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Using Decomposition Analysis to Determine the Main Contributing Factors to Carbon Neutrality across Sectors

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Abstract: This paper uses decomposition analysis to investigate the key contributions to changes in greenhouse gas emissions in different scenarios. We derive decomposition formulas for the three highest-emitting sectors: power generation, industry, and transportation (both passenger and freight). These formulas were applied to recently developed 1.5 °C emission scenarios by the Integrated Model to Assess the Global Environment (IMAGE), emphasising the role of renewables and lifestyle changes. The decomposition analysis shows that carbon capture and storage (CCS), both from fossil fuel and bioenergy burning, renewables and reducing carbon intensity provide the largest contributions to emission reduction in the scenarios. Efficiency improvement is also critical, but part of the potential is already achieved in the Baseline scenario. The relative importance of different emission reduction drivers is similar in the OECD (characterised by relatively high per capita income levels and emissions) and non-OECD (characterised by relatively high carbon intensities of the economy) region, but there are some noteworthy differences. In the non-OECD region, improving efficiency in industry and transport and increasing the share of renewables in power generation are more important in reducing emissions than in the OECD region, while CCS in power generation and electrification of passenger transport are more important drivers in the OECD region.

Keywords: net-zero emission; decomposition analysis; mitigation; integrated assessment; shared socioeconomic pathways; climate change; Paris Agreement; scenarios

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1. Introduction

The Paris Agreement calls for achieving a balance between anthropogenic emissions and removals by sinks of greenhouse gases in the second half of this century (also called net-zero emissions) in order to achieve the objective of holding the global average temperature increase to well below 2 °C and preferably 1.5 °C. In line with this, many countries have set net-zero emissions targets. Scenarios developed by Integrated Assessment Models (IAMs) have shown that achieving these targets requires a fast transition in energy and land-use systems on a global scale [1]. There are, however, important differences in the strategies applied to reduce emissions to net-zero. Such strategies differ, for instance, in terms of choices made in the power system (focusing on renewables, nuclear power or carbon capture and storage (CCS)), the importance of bio-energy, the role of negative emissions (e.g., reforestation and bio-energy-CCS (BECCS)), the role of non-CO_2 greenhouse gases, the role of lifestyle change and the timing of reductions (e.g., [2,3]). Understanding the relative importance of these drivers in mitigating emissions is crucial to support and accelerate the energy transition, which is the main aim of IRENA's Long-Term Energy Transition (LTES) initiative. Decomposition analysis can identify the importance of each of these factors. This technique has been applied frequently to explain historical emission trends.

Decomposition has been extensively used to at trends in scenarios, but mostly at the aggregated level of Kaya indicators [4–6]. However, also more detailed level decomposition schemes have been used, such as those applied by van den Berg [7], who focused on the residential sector and passenger transport; Sharmina, et al. [8] and Edelenbosch et al. [9], who focused on passenger transport and industry; Llop [10], who did a structural decomposition analysis of gross energy output; Karmellos, et al. [11], who applied decomposition analysis on the EU power sector; Marcucci and Fragkos [12], who focused on long-term drivers of alternative net-zero pathways in China, India, Europe, and the USA; Guan et al. [13], who conducted decomposition analysis to investigate the driving forces of CO_2 emission in China; Jiang, Su, and Li [14], who conducted a decomposition analysis of the Chinese power grid. However, a thorough decomposition of all important emission sources globally has not yet been conducted, and none of the above studies included carbon capture and storage as decomposition factor.

This study applies decomposition analyses on the newly developed IMAGE 3.2 [15] 1.5 °C scenarios to analyse the largest contributing factors to emission reductions. This study uses recently published scenarios based on the Shared Socio-economic Pathways (SSPs), looking at different mitigation routes. The latter include the default strategy and two alternatives: one focusing strongly on a rapid expansion of renewables and electrification and one focusing strongly on lifestyle changes. In the study here, we use these scenarios. We analyse the results at the global level and for the OECD and non-OECD region (The OECD region includes Canada, the USA, Mexico, Western Europe, Central Europe, Turkey, Korea region, Japan, and Oceania. The non-OECD region covers Central America, Brazil, South America, Africa, Ukraine region, Central Asia, Russia region, Middle East, India, China, South-eastern Asia, and South Asia (https://models.pbl.nl/image/index.php/Region_classification_map), as these show very different characteristics. Emissions per capita and income levels per capita are relatively high in the OECD region, whereas the carbon intensity of the economy is relatively high in the non-OECD region.

Unlike previous studies, which only applied decomposition analysis on one or two energy sectors or for specific regions, this study uses the decomposition method to analyse changes in CO_2 emissions in the three sectors with the highest emission levels globally: power generation, industry, and transport (including passenger travel and freight transport). For all other emission sources (residential, services, land use, waste, and other non-CO_2 greenhouse gas emissions), we discuss the changes in emissions without applying a decomposition analysis. The paper aims to identify the main contributing factors to emission reductions in existing long-term 1.5 °C scenarios globally and in OECD and non-OECD regions.

2. Materials and Methods

While the decomposition method applied in this paper is generically applicable to scenario output of IAMs, we apply decomposition analysis here to existing scenarios developed by the IMAGE 3.2 Integrated Assessment model. We focus specifically on the changes in emissions from power generation, industry and transport for the SSP2 baseline and two 1.5 °C mitigation scenarios. Below, we explain the decomposition analysis and present the framework.

2.1. Decomposition Analysis

Decomposition analysis is used to identify the key contributions to changes in GHG emissions in scenarios. This decomposition analysis is applied to CO_2 emissions from energy use in industry, power generation, and transport. The decomposition is not applied to all other sources of GHG emissions as most of these sources are either relatively small or modelled in less detail. We focus on 2050 as total GHG emissions are very close to net-zero by this year in the mitigation scenarios.

Several decomposition methods have been developed to study the impacts of structural change on energy use in industry or on energy-related gas emissions. In literature, two forms of decomposition methods are mostly used: the Divisia based method and the Laspeyres based method [16,17]. As the scenarios used include negative emission values (via carbon dioxide removal technologies), we use the Laspeyres method instead of the Divisia method. However, the Laspeyres-based method leads to residuals, which means that the sum of each contributing factor to changes in emissions does not equal the total changes in emissions. Therefore, we use the Shapley/Sun method, which is based on the Laspeyres method but does not lead to residual values [9,16,18,19].

Due to the structural differences between the sectors, we have derived different formulas to show the contribution of the factors to emission changes for each sector. For transport, we have used an adapted version of the method used by van den Berg [7], who identified activity, mode shift, intensity, and fuel mix. We have added population as a driving factor to show the impact of increasing population on emissions explicitly. The resulting formula is given in Table 1.

Table 1. Decomposition formula for transport.

Population		Activity		Mode Shift		Efficiency		Carbon Intensity
Pop	$\times$	$\frac{Pkm\ or\ Tkm}{Pop}$	$\times$	M	$\times$	$\frac{FE}{Pkm}$	$\times$	$\frac{CO_2}{FE}$

Pop: population, Pkm: passenger-kilometer, Tkm: tonne-kilometer, M: mode share (%), FE: final energy use (TJ), CO_2: CO_2 emissions from transport (Gt).

We have applied this decomposition to both passenger travel and freight transport. We use the same equation for these subsectors; the only difference is that for passenger travel activity, we use passenger distance (Pkm) and for freight transport tonne-kilometres (Tkm). The travel modes also differ between passenger travel and freight transport. In passenger travel, we consider four modes: bus, train, car, and airplane. In freight transport, there are five modes: national shipping, international shipping, train, medium truck, heavy truck, and air cargo.

