Public finance resilience in the transition towards carbon neutrality: a computable general equilibrium analysis*

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Abstract

This paper presents a detailed economic modelling analysis of public finance in the transition towards carbon neutrality. We outline results from a Net-Zero Emission Ambition scenario, reflecting the ambition to achieve net-zero greenhouse gas emissions globally by mid-century, using a broad and region-specific policy package that combines various policy instruments: carbon pricing, removal of fossil fuel support, regulations in the power sector, and other policies that stimulate investments by firms and households to reduce and decarbonize energy use. The analysis relies on the OECD global computable general equilibrium ENV-Linkages model. Our results show that transitioning towards emissions neutrality involves relatively modest economic and fiscal consequences. The scenario achieves emissions neutrality while maintaining continued economic growth, despite a limited negative impact on global GDP (which excludes the benefits from reduced climate damages) and on public revenues. In our central scenario we find that net public revenues slightly decrease globally in 2050 (-0.5% of *Baseline* GDP). The fiscal effects reflect a trade-off between instruments that increase public revenues (carbon pricing) or reduce public expenditures (fossil fuel subsidies removal), on the one hand, and more costly instruments (subsidies) and indirect effects (tax base erosion and changes in fiscal and economic structure) on the other hand.

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1. Introduction

Most countries worldwide have committed to achieving carbon neutrality by mid- 21st century, in line with the Paris Agreement and its objective to limit global warming to well below 1.5°C by the end of the century. Achieving carbon neutrality requires substantial structural changes to the economy, including the mobilisation of significant investment to support the greening of economic activities. In the current socioeconomic context, concerns have emerged on the fiscal feasibility of achieving carbon neutrality as well as the need to ensure economic resilience to potential future disruptions.

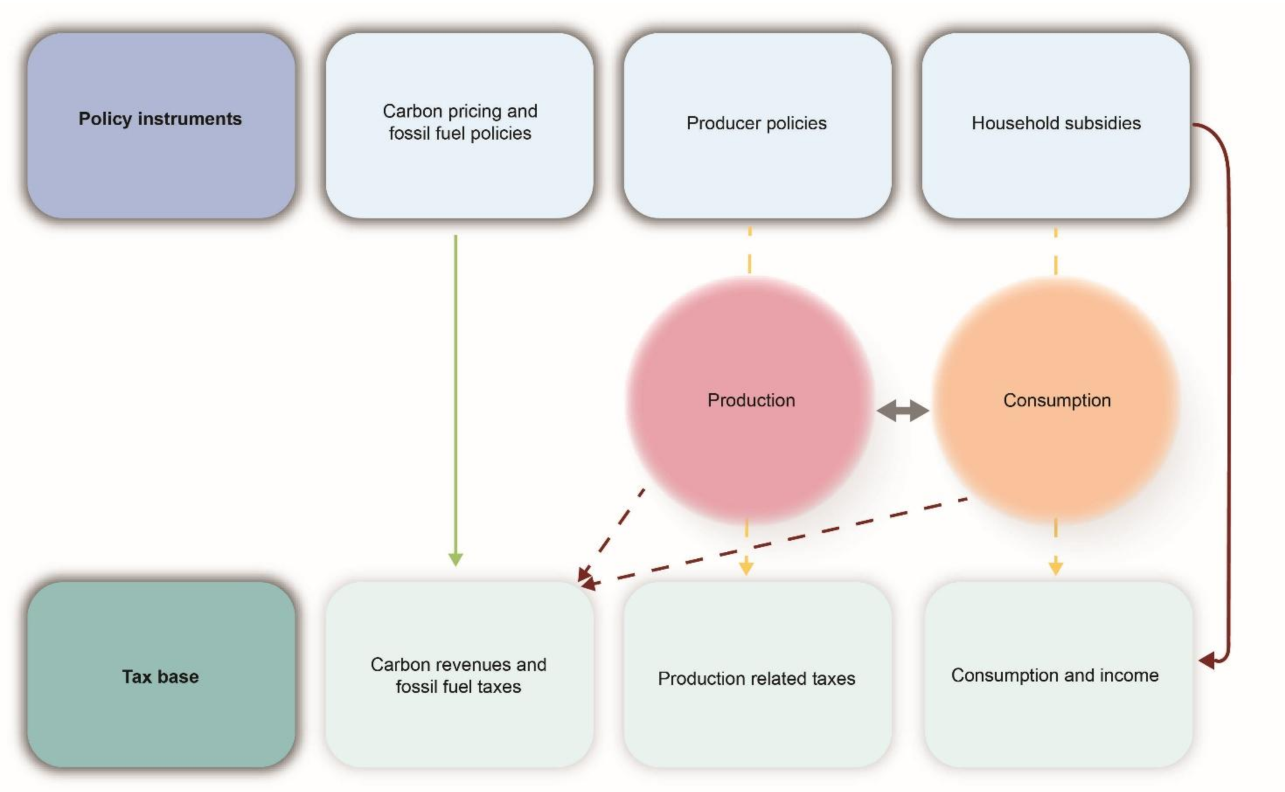
There is a large literature providing quantitative assessments of the economic consequences of climate policies and on the policy requirements of scenarios that are compatible with the Paris Agreement (Geiges et al., 2020[1]; van Soest, den Elzen and van Vuuren, 2021[2]; Rogelj, 2018[3]). Recently, the literature has focused more specifically on scenarios that aim to reach global net-zero emissions (NZE) – i.e., a situation where greenhouse gas (GHG) emissions from economic activity are balanced by carbon sequestration. The International Energy Agency (IEA, 2021[4]) was the first to provide a roadmap for achieving net-zero emissions in the energy sector. Several net-zero emission scenarios are also presented in the Sixth Assessment Report (AR6) of IPCC Working Group (Riahi et al., 2022[5]). The Network for Greening the Financial System (NGFS) presents two net-zero emission scenarios that highlight the importance of the pathway shape toward net-zero (Bertram et al., 2021[6]). A few recent studies quantified the economy-wide effects of reaching carbon neutrality (Liu, McKibbin and Jaumotte, 2021[7]; Drummond et al., 2021[8]).

One specific aspect of ambitious carbon policies is whether they significantly erode the tax base for government revenues, and whether extreme measures will be necessary for governments to ensure the continued provision of public goods. Given the expected substantial decline in revenues from energy-related taxes, this question is an important part of the transition to a carbon-neutral economy.

This paper contributes to the existing literature by providing a first modelling assessment of the fiscal resilience – or, as referred to throughout, *the effect on net public revenues expressed as a share of Baseline GDP* – of the transition to net-zero emissions, considering the need to finance new and more efficient technologies.[1] The choice of the policy instruments and their design have significant implications on public finance; while carbon taxes and (auctioned) emission trading systems directly generate public revenue, subsidies reduce available public finance. The effect of the full policy package also depends crucially on indirect effects, such as the effects of energy efficiency measures on tax revenues from fossil fuel taxation. A schematic representation of such links is presented in Figure 1.

[1] We evaluate fiscal resilience in relative rather than absolute terms and as a matter of degree (i.e., more or less resilient) rather than against a fixed threshold. Any formal indicator would ultimately be arbitrary, and our interpretation is more closely aligned with how the term is used in policy circles.

Figure 1: Schematic representation of the links between policy instruments and fiscal revenues



Notes: Green lines denote increase fiscal revenues, red lines reduced revenues and yellow lines ambiguous changes in revenues; indirect effects are denoted by dashed lines.

The paper presents a scenario analysis, focused on a *Net-Zero Emission (NZE) Ambition* scenario, which reflects the ambition to achieve net-zero GHG emissions globally by mid-century. In this scenario, all countries that have announced a commitment to achieve net-zero emissions by 2050 or later are assumed to meet their targets, while the remaining countries achieve net-zero emissions by 2060. This net-zero scenario is compared to a *Baseline* scenario which reflects policies currently in place or legislated for implementation. While many countries have adopted net-zero emission targets, there is a well-known implementation gap (United Nations Environment Programme, 2024[9]), which is taken into account in the *Baseline* scenario. Both scenarios are presented with a 2050 time horizon.

The scenario analysis is based on the OECD's global computable general equilibrium (CGE) model ENV-Linkages (Chateau, Dellink and Lanzi, 2014[10]). Using a global CGE model allows to take into account regional economic structures and policy responses, and to take into consideration international effects through trade. This type of model is also tailored to analyse the fiscal consequences of global climate policies, as it takes into account different taxation categories, while maintaining a global coverage. Compared with other similar models, such as ENVISAGE (van der Mensbrugghe, 2024[11]), GDYN-E (Antimiani et al., 2013[12]), or GTAP-E-RD (Aguiar, Corong and van der Mensbrugghe, 2020[13]), the main advantage of relying specifically on the ENV-Linkages model is its strong integration of economic, energy, and environmental processes, supported by careful calibration of its baselines with the IEA's World Energy Outlooks. Further, ENV-Linkages includes a modelling of capital vintages, which implies more realistic results on the socio-economic effects of climate policies.[2] For this project, the model covers the world in 26 regions, allowing to take into account direct and indirect effects, including through international trade.

A key methodological novelty is that, while most modelling analysis only rely on carbon pricing, the instruments considered in this paper aim to be closer to the political reality of differentiated climate policies across countries. We include also removal of fossil fuel support, regulations in the power sector, and other policies to reduce and decarbonise energy consumption by firms and households. The policies focus on reducing emissions from all major GHG sources, including transport and buildings, energy efficiency and electrification; these are modelled taking into account the costs of technology implementation and energy efficiency improvements. As a global modelling analysis, the paper stops short of providing a detailed representation of actual policies implemented by individual countries, as that would require a full stocktake which is not readily available. Furthermore, actually implemented policies often come with specific clauses that are not readily implementable in a CGE context. To model the policies on best available information, we use detailed data and projections from the International Energy Agency's Global Energy Climate Model (IEA, 2021[14]) (IEA, 2021[4]), to accurately represent both the investment needed and the corresponding changes in energy demand, therefore reflecting region-specific policy mixes.

Our results show that, without considering the reduction in climate damages and risks, the *NZE Ambition* scenario implies a slowdown of economic growth of around 0.4 percentage points per year between 2019 and 2050, leading to a 12% loss in global gross domestic product (GDP) in 2050 compared to *Baseline*. We find that net public revenues slightly decrease globally in 2050 (-0.5% of *Baseline* GDP), reflecting a trade-off between instruments that increase public revenues, not least carbon pricing, or reduce public expenditures, such as removal of fossil fuel support, and the decrease in public revenues from more costly instruments such as subsidies as well as the erosion of other tax bases. These indirect effects comprise the erosion of energy-related tax bases as well as indirect effects of the policy package on economic and fiscal structures. Revenues from production factor taxes, production taxes and consumption taxes fall below *Baseline* levels as economic growth slows down and economic activity shifts towards sectors with lower average tax rates.

Carbon pricing is also affected by such indirect effects: erosion of the different tax bases reduces by around half the potential for net public revenues from carbon pricing. Indeed, within the *NZE Ambition* policy package, carbon pricing revenues could represent 2.5% of Baseline GDP, but the erosion of other tax revenues reduces the amount recyclable – i.e., the final contribution of the carbon pricing instrument to net public revenues – to 1.1% of Baseline GDP.

[2] Additional details and comparison across models are provided in (Dellink, Van der Mensbrugghe and Saveyn, 2020[63]).

Whereas the regional changes in net public revenues in the *NZE Ambition* scenario depend on country characteristics and policy mix, every region is impacted negatively, with changes in net public revenues as percentage of *Baseline* GDP ranging from -0.1% to -3.4%. The negative impacts on public revenues are larger in the regions where investment-related instruments – as opposed to carbon pricing – constitute the largest part of the mitigation effort (e.g., OECD Americas). Furthermore, countries with an economic structure specialized in fossil-fuel production activities (e.g., the Middle Eastern region) are more at risk in the long-run both in terms of economic impacts and public finance, while countries with large fossil fuel support can reduce public spending (e.g., Africa) through their removal. Finally, countries that are projected to have stronger negative effects on economic growth (e.g., Other Eurasia) are more at risk of adverse indirect effects due lower production- and consumption-related sources of public revenues.

The rest of the paper is structured as follows. Section 2 presents the scenario design and modelling strategy, as well as the mechanisms that drive the public finance implications of the policy instruments. Section 3 presents results on emission projections and economic consequences of the net-zero emission scenario while Section 4 provides an overview of the implications of the net-zero emission scenario on public finances. Finally, Section 5 concludes with a discussion of the context in which the findings from the modelling analysis should be placed.

2. Scenario design and modelling strategy

2.1 Scenario design

Our paper presents a scenario with the ambition to achieve net-zero GHG emissions (NZE) by the middle of the century (the *NZE Ambition* scenario*)*. Both CO_2 and non-CO_2 greenhouse gas emissions are important in limiting climate change and can be subject to similar policies (IPCC, 2018[15]) and are therefore considered in this paper.[3] The *NZE Ambition* scenario includes a combination of policy instruments to achieve the necessary emission reductions.

For 2030, the scenario assumes that countries reach their Nationally Determined Contributions (NDCs) emission targets.[4] Beyond 2030, countries achieve net-zero emissions by gradually reducing their "gross" emissions to equal domestic carbon sequestration, including both afforestation, forestry and land use (AFOLU) and negative emission technologies (NETs).[5] Country-specific net-zero emission targets are therefore achieved

[3] "Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales (high confidence)" (IPCC, 2018[15]).

[4] The NDC emission targets for 2030 are based on the assessment in the Climate Watch database (Climate Watch, 2022[16]). New NDCs are not considered for coherence, as only a few countries have submitted their 2025 NDCs so far. Additional details are provided in Annex B.

[5] AFOLU sequestration projections are taken from the IMAGE model (Stehfest et al., 2014[17]; PBL, 2022[18]). NETs projections and projections of gross emission reductions obtained through Carbon Capture, Utilisation and Storage (CCUS) are from the World Energy Outlook (IEA, 2021[14]). Multiple pathways exist to reach net-zero emissions, depending on the extent countries choose to rely on

when gross emissions equal carbon sequestration. The model differentiates between three categories of countries, according to their declared NZE targets (Climate Watch, 2022[16]):[6]

- Countries that have pledged to achieve carbon neutrality by 2050 gradually reduce gross emissions to reach the domestic potential for carbon sequestration by 2050.
- Countries with a carbon neutrality pledge by 2060 gradually reduce gross emissions between 2030 and 2050 following a pathway that allows them to reach net-zero emissions in 2060.
- Countries that do not have a carbon neutrality target by 2060 (including countries that have NZE targets for later in the century) are assumed to achieve carbon neutrality jointly[7] by 2060 and gradually reduce gross emissions between 2030 and 2050 towards this target.

The emission levels corresponding to this set up are presented in Table 1, aggregated to the ENV-Linkages regions used for the modelling analysis (detailed mapping is provided in Annex A). The country-specific targets for 2050 imply that global gross GHG emission levels amount to 19.9 Gigatonnes of CO_2 equivalents (Gt CO_2e). At the same time, estimates from the IMAGE model (Stehfest et al., 2014[17]; PBL, 2022[18]) on AFOLU sequestration and World Energy Outlook (IEA, 2021[14]) on NETs indicate that total carbon sequestration in 2050 could reach 5.4 Gt. Therefore, in the *NZE Ambition* scenario global net GHG emissions in 2050 amount to 13.1 Gt.

different technology developments. The policies and measures included in this analysis rely on some technological developments, not least in the use of CCUS in power generation and industry, but do not rely on large-scale bioenergy with CCS (BECCS) or a transition to a hydrogen economy. These assumptions are chosen to strike a balance between important technological developments that are deemed plausible by experts, without overly relying on technologies that are not yet proven to be viable. Alternative pathways could be constructed that would generate different sectoral profiles of remaining emissions by 2050. Such alternatives would also affect the costs of the transition, but it is a priori unclear whether costs would be higher or lower, given the uncertainty surrounding cost developments of so-called backstop technologies.

[6] Annual targets for intermediate years (between 2019 and 2030; and between 2030 and 2050 or 2060) are obtained through linear interpolation. Hence, for regions without a 2050 target, the 2050 target derives from the linear interpolation of the 2030 NDC targets and the 2060 carbon neutrality targets.

[7] While countries with a pledge for 2050 or 2060 are assumed to meet their targets individually, for countries without targets, sequestration capacity in one country can balance out emissions in another country. In aggregate, emissions are reduced so as to achieve net-zero emissions at global level.

Table 1: Economy-wide GHG emission targets in 2030 and 2050 in the *NZE Ambition* scenario

GHG emissions, in Gigatonnes (Gt CO_2e)

<table>
<tr><th>Country/Region</th><th>2019 Emissions</th><th>2030 Emissions (NDC)</th><th>2050 Gross emissions</th><th>2050 Net emissions</th></tr>
<tr><td colspan="5">Countries/Regions with a stated NZE target in 2050</td></tr>
<tr><td>Australia and New Zealand</td><td>0.75</td><td>0.59</td><td>0.23</td><td>0</td></tr>
<tr><td>Brazil</td><td>1.23</td><td>0.71</td><td>0.51</td><td>0</td></tr>
<tr><td>Canada</td><td>0.83</td><td>0.52</td><td>0.11</td><td>0</td></tr>
<tr><td>Chile & Colombia</td><td>0.34</td><td>0.28</td><td>0.14</td><td>0</td></tr>
<tr><td>European Union</td><td>4.16</td><td rowspan="3">3.05</td><td rowspan="3">0.70</td><td rowspan="3">0</td></tr>
<tr><td>Other OECD Europe</td><td>0.86</td></tr>
<tr><td>UK</td><td>0.53</td></tr>
<tr><td>Japan</td><td>1.23</td><td>0.77</td><td>0.12</td><td>0</td></tr>
<tr><td>Korea</td><td>0.69</td><td>0.45</td><td>0.06</td><td>0</td></tr>
<tr><td>South Africa</td><td>0.54</td><td>0.29</td><td>0.06</td><td>0</td></tr>
<tr><td>United States</td><td>6.33</td><td>4.03</td><td>0.75</td><td>0</td></tr>
<tr><td>Other Southeast Asia</td><td>1.92</td><td>1.40</td><td>0.39</td><td>0</td></tr>
<tr><td colspan="5">Countries/Regions with a stated NZE target in 2060</td></tr>
<tr><td>China</td><td>14.53</td><td>12.41</td><td>5.63</td><td>4.71</td></tr>
<tr><td>India</td><td>3.98</td><td>5.36</td><td>3.26</td><td>2.71</td></tr>
<tr><td>Indonesia</td><td>1.02</td><td>0.77</td><td>0.64</td><td>0.37</td></tr>
<tr><td>Russia</td><td>2.42</td><td>2.14</td><td>0.76</td><td>0.71</td></tr>
<tr><td colspan="5">Countries/Regions with an assumed joint NZE target in 2060</td></tr>
<tr><td>Caspian</td><td>0.84</td><td>0.83</td><td rowspan="8">6.57</td><td rowspan="8">4.57</td></tr>
<tr><td>Mexico</td><td>0.78</td><td>0.52</td></tr>
<tr><td>Middle East</td><td>3.24</td><td>3.60</td></tr>
<tr><td>North Africa</td><td>0.92</td><td>0.87</td></tr>
<tr><td>Other Latin America</td><td>1.36</td><td>0.90</td></tr>
<tr><td>Other Africa</td><td>1.97</td><td>2.23</td></tr>
<tr><td>Other Asia</td><td>1.42</td><td>1.55</td></tr>
<tr><td>Other Europe</td><td>0.56</td><td>0.40</td></tr>
<tr><td>World</td><td>52.4</td><td>44.1</td><td>19.9</td><td>13.1</td></tr>
</table>

Notes: Authors' computations based on Climate Watch (2022[16]) for 2030 and NZE commitments, and sequestration in 2050 based on IMAGE dataset (Stehfest et al., 2014[17]; PBL, 2022[18]) and IEA (2021[4]).

The *NZE Ambition* scenario is compared to a reference *Baseline* scenario with much lower ambition on climate change. The *Baseline* scenario incorporates policies that were implemented by 2021[8] as well as policies that were by then already legislated but not yet implemented.[9] For instance, for the European Union, the *Baseline* includes the EU Emissions Trading Scheme (ETS), including the proposed revisions for the Fit-for-55 package. There is no guarantee that the policies implemented and legislated will meet the NDC targets by 2030. Therefore, the *Baseline* includes the policies until 2021 that support the targets but not the targets themselves.

[8] The cut-off date for the *Baseline* policies derives from IEA's World Energy Outlook 2021.

[9] Some jurisdictions have enacted climate policies after the publication of the World Energy Outlook 2021, such as the Inflation Reduction Act in the United States of America. These climate policies have not been included in the baseline.

Updates in NDC targets[10] since 2021 as well as additional policies needed to reach the target are accounted for in the *NZE Ambition* scenario.

In the *Baseline* scenario, the global economy gradually becomes less energy- and fuel-intensive over time but remains far off meeting the NZE ambitions. Following the OECD long-term economic projections (Guillemette and Turner, 2021[19]), the *Baseline scenario* reflects sustained global economic growth over time, with gross domestic product (GDP) growing faster in non-OECD countries.[11]

Both scenarios are developed in the OECD ENV-Linkages dynamic global Computable General Equilibrium (CGE) model (see Annex A), with a 2050 time horizon. The main advantage of using a CGE model is that, exploiting its sectoral and regional dimensions, the analysis can consider both the economy's supply and demand side, capturing the overall economy-wide effect of policies. Furthermore, thanks to the sectoral details and the specification of government accounts, CGE models allow for a detailed calculation of the various components of public budgets and thus an evaluation of the direct and indirect impacts of policies on the fiscal space. When studying the impacts of climate policies, CGE models typically focus on fiscal policies only. However, for this project, ENV-Linkages has been extended to represent a wider set of policy instruments.

2.2 Policy instruments in the NZE scenario

Governments have a wide array of policy instruments they can use to achieve emission reductions. This paper focuses on six key policies to decarbonise the economy, which were chosen because (i) they reach all key sources of GHG emissions,[12] and (ii) they contain some of the most widely used instruments available to governments to reach net-zero emissions.[13] The instruments considered are:

- Carbon pricing;
- Fossil fuel support removal (FFSR);
- Regulations in the power sector to enforce a switch away from fossil fuels;
- Regulations to stimulate investments to decarbonise building and transport emissions;
- Policies to stimulate firms' energy efficiency improvement;
- Subsidies to reduce and decarbonise energy consumption by households.

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[10] The cut-off date for NZE Ambition NDCs is November 2022.

[11] The *Baseline* policy and energy- and fuel-intensity changes are derived from the Stated Policies Scenario (STEPS) from the International Energy Agency (IEA)'s World Energy Outlook (IEA, 2021[14]). More information on the *Baseline* calibration is provided in Annex A.

[12] All GHG emissions from fossil combustion, agriculture, process emissions and fugitive emissions are covered by the policy package (including carbon pricing).

[13] As discussed in the introduction, they do not reflect all current policies, not least because the ambition level of the scenarios investigated here go beyond what is reachable with current policies only.

Concerning the fiscal consequences, policy instruments that directly affect prices, i.e., carbon pricing, fossil fuel support removal and subsidies to decarbonise household consumption, imply a direct change in taxes and subsidies imposed by government. Other instruments, i.e., those inducing decarbonisation of the power sector and other production sectors, do not have a direct effect on taxes or subsidies, but do indirectly effect these by influencing economic activity and demand in these sectors. In the modelling set up, the treatment of the costs of decarbonisation through regulations differs across the agents. For firms, extra investments to comply with the regulations correspond to an increased intermediate consumption through reduced input efficiency, hence not increasing the capital stock of the economy.[14] For households, these costs correspond to an increased final demand, through a subsidy with no preference change. This increased final demand represents the economic activity that is associated with the decarbonization.

Since our paper presents a global analysis, the policy package and regional differentiations are stylised and rely on the information available at global level. First, regulations and household subsidies are modelled in linking the ENV-Linkages model with the Global Energy Climate Model (GECM) of the IEA (IEA, 2021[14]; IEA, 2024[20]) to represent the sectoral investment needed to achieve a cleaner energy mix and higher energy efficiency, as well as the corresponding changes in energy demand to decarbonise energy production and use (Chateau, Magné and Cozzi, 2014[21]). Second, fossil fuel support measures are removed, with effects that vary by region according to the current levels of reliance on fossil fuel support. Finally, carbon pricing is used to ensure the achievement of emission targets, with the level of carbon pricing being adjusted to reach the *NZE Ambition* scenario targets for 2030 and 2050 described in Section 2.1. Therefore, regions rely more on carbon pricing if the ambition of the other policy instruments is more limited.[15] Carbon revenues from carbon pricing are used to finance the transition, including the costs of increasing energy efficiency and subsidies for cleaner technologies, although carbon prices are determined by the emissions target and not by the fiscal impacts. More details on the modelling approach are provided in Annex B.

The degree to which each of these instruments is used varies by region and depends on their domestic circumstances: (i) their level of emissions by source, (ii) the required economy-wide emission reductions, (iii) the feasibility of decarbonising each sector, including investment requirements, and (iv) to a certain extent, institutional constraints and preferences. While political considerations (including speculations on future changes in preferences) are not included in determining the portfolio of instruments used in the package, the calibration of the policy package depends on available data on current policies, for each region, which do reflect regional preferences for different types of instruments (e.g. pricing vs non-pricing). More specifically,

[14] This modelling approach indirectly assumes that investment decisions are not affected by political economy issues, such as policy uncertainty.

[15] This has the advantage of leading to the least distortions and avoiding excessive costs.

as the ENV-Linkages model is linked to the IEA's GECM model, it benefits from the extensive data collection on policy instruments underpinning the IEA scenarios (IEA, 2024[20]).[16]

Technical and technological changes are taking into account in the development of the scenarios, by reflecting the changes in energy mix and energy efficiency from the IEA (IEA, 2021[14]). While there is no explicit modelling of investments in Research and Development (R&D) and their impacts on innovation and technologies, the calibration of the scenario reflects fuels and technologies that are either already commercially available or at a relatively advanced stage of development, with declining costs over time, following learning curve approaches (IEA, 2024[20]).

Carbon pricing

In the *NZE Ambition* scenario, we assume that countries with an NZE target in 2050 or 2060 to implement an emission trading system matching the chosen emission pathway, covering both CO_2 and non-CO_2 emissions, and both combustion, process and agriculture emissions. For these regions, carbon prices differ across regions as the carbon price level is chosen to meet the region-specific emission reduction.[17] In regions composed of countries without an NZE commitment, emission targets are instead integrated in the *NZE Ambition* scenario as a single emission trading system that ensures that the joint emission reduction target is met.[18] Thus, these regions share a common carbon price. In both cases, emission permits are assumed to be auctioned by the government rather than grandfathered to existing emitters.[19] In the *NZE Ambition* scenario, we allow carbon pricing covering all sectors of the economy, including GHG emissions from agricultural sectors (including energy- and agricultural processes emissions like manure management and enteric fermentation, but excluding land use change emissions), process and fugitive emissions.

