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Public finance resilience in the transition towards carbon neutrality

Modelling policy instruments in a global net-zero emissions scenario

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By Jean Fouré, Rob Dellink, Elisa Lanzi, Filippo Pavanello (1)

1) OECD Environment Directorate

Authorised for publication by Jo Tyndall, Director, Environment Directorate.

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JEL codes : Q54, Q43, H20, H23, H61, C68

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Jean Fouré, Jean.Foure@oecd.org, +33 (0)1 45 24 98 81
Rob Dellink, Rob.Dellink@oecd.org, +33 (0)1 45 24 19 53
Elisa Lanzi, Elisa.Lanzi@oecd.org, +33 (0)1 45 24 14 78

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Abstract

This paper presents a detailed economic modelling analysis of public finance in the transition towards carbon neutrality. It outlines results from a *Net-Zero Emission Ambition* scenario, which reflects the ambition to achieve net-zero carbon dioxide 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 decarbonise energy use. The analysis relies on the OECD global computable general equilibrium ENV-Linkages model.

Results show that transitioning towards carbon neutrality is feasible when considering economic and fiscal consequences. The scenario achieves carbon neutrality while maintaining continued economic growth, despite a limited negative impact on global GDP and on public revenues. 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.

Keywords: net-zero, climate mitigation, public budget, computable general equilibrium models.

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Résumé

Ce papier présente une analyse économique sur les finances publiques dans la transition vers la neutralité carbone. Il dresse ses résultats à partir d'un scénario d'*Ambition neutralité carbone*, qui reflète l'ambition d'atteindre zéro émission nettes de dioxyde de carbone au niveau mondial vers la moitié du siècle, en utilisant une large gamme d'instruments économiques, spécifique à chaque région : tarification du carbone, retrait des subventions aux énergies fossiles, réglementations de la production d'électricité, et autres politiques publiques qui stimulent l'investissement des entreprises et des ménages pour réduire et décarboner leur demande d'énergie. Cette analyse repose sur le modèle d'équilibre générale calculable de l'OCDE, ENV-Linkages.

Les résultats montrent que la transition vers la neutralité carbone est faisable même en considérant ses implications économiques et fiscales. Le scénario atteint la neutralité carbone tout en maintenant une croissance soutenue, malgré les effets négatifs mais limités sur le PIB mondial et les rentrées fiscales. Ces effets sur la fiscalité résultent d'un équilibre entre des instruments qui apportent des rentrées fiscales (tarification du carbone) ou réduisent les dépenses publiques (retrait des subventions aux énergies fossiles) d'un côté, et des instruments plus coûteux (subventions aux ménages) et des effets indirects (érosion de l'assiette fiscale et changements dans la structure économique), de l'autre côté.

Mots clés : zéro émissions nettes, atténuation du changement climatique, budgets publics, modèles d'équilibre général calculable.

Classification JEL : Q54, Q43, H20, H23, H61, C68.

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This paper presents an economic modelling analysis of a scenario aimed at achieving the transition towards net-zero emissions by the middle of the century, with focus on the fiscal consequences of the transition. This paper contributes to the OECD Horizontal Project on "Building Climate and Economic Resilience in the Transition to a Low Carbon Economy".

This paper was prepared by Jean Fouré, Rob Dellink and Elisa Lanzi of the OECD Environment Directorate, and Filippo Pavanello of the University of Bologna, under the guidance of Shardul Agrawala, Head of the Economy Environment Integration Division at OECD Environment Directorate.

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Executive Summary

Urgent policy action to mitigate climate change has become an important priority for policy makers. To curb the adverse effects of global warming, the Intergovernmental Panel on Climate Change (IPCC) recommends limiting the global temperature increase to 1.5°C by the end of the 21st century, which implies the need to achieve carbon neutrality by mid-century. While governments prepare to support the transition towards carbon neutrality, they might struggle to find enough financial resources to do so. The disruptive events of recent years have highlighted the importance of ensuring economic resilience in response to shocks. In this context, governments need to design policy packages that achieve strong emission reductions while carefully considering the implications on public finances.

This paper presents a detailed economic modelling analysis of public finance resilience – or more precisely the change in net public revenues – in the transition towards carbon neutrality. Based on the OECD's global computable general equilibrium model ENV-Linkages, the paper presents a *Net-Zero Emission (NZE) Ambition* scenario, which reflects the ambition to achieve net-zero carbon dioxide (CO_2) emissions globally by mid-century, i.e., where carbon emissions do not exceed carbon sequestration. Specifically, all countries that have announced a commitment to achieve net-zero emissions by 2050 meet their target, while all other 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 to be implemented. Both scenarios are presented with a 2050 time horizon.

To achieve these emission reductions, ENV-Linkages has been tailored to model a broad policy package that combines various policy instruments. The policy package combines 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 decarbonise energy use, such as buildings refurbishment requirements and bans on combustion vehicles. Overall, the policy package targets all sources of CO_2 emissions, including fossil fuel combustion as well as process and fugitive emissions.

The extent to which each of these instruments is used varies by region and depends on domestic circumstances, not least the level of emissions by source and the required emission reductions. The regional policy mix results from combining carbon pricing (with levels adjusted to reach the CO_2 emissions abatement necessary to achieve carbon neutrality), the removal of fossil fuel support as indicated in the OECD Inventory of support measures for fossil fuels, and other investment-stimulating instruments quantified linking ENV-Linkages to the Global Energy Climate Model of the International Energy Agency. While the policy mix varies by region, providing country-specific results is outside the scope of this study, since doing so would need a careful consideration of country characteristics and policy roadmaps.

The ENV-Linkages model is used to evaluate the effects of this policy package on public finances, measured using net public revenues, i.e., the difference between tax revenues and subsidy expenditures. The model distinguishes direct effects, such as additional revenues from an increase in carbon prices, and indirect effects, such as changes in tax revenues on energy or labour due to reallocation of economic activity. The model finds that the mix of policy instruments chosen matters greatly in terms of the fiscal implications of the transition. While carbon taxes generate revenues and phasing out fossil fuel support decreases public expenditures, additional subsidies to low-carbon alternatives increase public expenditures. Policies that decrease energy demand can decrease public revenues from energy taxes but can also increase public revenues in the rare cases in which subsidies to energy are larger than taxes. The modelling results are indicative primarily of direct and indirect effects at the global and regional level, rather than forecasts for specific countries. Which policy instruments are preferable and feasible in the domestic context depends on a country's industrial structure, social preferences and political constraints.

In the *Baseline* scenario global CO_2 emissions are projected to increase from 36 gigatonnes (Gt) in 2019 to 40 Gt in 2050, setting a pathway towards a 4°C temperature increase by the end of the century. The *NZE Ambition* scenario reduces global CO_2 emissions to 11 Gt by 2050. Existing estimates of carbon sequestration through afforestation and other land-use sequestration as well as carbon capture and storage amount to 5.4 Gt by 2050. Thus, net global CO_2 emissions reach 5.6 Gt in 2050 and are on a trajectory to achieve climate neutrality before 2060, in line with the IPCC objective. In this scenario, the global average temperature increase peaks just above 1.5°C in the second half of the century. Without considering the reduction in climate damages and risks, the *NZE Ambition* scenario implies a slowdown of economic growth of around 0.2 percentage points per year between 2019 and 2050, leading to a 5.6% loss in global gross domestic product (GDP) in 2050 compared to *Baseline*.

The results of the region-specific mix of instruments in the *NZE Ambition* scenario show that net public revenues slightly decrease globally in 2050 (-1.8% 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 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 0.9% 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 0.4% of Baseline GDP.

The regional changes in net public revenues in the *NZE Ambition* scenario depend crucially on country characteristics and policy mix, but every region is impacted negatively, with changes in net public revenues as percentage of *Baseline* GDP ranging from -0.7% 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.

In the past, public budgets have been able to address changes in the economic structure, for instance through the creation of the value-added tax. 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 particular, governments should be aware of the different mechanisms at play when implementing carbon pricing: (i) revenues from carbon pricing decrease as its own tax base, CO_2 emissions, erode over time in the transition ; (ii) net public revenues from other sources (e.g. revenues from fossil fuel taxes) may also decrease substantially as a consequence of carbon pricing policies, even though some tax revenues (e.g. tax revenues from the production of renewable electricity) increase in parallel. In turn, this means that revenues available to governments to finance other policies, such as carbon sequestration or the just transition, might be lower than carbon revenues. This should 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.

Overall, the analysis presented in this paper shows that transitioning towards carbon neutrality is not only desirable from an environmental viewpoint, but also feasible when considering economic and fiscal consequences. Governments can choose and design their policy package according to their economic and energy context, while also considering the need to effectively decarbonise virtually all sources of emissions and maintaining the resilience of the fiscal system.