Decomposition of emissions from power generation and industry has been applied only in a few previous studies. In Karmellos et al. [11], emissions from power generation are decomposed by the following factors: the activity effect, defined as changes in Gross Domestic Product (GDP); the electricity intensity effect, defined as changes in the ratio of total electricity consumption to total GDP; the electricity trade effect, defined as changes in the ratio of electricity production to electricity consumption; the energy efficiency effect, defined as changes in the ratio of fuel input to the respective electricity output; and the fuel mixture effect, defined as changes in the share of a fuel in the total energy input of the power sector of the country. In Edelenbosch et al. [9], population growth, final energy use per capita, the share of electricity and hydrogen, and direct emissions of non-electric fuels are used as decomposition factors for industry.

The above studies excluded CCS as decomposition factors. Since CCS is potentially an important factor for emission reduction, we include this as an additional factor. This means that we define carbon intensity as the sum of CO_2 emissions and CO_2 captured divided by the energy use of fossil fuels (primary in the case of power generation and final in the case of industry). CCS includes all carbon captured, so both from resulting from the burning of fossil fuels and bioenergy. Furthermore, switching to renewables is a crucial mitigation strategy for power generation and has been included in the decomposition. For industry, we have selected electrification as a separate factor following Edelenbosch et al. [9]. For both industry and power generation, carbon intensity only relates to fossil fuels and biomass carbon intensity (i.e., fuel switch between coal, oil, gas, and biomass). The formulas for industry and power generation are given in Tables 2 and 3, respectively.

Table 2. Decomposition formula for industry.

Population		Activity		Electrification		Efficiency		Carbon Intensity		CCS
Pop	$\times$	$\frac{Act}{Pop}$	$\times$	$(1-\%Elc)$	$\times$	$\frac{FE}{Act}$	$\times$	$\frac{CO_2+CCS}{FE(1-\%Elc)}$	$-$	CCS

Pop: population; *Act*: industry production value-added (US$/cap); *Elc*: electricity share in energy use (%); *FE*: total final energy use of industry (TJ); CO_2: CO_2 emissions from industry (Gt CO_2); *CCS*: carbon capture and storage in industry, including BECCS (Gt CO_2).

Table 3. Decomposition formula for power generation.

Population		Activity		Renewables		Efficiency		Carbon Intensity		CCS
Pop	$\times$	$\frac{elec\ prod}{pop}$	$\times$	$elec\ prod\ (1-\%nonfos)$	$\times$	$\frac{PE\ (1-\%nonfos)}{elec\ prod\ (1-\%nonfos)}$	$\times$	$\frac{CO_2+CCS}{PE(1-\%nonfos)}$	$-$	CCS

elec prod: electricity production (GWh); *%nonfos*: share of renewables and nuclear in primary energy use of power generation (%); *PE*: total primary energy use of power generation (TJ); CO_2: CO_2 emissions from power generation (Gt CO_2); *CCS*: carbon capture and storage in power generation, including BECCS (Gt CO_2).

2.2. Scenarios

The analysed scenarios were developed by the Integrated Assessment model IMAGE 3.2 [15]. IMAGE is a comprehensive ecological–environmental model framework that simulates the environmental consequences of human activities worldwide. A detailed description of the model can be found in the online documentation [15].

Three IMAGE scenarios are analysed: a baseline scenario for reference and two 1.5 °C mitigation scenarios (Table 4). The Baseline scenario is an updated version of the SSP2 baseline by van Vuuren et al. [20], calibrated to 2020 data where possible. SSP2 is based on middle-of-the-road socio-economic projections (e.g., population growth, economic growth, technology development, and lifestyle change). The recent update includes model updates, new insights in technology development and the impact of COVID-19 and its recovery measures (see [15]).

Table 4. Description of scenarios.

Scenario	Main Assumptions
Baseline	The Baseline scenario follows the SSP2 baseline assumptions; main drivers are updated to 2015–2020 data, including near-term projections up to 2025 for GDP following IMF (to account for COVID-19). Drivers follow relative growth rates of original SSPs from 2025 onwards. See Van Vuuren et al., 2021 [15].
1.5 °C Renewable scenario	A carbon tax is introduced to reach an end-of-century radiative forcing of 1.9 W/m^2 compared to preindustrial times. High electrification rates in all end-use sectors are possible.
1.5 °C Lifestyle scenario	A carbon tax is introduced to reach an end-of-century radiative forcing of 1.9 W/m^2 compared to preindustrial times. consumers change their habits towards a lifestyle that leads to lower GHG emissions.

Two 1.5 °C scenarios are based on the SSP2 baseline but assume climate policy to reach 1. 5 °C. In the 1.5 °C Renewable scenario, it is assumed that high electrification rates in all end-use sectors are possible due to optimistic assumptions about the integration of variable renewable energy technologies and costs of transmission, distribution, and storage. As a result, the 1.5 °C Renewable scenario has a higher electrification rate and a higher renewable share. In the 1.5 °C Lifestyle scenario, consumers change their habits towards a lifestyle that leads to lower GHG emissions. This includes a less meat-intensive diet conforming to health recommendations, less CO_2-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1 °C in heating and cooling reference levels) and a reduction in the use of several domestic

appliances. These assumptions lead to more structural changes at the sector level, leading to less energy consumption [7,21–23] (also see [15]).

3. Results

In the first part of the results section, we show the total emissions by source under the three scenarios. In the second part, the results of the decomposition analysis are shown.

3.1. Total Emissions by Source

The three highest-emitting sources for which we apply decomposition are responsible for about half of total CO_2, CH_4, and N_2O emissions in the Baseline scenario, both by 2030 and 2050 (Figure 1). Based on the output from the IMAGE model, 11 other emission sources can be distinguished. The sum of the emissions from these sources equals the total of CO_2, CH_4, and N_2O emissions. Figure 1 shows global greenhouse gas emissions by 2030 and 2050 for these sources and separately for OECD countries and non-OECD countries.

In the Baseline scenario, GHG emissions continue to increase, especially in the non-OECD region. By 2050, the power sector will be responsible in the SSP2 scenario for the largest share of GHG emissions. Other large emitting sources are transport, CO_2 emissions due to land use, industry, and non-CO_2 energy. By 2050, non-OECD countries will be responsible for 77% of global GHG emissions in the baseline.

Total GHG emissions are net-negative in the OECD region in the mitigation scenarios by 2050. In the non-OECD region, emissions in 2050 are still positive, mostly from land-use emissions and transport (due to less efficient and higher carbon-intensive fuel usage than the OECD region). GHG emissions are reduced strongly across all sources in the 1.5 °C scenarios, especially CO_2 emissions from power generation and land use, where emissions are negative by 2050. For most other sources, emissions are close to zero. However, there are still considerable remaining CH_4 and N_2O emissions from animal husbandry and other land-use activities (agriculture and forestry), and, to a lesser degree, CO_2 emissions from transport. The emissions from these sources are more difficult to reduce in the IMAGE model (consistent with most other scenarios). Therefore, negative CO_2 emissions through BECCS and reforestation and afforestation are needed to achieve overall net-zero GHG emissions.

The clearest difference between the 1.5 °C Lifestyle scenario and the 1.5 °C Renewable scenario is the difference in non-CO_2 emissions from animal husbandry and land-use CO_2 emissions. This is largely caused by changing diets in the 1.5 °C Lifestyle scenario. The lower consumption of meat directly reduces emissions from animal husbandry. At the same time, less grazing land is needed, which frees up land that can be used for reforestation, leading to substantial negative land-use CO_2 emissions. By 2050, this also leads to lower emissions in the Lifestyle scenario—although initially, emissions are reduced more strongly in the Renewable scenario in power, industry, and transport sectors due to a faster switch to renewable energy.

The next section analyses the CO_2 emission reductions of power generation, transport, and industry in more detail using the decomposition analysis.

3.2. Main Mitigation Drivers

Here, we analyse how different factors contribute to mitigation in different strategies. For power generation, industry, and transport, we first show the waterfall charts that provide insight into the emission changes, then present the energy mix in 2015 and 2050 for the three scenarios to provide more detail on some of these factors.