Carbon pricing increases the price of energy used in production and consumption based on carbon content of the energy sources, i.e., fossil fuel use. This additional pricing of fossil fuel inputs leads to higher prices of emission-intensive commodities. This induces (i) an increase in expenditures in all sectors to improve energy efficiency, insofar the increase in expenditures is lower than the avoided carbon price payments associated

16 As outlined in the GECM model documentation (IEA, 2024[20]), IEA policy tracking efforts include the IEA's Energy Policy Inventory, a unique database on the current state of energy policy worldwide, tracking regulations, government spending programmes and trade policies, along with information on carbon capture, utilisation and storage (CCUS), methane abatement, hydrogen and critical minerals policies. This policy information is collected by the IEA from governments, partner organisations and IEA analysis. As such, the aggregate IEA projections have been prepared considering country-specific policies during the model preparation.

17 If the target is met even without carbon pricing (e.g., if other policy instruments trigger sufficient mitigation) the carbon price remains at *Baseline* levels and emissions can be lower than the target. This however only occurs temporarily before 2050, so that in that year all emissions are covered by a carbon price.

18 In this joint carbon market, all revenue from domestic emission taxation accrues the domestic public budget, and there is no trading across regions.

19 In reality, many countries include exemptions, free allowances or e.g. payment thresholds in their design of a carbon pricing mechanism. Such considerations imply both a lower average price paid and lower emission reductions, as the scope of the pricing scheme is diminished. Thus, the effective carbon price is lowered (OECD, 2023[37]). In the modelling simulations below, the carbon price included reflects this effective rate, not the nominal rate before exemptions, etc.

with the energy use, and (ii) a shift in demand away from these commodities towards less emission-intensive commodities.[20] These substitution effects away from carbon-intensive energy sources in turn affect the price of fossil fuels, and lead to adjustments of energy supply. Carbon price also triggers abatement in non-combustion emissions, with the cost of mitigation being paid as an iceberg cost, and the cost and level of abatement following marginal abatement cost curves gathered from the literature (see Annex A). The levels of carbon price by region, as adjusted by the model to reach emission targets in 2030 and 2050, range between USD 0 and USD 778 across ENV-Linkages regions in 2050. Although carbon prices as well as other instruments differ widely between regions, they do not trigger any leakage in the *NZE Ambition* scenario, as emissions are capped for all global regions. Thus, any carbon leakage that might be triggered in a specific sector will be fully compensated by emission reductions in other sectors to ensure total emissions do not exceed the emission cap.

Fossil fuel support removal

We consider two kinds of support on fossil fuel: (i) subsidies to the production of fossil fuels (extraction and transformation) and to power generation from fossil fuels, and (ii) subsidies to fossil fuel consumption (consumption by households and firms). We construct the level of subsidy to fossil fuel production and consumption to be phased out using data from both fossil fuel support from the OECD Inventory of support measures for fossil fuels (OECD, 2022$_{[22]}$) and subsidies data from the IEA Fossil Fuel Consumption Subsidy Database (IEA, 2021$_{[23]}$). Starting from these databases, all support is assumed to be a subsidy, which the modelling approach separates from total production and consumption taxation available in the GTAP database (Aguiar et al., 2019$_{[24]}$). The corresponding levels of net tax rate (tax minus subsidy) on fossil fuel consumption and production are provided in Annex B.

Phasing out fossil fuel support by 2030 results in an increase of the producer price of extracting or transforming fossil fuels, the producer price of generating power from fossil fuel sources and the end-user price of fossil fuels to consumers (both due to increases in producer prices and decrease in support to fossil fuel consumption). Overall, fossil fuel support removal leads to a reduction in emission-intensive energy demand,[21] thus mitigating GHG emissions.

[20] For fossil fuel combustion emissions, the carbon price increases the price of energy depending on the CO_2 emission factor of the fossil fuel commodity: the additional cost is therefore the highest for coal, while it is lower for gas. For industrial process emissions, as well as for fugitive emissions, the emissions are linked to the production level instead of the fossil fuel content. The carbon price therefore acts as an incentive to deploy end-of-pipe type mitigation actions, where emissions per unit of output can decrease at the at the cost of a lower productivity (more inputs and factors are needed to produce the same amount of output). As such, mitigation actions are implemented as long as their productivity cost is lower than the carbon price. The relation between carbon price, emissions abated, and corresponding costs is calibrated based on the mitigation potentials in each sector responsible for process CO_2 emissions (see Annex B).

[21] On the contrary, the phasing-out of subsidies to electricity consumption could lead to adverse effects such as slowing down electrification. For this reason, they are not included in the *NZE Ambition* scenario.

Regulations in the power sector to transition away from fossil fuels

Regulations in power generation include the phase-out of coal power as well as a transition towards renewables energy (wind, solar, hydropower, and other renewables) and a stronger reliance on nuclear power. To achieve this shift, power companies increase their demand for construction, electric equipment, and other manufacturing goods, reflecting the investments in building up generation capacity. Due to the imposed shift in the power mix, total emissions from power generation decline.

The resulting level of additional investment, elaborated in Annex B, represents costs for producers. Due to inertia in the economy and the long-lasting nature of durable goods that cause emissions, these investments in low-carbon technologies will have to be ramped up quickly, with a peak by 2030, to ensure sufficient emission reductions by 2050.

Regulations to stimulate firms' investments to decarbonise building and transport emissions

We include specific policies in the *NZE Ambition scenario* to represent the actions necessary to achieve the decarbonisation of emissions related to the use of transport and buildings in production sectors. They include for instance requirements for the refurbishment of commercial buildings or bans on combustion vehicles. We modelled them by imposing an increased investment by firms in low-carbon alternatives to decrease emission intensity and to electrify their energy mix (see Annex B).

For transport, the regulations increase the demand for more efficient transport equipment (including electric vehicles) and electric equipment, shifting energy demand away from fossil fuels. For buildings, regulations target emissions from commercial buildings by improving energy efficiency, increasing demand for construction and appliances while shifting from fossil fuels to electricity.

Policies to stimulate firms' energy efficiency improvement

The policy package includes policies to stimulate the improvement in energy efficiency in the production of goods and services. The policy cost of these energy efficiency improvements is not included in the model, and these are not linked to a specific policy instrument. Rather, they are assumed to be the result of government stimulus actions such as information campaigns, green public procurement, as well as from increased awareness of energy use in production. However, public budgets are impacted indirectly by the consequences of these instruments on energy-related fiscal bases.

Subsidies to reduce and decarbonise energy consumption by households

Subsidies to households to stimulate energy efficiency and switch towards less polluting energy sources (such as from combustion engine to electric vehicles) are modelled in a way that is similar to the policies to decarbonise firms' transport or buildings in that they combine increased use of low-carbon alternatives and decreased emission intensity. However, for households, the increased expenditure for low-carbon alternatives is stimulated by government subsidies.[22] Thanks to the subsidies, households' increased expenditures on housing costs (new buildings and refurbishments, electric equipment), transport equipment and transport services (see Annex B) are (partially) compensated by the government.[23]

2.3 Modelling the fiscal consequences of the NZE Ambition policy package

The fiscal implications of the various instruments vary widely. The fiscal space for every region is depicted in this paper as net public revenues, i.e., the difference between tax revenues and subsidy expenditure. This excludes for example rents from extraction of fossil fuels accruing to governments.[24] The detailed description of production and consumption activities in the ENV-Linkages model can be used to distinguish different sources of changes in net public revenues, relying on its base year data, which is calibrated using the GTAP database (Aguiar et al., 2019[24]):

- Carbon revenues, i.e., carbon taxes and revenues from the auctioning of emission permits;
- Net revenues from taxes and subsidies on production and consumption of *fossil fuels*, i.e., those levied on extraction, processing and consumption of fossil fuels as well as on power generated from fossil fuels, including e.g. fuel excise taxes;
- Net revenues from taxes and subsidies on *production* activities, other than fossil fuels;
- Net revenues from taxes and subsidies on *consumption*, other than fossil fuels;
- Net revenues from taxes and subsidies on *production factors*, including capital and labour;
- Net revenues from taxes and subsidies on *income*, including income transfers to households;
- Net revenues from taxes and subsidies on imports and exports (*trade*).

The impact on net public revenues is different from the impact on public deficit because governments also have other expenditures such as government final demand or direct public investment. In ENV-Linkages, public deficit is imposed exogenously based on macroeconomic projections (Guillemette and Turner, 2021[19]; OECD, 2022[25]) and remain by assumption identical in the *Baseline* and *NZE Ambition* scenario. This exogenous government (in)balance is ensured by the government closure rule, which in the *NZE Ambition* scenario is based on a lump-sum transfer to households:[25] if government net revenues increase, then households

[22] In reality, small businesses are often also eligible for such subsidies, but this could not be captured in the modelling framework.

[23] The subsidy rates are chosen such that they trigger the required amount of investment by households. This means that the cost of these investments is not fully covered by the subsidy.

[24] In the model, the assumption is made that all primary production factors are owned by households rather than government.

[25] Several alternative closure rules can be used in the model, such as through labour taxes or income taxes (the latter is used by default in the *Baseline* scenario). Lump-sum transfers have been chosen because they are non-distortive policies with limited implications on net public revenues, therefore simplifying the interpretation of results. Conversely, using e.g., labour taxes as a closure rule would prevent from interpreting the results on net public revenues.

will benefit from an additional transfer. Consequently, the impacts on net public revenues discussed in Section 4 can be understood as pressures on public budgets exerted by the transition to carbon neutrality rather than an impact on public deficit.

We summarise in Table 2 the main expected direct (change in tax or subsidy rate) and indirect effects (change in tax base at constant rate) of the policy instruments on the fiscal space. Besides the direct effects of the various policies on the various income and expenditure sources of the government, there are significant indirect effects. Perhaps most importantly, any policy that reduces energy use without increasing taxes on energy or CO_2 emissions will lower public revenues from energy taxes. But indirect effects extend beyond the energy sector: any change in sectoral production levels from the policy will change tax payments (in absence of any change in tax rates). These indirect effects have no straightforward direction: for instance, if an economic activity with higher production tax rates is favoured by the policy, then some additional revenues will accrue to public budgets. Conversely, if the policy lowers labour demand, then revenues from labour taxation will decrease. Consequently, a modelling exercise is needed to assess the order of magnitude of the direct effects of climate mitigation policies, and to assess the direction and magnitude of indirect effects. The overall effect on the government fiscal space is therefore the result of the full economic consequences of the policy package and requires a large-scale model like ENV-Linkages to assess numerically.

Table 2: Key effects of the policy instruments on fiscal space, compared to a no-policy Baseline scenario – ex-ante evaluation

Policy instrument Tax base	Carbon pricing (auctioned emission permits)	Fossil fuel support removal	Power sector decarbonisation regulations	Building and transport decarbonisation regulations	Firm's energy efficiency improvement policies	Subsidies to decarbonise household consumption
Carbon	+ (direct)	- (indirect)	- (indirect)	- (indirect)	- (indirect)	- (indirect)
Fossil fuels	- (indirect)	+ (direct: reduced subsidy expenditures)	- (reduced demand for energy)	- (reduced demand for energy)	- (reduced demand for energy)	- (reduced demand for energy)
Production (other than fossil fuels)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)
Consumption (other than fossil fuels)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	- (direct)
Production factors	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)
Income	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)
Trade	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)	? (indirect)

Notes: (1) The effects of specific instruments compared to a scenario where only carbon pricing is used to meet the objectives would be different. Specifically, indirect effects would be compared to a different scenario and could thus change in magnitude and potentially even in sign. A typical example is the effect of regulations through reduced demand for energy – a carbon pricing only scenario would also provide such demand reductions, leaving less or no space for regulations to further reduce demand when they are added to the policy mix; (2) All cells with direct effects are also affected indirectly. For example, fossil fuel support removal directly reduces fuel subsidy expenditures, but the resulting effect on energy use affects energy tax revenues indirectly. As these indirect effects tend to be (considerably) smaller than the direct effect, these are not made explicit in the table.

The choice of policy instrument, as well as specific design features, can significantly affect the implication of the policy on the fiscal system, even if the effects on economic activity and emissions are the same. For example, carbon pricing, through carbon taxes or auctioned emission permit trading, adds a revenue to public budgets. If the emission permits are, however, distributed for free, the value of the permits gets transferred to the polluters and public revenues are unchanged. Similarly, achieving energy efficiency improvements through subsidies puts a drain on the fiscal space whereas information and awareness campaigns do not (apart from the minor policy implementation costs associated with such campaigns).

3. A pathway to carbon neutrality

This section presents the emission and economic outcomes of the *NZE Ambition* scenario. We first describe the *Baseline* trajectory to establish the counterfactual, then show how the policy package achieves net-zero emissions, and finally quantify the macroeconomic costs of the transition.

3.1 The Baseline scenario makes it challenging to reach net-zero emissions

The *Baseline* scenario projects a steady increase in gross GHG emissions, reaching 71 Gt in 2050[26] compared to 52 Gt in 2019 (Figure 2, Panel A). While combustion CO_2 emissions continue to represent the largest share, emissions from other GHGs and from industrial processes increase more rapidly over time. This increase in GHG emissions implies an increase in the global average surface temperature of around 2.3°C in 2050 compared to pre-industrial levels (compared to e.g., +1.2°C in 2019), as estimated using the MAGICC climate model.[27] Continuing this trend to the end of the century would imply a temperature increase of at least 3.4°C in 2100, and possibly up to 5.5°C, with an expected increase of around 4.2°C (Figure 2, Panel B), depending on how sensitive the climate is to an increase in concentrations of GHG (climate sensitivity).[28]

The projected increase of the global average temperature in the ENV-Linkages *Baseline* echoes the results of the latest IPCC scenarios with fairly high radiative forcing (IPCC, 2022$_{[26]}$), which would result in high climate damages as well as an increase in the risks of reaching large-scale tipping points in the global climate, such as the disintegration of the Greenland and West Antarctic Ice Sheets, permafrost collapse, and the breakdown of

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[26] The *Baseline* scenario is aligned with OECD expertise but uses some information from the STEPS scenario from the WEO 2021. The *Baseline* differs significantly from the IEA projections in terms of macroeconomic and sectoral assumptions, i.e. both the scale of economic activity and the structural change in the economy are not based on IEA scenarios but on OECD expertise. Only power generation and households' energy demand are directly calibrated on the STEPS scenario; and for transport services, only the energy mix is calibrated and not activity level, as that is assumed to follow the structural economic projections. Importantly, for industrial sectors the *Baseline* scenario is more conservative on energy efficiency improvements, and for transport the projected activity levels are significantly higher. Consequently, *Baseline* emissions in 2050 in ENV-Linkages are clearly different from emissions in the WEO's STEPS scenario.

[27] This corresponds to the 1850-1900 average. Temperatures are simulated using MAGICC 7 live, reporting median temperature as well as 5^{th} and 95^{th} percentile of the climate sensitivity.

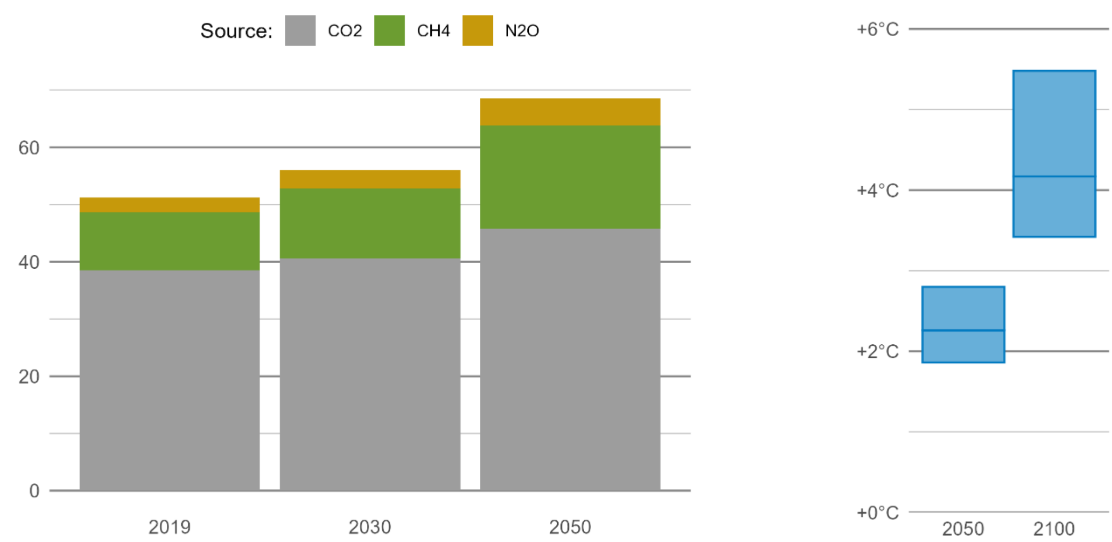
[28] Additional information on the *Baseline* scenario, including how it compares to other reference scenario, sectoral changes and regional economic growth, is presented in Annex F.

the Atlantic Meridional Overturning Circulation, among others. These damages can result in high socio-economic costs (Dietz et al., 2021[27]; Dietz and Koninx, 2022[28]; Cai and Lontzek, 2019[29]) and in an additional demand for public finances to adapt and mitigate the adverse effects of climate change (de Mello and Martinez-Vazquez, 2022[30]).

Figure 2: The *Baseline* scenario projects an increase in GHG emissions that is expected to exceed 2°C by 2050 and could lead to 3.4-5.5°C in 2100

Panel A. Global GHG emissions, excluding LULUCF (Gt CO_2e)

Panel B. Global average surface temperature increase compared to 1850-1900 (°C)



Notes: LULUCF stands for Land use, land-use change and forestry. Error bars in Panel B represent the 5th and 95th percentiles of the climate sensitivity in 2100.

3.2 Emission reductions and sequestration in the NZE Ambition scenario

Our *NZE Ambition scenario* achieves significant reductions in GHG emissions, with gross emissions reaching 19.9 Gt CO_2e in 2050 (Figure 3).[29] These gross emissions are partly offset by carbon sequestration thanks to afforestation and other land-use (AFOLU) as well as Negative Emission Technologies (NETs)[30] so that "net" (i.e. including sequestration in carbon sinks) GHG emissions in 2050 amount to 13.1 Gt; on track to achieve net-zero emissions in all regions before 2060. The corresponding increase in global average temperature, as estimated using the MAGICC climate model, attains 1.9°C by 2050 (confidence interval: 1.5 – 2.4°C) and

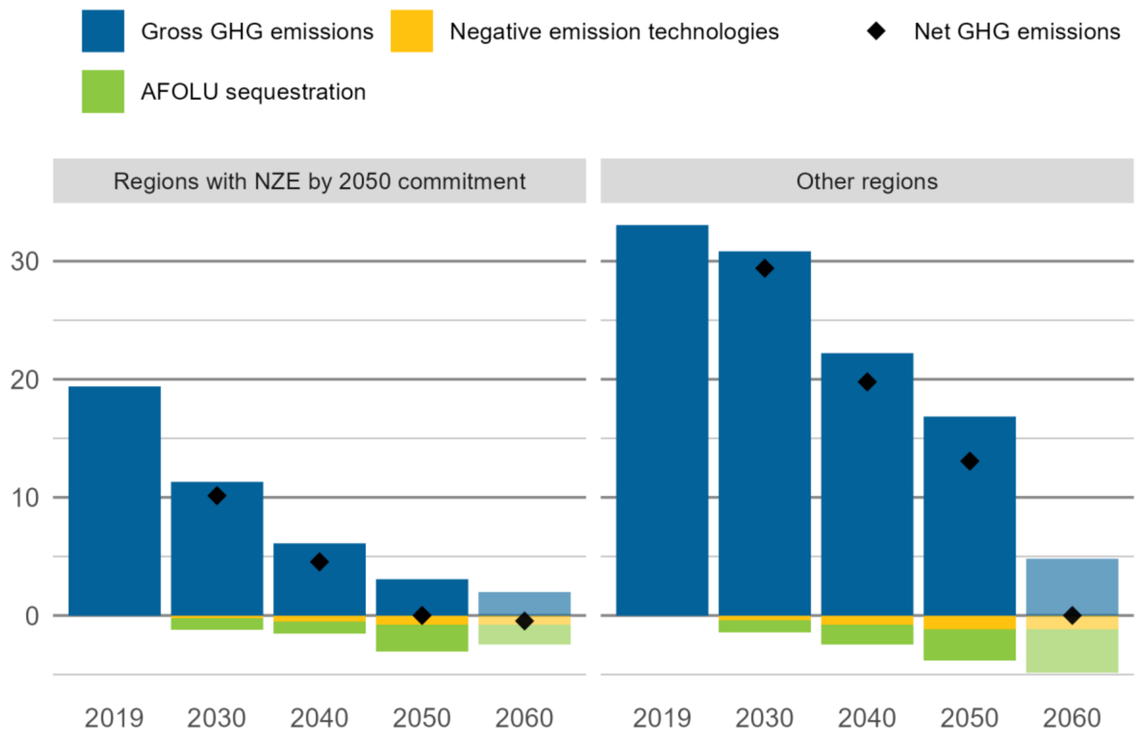
[29] Furthermore, 5.7 Gt of possible CO_2 emissions are avoided thanks to the increased use of Carbon Capture, Utilization and Storage (CCUS). CCUS is not modelled explicitly and happens at zero cost, so it could not be considered as a policy instrument *per se*.

[30] Negative Emission Technologies (NETs) considered here are defined after the IEA NZE scenario and include for Bioenergy with carbon capture and storage (BECCS) and Direct air capture with carbon capture and storage (DACCS). They are not modelled explicitly and happen at zero cost.

peaks around the same level in 2059. Temperature is projected to reach 1.3°C by 2100 (interval: 1.0 – 1.9°C), thus remaining below 2°C and possibly 1.5°C, apart from a short period in the middle of the century.[31]

Figure 3: Gross and net GHG emissions steadily decline in the *NZE Ambition* scenario

Emissions and sequestration of GHG in the NZE Ambition scenario (Gt CO_2e)



Notes: The modelling exercise only considers years up to 2050. Data on carbon sequestration is from the IMAGE model (Van Vuuren et al., 2021[31]).

We find that most emission reductions result from the decarbonisation of the energy system. A decrease in the energy intensity of the global economy and a reduction of global economic output also contribute to emission abatement. Overall, the *NZE Ambition* scenario implies a strong shift away from fossil fuel-intensive sectors. All regions participate in the emission reduction efforts, with higher reductions in large emitters and smaller in countries with large carbon sinks (e.g. countries with extended forest areas).

3.3 Most economic costs of the net-zero transition come after 2030

While the global economy keeps growing over time, the *NZE Ambition* scenario results in a slowdown of GDP growth, both between 2019 and 2030 and between 2030 and 2050. The average global GDP growth rate goes from 2.4% per annum in the *Baseline* between 2019 and 2030 to 2.2% and decreases from 2.1% between 2030

[31] The temperature increase estimates are calculated with the MAGICC 7 model, based on OECD ENV-Linkages model GHG emission projections, using SSP1-1.9 scenario for other emissions and trajectory after 2050. The ranges represent the 5th and 95th percentiles of the climate sensitivity in 2100.

and 2050 in the *Baseline* scenario to 1.6% in the *NZE Ambition* scenario. This leads to a reduction of global GDP compared to *Baseline* by 2.9% in 2030 and 12% in 2050. These "macroeconomic costs" need to be put into context as they exclude avoided climate damages, particularly reduced risks of climate tipping points, which could not be quantified in this paper, as well as important co-benefits from emissions reductions as for example on health. They also result from the chosen modelling framework, which employs conservative assumptions on future technological options to reduce emissions and in which, by design, the required investments crowd out other productive investments rather than adding to the capital stock, and so do not generate offsetting growth.

The increasing economic costs post-2030 highlight the insufficient ambition of the NDCs in 2030 to set the world on the path to NZE by the middle of the century. They also reflect the considerable inertia in the economic system: a portion of future emissions are already tied up ("committed") in the energy requirements of existing long-lasting durable goods, such as houses, transport equipment and heavy machinery, and are thus hard to abate. Overcoming these "baked in" emissions requires a steady policy signal and long-term planning. If investments made in the coming ten years are not climate-friendly, there will be a large amount of "stranded assets", i.e., fossil-fuel based power plants and durables with high emissions footprints incompatible with net-zero targets. The costs used in this paper assume that investors foresee future policy signals and adjust their investments accordingly, hence minimizing the risk of additional stranded assets, which could represent a serious issue and threaten the resilience of the net-zero transition. The *NZE Ambition* scenario implies a least-cost transition that involves combining a gradual ramping up of policy stringency with immediate climate-friendly investments.[32]

The macroeconomic effects of the transition differ by region. Regional differences depend on the level of mitigation ambition (compared to sequestration potential), *Baseline* emissions, the mix of policy instruments employed and the economic structure of the region in question. Annex C provides such regional breakdown of macroeconomic effects, showing how GDP impacts vary with mitigation ambition, economic structure and reliance on fossil fuel production.

4. The effect of policy instrument choice on public finance

This section examines how the policy instruments in the *NZE Ambition* scenario affect net public revenues. We first describe the fiscal structure in the *Baseline* (Section 4.1), then analyse the direct and indirect fiscal

[32] The modelling abstracts from changes in international migration and changes in cross-country capital flows as driven by the policy scenario, i.e., international movements of labour and capital are fixed at their baseline projection levels (with capital movements further determined by assumptions on current account balances, to ensure closure on the trade balance. Factor mobility within regions is included in the modelling, however; given the aggregate nature of the regions, this includes some international factor mobility at the country level. This is especially important for the European Union. Assumptions on labour and capital mobility affect all countries involved; see e.g. (Dellink, van der Mensbrugghe and Saveyn, 2020[62]). There is insufficient data to model the direction of such flows and the effect on fiscal revenues are a priori unclear.

effects of each instrument (Section 4.2), the erosion of carbon pricing revenues by other tax base changes (Section 4.3), the regional variation in fiscal outcomes (Section 4.4), and the sensitivity of results to the policy mix and mitigation trajectory (Section 4.5).

4.1 The largest public revenues come from taxes on production factors and consumption

As described in Section 2.3, net public revenues (tax revenues minus subsidy expenditures) in the ENV-Linkages model can be grouped as revenues from carbon pricing, net taxes on fossil fuels (production and consumption), net taxes on production (excl. fossil fuels), net taxes on consumption (excl. fossil fuels), production factors, household income and international trade.