1 Introduction

Most countries around the world have now committed to achieving carbon neutrality by the middle of the 21st century, following the guidelines of the Intergovernmental Panel on Climate Change (IPCC) for limiting global warming to 1.5°C by the end of the century. Achieving carbon neutrality implies substantial changes to the structure of the economy, with the need for significant investment to stimulate the greening of economies. At the same time, the global COVID-19 pandemic led to high public spending for the recovery, and only part of it is labelled as "green" according to the OECD Green Recovery database (OECD, 2021[1]). Furthermore, the current geopolitical context has driven up energy prices and inflation, which in turn causes rising interest rates. In this context, concerns arise on the fiscal feasibility of achieving carbon neutrality and on the need to ensure economic resilience to possible future disruptions.

There is a large literature with 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[2]; van Soest, den Elzen and van Vuuren, 2021[3]; Rogelj, 2018[4]). Recently, the literature has focused more specifically on scenarios that aim at reaching global net-zero emissions (NZE) – i.e. a situation where carbon dioxide (CO_2) emissions from economic activity are balanced by carbon sequestration in sinks. The International Energy Agency (IEA) "Net Zero by 2050" (International Energy Agency, 2021[5]) was the first major report to provide a detailed roadmap to achieve net-zero emissions in the energy sector. Several net-zero emission scenarios are also presented in Chapter 3 of Working Group III Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (Riahi et al., 2018[6]). Pulling together results from various Integrated Assessment Models, the Network for Greening the Financial System (NGFS) presents two net-zero emission scenarios with differing pathways to highlight the importance of the shape of the pathways to net-zero, not just reaching the end goal itself (Bertram et al., 2021[7]). In addition to these model comparison exercises focus on pathways to reach net-zero emissions, a few recent studies quantify the economy-wide effects of reaching carbon neutrality (Liu, McKibbin and Jaumotte, 2021[8]; Drummond et al., 2021[9]).

This paper contributes to the existing literature by providing a first modelling assessment of the fiscal resilience – or more precisely the effect on net public revenues – of the transition to net-zero emissions, considering the policy ambition needed to limit climate change to 1.5 °C. It does so by modelling a net-zero emission scenario in which carbon neutrality is achieved in all countries thanks to a stylized but realistic mix of policy instruments. While recent modelling studies model the transition to carbon neutrality at the aggregate level, this paper presents a novel analysis using the OECD ENV-Linkages global computable general equilibrium (CGE) model (Chateau, Dellink and Lanzi, 2014[10]). The sectoral details of a dynamic CGE modelling framework enables the linking of emissions to specific inputs in production and consumption, as well as economic transactions to changes in tax revenues and subsidy payments, and thus to public revenues.

The instruments considered include carbon pricing, removal of fossil fuel support, regulations in the power sector, and other policies to reduce and decarbonise energy consumption by firms and households, focusing on reducing emissions from transport and buildings, increasing energy efficiency and electrification. These other policies cover all major CO2 emission sources. This analysis introduces an innovative modelling approach, where ENV-Linkages is linked to the International Energy Agency's Global Energy Climate Model (International Energy Agency, 2021[5]), to accurately represent both the investment needed and the corresponding changes in energy demand. The instrument mix is chosen because it can achieve the very ambitious emission reductions required for reaching net-zero CO_2 emissions, i.e. the combination of the various instruments reaches all key sources of CO_2 emissions (fossil fuel combustion, process and fugitive emissions).

The choice of the policy instruments and their design have significant implications on public finance. For instance, while carbon taxes and (auctioned) emission trading systems might 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.

The results of the model simulations presented in this paper are indicative primarily of the size of the various direct and indirect effects, rather than a forecast of the fiscal effects of carbon neutrality policies in general. Which policy instruments are preferable and feasible in the domestic context depends on countries' industrial structure, social preferences, and political constraints (D'Arcangelo et al., 2022[11]). Governments have leeway in choosing and designing their policy package, albeit within relatively strict constraints given by the need to effectively decarbonise virtually all sources of emissions and maintaining resilience of the fiscal system.

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 overview

This paper presents a scenario with the ambition to achieve net-zero CO_2 emissions (NZE) by the middle of the century (the *NZE Ambition* scenario). While the role of non-CO_2 greenhouse gas emissions in limiting climate change is important and can be subject to similar policies as carbon pricing, this paper focuses solely on CO_2 emissions to reflect the definition of "net-zero" in IPCC reports (IPCC, 2018[12]).[1] 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.[2] 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).[3] Country-specific net-zero emission targets are therefore achieved when gross emissions equal carbon sequestration. The model differentiates between three categories of countries, according to their declared NZE targets (Hale et al., 2022[13]):[4]

- Countries that have pledged to achieve carbon neutrality by 2050 gradually reduce gross emissions to reach the domestic potential for carbon sequestration by 2050.

[1] "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[12]).

[2] The NDC emission targets for 2030 are based on the assessment in the Climate Watch database (Climate Watch, 2022[17]). Additional details are provided in Annex B.

[3] AFOLU sequestration projections are taken from the IMAGE model (Stehfest et al., 2014[14]; PBL, 2022[15]). NETs projections and projections of gross emission reductions obtained through Carbon Capture, Utilisation and Storage (CCUS) are from the World Energy Outlook (International Energy Agency, 2021[16]). Multiple pathways exist to reach net-zero emissions, depending on the extent countries choose to rely on 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 he 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.

[4] 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.

- 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[5] 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 2.1, 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 net CO_2 emission levels amount to 5.6 Gigatonnes (Gt). At the same time, estimates from the IMAGE model (Stehfest et al., 2014[14]; PBL, 2022[15]) on AFOLU sequestration and World Energy Outlook (International Energy Agency, 2021[16]) on NETs indicate that total carbon sequestration in 2050 could reach 5.4 Gt. Therefore, in the *NZE Ambition* scenario global gross CO_2 emissions in 2050 amount to 11.0 Gt.

[5] 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 2.1. Economy-wide CO_2 emission targets in 2030 and 2050 in the *NZE Ambition* scenario

CO_2 emissions, in Gigatonnes (Gt)

<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>0.45</td><td>0.30</td><td>0.06</td><td>0</td></tr>
<tr><td>Brazil</td><td>0.41</td><td>0.22</td><td>0.20</td><td>0</td></tr>
<tr><td>Canada</td><td>0.62</td><td>0.35</td><td>0.04</td><td>0</td></tr>
<tr><td>Chile & Colombia</td><td>0.17</td><td>0.26</td><td>0.06</td><td>0</td></tr>
<tr><td>European Union</td><td>3.21</td><td rowspan="3">2.41</td><td rowspan="3">0.42</td><td rowspan="3">0</td></tr>
<tr><td>Other OECD Europe</td><td>0.56</td></tr>
<tr><td>UK</td><td>0.43</td></tr>
<tr><td>Japan</td><td>1.18</td><td>0.72</td><td>0.09</td><td>0</td></tr>
<tr><td>Korea</td><td>0.57</td><td>0.40</td><td>0.04</td><td>0</td></tr>
<tr><td>South Africa</td><td>0.49</td><td>0.61</td><td>0.04</td><td>0</td></tr>
<tr><td>United States</td><td>5.57</td><td>2.97</td><td>0.38</td><td>0</td></tr>
<tr><td>Other Southeast Asia</td><td>1.19</td><td>1.25</td><td>0.24</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>10.29</td><td>13.40</td><td>3.42</td><td>2.49</td></tr>
<tr><td>India</td><td>2.38</td><td>4.59</td><td>1.24</td><td>0.69</td></tr>
<tr><td>Indonesia</td><td>0.52</td><td>0.60</td><td>0.39</td><td>0.12</td></tr>
<tr><td>Russia</td><td>1.69</td><td>1.80</td><td>0.60</td><td>0.49</td></tr>
<tr><td colspan="5">Countries/Regions with an assumed joint NZE target in 2060</td></tr>
<tr><td>Caspian</td><td>0.58</td><td>0.80</td><td rowspan="8">3.78</td><td rowspan="8">1.78</td></tr>
<tr><td>Mexico</td><td>0.49</td><td>0.38</td></tr>
<tr><td>Middle East</td><td>2.04</td><td>2.76</td></tr>
<tr><td>North Africa</td><td>0.58</td><td>0.79</td></tr>
<tr><td>Other Latin America</td><td>0.70</td><td>0.53</td></tr>
<tr><td>Other Africa</td><td>0.38</td><td>0.49</td></tr>
<tr><td>Other Asia</td><td>0.75</td><td>0.89</td></tr>
<tr><td>Other Europe</td><td>0.36</td><td>1.50</td></tr>
<tr><td>World</td><td>35.6</td><td>38.0</td><td>11.0</td><td>5.6</td></tr>
</table>

Source: Own computations based on Climate Watch (2022[17]) for 2030 and NZE commitments, and sequestration in 2050 based on IMAGE dataset (Stehfest et al., 2014[14]; PBL, 2022[15]) and IEA (2021[5]).

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[6] as well as policies that were by then already legislated but not yet implemented.[7] 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

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

[7] 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.

but not the targets themselves. Updates in NDC targets[8] since 2021 as well as additional policies needed to reach the target are accounted for in the *NZE Ambition* scenario.

