ELEVATE: Enabling and Leveraging Climate Action Towards Net-Zero Emissions

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Dissemination Level		
PU	Public	√

1. Changes with respect to the description of work

Although effects of COVID-19 are present in the scenarios' historical information, its recovery measures are not highlighted in this analysis.

2. Dissemination and uptake

This deliverable is public and will be available at ELEVATE's website.

3. Short summary of results (<250 words)

For this deliverable, global and national modelling teams developed scenarios reflecting current policies, Nationally Determined Contributions (NDCs), Long Term Strategies (LTS), and mitigation trajectories to limit end-of-century global warming of 1.5 and 2 ^{o}C. Those scenarios are used to assess current progress in climate mitigation and to study implications of the pathways from multiple perspectives: the global level, the national level, associated energy systems and their feasibility, national sectors, and economic costs. Globally, we found that (extended) current policies lead to implementation gaps of 6.4 Gt with NDCs by 2030 and 30 Gt with LTS by 2050. Global energy systems in line with temperature targets contain high shares (32-78%) of renewable energy by 2050. However, associated feasibility concerns should be considered: models could exceed thresholds on the use of bioenergy, for instance. The analysis on economic costs found that when looking at only costs and not including avoided costs and damages, more stringent climate action can have negative effects on GDP, with varying costs or even gains identified across regions and sectors. On a national and regional level, we also found that additional policies are still needed to reach NDCs for most analysed countries, and sector level analyses demonstrated local opportunities for mitigation. Additional to the primary scope of the deliverable we aimed to contribute to future scenario development, by exploring the influence of methods extending the Current Policies and NDC scenarios towards 2100. We found major contrasts between emission pathways resulting from different methods.

4. Evidence of accomplishment

See report below.

Version log

Version	Date	Released by	Nature of Change
1	20-01-2025	Elena Hooijschuur	First draft
2	12-02-2025	Elena Hooijschuur	Revised version based on internal review

Table of contents

1. Introduction

Under the Paris Agreement, countries agreed to limit global temperature increase to well-below 2 °C and pursue efforts to keep it below 1.5 °C. Scenarios can be used to evaluate the current progress towards these temperature targets, and to explore how gaps between the current situation and targets could be bridged. For this deliverable, both global and national modelling teams developed scenarios including the latest developments, reflecting current policies, Nationally Determined Contributions (NDCs), Long Term Strategies (LTS, often net-zero targets), and mitigation trajectories to limit end-of-century global warming to 1.5 and 2 °C.

We use the developed scenarios to assess current progress towards more ambitious goals and to provide insights in implications of the pathways from multiple perspectives. On a global level, we describe the energy systems associated with the scenarios, being a key element in decarbonization (section 3.2), and review where the projected energy system transformations raise any feasibility concerns (section 3.3, based on work in ELEVATE Task 2.2). Based on global model results, we also compare the economic costs (focusing on changes in GDP) associated with the different scenarios (section 4). Additionally, we provide insights in regional and national developments, focusing on sectors that are of high importance for climate mitigation in the specific region (sections 5 and 6). These national analyses include, where possible, an assessment of enablers for policies associated with the sector of interest (based on work in ELEVATE Work Package 3). Finally, beyond the primary scope outlined in the Grant Agreement, we aim to contribute to future scenario development by exploring methods for extending the current policy and NDC scenarios from 2030 to 2100 (section 2.3).

2. Methods

2.1. Models

13 modelling teams participated in this task: global models REMIND-MAgPIE, COFFEE, WITCH, MESSAGEix-GLOBIOM, GCAM, AIM, GEM-E3 and IMAGE; and national models BLUES (Brazil), India-MARKAL, VESPA (Poland), IPAC-AIM/technology (China), and AIM/Enduse-Japan. Their model documentation can be found on the IAMC common Integrated Assessment Model (IAM) documentation: https://www.iamcdocumentation.eu/IAMC_wiki.

2.2. Scenarios

The scenario protocol and supporting files can be found on Zenodo (ELEVATE modelling protocol on global and national climate policy pathways and Climate Policy Modelling Protocol). The protocol outlines 6 scenarios, which are based on the updated socioeconomic pathways that were part of ELEVATE Work Package 6 and included updates on population and GDP trajectories. The scenarios represent current policies and targets, and uniform carbon price based mitigation pathways towards a global warming of 1.5 and 2 °C by the end of the century. Table 1 shows an overview of all developed scenarios and their naming as used in this report and in the scenario database.

Table 1: Overview of scenarios

	Scenario name	National team scenario name for database	Global team scenario name for database
0	1.5/2°C	ELV-SSP#-15C-N ELV-SSP#-2C-N	ELV-SSP#-650P-400F ELV-SSP#-1150F
1a	Current Policies with constant carbon price after 2030/2040 (CP)	ELV-SSP#-CP-D0-N	ELV-SSP#-CP-D0
1b	Current Policies with increasing carbon price after 2030/2040 (at a rate up to 3%) (optional)	ELV-SSP#-CP-D#-N	ELV-SSP#-CP-D#
2a	NDC with constant carbon price after 2030/2040 (NDC)	ELV-SSP#-NDC- D0-N	ELV-SSP#-NDC- D0
2b	NDC with increasing carbon price after 2030/2040 (at a rate up to 3%) (optional)	ELV-SSP#-NDC- D#-N	ELV-SSP#-NDC-D#
3	NDC-LTS	ELV-SSP#-NDC-LTS-N	ELV-SSP#-NDC-LTS
4	LTS	ELV-SSP#-LTS-N	ELV-SSP#-LTS
Notes: SSP# = SSP1, SSP2 or SSP3 (# = 1, 2 or 3) D# = increasing in carbon price # (0 (for constant c-price case) or up to 3%, modellers choice) N = national modelling scenarios			

The 1.5 and 2 °C scenarios follow current policies until 2025 and start additional climate action after. For global models, the 1.5 °C scenario has a CO_2 emissions peak budget of 650 $GtCO_2$ (from 2020 to the time of net zero emissions), and additionally a full century budget of 400 $GtCO_2$ (from 2020–2100). For national models, these scenarios followed the carbon budgets as presented in Table 2. These budgets were calculated based on recent results from the IMAGE model. A model that could not achieve these budgets aimed for the lowest budgets feasible.

Table 2: National CO_2 budgets for 2020-end year period based on recent results from the IMAGE model

National Team	End year	CO_2 Budget 2020 - end year in $GtCO_2$			
		Full century budget 1.5°C	Full century budget 1.5°C (excl. LULUCF)	Full century budget 2°C	Full century budget 2°C (excl. LULUCF)
Brazil	2060	-0.85	-6.8	10	6.9
India	2070	32	30	88	86
Poland	2070	3.9	3.8	6.3	6.2
Saudi Arabia	2100	7.6	7.6	19	19
China	2060	149	155	280	284
Japan	2050	8.7	9.5	13.9	14.7

Current policies are defined as currently implemented policies adopted by governments (through legislation) or non-binding targets backed by effective policy instruments. Ambitions and pledges are not included. Modelling teams developed the Current Policies scenario based on the latest policies update, as listed in the current policy protocol spreadsheet which contains climate policies known by July 2023. After the last major policy ended, which is in 2030 or 2040, the ambition level of countries and regions remains constant throughout the rest of the time frame. This could be implemented in two ways: For each region, the "equivalent" carbon price (which lead to current policy emission levels compared to the SSP2 baseline scenario) in 2030/2040 was determined and kept constant until 2100 or the last year possible for the model; Optionally, the equivalent carbon price was additionally increased over time at the same rate as the discount rate in the model or a value of the modelers preference up to 3%. By default, results in this deliverable use the scenarios extended with the constant carbon price. An elaborate exploration of extension methods is included in section 2.3.

The NDC scenario represents the short-term goals of each country or region by implementing the targets for 2030 as defined in their NDC submission. If a region had a conditional NDC, this is the NDC that was implemented. After 2030, the same extension methods as for the Current Policies scenario were applied.

The NDC-LTS scenario considers both the NDC pledges and the Long Term Strategy pledges (LTS, net-zero targets). Global modelling teams considered all net-zero pledges, aggregating them to their specific model regions. If countries within a model region have different net-zero targets, the region's strategy was calculated based on those countries' contribution to the total GHG emissions of the region by a calculated (weighted) target year. These strategies were implemented as a reduction compared to the NDC scenario (extended with the constant carbon tax) by an indicated target year (see Table 3 for an example). After reaching the LTS, emissions were kept around the same level between the target year and 2100. National modelling teams made sure that the LTS target year was included in the timeframe of their model.

Table 3: Example of a regional LTS

GCAM Region	Countries	Target year	Share of GHG emissions covered by net-zero targets
Eastern Africa	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda	2050	56%

2.3. Extension methods for scenarios reflecting policies and pledges

To assess progress towards the Paris Agreement's temperature goals, the developed scenarios reflecting policies and pledges are compared with the scenarios limiting global warming to 1.5 and well below 2 °C. Additionally, the scenarios reflecting policies and pledges are often used to show the consistency of current efforts with climate targets by calculating their full century impact on global mean temperature. The results of this are widely used, for instance for the key conclusions of UNEP on global warming resulting from current efforts (UNEP 2024). Because current policies and current NDCs typically have 2030 as their target year, an assumption about developments between 2030 and 2100 needs to be made. These assumptions strongly influence the outcomes of the comparison with long-term climate goals and scenarios.

Researchers have developed various methods to extend scenarios from 2030 to 2100. Some earlier assessment of the options have been made (Gutshow et al. 2018, Jefferey et al. 2018, Sognnaes et al. 2021), but we did not find studies that explore the broad set of extension methods that can be applied with IAMs, and additionally the effects of methods on regional pathways seems not mapped yet. The latter is relevant because methods can have significantly different effects on a regional level. Therefore, we aimed to contribute to the discussion on extension methods by a) providing a broad overview of methods and parameter choices, and their implications for end-of-century temperature and global and national pathways and b) providing insights in the perspective of stakeholders.

We collected 25 extension methods (Table 4, grouped per overarching principle) and applied them using the IMAGE model to the latest Current Policies and NDC scenarios. Methods based on principle 'pathway selection' were not implemented, as we believe this principle is more valuable when one does not have an IAM. Additionally, we collected the preferences of stakeholders in the III ELEVATE International Stakeholder Workshop and via an online questionnaire which was shared with the ELEVATE forum: https://www.elevate-climate.org/questionnaire-on-policy-

scenarios. Some of the other participating teams also developed scenarios extended with varying carbon price methods (Box 1).

Table 4: Extension principles and methods. Methods in italics were not implemented.

Extension principle	Extension method	Described and/or used by
Carbon price	Apply carbon price leading to 2030 emission levels and keep it constant	
Carbon price	Apply carbon price leading to 2030 emission levels and increase it with global GDP growth rates	
Carbon price	Apply carbon price leading to 2030 emission levels and increase it with global per capita GDP growth rates	
Carbon price	Apply carbon price leading to 2030 emission levels and increase it with a discount rate	
Carbon price	Apply carbon price leading to 2030 emission levels and increase it with regional GDP growth rates	van Soest et al. 2021
Carbon price	Apply carbon price leading to 2030 emission levels and increase it with regional per capita GDP growth rates	Sognnaes et al. 2021
Carbon price	Apply carbon price leading to 2030 emission levels and increase it with the discount rate in the model or a chosen rate (1%/3%/5%)	
Policies	Extend individual policies. E.g. when there is a policy aiming for 30% of energy provided by wind farms by 2030, keep this target until 2100. For NDCs, if there is for instance a target of 55% reduction by 2030 compared to BAU levels, keep this relative level until 2100.	
No more policies	Do not apply any carbon price, policies, or emission target after 2030	
Emission reductions	Continue emission reductions as in 2020-2030	
Emission reductions	Continue emission reductions per capita as in 2020-2030	
Emission reductions	Continue emission reductions per GDP as in 2020-2030	Sognnaes et al. 2021/ Vrontisi et al. 2018/ Jefferey et al. 2018
Emission reductions	Continue emission reductions as in 2020-2030, converging to 1	Gutshow et al. 2018
Emission reductions	Continue emission reductions per capita as in 2020-2030, converging to 1	
Emission reductions	Continue emission reductions per GDP as in 2020-2030, converging to 1	
Emission reductions	*Apply a chosen emission reduction rate after 2030*	*Jefferey et al. 2018/ Climate Interactive 2017*
Emission levels	Keep emission levels constant after 2030	Gutshow et al. 2018/ Climate Interactive 2017/ Jefferey et al. 2018
Emission levels	Keep emission per capita levels constant after 2030	
Emission levels	Keep emission per GDP levels constant after 2030	
Emission levels	Keep emission levels compared to no new policies baseline in 2030 constant	Roelfsema et al. 2020/ Jefferey et al. 2018
Pathway selection	*For a defined period of overlap with the NDC pathway, determine the scenarios with the least distance to the NDC pathway. Subsequently, construct an extension pathway from the selected scenarios. Scenarios can be weighted or filtered to weaken the influence of large sets of pathways that use similar assumptions and models.*	*Gutshow et al. 2018*
Pathway selection	*Constant quantile extension: determine the quantile of scenarios in scenario database that NDC pathway is in line with use it to construct an extension pathway.*	*Gutshow et al. 2018/ Jefferey et al. 2018/ Climate Action Tracker 2015*
Pathway selection	*Apply the growth rates of a predefined scenario*	*Gutshow et al. 2018/*

		IEA 2015/ Climate Interactive 2017
Pathway selection	*Converge back to business as usual/no policies/chosen RCP scenario*	*Gutshow et al. 2018/ Jefferey et al. 2018*
Pathway selection	*Select scenarios (e.g. from AR5 scenario database) with constant policy assumption and smoothing spine fit 2030 to 2100 GHG levels to extend NDC levels to 2100*	*Jefferey et al.2018/ Rogelj den Elzen et al. 2016/ UNEP 2017*

Figure 1 shows the global GHG emissions pathways resulting from the methods listed in Table 4 implemented in IMAGE, coloured per principle (Appendix A contains figures showing the emission pathways per method and per region). Figure 2 and 3 summarise the relative position of cumulative emission resulting from the methods compared to median cumulative emissions, per region[1]. Note that in these figures, the scale on the y-axis differs: for the NDC scenario, differences are larger than for the Current Policies scenario. Extension methods based on *carbon taxes* lead globally to emission pathways that are relatively low (NDC scenario) to closer to median levels (Current Policies scenario) compared to other methods. This is also the case for most regions, although for a few regions this principle results in pathways that are higher than the median. Methods based on *emission reductions* globally result in slightly higher pathways compared to those based on carbon taxes, and can result in both relatively low and relatively high emission pathways regionally. For extension methods based on the principle of *emission levels*, results largely differ per method. Extending emission levels compared to BAU or emission levels per GDP results in high emission pathways globally, and median to relatively high emission pathways on a regional level. The other methods within this principle lead to various relative positions compared to other options. Extension assuming *no more efforts after 2030* or *continuing policies* result in high pathways globally, while median to relatively high pathways on a regional level.

To gain insight in which principles make sense to stakeholders, we asked stakeholders to indicate their preference for extension principles by giving the principles scores from 1 to 6. Respondents were part of the ELEVATE forum or the ELEVATE consortium, and indicate to work in governments, the private sector, NGOs and academia. They are from a broad range of countries including Nigeria, Germany, India, Mali, Greece, Brazil, Saudi Arabia, Bulgaria, the Netherlands, the USA, Eritrea, Iraq, Norway, Latvia and Singapore. The respondents indicate to have a relatively low preference for the extension assuming no more efforts. Also, they gave relatively often high scores for extension based on policies (Figure 4).