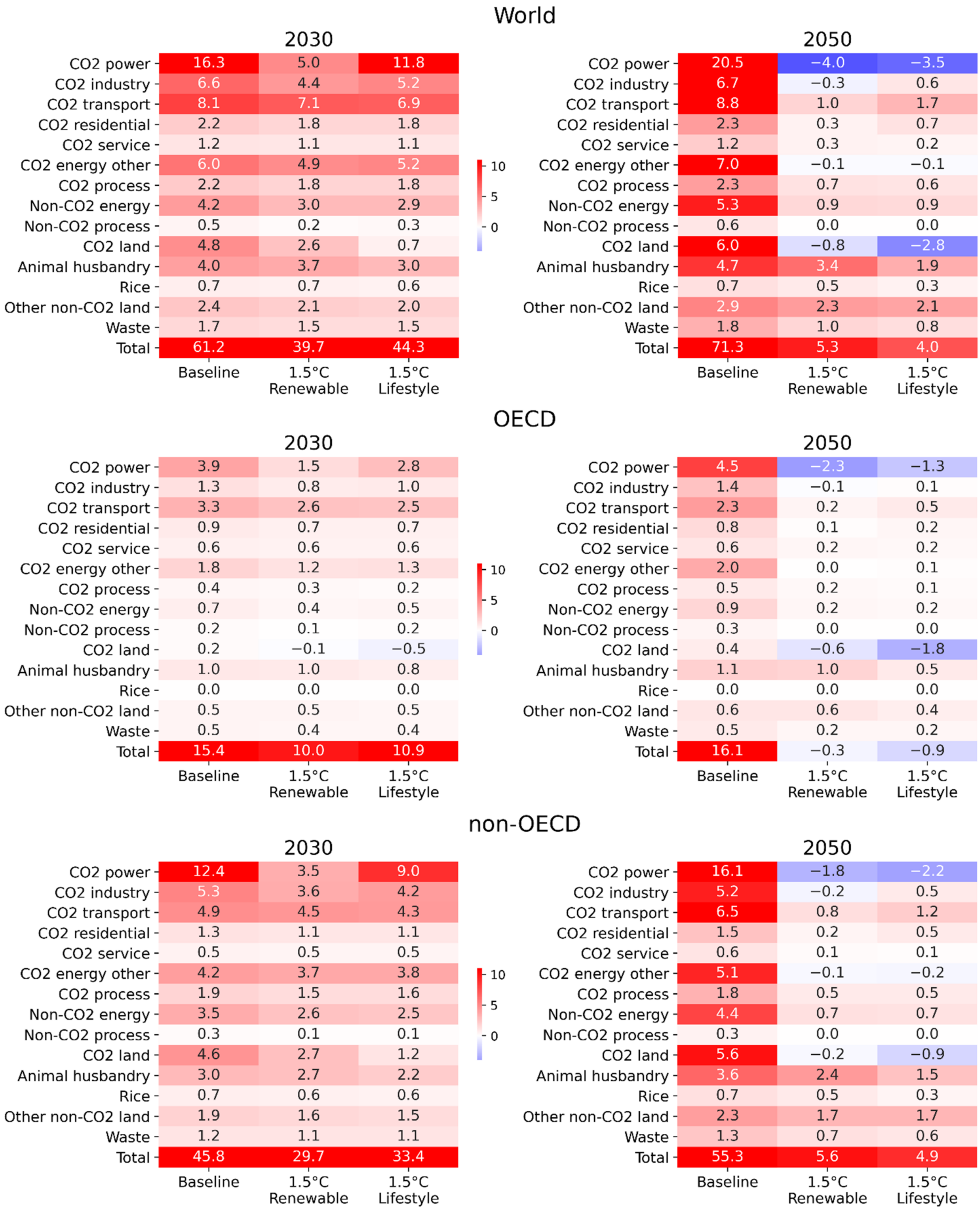

Figure 1. Total greenhouse gas emissions by emission source in 2030 and 2050 in Gt CO_2-eq. (using IPCC AR4 100-year global warming potentials [24]). The emission sources combined account for around 97% of global GHG emissions in recent years [25].

3.2.1. Power Generation

In power generation, we decompose emission trends into population change, activity change (power generation per capita), changes in efficiency (power generation divided by energy use in power generation), changes in non-fossil share (renewable and nuclear power generation), changes in non-renewable CO_2 intensity, and CCS.

In the Baseline scenario, CO_2 emissions from power generation strongly increase between 2015 and 2050, from 13.5 Gt CO_2/y to 20.5 GtCO_2/y (Figure 2). This is mainly due to higher electricity consumption per capita (9.8 GtCO_2/y), followed by population growth (4.1 GtCO_2/y). Efficiency improvements have a downward impact of 4.8 Gt CO_2 on emissions in the Baseline, followed by 2.1 Gt CO_2 reduction due to a reduction in carbon intensity. The latter is a result of changes in the energy mix: the share of coal decreases from 45% to 35%, and the share of natural gas increases from 18% to 29% (Figure 2).