The global economy gradually becomes less energy- and fuel-intensive over time in the *Baseline* scenario but remains far off meeting the NZE ambitions. Following the OECD long-term economic projections (Guillemette and Turner, 2021[18]), the *Baseline scenario* reflects sustained global economic growth over time, with gross domestic product (GDP) growing faster in non-OECD countries.[9]

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 (see Section 2.2).

2.2. Policy instruments in the NZE Ambition 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 CO2 emissions,10 and (ii) they contain some of the most widely used instruments available to governments. 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.

The 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.

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,

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

[9] 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 (International Energy Agency, 2021[16]). More information on the *Baseline* calibration is provided in Annex A.

[10] All CO_2 emissions from fossil combustion, process CO_2 emissions and fugitive emissions are covered by the policy package (including carbon pricing). However, emissions from chemical use and land-use because the ENV-Linkages model lacks specific mitigation options for these emissions sources and because they are generally excluded from carbon pricing in existing practices (Henderson et al., 2021[21]).

and (iii) the feasibility of decarbonising each sector, including investment requirements. Political considerations are not included in determining the portfolio of instruments used in the package.

Since this 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 linking the ENV-Linkages model with the Global Energy Climate Model of the IEA (International Energy Agency, 2021[16]) to represent the sectoral investment needed and the corresponding changes in energy demand to decarbonise energy production and use (Chateau, Magné and Cozzi, 2014[19]). 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. More details on the modelling approach are provided in Annex B.

2.2.1. Carbon pricing

In the *NZE Ambition* scenario, countries with an NZE target in 2050 or 2060 are assumed to implement an emission trading system matching the chosen emission pathway (see Section 2.1). For these regions, carbon prices differ across regions as the carbon price level is chosen so as to meet the region-specific emission reduction.[11] In regions composed of countries without an NZE commitment, emission targets are integrated in the *NZE Ambition* scenario as a single emission trading system that ensures that the joint emission reduction target is met.[12] 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. In the *NZE Ambition* scenario, carbon pricing covers all sectors of the economy, including CO_2 emissions from agricultural sectors (see Box 2.1).

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 with the energy use, and (ii) a shift in demand away from these commodities towards less emission-intensive commodities.[13] These substitution effects away from carbon-intensive energy sources in turn affect the price of fossil fuels, and lead to adjustments of energy supply. The levels of carbon price by region, as adjusted by the model to reach emission targets in 2030 and 2050, are provided in Annex B and range between USD 0 and USD 714 across ENV-Linkages regions in 2050. Although carbon prices as well as other instruments differ widely between regions, they do not trigger any leakage at the economy-wide level in the *NZE Ambition* scenario, because – by design – the maximum level of economy-wide

[11] 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.

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

[13] 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).

emissions is capped in the scenario. In other words, if the policy induces a shift in sectoral economic activity from one country to another (the narrow interpretation of carbon leakage), this does not expand total economy-wide emissions in the destination country, as all countries are assumed to be on a pathway to net-zero. 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 economy-wide emissions do not exceed the emission cap, potentially with an increase in the level of carbon pricing necessary to achieve this cap.

The substitution away from carbon-intensive energy sources affects the price of fossil fuels, and leads to adjustments of energy supply, but can also boost demand for fossil fuels in sectors and regions that are not covered by carbon pricing. This increased demand for carbon-intensive energy sources outside the scope of the carbon pricing instrument is called carbon leakage. In the global scenario envisaged here, such leakage effects do not occur, as all regions cap their total emission levels.

Box 2.1. The role of agriculture and AFOLU in the net-zero transition

The *NZE Ambition* scenario focuses on CO_2 emissions and includes the carbon dioxide emissions in the agricultural sector; for instance, carbon emissions in agriculture are included in the carbon pricing scheme. Furthermore, the modelling includes AFOLU sequestration that allows gross emissions to remain positive in the scenario; the scope for AFOLU sequestration depends crucially on land use and thus links to agricultural practices.

The assessment of the effects of the scenario presented in this paper considers induced changes in such emissions as a result of changes in agricultural activity induced only by the policy instruments outlined in this section. The scenario does not include specific policies to reduce agriculture-related methane (CH_4) and nitrous oxides (N_2O) emissions, nor phase-out of environmentally harmful agricultural subsidies and reform or reorientation of other support that targets emission-intensive products. Such policies could be part of a cost-effective mix of climate policies (OECD, 2022[20]; Henderson et al., 2021[21]; Fell et al., 2022[22]). Especially payments based on output and on unconstrained use of inputs, together with market price support, potentially increase GHG emissions (OECD, 2022[23]). Reforming market distorting subsidies can furthermore significantly improve the fiscal outcomes of the policy mix as the financial flows involved are significant; for example, budgetary transfers to support agricultural producers amount to almost 300 billion USD (OECD, 2022[23]).

In a broad climate policy, specific mitigation actions in agriculture are an essential part of the instrument mix. Furthermore, government policies can be considered to stimulate farmers to increase the sequestration of carbon on their lands. OECD (2019[24]) presents detailed analyses of relevant mitigation options in this domain.

2.2.2. Fossil fuel support removal

Two kinds of support on fossil fuel are considered: (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). The level of subsidy to fossil fuel production and consumption to be phased out is constructed using data from both fossil fuel support from the OECD Inventory of support measures for fossil fuels (OECD, 2022[25]) and subsidies data from the IEA Fossil Fuel Consumption Subsidy Database (IEA, 2021[26]). 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[27]). 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 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,[14] thus mitigating CO_2 emissions.

2.2.3. 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. These regulations result in a switch of investments in power infrastructure away from fossil fuels towards renewables and nuclear. Regulations in this sector shift the power mix towards these electricity sources, thus decreasing fossil-fuel based power generation. 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, in order to ensure sufficient emission reductions by 2050.

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

Specific policies are included 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. They are modelled 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. Thus, energy demand shifts away from fossil fuels. For buildings, regulations target emissions from commercial buildings by improving energy efficiency. As for transport investments, the demand for durable goods used in the building sectors increases and the demand for fossil fuels decreases. This implies increased demand for construction and appliances combined with a shift from fossil fuels to electricity.

2.2.5. 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.

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[14] 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.

2.2.6. 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.[15] 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.[16]

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.[17] 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[27]):

i. *Carbon* revenues, i.e. carbon taxes and revenues from the auctioning of emission permits;
ii. 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;
iii. net revenues from taxes and subsidies on *production* activities, other than fossil fuels;
iv. net revenues from taxes and subsidies on *consumption*, other than fossil fuels,
v. net revenues from taxes and subsidies on *production factors*, including capital and labour;
vi. net revenues from taxes and subsidies on *income*, including income transfers to households;
vii. 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[18]; OECD, 2022[28]) 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:[18] if government net revenues increase, then households will benefit from an additional transfer. Consequently, the impacts on net public revenues

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

[16] 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.

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

[18] 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.

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.

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 are summarised in Table 2.2. 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 2.2. Key effects of the policy instruments on fiscal space

Policy instrument Tax base	Carbon pricing (auctioned emission permits)	Fossil fuel support removal	Power sector decarbonisation regulations	Building and transport decarbonisation regulations	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)

Source: Authors' own elaboration

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

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

The *Baseline* scenario projects a steady increase in gross CO_2 emissions, reaching 40 Gt in 2050[19] compared to 36 Gt in 2019 (Figure 3.1, Panel A). While combustion emissions continue to represent the largest share, emissions from industrial processes increase more rapidly over time. This increase in CO_2 emissions implies an increase in the global average surface temperature of around 2°C in 2050 compared to pre-industrial levels, as estimated using the MAGICC climate model.[20] Continuing this trend to the end of the century would imply a temperature increase of at least 2.8°C in 2100, and possibly up to 4.6°C, with an expected increase of around 3.5°C (Figure 3.1, Panel B), depending on how sensitive the climate is to an increase in concentrations of CO_2 (climate sensitivity).[21]

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[29]), 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 the Atlantic Meridional Overturning Circulation, among others. These damages can result in high socio-economic costs (Dietz et al., 2021[30]; Dietz and Koninx, 2022[31]; Cai and Lontzek, 2019[32]) and in an additional demand for public finances to adapt and mitigate the adverse effects of climate change (de Mello and Martinez-Vazquez, 2022[33]).

[19] Although the *Baseline* scenario is based on information from the STEPS scenario from the WEO 2021, it differs significantly in terms of macroeconomic and sectoral assumptions (only power generation, transport services and households energy demand are directly calibrated on the STEPS scenario). The two scenarios do not share the same GDP growth trajectory (some countries having higher growth rates, others having lower growth rates). Furthermore, for industrial sectors the *Baseline* scenario is more conservative on energy efficiency improvements. Consequently, *Baseline* emissions in 2050 (40 Gt) in ENV-Linkages are different from emissions in the WEO's STEPS scenario (32 Gt).

