höhne et al.[13] Reaching GHG neutrality in our scenario development for IMAGE's corresponding model regions (see Table 1) might not always be feasible. However, reaching carbon neutrality is feasible for those regions, as will be elaborated below in the section "Emission projections for major emitters."

Most IMAGE regions contain more than one country, leading to complex calculations for NDC/net-zero targets when a clearly dominant emitting country does not exist in the IMAGE region. For certain regions, such as the Middle East and Southeast Asia, where only certain countries have a net-zero pledge, the quantification of the final emissions target level on a regional level is complex, and, therefore, no net-zero target was assumed. All 27 Member States of the European Union and the United Kingdom are included as a group in the IMAGE calculations as part of the Europe region; in the Results section, we present the results for EU28 (European Union and the United Kingdom).

Model implementation of the scenarios

CurPol (current policies) scenario

The CurPol scenario of IMAGE was derived from the original SSP2 baseline by introducing explicit policy measures and is reported in detail in Roelfsema et al.[34] More specifically, we used a modeling protocol[26] updated from Roelfsema et al.,[34] including a detailed spreadsheet listing policies by country to implement current policies in the IMAGE model. The CurPol scenario also considers the short-term (2020–2025) economic projections updated to include the implications of the COVID-19 pandemic, including changes in sectoral activity.[35] The emission development after 2030 assumes that countries will pursue equivalent effort (see below).

Mitigation scenarios

In the other scenarios, including the NDC and net-zero scenarios, we assume a cost-effective achievement of the NDC and net-zero emission target levels via a regionally differentiated carbon price in all regions. The carbon price is implemented from 2021 onward to reach the 2030 and net-zero targets, following a cost-effective pathway.

Post-2030 assumptions for the CurPol and NDC scenarios

The reduction effort reached in the target year for the CurPol and NDC scenarios is assumed to remain constant throughout the rest of the century. This was implemented by extrapolating the equivalent carbon price in 2030, using the GDP growth rate of the different regions up to 2100, following van Soest et al.[30] The equivalent carbon price represents the value of carbon that would yield the same marginal emissions reduction as the current or NDC policies in a region. If a region has a zero-carbon price while implementing the current policies or NDCs in 2030, a minimum carbon price of 1$/t$CO_2$ in 2030 was assumed. This represents an equivalent effort in the future. Moreover, other long-term benefits are also realized in the energy system, alongside the extended carbon price. The implementation of climate policies directly leads to renewable capacity increase and the avoidance of new fossil fuel infrastructure or CO_2-intensive industry (either through halting new fossil fuel power plant construction or coal phase-out via a premium on electricity production from coal). Additionally, advanced biofuel production and use is stimulated through mandatory use in fuel mixes, and energy efficiency measures in the building and industry sectors are stimulated. Consequently, technology costs for low-carbon energy supply options in the model decrease, while costs for fossil fuel supply increase. This in turn leads to increased (renewable) technology adoption rates and learning-by-doing, which propagate into the future well beyond 2030.

Land-use emissions

Our land use, land-use change and forestry (LULUCF) model emission projections have been harmonized toward each emitter's reported land-use emission estimates from 2015 onward.[36]

Country selection

The scenarios are modeled with the IMAGE model at the level of the 26 world regions (Table 1). The analysis focuses on six of the world's largest GHG emitters, representing approximately 70% of global GHG emissions. China, the United States, the EU, India, and Russia are, in the order mentioned, the five largest emitters. While not in the top 10 emitters globally, Brazil was selected as a country with a unique profile, as the majority of emissions result from land-use and land-use change compared to fossil fuel use as in the rest of the major emitters.

[b] The 26 IMAGE regions and their country coverage are described in: https://models.pbl.nl/image/index.php/Region_classification_map

TABLE 1 Net-zero GHG or CO_2 target year for the NDC and net-zero targets for the IMAGE regions based on official submissions and documents, and the net-zero GHG target years as assumed in the scenarios of this study.