In the *Baseline* scenario for 2019, based on the figures from the GTAP database (Aguiar et al., 2019[24]), most public revenue accrues from the taxation of production factors (labour, capital, etc.) and consumption and, to a lesser extent, from taxation of production (Figure 4). In many regions, income is the only fiscal base for which the net tax rate is negative, as government expenditure for transfers to households (redistribution) are larger than revenues from income taxes. Consequently, the balance of income taxation and transfers in 2019 represents a net cost for public finances instead of a net revenue in all regions, except Africa and the Middle East, Other Eurasia and Other Asia.

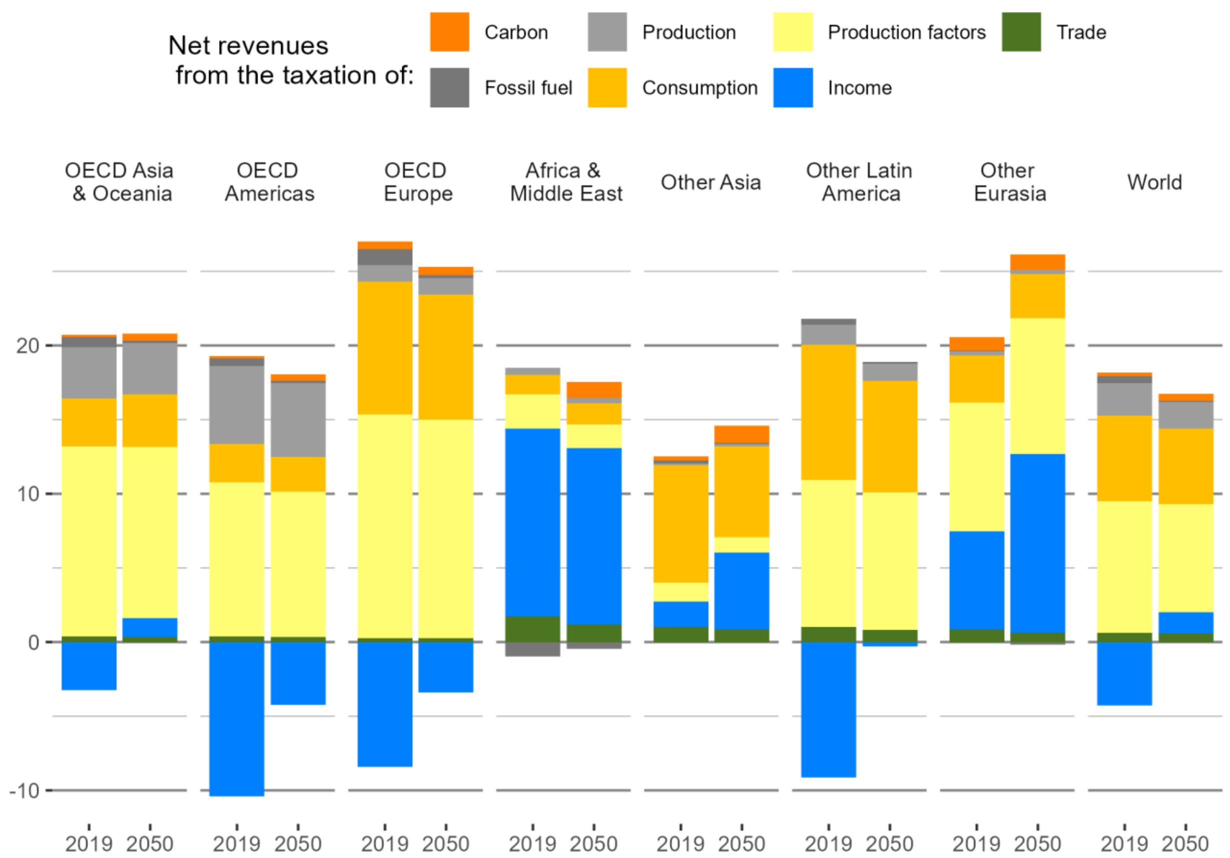
In the *Baseline* scenario, net public revenues as a share of GDP slightly increase between 2019 and 2050. This results from the *Baseline* calibration, which includes: (i) a change in the sectoral structure of the economy (servitisation); (ii) an evolution of tax and subsidy rates over time, reflecting current and legislated policies, and (iii) a constraint on the evolution of public deficit over time (see Annex A). In general, tax and subsidy rates are constant between 2019 and 2050 in the *Baseline* scenario, so most net public revenues increase with the fiscal base. The main exception is income taxation: this comprises income taxes (net effect of taxes and subsidies on income; these have an exogenous rate) and transfers between government and households; the latter adjusts to ensure that public deficit follows its exogenous pathway (see Section 2.3): GDP growth drives up both revenues and expenditures, and the resulting balance leads to a net increase in income tax revenues (incl. transfers to households) across most regions.

Net public revenues from fiscal bases related to climate change (carbon, fossil fuel production and fossil fuel consumption) remain very limited both in 2019 and 2050. In general, revenues from carbon pricing tend to increase because the average global carbon price on CO_2 is assumed to grow from USD 4 to USD 18 in the *Baseline* scenario (no taxation on other GHGs is present in the *Baseline* scenario), although with significant regional differences (see Annex B),[33] while CO_2 emissions continue to increase. In contrast, net revenues from the taxation of fossil fuel production and consumption decrease over time in all regions, as gradual improvements in energy efficiency over time erode the fiscal base.

[33] Average regional carbon prices in the *Baseline* scenario in 2050 range from USD 0 to USD 103.

Figure 4: Net public revenues increase over time in the *Baseline* scenario

Net public revenues in the *Baseline* scenario in 2019 and 2050, by fiscal base (% of GDP)



Notes: Net public revenues correspond to the difference between tax revenues and subsidies expenditure.

4.2 All policy instruments have significant indirect effects on public finance

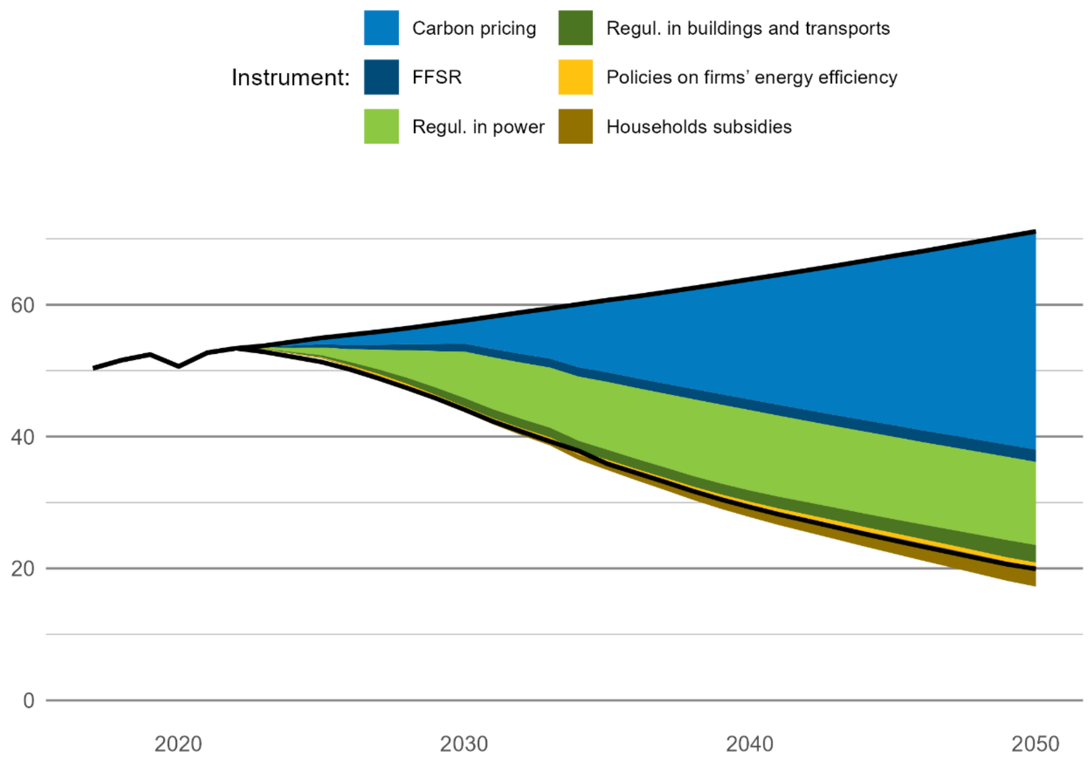
Before examining the fiscal effects in detail, it is useful to understand how each policy instrument contributes to emission reductions, as the size and nature of its contribution shapes the magnitude of both direct and indirect fiscal effects. Emissions reductions in the *NZE Ambition* scenario are achieved using all policy instruments considered, but the largest contributions are from carbon pricing, followed by regulations in the power sector (Figure 5). Before 2030, most reductions occur due to regulations in power generation, whereas subsidies to households are in place but do not yet materialize into significant emission reductions. This is because households' direct emissions from residential buildings and transport are pervasive and renewing a significant share of the vehicle fleet or renovating residential buildings takes time. Between 2030 and 2050 on the contrary, households' emissions start to significantly contribute to the mitigation effort, while at the same time carbon prices rise.

The combined policy instruments lead to interactions (e.g., the effect of regulations in the power sector on emissions is different if they are implemented in parallel to carbon pricing or not) and are implemented in parallel to the ramping up of Carbon Capture, Utilization and Storage (CCUS) over time, especially after 2030.

These two factors bridge the gap between levels of emissions reductions achieved by individual policy instruments and those seen in the *NZE Ambition* scenario.[34]

Figure 5: Not all policy instruments in the *NZE Ambition* scenario contribute equally to emission mitigation

Contribution of the different policy instruments to *NZE Ambition* CO_2 emission mitigation (Mt CO_2)



Notes: The difference between the sum of instruments' contributions and the lower solid black line corresponds to induced effects not attributable to a specific instrument, including CCUS and interactions between instruments.

The largest effects on public finances of the policy instruments considered are the direct effects of carbon pricing (net additional revenues) and household subsidies (net additional expenditure), and to a lesser extent fossil fuel subsidies removal (net additional revenues), as shown in Figure 6. Even if limited on average, phasing out of environmentally harmful subsidies, such as fossil fuel subsidies, supports public budget, especially in countries where they are the highest. However, all instruments entail large indirect effects that reduce net public revenues. These indirect effects impact the various fiscal bases, and especially those related to production and consumption of fossil fuels. As the policies employed take effect, the resulting reduction in

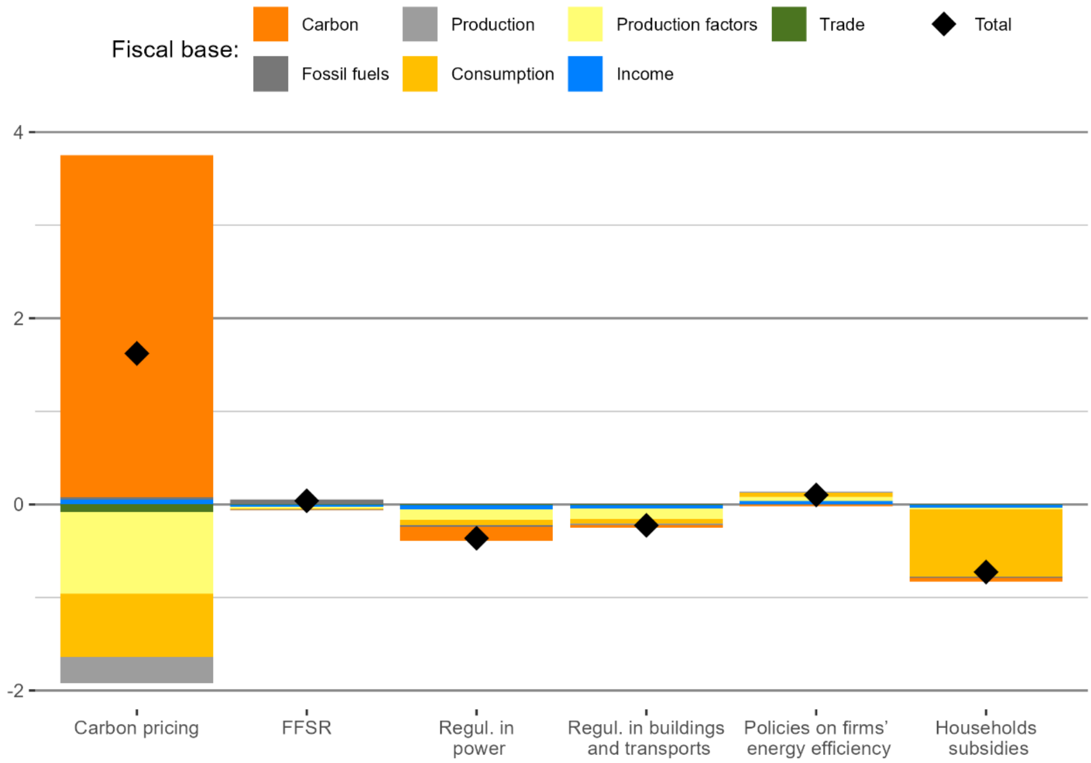
[34] It is important to note that the interaction effects between policy instruments are inherently non-linear in a computable general equilibrium framework. A full additive decomposition of the fiscal effects of each instrument is therefore not feasible without imposing an arbitrary sequencing of policy introduction. Instead, we present the interaction effects as a residual term in our decomposition and discuss their economic drivers, which we believe provides a more transparent and economically meaningful characterisation of the policy interplays.

fossil fuel production and consumption also leads to a commensurate reduction in revenues from taxing fossil fuel production and consumption.

Indirect effects also occur from changes in economic activity, which rescale sectoral and economy-wide tax payments. When economic activity contracts, it means that overall production decreases and hence revenues from the taxation of production factors (labour, capital) decrease. Furthermore, households' income and consumption levels decrease, leading to lower public revenues from consumption taxation and higher net public revenues from income taxation and transfers (the latter reflects a decrease in expenditures, because on average government expenditures for transfers to households are larger than revenues from income taxes). The indirect effects of the policy package on production factors and consumptions taxation revenues are larger than for changes in households' income, because the former tax bases represent a larger share of public revenues than the latter (see Figure 4). Therefore, any policy instrument which expands economic activity (e.g. policies to stimulate firms' energy efficiency improvements) will generate additional net public revenues through indirect effects, while activity-contracting instruments (e.g. regulations in the power sector) will decrease net public revenues through indirect effects.

Figure 6: Direct effects of market-based instruments entail the largest changes in net public revenues, but all policy instruments have significant indirect effects

Effect of individual policy instruments on net public revenues in 2050, by fiscal base (% of GDP)



Notes: Each category corresponds to a scenario where only the policy instrument mentioned is implemented. FFSR stands for "Fossil fuel subsidy removal".

Each policy instrument also has different macroeconomic effects beyond its impact on public finances, leading to different levels of efficiency in reducing GHG emissions or distributional effects between sectors and between other economic agents.[35]

4.3 The revenues generated by carbon pricing are partially offset by the erosion of other fiscal bases

Carbon pricing generates significant revenues. In 2050, revenues from carbon pricing increase from 0.5% of *Baseline* GDP in the *Baseline* scenario to 2.5% of *Baseline* GDP in the *NZE ambition* scenario. This is the outcome of three main drivers, illustrated in Figure 7: carbon prices increase significantly (2nd column)[36], but at the same time GHG emissions decrease compared to the Baseline, both due to carbon pricing (3rd column) and other instruments (4th column). In addition, due to indirect effects of carbon pricing on other tax bases (Figure 6), only around half of revenues from carbon pricing can be recycled.

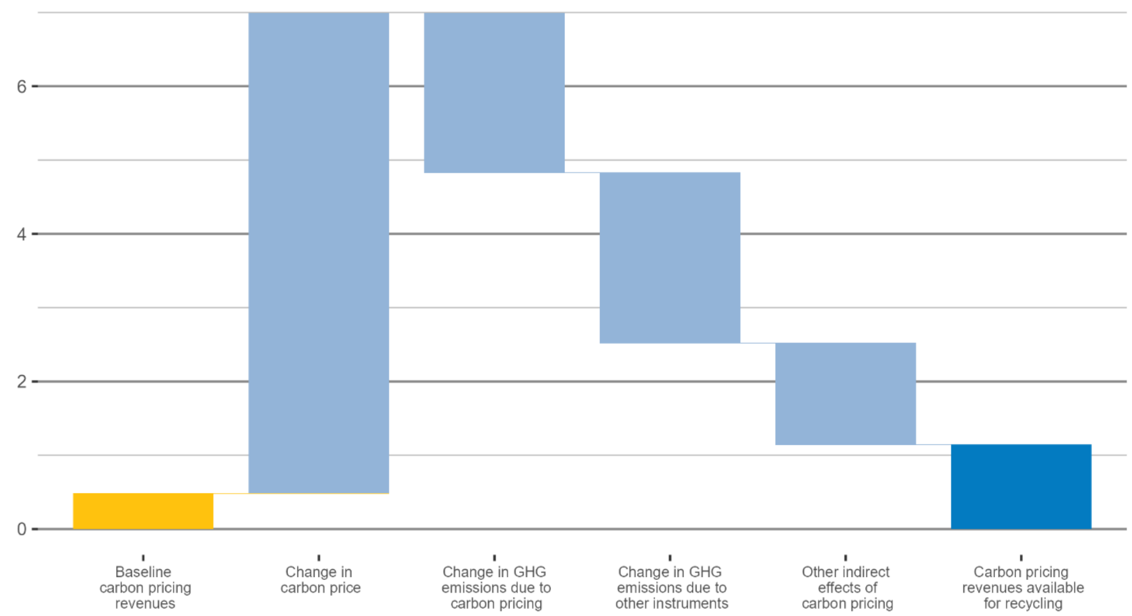
[35] Comparing the effectiveness of the instruments is outside the scope of this paper as it would require further analysis to identify a relevant set of metrics, such as a carbon price equivalent or measures of job reallocation, and to account for the large interaction effects between instruments.

[36] Levels of carbon prices in the *NZE Ambition* scenario are provided in Annex B.

As a result, the 2.5% of Baseline GDP of carbon revenues in the *NZE Ambition* scenario only translate into potentially 1.1% net revenues (6th column in Figure 7). Similar results occur when carbon pricing is implemented alone (Figure 6) without any other policy instruments, generating 3.8% of *Baseline* GDP, reducing to 1.9% of *Baseline* GDP due to indirect effects, thus also reducing the potential for revenue recycling by around half. This exemplifies the importance of considering indirect effects when assessing the revenue recycling potential of carbon pricing measures, with many current assessments assuming all revenues can be recycled, not accounting for indirect effects. The recyclable share of gross carbon-pricing revenue thus offers a useful complementary diagnostic of the fiscal system's resilience, albeit a partial one, since it isolates the carbon-pricing channel rather than capturing the broader fiscal space.

Figure 7: The net public revenues of carbon pricing are partially offset by eroding tax bases

Carbon pricing revenues in 2050 (% of *Baseline* GDP)



Notes: Baseline carbon pricing revenues reflect current policies and includes e.g. the EU ETS and carbon tax schemes in a range of countries.

The revenues from carbon pricing in the *NZE Ambition* scenario are not sufficient to finance the other policies included in the scenario, such as subsidies to households in order to decarbonize transport and residential buildings. Indeed, once direct and indirect effects of all policy instruments are accounted for, the overall impact on global public finances is a decrease of net public revenues by 0.5% of *Baseline* GDP.

4.4 The NZE Ambition scenario projects a downward pressure on government budget balances, with large regional differences

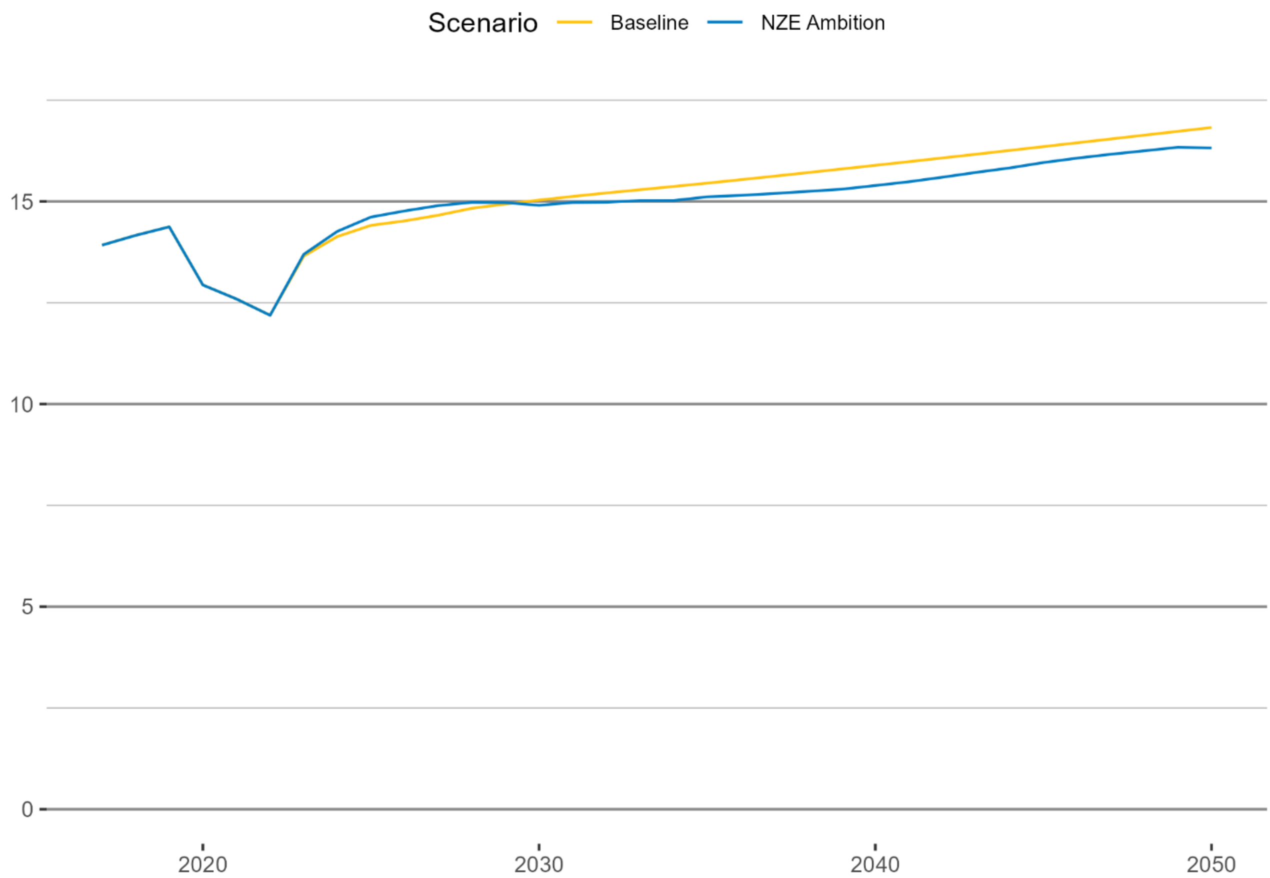
The effects of the policy package on public revenues are limited at the global level, with global net public revenues declining by -0.1% of *Baseline* GDP in 2030 and -0.5% in 2050, as shown in Figure 8. Nonetheless, it is clear from the figure that the baseline trends dominate when looking at absolute results.

Leading up to 2030, the results are driven primarily by the policy instruments linked to investments as well as fossil fuel support removal. First, carbon pricing revenues are limited, as the required emission reductions are not yet sharp enough to lead to high carbon prices. Second, the removal of fossil fuel support leads to significant additional net revenues. Third, subsidies to households to decarbonize their energy demand start to weigh on public budgets, while the transformation of the energy sector and the policies to decarbonize transport and buildings entail significant upfront investments and bring short-term economic costs. The effects of the policy package on energy-related net tax revenues are limited, as the required emission reductions do not reduce total energy demand much below the *Baseline* levels.

In the long run, households' subsidies take ever increasing precedent, while policies inducing increased investments also continue to strain public budgets, representing on average additional costs for public finance compared to the *Baseline* scenario. At the same time, the benefits of fossil fuel support removal (decreased government expenditures) erode as they are fully phased out already in 2030. The increase in carbon pricing revenues between 2030 and 2050 fails to compensate for the increased costs to public finances of other instruments.

Figure 8: Baseline trends are more important in determining changes in global net fiscal revenues over time than the impacts in the NZE Ambition policy scenario

Net public revenues over time (% of Baseline GDP)



These impacts differ substantially across regions (Figure 9), depending on regional characteristics (economic structure) as well as on the policy mix employed in each region under the *NZE Ambition* scenario. Overall, the net-zero transition represents a net cost for public finances in all regions, ranging from -3.4% to -0.1% of *Baseline* GDP.

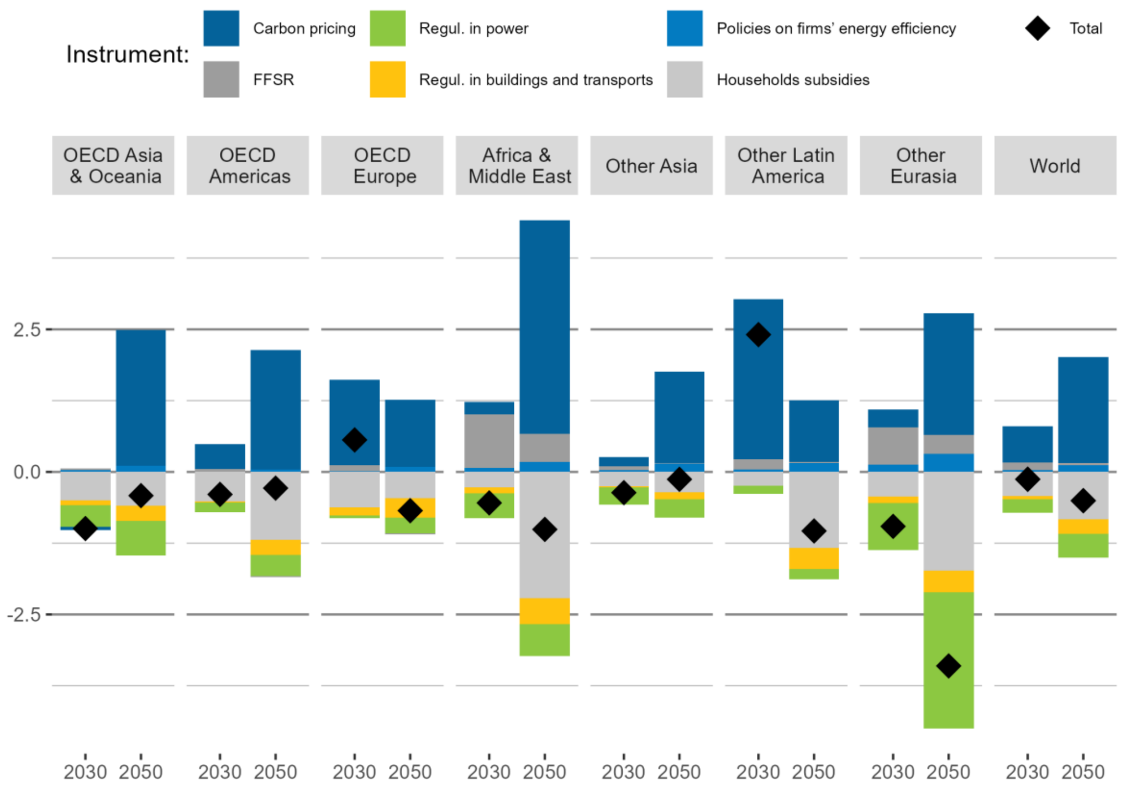
In the short-, to medium-term, two regions experience an increase in net public revenues in 2030, for different reasons. In Africa & Middle East, the decrease in government expenditures resulting from the removal of fossil fuel subsidies generates significant net revenues in 2030. In Other Latin America, 2030 targets are sufficiently ambitious to trigger significant carbon prices, generating revenues.