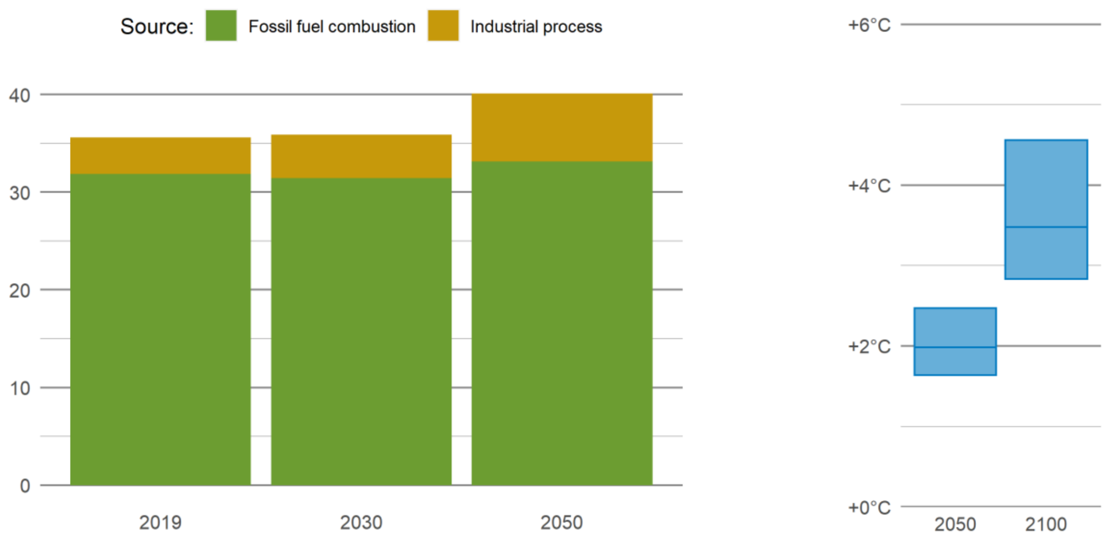
[20] This corresponds to the 1850-1900 average. Temperatures are simulated using MAGICC 7 live, reporting median temperature as well as 5th and 95th percentile of the climate sensitivity.

[21] 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.

Figure 3.1. The *Baseline* scenario projects an increase in CO_2 emissions that is expected to reach 2°C by 2050 and could lead to 2.8-4.6°C in 2100

Panel A. Global CO_2 emissions, excluding LULUCF (Gt)

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.
Source: OECD ENV-Linkages model (Panel A) and MAGICC 7 based on OECD ENV-Linkages model CO_2 emissions and SSP3-7.0 for other emissions (Panel B).

3.2. The *NZE Ambition* scenario reduces gross emissions to levels that can be compensated by sequestration

The *NZE Ambition scenario* achieves significant reductions in CO_2 emissions, with gross emissions reaching 11 Gt in 2050 (Figure 3.2).[22] These gross emissions are partly offset by carbon sequestration thanks to afforestation and other land-use (AFOLU) as well as Negative Emission Technologies (NETs)[23] so that "net" (i.e. including sequestration in carbon sinks) CO_2 emissions in 2050 amount to 5.6 Gt; on track to achieve net-zero emissions in all regions before 2060 (see Section 2.1). The corresponding increase in global average temperature, as estimated using the MAGICC climate model, attains 1.5°C by 2050

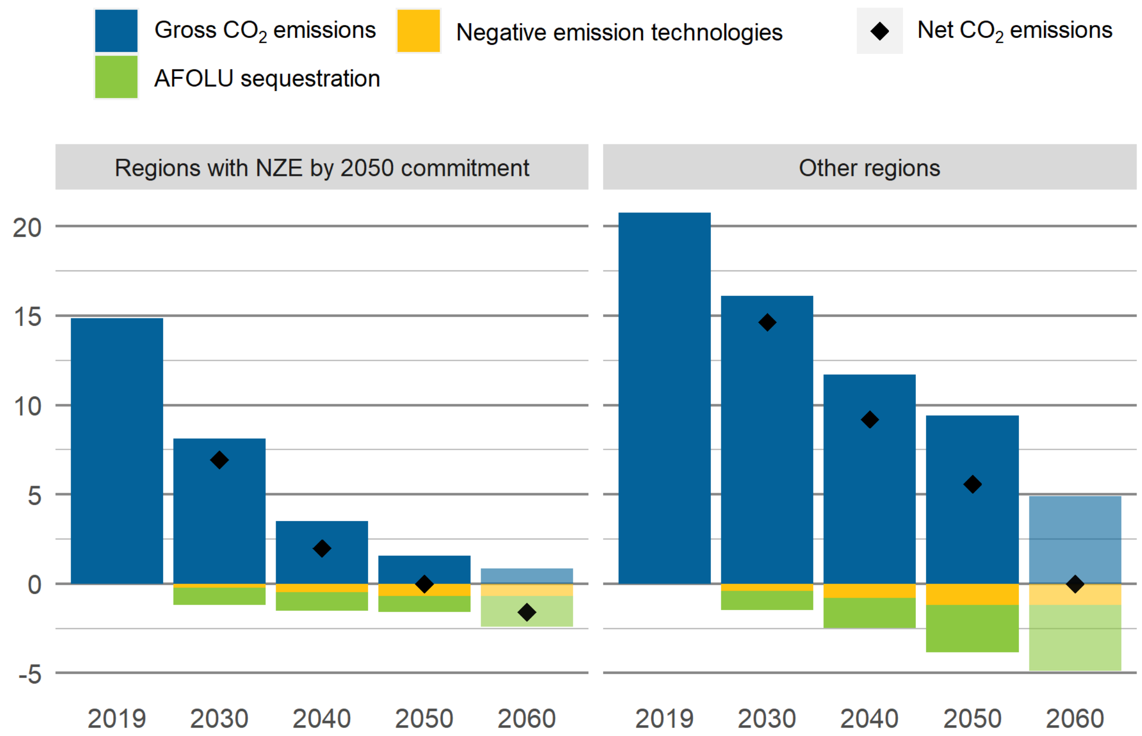
[22] Furthermore, 5.7 Gt of possible CO_2 emissions are avoided thanks to the increased use of Carbon Capture, Utilization and Storage (CCUS). CCUS is not modelled explicitly, and in particular its costs are not included in the *NZE Ambition* scenario, but the associated avoided emissions are accounted in the calculation of gross and net emissions.

[23] 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 therefore their costs are not included in the *NZE Ambition* scenario, but the associated carbon sequestration is accounted in the calculation of net emissions.

(confidence interval: 1.2 – 2.1°C), and is projected to reach 1.3°C by 2100 (interval: 0.9 – 1.9°C), thus remaining below 2°C and possibly 1.5°C, apart from a short period in the middle of the century.[24]

Figure 3.2. Gross and net CO_2 emissions steadily decline in the *NZE Ambition* scenario

Emissions and sequestration of CO_2 in the NZE Ambition scenario (Gt CO_2)



Note: The modelling exercise only considers years up to 2050.
Source: OECD ENV-Linkages model and IMAGE dataset (Van Vuuren et al., 2021[34]).

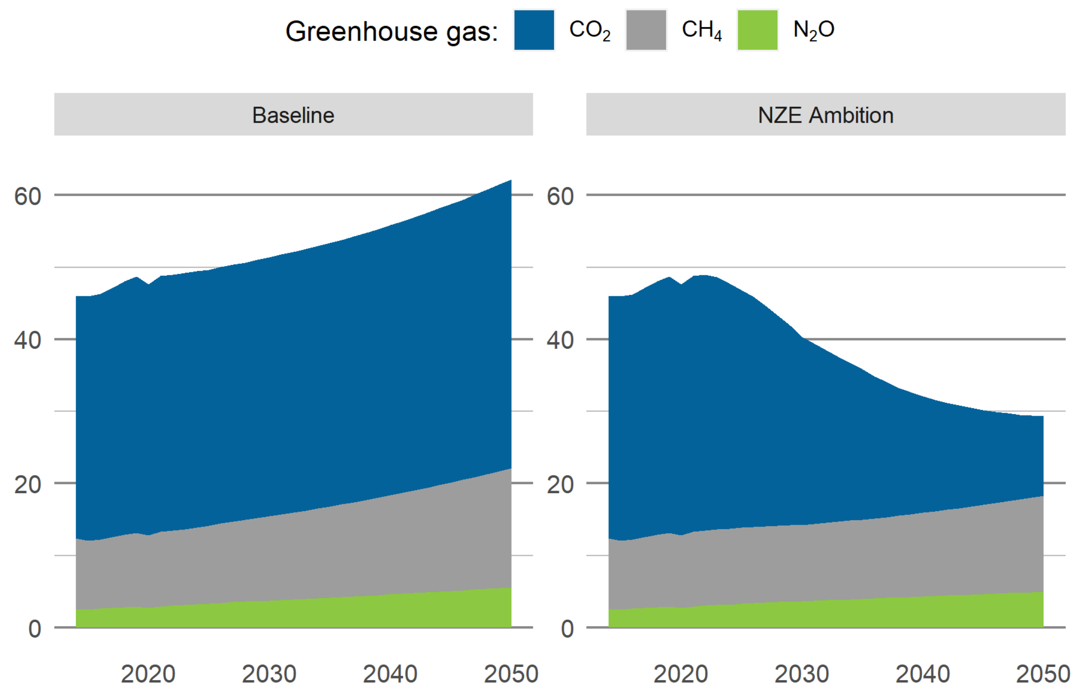
Most emission reductions result from the decarbonisation of the energy system. A decrease in the energy intensity of the global economy and a reduction of global economic output also contribute to emission abatement. Overall, the *NZE Ambition* scenario implies a strong shift away from fossil fuel-intensive 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). Additional results on this scenario are provided in Annex C.