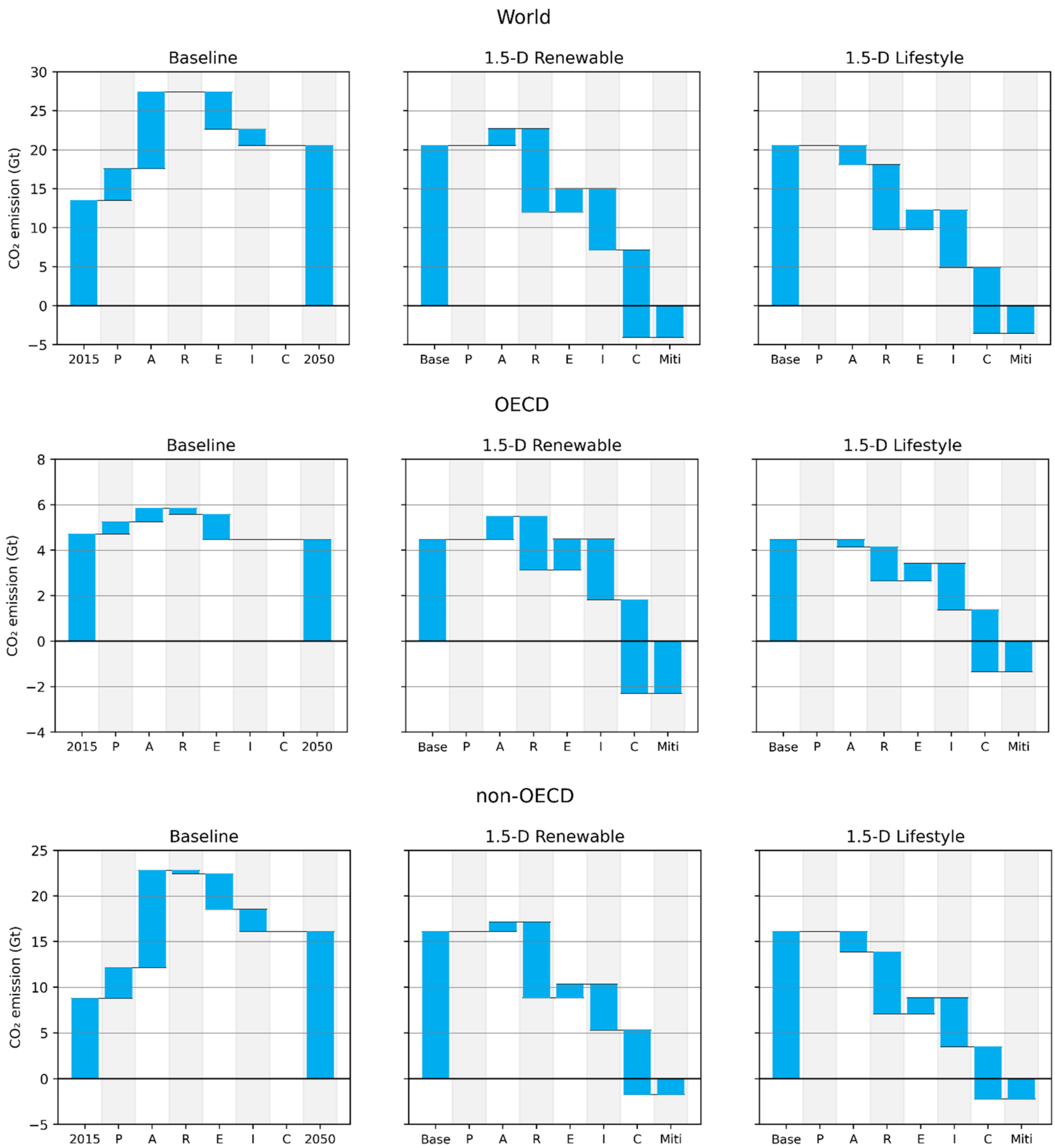

Figure 2. Changes in power generation emissions between 2015 and 2050 (Baseline) and between Baseline and the mitigation scenarios (in 2050) due to different drivers. P: population growth, A: activity changes, R: renewable and nuclear share, E: efficiency, I: carbon intensity, C: CCS.

Figure 2 also shows the decomposition analysis between the Baseline scenario and the 1.5 °C scenarios. The 1.5 °C Renewable and Lifestyle scenarios show substantial (−4 and −3.5 Gt CO_2) net-negative CO_2 emissions by 2050, made possible by the use of BECCS. This is reflected in the decomposition analysis, which shows that CCS is the most important driver for emission reduction in both 1.5 °C scenarios, leading to 8 Gt CO_2 reduction in the 1.5 °C Lifestyle scenario and 11 Gt CO_2 reduction in the 1.5 °C Renewable scenario. CCS is applied both on natural gas and bioenergy power plants.

Increasing the share of non-fossil energy (renewables and nuclear) has a similar impact on reducing emissions as CCS in both 1.5 °C scenarios. Indeed, the share of renewables and nuclear power in the energy mix increases from 14% in 2015 to 45–48% in 2050 in the 1.5 °C scenarios (Figure 3). CO_2 intensity improvements also contribute strongly to reducing emissions. This is mainly a consequence of carbon-intensive coal being phased out almost completely. In contrast, natural gas still has a significant share in the energy mix (largely with CCS).

The main difference between the two 1.5 °C scenarios is the contribution of the activity factor. In the 1.5 °C Renewable scenario, there is even an upward impact on emissions compared to baseline, resulting from higher electrification rates in end-use sectors. In contrast, in the Lifestyle scenario, some of the assumed changes reduce electricity demand increase somewhat. The stronger impact of especially renewables and CCS in reducing emissions means that overall, CO_2 emissions from power generation are slightly lower in the Renewable scenario than in the Lifestyle scenario.

The non-OECD region has higher population and activity growth, causing a significant increase in emissions in the Baseline scenario. In the non-OECD region, renewables play a more important role in reducing emissions than in the OECD region, while CCS plays a more important role in the OECD region.

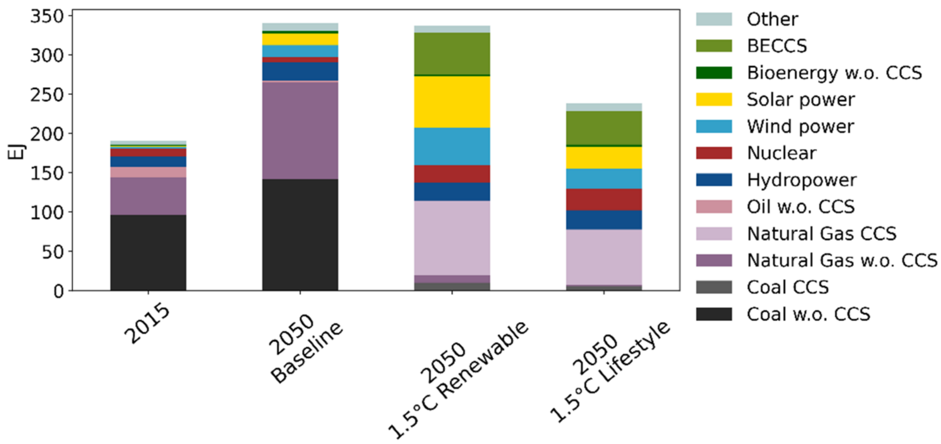

Figure 3. The global primary energy mix of power generation.

3.2.2. Industry

For industry, we decompose emission trends into the contribution of population change, activity change (industrial value-added per capita), changes in production efficiency, electrification, changes in non-renewable CO_2 intensity, and CCS.

Strong growth in activity is the most important contribution to increasing industrial emissions in the Baseline, followed by population growth (Figure 4). A strong improvement in energy efficiency partly offsets the increase in activity and population growth. In total, industrial emissions increase by 23% between 2015 and 2050 in the Baseline scenario.

In both 1.5 °C scenarios, CCS is the most important factor for reducing emissions from industry. In the 1.5 °C Renewable scenario, electrification and improving overall CO_2 intensity lead to higher emission reductions than in the 1.5 °C Lifestyle scenario. This leads to lower total industrial emissions in the 1.5 °C Renewable scenario than in the Lifestyle scenario, despite the higher impact of efficiency improvements in the 1.5 °C Lifestyle scenario.

In the baseline, activity and population growth leads to a much stronger emission increase in the non-OECD region than the OECD region. Efficiency improvement contributes more to emission reduction in the non-OECD region than in the OECD region.

The energy mix of the two 1.5 °C scenarios is similar by 2050: coal and oil are replaced by electricity and bioenergy (Figure 5). The main differences are (i) much lower energy use in the Lifestyle scenario, which was reflected by the stronger impact of energy efficiency in reducing emissions, and (ii) a much stronger electrification rate in the Renewable scenario.