Within the OECD in the long run, the impacts on public finances are larger in the regions where investment-related instruments and FFSR are stringent enough to achieve all or a significant part of the emissions reductions required to achieve their target (e.g. in OECD Europe). In regions where carbon pricing plays a significant role in the *NZE Ambition* scenario (OECD Asia & Oceania), the net effects on public finances are primarily driven by the direct cost of households' subsidies and the magnitude of indirect effects of all instruments.

Results also differ across non-OECD regions, as each region covers countries with very different characteristics. For instance, the Other Asia region includes countries that have stringent commitments, such as China or Indonesia. However, in Indonesia, carbon sequestration is so large that carbon pricing levels needed to achieve carbon neutrality are lower than those in other regions.

Figure 9: Changes in net public revenues in the *NZE Ambition* scenario range from -0.1% to -3.4% of *Baseline* GDP in 2050 depending on the region

Changes in net public revenues in the *NZE Ambition scenario* compared to the *Baseline* in 2050 (% of *Baseline* GDP)



4.5 The policy mix and mitigation trajectory significantly affect public finance

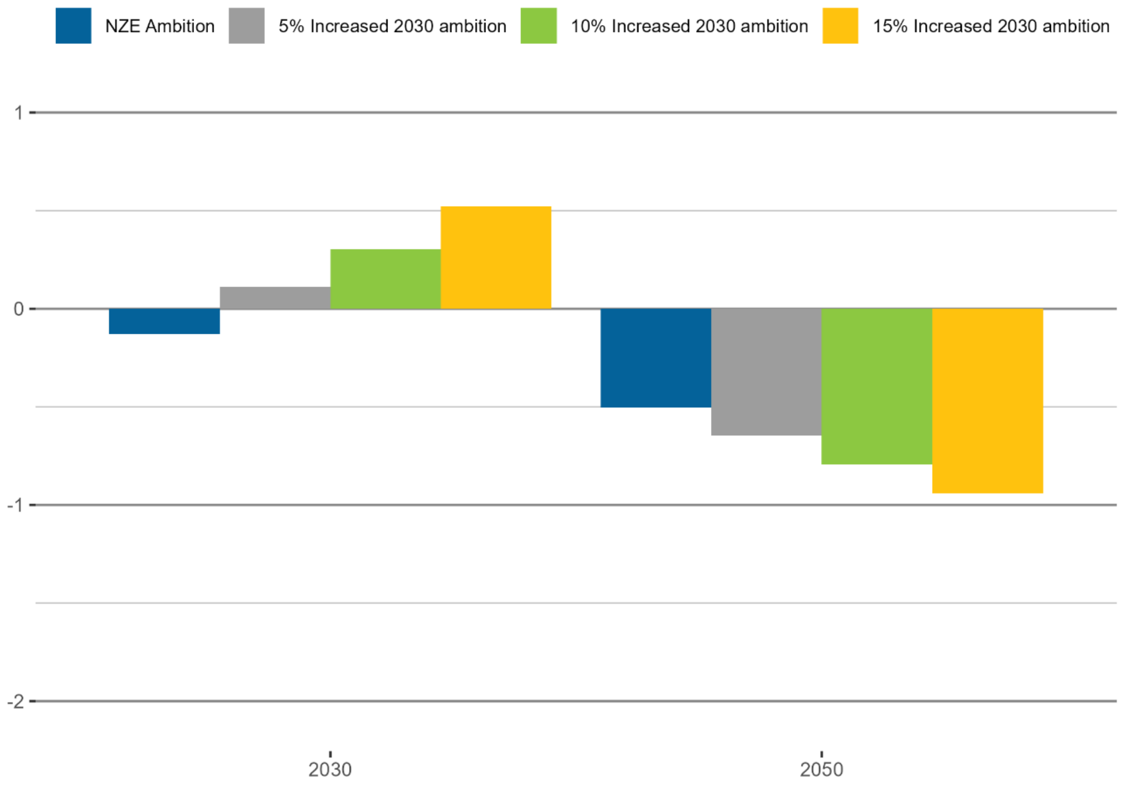
The *NZE Ambition* scenario proposes one possible path to achieve the net-zero transition, but many different pathways are possible. In the framework of the Paris Agreement, countries are free to set their targets and to choose policies to achieve such targets. In the *NZE Ambition* scenario, the emission targets for 2030 and 2050 are based on existing pledges (NDCs and net-zero commitments respectively) and the mix of policy instruments is driven by the potential for emission reductions through regulations. However, the level of ambition of current NDCs do not seem to be in line with a least-cost pathway to net-zero by 2050 (Climate Action Tracker, 2021[32]; Glynn et al., 2022[33]), and countries may rely more (or less) on carbon pricing than the *NZE Ambition* scenario assumes. Alternative scenarios are therefore needed to illustrate the sensitivity of the public finances impacts of the net-zero transition to (i) the impact of earlier climate action and (ii) the choice of policy instruments.

The first set of these alternative scenarios focuses on the timing of mitigation action. In the *Increased 2030 ambition* scenarios, the emission reduction objectives for 2050 are identical to the *NZE Ambition* scenario, but a significant part of the 2030-2050 mitigation (5, 10 and 15%) is moved to the current decade. The increased short-term ambition is assumed to be met through increased carbon pricing, keeping the ambition levels of the other policy instruments unchanged. The target for 2050 remains the same as in the *NZE Ambition* scenario, implying that the composition of different instruments by 2050 is unchanged from the *NZE Ambition* scenario.

Earlier mitigation implies a trade-off for governments with respect to their finances: it brings additional revenues in the medium term but also increases the cost for public finance in the long term (Figure 10). Extra revenues in 2030 stem from increased carbon prices, required in these scenarios to achieve higher ambition while other instruments' ambition levels remain constant. For the most significant increases in 2030 ambition, the extra revenues generated could exceed the cost of other policies from the *NZE Ambition* scenario as well as the negative indirect effects, leading to an increase in public revenues. This increase in medium-term public revenues however comes at the price of slowing down GDP growth, which lowers net public revenues in 2050 by further eroding existing tax bases, although the effect is substantially smaller than the effect in 2030. Overall, increasing the ambition for 2030 can thus be a way for governments to find additional resources to finance the investments needed by 2030 for the transition, with only limited impact on long-term finances.

Figure 10: Earlier mitigation action brings additional public revenues in the medium term, but slightly less in the long-term

Change in global net public revenues depending on the ambition in 2030 (% of Baseline GDP)

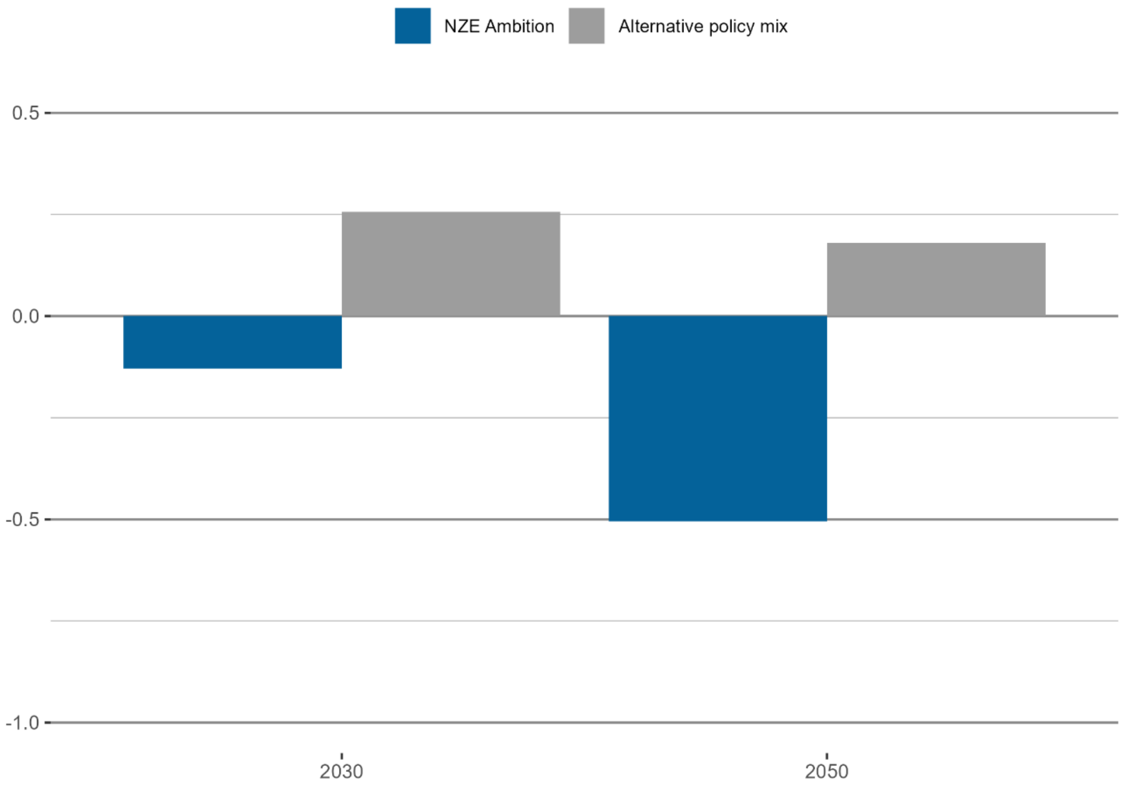


The second type of alternative scenario focuses on the policy mix and increases the role of carbon pricing compared to the other policy instruments without changing the emission targets. Specifically, the *Alternative Policy Mix* scenario decreases the contribution of regulations (in power, buildings and transport), subsidies, and other policies to stimulate firms' energy efficiency improvements to reducing CO_2 emissions by 15%, also decreasing their costs by the same amount. Fossil fuel support is still fully removed. In this scenario, the 2030 and 2050 targets remain identical to those of the *NZE Ambition* scenario, resulting in higher carbon prices required to meet the same emission targets.

Contrary to the *Increased 2030 ambition* scenarios, the *Alternative Policy mix* scenario increases net public revenues compared to the *NZE Ambition* scenario both in 2030 and 2050 (Figure 11). Indeed, the increase in carbon prices needed to compensate for the weaker effects of the other policy instruments increases revenues both in the medium and long run. The balance between the different policy instruments is thus key to the fiscal consequences of the net-zero transition, and a balance can be found between revenues and costs to match domestic circumstances.

Figure 11: The choice of policy instruments in the net-zero transition influences public finances significantly

Changes in net public revenues compared to the *Baseline* in 2030 and 2050 (% of *Baseline* GDP)

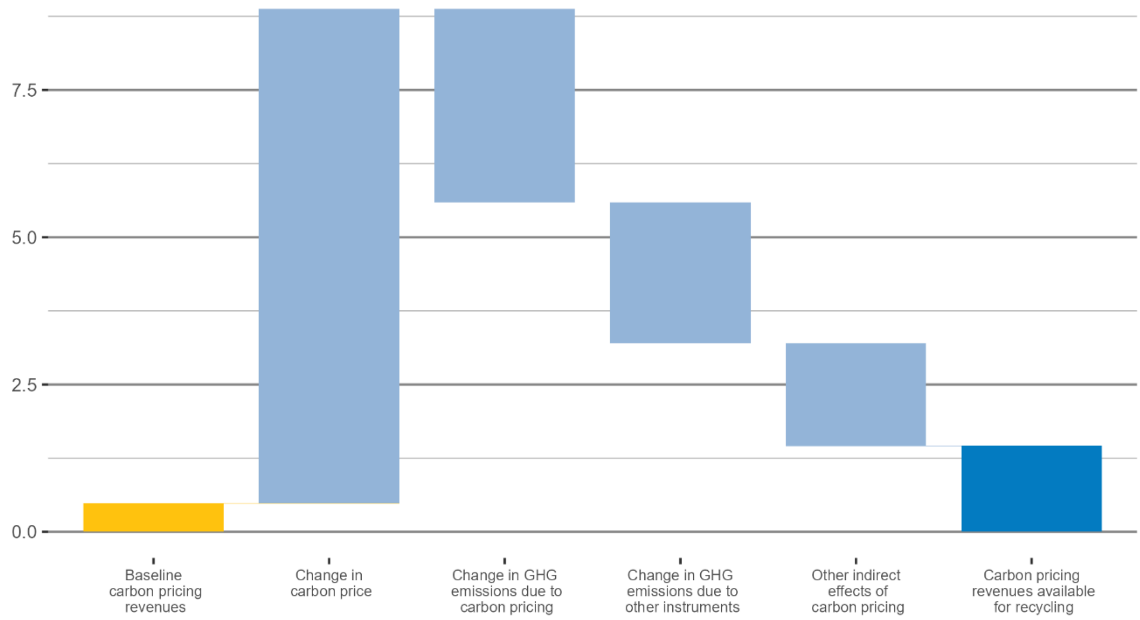


In the *NZE Ambition* scenario, the revenues from carbon pricing are so much eroded by other instruments and indirect effects of carbon pricing on other tax bases that the revenues available for recycling are much lower than expected (Figure 7). In contrast, the *Alternative Policy Mix* scenario – which increases the relative contribution of carbon pricing and decreases the share of other instruments, while keeping the same mitigation level – finds a positive balance. Carbon prices increase a lot compared to the *NZE Ambition* scenario, leading to proportionately larger carbon price revenues (column 2 in Figure 12, amounting to around 8.9% of *Baseline* GDP, compared to column 2 in Figure 7 corresponding to 7.0% of *Baseline* GDP in the *NZE Ambition* scenario). Relying more on carbon pricing also increases the revenues available for recycling after considering the erosion of the emissions base and the indirect effects of carbon pricing on other tax bases (column 6 in Figure 12, corresponding to around 1.5% of *Baseline* GDP, compared to 1.1% in the *NZE Ambition* scenario in Figure 7).

Higher emissions reductions associated with carbon pricing erode the tax base upon which carbon price revenues are derived in the long-term (Figure 12, column 3). Somewhat counterintuitively, relying more on carbon pricing also leads to a larger erosion of carbon price revenues due to other instruments as, while other instruments result in lower overall emissions reductions, the associated loss of revenue is greater due to higher carbon price levels. Similarly, the indirect effects of carbon pricing on other tax bases are larger in value terms, but smaller in relative terms.

Figure 12: The balance between different policy instruments can change the carbon pricing revenues available for recycling

Carbon pricing revenues in 2050 (% of *Baseline* GDP)



Notes: Baseline carbon pricing revenues reflect current policies and includes e.g. the EU ETS and carbon tax schemes in a range of countries. This figure presents the same decomposition as Figure 7 but using the *Alternative policy mix* scenario instead of *NZE Ambition* scenario.

5. Conclusions

Our study contributes to understanding the potential fiscal implications of a net-zero emissions scenario by 2050. We address this question using the global Computable General Equilibrium (CGE) model ENV-Linkages and examine a comprehensive mitigation policy package rather than relying solely on carbon pricing. Our results indicate that achieving net-zero emissions involves a modest reduction in economic growth and net public revenues. Specifically, we find that the transition leads to a global GDP loss of 12% in 2050 relative to Baseline – excluding the benefits from reduced climate damages and other climate co-benefits, such as air pollution – and a decrease in net public revenues on average by 0.5% of Baseline GDP. While this impact is non-negligible, it is likely much inferior to the possible negative impacts of climate change on the economy and the relative need to mobilise public funds to address climate emergencies. Overall, our analysis suggests that governments can – within boundaries – choose and design their policy package according to their economic and energy context, while also considering the need to effectively decarbonise and maintaining the resilience of the fiscal system.

The ex-ante framework presented in Section 2 (Table 2) anticipated how each policy instrument would affect the various tax bases. The simulation results, summarised in Table 3, broadly, confirm that the key direct effects have the expected sign. However, some of the indirect effects are stronger than some of the direct effects. Specifically, the effect of the fossil fuel subsidy removal on fiscal revenues is relatively small, while some indirect effects of the carbon pricing scheme – especially effects on fiscal revenues from taxes on consumption and production factors – are substantially larger. Some of the effects on revenues from income taxation are also significant, first and foremost from the subsidy to decarbonise households' consumption, but also from the regulatory instruments. These reflect the negative macroeconomic effects of these policy instruments. In contrast, carbon pricing can boost tax revenues from income taxation. While the precise numbers clearly depend on the specific model assumptions and assumptions on how the policy instruments are implemented (and for small numbers the sign of the effect may also be ambiguous), the overarching lesson is clear: a robust assessment of the fiscal implications of decarbonisation must account for the indirect effects of policy instruments on conventional tax bases, not only their direct revenue consequences.

Table 3: Key effects of the policy instruments on fiscal space, compared to a no-policy Baseline scenario – ex-post numerical evaluation

Policy instrument Tax base	Carbon pricing (auctioned emission permits)	Fossil fuel support removal	Power sector decarbonisation regulations	Building and transport decarbonisation regulations	Firm's energy efficiency improvement policies	Subsidies to decarbonise household consumption
Carbon	+3.7	0.0	-0.2	0.0	0.0	0.0
Fossil fuels	0.0	+0.1	0.0	0.0	0.0	0.0
Production (other than fossil fuels)	-0.3	0.0	0.0	0.0	0.0	0.0
Consumption (other than fossil fuels)	-0.7	0.0	-0.1	-0.1	0.0	-0.7
Production factors	-0.9	0.0	-0.1	-0.1	0.0	0.0
Income	+0.1	0.0	-0.4	-0.3	0.1	-0.8
Trade	-0.1	0.0	0.0	0.0	0.0	0.0

Our findings need to be interpreted in the context of future uncertainties and the modelling set, including baseline developments (trends in socioeconomic variables as well as damages from climate change), the speed of technological development and the costs of low-carbon alternatives, as well as the scenario design, and specifically the data and information sources used to model the different policy instruments. The specific data sources and modelling framework used influence the results on the economic consequences of the transition, which – at 3% in 2030 – is at the higher end compared to the average of 1% found in other models (Chepeliev, Kanudia and van der Mensbrugghe, 2024[34]), although that mostly covers scenarios that are somewhat less stringent than the NZE Ambition scenario presented here. As this literature is still in its infancy, and results are very sensitive to model assumptions (e.g. on the quantification of the avoided impacts of climate change), a direct comparison is not straightforward. Notably, the assumptions undertaken in our analysis are conservative on the availability of technologies in the future. These are limited and do not include explicitly the possibility of innovation of further development of technologies that are not yet marketed. In addition, our findings only consider mitigation policies and do not explicitly represent policies to develop carbon sequestration through AFOLU or negative emission technologies. Depending on the strategy chosen for carbon sequestration, the results might vary. These assumptions affect global results, but especially results at regional level, where variations are larger.

In particular, carbon sequestration through AFOLU and negative emission technologies is treated in our scenario as exogenous and costless, effectively defining the net-zero target as the point where gross emissions equal an exogenously determined sequestration potential. If sequestration were modelled as costly and endogenous, the fiscal effects could differ in two important ways. On the one hand, public expenditures to support sequestration deployment (e.g., subsidies for direct air capture or afforestation programmes) would put additional pressure on public finances, reinforcing the pattern we observe for other investment-related instruments in our policy package. On the other hand, greater sequestration capacity could allow for lower carbon prices or less stringent regulations to achieve the same net-zero target, partially offsetting the fiscal cost. The existing literature modelling as endogenous the deployment of such technologies suggests that the latter channel is likely to dominate: (Realmonte et al., 2019[35]) find that Direct Air Carbon Capture and Storage (DACCS) availability reduces carbon prices by 60 to over 90% in inter-model comparisons, while (Gilmore et al., 2023[36]) show that including Direct Air Capture (DAC) in a CGE framework lowers global welfare losses by up to approximately 1% of GDP. A further step would be to endogenise the cost evolution of sequestration technologies. This could cut either way: strong technology improvements effects could drive costs down rapidly, amplifying the cost-reducing benefits in the long run; alternatively, scaling up may reveal bottlenecks that keep costs high. Crucially for public finance, even under optimistic learning assumptions, the fiscal burden may be front-loaded: governments would need to finance the early, expensive phase of deployment that triggers cost reductions, creating a tension between short-term fiscal costs and long-term fiscal benefits. Exploring these dynamics would require modelling endogenous technological change in sequestration, which is beyond the scope of the current analysis but represents a valuable avenue for future research.

While the modelling approach presented in our paper includes some degrees of technological progress, with additional investments in research and development and assuming that these investments would result in faster technological development and innovation, reaching net-zero emissions by the middle of the century would be less costly and possibly also boost economic growth. However, the fiscal consequences of policies to boost low-carbon innovation are not straightforward to assess, not least due to the interaction effects with other policy instruments, and beyond the scope of the current analysis. The modelling analysis also rests on the assumption of full investor foresight and does not reflect the possible impacts of policy uncertainty and lack of policy credibility. This assumption likely leads to an understatement of transition risks and costs, as real-world policy signals are often delayed, contested, or revised, and investors face uncertainty, myopia, and coordination failures. Imperfect expectations can result in continued investment in carbon-intensive assets followed by abrupt repricing once policies are clarified or enforced, increasing the likelihood of stranded assets. These factors represent potentially important sources of bias in our estimates of fiscal pressure.

Our scenario represents only one possible pathway to achieve net-zero emissions by the middle of the century. Other policy packages could be modelled, deepening the implementation of policy instruments, and using more detailed information, such as the effective carbon rates analysis by OECD (2023[37]) and reform of market-distorting subsidies beyond fossil fuels. The design of specific policies could also be changed. For example, our policy package contains significant increases in investments, but, by design, these do not boost economic growth, as they are assumed to crowd out other productive investments. Further analysis can be done to identify how specific policy instruments in the policy package can be designed to be growth-enhancing and thus prevent the negative indirect effects on public revenues found in the current analysis. Finally, it would be very interesting to specify a scenario that does not rely on carbon pricing at all. This would, however, require an in-depth analysis of the associated emission sources such that plausible alternative instruments for decarbonising these sources can be formulated. As this paper presents a first analysis of the fiscal consequences of the net-zero emission transition, several additional developments on this issue can be envisaged. First, a multitude of scenarios can easily be envisaged that would shed further light on the impact of baseline assumptions, the role of specific policy instruments, on the speed of decarbonisation, on regional differentiation in the timing of policies and in the policy mixes used, etc. Such additional scenario analysis is beyond the scope of the current paper, but it would allow for a much richer understanding of the main uncertainties surrounding the key insights in this paper. Second, the global analysis presented in this paper can be followed by more detailed analyses for specific countries. The modelling in the current paper takes into account regional differences in economic and energy structures. However, setting up national strategies towards carbon neutrality needs more detailed insights into the specific characteristics of the country, especially because most regions with a commitment to achieve carbon neutrality by 2050 have produced net-zero policy plans with differing levels of detail. Deriving concrete guidance on optimal policy mixes for individual countries or country groups would require detailed data on national fiscal structures, existing policy landscapes, and technology adoption potential. Country-level analyses building on the global framework presented here are an important avenue for future research.

Overall, the global analysis presented here can form the basis for ensuring that the international context of such country studies is properly considered. Given the potentially large impacts on public finances, transition plans could include a fiscal strategy, based on a detailed analysis of direct and indirect effects on the fiscal implications of climate change policies that guarantees the fiscal sustainability of the chosen policy package. In turn, revenues available to governments to finance other policies, such as carbon sequestration or the just transition, might be lower than carbon revenues. This could be reflected in any plan to recycle carbon price revenues. Flanking policies to address undesirable effects of the policy package on specific economic agents, such as income losses for poor households, may also require additional public funds in a context where public finances also need to address many other objectives unrelated to climate change. As commonly known, model projections are not predictions and the recommendations provided in this paper need to be compared and confronted with the political acceptability and feasibility of fiscal policies. However, current policy developments show the increasing importance of carbon pricing in policy mixes and the increasing amount of revenues raised through carbon pricing (World Bank, 2026[38]) and highlight the need to increasingly integrate Nationally Determined Contributions (NDCs) with economic and fiscal policies for successful implementation (Jeudy-Hugo, 2024[39])

Declarations

The views expressed here are those of the authors. This paper does not necessarily represent the views of the OECD or its member countries. The authors are solely responsible for any errors in the manuscript.

Competing interests

The authors declare they have no financial or personal relationships with any person or organization that could inappropriately influence or bias in any way the following manuscript.