The *NZE Ambition* scenario also entails reduction in non-CO_2 greenhouse gases (Figure 3.3), even though CH_4 and N_2O are not targeted directly by any specific policy. CH_4 emissions are reduced by 19.2% while N_2O emissions decrease by 10.9% compared to *Baseline*. These reductions are the result of a decrease in economic activities, such as fossil fuel production or agriculture.

[24] The temperature increase estimates are calculated with the MAGICC 7 model, based on OECD ENV-Linkages model CO2 emission projections, using SSP1-1.9 scenario for other emissions. The ranges represent the 5th and 95th percentiles of the climate sensitivity in 2100.

Figure 3.3. The *NZE Ambition* scenario also reduces emissions from other greenhouse gases

Greenhouse gas emissions by gas (Mt CO2e)



Note: The Global Warming Potential used to convert emissions into CO_2-equivalents comes from the AR6 (IPCC, 2021[35])
Source: OECD ENV-Linkages model.

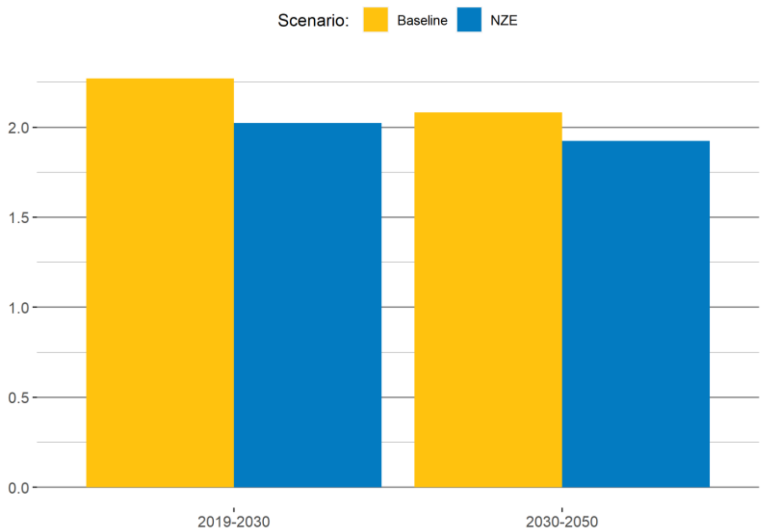
3.3. Most economic costs of the net-zero transition come after 2030

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 (Figure 3.4). The average global GDP growth rate goes from 2.3% per annum in the *Baseline* between 2019 and 2030 to 2.0% and decreases from 2.1% between 2030 and 2050 in the *Baseline* scenario to 1.9% in the *NZE Ambition* scenario. This leads to a reduction of global GDP compared to *Baseline* by 2.6% in 2030 and 5.6% 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 (Box 3.1), as well as important co-benefits from emissions reductions as for example on health.

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.[25]

Figure 3.4. Average annual growth of the global economy remains robust in the *NZE Ambition* scenario

Average annual growth rate of GDP (%)



Source: OECD ENV-Linkages model.

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. Additional results are provided in Annex C.

[25] The modelling abstracts from changes in international migration and 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. If labour and capital would move internationally, this could affect all countries involved. There is insufficient data to model the direction of such flows and the effect on fiscal revenues are a priori unclear.

Box 3.1. The costs of inaction and the benefits of policy action of climate change

Quantifying the economic implications of different climate pathways is not trivial. Recent modelling studies, as assessed by the IPCC (2022[29]), tend to have damages modelled as an upward sloping function of temperature increase with damages of 1-7% of GDP by 2100 from a 4°C temperature increase. Econometric estimates of the damages of climate change vary widely, with some finding significant effects only for developing countries (Dell, Jones and Olken, 2012[36]) while others find very large effects globally (Burke, Hsiang and Miguel, 2015[37]; Burke, Davis and Diffenbaugh, 2018[38]). Kahn et al. (2021[39]) synthesise the existing empirical literature as supporting roughly a 4-10% GDP loss from a 4°C temperature increase.

Additionally, emerging evidence highlights the increasing risks of systemic changes caused by climate change. These include large-scale tipping points in the global climate, such as the disintegration of the Greenland and West Antarctic Ice Sheets and permafrost collapse, as well as climate change-induced impacts that could cause abrupt changes to the economic system, such as water scarcity. The potentially drastic climate and economic consequences of these risks can imply much higher costs of inaction (Dietz et al., 2021[30]; Dietz and Koninx, 2022[31]; Cai and Lontzek, 2019[32]).

The macroeconomic costs of action presented in this paper do not account for the reduction in climate damages and risks resulting from lower CO_2 emissions. A robust quantification of these benefits is not available due to methodological and data shortcomings. The most recent IPCC assessment of the costs and benefits of stringent mitigation action (IPCC, 2022[40]) concludes that cost-benefit analysis (CBA) and CBA integrated assessment models "remain limited in their ability to represent all damages from climate change, including non-monetary damages, and capture the uncertain and heterogeneous nature of damages and the risk of catastrophic damages.

Importantly, the major benefits of the *NZE Ambition* scenario are reaped after 2050: in the *Baseline* the average global temperature increase by 2050 is around 2°C but stronger temperature increases in the second half of the century drive larger damages. Since temperature increases hardly exceed 1.5°C in the *NZE Ambition* scenario and decline after 2050, the largest differences in temperature – and thus the largest benefits – are reaped after 2050. Due to the differences in timing, it is difficult to compare the costs and the benefits of policy action. A thorough comparison entails calculating the present value of all costs and benefits. Evaluating current costs versus future benefits is fraught with difficult assumptions surrounding discounting.

4 The effect of policy instrument choice on public finance

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[27]), 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 4.1). 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. As a consequence, 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.

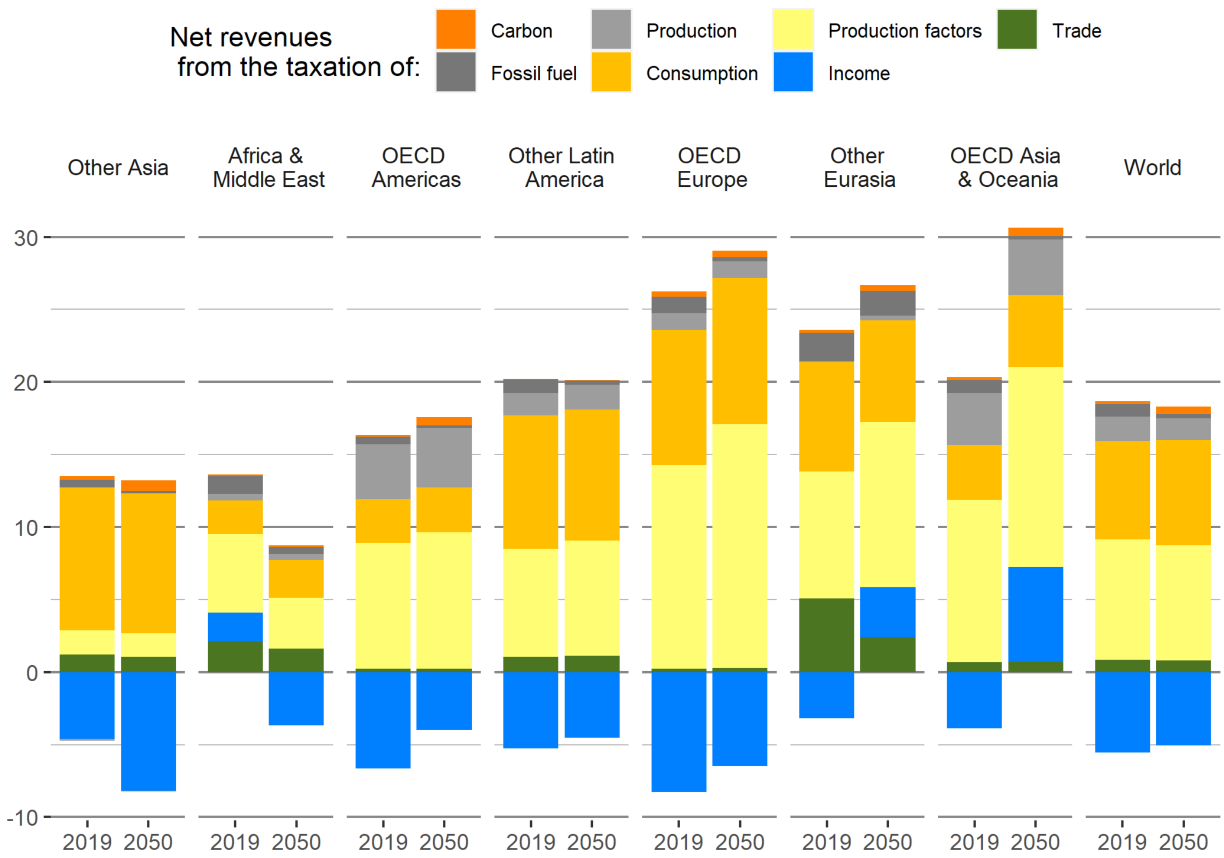
In the *Baseline* scenario, net public revenues as a share of GDP slightly increase between 2019 and 2050. This results from the *Baseline* calibration, which includes: (i) a change in the sectoral structure of the economy (servitisation); (ii) an evolution of tax and subsidy rates over time, reflecting current and legislated policies, and (iii) a constraint on the evolution of public deficit over time (see Annex A). In general, the tax and subsidy rates are constant between 2019 and 2050 in the *Baseline* scenario, which explains that most net public revenues increase with the fiscal base. Most differences between 2019 and 2050 happen because of changes in income taxation. This comes from the assumption that governments will use net income taxation (which includes actual income taxes as well as transfers to households) to ensure that public deficit follows its exogenous pathway in the *Baseline* scenario. Due to GDP growth in the *Baseline*, overall public revenues and expenditures tend to increase. The equilibrium between these two variations results in a net increase in income tax revenues (or net decrease in transfers to households). In OECD Asia & Oceania and Other Eurasia households' revenues change from being net subsidized in 2019 to net taxed in 2050.