[1] IMAGE regions, details can be found on [Spatial dimension - IMAGE - IAMC-Documentation]

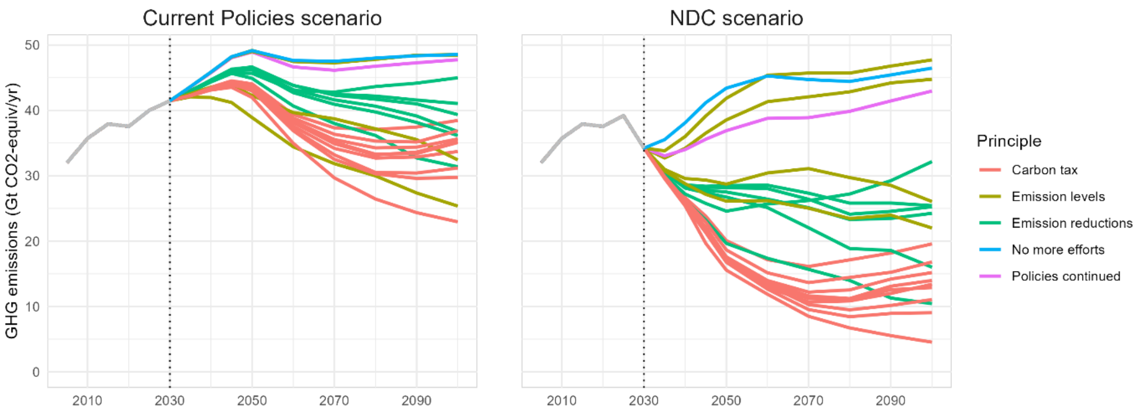

Figure 1: Global GHG emissions pathways resulting from different extension methods, per principle

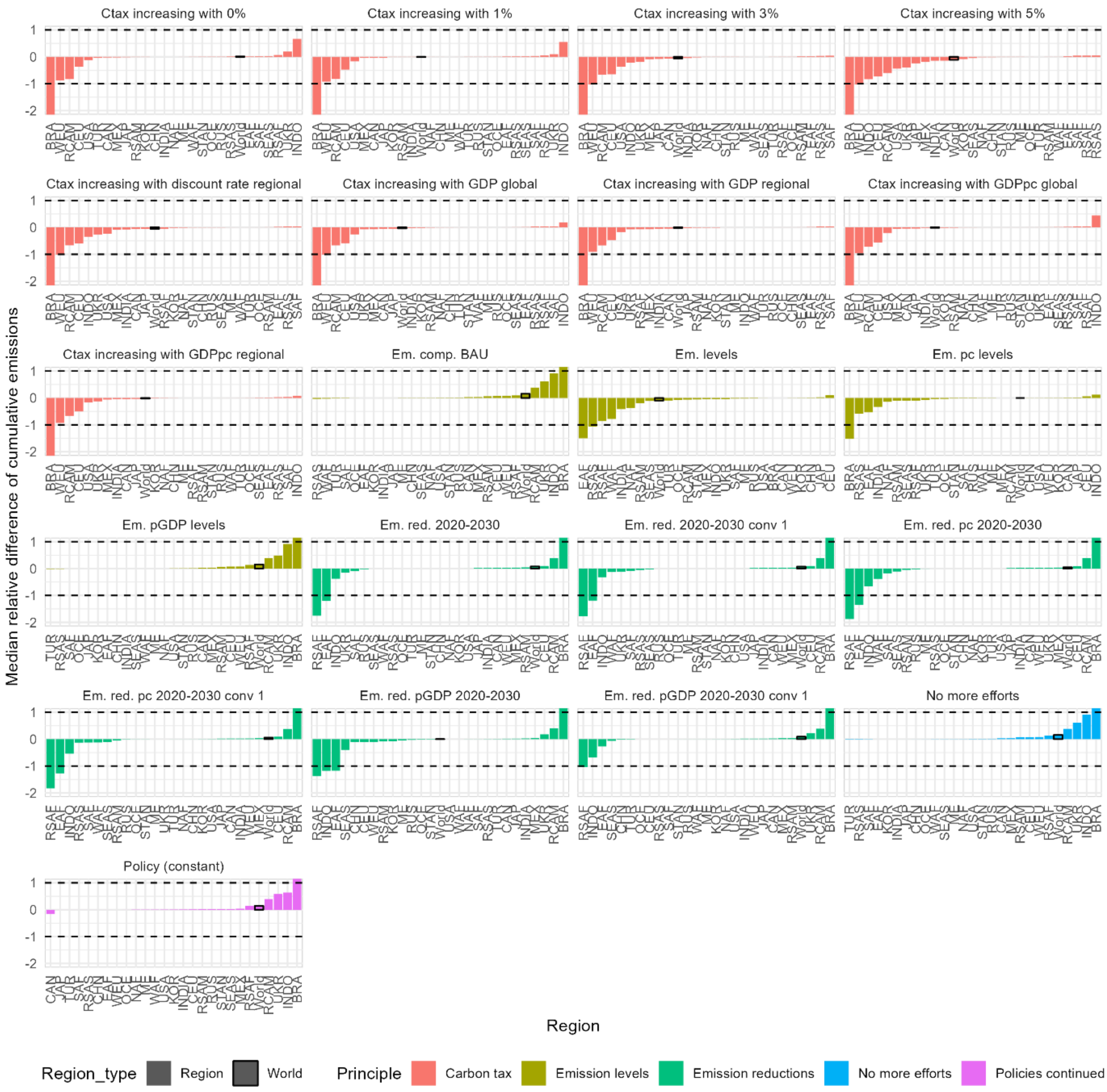

Figure 2: Median relative difference of cumulative emissions ($\frac{cumulative\ emissions_{method} - cumulative\ emissions_{median}}{|cumulative\ emissions_{median}|}$) *per method and per region, for the Current Policies scenario. For methods based on carbon taxes, Brazil shows cumulative emissions that differ -12 to -14 times its median cumulative emissions, which is not fully included in the figure.*

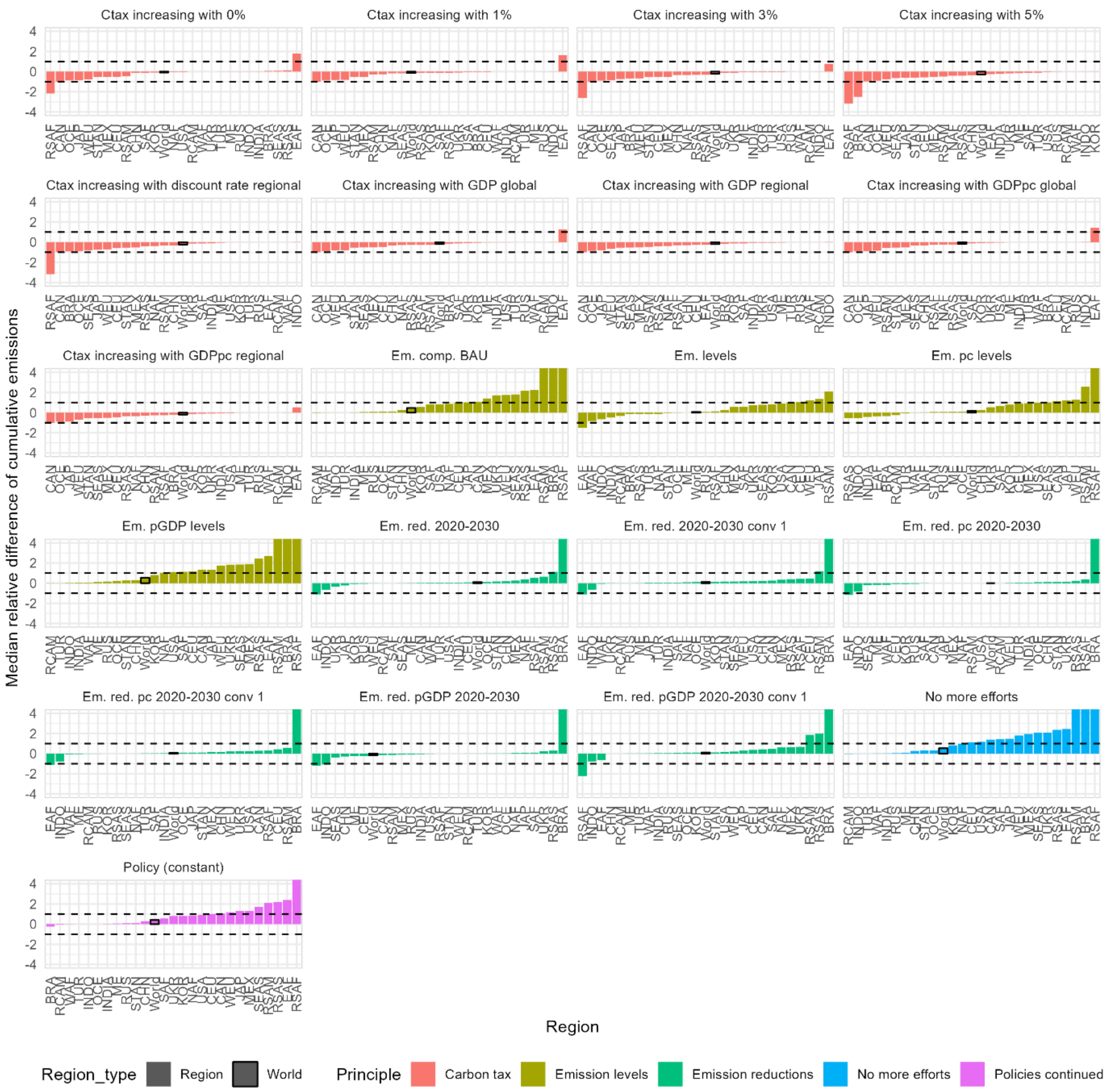

Figure 3: Median relative difference of cumulative emissions ($\frac{cumulative\ emissions_{method} - cumulative\ emissions_{median}}{|cumulative\ emissions_{median}|}$) per method and per region, for the NDC scenario. The higher end of the y-axis is limited to 4 for readability purposes. Very high median relative differences for Rest of South Africa, Rest of South America and Brazil are not fully included in the figure and can be between 4 and 10.

Figure 4: stakeholders' opinions on extension principles. A low number indicates a low preference, while a high number indicates a high preference. The results for the Current Policies scenario are based on 34 respondents, while the results for the NDC scenario are based on 24 respondents.

Box 1: Implications of various carbon price based methods for other models

Figure 5 shows that the impact of similar extension methods highly differs across models: similar carbon tax based methods result in different pathways. Especially for the NDC scenario pathways based on IMAGE are relatively low compared to other models, suggesting that for other models the position of carbon tax based methods compared to other methods could well be different. Additionally, the impact of an increasing carbon tax varies: for some models the difference between a constant carbon tax and a carbon tax increasing with for instance 2% is minor (e.g. GEM-E3), while for others it is more significant (e.g. AIM). Part of this can be explained by the different sensitivities of models to carbon taxes (Dekker et al. 2023). Additional research would be necessary to explore this further.

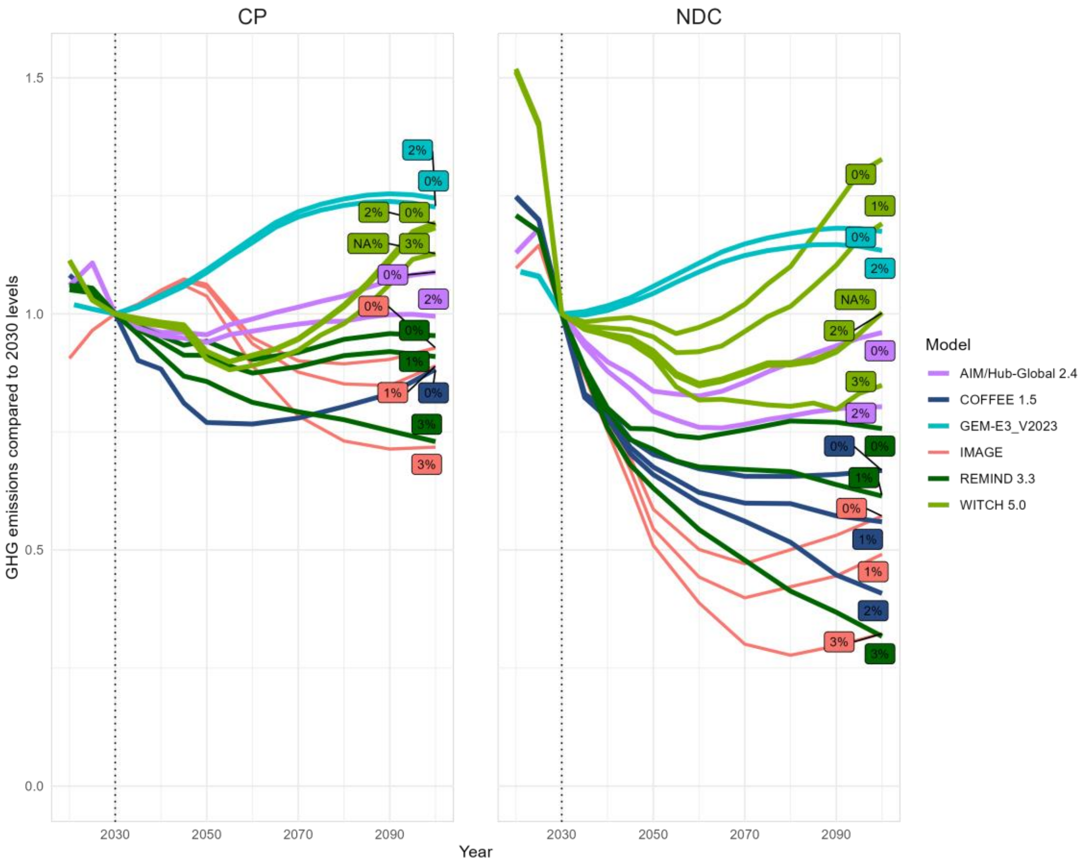

Figure 5: Global GHG emissions compared to 2030 levels, resulting from different extension methods based on a carbon tax, per model. Labels indicate the annual increase of the 2030 equivalent carbon tax.

3. Global results

In this section, global results are presented. It first provides a description of the emission pathways resulting from the scenarios described in section 2. Subsequently, we present an analysis of associated primary energy systems. The section concludes with a discussion on feasibility concerns associated with the projected developments in primary energy.

3.1. Emission pathways

Figure 6 shows the GHG emission pathways resulting from the scenarios reflecting current policies (CP), NDCs, NDCs and LTS (NDC-LTS), LTS and mitigation pathways with a uniform carbon price towards global warming of 2 and 1.5 ^{o}C by the end of the century. Extended current policy efforts lead to a projected end-of-century temperature increase of 2.4-3.1 ^{o}C (based on MAGICC, 'Model for the Assessment of Greenhouse Gas Induced Climate Change', version 7.5.3), extended efforts in line with current NDCs to 1.9-2.8 ^{o}C. End-of-century temperatures projected from extended efforts after NDC-LTS and LTS are, with 1.7-2^{o}C and 1.8-2.1 ^{o}C respectively, much closer to reaching the goals of the Paris Agreement. Note that these end-of-century temperature ranges depend on the chosen extension method, as explained in section 2.3.

The difference between emission levels resulting from current policies and national pledges can be called the *implementation gap* (van Vuuren et al. 2024). By 2030, the implementation gap between current policies and NDCs is projected to be 6.4 Gt based on an average emission pathway. By 2050, the implementation gap between (extended) current policy efforts and LTS reaches 30 Gt. The *ambition gap* represents the difference between emission levels resulting from all national pledges and those resulting from pathways with a uniform global carbon price leading to the objective of international climate policy (van Vuuren et al. 2024). By 2050, the ambition gap between the average NDC-LTS pathway and the average 1.5 ^{o}C pathway is 9.6 Gt. Compared to the 2 ^{o}C pathway, there is no remaining ambition gap by 2050: the average emission level resulting from the NDC-LTS pathway by 2050 is lower, with a difference of 5.7 Gt.

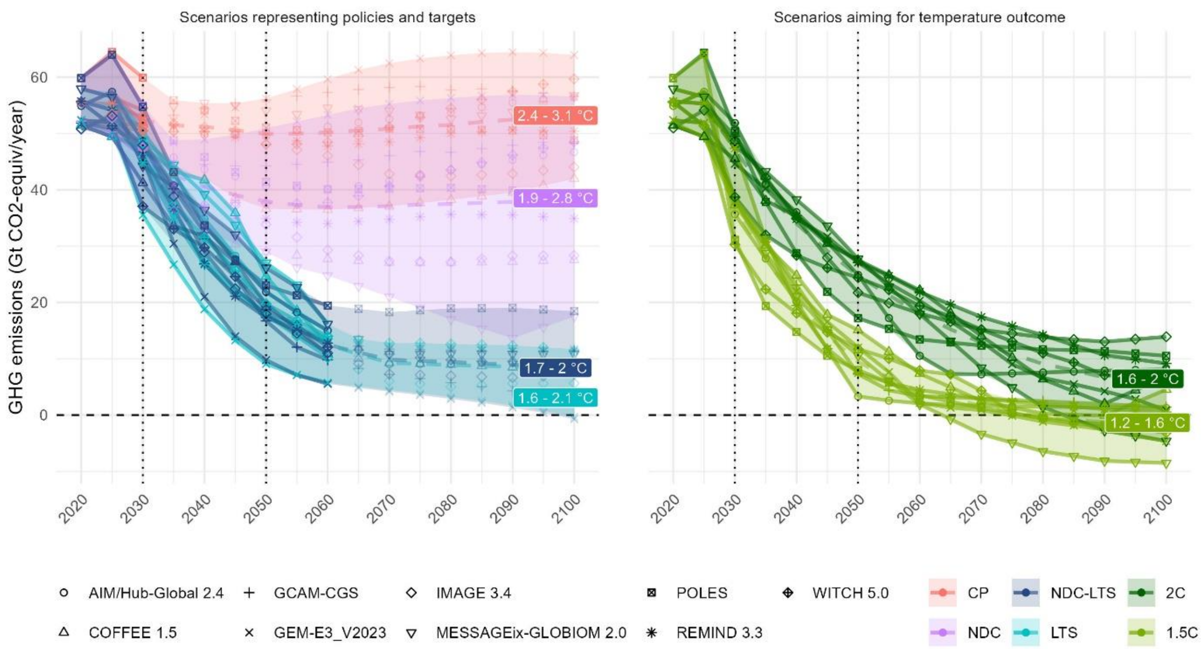

Figure 6: GHG emission pathways per scenario and per model. Solid lines represent trajectories towards national targets, while shaded areas with dots only represent emission pathways based on extension of efforts after the targets are met. The dashed lines represent the average pathway, the boxes show the temperature range resulting from the scenarios.

3.2. Primary energy

Figure 7 shows projected global primary energy use across models and scenarios. Renewable energy is projected to cover 52-78% of primary energy (including biomass with and without CCS) for the 1.5 ºC scenario by 2050, while 58-90% by 2100. For the 2 ºC scenario, this is 32-60% and 56-86%, respectively. For the LTS and NDC-LTS scenarios, the range is slightly lower compared to the 2 ºC scenario (42-61% by 2050, 51-79% by 2100). In contrast, the shares are significantly lower for the (extended) NDC and Current Policies scenarios (26-47% and 21-35% by 2050, respectively).