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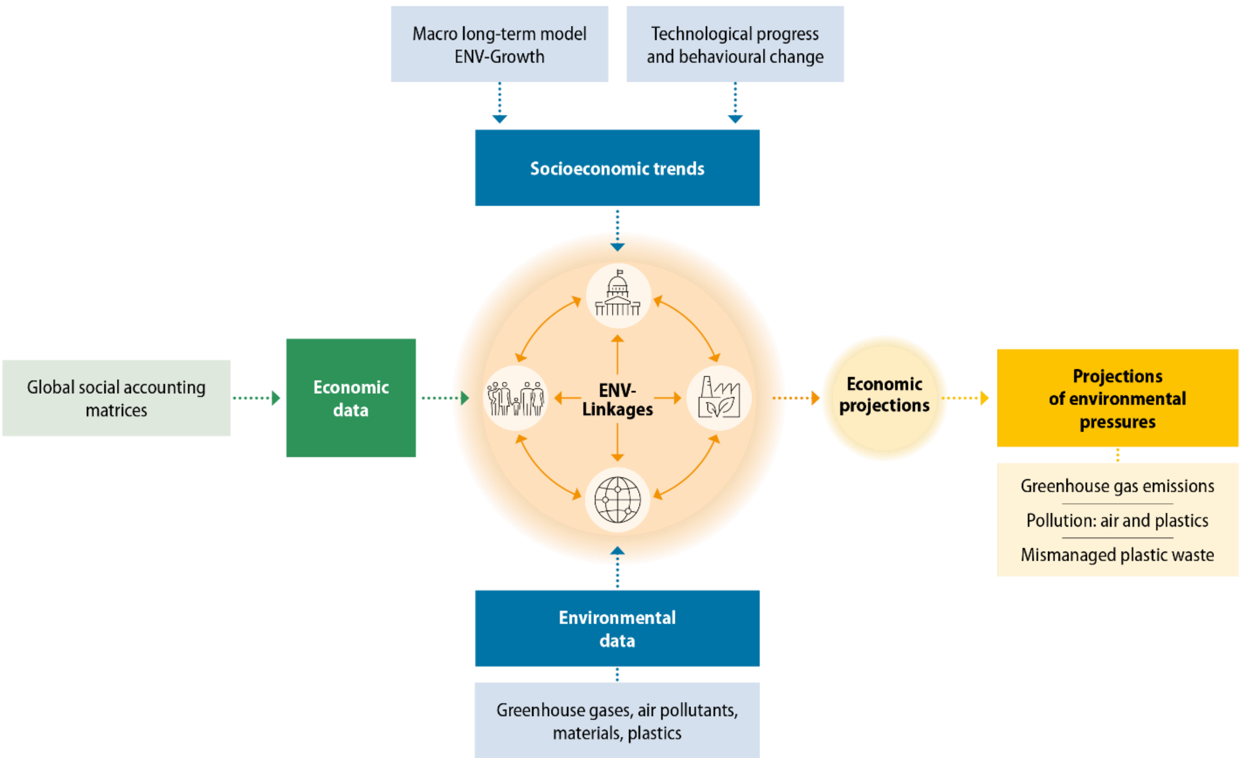
Supplementary Information

A. The ENV-Linkages model

Model description

The ENV-Linkages model is global recursive-dynamic computable general equilibrium model that describes economic activities in different sectors and regions and how they interact.



The baseline calibration is based on the GTAP 10 database (Aguiar et al., 2019[24]) and GTAP-Power satellite account (Chepeliev, 2020[40]). In this paper, the GTAP database has been aggregated to 26 regions and 37 sectors. Regions have been chosen to match the ones used by the World Energy Outlook 2021 (Table A.1). Economic activities isolate energy activities, energy intensive industries, transport and equipment sectors, while the rest of the economy is aggregated in broad sectors (Table A.2).

The model links economic activity to environmental pressures, including greenhouse gas emissions, air pollutants and materials. Greenhouse gas emissions in ENV-Linkages are quantified based on data from the International Energy Agency, GTAP and EDGAR. CO_2 emissions from combustion of energy are directly linked to the use of different fuels in production using constant coefficients, while process CO_2 emissions are substitutes to production in sectors where they are generated. The modelling of process CO_2 emissions follows the seminal work by Hyman et al. (2002[41]) by introducing these emissions as a substitute to production. The elasticities of substitution of the corresponding CES function are calibrated to match maximum abatement levels documented in the literature (see Annex B).

Production in ENV-Linkages is assumed to operate under cost minimisation and constant returns-to-scale technology. The production functions are specifically tailored for agricultural sectors (intensification vs. extensification), and electricity production (cost-minimizing decision by representative agent based on available technologies: coal, oil, gas, nuclear, hydro, wind, solar and other).

Household consumption demand is the result of a static maximisation behaviour: a representative consumer in each region – who takes prices as a given – optimally allocates disposable income among the full set of consumption commodities and savings. Savings is considered as a standard good in the utility function and does not rely on forward-looking behaviour by the consumer.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium.

Table A.1: ENV-Linkages regional aggregation

Aggregated region	ENV-Linkages regions	GTAP regions
OECD America	Canada (CAN)	Canada (CAN)
	Mexico (MEX)	Mexico (MEX)
	United States (USA)	United States of America (USA)
	Central and South America A (CSAMa)	Chile (CHL), Colombia (COL)
OECD Asia & Pacific	Australia and New Zealand (AUNZ)	Australia (AUS), New Zealand (NZL)
	Japan (JPN)	Japan (JPN)
	Korea (KOR)	Korea, Republic of (KOR)
OECD Europe	European Union A (EUa)	France (FRA), Germany (DEU), Italy (ITA)
	European Union B (EUb)	Austria (AUT), Belgium (BEL), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), Greece (GRC), Hungary (HUN), Ireland (IRL), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Netherlands (NLD), Poland (POL), Portugal (PRT), Slovakia (SVK), Slovenia (SVN), Spain (ESP), Sweden (SWE)
	Other OECD Europe (OEURa)	Switzerland (CHE), Norway (NOR), Rest of European Free Trade Association (XEF), Israel (ISR), Türkiye (TUR)
	UK (OEURc)	United Kingdom (GBR)
Africa & Middle East	Middle East (ME)	Bahrain (BHR), Iran, Islamic Republic of (IRN), Jordan (JOR), Kuwait (KWT), Oman (OMN), Qatar (QAT), Saudi Arabia (SAU), United Arab Emirates (ARE), Rest of Western Asia (XWS)
	North Africa (NAFR)	Egypt (EGY), Morocco (MAR), Tunisia (TUN), Rest of North Africa (XNF)
	South Africa (SAFR)	South Africa (ZAF)
	Other Africa (OAFR)	Benin (BEN),Burkina Faso (BFA),Cameroon (CMR),Côte d'Ivoire (CIV),Ghana (GHA),Guinea (GIN),Nigeria (NGA),Senegal (SEN),Togo (TGO),Rest of Western Africa (XWF),Rest of Central Africa (XCF),South Central Africa (XAC),Ethiopia (ETH),Kenya (KEN),Madagascar (MDG),Malawi (MWI),Mauritius (MUS),Mozambique (MOZ),Rwanda (RWA),Tanzania, United Republic of (TZA),Uganda (UGA),Zambia (ZMB),Zimbabwe (ZWE),Rest of Eastern Africa (XEC),Botswana (BWA),Namibia (NAM),Rest of South African Customs Union (XSC),Rest of the World (XTW)
Other Asia	China (CHN)	China (CHN), Hong Kong, Special Administrative Region of China (HKG)
	India (IND)	India (IND)
	Indonesia (INDO)	Indonesia (IDN)
	Other Asia (OASIA)	Rest of Oceania (XOC), Mongolia (MNG), Taiwan (TWN), Rest of East Asia (XEA), Bangladesh (BGD), Nepal (NPL), Pakistan (PAK), Sri Lanka (LKA), Rest of South Asia (XSA)
	Other Southeast Asia (OASEAN)	Brunei Darussalam (BRN), Cambodia (KHM), Lao PDR (LAO), Malaysia (MYS), Philippines (PHL), Singapore (SGP), Thailand (THA), Viet Nam (VNM), Rest of Southeast Asia (XSE)
Other Eurasia	Russia (RUS)	Russian Federation (RUS)
	Caspian (CASP)	Kazakhstan (KAZ), Kyrgyzstan (KGZ), Tajikistan (TJK), Rest of Former Soviet Union (XSU), Armenia (ARM), Azerbaijan (AZE), Georgia (GEO)
	European Union C (EUc)	Bulgaria (BGR), Croatia (HRV), Cyprus (CYP), Malta (MLT), Romania (ROU)
	Other Europe B (OEURb)	Albania (ALB), Belarus (BLR), Ukraine (UKR), Rest of Eastern Europe (XEE), Rest of Europe (XER)
Other Latin America	Brazil (BRA)	Brazil (BRA)
	Other Latin America (CSAMb)	Rest of North America (XNA), Argentina (ARG), Bolivia (BOL), Ecuador (ECU), Paraguay (PRY), Peru (PER), Uruguay (URY), Venezuela (Bolivarian Republic of) (VEN), Rest of South America (XSM), Costa Rica (CRI), Guatemala (GTM), Honduras (HND), Nicaragua (NIC), Panama (PAN), El Salvador (SLV), Rest of Central America (XCA), Dominican Republic (DOM), Jamaica (JAM), Puerto Rico (PRI), Trinidad and Tobago (TTO), Rest of Caribbean (XCB)

Table A.2: ENV-Linkages sector aggregation

ENV-Linkages Activity	GTAP sector		ENV-inkages Activity	GTAP sector
Primary			**Manufacturing**	
Animal agriculture (AnimAgr)	Crops nec (ocr), Bovine cattle, sheep and goats, horses (ctl), Animal products nec (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)		Chemicals (Chemicals)	Chemical products (chm)
Mining (Mining)	Other Extraction (formerly omn Minerals nec) (oxt)		Electric equipment (ElecEqui)	Electrical equipment (eeq)
Other agriculture (OthAgr)	Forestry (frs), Fishing (fsh)		Food (Food)	Bovine meat products (cmt), Meat products nec (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products nec (ofd), Beverages and tobacco products (b_t)
Vegetal agriculture (VegAgr)	Paddy rice (pdr), Wheat (wht), Cereal grains nec (gro), Vegetables, fruit, nuts (v_f), Oil seeds (osd), Sugar cane, sugar beet (c_b), Plant-based fibers (pfb)		Iron and steel (IronSteel)	Ferrous metals (i_s)
Energy			Minerals (Minerals)	Mineral products nec (nmm)
Coal (coa)	Coal (coa)		Other EITE (OthEITE)	Paper products, publishing (ppp), Basic pharmaceutical products (bph), Rubber and plastic products (rpp)
Coal power (clp)	Coal base load power generation (CoalBL)		Other manufacturing (OthManuf)	Wood products (lum), Metal products (fmp), Computer, electronic and optical products (ele), Machinery and equipment nec (ome), Manufactures nec (omf)
Gas (gas)	Gas (gas)		Other metals (OthMetals)	Metals nec (nfm)
Gas manufacture and distribution (gdt)	Gas manufacture, distribution (gdt)		Textile (Textile)	Textiles (tex), Wearing apparel (wap), Leather products (lea)
Gas power (gsp)	Gas base load power generation (GasBL), Gas peak power generation (GasP)		Transport equipment (TransEqui)	Motor vehicles and parts (mvh), Transport equipment nec (otn)
Hydro power (hyd)	Hydro base load power generation (HydroBL), Hydro peak power generation (HydroP)		**Services**	
Nuclear power (nuc)	Nuclear power generation (NuclearBL)		Air transportation (atp)	Air transport (atp)
Oil (oil)	Oil (oil)		Construction (cns)	Construction (cns)
Oil power (olp)	Oil base load power generation (OilBL), Oil peak power generation (OilP)		Dwellings (Dwellings)	Dwellings (dwe)
Other power (xel)	Other base load power generation (OtherBL)		Finance Insurance Business services (FinInsBus)	Trade (trd), Warehousing and support activities (whs), Financial services nec (ofi), Insurance (formerly isr) (ins), Real estate activities (rsa), Business services nec (obs)
Petroleum and coal products (p_c)	Petroleum, coal products (p_c)		Ground transportation (otp)	Transport nec (otp)
Power transport and distribution (etd)	Power transport and distribution (TnD)		Other services (OthServ)	Accommodation, Food and service activities (afs), Communication (cmn), Recreational and other services (ros)
Solar power (sol)	Solar peak power generation (SolarP)		Public services (PubServ)	Public Administration and defense (osg), Education (edu), Human health and social work activities (hht)
Wind power (wnd)	Wind base load power generation (WindBL)		Water and waste (wts)	Water (wtr)
			Water transportation (wtp)	Water transport (wtp)

The calibration of the ENV-Linkages model *Baseline* scenario

The Baseline scenario is carefully calibrated to offer a credible projection of economic activity by 2050 without ambitious climate action but including the impact of existing and stated policies. The Baseline calibration includes technological progress through various productivity parameters (e.g. autonomous energy efficiency improvements and labour productivity improvements). Particular attention is given to the calibration of the energy sector, including power generation and energy demand.

The ENV-Linkages model is calibrated using the GTAP 10 database (Aguiar et al., 2019[24]) for 2014. The Baseline scenario follows the projected population trends of the World Population Prospects (United Nations, 2018[42]) ("medium scenario"). For OECD countries and a number of emerging economies, the macroeconomic projections follow the OECD's short-term economic forecasts (OECD, 2021[43]) and the long-term projections of OECD Economics Department (Guillemette and Turner, 2021[19]).[1] For regions that are not covered by the OECD databases, short-term economic forecasts of the International Monetary Fund (IMF, 2020[44]) are combined with long-term macroeconomic projections from the OECD ENV-Growth model, which expands the OECD long term projections methodology to other countries (OECD, 2022[25]).

Specific assumptions are made in the *Baseline* regarding public finances. By definition for a business-as-usual scenario, almost all tax and subsidy rates are held constant over time. The first exception to this rule is support to fossil fuel production and consumption, which are updated between 2014 and 2019 using external data (see Annex B). The second exception if carbon prices, which follow the trajectory projected by the World Energy Outlook. The final exception is income tax rates, which adjust such that the public deficit follows a trajectory projected by the OECD Economics Department and ENV-Growth model (measured in percentage of GDP). These macroeconomic trends are complemented by sector-specific information on productivity growth, energy production and energy efficiency. For example, land and capital productivity in agricultural sectors are from the IMPACT model (Robinson et al., 2015[45]), while labour productivity in manufacturing is assumed to grow 2 percentage points faster per year compared to services. Power production and energy demand (by households, manufacturing and services) are calibrated using information from the Stated Policies Scenario (STEPS) from the IEA World Energy Outlook (IEA, 2021[14]). However, the global energy trends in ENV-Linkages' Baseline scenario do not match those of IEA's STEPS scenario as a number of key drivers of the energy system, especially on the demand side, are endogenous in the model.

[1] The *Baseline* scenario is used to calibrate trends in labour productivity that guarantee the matching of OECD projected GDP. This level of labour productivity is then used in other scenarios to allow GDP to vary.

Modelling process CO_2 emissions in ENV-Linkages

Definition and abatement modelling

While combustion emission abatement is common in CGE models (an increase in carbon price will lower demand for the more emission-intensive energy carriers), non-combustion emissions deserve a specific modelling to accurately represent abatement possibilities. This modelling covers process emissions (CO_2, CH_4 and N_2O emissions produced during industrial processes, e.g. the calcination of carbonates during cement production results in the release of process CO_2 emissions to the atmosphere), fugitive emissions (e.g. leaks in fossil fuel extraction sectors) as well as emissions associated with capital use (e.g. CH_4 emissions from enteric fermentation) or land use (e.g. CH_4 emissions from rice cultivation), for which end-of-pipe measures can be taken to reduce emissions beyond the simple reduction in corresponding activity level.

Two main approaches cohabit in CGE models to handle such emissions, that were introduced respectively in Hyman et al. (2002[41]) – for non-CO_2 greenhouse gases (GHG), where GHG emissions enter the production function directly, with a small price level for calibration – and in Fæhn and Isaksen (2016[46]). This paper elaborates on Fæhn and Isaksen (2016[46]) because we identified that the Hyman et al. (2002[41]) applied in the ENV-Linkages context led to model homogeneity problems: the mitigation level and cost depended on the units chosen (tonnes or tonnes of CO_2 equivalent ; as well as the small price level used for initialization).

The top of ENV-Linkages production is represented by structure presented in Figure A.1, where for each region r, activity a, vintage v and year t, $xpx_{r,a,v,t}$ is the sector output (with price $pxp_{r,a,v,t}$), made of a combination of value added $va_{r,a,v,t}$ (with price $pva_{r,a,v,t}$) and intermediate consumption $nd1_{r,a,v,t}$ (with price $pnd1_{r,a,v,t}$) using a CES function with elasticity σ^p. Taking into consideration the potential TFP and efficiency levels λ (basically constant at 1), this translates into the following equations:

$$\left(TFP^{xpx}_{r,a,t}\cdot pxp^{T}_{r,a,v,t}\right)^{1-\sigma_p} = and1_{r,a,v,t}pnd1^{1-\sigma_p}_{r,a,v,t} + ava_{r,a,v,t}pva^{1-\sigma_p}_{r,a,v,t}$$

$$TFP^{xpv}_{r,a,v,t}uc_{r,a,v,t} = axp_{r,a,v,t}\frac{pxp_{r,a,v,t}}{\lambda^{xp}_{r,a,v,t}}$$

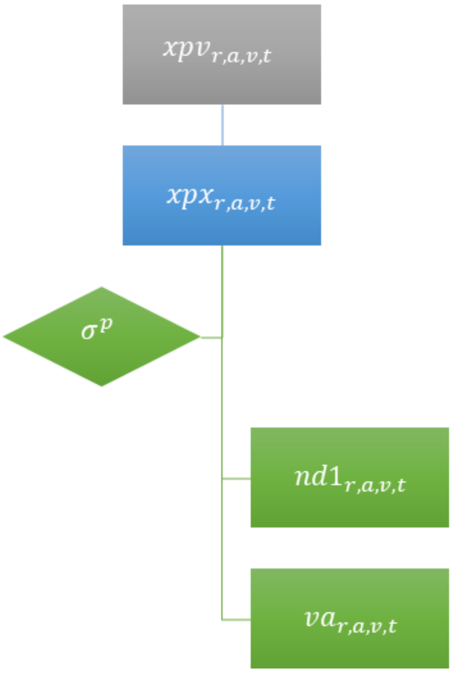
$$xpx_{r,a,v,t} = axp_{r,a,v,t}\left(\frac{xpv_{r,a,v,t}}{TFP^{xpv}_{r,a,v,t}\lambda^{xp}_{r,a,v,t}}\right)$$

Where $uc_{r,a,v,t}$ is the unit cost of production. We introduce an upper level of production $xpv_{r,a,v,t}$ with price $pxv_{r,a,v,t}$) whose price will include process and fugitive emission pricing $PEmissAct_{r,a,t}$:

$$pxv_{r,a,v,t} = uc_{r,a,v,t}\left(1 + uctax_{r,a,v,t}\right) + PEmissAct_{r,a,t}$$

Where $PEmissAct_{r,a,t} = \sum_{em,s} emiTax_{r,em,s,a,t} * emiract_{r,em,s,a,t}$, i.e. the sum over all compound em (CO_2, CH_4 and N_2O) and source s (process and fugitive) of all emission pricing $emiTax_{r,em,s,a,t}$ times emission intensity of activity $emiract_{r,em,s,a,t}$.

Figure A.1. Top of ENV-Linkages production function



Source: own elaboration based on (Chateau, Dellink and Lanzi, 2014[10])

We build on the Fæhn and Isaksen (2016[46]) approach by further defining how emission factors are calculated:

$$emiract_{r,em,s,a,t} = emiract0_{r,em,s,a} - \frac{Xemi_{r,em,s,a,t}}{\sum_v xpv^T_{r,a,v,t}}$$

Where $Xemi_{r,em,a,t}$ is the (endogenous) abatement level and $emiract0_{r,em,s,a}$ the initial emission factors stemming from emissions accounts. For better scaling of the model and simpler notations, let's define $XEmiAbat_{r,em,a,t} = Xemi_{r,em,a,t}/\left(emiract0_{r,em,a} \sum_v xpv^T_{r,a,v,t}\right)$ and ultimately:

$$emiract_{r,em,s,a,t} = emiract0_{r,em,s,a}\left(1 - XEmiAbat_{r,em,s,a,t}\right)$$

By extension, we can similarly define an abatement in emission factor on factor-based emissions:

$$emirfp_{r,em,s,a,t} = emirfp0_{r,em,s,a}\left(1 - XEmiAbat_{r,em,s,a,t}\right)$$

Compounds still covering CO_2, CH_4 and N_2O, but this time emission sources covering land and capital related emission sources (rice, liming, manure management, enteric fermentation, land).

Abatement cost

Let's assume we have a marginal abatement cost $c\left(Xemi_{r,em,s,a,t}\right)$. The total cost paid by the producer to abate a certain level of emission $Xemi^{tot}_{r,em,s,a,t}$ is:

$$XIceberg_{r,em,s,a,t} = \int_0^{Xemi^{tot}_{r,em,s,a,t}} c\left(Xemi_{r,em,s,a,t}\right) dXemi_{r,em,s,a,t}$$

If we assume that this cost is an iceberg cost (a part of production xpx that is lost in the process of abatement), we can write:

$$\sum_v xpv^T_{r,a,v,t} = \sum_v \frac{TFP^{xpv}_{r,a,v,t}\cdot \lambda^{xp}_{r,a,v,t}}{axp_{r,a,v,t}} xpx^T_{r,a,v,t} + \sum_{em,s} \text{X}Iceberg_{r,em,s,a,t}$$

For better scaling of the model, let's define $\text{X}IcebergAbat_{r,em,s,a,t} = \frac{\text{X}Iceberg_{r,em,s,a,t}}{\sum_v xpx^T_{r,a,v,t}}$

$$\sum_v xpv^T_{r,a,v,t} = \sum_v \frac{TFP^{xpv}_{r,a,v,t}\cdot \lambda^{xp}_{r,a,v,t}}{axp_{r,a,v,t}} xpx^T_{r,a,v,t} + \sum_v \sum_{em,s} XIcebergAbat_{r,em,s,a,t}\ xpx^T_{r,a,v,t}$$

And

$$\sum_v xpv^T_{r,a,v,t} = \sum_v xpx^T_{r,a,v,t} \left(\frac{TFP^{xpv}_{r,a,v,t}\cdot \lambda^{xp}_{r,a,v,t}}{axp_{r,a,v,t}} + \sum_{em,s} \text{X}IcebergAbat_{r,em,s,a,t} \right)$$

As such, this iceberg cost implementation is equivalent to defining a new TFP, $\widetilde{TFP}^{xpv}_{r,a,v,t}$ as

$$\widetilde{TFP}^{xpv}_{r,a,v,t} = TFP^{xpv}_{r,a,v,t} + \frac{axp_{r,a,v,t}}{\lambda^{xp}_{r,a,v,t}} \sum_{em,s} \text{X}IcebergAbat_{r,em,a,t}$$

And we have still

$$\sum_v xpv^T_{r,a,v,t} = \sum_v xpx^T_{r,a,v,t} \left(\frac{\widetilde{TFP}^{xpv}_{r,a,v,t}\cdot \lambda^{xp}_{r,a,v,t}}{axp_{r,a,v,t}} \right)$$

MACCs functional forms

The level of abatement and the cost of such abatement depend on the marginal abatement cost curves (MACCs) chosen, under particular constraints. First, for a simple implementation in a CGE framework, smooth derivatives are needed for the MACCs. Second, information on abatement levels is not often available, and the MACCs need to be derived from very few data points (particularly regarding process CO_2 emissions according to our literature review). To take these constraints, we propose the following formulation for the MACCs:

$$\text{X}EmiAbat_{r,em,a,t} = abat(\text{p}) = \overline{\text{abat}} * \frac{p}{\bar{p} * \frac{1-s}{s} + p}$$

Where p is short for the emission pricing $emiTax_{r,em,s,a,t}$, $\overline{\text{abat}}$ the maximum abatement feasible (at infinite carbon price) and s the share of total abatement that is achieved at base price $\bar{p}$. Inverting this function yields, for a given level of abatement X:

$$c(\text{X}) = \bar{p}.\frac{1-s}{s}.\frac{\text{abat}/\overline{abat}}{1-\text{abat}/\overline{abat}} = \bar{p}.\frac{1-s}{s}.\frac{\text{X}/\ \overline{abat}.emiract0_{r,em,a}\cdot \sum_v xpv^T_{r,a,v,t}}{1-\text{X}/\ \overline{abat}.emiract0_{r,em,a}\cdot \sum_v xpv^T_{r,a,v,t}}$$

The total abatement costs for a total abatement of $\text{X}emi_{r,em,a,t}$ is given by:

$$\text{X}Iceberg_{r,em,a,t} = \int_0^{\text{X}emi_{r,em,a,t}} c(\text{X}) d\text{X}_{r,em,a,t}$$

Using integration by substitution, substitution for $u = 1 - \frac{\text{X}}{\overline{abat}.emiract0_{r,em,a}\cdot \sum_v xpv^T_{r,a,v,t}}$, and then replacing back, we get the following formulation for total abatement:

$$\text{X}IcebergAbat_{r,em,a,t} = -\frac{\sum_v xpv^T_{r,a,v,t}}{\sum_v xpx^T_{r,a,v,t}}.\bar{p}.\frac{1-s}{s}.\overline{abat}.emiract0_{r,em,a}\cdot \left[\ln\left(1 - \frac{\text{X}EmiAbat_{r,em,a,t}}{\overline{abat}}\right) + \frac{\text{X}EmiAbat_{r,em,a,t}}{\overline{abat}} \right]$$

Data and calibration of MACCs

We calibrate our MACCs based on a literature review, summarized in Table A3.

Table A.3 Data used to calibrate ENV-Linkages non-combustion MACCs

Sector	GHG	Source	Gtap sector	Source	Details
Non-metallic minerals (Cement)	CO2	Process	nmm	McKinsey (2020[47]), International Energy Agency (2018[48])	Maximum abatement of 30% (27-30% range)
Iron & Steel	CO2	Process	i_s	Sun et al. (2022[49]), Yu et al. (2018[50])	Maximum abatement of 45% (23-45% range)
Chemicals (Ammonia)	CO2	Process	chm	The Royal Society (2020[51])	Maximum abatement of 30% (15% range)*
Refineries	CO2	Fugitive	p_c	(Byrum, Pilorgé and Wilcox, n.d.[52]), (Johansson et al., 2012[53]), (Chan et al., 2016[54])	Maximum abatement of 10% (0—10% range)
Fugitive emissions (oil and gas)	CO2	Fugitive	oil, gas	(Laconde, 2018[55])	Maximum abatement of 95% (100% range, but infeasible for the model)
	CH4	Fugitive	oil,gas	U.S. EPA (2019[56])	Category ENERGY,COL
Fugitive emissions (coal)	CO2	Fugitive	coa	(Laconde, 2018[55])	Maximum abatement of 95% (100% range, but infeasible for the model)
	CH4	Fugitive	coa	U.S. EPA (2019[56])	Category ENERGY,GAS
Waste management	CO2	Process	wtr	(Bogner et al., 2008[57])	Maximum abatement of 95% (100% range, but infeasible for the model)
	CH4	Process	wtr	U.S. EPA (2019[56])	Category WASTE,WWR
	N2O	Process	wtr	U.S. EPA (2019[56])	Category WASTE,WWR
Aluminium	CO2	Process	nfm	(International Aluminium, 2021[58])	Maximum abatement of 95%
VegAgr	N2O	Land	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk	U.S. EPA (2019[56])	Category AGRICULTURE,CROP
	CH4	Rice	pdr	U.S. EPA (2019[56])	Category AGRILCULTURE,RICE
AnimAgr	CH4	Manure management	ctl, oap, rmk	U.S. EPA (2019[56])	Category AGRICULTURE,LIVE
	CH4	Enteric fermentation	ctl, oap, rmk	U.S. EPA (2019[56])	Category AGRICULTURE,LIVE

Notes: * For chemicals, the large number of different chemicals produced by the sector make difficult to determine an aggregate abatement potential based on figures for Ammonia only. Therefore, an arbitrary value of twice the Ammonia emissions is retained.
Source: Own elaboration.