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 is assumed to grow from USD 4 to USD 21 in the *Baseline* scenario, although with significant regional differences (see Annex B),[26] 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.

[26] Average regional carbon prices in the *Baseline* scenario in 2050 range from USD 0 to USD 99.

Figure 4.1. 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)



Note: Net public revenues correspond to the difference between tax revenues and subsidies expenditure.
Source: OECD ENV-Linkages model.

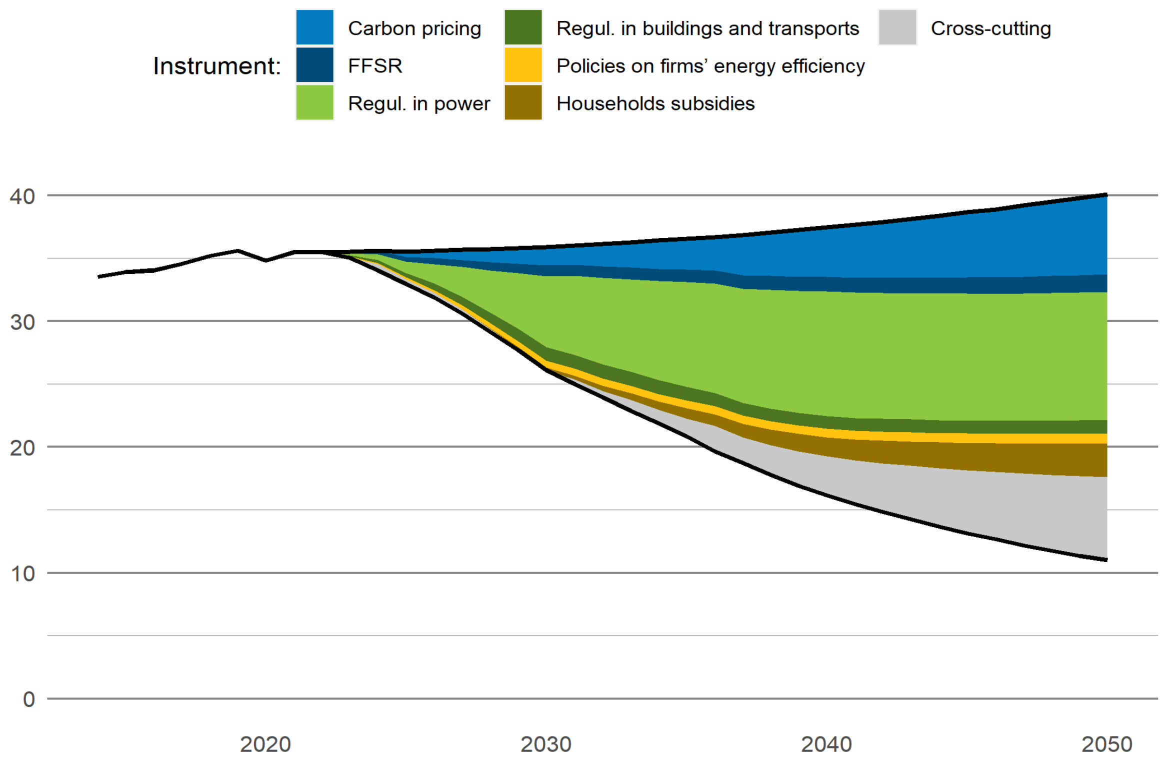
4.2. All policy instruments have significant indirect effects on public finance

Emissions reductions in the *NZE Ambition* scenario are achieved through the use of all policy instruments considered, but the largest contributions are from regulations in the power sector, followed by carbon pricing (Figure 4.2). 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 transports 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.

Figure 4.2. 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)



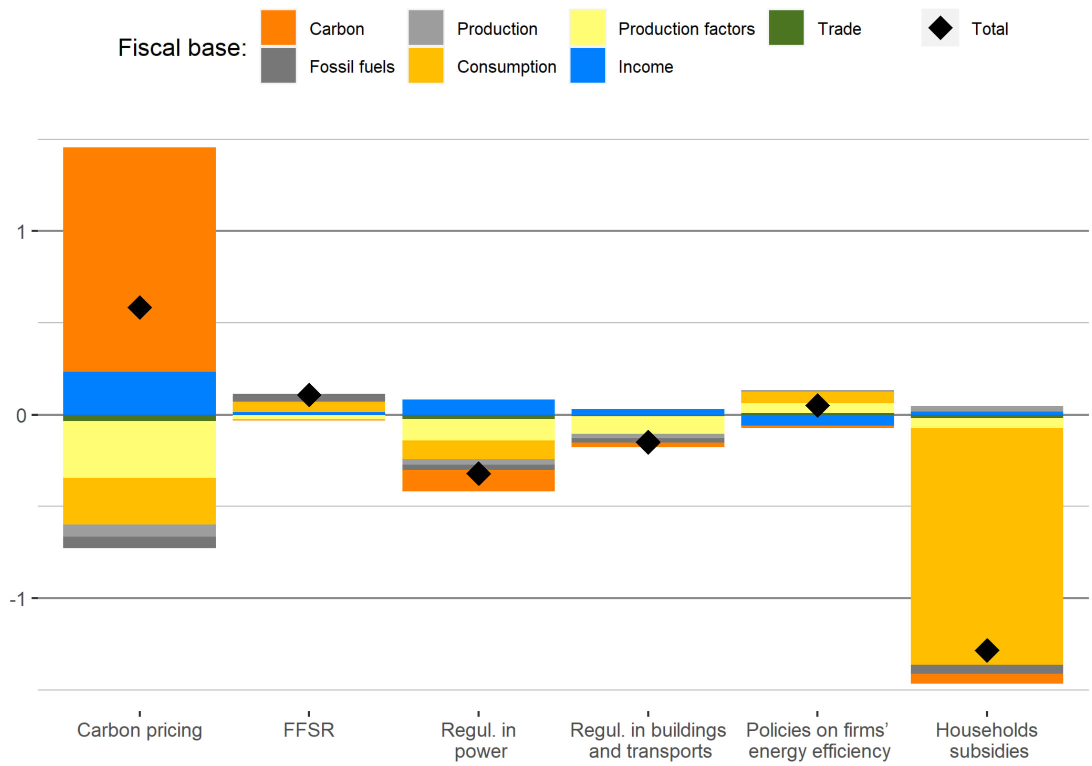
Note: "Cross-cutting" correspond to induced effects not attributable to a specific instrument, including CCUS and interactions between instruments.
Source: OECD ENV-Linkages model.

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 4.3. Even if the global average effects are limited, phasing out of environmentally harmful subsidies, such as fossil fuel subsidies, supports public budget, especially in countries where they are the highest (see Section 4.4). 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 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 household income, because the former tax bases represent a larger share of public revenues than the latter (see Figure 4.1). 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 4.3. 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)



Note: Each category corresponds to a scenario where only the policy instrument mentioned is implemented. FFSR stands for "Fossil fuel subsidy removal".
Source: OECD ENV-Linkages model.

Each policy instrument also has different macroeconomic effects beyond its impact on public finances, leading to different levels of efficiency in reducing CO_2 emissions or distributional effects between sectors and between other economic agents.[27]

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 0.9% of *Baseline* GDP in the *NZE ambition* scenario. This is the outcome of three main drivers, illustrated in Figure 4.4: carbon prices increase significantly (2nd

[27] 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.

column)[28], but at the same time CO_2 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 (illustrated in Figure 4.3), only around half of revenues from carbon pricing can be recycled (see Box 4.1).