The renewable shares are mostly composed of solar, wind, biomass and a limited amount of hydro energy. Shares projected by the AIM and COFFEE models depend mostly on biomass without CCS with either solar (AIM) or wind (COFFEE) energy. Shares projected by REMIND depend on biomass without CCS together with major use of both wind and solar energy. In contrast, GCAM-CGS projects little use of biomass and combines an increased use of wind and solar energy instead. Renewable energy use projected by the other models (GEM-E3, WITCH, IMAGE, POLES and MESSAGEix-GLOBIOM) depends mostly on a combination of wind energy, solar energy, biomass with CCS and biomass without CCS. Finally, hydro energy plays a limited role for all models, while geothermal energy plays a larger role for the MESSAGEix-GLOBIOM and POLES models only, especially by 2100.

The role of fossil fuels with CCS differs across models. They do not have a significant role in the energy system transformations projected by COFFEE, GCAM-CGS, MESSAGEix-GLOBIOM and REMIND. However, gas with CCS does play a significant role in more ambitious scenarios by AIM, GEM-E3, IMAGE, and WITCH, while a minor role for some scenarios by POLES. Additionally, coal with CCS plays a role in scenarios by WITCH, and a minor role in scenarios by GEM-E3, IMAGE and POLES.

For fossil fuels without CCS, the remaining shares for the 1.5 °C scenario are 17-34% by 2050 and 0-18% by 2100, while for the 2 °C scenario these shares are 35-64% and 1-23%, respectively. Compared to the 2°C scenario, the shares projected for the NDC-LTS and LTS scenarios are slightly lower in the short term (25-55% by 2050) and higher in the long term (8-33% by 2100).

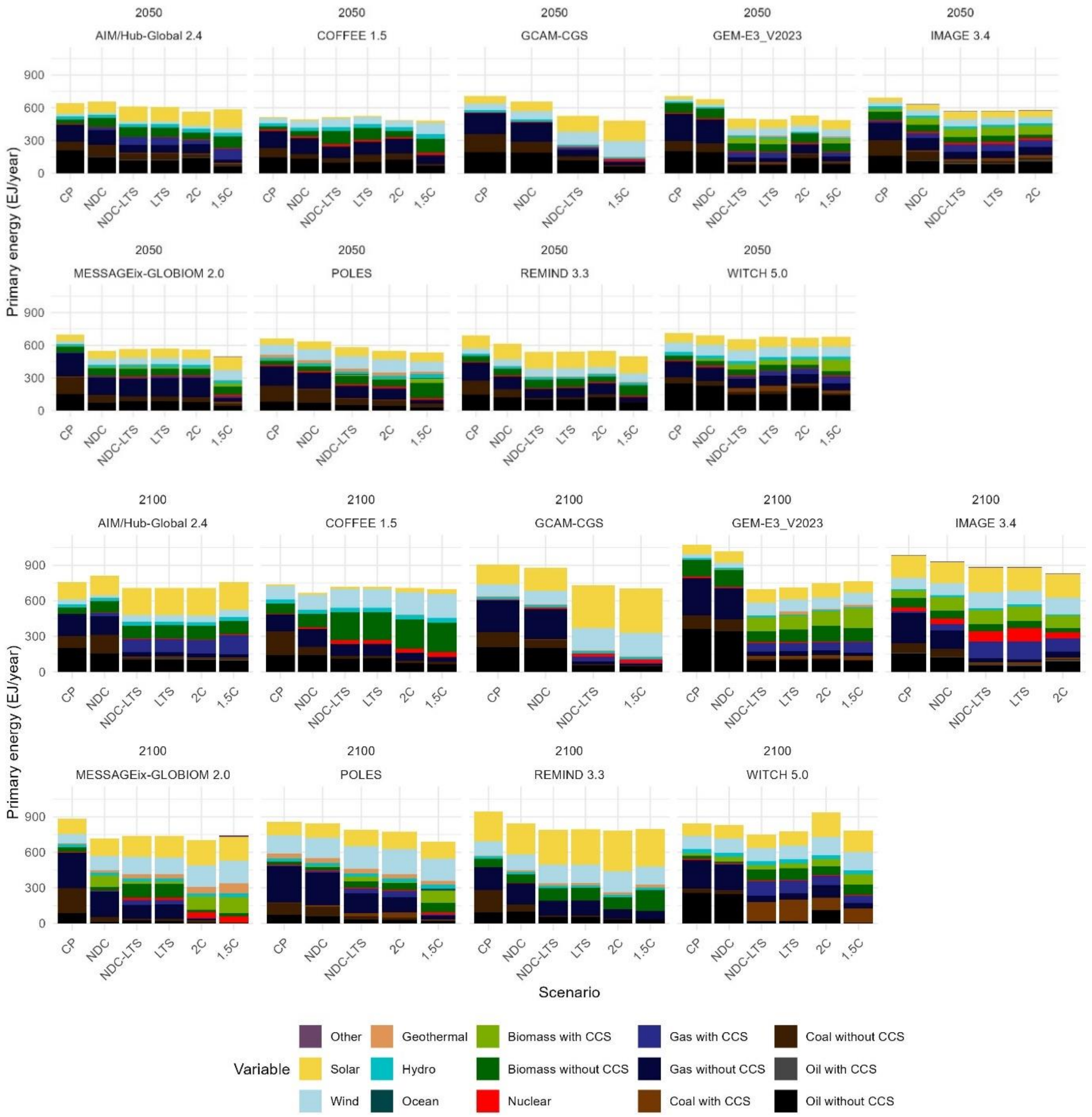

Figure 7: Primary energy levels per technology, per scenario and per model for 2050 and 2100.

3.3. Feasibility considerations

This section explores feasibility considerations for the scenario implementation described above. The feasibility dimensions and analysis thereof are based on the work presented in Deliverable 2.2. The focus is on the global level, examining insights across the models and scenarios considered. The feasibility dimensions assessed are global i) bioenergy use, in terms of demand for primary energy of biomass, ii) Carbon Capture and Storage in terms of CO2 captured per year, iii) yearly growth rate of PV power plant installations, iv) yearly growth rate of Wind power plant installations, v) yearly growth rate of final energy savings, vi) coal phase out in primary energy demand within a decade, vii) natural gas phase out in primary energy demand within a decade.

In line with the literature findings described in Deliverable 2.2, and additional indicators and thresholds that are of relevance to this set of scenarios, the threshold values for each of the feasibility dimensions are as follows: i) for biomass is set at 100 EJ/year (Creutzig et al. 2015), with a 10% tolerance, indicating for a maximum of 110 EJ/year, ii) the threshold value for carbon capture and storage (CCS) capacity until 2050 is set at 8.7 Gt CO_2/year (Grant et al. 2022), with a 10% tolerance, iii) for the capacity of solar electricity generation, the threshold indicator is defined as a yearly increase of 10% to 30% in solar capacity by 2030 compared to 2020 (Deliverable 2.2), iv) for the capacity of wind electricity generation, the threshold indicator is defined as a yearly increase of 5% to 20% in wind capacity by 2030 compared to 2020 (Deliverable 2.2), v) for global coal primary energy use, the feasibility indicator sets a maximum limit of a 50% decline in coal energy consumption by 2030 compared to 2020 (Deliverable 2.2 and partially relaxed for the assessment in this report), vi) for the feasibility indicator for gas primary energy use sets a maximum limit of a 50% decline by 2030 compared to 2020 (proposed for this report).

As seen in Figure 8 to Figure 13, the feasibility indicator with the highest concerns across all models is the use of bioenergy. It is however important to note that this is a more conservative value across the literature, and that a more lenient threshold would be around 270-300 EJ/year (see also deliverable 2.2). The number of scenario runs exceeding the threshold increases with the mitigation effort. This exceedance is more pronounced in scenarios involving higher GHG emissions mitigation efforts. In contrast, fewer cases surpass the feasibility indicator under the current policy and NDC scenarios. A few models (notably IMAGE and GEM-E3) already exceed the threshold in the Current Policies and NDC scenarios, while most models start exceeding the threshold after 2050 in all mitigation scenarios. In particular, in the well below 1.5C scenario, almost all models exceed the threshold. This indicates that there needs to be a greater attention to land use and sustainability assumptions in models, and more research into sustainable levels of biomass in global IAMs that are more aligned with the more conservative bottom up estimates.

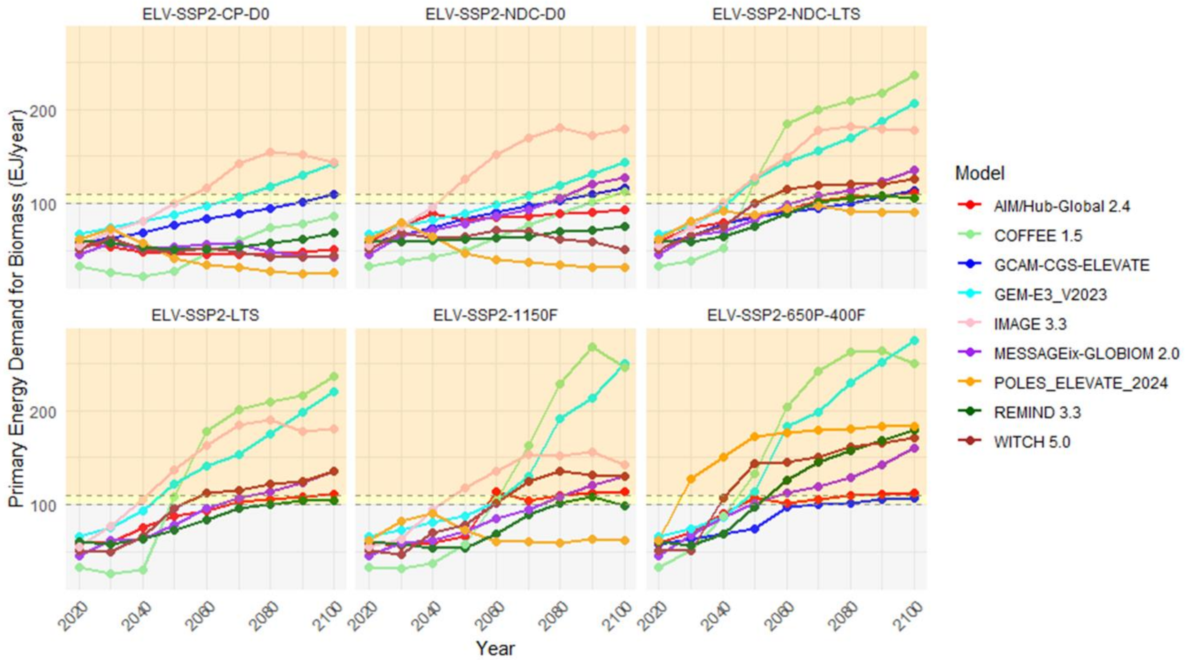

Figure 8: Global primary biomass energy demand.

Regarding CCS capacity, only a few models exceed this threshold within this period, and these cases occur exclusively in scenarios with higher GHG mitigation efforts, such as NDC LTS, LTS, and the cost-optimal scenarios aligned with a 1.5°C and a 2.0°C temperature goal. Figure 9 shows the assumptions about CCS across different models and scenarios up to 2050.

Regarding solar capacity, the results indicate that all scenarios and models fall within what we assume to be a feasible range, except for the COFFEE model, which shows an underestimation of solar energy growth with an annual growth rate below 10%. Across scenarios and models, the annual growth rate of solar capacity ranges from 3% to 25%, with an average of 17%, which is in line with the rates observed in different regions and contexts (see also Deliverable 2.2). For almost all models, highest growth rates are registered in the NDC and LTS scenarios, compared to the cost-optimal global mitigation ones.

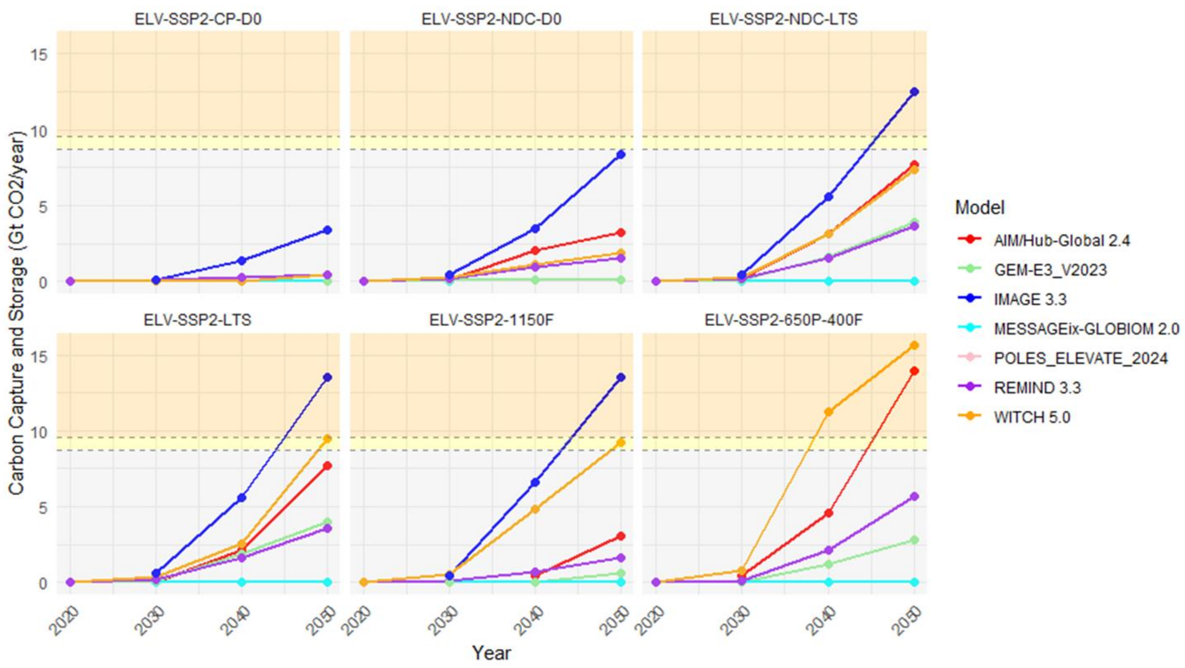

Figure 9: Adoption of carbon capture storage at global level until 2050.

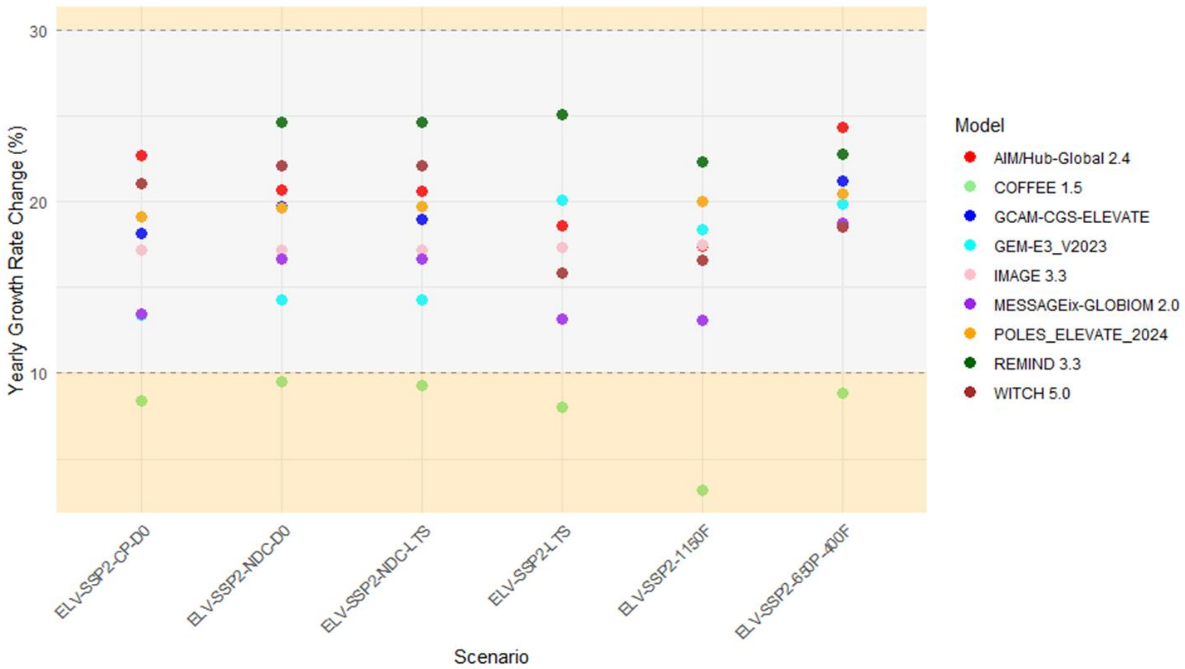

Figure 10: % annual change in global capacity of solar for electricity production in 2030 compared to 2020.

Regarding wind capacity, the results show that all scenarios and models fall within the proposed feasibility corridor, except for the AIM/Hub-Global model, which has an annual growth rate below 5%. Across scenarios and models, the annual growth rate of wind capacity ranges from 4% to 18%, with an average of 10%. This indicates that most scenarios describe a slow penetration of wind power, when compared to what is feasible as described in the literature based on the past observations but also the characteristics of this technology (Deliverable 2.2; Wilson et al. 2020).