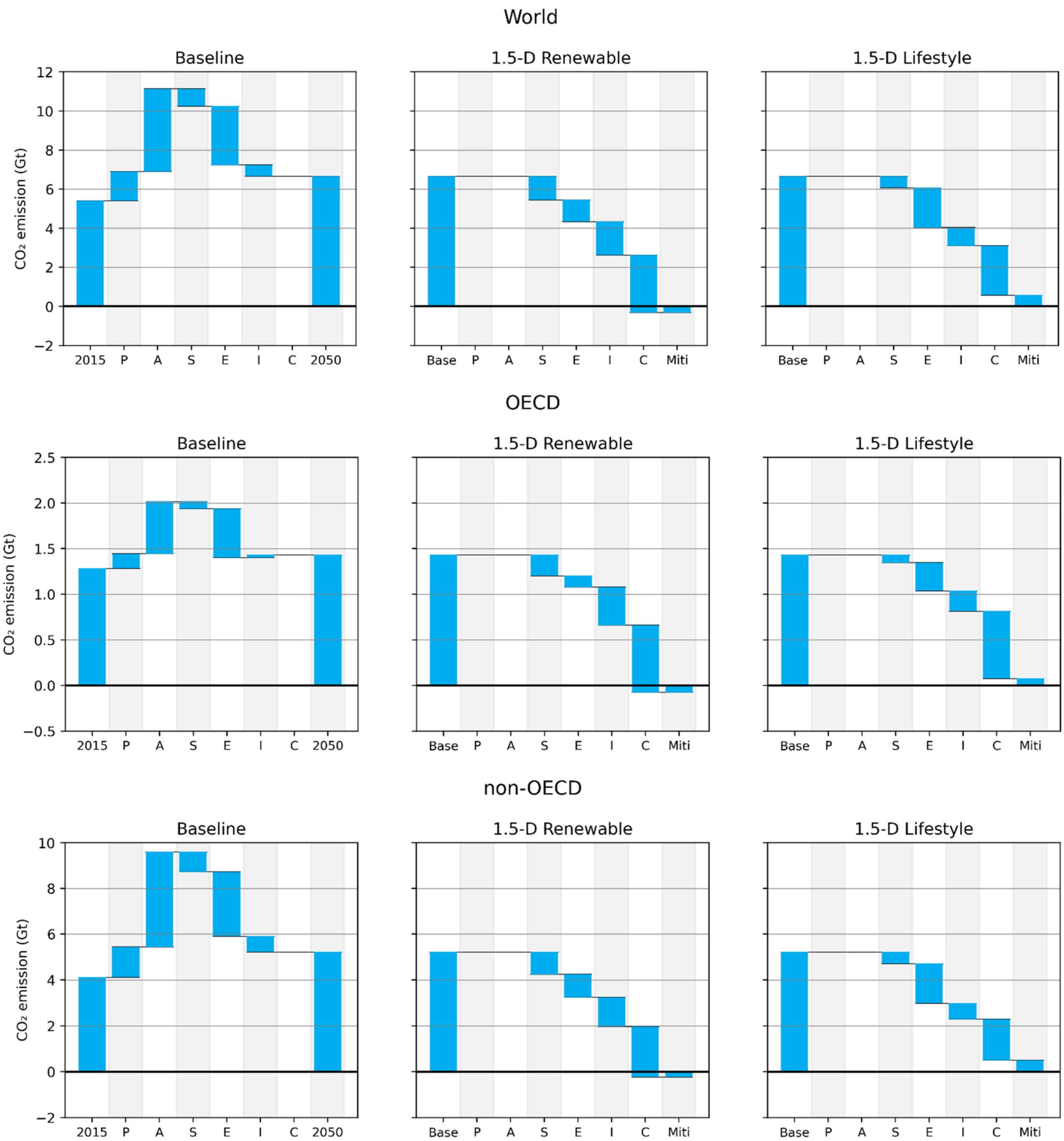

Figure 4. Changes in industry emissions between 2015 and 2050 (Baseline) and between Baseline and the mitigation scenarios (in 2050) due to different drivers. P: population growth, A: activity changes, S: electrification, E: efficiency, I: carbon intensity of non-renewable fuels, C: CCS.

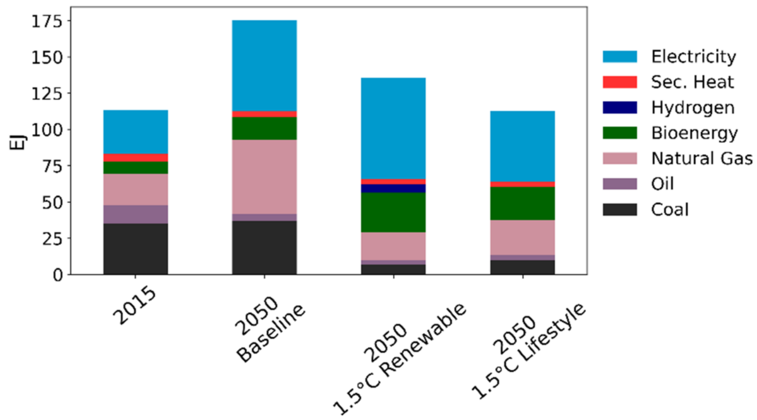

Figure 5. The global energy mix of industry in the baseline and the two 1.5 °C scenarios. (sec. heat = secondary heat).

3.2.3. Transport

IMAGE divides the emission sources into three sectors in the transport sector: passenger travel, freight transport, and bunkers (international aviation and international shipping). We apply the decomposition analysis to passenger travel and freight transport, including bunkers in these two subsectors. Figure 6 shows the decomposition results for passenger travel, and Figure 7 illustrates the energy mix. Also, Figure 8 shows the decomposition results for freight transport, with Figure 9 shows its energy mix.

Passenger Travel

In the Baseline scenario, CO_2 emissions of passenger travel increase from 4.3 Gt in 2015 to 7.6 Gt by 2050, due to the increasing travel distance per capita (contributing to 2.4 Gt emission increase), population growth (1.4 Gt emission increase), and switching to more carbon-intensive travel modes (1.1 Gt emission increase). The latter is due to a shift from public transport to car and air travel: the share of distance travelled by car increases from 39% to 47% and by air from 9% to 12% between 2015 and 2050. Efficiency improvements in cars and a shift to more electric cars partly offset the increases in emissions due to the above factors, contributing to a 1.7 Gt emission reduction.

There is a large difference between the OECD and non-OECD regions. In the OECD region, CO_2 emissions decrease in the Baseline scenario as the impact of the activity increase and mode shift on emissions is much smaller, also the impact of efficiency improvements is much higher than in the non-OECD region.

In the Renewable and Lifestyle 1.5 °C scenarios, CO_2 emissions decrease to 1.1 Gt and 1.3 Gt in 2050, respectively. The contributing factors to these reductions are similar for both 1.5 °C scenarios, with efficiency and CO_2 intensity improvements (mainly electrification) having the most impact. Electrification is a crucial aspect because passenger cars are responsible for the lion's share of energy demand. The electricity share in total passenger travel increases to 65% in 2050 in the Renewable scenario and 49% in the Lifestyle scenario (Figure 7). Mode shift contributes strongly to emission reduction in the 1.5 °C Lifestyle scenario as well. This is mainly due to a shift away from flying (share of total travel distance from 9% in 2015 to 5% in 2050, compared to 12% in baseline in 2050) and bus (from 26% to 20%) to train (from 6% to 16% share of travel distance).

Perhaps counterintuitively, the impact of activity reduction on emissions is lower in the Lifestyle scenario than in the Renewable scenario—even though total passenger kilometres are less in the Lifestyle scenario. The reason for this is that the travel modes are more emission-intensive (due to less electrification) in the Lifestyle scenario than in the Renewable scenario (Figure 7).

In the non-OECD region, energy efficiency improvement of cars and buses (relative to Baseline) is a more important contributing factor for emission reductions than in the OECD region.