B. Modelling of the NZE Ambition scenario policy instruments

Overview of the calibration strategy

The NZE Ambition scenario is composed of the following policy instruments:

- Carbon pricing
- Fossil fuel support removal
- Regulations in the power sector to enforce a switch away from fossil fuels
- Regulations to stimulate investments to decarbonise building and transport emissions
- Policies to stimulate firms' energy efficiency improvement
- Subsidies to decarbonise household consumption

Instruments other than carbon pricing and fossil fuel support removal are calibrated using preliminary scenarios, because calibrating all the required endogenous variables at the same time using multiple MCP is too complex in a large-scale model like ENV-Linkages for the solver to find easily a solution. Therefore, a total of 16 scenarios are implemented to calibrate the full set of instruments:

1. For each of the four activities group (Power, Transport services, Other services, Households), a scenario calibrating energy efficiency or energy mix.
1. For each of the four activities group, and for each instrument type (regulation or subsidy), a scenario calibrating input efficiency or subsidies rate, on top of the same assumptions as step 1.
2. Four scenarios gathering the information from steps 1 and 2: regulation for households and regulation for firms, regulation for households and subsidies for firms, subsidies for households and regulation for firms, and finally regulation for households and regulation for firms.

The calibration steps 1 and 2 use information for the World Energy Outlook 2021 (IEA, 2021[14]), as described at the end of this annex.

In the end, only the 3rd step is used the results for the combination of policy instruments other than carbon pricing and fossil fuel support removal. This 3rd step corresponds to the scenario used in Section 4 called "*NZE Ambition* excl. carbon pricing and FFSR".

Ultimately, the *NZE Ambition* gathers all the previously calibrated information, on which are added carbon pricing and removal of fossil fuel support.

Carbon pricing

Modelling of carbon prices

Carbon pricing increases the price of carbon-intensive energy sources compared to other sources. This additional pricing based on the carbon content of production and consumption leads to higher prices of emission-intensive commodities, inducing (i) an increase in expenditures to improve energy efficiency, and (ii) a shift in demand away from these commodities towards less emission-intensive commodities.

For fossil fuel combustion emissions, the carbon price increases the price of energy depending on the GHG emission factor of the fossil fuel commodity: the additional cost is therefore the highest for coal, while it is lower for gas. For non-combustion emissions, the emissions are linked to the production or production factor level instead of the fossil fuel content. The carbon price therefore acts as an incentive to deploy end-of-pipe type mitigation actions, where emissions factors can decrease at the cost of a lower productivity (more inputs and factors are needed to produce the same amount of output). As such, mitigation actions are implemented as long as their productivity cost is lower than the carbon price. The relation between carbon price, emissions abated, and corresponding costs is calibrated based on the mitigation potentials in each sector responsible for non-combustion GHG emissions (see Annex A).

Determination of emissions targets in the NZE Ambition scenario

2030: Nationally determined contribution (NDCs)

In 2030, the emission targets correspond to countries' NDCs. The data from the Climate Watch database (Climate Watch, 2022[16]) is aggregated and converted to a homogenous metrics: the level of emissions in 2030. This analysis covers three types of NDC. First, for countries which pledged for an absolute reduction (a reduction in percentage point compared to a point in history, often 1990), the target level of emissions in 2030 is recovered by applying the percentage reduction to emissions as measured in the EDGAR v6 database (Crippa et al., 2021[59]). For countries whose NDC consist in a reduction in the carbon intensity of GDP, the EDGAR v6 emissions and the GDP projections from the ENV-Growth model (the same used for the ENV-Linkages baseline) are combined to compute the level of emissions in 2030. For countries whose pledge is labelled as a percentage reduction from a Business-as-Usual scenario, the target for 2030 is computed using the CO_2 emissions from the ENV-Linkages *Baseline*.

2050: Carbon neutrality for regions with an NZE commitment for 2050, and on the path to carbon neutrality by 2060 for others

Setting region-specific NZE targets required making assumptions about the level of "gross" emissions (i.e. without accounting for carbon sequestration) that each region will reach in 2050. The Climate Watch database

(2022[16]) is used to assess how advanced countries are in setting targets. This dataset collects data on targets and on the way these targets are set up in domestic policies: in the law, in a policy document, in a declaration, only proposed or not envisaged. This paper uses a very broad definition of commitment to net-zero emissions by considering that countries with a target set in a policy document or more are committed to net zero. This information gives the list of regions in ENV-Linkages that will be assumed to reach net-zero GHG emissions by 2050 in the scenario.

The level of gross emissions in 2050 is defined as the level of carbon sequestration the same year, hence defining carbon neutrality. However, the ENV-Linkages model does not currently represent carbon sequestration. Therefore, three pieces of information are gathered: one for carbon sequestration from Agriculture, Forestry and Other Land Use (AFOLU), one for emissions avoided through Carbon Capture, Utilization and Storage (CCUS) and one for Negative Emission Technologies (NETs). AFOLU sequestration by region is provided by the PBL IMAGE dataset (Van Vuuren et al., 2021[31]), in a 2°C compatible pathway. CCUS and NETs usage is provided by IEA (2021[4]), for the global level of respectively 5.7 Gt of CCUS and 1.9 Gt sequestered using NETs in 2050. Ultimately, the level of gross emissions targeted in 2050 corresponding to carbon neutrality is recovered by adding AFOLU and NETs sequestration: net-zero emissions are reached when gross emissions balance carbon sequestration.

For the regions that do not have yet a pledge to reach carbon neutrality by 2050, the *NZE Ambition* scenario start from the assumption that they will collectively achieve carbon neutrality by 2060. The 2050 milestone in gross GHG emissions for this group of regions is set as a linear interpolation between GHG emissions level in 2030 and the level of carbon sequestration from AFOLU in 2060 from IMAGE, plus the level of NETs following the same method as above.

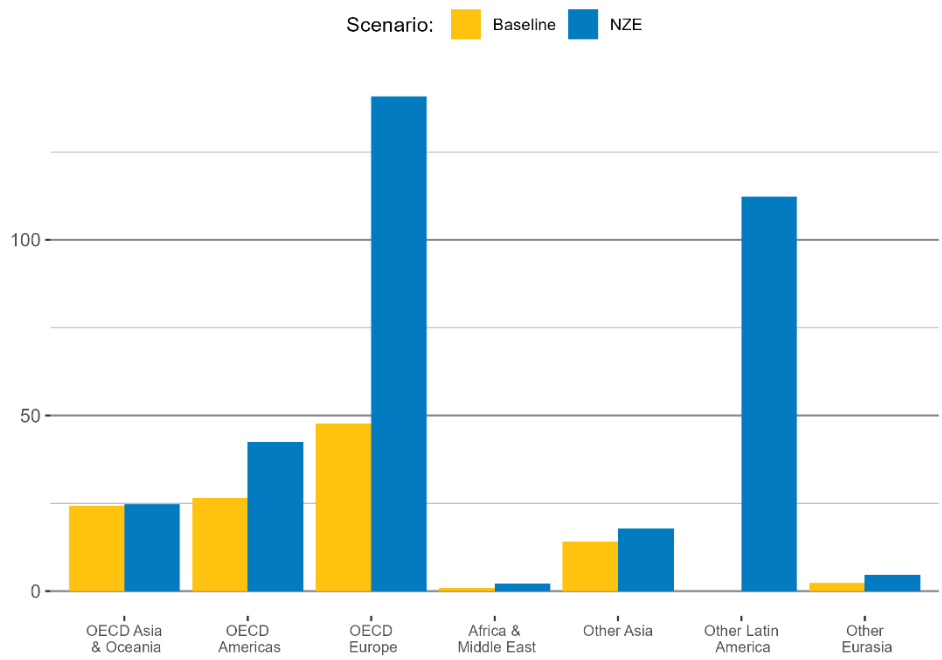
Resulting carbon prices

As a result of the assumption in the NZE Ambition scenario described above, the model determines the level of carbon pricing that is necessary to achieve the emission targets. These average levels are depicted in Figure B.1.

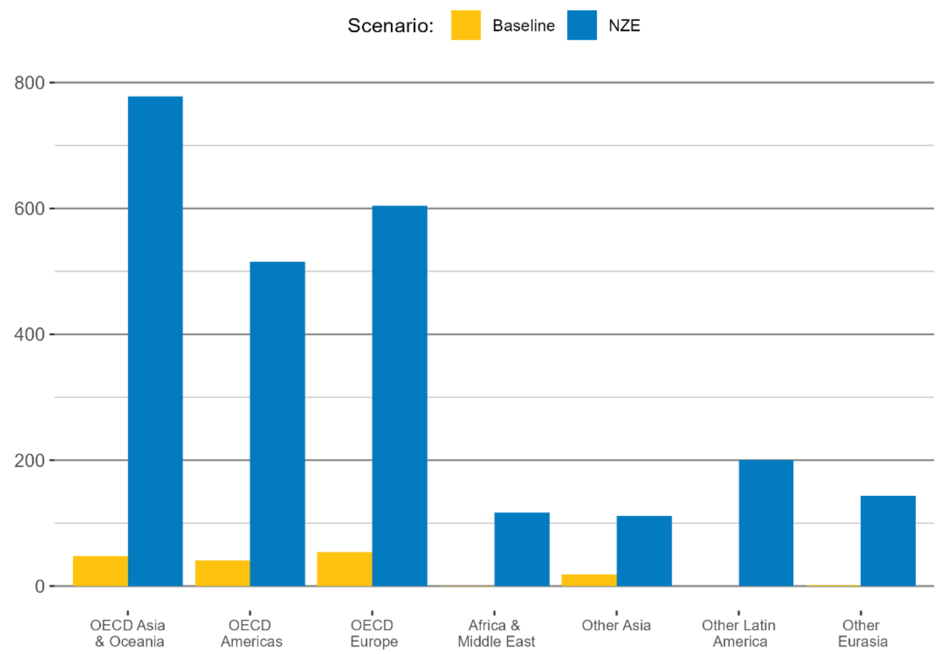
Figure B.1: The NZE Ambition scenario requires high carbon prices to reach emission targets in 2050

Average carbon price on CO_2 emissions (constant 2014 USD)

Panel A. 2030



Panel B. 2050



Fossil fuel support removal

The fossil fuel support data used in the ENV-Linkages model are mainly constructed from a sector-detailed version of the OECD Inventory of support measures for fossil fuels (the "Inventory") (OECD, 2022[22]) for the years 2014 and 2019. This data set contains information for two kinds of beneficiaries, producer (PSE) and consumer (CSE). Measures falling under the Inventory's general services support (GSSE) are not included in this analysis. Several economic activities are mapped to ENV-Linkages through ISIC Rev.4 codes that were provided by both sources. When the classification codes are not available, the concordance is reached using the sectors' description provided. When fossil fuel support inventory sectors or energy commodities are more aggregated than in the GTAP database, fossil fuel support is downscaled based on GTAP energy data.

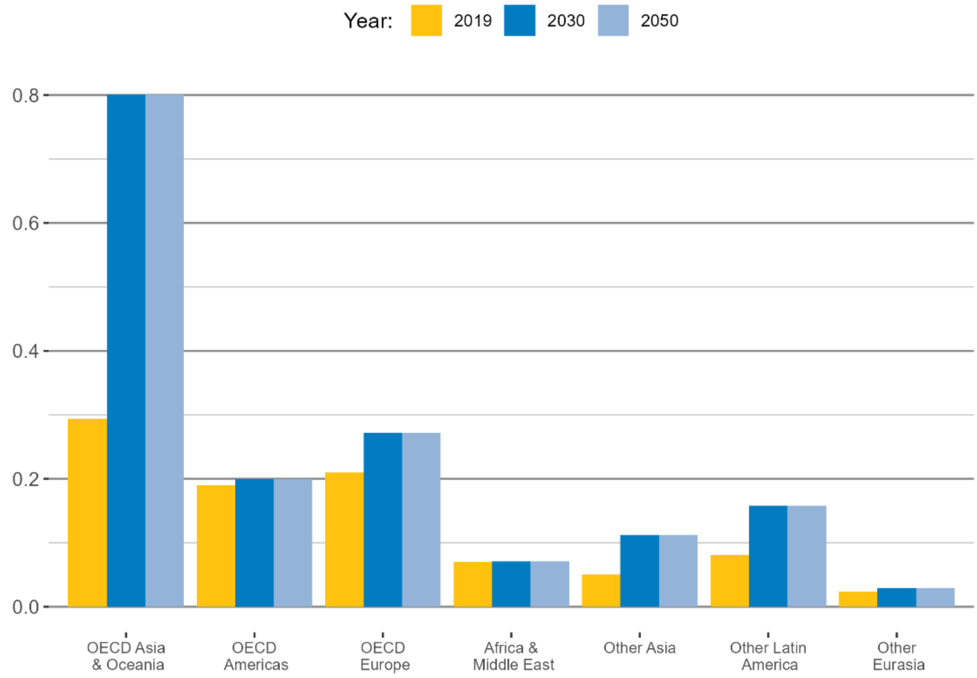
Finally, the dataset is extended with additional data gathered from the IEA Fossil Fuel Support Database (IEA, 2021[23]) for the years 2014 and 2019. This is because the OECD Inventory currently covers fossil fuel support in 50 OECD countries, G20 and Eastern Partnership (EaP) economies. The IEA Database instead contains figures about consumer fossil fuel subsidies for around 40 emerging economies where there is an existence of a lower consumer end-use price of fossil fuels relative to the international reference price, particularly seen in major oil-producing countries.

The ENV-Linkages model assumes that all the support corresponds to a subsidy on production (for producer support) or on consumption (for consumer support). The corresponding tax rates are recovered in the model by splitting net production tax revenues and net consumption tax revenues between (i) negative revenues from fossil fuel subsidies and (ii) other (positive or negative) revenues. In *the NZE Ambition* scenario, only the fossil-fuel support parts of production and consumption taxation are phased out. The resulting levels for net tax rates on fossil fuel production and consumption are depicted in Figure B.2 and Figure B.3.

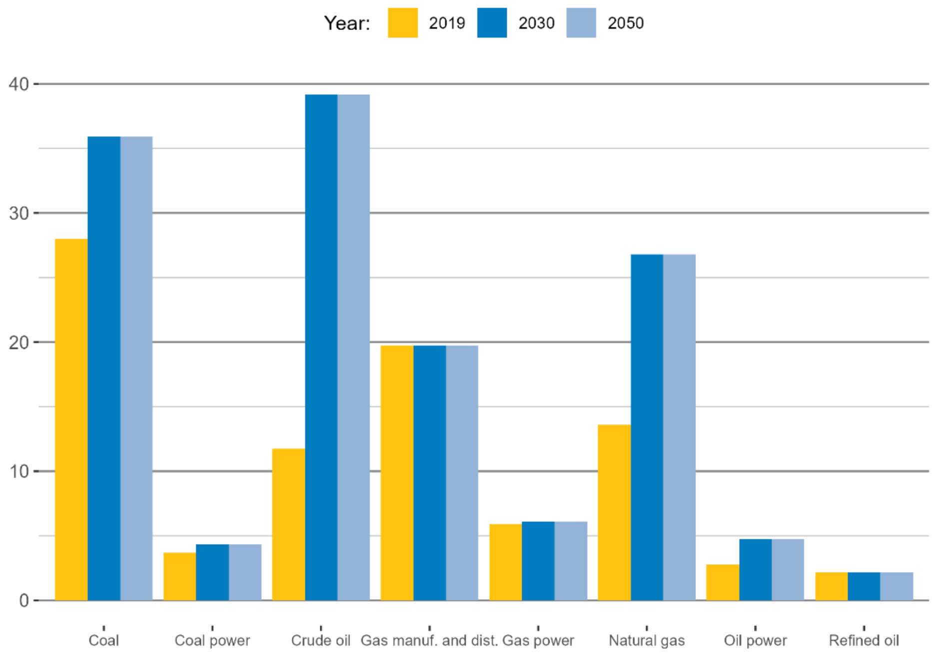
Figure B.2: The *NZE Ambition* scenario increases net tax rates on fossil fuel production and transformation

Average net tax rate on fossil fuel production in the NZE Ambition scenario (%)

Panel A. Average net tax rate on fossil fuel production by regions (%)



Panel B. Global average net tax rate on fossil fuel production and transformation by sector

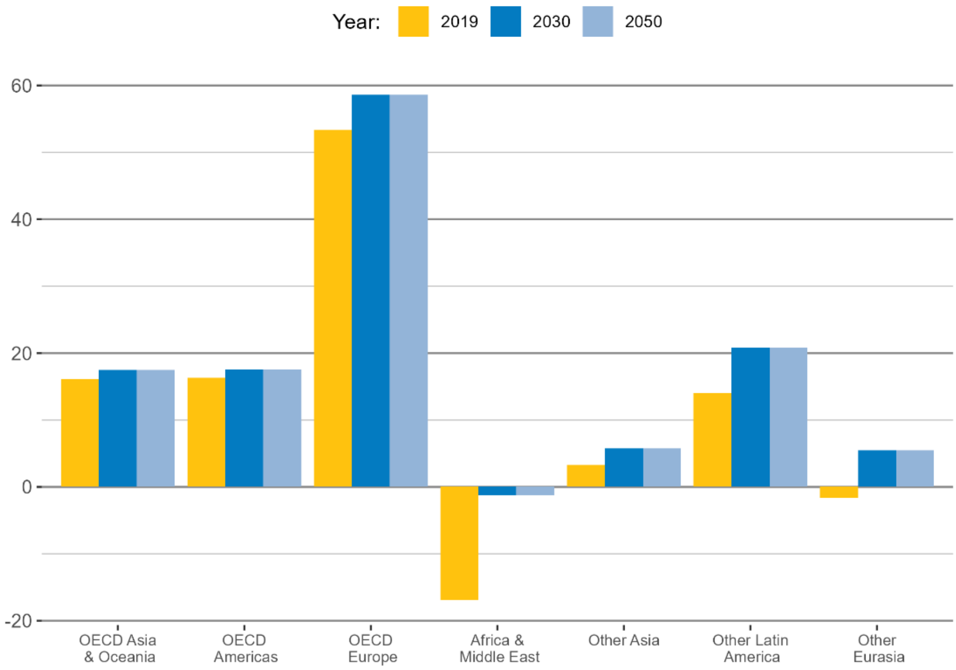


Notes: The figures presented are the arithmetic average of fossil fuel production net tax rate, weighted by the sector output in 2019.

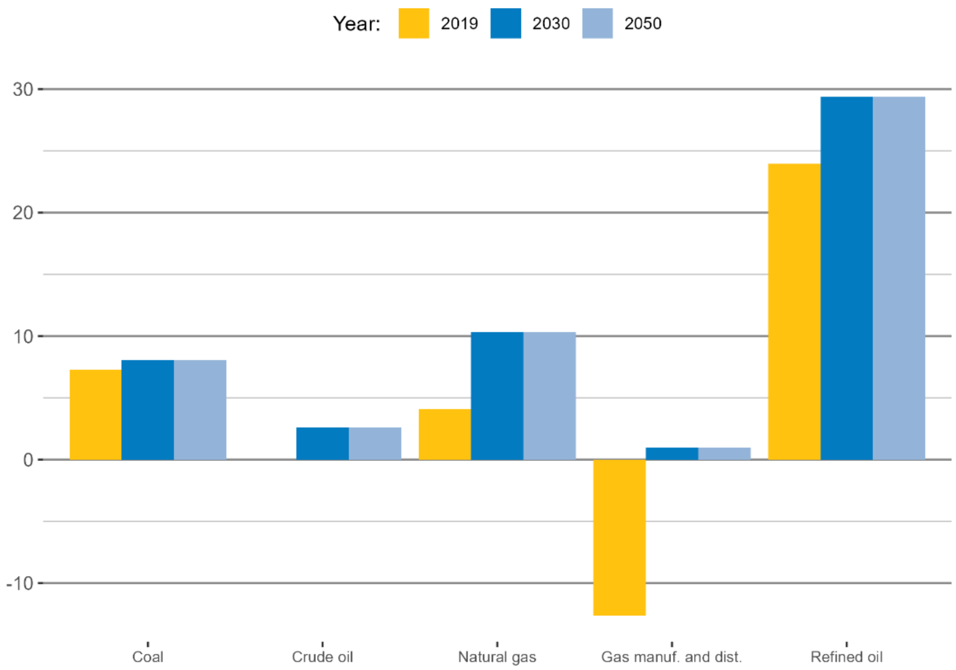
Figure B.3: The *NZE Ambition* scenario increases net tax rates on fossil fuel consumption

Average net tax rate on fossil fuel consumption in the NZE Ambition scenario (%)

Panel A. Regional average net tax rate on fossil fuel consumption



Panel B. Global average net tax rate on fossil fuel consumption



Notes: The figures presented are the arithmetic average of fossil fuel consumption net tax rate, weighted by demand in 2019.

Subsidies to decarbonise household energy consumption

Calibration of changes in household energy demand

For households, the preference parameter (similar to an efficiency) $\lambda^{ce}_{r,e,h,t}$ is calibrated in the preliminary step 1 trying to reproduce at best the as endogenously such that the energy demand by households follows the dynamics coming from external sources:

$$\lambda^{ce}_{r,e,h,t} : xa_{r,e,h,t} = xa_{r,e,h,t-1} \cdot \frac{EnergyDemand_{r,e,h,t}}{EnergyDemand_{r,e,h,t-1}}$$

Calibration of subsidies rates to decarbonize household energy consumption

The level of subsidy required to achieve the required level of expenditure is modelled through a decrease in consumption taxes. For each commodity i, activity a (households) in region r at time t, the level of consumption tax $paTax_{r,i,a,t}$ is defined as:

$$paTax_{r,i,a,t} : paTax_{r,i,a,t} = paTax^{BAU}_{r,i,a,t} + paTax^{cost}_{r,i,a,t}$$

Where $paTax^{BAU}_{r,i,a,t}$ is the level of consumption tax in the business-as-usual, corresponding to a fixed tax rate between 2014 and t and $paTax^{cost}_{r,i,a,t}$ is the endogenous subsidy (negative tax) calibrated to trigger the required expenditure for households. The calibration of policy instruments in preliminary scenarios is done through a mixed complementarity problem (MCP). This corresponds to the following equations:

$$paTax^{cost}_{r,i,a,t} : xa_{r,i,a,t} \geq xa^{BAU}_{r,i,a,t} + Expenditure_{r,i,a,t} \quad \perp \quad paTax^{cost}_{r,i,a,t} \leq 0$$

Where $xa_{r,i,a,t}$ is the level of consumption, $xa^{BAU}_{r,i,a,t}$ the level of consumption in the BAU scenario, $Expenditure_{r,i,a,t}$ the required cost for the transition. This formulation as an MCP problem allow for two different cases: (i) if expenditures are lower than the target value $xa^{BAU}_{r,i,a,t} + Expenditure_{r,i,a,t}$, then the endogenous tax $paTax^{cost}_{r,i,a,t}$ will be stricty lower than zero; (ii) if the level of expenditure is already sufficient without subsidy, then the endogenous subsidy remains at 0. This second case can happen when, for instance, the macroeconomic impact of the scenario lead to more revenues for households, who in turn increase their expenditure on vehicles or construction services.

Regulation targeting households

Although not used in the main *NZE Ambition* scenario, there is also a possibility to enforce household energy demand through regulation. Regulation targeting households also share the same principle, but due to structural differences in the way households final demand is implemented in the model (ELES demand function), it is the level of minimal consumption $\theta_{r,k,h,t}$ that is determined endogenously by the model. $\theta_{r,k,h,t}$ corresponds to the subsistence minimum for consumer in region r, for commodity k (consumer commodities are mapped to standard commodities i on a one-to-one basis excepted for energy goods that are aggregated in a single consumer commodity but is not concerned by regulations) by household h (there is only one household per region). The level of minimal consumption becomes:

$$\theta_{r,k,h,t} : \theta_{r,k,h,t} = \theta^{BAU}_{r,k,h,t} + \theta^{cost}_{r,k,h,t}$$

The corresponding MCP is the following:

$$\theta^{cost}_{r,k,h,t} : xc_{r,k,h,t} \geq xc^{BAU}_{r,k,h,t} + Expenditure_{r,k,h,t} \quad \perp \quad \theta^{cost}_{r,k,h,t} \geq 0$$

where $xc_{r,k,h,t}$ is the level of consumption, $xc^{BAU}_{r,k,h,t}$ the level of consumption in the BAU scenario and $Expenditure_{r,i,a,t}$ the required cost for the transition.

Regulation in the power sector to enforce a switch away from fossil fuels

Change in the power mix

In the Power sector, total power production is a Leontief function of all power generation technologies $elya$ (coal, oil, gas, nuclear, wind, solar, hydro, other) that are gathered into different power bundles pb (fossil, nuclear, hydro, renewables). The calibration step then consists in setting CES share parameters for each generation technology in power bundles $as_{r,elya,t}$ and the share of each power bundle in total power generation $apb_{r,pb,t}$ according to desired targets:

$$as_{r,elya,t} = \frac{PowerGeneration_{r,elya,t}}{\sum_{elya \in pb} PowerGeneration_{r,elya,t}}$$

$$apb_{r,pb,t} = \frac{\sum_{elya \in pb} PowerGeneration_{r,elya,t}}{\sum_{elya} PowerGeneration_{r,elya,t}}$$

Where $PowerGeneration_{r,elya,t}$ corresponds to the targeted power production coming from external sources.