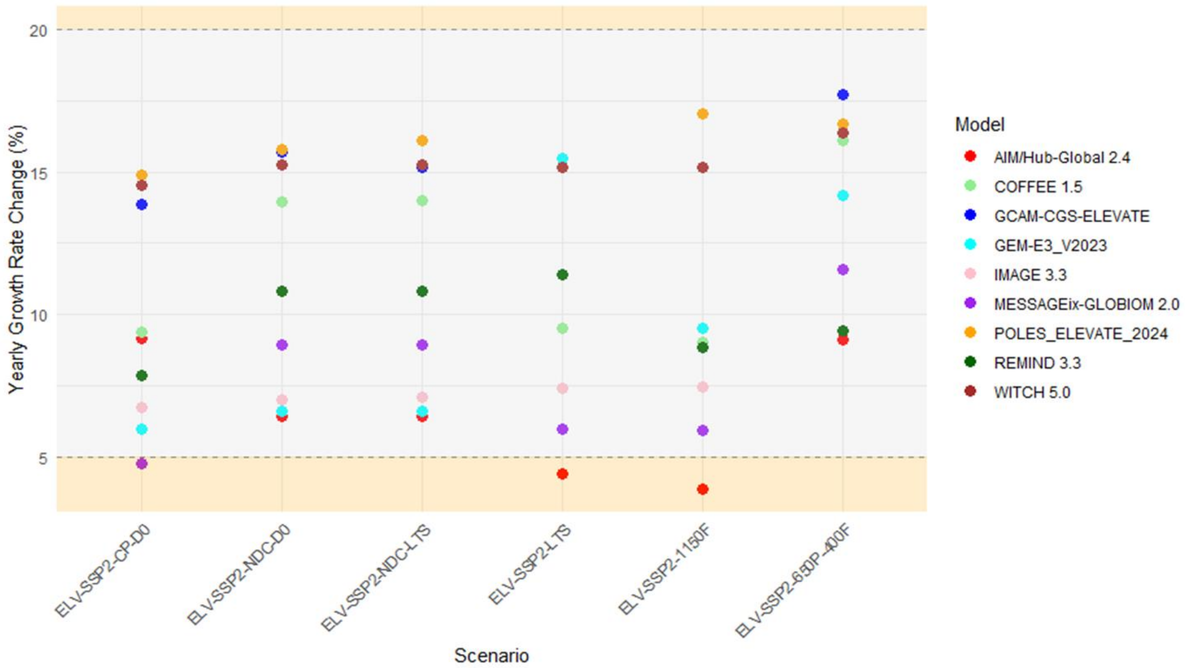

Figure 11: % annual change in global capacity of wind for electricity production in 2030 compared to 2020.

Regarding the coal phase-out, as shown in Figure 12, there are only a few cases that exceed this threshold, with declines greater than 50%, notably by WITCH model and in one scenario by COFFEE. Given that the global carbon budget for 1.5C is almost exhausted, the most abrupt coal phase out is observed in the 1.5C scenario. All other scenarios describe a slower phase-out that is considered less concerning, even though higher rates such as around 30% decline would also be considered on a challenging side from the feasibility perspective (Xie et al. 2024).

Regarding the gas phase-out, as indicated in Figure 13, all models are below the suggested decline rate that would imply also a major infrastructural change in the gas sector.

Overall, the results across models and scenarios suggest that the primary sources of uncertainty and feasibility concerns stem from a sustainability-driven perspective. Specifically, global IAMs tend to assume higher biomass potential and greater carbon storage availability compared to many other bottom-up estimates. These deviations are particularly notable in scenarios with higher GHG mitigation efforts, where biomass consumption frequently exceeds the defined threshold, and CCS adoption occasionally surpasses feasibility limits.

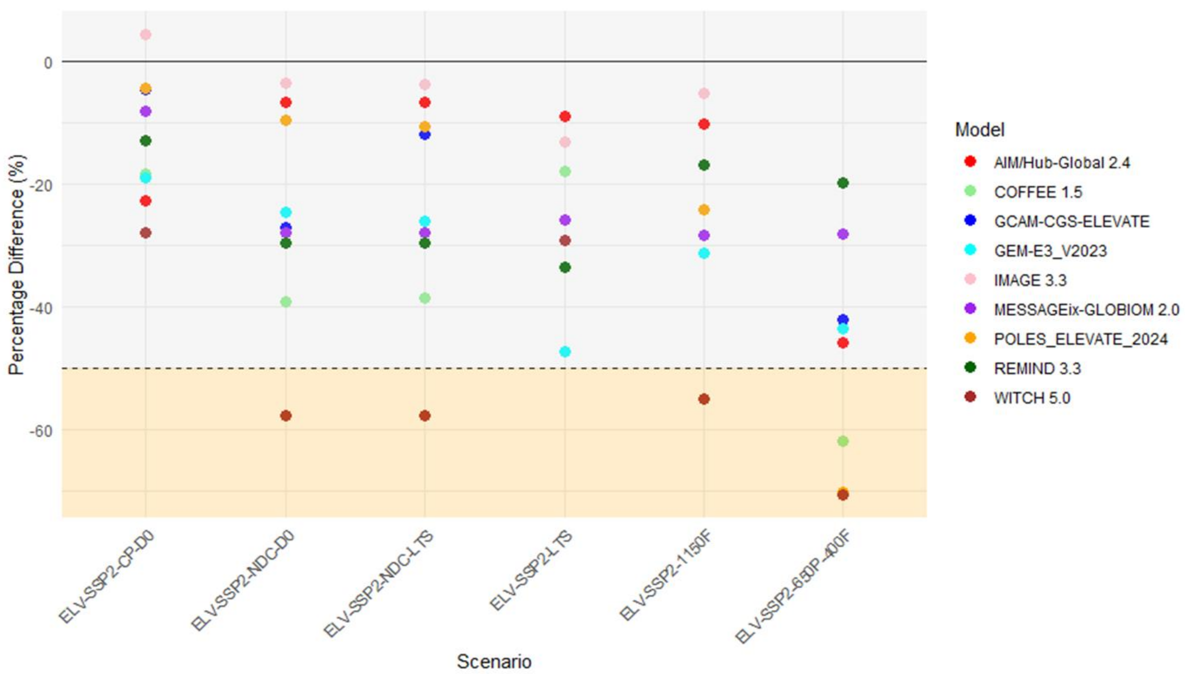

Figure 12: % Change in global primary energy of coal produced in 2030 compared to 2020.

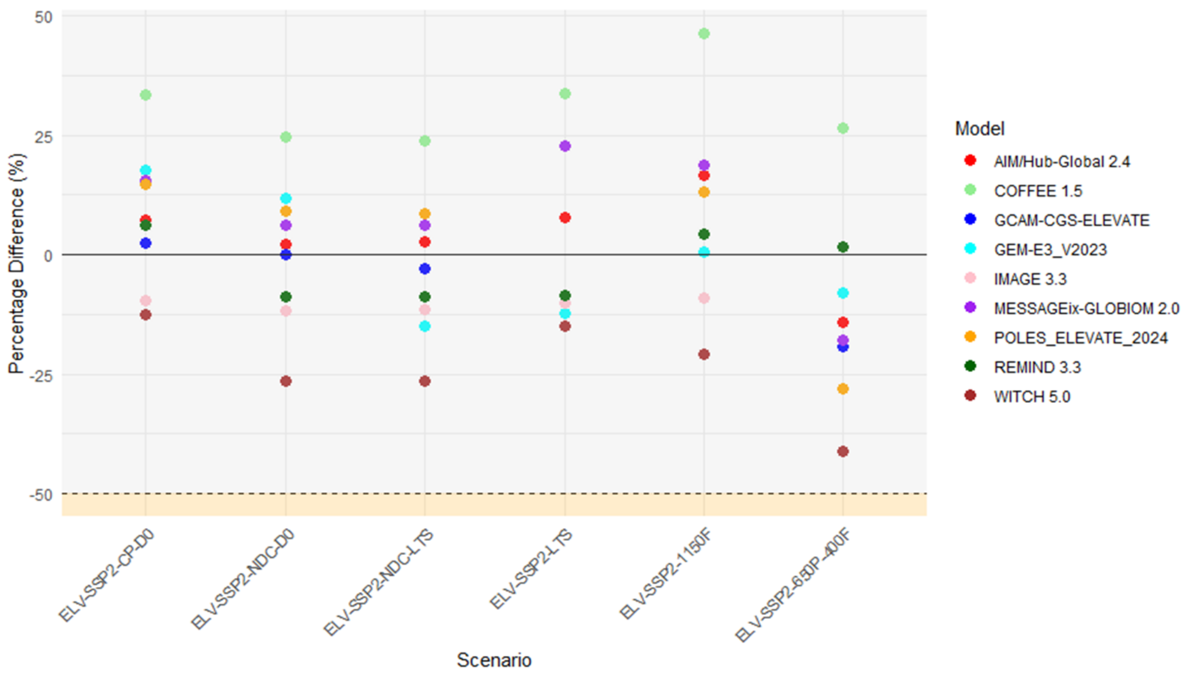

Figure 13: % Change in global primary energy of gas produced in 2030 compared to 2020.

4. Economic costs

This section examines the economic costs of the scenarios under consideration, focusing on the percentage change in GDP compared to the reference scenario (ELV-SSP2-CP-D0) at the global level and in major emitting countries. Figure 14 illustrates the GDP impacts of GHG emissions mitigation scenarios globally. We highlight that this assessment only considers the potential cost implications from any structural changes and technology adoption that are implicit to the low-carbon transition without capturing the avoided costs and damages that are expected with the achievement of ambitious mitigation pathways as described in the scenarios analysed.

Stringent climate policies are expected to result in structural changes, and to some extent to more costly production processes and a shift away from carbon-intensive consumption patterns, leading to negative implications on GDP. This is consistent across all scenarios and models. The percentage change in GDP compared to the reference scenario ranges between (1%, -3.5%) in 2030, (0%, -6.7%) in 2050, and (0.1%, -9%) in 2100. Among the scenarios, the NDC-LTS scenario results in the highest cumulative GDP losses (2020–2100) for the GCAM and GEM-E3 models. In contrast, the cost-optimal scenario ELV-SSP2-650P-400F, equivalent to a cost-optimal effort for limiting temperature rise to 1.5°C, shows the highest GDP losses for models such as REMIND, AIM/Hub, WITCH and MESSAGEix-GLOBIOM. The different cost estimations across models can be associated also with the mitigation effort that is implied by each model for each scenario, namely the emission reductions necessary to meet the targets or the cumulative carbon budget relative to the reference scenario as indicated in Figure 6.

The cost-optimal scenario consistent with limiting global temperature rise to 1.5°C achieves greater global emission reductions across all models. However, in the GCAM and GEM-E3 models, the effort required to achieve the 1.5 C carbon budget compared to the NDC-LTS scenario is relatively smaller than in other models, thus indicating that a cost-optimal mitigation effort allocation results in lower costs when compared to a fragmented action such as in the NDC-LTS scenario.

The NDC scenario, which features the least ambitious GHG mitigation targets, has the smallest negative impact on GDP across all models, with GDP losses ranging from (0%, -1.6%). In the short-term, most models register a lower cost in the LTS scenario compared to the NDC-LTS, with the exception of GEM-E3 which shows higher GDP losses under the LTS scenario until 2040. This divergence can be attributed to the theoretical framework of each model, considering factors such as the agent’s foresight and the respective (or absence thereof) of discount rates, the consideration of macroeconomic implications of stranded assets as well as the evolution of technology costs via the consideration of learning-by-doing and other knowledge effects for clean energy technologies.

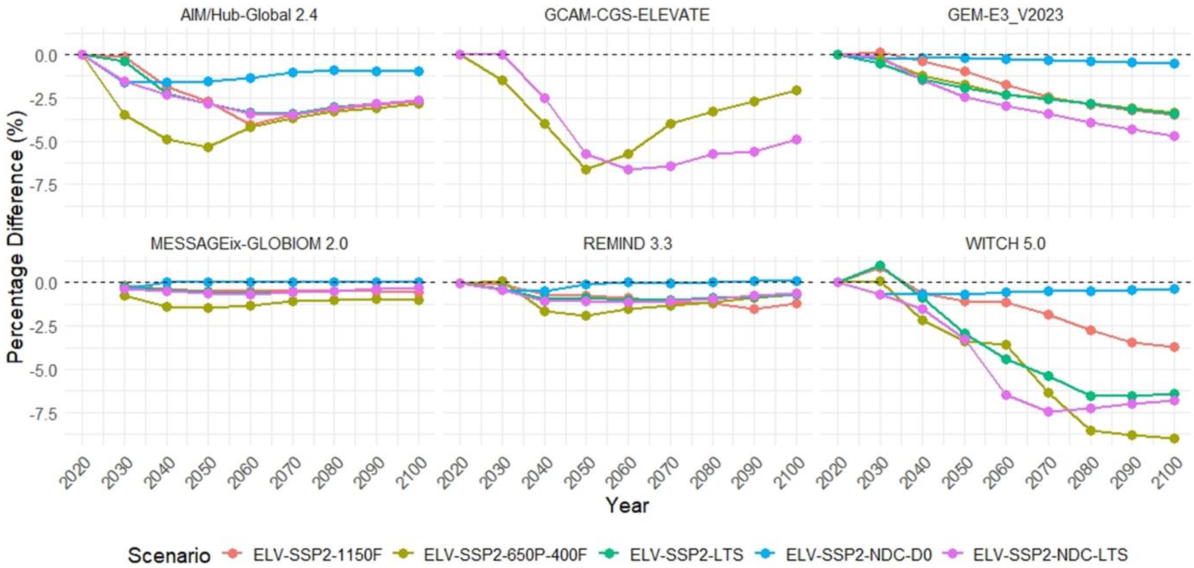

Figure 14: % Change of Global GDP compared to ELV-SSP2-CP-D0[2]

Figure 15 shows the GDP impact at the regional level, focusing on the major emitting countries. Across scenarios and models, the range of GDP changes by region/country is as follows: Brazil (-5.5% to -0.7%), China (-6.1% to 0.2%), India (-23% to 0.9%), Indonesia (-29.4% to -0.1%), Japan (-1.7% to 0%), North America (-2.5% to 0%), and Europe (-1.5% to 1.4%). Scenarios with an implementation of a uniform carbon pricing (or equivalent carbon value[3]) across sectors and regions can result in the cost-optimal allocation of emission reduction efforts across global regions, with no consideration of fairness and economic capacity implications. In such a context, Europe experiences the smallest GDP losses, benefiting from a more ambitious mitigation action already in the current policies scenario, while the highest GDP losses are observed in India and Indonesia that indicate large emission reduction potentials. This is the case for most models, even when high values such as those reported by WITCH model are not considered.

[2] ELV-SSP2-NDC-D0, ELV-SSP2-1150F and ELV-SSP2-LTS scenarios are not included for "GCAM-CGS-ELEVATE".

[3] A carbon value implementation can drive emission reductions as it acts as a pricing signal with no associated pricing of remaining emissions.

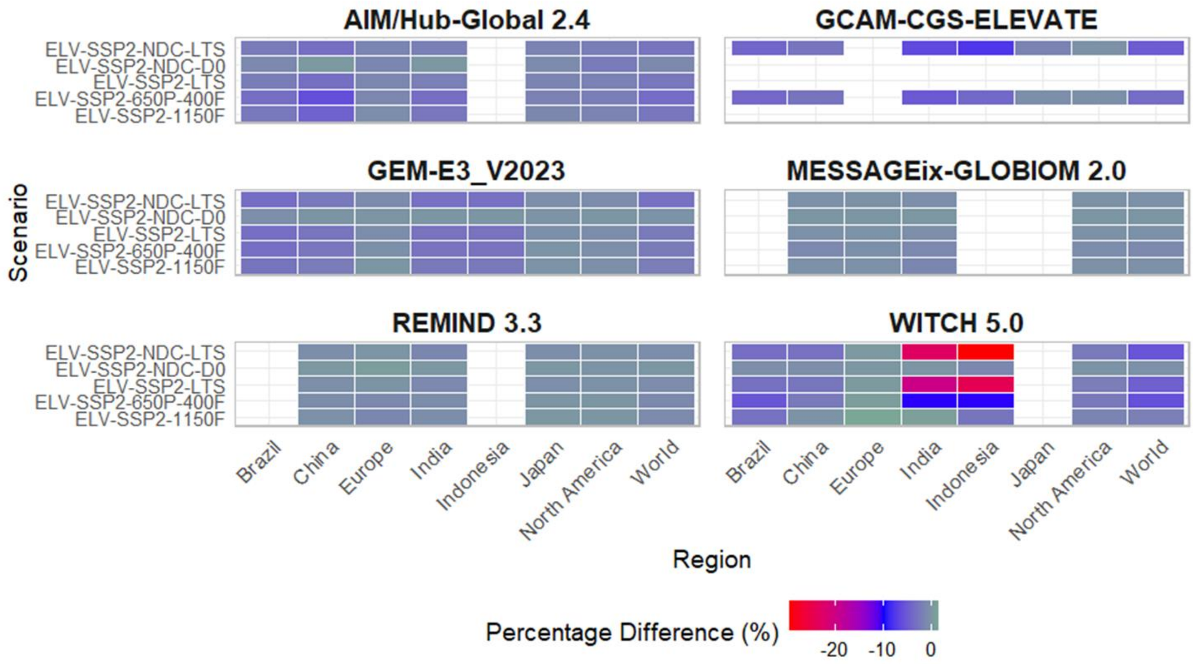

Figure 15: % Change of regional GDP compared to ELV-SSP2-CP-D0[4].

Table 5 shows the range of GDP change compared to reference by region and scenarios. The higher GDP losses are observed to be in the NDC LTS scenario for India and Indonesia.

Table 5: GDP change compared to reference (CP_D0) range by scenario and country across models.