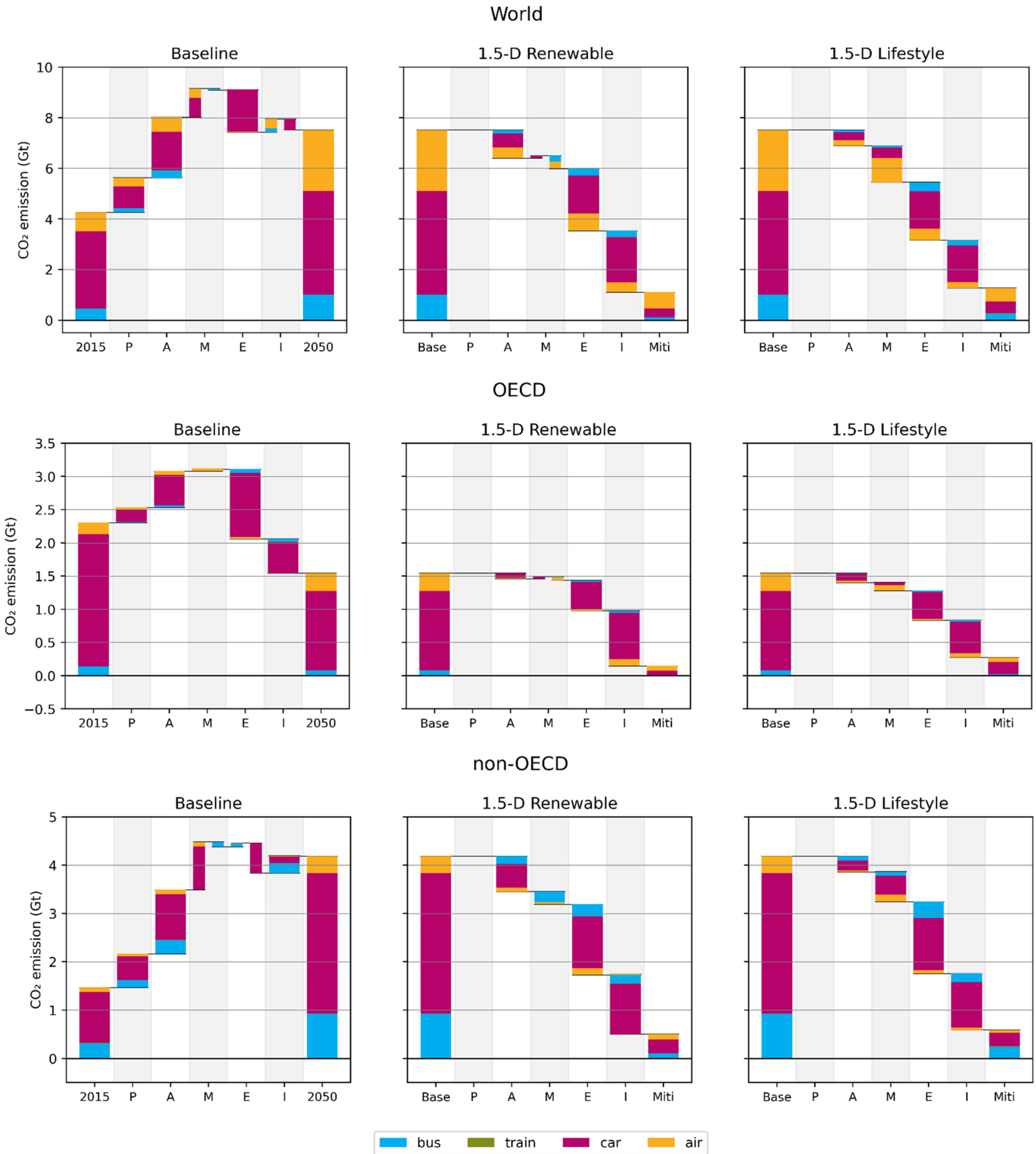

Figure 6. Changes in passenger travel emissions between 2015 and 2050 (Baseline) and between the Baseline and mitigation scenarios (in 2050) due to different drivers. P: population; A: activity; M: mode shift, E: efficiency, I: carbon intensity (includes the impact of electrification). Emissions from international bunkers are shown in global graph only.

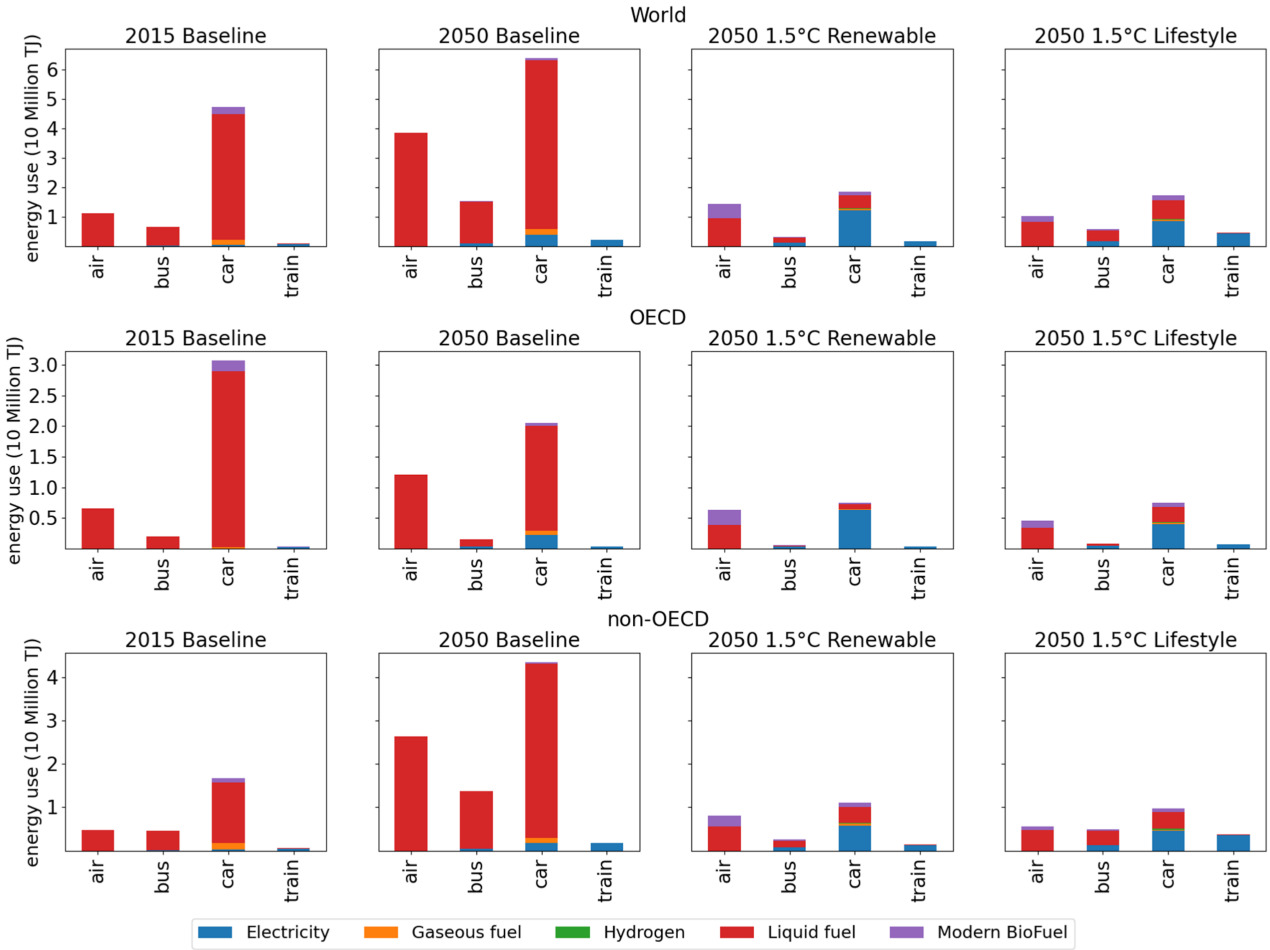

Figure 7. Energy mix by passenger travel mode.

Freight Transport

CO_2 emissions from freight transport are projected to increase strongly in non-OECD countries and decrease in OECD countries in the Baseline, leading globally to a small total increase by 2050. The increase in activity levels, mainly from trucks, is almost completely offset by efficiency improvements of these trucks (Figure 8). In OECD countries, CO_2 intensity improvement contributes substantially to emission reduction in the baseline, mainly due to the increase in the share of plug-in electric trucks.

In the 1.5 °C Renewable scenario, emissions are reduced to almost zero, whereas some remain in the 1.5 °C Lifestyle scenario. Switching to less carbon-intensive fuels for medium and heavy trucks is the largest contributing factor for emission reduction in both scenarios, but especially in the Renewable scenario. In 2050, 75% of truck fuel consists of hydrogen in the 1.5 °C Renewables scenario, with an additional 11% of modern biofuels and 6% electricity (Figure 9). The Lifestyle scenario has a stronger impact of efficiency in reducing emissions, but this cannot offset the stronger impact of switching to non-fossil energy in the Renewable scenario.