IMAGE region	Official net-zero target year	Emission type	Net-zero status of the main emitting country within the region	Assumed net-zero GHG target year
Canada	2050	GHG	Canada: in law	2050
USA	2050	GHG	USA: in policy document	2050
Mexico	No net-zero target		Mexico: under discussion	
Rest of Central America	N.A.		N.A.: two countries[a]	
Brazil	2050	GHG	Brazil: in policy document	2050
Rest of South America	N.A.		N.A.: three countries[b]	
Northern Africa	N.A.		N.A.	
Western Africa	N.A.		N.A.: three countries[c]	
Eastern Africa	N.A.		N.A.	
South Africa	2050	CO_2	South Africa: declaration/pledge	2065
Western Europe	2050	GHG	EU27, UK: in law	2050
Central Europe	2050	GHG	EU27: in law	2050
Turkey	2053	CO_2	Turkey: in policy document	2068
Ukraine	2060	GHG	Ukraine: in policy document	2060
Central Asia	2060	CO_2	Kazakhstan: pledge	2075
Russia	2060	CO_2	Russia: pledge	2075
Middle East	N.A.		N.A.: three countries[d]	
India	2070	Unclear[e]	India: declaration/pledge	2070
South Korea	2050	Unclear[e]	South Korea: in law	2050
China	2060	Unclear[e]	China: in policy document	2060
Southeast Asia	N.A.		N.A.: three countries[f]	
Indonesia	2060	GHG	Indonesia: proposed/in discussion	2060
Japan	2050	GHG	Japan: in law	2050
Oceania	2050	GHG	Australia: pledge; New Zealand: in law	2050
Rest of South Asia	N.A.		N.A.: one country[g]	
Rest of South Africa	N.A.		N.A.	

Abbreviations: GHG, global greenhouse gas; N.A., not available; NDC, Nationally Determined Contribution.
[a]Only Costa Rica and Panama are in the policy document, representing 11% of the CO_2 emissions of the region.
[b]Only Chile, Ecuador, and Uruguay are in the policy document, representing 22.4% of the emissions of the region.
[c]Only Nigeria declaration/pledge, representing 57.5% of the CO_2 emissions of the region.
[d]Only Saudi Arabia, Israel, and United Arab Emirates declaration/pledge, representing 38.3% of the CO_2 emissions of the region.
[e]For India, South Korea, and China, we assume the coverage of all GHGs under their net-zero ambition, as explained in detail in Section "Net-zero GHG targets."
[f]Thailand, Viet Nam, and Malaysia are in the policy document (net-zero targets for CO_2 by 2050), representing 74% of the CO_2 emissions of the region.
[g]Only Sri Lanka is in the policy document, representing 5.5% of the CO_2 emissions of the region.
Source: Net Zero Tracker: https://www.zerotracker.net/ (Ref. 31); Climate Watch Net zero tracker: https://www.climatewatchdata.org/net-zero-tracker (Ref. 6).

IMAGE model

We applied the IMAGE integrated assessment modeling framework, version 3.2, to explore the implications of environmental consequences of human activities worldwide.[24,29,37,38] IMAGE includes a detailed description of the energy and land-use system and simulates most of the socioeconomic parameters for 26 major economies and world regions and most environmental parameters based on a geographical grid. The IMAGE modeling 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.[24,39] TIMER describes 12 primary energy carriers in 26 world regions and analyzes 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 carbon capture and storage (CCS) technology.

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.[40]

The FAIR model of IMAGE calculates the impact of climate mitigation policies using carbon prices and marginal abatement cost (MAC) curves representing costs of mitigation actions to determine a cost-effective emission pathway.[38,41] It captures the time- and pathway-dependent dynamics of the underlying TIMER model by scaling the MAC curves based on the reduction effort from the previous years.[c] The MAC curves in FAIR are based on (1) the IMAGE energy model TIMER for energy-related CO_2 emissions[38] and (2) MACs for non-CO_2 GHG emissions that were all updated based on recent literature.[42] 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.[39]

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.

Our temperature outcomes are estimated for the median global mean surface air temperature with the reduced-complexity carbon cycle and climate model MAGICC 7.5.3.[43,44]

[c] The model limits the MAC curves to 4000 US$/tC (1100 $/t$CO_2$), as the underlying TIMER model provides little additional emission reductions above this value.

RESULTS

Global emissions and temperature increase projections

While the NDC scenario projections show considerable emission reductions compared to the CurPol scenario, the projected global emissions are not close to what is needed to keep global warming to 1.5°C. The difference of almost 60 Gt CO_2eq in 2050 between the CurPol and the 1.5°C scenarios is reduced by one-fourth by the full implementation of the NDCs and further extrapolation. The NZ and NDC-NZ scenarios provide additional emission reductions, further curtailing the difference with the cost-effective emissions pathway for 1.5°C by two-thirds by 2050. Still, more reductions are needed to reach the 1.5°C target.