	Brazil	China	India	Indonesia	Japan	North America	Europe	World
ELV-SSP2-NDC-D0	(-1.18% , -0.69%)	(-0.66% , 0.18%)	(-0.14% , 0.12%)	(-1.27% , -0.08%)	(-1.06% , 0.01%)	(-2.4% , -0.03%)	(-1.38% , 0.62%)	(-1.15% , -0.02%)
ELV-SSP2-NDC-LTS	(-4.22% , -2.39%)	(-3.49% , -0.5%)	(-23.12% , -0.71%)	(-29.43% , -3.24%)	(-1.66% , -0.67%)	(-2.43% , -0.37%)	(-1.48% , 0.19%)	(-5.61% , -0.47%)
ELV-SSP2-LTS	(-3.43% , -2.21%)	(-3.51% , -0.49%)	(-19.85% , -0.7%)	(-24.2% , -3%)	(-1.54% , -0.58%)	(-2.16% , -0.38%)	(-1.3% , 0.41%)	(-4.62% , -0.45%)
ELV-SSP2-1150F	(-3.23% , -2.61%)	(-4.49% , -0.24%)	(-2.66% , 0.88%)	(-2.97% , -2.49%)	(-1.26% , 0%)	(-1.64% , -0.05%)	(-1.36% , 1.42%)	(-2.79% , -0.48%)
ELV-SSP2-650P-400F	(-5.48% , -3.42%)	(-6.11% , -0.8%)	(-10.33% , -0.74%)	(-10.35% , -3.02%)	(-1.71% , -0.15%)	(-2.52% , -0.1%)	(-1.29% , 0.65%)	(-5.92% , -1.09%)

[4] Empty columns are excluded from results of the specific region due to different regional aggregation of the corresponding model.

5. Regional results

To provide a comprehensive overview, this section presents results based on global models for three major regions, which were not covered by national models participating in Task 2.3: Europe, the USA and the African region. We provide an analysis on emission pathways and focus on sectors relevant for the regions.

5.1. Europe

Global models vary in their geographical representation, and the European region is included in different ways. In the figures presented in this section, POLES results represent the EU-27, GEM-E3 results represent the EU-28, and results by other models represent a larger European region (more information can be found on the IAMC common Documentation: https://www.iamcdocumentation.eu/IAMC_wiki). To allow both insights for the European Union and insights from the diversity that multiple models bring, multiple scales are included in this section.

The European Union aims to reduce its GHG emissions by 55% with its NDC for 2030 and reach net-zero GHG emissions by 2050 with its LTS. The Current Policies scenario shows significant reductions, resulting in the average emissions that are a little above those for the NDC scenario by 2030. The models show a larger implementation gap between the (extended) Current Policies scenario and the (NDC-)LTS scenario by 2050. For all models except IMAGE, 2050 emissions levels from the (extended) NDC scenario are also higher than those resulting from the (NDC-)LTS scenario (Figure 16).

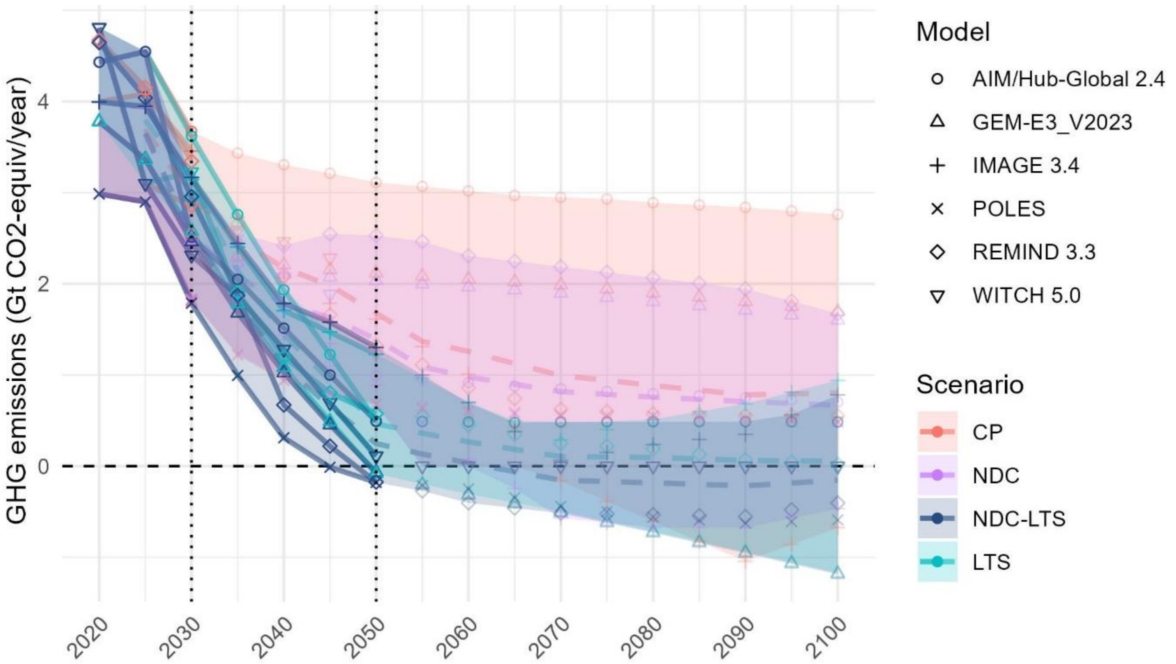

Figure 16: GHG emission pathways for the Europe per scenario and per model. Solid lines represent trajectories towards national targets, while shaded areas with dots only represent emission pathways based on extension of efforts after the targets are met. The dashed lines represent the average pathway.

In the aim of the European Union to reach net-zero GHG emissions by 2050, industry is a sector that is hard to abate. With its Green Deal Industrial Plan the region prepares for the transition of the sector, by aiming for a predictable and simplified regulatory environment, fast access to funding, enhancing skills and open trade for resilient supply chains (European Commission, 2023). Figure 17 shows how models project the role of CO_2 emissions from industrial processes by 2050. In the NDC-LTS and LTS scenario, emissions from industrial processes do not reach net-zero by 2050: models project remaining emissions from industrial processes between 30 and 160 Mt CO_2 per year. For most models, levels resulting from (extended) current policy efforts are significantly higher, with differences up to 50 Mt CO_2 per year. Figure 18 shows the final energy use of the industrial sector for Europe by 2050. The projected total final energy use for the NDC-LTS and LTS scenarios is similar to the use projected for the (extended) Current Policies scenario. However, its composition is different: the NDC-LTS and LTS scenarios indicate fossil fuels shares of 7-22%, which is lower than the 21-36% projected under (extended) current policies.

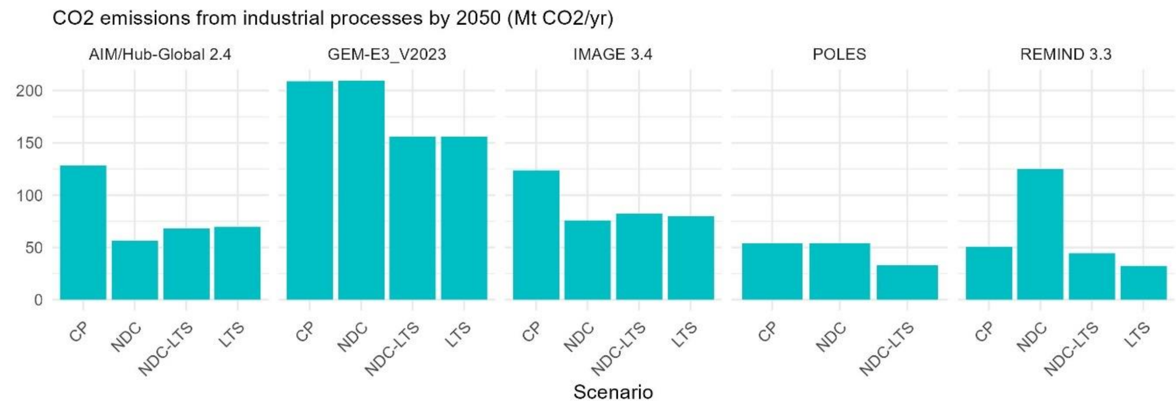

Figure 17: CO_2 emissions from industrial processes by 2050 for Europe, per model and scenario.

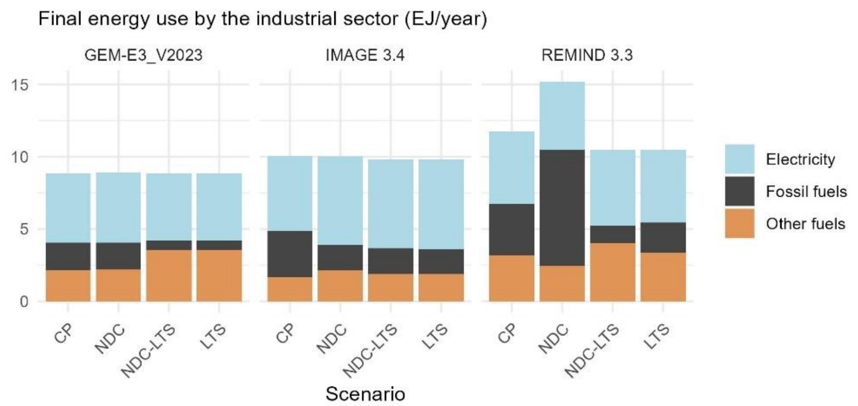

Figure 18: Final energy use by the industrial sector by 2050 for Europe, per type, model and scenario. 'Other fuels' includes among others biomass, heat, and hydrogen.

5.2. USA

The USA aims to reduce GHG emissions by 50-52% by 2030 in its NDC, and to reach net-zero GHG emissions by 2050 in its LTS. Figure 19 shows a large range for the emissions resulting from current policies by 2030: the lowest estimation is around 2.6 Gt, being well in line with the NDC scenario, while the highest is 8.8 Gt. The (extended) Current Policies scenario reduces emissions further after 2030, but not enough to be in line with the (NDC-)LTS scenario by 2050. For most models (the exceptions being AIM and IMAGE), the NDC scenario does not reduce emissions rapidly enough to be in line with the (NDC-)LTS scenario by 2050 either. However, the importance of aiming for short-term targets as well is highlighted by the difference between the NDC-LTS and LTS scenario, as the NDC-LTS scenario shows significantly higher emissions than the LTS scenario before 2050 for some models.

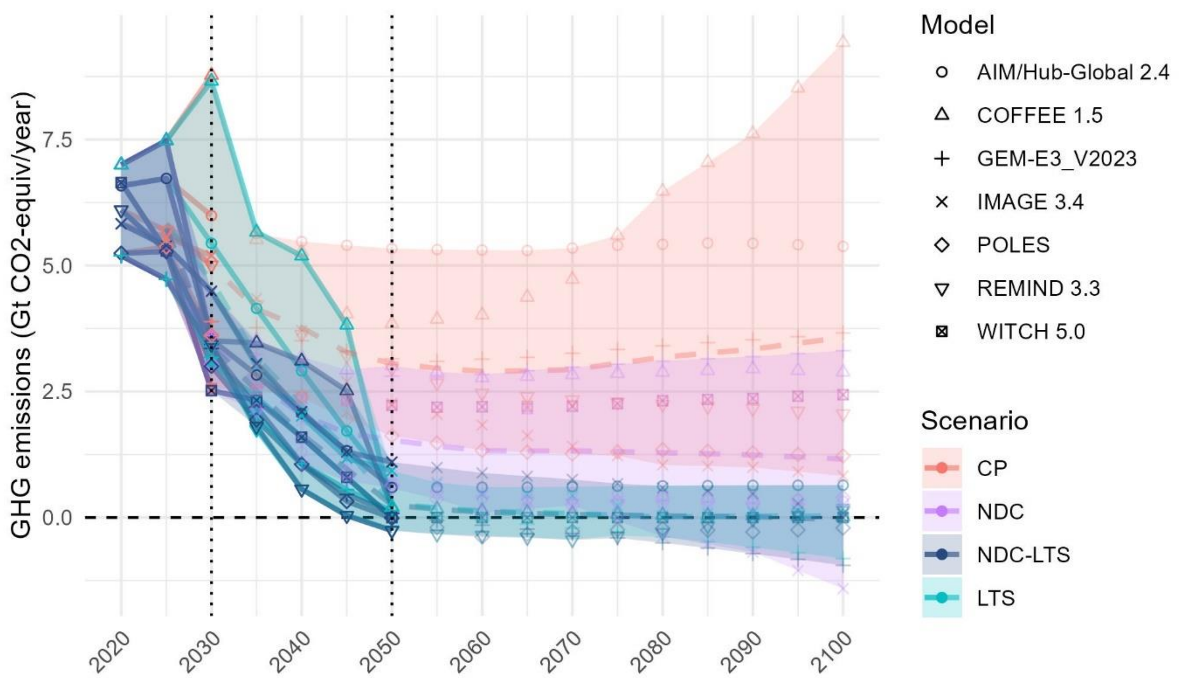

Figure 19: GHG emission pathways for the USA per scenario and per model. Solid lines represent trajectories towards national targets, while shaded areas with dots only represent emission pathways based on extension of efforts after the targets are met. The dashed lines represent the average pathway.

As for Europe, emissions from industrial processes are not projected to reach net-zero in the NDC-LTS and LTS scenario for the USA (Figure 20). However, their levels are projected to be low: projections vary between around 10 and 50 Mt. Generally, this is between around 40 and 200 Mt less than projected from (extended) current policy efforts in the Current Policies scenario. Figure 21 shows the final energy use by the industrial sector for the USA. Total final energy use is projected to be slightly lower in the NDC-LTS and LTS scenarios, compared to the (extended) Current Policies scenario. The share of fossil fuels is projected to be significantly lower in the scenarios aiming for LTS as well: 3-33%, compared to 40-50% in the Current Policies scenario.

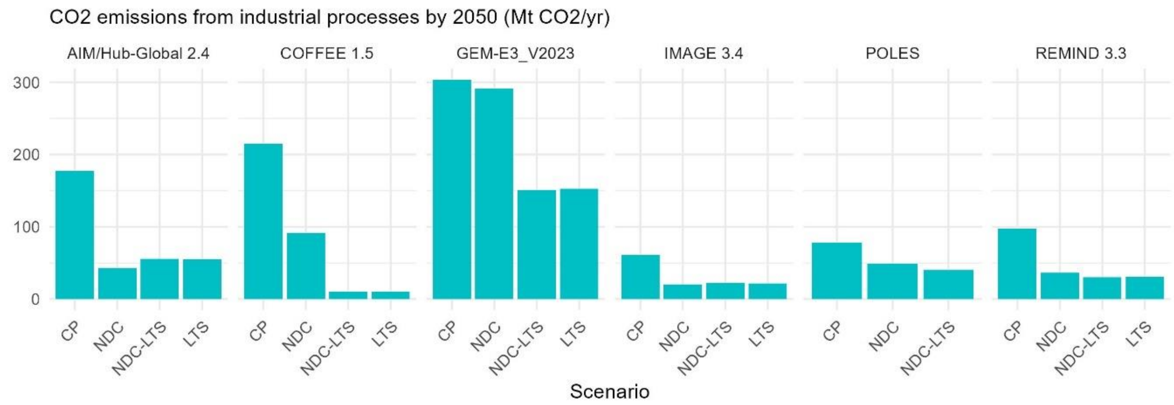

Figure 20: CO_2 emissions from industrial processes by 2050 for the USA, per, model and scenario.

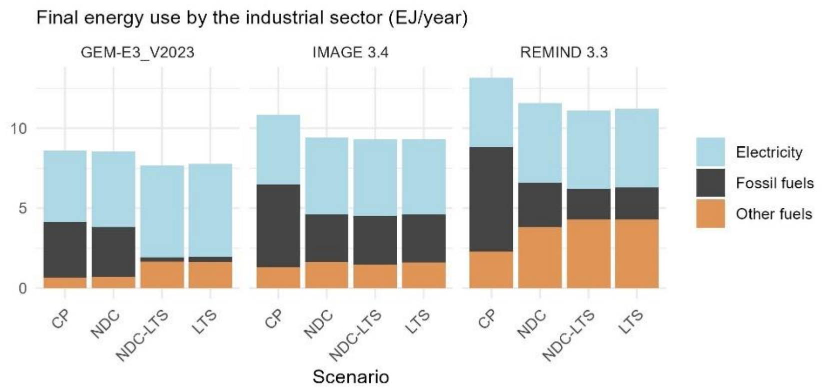

Figure 21: Final energy use by the industrial sector by 2050 for the USA, per type, model and scenario. 'Other fuels' includes among others biomass, heat, and hydrogen.

5.3. Africa

Figure 22 shows the GHG emission pathways for the African region (R10 regional hierarchy[5]). By 2030, emissions projected for the Current Policies scenario are slightly higher than those projected for the NDC scenario: the regional implementation gap between average emissions resulting from current policies and average emissions resulting from NDCs is projected to be 0.7 Gt. Note that emissions resulting from current policies can be an overestimation, as the current policies protocol included only South African policies within the African region. Models project an implementation gap of 2.9 Gt by 2050 between projected emission levels based on current LTS and (extended) current policy efforts.