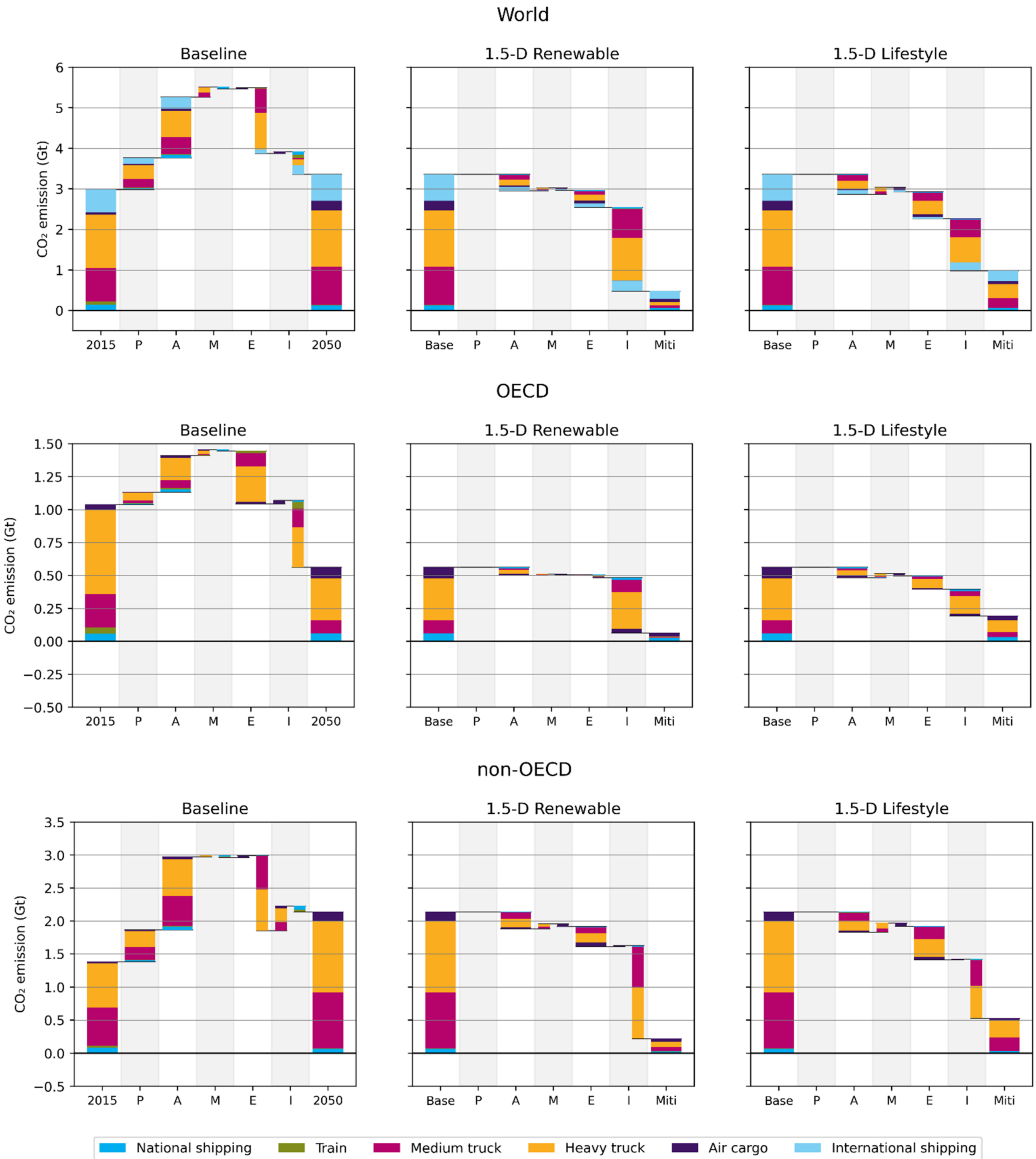

Figure 8. Changes in freight transport emissions between 2015 and 2050 (Baseline) and between the Baseline and mitigation scenarios (in 2050) due to different drivers. P: population; A: activity; M: mode, E: efficiency, I: carbon intensity (includes the impact of electrification). Emissions from international bunkers are only shown in global graph.

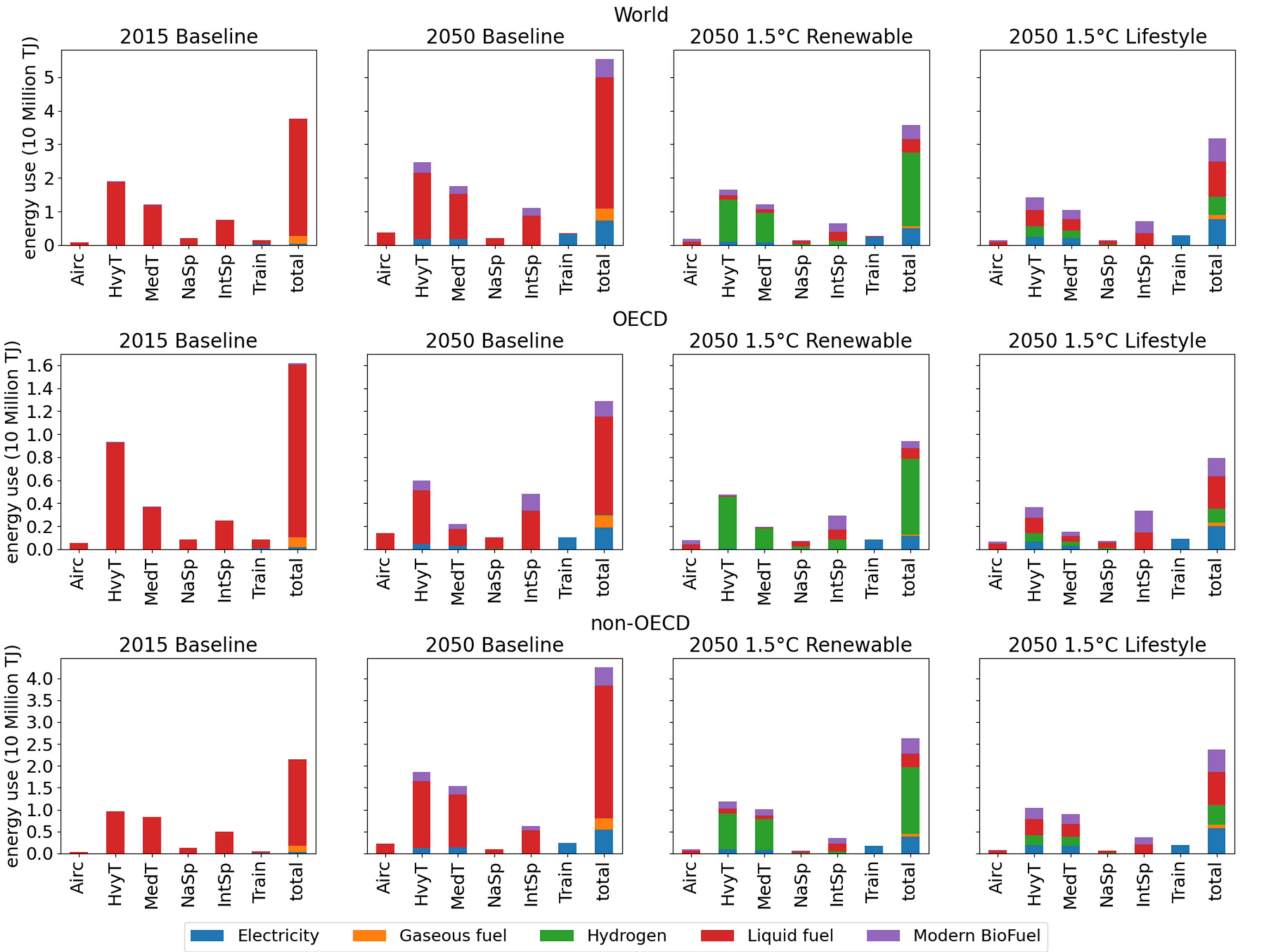

Figure 9. The energy mix of freight transport. Ship: national shipping, Train: freight train, MedT: medium truck, HvyT: heavy truck, Airc: air cargo.

3.2.4. Synthesis

Figure 10 synthesises the results of the decomposition analyses. It shows the reductions relative to the Baseline scenario caused by each factor. By far, the largest reductions take place in power generation, with renewables, CCS, and improving the carbon intensity (mainly by switching from coal to natural gas) all being major drivers. CCS is also an important contribution to emission reduction in industry.