The NZ scenario follows a linear pathway directly toward the longer-term net-zero targets and shows 7.5 Gt CO_2eq lower emissions by 2030 compared to the NDC-NZ scenario, and, therefore, lower reduction rates after 2030. However, the emissions level in 2100 remains identical to the NDC-NZ scenario. Meeting the NDC targets first and then moving toward the net-zero goals (NDC-NZ) leads to 18 Gt CO_2eq additional cumulative emissions between 2020 and 2050, where the emissions profiles of the two scenarios converge, rather than moving directly to net-zero targets (NZ). This indicates that, on a global level, a significant reduction can be achieved by strengthening the NDCs toward a pathway that would directly aim for achieving the net-zero targets.

Regarding related climate consequences, the CurPol and NDC scenarios lead to a projected global mean temperature increase of well above 2°C by 2100. Full implementation of the announced net-zero targets (NDC-NZ and NZ) would bring the global mean temperature increase below 2°C by 2100 (1.9°C and 1.85°C, respectively). However, both net-zero approaches do not lead to GHG neutrality on a global level, as only certain regions of the world (representing 79% of global emissions) have a net-zero target, and remain higher than the global mean temperature projections under the *1.5°C* scenario (Figure 1).

Emission projections for major emitters

Among the major emitters, only the United States and EU have an NDC target that sets them on a cost-effective path to meet their net-zero targets in 2050 (Figure 2). However, they would still need to implement some additional effort after 2030 to stay on that path, as simply following their NDC scenario, they only achieve net-zero GHG emissions between 2055 and 2060. The NDC targets for China, India, Brazil, and Russia are clearly above a linear pathway toward their respective net-zero targets year. Their emissions need to be reduced rapidly after 2030 to reach their net-zero GHG emissions targets (see Supplementary File S1). Recognizing that these countries face very different national circumstances, strengthened and more ambitious

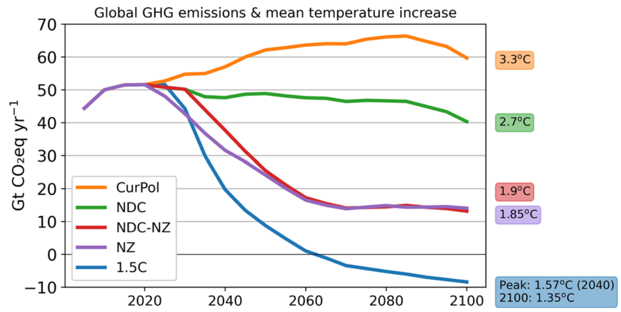

FIGURE 1 Global greenhouse gas emission projections and global mean temperature increase projections for all scenarios. For the 1.5°C scenario, projections for the peak of global temperature increase and the final temperature increase in 2100 is presented. All other scenarios have a continuous temperature increase until 2100. The temperature increase projections for the CurPol and the NDC scenarios depend greatly on the post-2030 assumptions made in this study. Abbreviation: NDC, Nationally Determined Contribution.

near-term climate plans are needed for their net-zero targets to remain achievable.[12,45]

Under both net-zero scenarios, the United States, the EU, and Russia achieve their 2050 and 2075 net-zero targets. For the EU, these scenarios even lead to emission levels below their cost-effective *1.5°C* scenario. The projected emissions of the United States for the net-zero scenarios are similarly lower than their cost-effective 1.5°C scenario. This signifies that developed countries can actually achieve more than their emission reductions projected under a cost-effective 1.5°C scenario just by implementing their announced net-zero pledges. The net-zero scenarios for Russia remain above its respective 1.5°C scenario for the first decades, but on a more aggressive downward trend later, achieving GHG neutrality in 2070, compared to 2075 in the 1.5°C scenario.