Regulations to enforce the change in power mix

Regulations follow the same modelling logic as subsidies for household energy demand and are calibrated in the preliminary step 1, but it is the input efficiency $\lambda^{io}_{r,i,a,t}$ that is endogenously determined by the model:

$$\lambda^{io}_{r,i,a,t} : \lambda^{io}_{r,i,a,t} = \lambda^{io,BAU}_{r,i,a,t} / \lambda^{io,cost}_{r,i,a,t}$$

Where $\lambda^{io,BAU}_{r,i,a,t}$ is the input efficiency in the business-as-usual, and $\lambda^{io,cost}_{r,i,a,t}$ is the endogenous efficiency modifier calibrated to trigger the required expenditure in sector a. The calibration of policy instrument is done through the following MCP:

$$\lambda^{io,cost}_{r,i,a,t} : xa_{r,i,a,t} \geq xa^{BAU}_{r,i,a,t} + Expenditure_{r,i,a,t} \quad \perp \quad \lambda^{io,cost}_{r,i,a,t} \geq 1$$

where, as in the previous case, $xa_{r,i,a,t}$ is the level of consumption, $xa^{BAU}_{r,i,a,t}$ the level of consumption in the BAU scenario, $Expenditure_{r,i,a,t}$ the required cost of transition.

Subsidies to enforce the change in power mix

Although not used in the NZE Ambition policy package, it is also possible to enforce the change in power mix by subsidies. The modelling is then exactly identical to the subsidies for households.

Regulations to stimulate investments to decarbonize building and transport emissions

Calibration energy efficiency changes

Energy efficiency changes follow a very different logic in the production function. The level of efficiency $\lambda^e_{r,e,a,t}$ is determined endogenously by the model in preliminary step 1 such that energy intensity demand follow the dynamics coming from external sources:

$$\lambda^e_{r,e,a,t} : \frac{xa_{r,e,a,t}}{xp_{r,a,t}} = \frac{xa_{r,e,a,t-1}}{xp_{r,a,t-1}} . \frac{EnergyDemand_{r,e,a,t}/Production_{r,a,t}}{EnergyDemand_{r,e,a,t-1}/Production_{r,a,t-1}}$$

Where $xa_{r,e,a,t}$ is the demand for energy e by sector a in region r in ENV-Linkages; $xp_{r,a,t}$ is the production of sector a ; $EnergyDemand_{r,e,a,t}$ is the energy demand coming from IEA and $Production_{r,a,t}$ is the production coming from the same external source.

Regulations to enforce decarbonisation

Regulations for firms to decarbonize their transport and building emissions is identical to the regulations targeting the power sector.

Subsidies to enforce decarbonisation

Although not used in the NZE Ambition scenario, there is also a possibility to enforce decarbonisation of firms' transport and buildings energy demand by using subsidies. In that case, the modelling is identical to subsidies targeting households.

Policies to stimulate firms' energy efficiency improvement

In other economic sectors, due to the lack of detailed external information, energy efficiency follows a simple constant-growth-rate path:

$$\lambda^e_{r,e,a,t} : \lambda^e_{r,e,a,t} = \lambda^e_{r,e,a,t-1} \left(1 + g^{\lambda^e}_{r,e,a,t}\right)$$

Where $g_{r,e,a,t}^{\lambda^e}$ is exogenous and is set in the *NZE Ambition* scenario to 4% per year in Services and 3% per year in Industry. As a comparison, the values for the *Baseline* scenario are 3% and 2.5% respectively for Services and Industry.

Use of the World Energy Outlook 2021 data to calibrate policy instruments

While the Stated Policies Scenario (STEPS) and Sustainable Development Scenario (SDS) from the IEA are provided with regional detail, the information on NZE is only global. The energy information required in ENV-Linkages for our *NZE Ambition* scenario is therefore built as an extension of the SDS scenario using an external input-based approach (van Vuuren, Lucas and Hilderink, 2007[60]) that allows to reach the global objectives of the IEA's NZE scenario (IEA, 2021[4]), while keeping regional differences in the dynamics. This regional downscaling method implicitly assumes that (i) the SDS captures different dynamics across the macro-regions, allowing the distinction from the global trend; (ii) the NZE and SDS designs are based on a similar set of assumptions. Both these assumptions are likely to hold as SDS projections are heterogeneous between regions, and IEA defines the NZE scenario as an extension of the SDS (IEA, 2021[4]).

The downscaling methodology for the NZE scenario mainly consists of four steps:

3. For each variable x – e.g. investment in wind energy – and macro-region m – e.g. Japan – in the IEA's World Energy Outlook (WEO) database, the ratio between the SDS region-specific yearly growth rates (sds_m) and the SDS world yearly growth rate (sds_g) is computed. This provides a measure of the relative speed at which a variable in a specific region grows with respect to the same variable worldwide.
4. For each variable x and macro-region m the above-computed ratio is multiplied by the NZE world yearly growth rate (nze_g). This allows to determine the NZE region-specific yearly growth rates.
5. For each variable x and macro-region m SDS values in the starting year (2000) are assumed to coincide with the NZE ones. However, for few sectors – like investment variables – the SDS and NZE global starting values are not identical. In these cases, data harmonisation is provided such that the sums across macro-regions in year 2000 is equal to the NZE global value in year 2000.
6. For each variable *x* and macro-region *m* starting from 2000, the procedure iteratively multiplies the yearly value for the NZE region-specific yearly growth rates (nze_m). That is, the value of variable *x* at time *t+1* in macro-region *m* in the NZE scenario is the solution of:

$$x_{m,t+1} = x_{m,t} \times nze_{m,t+1}$$

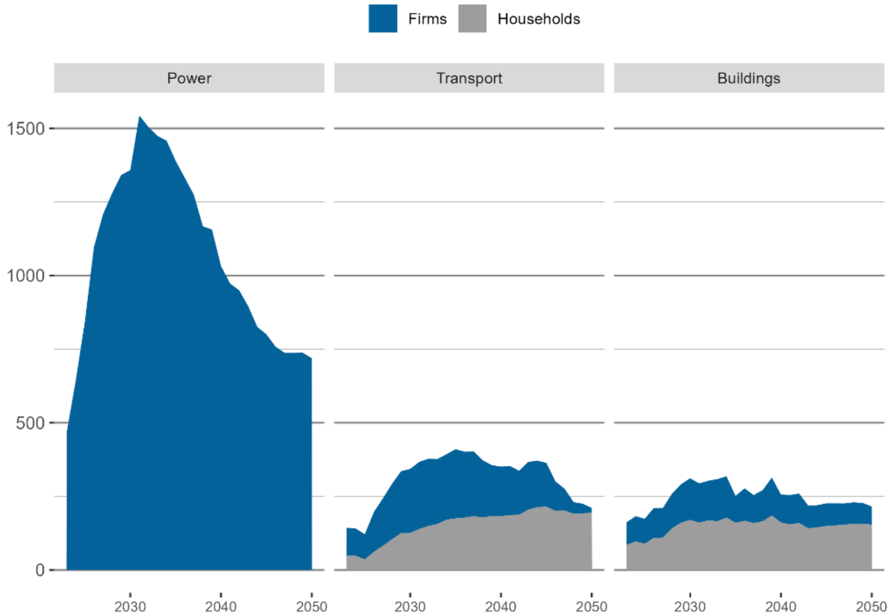
where:

$$nze_{m,t+1} = nze_{g,t+1} \times \left(\frac{sds_{m,t+1}}{sds_{g,t+1}}\right)$$

Figure B.4 shows the resulting levels of investment used to calibrate policy instruments.

Figure B.4: Levels of additional investments in the *NZE Ambition* scenario

Investments required in the NZE Ambition scenario by agent (billion constant 2014 USD)



Notes: Figures depicted here are lower than those published by the IEA because matching with ENV-Linkages agents and implementation in the *NZE Ambition* scenario was only possible for part of the costs: only efficiency investments in buildings are considered, and only investment in renewables and nuclear was considered in power.

C. Detailed modelling results

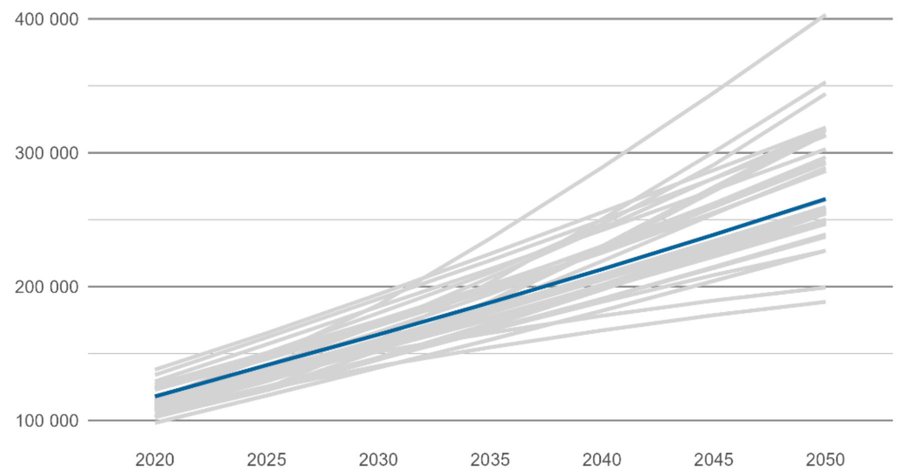
Baseline scenario

Comparing the ENV-Linkages Baseline to IPCC Working Group III scenarios

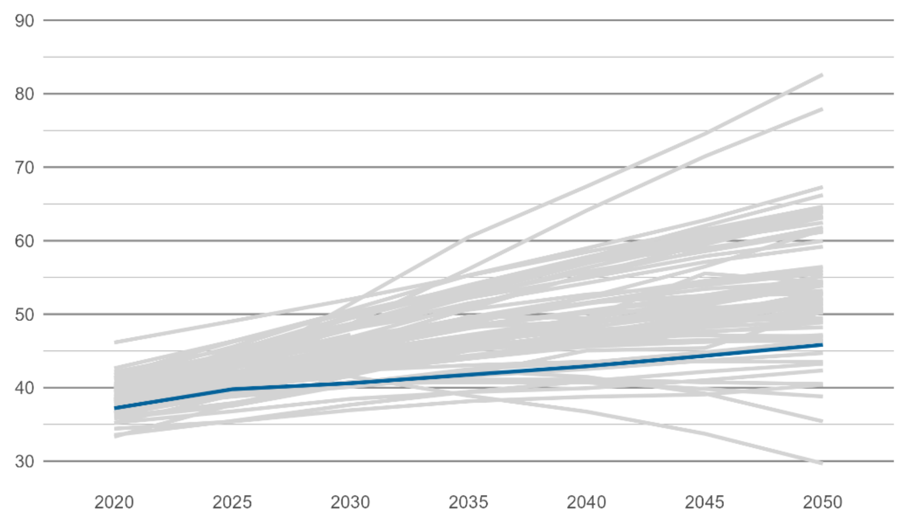
Comparing the ENV-Linkages *Baseline* with the set of scenarios presented in the 2022 IPCC Working Group III report (IPCC, 2022[61]), the *Baseline* appears in the medium range for economic growth, while in the low range for emissions (Figure C.1). This is due to the fact that the ENV-Linkages *Baseline*, as the World Energy Outlook (IEA, 2021[14]), takes into account existing as well as stated policies, while the majority of other baselines only take into account existing policies.

Figure C.1: The ENV-Linkages model *Baseline* falls within the IPPC AR6's range of projections

Panel A. Gross Domestic Product (Billion USD PPP)



Panel B. CO_2 Emissions (Gt)



Notes: ENV-Linkages projections are shown in blue. In grey all the "World" scenarios available in the IIASA AR6 Scenario Explorer.

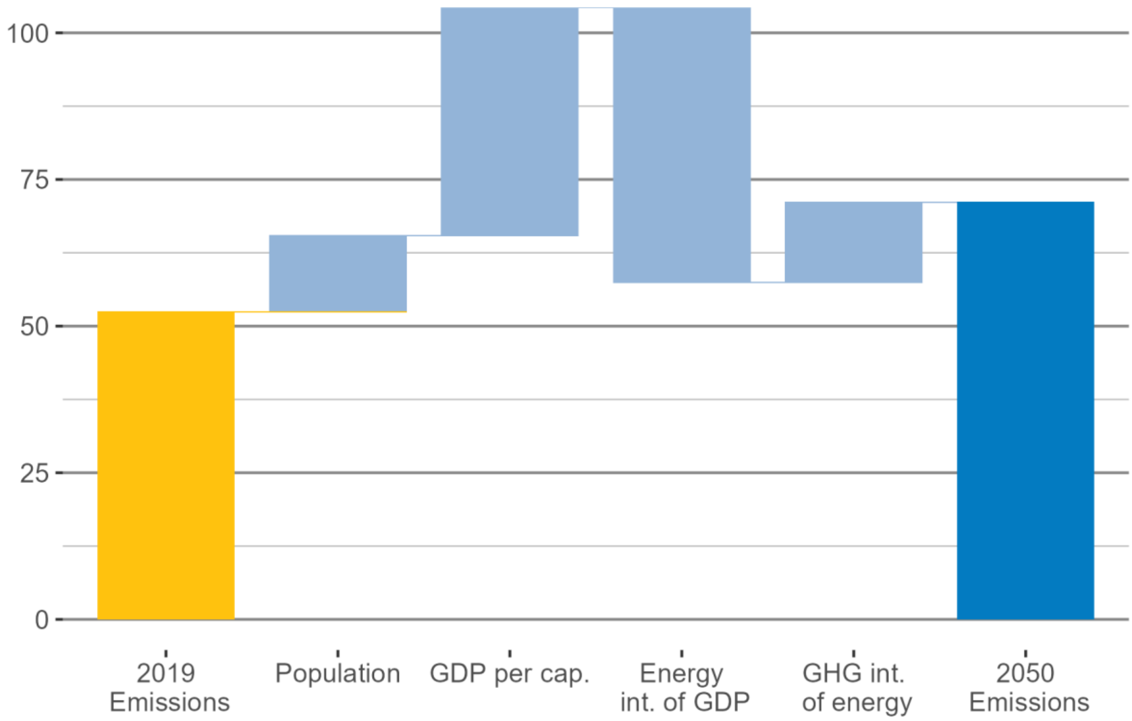
Drivers of changes in emissions

The *Baseline* growth in global emissions is the result of increasing scale effects from population and income growth, partially compensated by technology improvements (Figure C.2):

- Increases in *population* imply increased energy use and thus increased emissions; if each additional person would emit the same as the average person in 2019, global emissions would increase by about 13 Gt.
- Higher income (*GDP per capita*) levels are associated with increased production and consumption of goods and services. As virtually all economic activities use energy and emit greenhouse gases, the projected increase in economic activity leads to more GHG emissions. This income effect adds another 39 Gt of emissions by 2050.
- Energy efficiency and other technology improvements mean that over time less energy is needed to achieve the same production volumes in industry, i.e. the *energy intensity of GDP* declines. Furthermore, economic growth is projected to be larger in relatively clean services sectors than in industry, lowering the average energy efficiency of production. Together, this prevents around 47 Gt of emissions in 2060.
- The amount of GHG per unit of energy (the *CO_2 intensity of energy*) do not vary much in the *Baseline*: current and legislated policies lead to shifting away from fossil fuels but aren't strong enough to induce reductions in process emissions.

Figure C.2: Scale increases between 2019 and 2050 outweigh technology improvements in absence of more stringent policies

Decomposition of global emission variation between 2019 and 2050, *Baseline* scenario (Gt)



These global developments hide significant differences across countries and sectors. Furthermore, over time, some sectoral economic activity shifts across countries, and this affects the average GHG intensity of the global economy. For example, even if emission intensity of production decreases in all countries, shifts in economic activity from less towards more emission-intensive regions can result in an increase in the global average emission intensity.

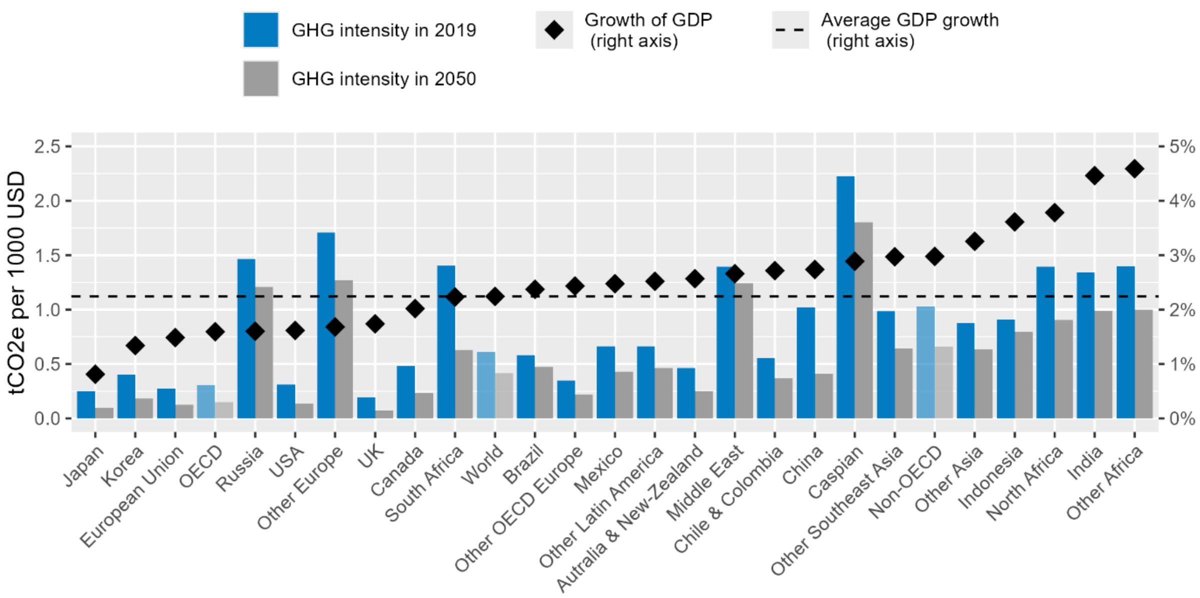
Changes in regional economic growth

Differences in growth rates of the economies of various countries significantly affect global emissions, as different countries specialise in different sectors and use different production techniques; furthermore, the energy system varies widely across countries. While the world economy is projected to grow at an average of 2.2% per year (Figure C.3), growth rates vary significantly across countries. Economic growth is projected to be relatively slow in OECD countries. It is higher in emerging and developing economies, as in these economies living standards converge towards those of richer countries. Indeed, regions' economies grow at different rates, ranging from 0.8% to 4.6%, with the highest levels of growth taking place in India and Sub-Saharan Africa (Other Africa). This results in a shift in the world economic balance from current industrialized countries to emerging and developing economies.

Countries with high GDP growth between 2019 and 2050 tend to have high GHG intensity of GDP (i.e. the combination of energy intensity of GDP and GHG intensity of energy) in 2019. Therefore, even though in all countries the intensity of GHG decreases, the GHG intensity of the global economy declines relatively little (thus with limited effect in driving global GHG emission changes, as shown in Figure C.3).

The projected changes in regional emissions highlight the need for global action to mitigate GHG emissions. Without limiting emissions in all countries, it will not be possible to achieve carbon neutrality at global level by the middle of the century. Countries with projected high emission intensity in the *Baseline* can also be expected to incur higher transition costs as it will be more difficult for them to green their economies.

Figure C.3: Most GDP growth in the *Baseline* scenario occurs in relatively emission-intensive regions

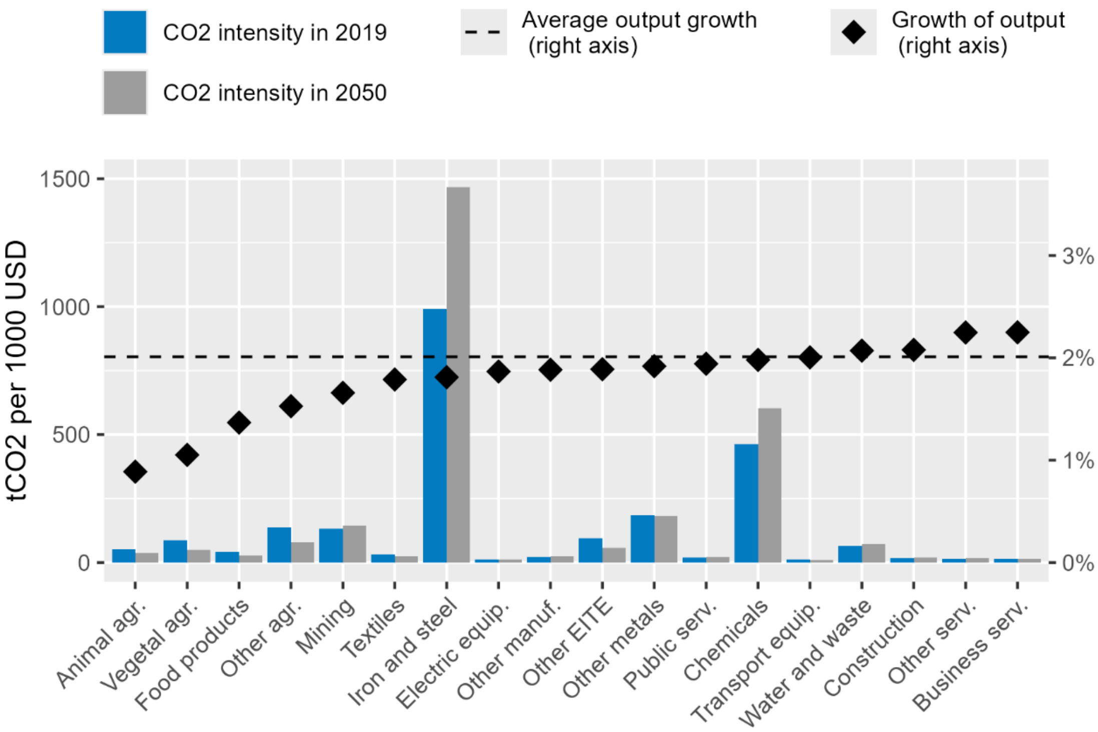


Sectoral changes

The structure of the economy changes over time as not all sectors grow at equal pace. On balance, at global level economic activity tends to shift over time to less emission-intensive sectors (Figure C.4). Indeed, with economic development, economies move towards services (this is referred to as "servitisation"). Emission intensive sectors, such as Iron and Steel and Mining instead grow less than the economy average.

Besides shifts between sectors that help gradually decarbonise the economy, the *Baseline* scenario includes energy efficiency improvements in each sector that result from energy efficiency improvements. These lead to a decrease in the average global CO_2 intensity of production in most sectors, such as the agricultural sectors. In many energy-intensive sectors, including Iron & Steel and Chemicals, regional technology improvements are outweighed by a regional shift in production from more energy-efficient to less energy-efficient regions, inducing an increase in global average CO_2 intensity of these sectors over time.

Figure C.4: Emission intensity in the *Baseline* scenario decreases thanks to a shift towards less emission-intensive sectors



Notes: "agr." = "agriculture", "manuf."="manufacturing", "serv."="services, "equip."="equipment".

NZE Ambition scenario

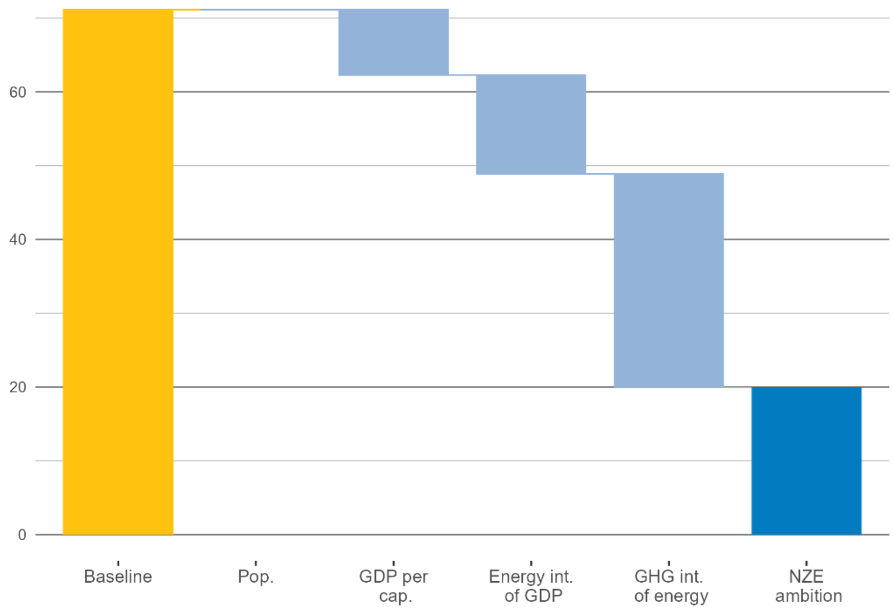
Decomposition of emission reductions in the NZE Ambition scenario

By far, the largest contribution to the global emission reductions in the *NZE Ambition* scenario comes from decarbonisation of the energy system, i.e. a reduction in the GHG intensity of energy (Figure C.5). This includes a large-scale switch in power generation towards low-carbon generation technologies, but also the recourse to CCUS to avoid emissions. Improvements in energy intensity – through a reduction of energy demand and a switch from energy-intensive sectors to less-intensive sectors – also contributes. The *NZE Ambition* scenario results in a reduction in economic activity (GDP) compared to the *Baseline*, which modestly contributes to emission abatement.[2] Finally, by assumption, population does not change between scenarios.

[2] Indeed, while GDP increases over time in the NZE Ambition scenario, it grows more slowly than in the *Baseline*.