Improving energy efficiency and electrification are the major contributors to reduce emissions in transport (note that electrification and carbon intensity have been analysed as one decomposition factor in transport—but its energy mix shows that electrification is the most important factor). Shifting to more climate-friendly modes of transport contributes significantly to reducing transport emissions in the Lifestyle scenario as well (note that emissions from international air are only visible in the global results, as these are not allocated to regions).

In all sectors, electrification plays a larger role in reducing emissions in the Renewables scenario, which is reflected by the positive effect of changes in activity on emissions from power generation in this scenario. Changes in efficiency also lead to an increase in emissions from power generation, as bioenergy has a relatively low efficiency.

While the OECD and non-OECD regions overall show a similar trend, there are some important differences as well. Efficiency improvement is more important in reducing emissions in industry and transport in the non-OECD region, while electrification has a more important role for reducing passenger transport in the OECD region. Renewables have a stronger impact in reducing emissions in power generation in the non-OECD region and CCS in the OECD region.

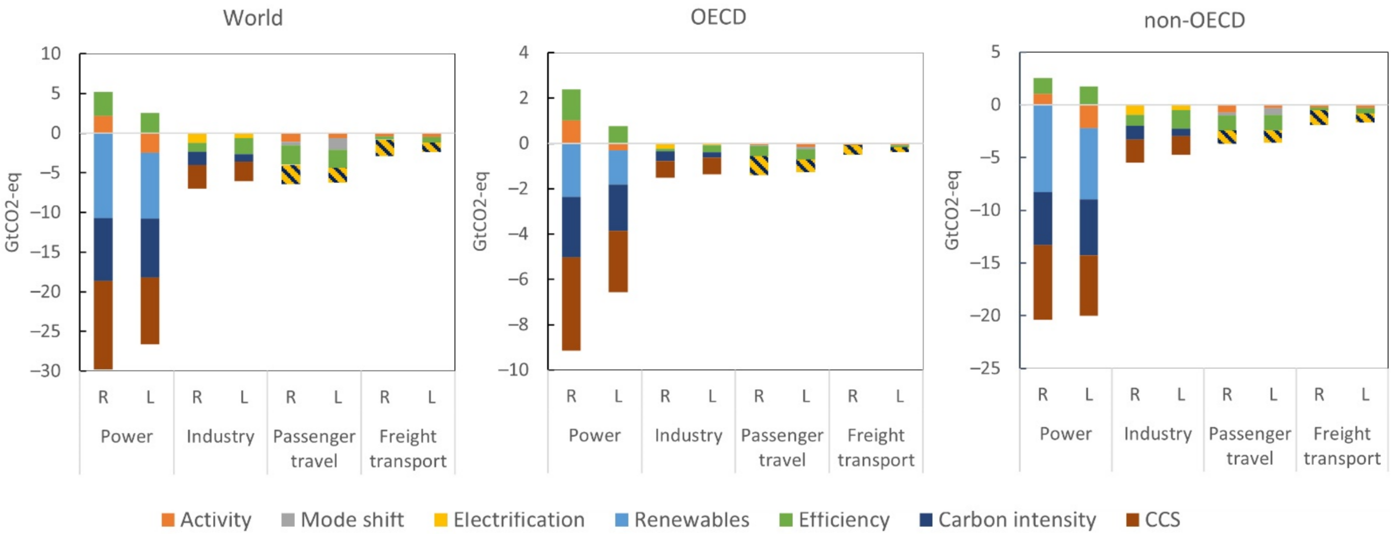

Figure 10. Changes in global emissions in mitigation scenarios by driving factor relative to the Baseline, 2050. R: Renewable, L: Lifestyle. Emissions from international bunkers are only shown in the global graph. Electrification and carbon intensity are one decomposition term in transport and therefore shown together.

4. Discussion

This study applied a decomposition analysis on the three highest CO_2 emitting sectors: power generation, industry, and transport. The IMAGE output, on which the decomposition was applied, allowed the extraction of relevant variables to decompose the changes in emissions in these sectors. However, other sectors such as land use, other energy sources, the residential sector, industrial processes, and non-CO_2 emissions also have a large potential to reduce greenhouse gas emissions. Therefore, we suggest that future work can focus on these sectors, especially the high CO_2 emitting sources such as land and other energy (including energy use for hydrogen and second heat production, biomass processing, and agriculture), to understand the factors contributing to mitigation and the possible mitigation strategies in these sectors as well.

In addition, we have applied decomposition analyses on an aggregate level for the whole industry and large world regions. For specific industry sectors (e.g., steel, cement, pulp and paper, food, and chemical industries) and regions, mitigation strategies may look very different [26]. Sectoral decomposition gives us a good overall view, but a more detailed decomposition analysis within the sector or for specific regions can be useful for more specific policy advice.

We only focused on one baseline and two 1.5 °C scenarios in this study. Other pathways may be analysed as well, e.g., 2 °C or current-policy scenarios. We have chosen to focus on 1.5 °C scenarios since we were mainly interested in how net-zero emission ambitions could be met. Future work could, for instance, focus on comparing decomposition results between 1.5 °C scenarios and current-policy scenarios, where the current-policy scenario reflects the drivers that are now being considered, and the 1.5 °C scenarios can show where the main progress can be made.

5. Conclusions

This study presents several decomposition techniques to focus on the most important contributions to emission reductions in recently developed deep mitigation scenarios and analyse the differences across scenarios, sectors and regions. Our main conclusions are as follows.

Decomposition is a useful tool for identifying the main contributions to changes in emissions in different sectors and regions, allowing easy comparison of scenarios. The analysis can easily show the largest contributions to emission reductions and compare trends across scenarios. Providing that sufficient data from the scenarios is available, this tool can also be used for other models and sectors.

CCS can play an important role in reducing emissions in power generation and industry. The IMAGE scenarios emphasise the role of renewables and lifestyle change in reducing emissions. However, CCS and especially BECCS are important drivers in reducing emissions in power generation and industry. BECCS provides the required negative emissions needed to offset remaining emissions in other sectors. This also means that if emissions from these latter sources can be reduced, the need for CCS—including BECCS—is reduced, as shown by the lower contribution of CCS in reducing emissions on the 1.5 °C Lifestyle scenario. CCS contributes more strongly to emission reductions in the 1.5 °C Renewable scenario, partly due to the relatively high electricity demand in this sector, driven by the high electrification rate.

Other technological measures are also important for reducing emissions, but their relative importance differs among the sectors. Reducing the overall carbon intensity of non-renewable fuels (switching from coal to gas and bioenergy) is an important contribution to reducing emissions in power generation and industry, while electrification is especially important in reducing transport emissions.

Efficiency improvement is an important contributing factor for reducing emissions in industry and transport. While efficiency is already improving strongly in the Baseline scenario, further improvements in the mitigation scenarios contribute substantially to emission reductions in industry and passenger travel. In power generation, changes in efficiency have an increasing impact on emissions, which is due to a switch to relatively less-efficient biomass. It is, of course, not a certainty that the efficiency improvements shown in the baseline occur without additional policies, which means that this remains an important aspect to focus on in mitigation scenarios—both for research and policymaking.

Changes in activity levels and mode shift contribute significantly to emission reductions in transport. While technology plays a strong role in reducing emissions, as the above conclusions show, lowering and changing passenger travel activity has a strong impact on reducing emissions from transport. This emphasises the importance of changing consumption patterns to reduce emissions.

While the factors contributing to emission reductions are similar in the OECD and non-OECD region, there are some crucial differences as well. These differences relate especially to the higher importance of efficiency improvement in the non-OECD region to reduce passenger travel and industry emissions. At the same time, electrification plays a more critical role in the OECD region. For power generation, renewables have a more substantial impact in reducing emissions in the non-OECD region.

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