Box 4.1. What is the potential for revenue recycling in the net-zero transition?

Revenue recycling corresponds to using the revenues from an increased carbon taxation to finance other policies. In the political discussions, many policies are presented as potential recycling strategies, among which three are particularly discussed:

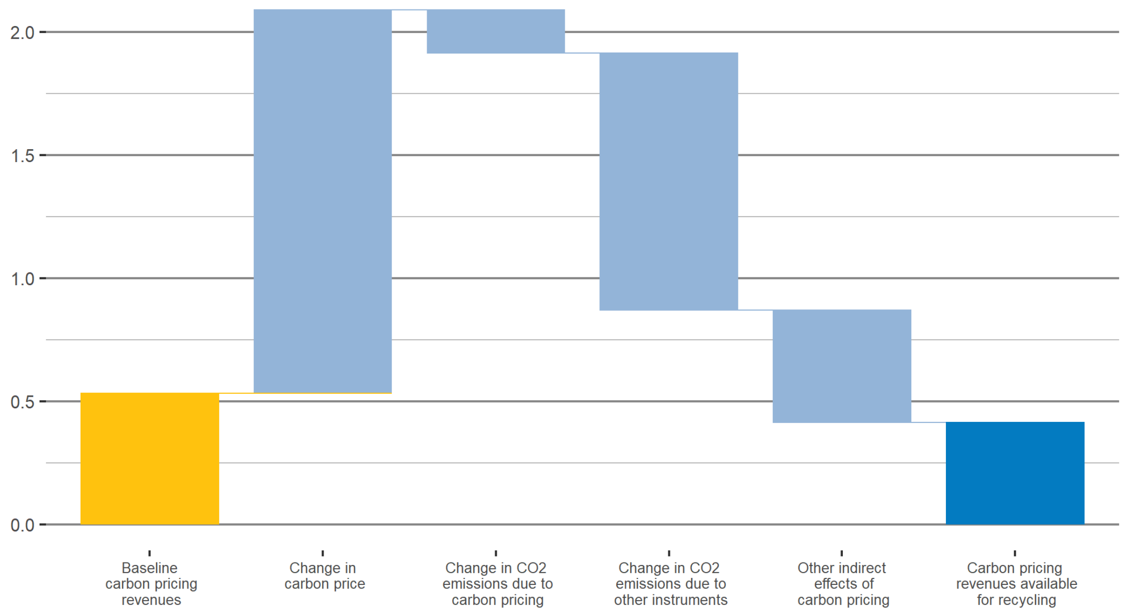
- Reducing labour taxes: by using carbon tax revenues to reduce labour taxes, which is considered in standard economics as a distortive tax, recycling could lead to higher GDP growth (or lower GDP cost of increasing carbon pricing). This option is also called “double dividend” because the carbon pricing policy would at the same time reduce the environmental externality and increase output and potentially employment.
- Financing carbon sequestration: in a net-zero emission world, residual CO_2 emissions are fully compensated by carbon sequestration. Many advocate that a “fair” price for sequestration is equal to the price of carbon emissions. Under such a scheme the value of carbon revenues from pricing gross emissions in a net-zero situation by definition equals the expenditures on sequestration, leaving no revenues for compensating for erosion of tax bases or financing of other policy instruments.
- Correcting distributional effects: carbon pricing is a regressive policy, which weighs more on households with lower budgets (as a proportion of their income) than on richer households. Recycling carbon pricing revenues into redistributive policies would help correcting this regressive bias, making the policy more acceptable for households.
- Financing other climate policies: some climate policies necessitate significant investments, and if these investments are to be financed by public spending, additional fiscal resources need to be levied. Carbon pricing can therefore be used to increase public revenues and finance other climate policies.

As a result, the 0.9% of Baseline GDP of carbon revenues in the *NZE Ambition* scenario only translate into potentially 0.4% net revenues (6th column in Figure 4.4), lower than *Baseline* carbon revenues. Similar results occur when carbon pricing is implemented alone (see Figure 4.3) without any other policy instruments, generating 1.2% of *Baseline* GDP, reducing to 0.6% 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.

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

Figure 4.4. The net public revenues of carbon pricing are partially offset by eroding tax bases

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



Note: Baseline carbon pricing revenues reflect current policies and includes e.g. the EU ETS and carbon tax schemes in a range of countries.
Source: OECD ENV-Linkages model.

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 1.8% 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 -0.4% of *Baseline* GDP in 2030 and -1.8% in 2050, as shown in Figure 4.5.

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 is 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 (Figure 4.5). 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.

These impacts differ substantially across regions (Figure 4.5), depending on regional characteristics (economic structure) as well as on the policy mix employed in each region under the *NZE Ambition* scenario (see Section 2). Overall, the net-zero transition represents a net cost for public finances in all regions, ranging from -3.4% to -0.7% of *Baseline* GDP.

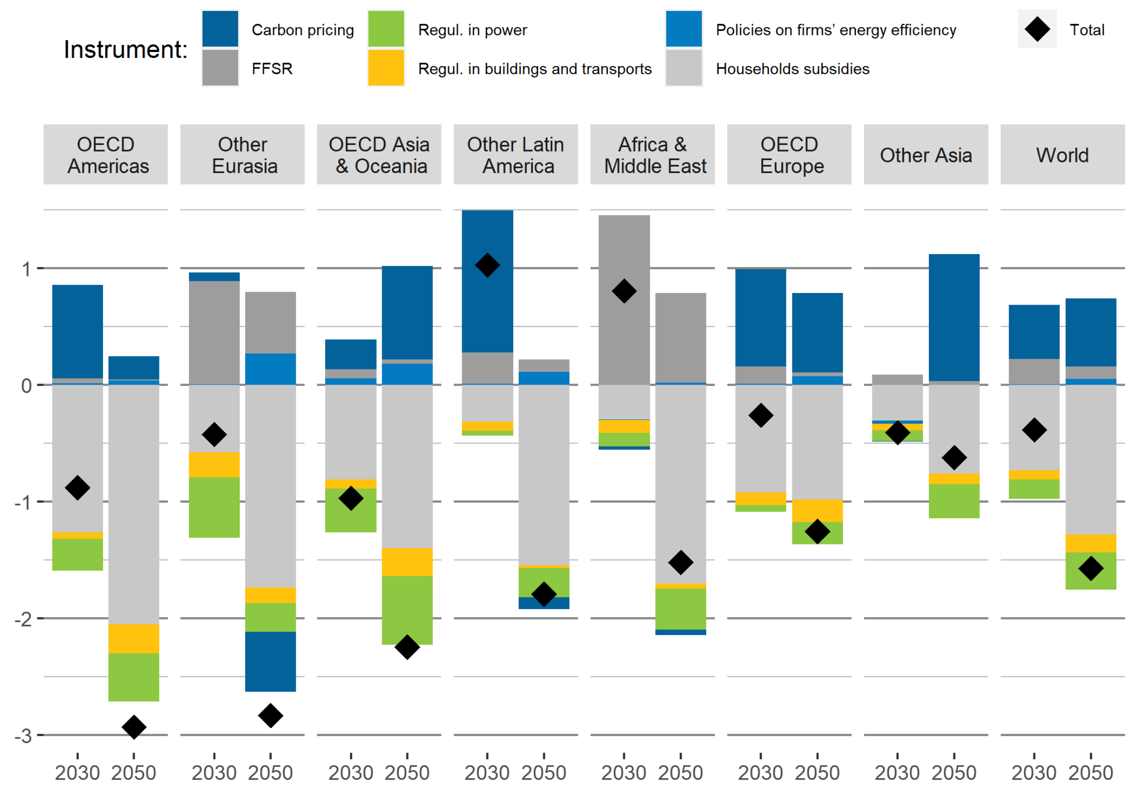
In the short-, to medium-term, two regions experience an increase in net public revenues in 2030, for different reasons. In Africa & Middle East, the decrease in government expenditures resulting from the removal of fossil fuel subsidies generates significant net revenues in 2030. In Other Latin America, 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 Americas). In regions where carbon pricing plays a significant role in the *NZE Ambition* scenario (OECD Asia & Oceania, OECD Europe), 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 very little carbon pricing is required to achieve the needed emission reductions. Some regions see a decrease in total net public revenues due to carbon pricing despite increasing carbon pricing revenues. In these regions, the negative indirect effects on other tax bases more than offset the additional carbon pricing revenues, either because the increase in carbon price is very limited (Other Latin America, Africa & Middle East) or because other tax bases – such as revenues from fossil fuel taxation and households' income taxation – are eroded significantly (Other Eurasia).

Figure 4.5. Changes in net public revenues in the *NZE Ambition* scenario range from -0.7% 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)



Source: OECD ENV-Linkages model

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 the 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[41]; Glynn et al., 2022[42]), 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.