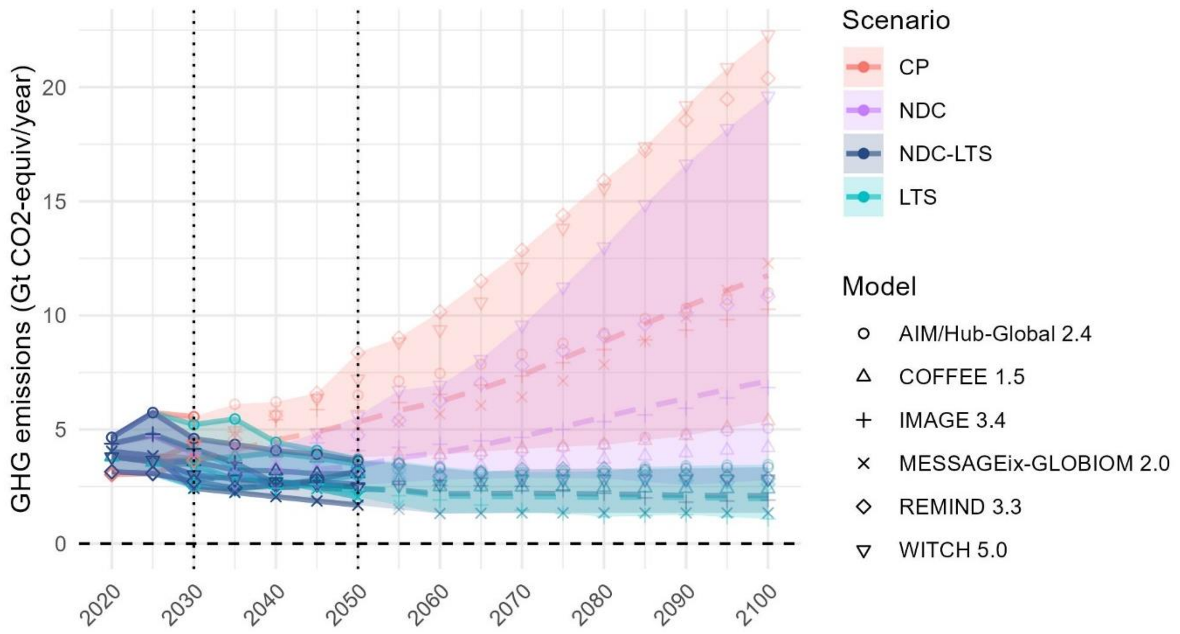

Figure 22: GHG emission pathways for Africa (R10) per scenario and per model. Solid lines represent trajectories towards national targets, while shaded areas with dots only represent emission pathways based on extension of efforts after the targets are met. The dashed lines represent the average pathway.

Solid biomass is a crucial energy source for the majority of the African population, particularly in rural and peri-urban areas. Mainly composed of wood, charcoal, and agricultural residues, biomass is widely available, especially in rural regions where access to modern energy infrastructure is limited. According to the World Bank,

[5] This region includes Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Réunion, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Eswatini, Togo, Tunisia, Uganda, Tanzania, Western Sahara, Zambia, Zimbabwe. Depending on the spatial resolution, some models report Northern Africa as part of the Middle East region.

approximately 600 million people in sub-Saharan Africa were still without electricity in 2023, reinforcing biomass as an essential alternative to meet basic energy needs. Unlike fossil fuels (gas, oil), which are often expensive and imported, biomass is a locally available, low-cost, or even free resource for many families. In several African countries, the use of wood or charcoal for cooking is deeply ingrained in daily habits. Although more modern technologies exist, their adoption remains limited due to economic and cultural constraints.

Dependence on biomass varies by region. In rural regions, up to 90% of inhabitants, particularly in countries such as Niger, Chad, or the DRC, rely exclusively on biomass for cooking and heating. In urban areas, although energy infrastructure is more developed, charcoal remains a popular alternative due to its affordability compared to electricity or liquefied petroleum gas (LPG).

Solid biomass is primarily used for cooking, with more than 80% of households, particularly in rural areas, relying on wood or charcoal. The main cooking methods include a) open fires, being highly inefficient, utilizing only 20-30% of thermal energy and generating significant smoke, and b) improved cookstoves: though still underutilized, these devices offer more efficient combustion, reduce wood consumption, and limit smoke emissions. Prolonged exposure to biomass smoke is a major cause of chronic respiratory diseases, particularly affecting women and children who spend the most time near cooking fires. Additionally, excessive use of firewood exacerbates deforestation, particularly in densely populated areas. While heating is less common in Africa due to its warm climate, certain mountainous or cold regions (such as in East and North Africa) depend on it. The same resources (wood, charcoal) are often used for heating homes in addition to cooking.

Solid biomass also plays a growing role in local electricity production through various initiatives. Some regions utilize agricultural residues (bagasse, peanut shells, rice husks) to generate electricity by biomass power plants. Biomass gasification converts solid biomass into combustible gas that can be used to generate electricity, particularly in off-grid areas. Although these solutions remain limited, they offer significant potential for rural electrification. Pilot projects in Tanzania, Kenya, and Ghana have demonstrated the feasibility of utilizing agricultural residues at a community scale.

The strong dependence on solid biomass for cooking, heating, and electricity production reflects Africa’s economic and structural realities. However, to ensure the long-term viability of this resource, it is essential to:

- Improve combustion technologies (improved cookstoves, modern power plants) to increase efficiency.

- **Promote sustainable forest resource management** to limit deforestation and ecosystem degradation.
- **Diversify accessible and affordable energy sources** to reduce reliance on biomass and mitigate its environmental and health impacts.

Adopting cleaner and more efficient solutions could improve living conditions while preserving the continent's natural resources.

Models project the role of solid biomass in the final energy use of the African region mainly in the Residential and Commercial sector and in the Industry sector. Figure 23 shows how this role changes over time: for the Industry sector, the use of solid biomass is constant or increasing, while the use of biomass in the Residential and Commercial sector typically decreases over time. The extent of the decrease is relatively stable, with remaining levels between none and 2 EJ/year by the end of the century. IMAGE is an exception, projecting an increase in the use of solid biomass in the Residential and Commercial sector over the second half of the century again. This increase is caused by population increasing faster than households move to cleaner fuels. The effect is more pronounced in scenarios with stronger mitigation, where carbon prices lead to higher prices for alternative fuels. The IMAGE team plans to improve this in future scenario development.

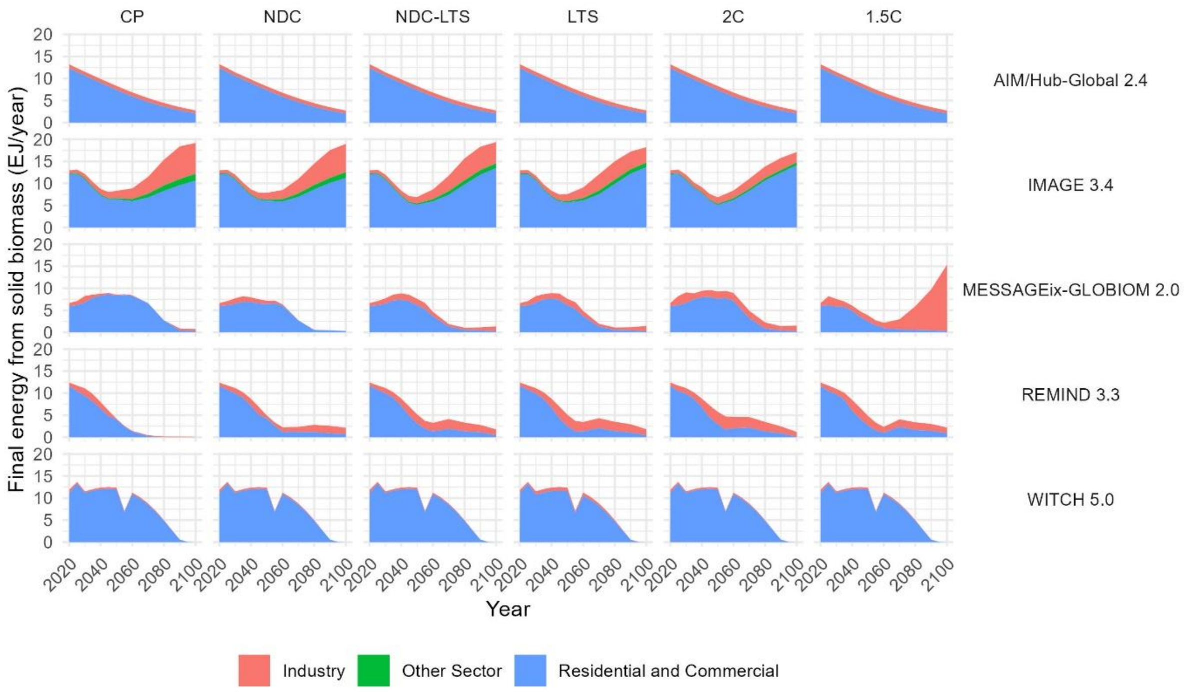

Figure 23: Final energy from solid biomass for Africa, per model, scenario and sector.

Figure 24 shows how use of solid biomass in the Residential and Commercial sector is projected to be replaced by other technologies in the scenarios. By 2025, final energy for this sector depends mostly on solid biomass, while by 2050 this is supplemented with energy from electricity, and to a smaller extent by solid fossils and liquid fuels. By 2100, most models project an increase in final energy use by the sector, with electricity as its major source. The results are relatively consistent across scenarios, suggesting that projections for regional developments have a greater influence on the results than the characteristics of the scenarios.

Figure 24: Final energy sources for Africa's Residential and Commercial sector, per model and scenario.

6. National results

This section presents the set of results generated by National IAMs considered in Task 2.3. These models encompass five countries, as shown in Figure 25. Together, these countries account for more than 40% of the world's population and approximately 28% of the global GDP in 2023 (World bank, n.d.). In terms of GHG emissions, they contribute an estimated 42.4% of total global emissions (OurWorldInData, 2023). The analysis in this section focuses on comparing and synthesizing these national-level results to better understand their implications within the broader context of ELEVATE project.

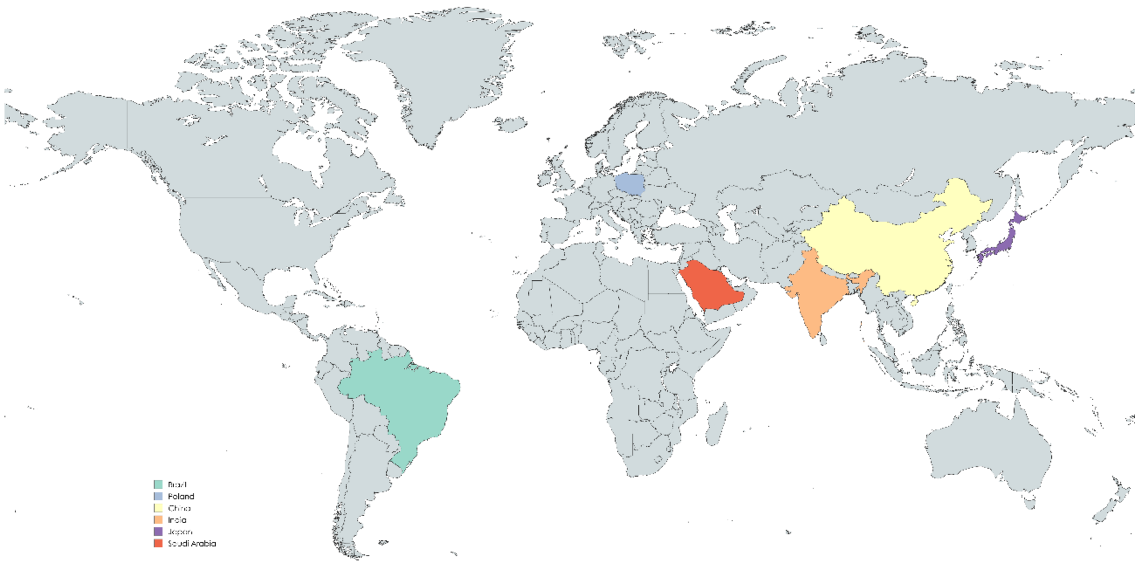

Figure 25: Regions represented by the models used in this task.

Regarding their NDCs, Brazil aims for a 53.1% reduction in GHG emissions by 2030 compared to 2005 levels. Japan commits to reducing GHG emissions by 46% by 2030 relative to 2013, with efforts to achieve a 50% reduction. China has pledged to peak CO_2 emissions before 2030 and reduce its carbon intensity by over 65% compared to 2005 levels by the same year. India targets a 45% reduction in emissions intensity of GDP by 2030 relative to 2005 and aims for 50% cumulative installed capacity from non-fossil fuel sources by the same year. The Kingdom of Saudi Arabia aims to reduce emissions by 278 MtCO2e annually by 2030, from the dynamic baseline emissions. Poland, through the EU's collective NDC, commits to a 55% reduction in GHG emissions by 2030 compared to 1990 levels (Climate Analytics, 2024).

Just as with the NDC targets, the countries represented in this study show diverse timelines for reaching net zero targets. Brazil, Japan, and Poland aim to achieve net zero GHG emissions by 2050, with Poland aligning with the European Union's regulations for mid-century decarbonization. China targets CO_2 neutrality by 2060, while Saudi Arabia targets net zero GHG emissions by 2060. India has committed to net zero emissions by 2070, without specifying whether the target covers all GHGs or only CO_2.

Figure 26 highlights the emissions pathway of GHG or CO_2 across the scenarios analyzed, for each country considered in this exercise. The Current Policies (CP) scenario consistently demonstrates the least ambitious trajectory, reflecting effects of policies currently in place for these countries. For all countries analyzed, the CP scenario maintains a higher level of GHG (or CO_2) emissions compared to other pathways.

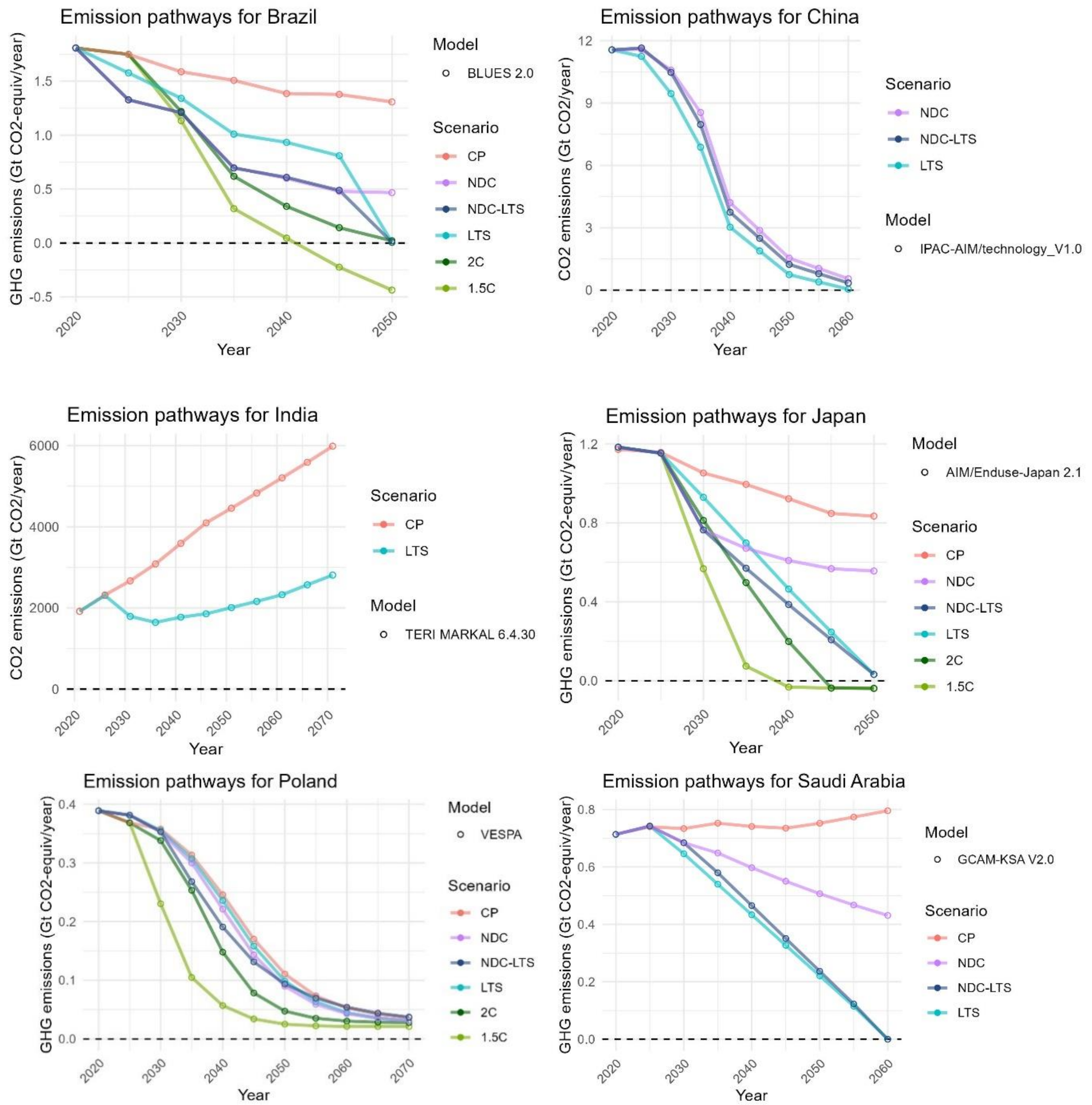

Figure 26: CO_2 and GHG emission pathways for the analyzed regions

The NDC scenario represents a step forward in ambition compared to the CP scenario in all of the analyzed countries. In the short term, as seen in the results for Japan and Brazil, the NDC scenario demonstrates a more aggressive reduction in its emissions pathway until 2030 then the temperature target scenarios. Beyond this point, however, the NDC scenarios fall short of the ambition required to the temperature scenarios.