The three other major emitting countries, China, India, and Brazil, reach net-zero emissions slightly after the intended target year. As explained above in the section "Description of scenarios," the exact pathway depends on the dynamics and reduction potential in the model. All three of the countries achieve CO_2 neutrality: India and China in 2060 and Brazil in 2045. GHG neutrality, however, is met a few years after the intended target year as a result of the relatively high residual non-CO_2 emissions. China reaches approximately 65% emission reductions compared to 2020 emissions by 2050 and reaches net-zero GHG emissions between 2065 and 2070 in both of its net-zero scenarios (NDC-NZ, NZ). Similarly, Brazil achieves the net-zero GHG target about 5 years later. India reaches a 95% reduction of GHG emissions by 2070 but reaches net zero after 2070. India is the only major emitter that is projected to strongly increase emissions under its NDC scenario. For India, reducing the NDC target to get closer to the linear pathway toward net-zero emissions has a significant impact.

As mentioned above in the sections "Description of scenarios" and "Model implementation of the scenarios," the induced benefits in the energy system from increased technology learning and reduced technology costs continue to influence the emission pathways beyond each country's target year. As such, negative emission technologies (in this case BECCS) for the United States and EU and land-use emission reductions from regrowing vegetation for Brazil lead to further emission reductions after their net-zero target year is reached.

Sectoral and individual GHG breakdown

Figure 3 shows the projected emissions for a six-sector aggregation at a global level under all scenarios. For the NDC-NZ scenario, global emissions in most sectors are reduced significantly by 2050 already (with land use resulting in negative emissions), except for transport and non-CO_2, where residual emissions are still notable and remain so until the end of the century.

Looking into detail in the NDC-NZ scenario breakdown of sectoral emissions per country, OECD countries that are on a linear path to meet their net-zero targets by 2050 (the United States and EU) have a relatively large contribution of negative CO_2 emissions in 2050, especially from the electricity sector—larger than in their respective 1.5°C scenario. Emissions in the transport, industry, and building sectors are also reduced significantly, with industrial emissions reaching zero by 2050 in both regions. However, residual emissions in the transport sector are still noticeable in the United States, where the contribution of the sector in total emissions is still significant. While Russia is witnessing lower emissions levels in all sectors by 2075, it has the largest percentage of GHG reductions of non-CO_2 gases, mostly reductions in methane (CH_4) emissions from oil and gas production. With its net-zero target in 2050, Brazil is projected to have most of the contributions to negative emissions come from the land-use sector. The high potential for negative emissions from reforestation and increased managed forest area is related to low land costs and high forest growth rates in the country.[46] This reduction in CO_2 emissions from land use also compensates for the high residual non-CO_2 emissions.

China and India, though not on track to meet their current net-zero targets, can achieve substantial emission reductions under all their net-zero scenarios. Both are projected to have significant reductions in CO_2 emissions in the electricity—the most significant mitigation option for both countries—industry, and transport sectors, although projected emissions from transport and industry in China are still considerable in 2060. China reaches net-zero CO_2 emissions by 2060, but still has residual non-CO_2 emissions, causing the country to achieve GHG emissions neutrality 5-10 years later.

Finally, for all major emitting countries, the non-CO_2 GHG emissions remain hard to abate in the net-zero and 1.5°C scenarios. N_2O emissions remain relatively constant in all six countries and time horizons, while F-gases practically reach net-zero emissions before 2050 in all regions. Emissions for CH_4 remain relatively stable for the United States and EU by 2050, decrease in China, and increase in India. For Brazil, CH_4 has a much more crucial role in total emissions reduction, contributing to 10% of the total GHG reductions between 2015 and 2050, with the reductions coming almost exclusively from the land-use sector. Non-CO_2 gases represent the largest percentage of residual emissions, which needs to be compensated by negative emissions in other sectors to reach net-zero GHG emissions.