Figure C.5: Most emission mitigation is due to improvements in GHG intensity of energy and energy intensity of GDP

Decomposition of global emission variation in 2050, *NZE Ambition* scenario compared to the *Baseline* (Gt CO_2e)



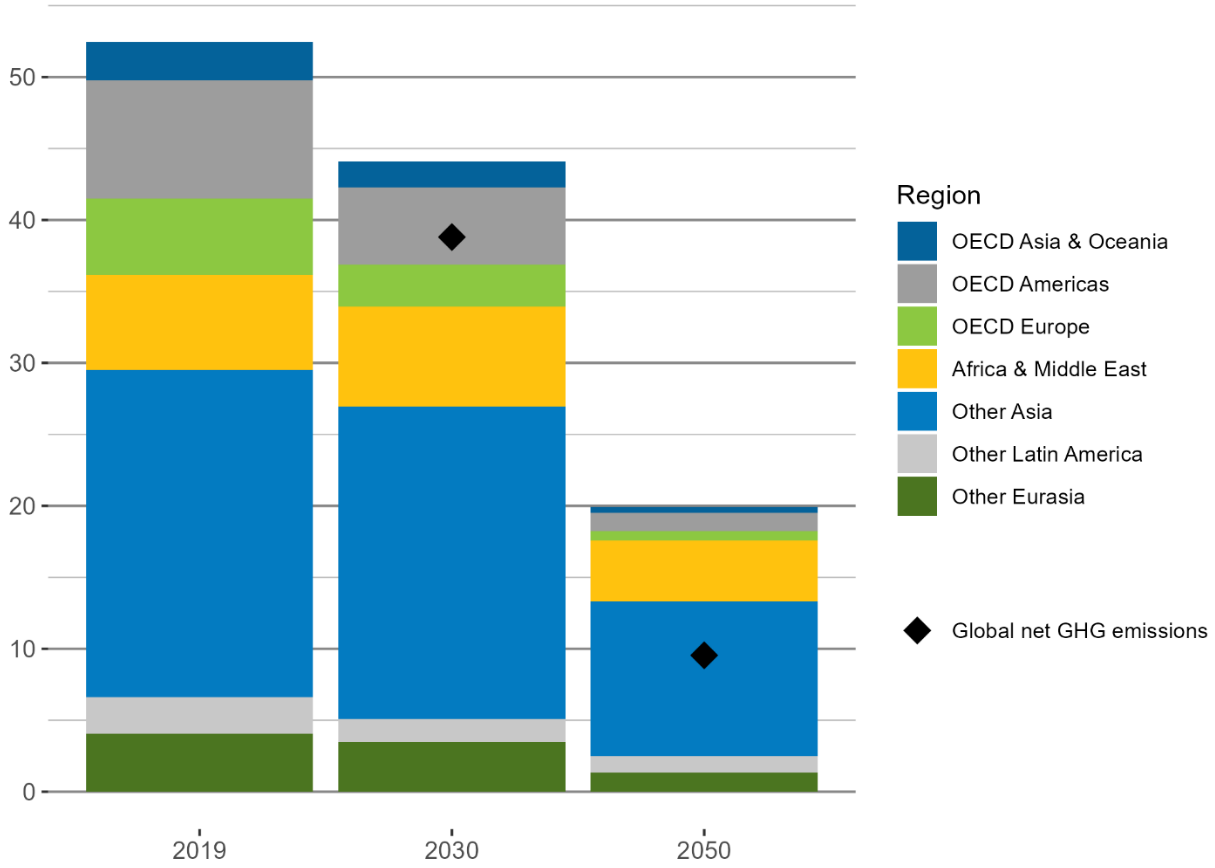
Regional emission reductions

The largest GHG emission reductions occur in OECD Europe, OECD America and non-OECD Asia (Figure C.6). Almost all countries within OECD Europe and OECD America are large emitters and have pledged to achieve carbon neutrality by 2050. In the *NZE Ambition* scenario, they also have limited potential for carbon sequestration through afforestation compared to some other countries with a 2050 carbon-neutrality pledge in other parts of the world, such as Brazil, Indonesia, and central Africa. This leads to large emission reduction in both percentage and Gt CO_2e. Most of the regions in non-OECD Asia have a target in the *NZE Ambition* scenario consistent with achieving carbon neutrality in 2060, postponing non-negligible amounts of mitigation to beyond 2050. Despite this lower level of ambition, given high base year emissions in the region, the resulting volume of emissions abated remains significant.

Emission reductions are also significant in a number of fossil fuel exporting countries that have a high energy intensity of the economy, including a number of countries in the Other Eurasia region, not least the Russian Federation. In these economies, significant emission reductions are induced by the negative trade consequences of the global policy package on top of the energy efficiency and carbon pricing policies. The slow-down of the global economy, and especially the reduced global demand for fossil energy, has negative consequences for income and production levels in these energy-dependant countries. These countries achieve large emission reductions at very high macroeconomic cost, due to the fact that the emission reductions result from a decrease in economic activity.

Figure C.6: Significant CO_2 emission mitigation by 2050 in the *NZE Ambition* scenario

GHG emissions, *NZE Ambition* scenario (Gt CO_2e)



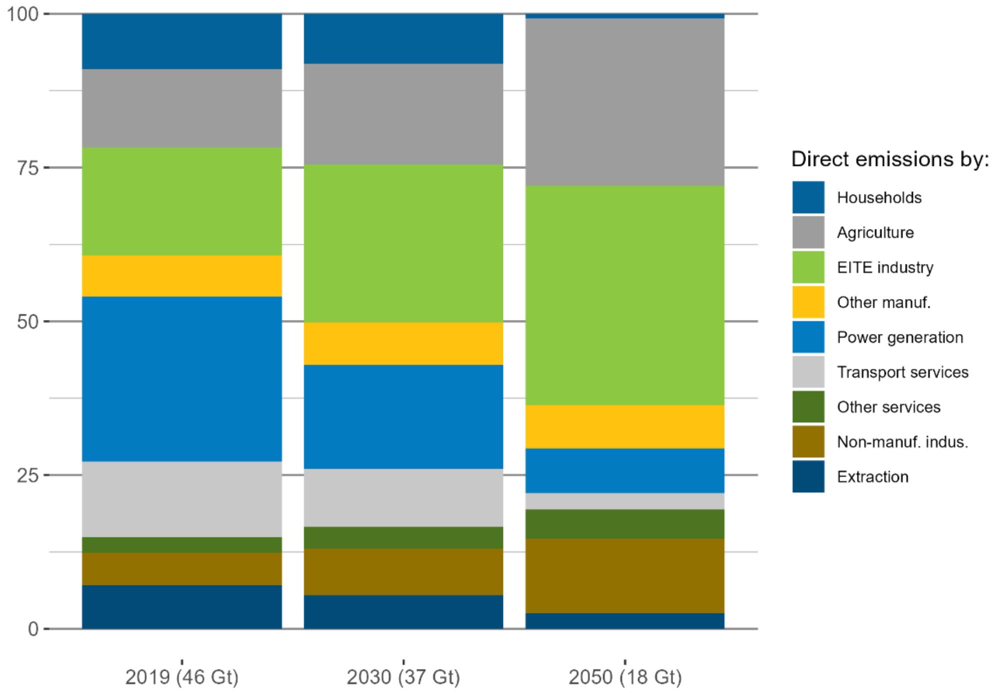
Sectoral emission reductions

In the *NZE Ambition* scenario, most residual emissions in 2050 are concentrated in energy-intensive and trade exposed (EITE) sectors, while other sectors decarbonise to a large extent (Figure C.7). Indeed, emissions in EITE sectors are often considered as "hard-to-abate", and this is reflected in the *NZE Ambition* scenario. In this scenario, no specific regulation in EITE sectors is implemented[3] but combustion and process emissions are both targeted by carbon pricing policies, which trigger substitutions away of fossil fuels and process emissions towards other inputs. In contrast, direct emissions by households and emissions from power generation are almost eliminated as the required emission reduction technologies (electric vehicles, housing refurbishment or low-carbon power generation) already exist and can be deployed widely. The transition to electric vehicles aids an almost full decarbonisation of the transport sector.

[3] In some cases, technologies to abate emissions exist and could have been added as regulation, but the lack of data to calibrate such policies have prevented their integration in the *NZE ambition* scenario.

Figure C.7: Most residual emissions in 2050 are concentrated in energy-intensive manufacturing sectors

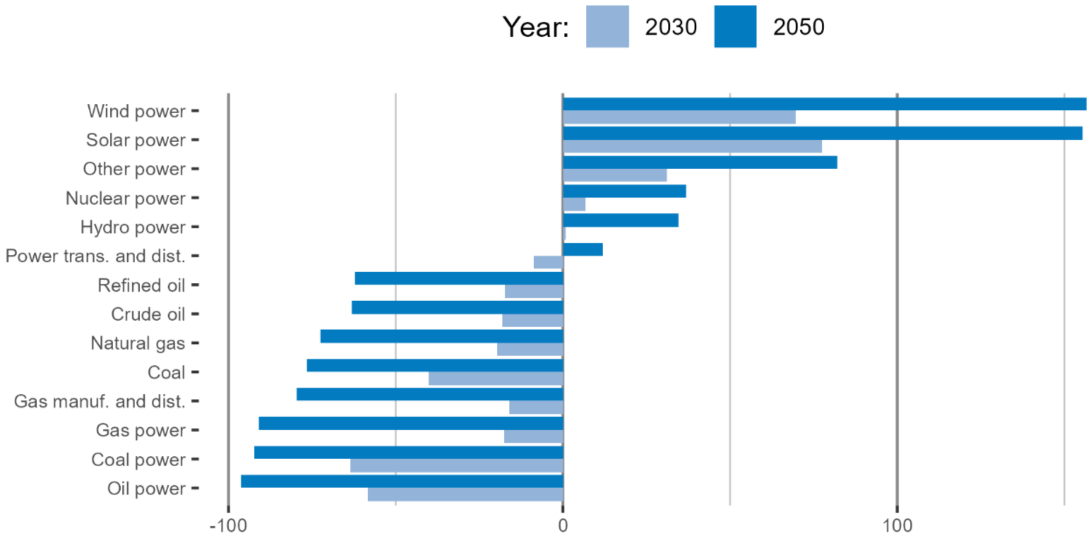
CO_2 emissions, *NZE Ambition* scenario (%)



The drastic transformation of the power sector that includes a shift away from fossil fuels does not imply a reduction in the overall volume of power generation (Figure C.8). Rather, power generation shifts from fossil fuels to nuclear and renewable sources. Fuel-based power generation does not have to contract to zero, however, because part of the sector can be combined with carbon capture utilization and storage (CCUS) to avoid emissions from burning fossil fuels to generate power.

Figure C.8: The composition of the energy sector changes dramatically, especially after 2030

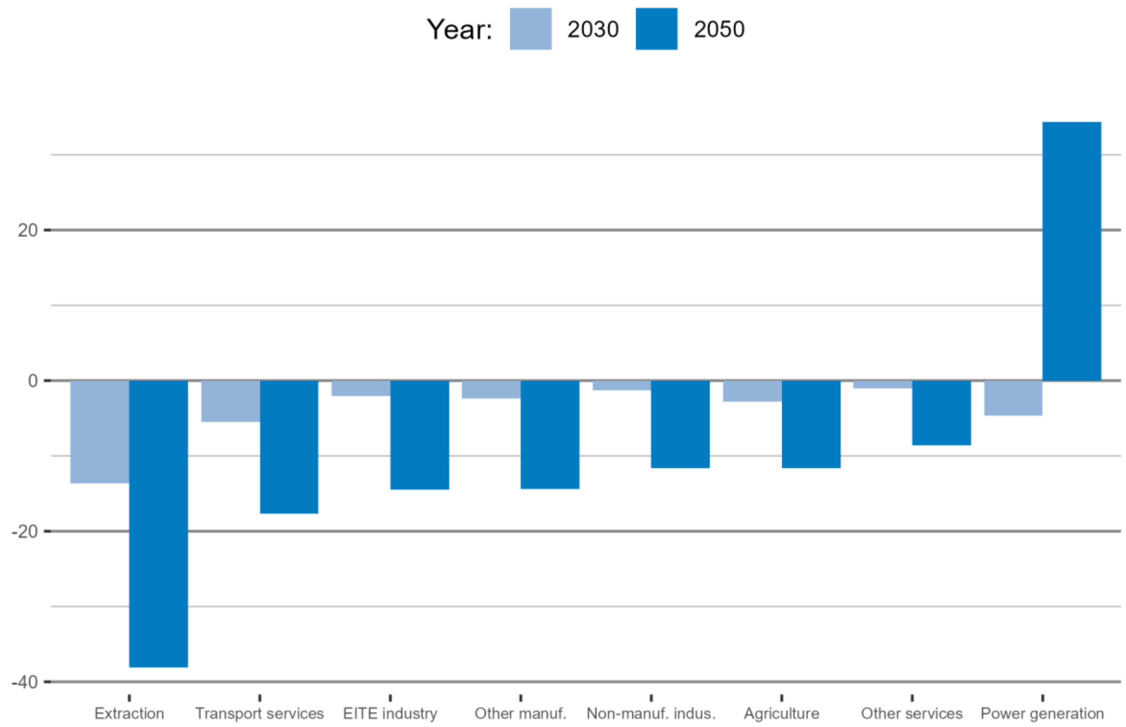
Variation in gross output for energy sectors, *NZE Ambition* scenario compared to the *Baseline* (%)



Total power generation expands considerably by 2030, but especially in the long-term (Figure C.9). A crucial part of the NZE transition is the electrification of energy, for instance the switch from cars with internal combustion engines to electric vehicles. This fits well within a low-carbon economy as long as power generation itself is decarbonised. By 2030, mining and extraction of natural resources, which includes extraction of fossil fuels, are most affected due to the sharp decline in the demand for fossil fuels. The Other manufacturing sector, which includes among others oil refining is also directly linked to the energy system transition. In other sectors, hardly any changes take place before 2030.

Figure C.9: Power generation sectors expand the most, while extraction and mining face major output reductions

Variation in gross output for aggregated sectors, *NZE Ambition* scenario compared to the *Baseline* (%)



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More prominent changes take place between 2030 and 2050, as largest shifts in sectoral production occur in response to more stringent policies. The decarbonisation of the energy system continues, leading to significant reductions in fuel extraction and oil refining (included in Other manufacturing). But transport services and EITE industry also contract significantly below *Baseline* levels, though not below 2019 levels.

Construction, as well as the electric and transport equipment subsectors included in Other manufacturing, are indirectly targeted by the energy efficiency policies: they provide an input to investment by the power sector in new low-carbon facilities, or to investment by households in low-carbon durable goods (electric and transport equipment). Increasing expenditures in these sectors can substitute for energy inputs: buying a more energy-efficient durable good implies higher upfront investment but lower energy consumption throughout the lifetime of the good. This increased demand for construction and durables for low-carbon alternatives is, however, drowned out by reduced demand that comes from the energy-intense sectors and fossil-fuel based power generation.

Regional GDP changes

The regional differences in macroeconomic impacts are significant, especially in 2050 (Figure C.10) and depend on the level of mitigation ambition (compared to sequestration potential), *Baseline* scenario level of emissions, the mix of policy instruments and the economic structure. First, countries with lower capacity to sequester carbon (AFOLU or NETs) have lower targets for gross emissions, driving up the need to decarbonise also the parts of the economy that are more difficult to reach, such as the EITE sectors. Second, countries with higher *Baseline* emissions need to reduce more. Large reductions in emissions require high carbon prices, which in turn lower economic activity. Third, in countries where energy efficiency instruments are used only to a limited extent, carbon prices needed to achieve their target are higher, hence lowering economic activity. This is the case for countries that rely heavily on EITE sectors, and that thus have a high energy intensity of GDP. These countries will have to decarbonise these sectors for which direct regulations to induce a switch to low-carbon production technologies do not exist. Another driver is the flexibility of the economy to switch to low-carbon technologies: faster-growing economies that invest a lot can more easily adjust those investments to low-carbon alternatives than more stagnant economies that rely heavily on already installed capital goods. Finally, the macroeconomic consequences are the result not only of the domestic mitigation efforts, but also of the changes in trade patterns induced by policies broad. Open economies that specialise in exporting energy or EITE commodities will tend to lose more in competitive position than more sheltered or diversified economies. In the end what matters is the relative stringency of the domestic policies vis-à-vis that of competitors.

There are less differences between regions in 2030, as the mitigation objective corresponding to NDCs is more uniform, and around -25% compared to *Baseline*. Impacts on GDP are also lower. These differences can be explained similarly to 2050, by Baseline emissions, policy instrument mix and economic structure, but also by the impact of regulations and direct subsidies: 2030 corresponds to the peak of investments, puts an upward pressure on economic activity in the construction, transport equipment and electric equipment sectors.

An important part of the change in economic activity resulting from the transition to the *NZE Ambition* scenario is a shift in the structure of final demand, away from household consumption towards public consumption (Figure C.11). This trend implies that the brunt of the final demand changes comes at the expense of household consumption, while government expenditures and thus the provision of public goods, remain much more stable (larger share of a smaller pie). Changes in relative prices further complicate the picture: the equivalence between GDP measured through expenditures or through income only holds in nominal terms, not in real terms. As a result, the share of government income in GDP can rise in the *NZE Ambition* scenario even as real government expenditures remain a constant share of GDP.

Figure C.10: The GDP cost of the NZE transition depends on the mitigation ambition and economic structure

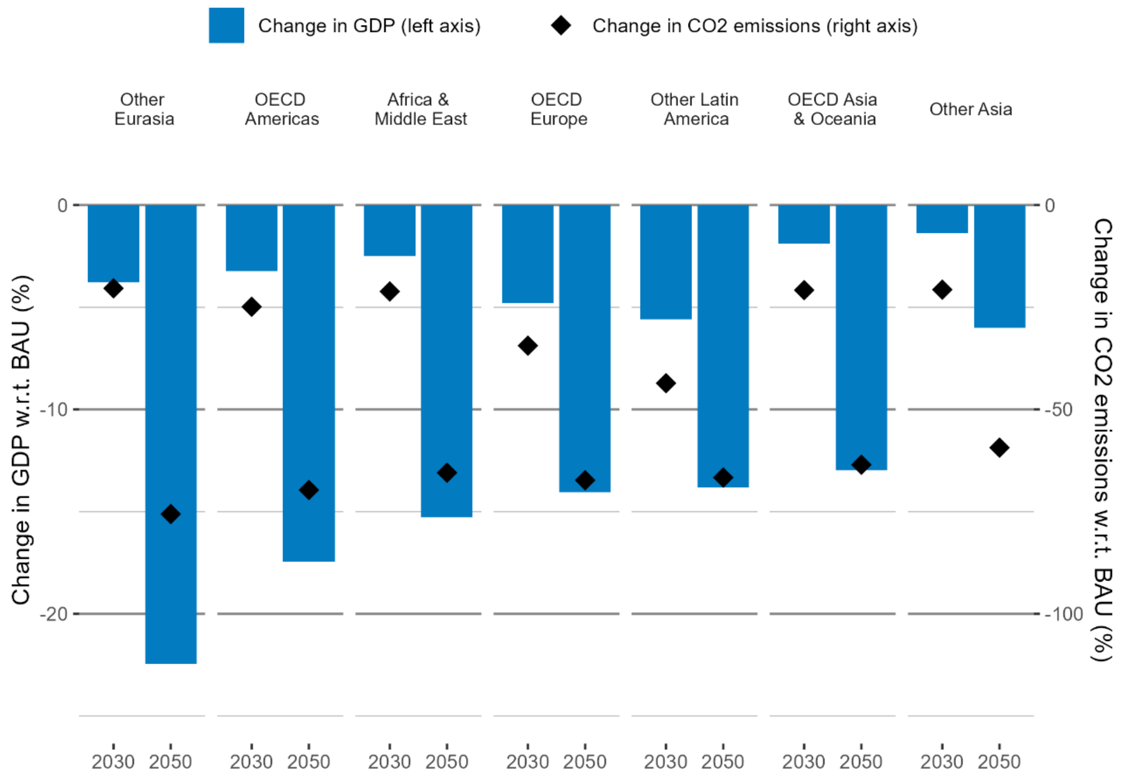
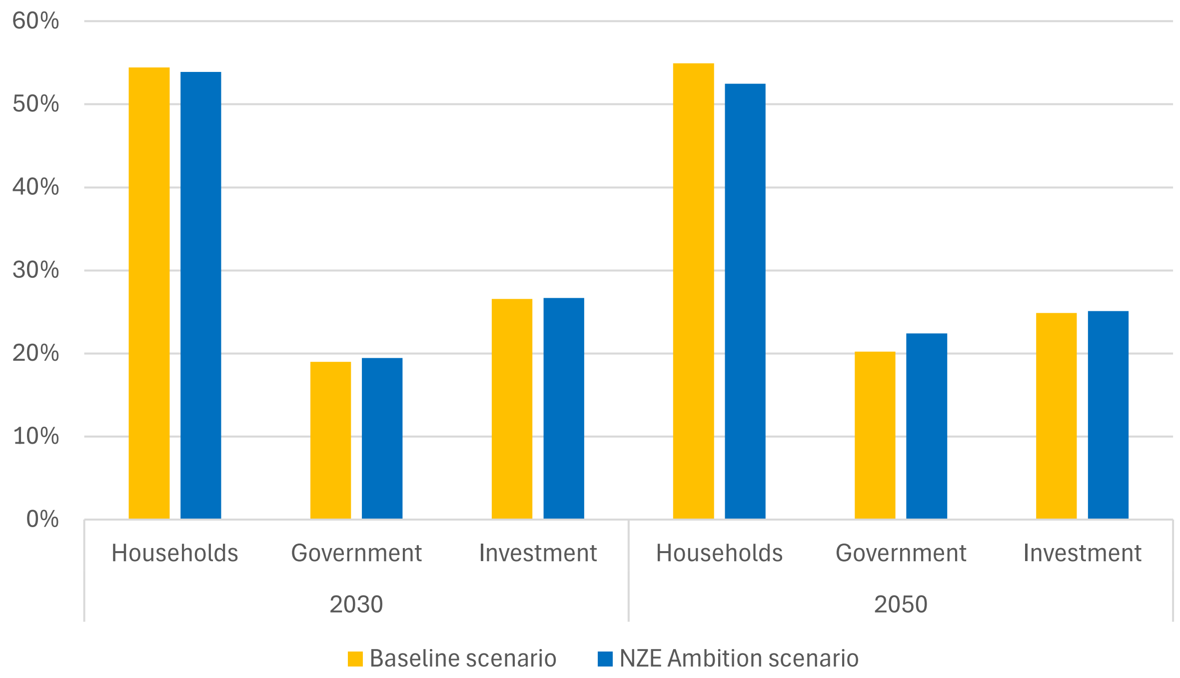


Figure C.11: The structure of final demand shifts from household consumption towards government consumption



Alternative specification of the NZE Ambition scenario based on CO_2 only

The main results of the NZE Ambition scenario on net fiscal revenues depend crucially on the implemented policies, as well as on the scope of these policies. The former is addressed in Section 4.5, and this Annex looks at the implications of the scope. Specifically, the main NZE Ambition scenario is run again, but with the scope limited to CO_2 only. While it is clear that a limited scope will be environmentally less effective if non-CO_2 GHGs are not included, and the IPCC approaches net-zero from a broad scope including all GHGs, some countries have actually specified their NZE targets in terms of CO_2 only.

Thus, it is interesting how the scope of the policy package, in terms of gases that are covered, interact with the policy mix. In a simplistic setting with taxation only, all fiscal results would simply scale with the emissions base. But for the more elaborate package in our main scenario, the effects of including or excluding non-CO_2 GHGs matters in ways that is not a priori clear.

Figure C.12 compares the net fiscal impacts of the full policy package of the NZE Ambition scenario for the settings with a scope on all GHGs versus CO_2 only. The Figure clearly shows that the fiscal situation improves when all GHGs are considered, i.e. the CO_2 only alternative leads to more pessimistic results. This result extends to all regions, albeit not in equal proportions.

The main reason for the more pessimistic fiscal results in the CO_2 only scenario is that the emission base for taxation is much smaller if non-CO_2 GHGs are excluded. In contrast, the elements in the policy package that have negative impacts on fiscal revenues – specifically household subsidies, regulations in buildings and transport, and regulations in the power sector – remain largely unchanged. This can be seen by comparing Figure C.13 with Figure 9 in the main text.

Figure C.12: Net fiscal revenues in alternative specifications of the NZE Ambition scenario

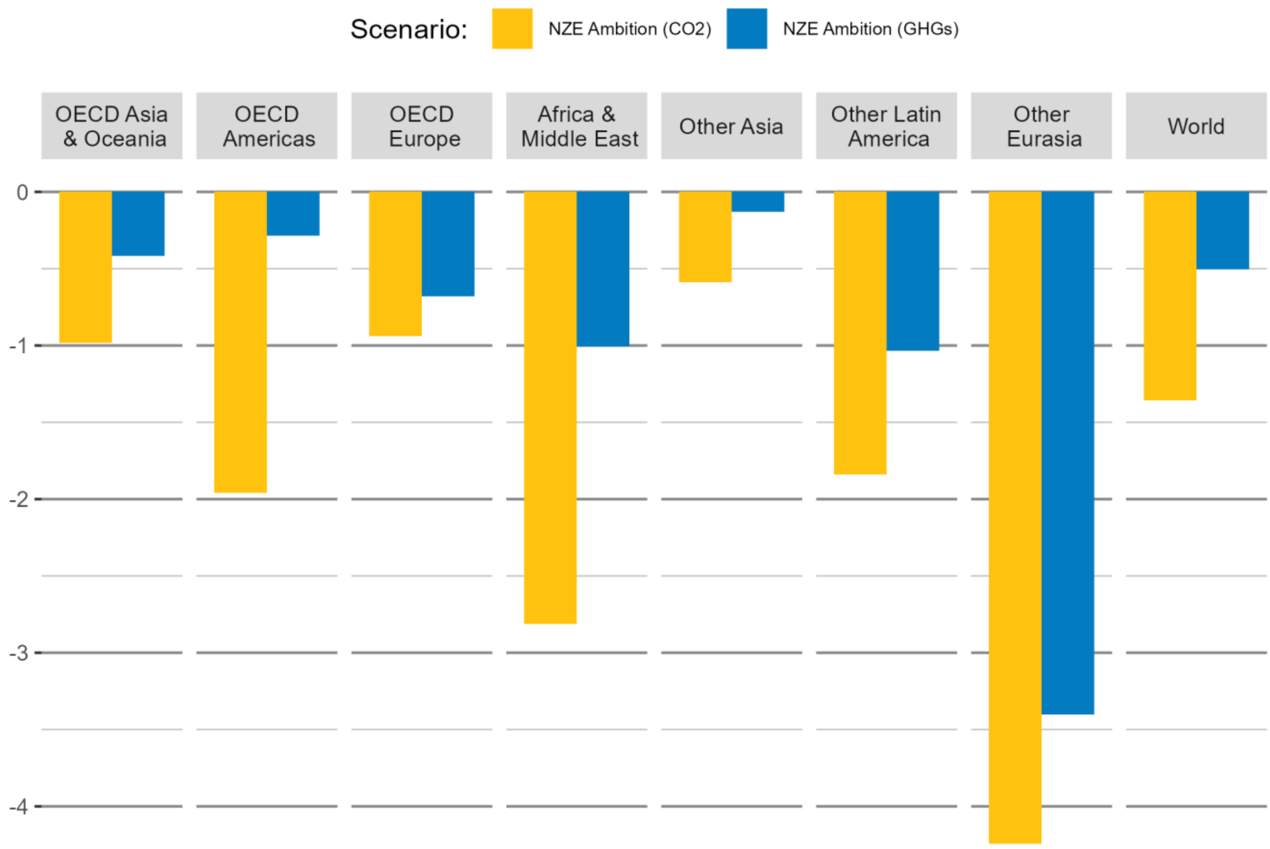


Figure C.13: Net fiscal revenues in the CO_2 only specification of the NZE Ambition scenario