The NDC-LTS scenario, which combines the NDC targets with the net zero year (LTS scenario) commitments for each region, presents different outcomes based on the country and model. For Brazil, the NDC-LTS scenario results in lower GHG emissions than the LTS scenario before 2050, indicating that the LTS scenario follows a less intensive mitigation approach until it reaches the country net zero emissions year. Conversely, in China, the LTS scenario mitigates more CO_2 than both the NDC and NDC-LTS scenarios, indicating that China's NDC targets might not fully reflect the mitigation efforts required for its net zero trajectory. Japan's NDC-LTS pathway, however, surpasses the LTS scenario in ambition, suggesting that Japan's NDC commitments actively support its progress toward net zero. In Poland, the LTS scenario follows a similar trajectory to the NDC and NDC-LTS pathways but achieves slightly less GHG mitigation until 2070. In Saudi Arabia, the LTS and NDC-LTS scenarios exhibit similar trajectories, achieving net zero by 2060, while the NDC scenario reduces emissions to nearly half of 2020 levels but still falls short of the LTS pathway. For India, the LTS scenario demonstrates a transformative decarbonization of the economy, placing it on a distinctly lower emissions trajectory compared to the CP scenario.

From a carbon-budget perspective, Brazil's NDC-LTS emissions are aligned with a 2°C temperature pathway, mirroring similar results for Poland. However, Japan's temperature scenarios suggest a much smaller carbon budget, approximately 20% lower than that of the NDC-LTS scenario, presenting a significant gap between its current NDC and net zero year commitments and a Paris-aligned world.

Across all models, the 1.5°C pathway consistently emerges as the most ambitious, requiring substantial and immediate reductions in GHG emissions. This demonstrates that current NDCs and net zero targets remain insufficient to meet the Paris Agreement goals, emphasizing the need for strengthened and accelerated mitigation efforts worldwide.

Moreover, each country has specific characteristics inherent to its economic, social, and regional contexts. The following sections will provide a more detailed analysis of the primary mitigation measures for each of the countries studied, demonstrating that, due to their differences in emissions profiles and key sectors of their local economies, each country has unique opportunities for CO_2 and GHG mitigation. It is important to note that every country, regardless of its size or economic power, has the potential to contribute to addressing the climate crisis.

6.1. Brazil

In 2020, the BLUES model shows that the Brazilian AFOLU sector (Agriculture, Forestry, and Other Land Use) is Brazil's primary source of CO_2 emissions. This sector, responsible for approximately 596 Mt CO_2/yr, surpassed the transport sector (196 Mt CO_2/yr) and the industrial sector (98 Mt CO_2/yr). However, the AFOLU sector's role in mitigation efforts will transition from the largest emitter in 2020 to the main mitigator by 2050 across all scenarios analyzed. In the current policies scenario (CP), the BLUES model forecasts a significant reduction in AFOLU emissions, reaching approximately 96 Mt CO_2/yr by 2050, primarily driven by Brazil's drastic reduction in deforestation rates. Scenarios with more ambitious climate assumptions indicate that the AFOLU and energy sectors could achieve negative CO_2 emissions as early as 2035.

The Nationally Determined Contributions (NDC) scenario exhibited lower negative emissions for the AFOLU (-770 Mt CO_2/yr) and energy supply sectors in 2050 than the Long-Term Strategies (LTS) scenario (-812 Mt CO_2/yr). However, in earlier periods, the NDC scenario demonstrates more negative emissions (-441, -506 and -691 Mt CO_2/yr in 2035, 2040 and 2045) in comparison to the LTS scenario (-160, -230 and -320 Mt CO_2/yr in 2035, 2040 and 2045). The NDC-LTS combination shows greater alignment with the Paris Agreement goals (1.5°C and 2.0°C), although it still presents carbon budgets above the levels required to meet climate targets. The 1.5°C scenario highlights the increased importance of negative emissions, primarily due to the expansion of reforestation and afforestation of native forests and the production of renewable liquid biofuels, such as those derived from sugarcane and lignocellulosic materials, combined with carbon capture and storage (BECCS). These efforts underscore the strategic role of the AFOLU sector in Brazil's transition to a low-carbon future, emphasizing its importance and potential.

This pivotal change in the AFOLU sector, mainly the broad implementation of renewable liquid biofuels is on par the country’s classification as an adaptative pragmatist region in the Deliverable 3.1 (D3.1), assuming this may be an innovative use of renewable energy policy, balancing sustainability with economic development.

Historically, Brazil had seen policies enabling bioenergy deployment, driven mainly by the abundance of biomass as a resource, but also seeking energy security and other goals. This behavior also corroborates with the narrative shown in the AFOLU sector.

6.2. Poland

The Vespa model is used to conduct an integrated assessment of Poland economy sectors, considering the CP, NDC, LTS, NDC-LTS, 2.0°C, and 1.5°C scenarios. The results indicate a consistent potential for emissions reduction across all analyzed scenarios, with national emissions decreasing from 390 Mt CO_2e/year in 2020 to values between 20 and 40 Mt CO_2e/year by 2070, depending on the scenario. The CP scenario exhibits a carbon stock accumulation similar to the LTS scenario, demonstrating that existing policies already address key sectors, such as electricity generation. However, the CP, NDC, LTS, and NDC-LTS scenarios are not ambitious enough to meet the climate targets outlined in the Paris Agreement. This underscores the urgent need to accelerate the transition to renewable energy sources and increase electrification in critical sectors such as transport and energy in Poland.

On a sector level, Poland's decarbonization relies heavily on reducing coal usage, which in 2025 still accounts for 50% of electricity generation and 70% of heating. Government strategies are already aimed at replacing coal with renewable sources such as solar, wind, and biomass or less polluting alternatives, like nuclear power. In more stringent scenarios, such as 2.0°C and 1.5°C, variable renewable energy sources play an even greater role, reducing the reliance on nuclear power, while natural gas complements the electricity mix. Electricity generation will increase by at least 50% between 2025 and 2070 across all scenarios, with a significant substitution of coal for biomass and natural gas for heating. Additionally, a reduction in heating demand will be observed by 2070, highlighting the importance of changes in consumer behaviour.

6.3. China

The IPAC-AIM model applied to China indicates a trend of increasing CO_2 emissions until 2025, followed by a progressive decline across all analyzed scenarios (NDC, LTS, and NDC-LTS). As reflected in the model, a notable aspect of China's climate strategy is the significant initial reduction of CO_2 emissions under the NDC and LTS frameworks, with marked decreases observed early in the analysis period. By 2060, CO_2 emissions in the NDC scenario will reach 577 Mt CO_2/year, compared to 341 Mt CO_2/year in the NDC-LTS scenario and only 42 Mt CO_2/year in the LTS scenario. The stringent requirements of the LTS scenario, which aim for near-zero emissions by 2060, necessitate the rapid adoption of CO_2 reduction measures throughout the analysis period. Consequently, the LTS scenario exhibits a cumulative carbon budget at least 10% lower than the other scenarios.

At the sectoral level, the energy sector, China's largest emitter in the base year, also offers the most significant mitigation potential. Emissions from the energy sector decrease from approximately 10,560 Mt CO_2/year in 2020 to 529 Mt CO_2/year in 2060 under the NDC scenario, 328 Mt CO_2/year under the NDC-LTS scenario, and 29 Mt CO_2/year under the LTS scenario. This transformation relies heavily on China's capacity to implement carbon capture and storage (CCS) technologies. The NDC scenario has the highest reliance on CCS technologies, capturing approximately 3.7 Gt CO_2/year by 2060. This total is distributed across fossil CCS, biomass CCS, and industrial CCS, with the fossil CCS contribution being at least twice as large as in any other scenario. These results highlight the critical role of CCS in reducing emissions from China's energy sector and achieving its climate goals.

Using the Deliverable 3.1 as basis, it becomes clear that this magnitude of CCS capacity deployment over the years may be possible with China's planned economy, heavily state-subsidized transition characteristic behaviour. The state may build a strong framework for this specific case, as it has done before, providing high levels of institutional capacity being directly involved, as CCS is part of the energy sector and the supply chain for cleaner energy.

6.4. India

The TERI Markal 6.4.30 model was employed to evaluate India's energy sector emissions and expansion under two scenarios: Current Policies (CP) and Long-Term Strategies (LTS). The CP scenario reveals a continuous growth in CO_2 emissions from the energy sector between 2016 and 2071, with relatively steady rates from 2021 onward. Without new government interventions, emissions will rise from 1.9 Gt CO_2/year in 2021 to approximately 6.0 Gt CO_2/year by 2071. In contrast, the LTS scenario shows a substantial reduction in emissions between 2026 and 2036, decreasing by 0.7 Gt CO_2/year during this period, from 2.3 Gt CO_2/year in 2026 to 1.6 Gt CO_2/year in 2036. However, emissions gradually increase again, reaching 2.8 Gt CO_2/year by 2071. This indicates that India's long-term strategies prioritize initial reductions without committing to net-zero emissions by the end of the analysis period.

From a sectoral perspective, electricity generation is pivotal in achieving decarbonization under the LTS scenario. Unlike the CP scenario, fossil fuel-based electricity generation, including coal and natural gas, is significantly reduced in the LTS scenario. By 2071, coal and natural gas will be entirely phased out, while fossil fuels will drop to 0.7 EJ/year from their 2026 levels of 5.0 EJ/year, 4.5 EJ/year, and 0.5 EJ/year, respectively. This transition is driven by a substantial increase in renewable energy sources such as solar, wind, hydro, and nuclear power. Their contributions grow from 0.05 EJ/year, 0.14 EJ/year, 0.49 EJ/year, and 0.14 EJ/year in 2026 to 12.2 EJ/year, 5.9 EJ/year, 2.4 EJ/year, and 3.5 EJ/year by 2071, representing a nearly 3,000% increase in demand for clean energy. This transformation underscores India's heavy reliance on clean energy expansion to meet its growing electricity demand and facilitate the electrification of its economy.

India's decarbonization through electrification and renewable energy expansion is completely on par with what is expected, following its cluster-classification of an adaptative pragmatist from the Deliverable 3.1. Auction systems may help to overcome challenges in renewable energy, namely lack of funding and economical development coupling with emissions mitigation.

6.5. Japan

The AIM/Enduse-Japan 2.1 model is employed to evaluate CO_2 emissions in Japan under different climate scenarios, including 1.5°C, 2.0°C, CP, NDC, LTS, and NDC-LTS. Since 2015, total CO_2 emissions have significantly reduced, particularly in the more ambitious scenarios such as 1.5°C. The CP scenario follows a declining trajectory until 2050, while the 1.5°C and 2.0°C scenarios achieve negative emissions starting in 2040 and 2045, respectively. The NDC scenario stabilizes emissions at approximately 500 Mt CO_2/year from 2040 onwards, whereas the LTS scenario, targeting carbon neutrality by 2050, displays continuous declines from 2025. The NDC-LTS combination scenario exhibited more significant mitigation in the early years, with notable reductions in 2030, when emissions were approximately 156 Mt CO_2/year lower than those in the standalone LTS scenario.

At the sectoral level, the electricity supply sector makes the largest contribution to emission mitigation by 2050, with reductions ranging from -184 Mt CO_2/year (2.0°C scenario) to 255 Mt CO_2/year (CP scenario). The total reduction in the electricity generation sector reached up to 668 Mt CO_2, considering 2020 emissions of 484 Mt CO_2/year. The 2.0°C scenario stands out for achieving the most significant emission reductions in the electricity sector. In comparison, the 1.5°C scenario demonstrates higher electrification in the industrial and transportation sectors, reducing their emissions from 210 Mt CO_2/year and 172 Mt CO_2/year in 2020 to approximately 20 Mt CO_2/year and 40 Mt CO_2/year, respectively, by 2050. However, the 1.5°C scenario requires greater carbon storage from biomass with CCS and exhibits a higher adoption of direct air capture technologies, up to seven times more than in the 2.0°C scenario. These findings highlight the complexity and challenges of achieving a sustainable energy transition aligned with Japan's climate targets.

6.6. Saudi Arabia

The GCAM-KSA v2.0 model is employed to evaluate the emission pathways for the Kingdom of Saudi Arabia under four scenarios: (i) Current Policies (CP) – implements the policies in action as of 2024 and their impact in the long run without any additional policy measures; (ii) NDC – implements the renewable energy target of reaching 50% generation capacity and Kingdom's target of reducing 278 MtCO2eq emissions from the baseline by 2030. The scenario continues the same decarbonization rate beyond 2030; (iii) NDC-LTS – implements achieving the NDC target by 2030 and a linear decline of GHG emissions from 2030 to 2060; (iv) LTS – implements a linear decline in GHG emissions from 2025 to 2060.

While the transition to renewable and clean energy technologies will be central to the net zero GHG emissions by 2060 strategy, integrating carbon dioxide removal (CDR) measures will be a crucial part of the strategy for Saudi Arabia. Hydrocarbons will likely remain a part of Saudi Arabia's energy mix for a long time due to the legacy of carbon intensive industries and their use in hard-to-decarbonize sectors. These sectors will consequently continue to emit GHGs, necessitating carbon removal technologies to offset these residual emissions. Our analysis shows that to reach net zero GHG emissions by 2060, Saudi Arabia must deploy CDR measures to remove 221 MtCO2 per year from the atmosphere to offset the overall GHG emissions in 2060. It is important to acknowledge that sectors such as petrochemicals, cement, heavy transport are currently considered challenging to decarbonize based on existing research and technological capabilities. However, given the continuous advancement of technology, there remains a potential for achieving complete decarbonization in these sectors in the future. Also, the current assessment assumes that the net zero emission target will be achieved within the borders of Saudi Arabia. It might be more economically viable to trade emissions, especially in the later decades of the transition, instead of resorting to large scale deployment of CDR technologies if their costs do not drop rapidly as anticipated.

7. Conclusions

For this deliverable, global and national modelling teams developed scenarios reflecting current policies, NDCs, LTS, and cost-optimal trajectories to limit end-of-century global warming of 1.5 and 2 ^{o}C. We used those scenarios to assess current progress in climate mitigation and to study implications of the pathways from multiple perspectives: we studied the global level, the national level, associated energy systems and their feasibility, economic costs and national sectors. Globally, we found that current policies lead to an implementation gap of 6.4 Gt with NDCs by 2030, and extended current policies to an implementation gap of 30 Gt with Long Term Strategies by 2050. However, the targets outlined in national Long Term Strategies do represent a step in the right direction, as the scenarios reflecting them project emission pathways close to limiting global warming to 2 ^{o}C. Global energy systems limiting end-of-century global warming of 1.5 and 2 ^{o}C contain high shares (32-78%) of renewable energy by 2050. However, associated feasibility concerns should be considered: models could exceed thresholds on the use of bioenergy, for instance. The analysis on economic costs across the scenarios found that when looking at only costs and not including avoided costs and damages, more stringent climate action can have negative effects on GDP, with varying costs or even gains identified across regions and sectors. On a national and regional level, we found that additional policies are still needed to reach NDCs for most analysed countries as well, and sector level analyses demonstrated local opportunities in industry, use of solid biomass, the AFOLU sector, coal use, CCS and electricity generation. Additional to the primary scope of the deliverable we aimed to contribute to future scenario development, by exploring the influence of methods extending the Current Policies and NDC scenarios towards 2100. We found major contrasts between emission pathways resulting from different methods.

The work conducted in the current Task will be further used in other ELEVATE's Task 6.3, in which transition scenarios to net-zero will be developed. The global scenarios developed in this Task will be updated when necessary. In consultation with the consortium, lessons learnt during this task will also be taken into account in the Task 6.3 protocol.