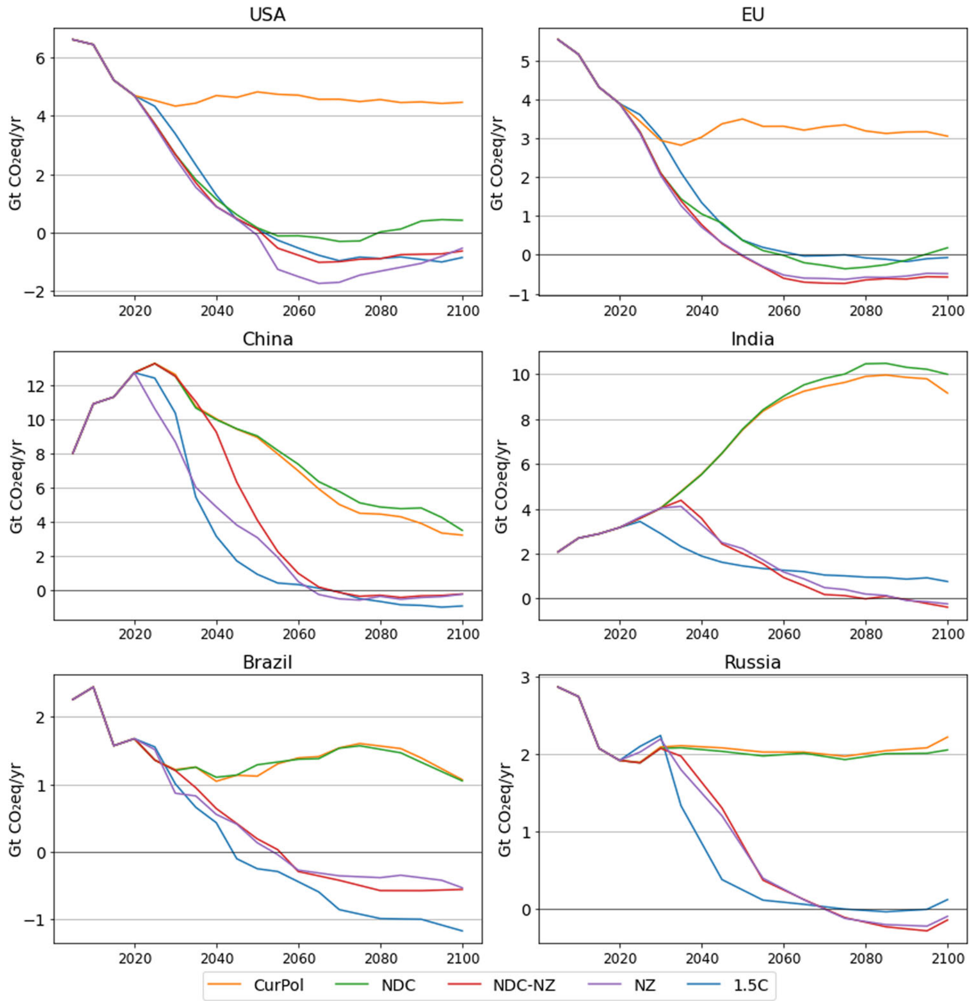

FIGURE 2 Greenhouse gas emissions projections of major emitters for all scenarios.

DISCUSSION AND CONCLUSIONS

In this work, we analyzed several different scenarios, including current policies, NDC, and net-zero targets as well as combinations of the above. The scenarios assume a cost-effective pathway of regions reaching their respective NDC or net-zero targets and were assumed to be implemented from 2021 onward.

Our study finds that, under full implementation of the NDCs, global emissions are projected to reduce by a quarter of what is necessary for a least-cost 1.5°C pathway by 2050, compared to a current policies scenario. Full implementation of the announced net-zero targets would further reduce this by 25 Gt CO_2eq by 2050, closing 70% of the difference in the global emissions between current policies and the 1.5°C scenario. In their current form, however, all announced net-zero pledges result in emission and temperature increase levels that are quite higher than needed to implement the Paris Agreement.

The NDC announcements lower the global temperature increase by 0.6°C compared to current policies projection (2.7°C vs. 3.3°C). All currently announced net-zero targets, if fully implemented (NZ scenario), would further reduce the average global temperature increase, achieving a below 2°C level (1.85°C by 2100). However, additional action is needed on a national level to further close the difference with the 1.5°C scenario.

For certain regions, the cost-effective emission pathways as projected by IMAGE are consistent with the emission pathways outlined in their long-term climate plans—the Biden administration's Long-Term Strategy for the United States[11] and the EU's 2050 net-zero GHG target both set the regions on an emission trajectory aligned with their net-zero pledges.[10] On a sectoral level, our projections show similar trends as highlighted in the official strategy documents of the United States and the EU: a fully decarbonized power sector before 2050; significant reductions in the transport, industry, and buildings sectors induced by more electrification; and a transition to low-carbon fuels and reductions in land-use and non-CO_2 emissions wherever that is possible.

Brazil's indicated long-term objective of reaching carbon neutrality by 2050 is feasible in IMAGE 5 years later. Like the other three major emitting countries (China, India, and Russia), the region's NDC targets alone are insufficient to set them on a path to meet their announced net-zero targets, signaling that an increased mitigation effort is needed after 2030. Additionally, all the above countries lack clarity in their net-zero announcements, not providing specifics on how they expect

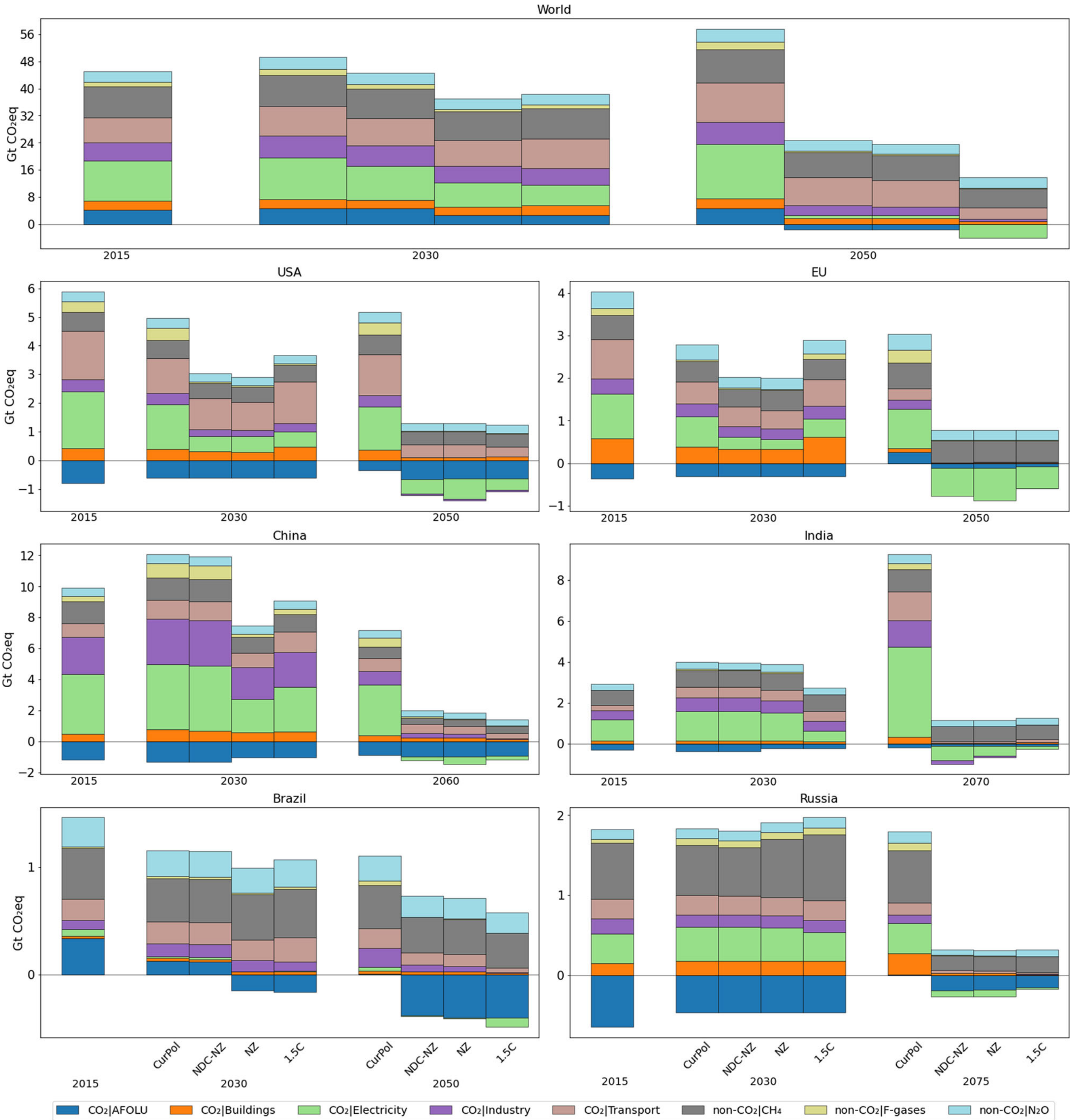

FIGURE 3 Sectoral emissions projections on a global and major emitter level, and for all major GHG gases. Emission projections are presented for different scenarios, and for the years 2015, 2050, and 2100 on a global level, and 2015, 2030, and each region's respective net-zero GHG target year. Abbreviation: GHG, global greenhouse gas.