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Appendix A: regional pathways from extension methods

A.1. Current Policies scenario

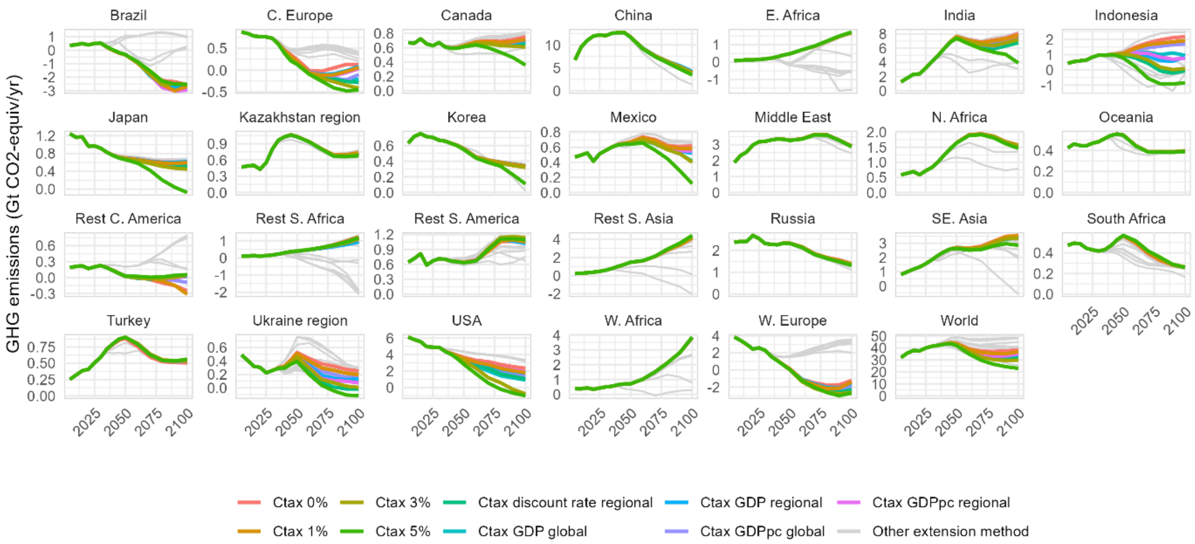

Figure X: Current Policy scenario emission pathways resulting from extension methods based on a carbon tax

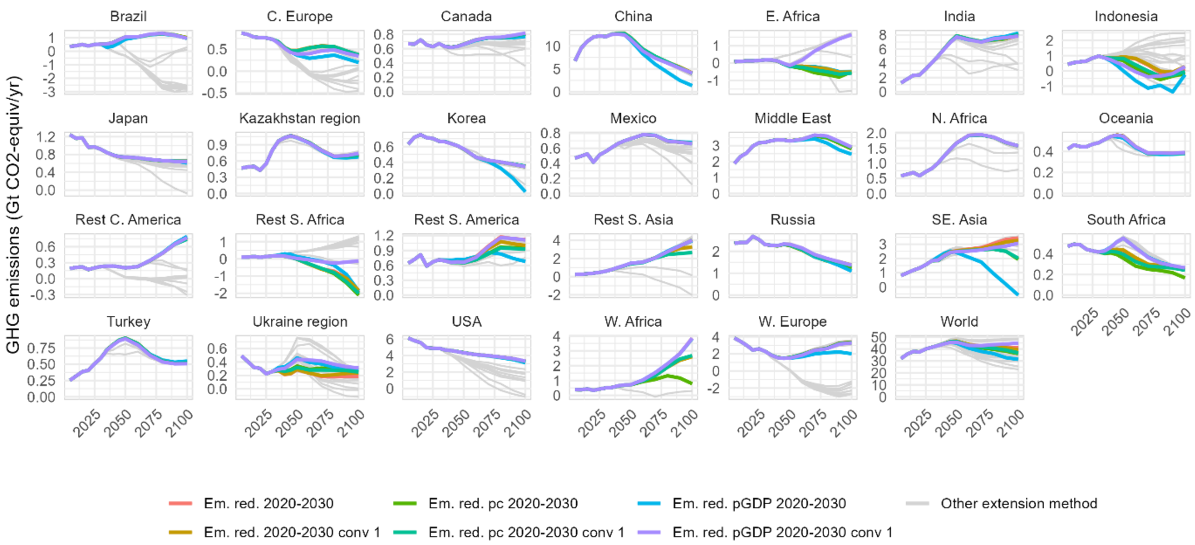

Figure X: Current Policy scenario emission pathways resulting from extension methods based on emission reductions

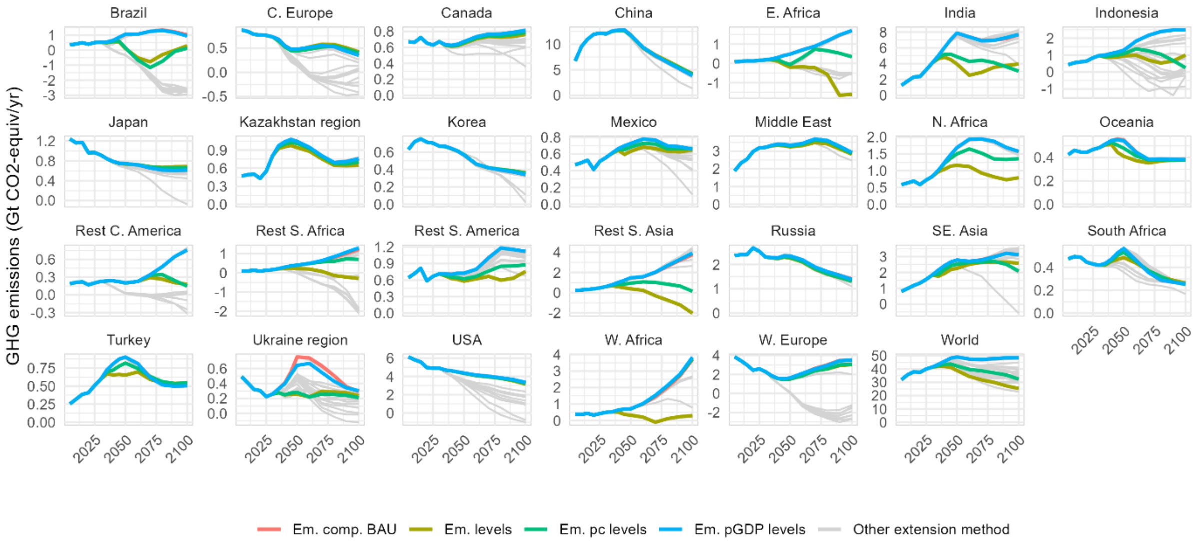

Figure X: Current Policy scenario emission pathways resulting from extension methods based on emission levels

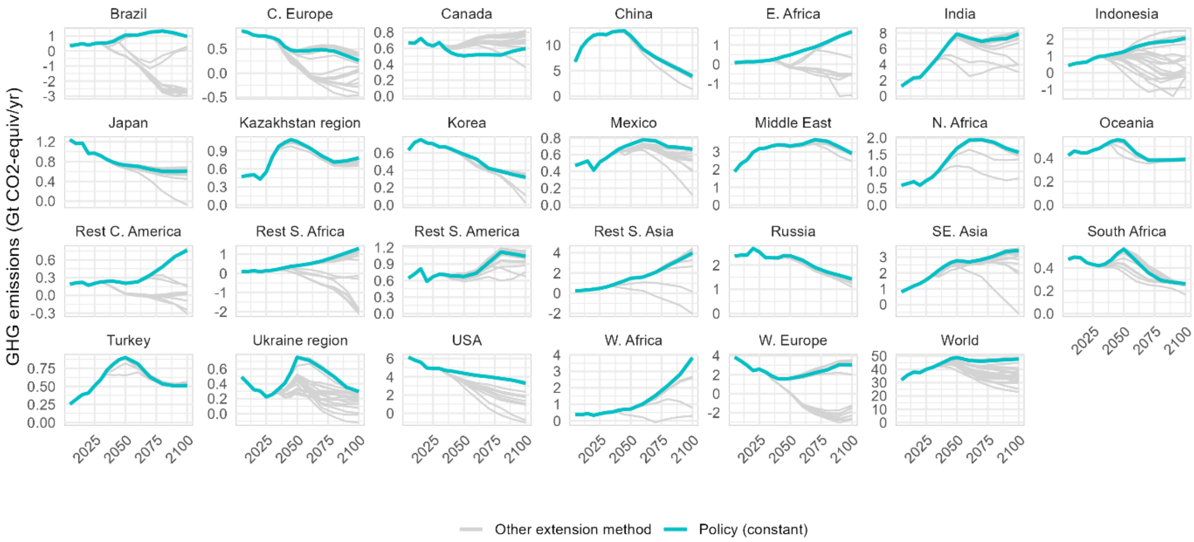

Figure X: Current Policy scenario emission pathways resulting from extension method based on policies

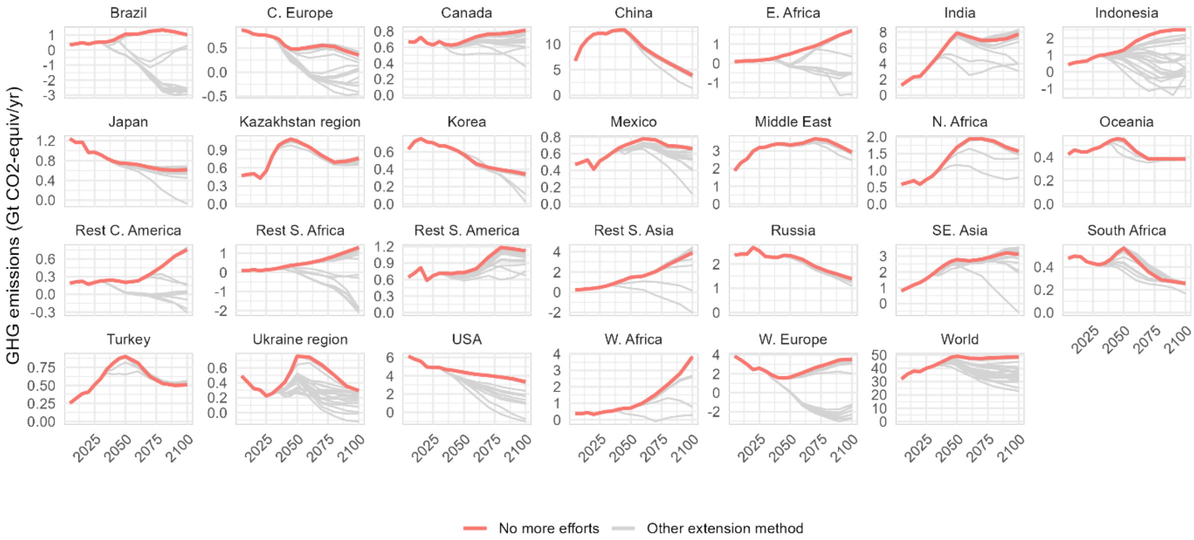

Figure X: Current Policy scenario emission pathways resulting from extension method assuming no more efforts

A.2. NDC scenario

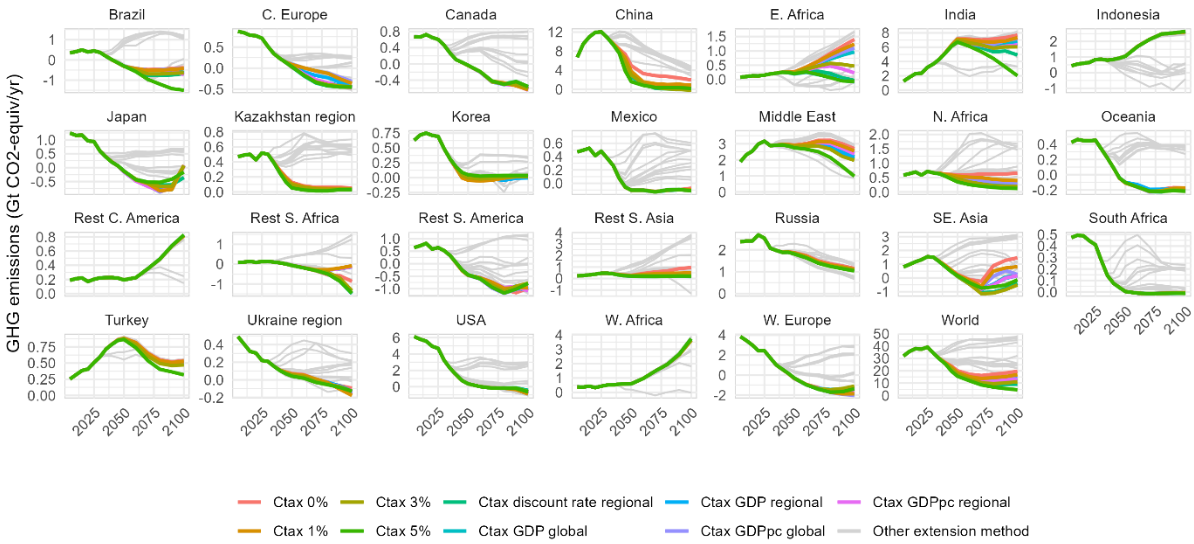

Figure X: NDC scenario emission pathways resulting from extension methods based on a carbon tax

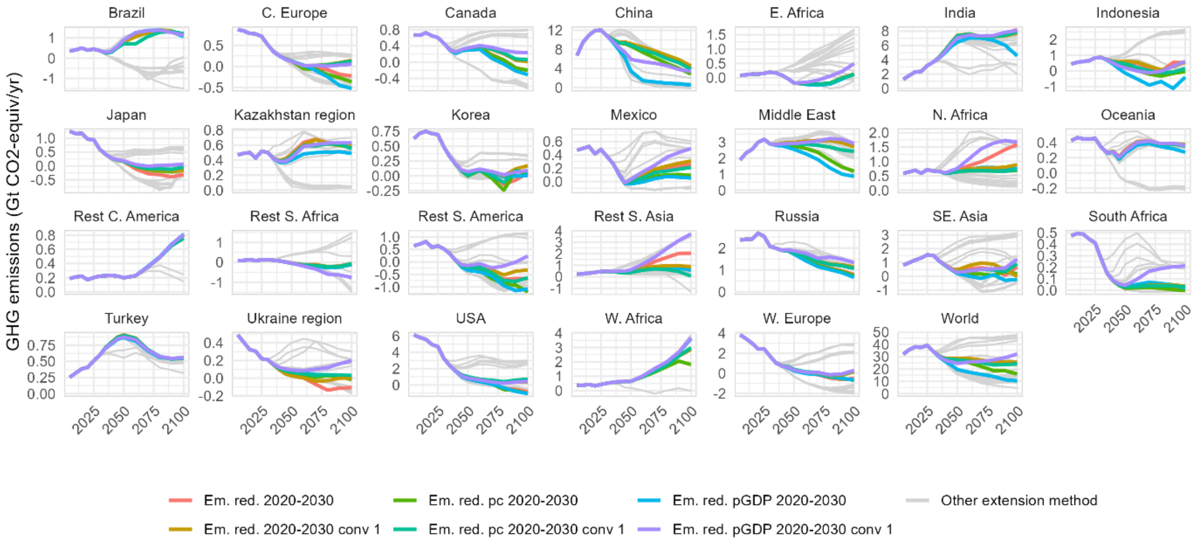

Figure X: NDC scenario emission pathways resulting from extension methods based on emission reductions

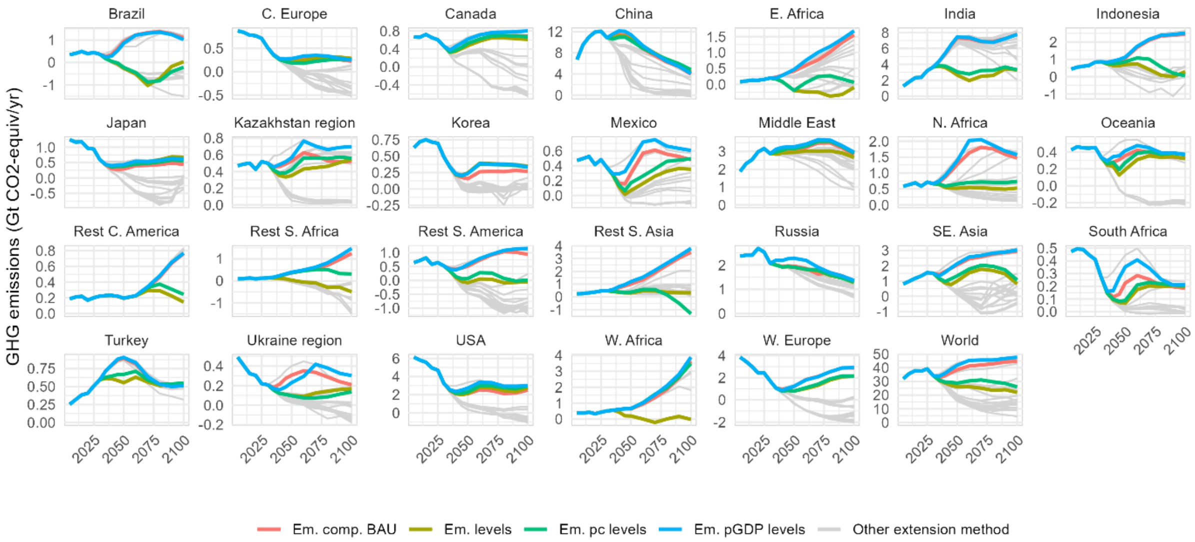

Figure X: NDC scenario emission pathways resulting from extension methods based on emission levels

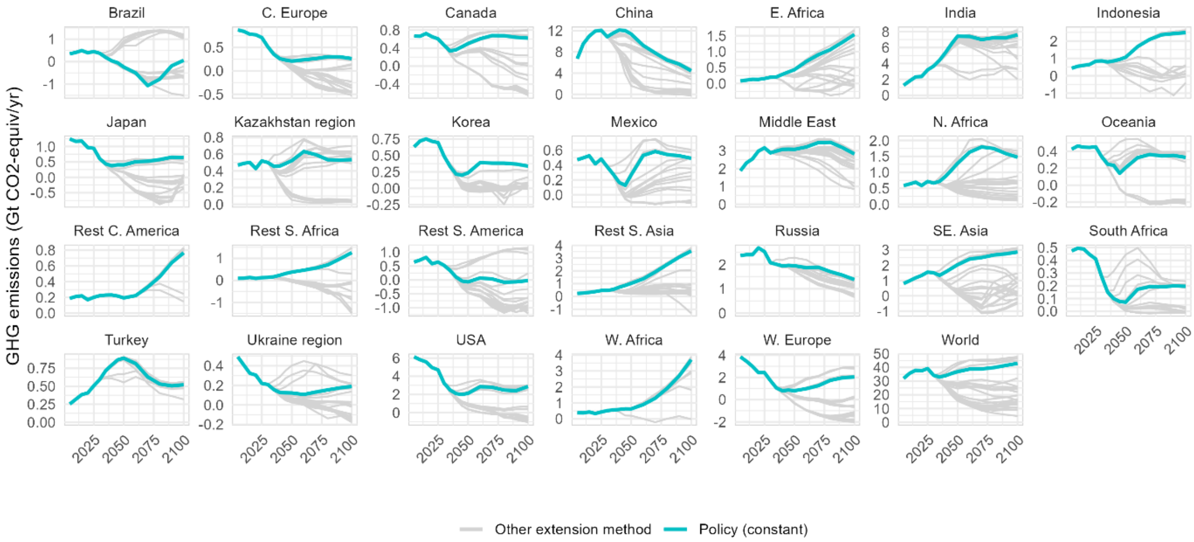

Figure X: NDC scenario emission pathways resulting from extension method based on policies

Figure X: NDC scenario emission pathways resulting from extension method assuming no more efforts