to achieve their respective targets. For China, the situation is not fully clear on whether the country's neutrality pledge by 2060 is related to CO_2 emissions only or includes all GHGs, which will affect the results on a national and global level significantly. In this work, we assume a GHG net-zero target by 2060, similar as assumed in national studies on China's net-zero goals.[32,33]

Our findings highlight the sectors where each major emitter needs to enhance their ambition and efforts to achieve their long-term goals in a cost-effective way. In general, all countries need to focus on the potential for negative emissions, especially in the electricity and the land-use sector. Non-CO_2 emissions are usually hard to abate for all regions, and the residual emissions need to be compensated by negative emissions in the other sectors to reach the net-zero pledges. If non-CO_2 emissions could be reduced further, all regions would be able to meet their net-zero target years. Finally, special attention needs to be given to residual emissions in sectors that are difficult to completely reduce due to economic and infrastructure reasons, such as emissions in industry, transport, and agriculture,[47] where emissions seem to persist even after their net-zero target is achieved. Focusing on reducing the emissions in these specific sectors can not only enable these countries achieve their net-zero targets on the pledged date (or even earlier) but can also have parallel benefits on a global scale. Reaching carbon neutrality, which is feasible for all major emitters, in combination with non-CO_2 reductions, is sufficient for stabilizing global mean temperature. Achieving GHG neutrality by reducing these persistent sectoral emissions (including non-CO_2) can actually lead to a decrease in global temperature.

It is also important to highlight that the 1.5°C scenarios are developed with a global target in mind and allocate emission reductions in regions based on a cost-effective implementation only. This usually leads to unbalanced emission reductions assigned to developing countries, as is shown in Figure 3, where India and China have equivalent contributions to negative emissions (and emission reductions) in their net-zero and 1.5°C scenarios by their target year. As such, a comparison of national net-zero and LTS scenarios with respective 1.5°C scenarios should be regarded cautiously; comparison with 1.5°C scenarios makes more sense on a global level to ascertain the cumulative effects of examined pathways but might not always be representative of national or regional results.

In all scenarios, the mitigation outcomes depend overwhelmingly on the short-term reductions assumed. It is taken for granted that action consistent with net-zero pledges begins immediately and is not delayed. With our scenarios being cost-effective and starting from 2021 onward, we do not account for the political feasibility and social and institutional challenges of the transition toward a low-carbon economy.[48] Some previous integrated assessment model (IAM) research has been done in terms of accounting for political feasibility over simple cost-effective approaches by allowing for the selection and implementation of previously successful policies instead of straightforward cost-effective pathways.[30] Brutschin et al.[48] proposed a novel and versatile multidimensional framework that allows evaluating and comparing decarbonization pathways by systematically quantifying feasibility concerns across geophysical, technological, economic, sociocultural, and institutional dimensions.

Additionally, changes in national political priorities or foci induced by governmental transitions could mean that a country's climate plans can be altered significantly from their currently announced LTS. Climate policy constraints, such as a lack of democratic norms and public climate awareness, exposure to corruption, low levels of social trust, and economic reliance on fossil fuel production and extraction, as described in, for example, Lamb and Minx,[49] can greatly affect national climate progress; wealthy OECD states are more willing and have the ability to do more in terms of climate commitments and ambition than fragile democracies or fossil fuel–dependent states can.

Our results, in combination with results from other IAMs and national models with more granularity, can assist national policymaking in the decision to strengthen their short- and long-term climate strategy, in the form of enhancing their NDC and net-zero pledge ambitions, in order to keep the Paris climate goals within reach.

AUTHOR CONTRIBUTIONS

I.D. led the analysis, modeling, and writing of the manuscript. M.d.E. and D.P.v.V. contributed to the analysis, interpretation, and discussion of the results and the writing of the manuscript.

ACKNOWLEDGMENTS

This work was supported by the European Union's Horizon 2020 research and innovation program (Grant agreement no. 821471: ENGAGE; Grant agreement no. 821124: NAVIGATE).

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

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PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/nyas.14970

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SUPPORTING INFORMATION

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How to cite this article: Dafnomilis, I., den Elzen, M., & van Vuuren, D. P. (2023). Achieving net-zero emissions targets: An analysis of long-term scenarios using an integrated assessment model. *Ann NY Acad Sci*, *1522*, 98–108. https://doi.org/10.1111/nyas.14970