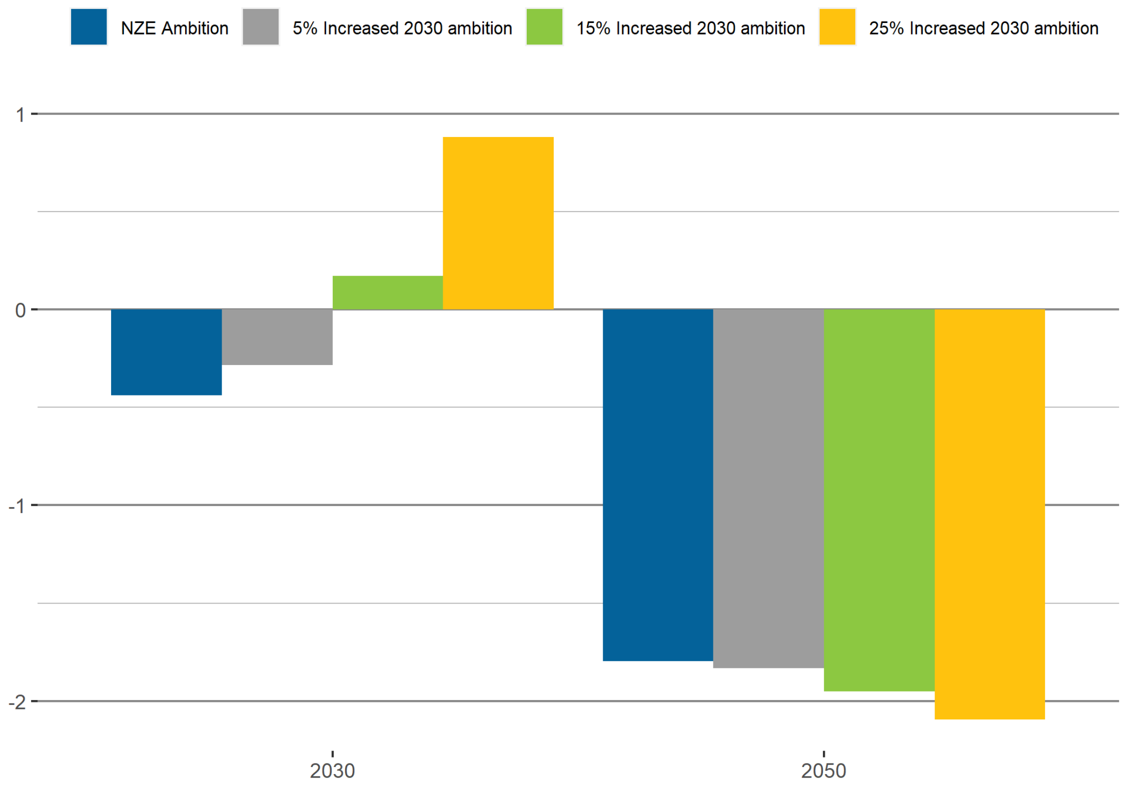
The first set of these alternative scenarios focus on the timing of mitigation action. In the *Increased 2030 ambition* scenarios, the emission reduction objectives for 2050 are identical to the *NZE Ambition* scenario but a significant part of the 2030-2050 mitigation (5, 15 and 25%) is moved to the 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 4.6). 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 4.6. 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)



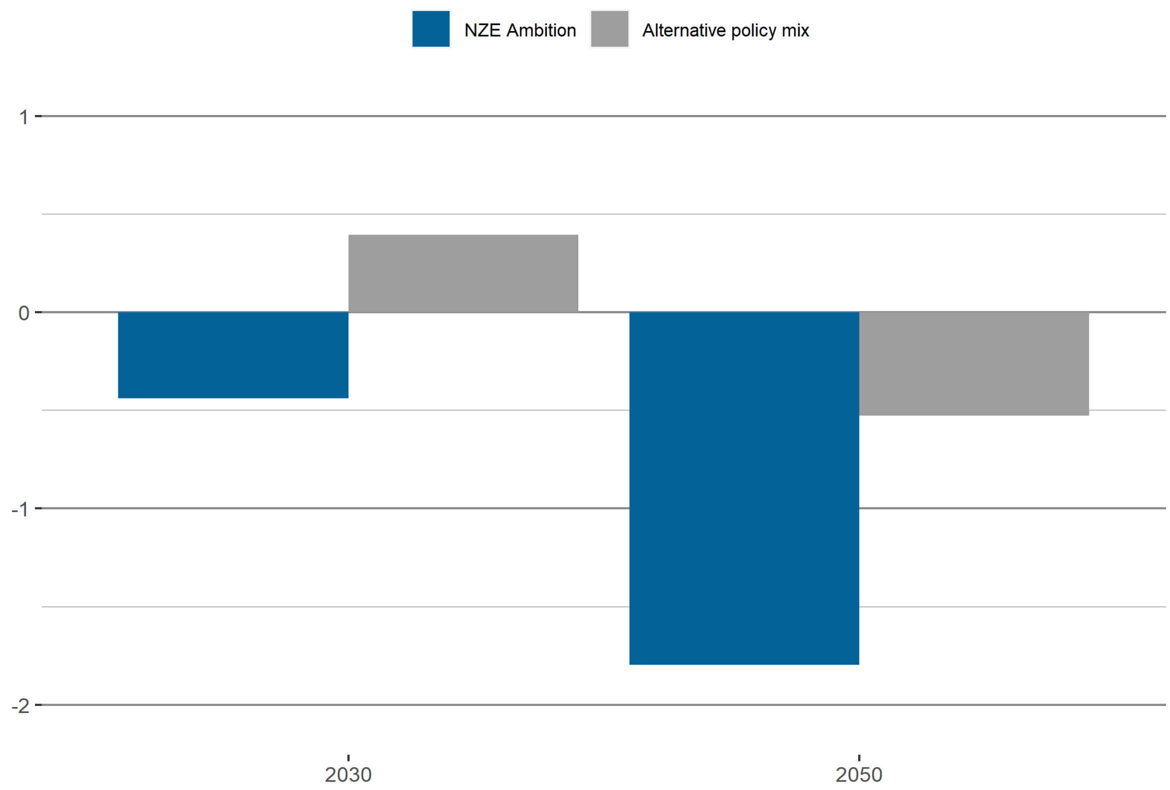
Source: OECD ENV-Linkages model.

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 25%, 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 4.7). 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 4.7. 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)



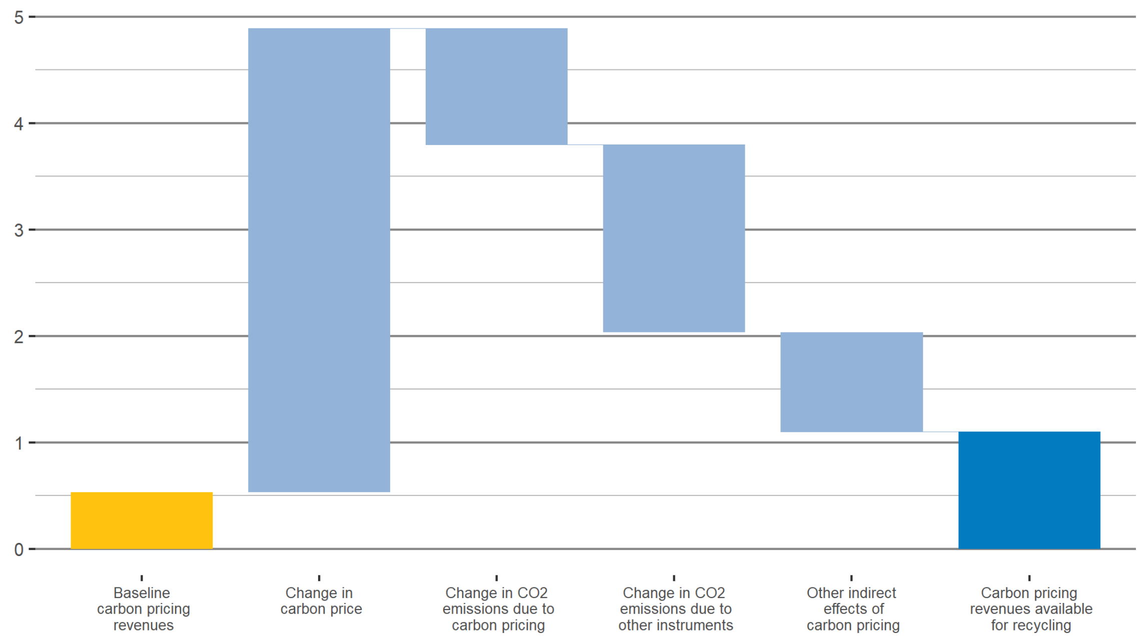
Source: OECD ENV-Linkages model.

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 lower than in the *Baseline* (Figure 4.4). 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 more than double compared to the *NZE Ambition* scenario, leading to proportionately larger carbon price revenues (column 2 in Figure 4.8, amounting to around 4.9% of *Baseline* GDP, compared to column 2 in Figure 4.4 corresponding to 2.1% 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 4.8, corresponding to around 1.1% of *Baseline* GDP, compared to 0.4% in the *NZE Ambition* scenario in Figure 4.4).

Higher emissions reductions associated with carbon pricing erode the tax base upon which carbon price revenues are derived in the long-term (Figure 4.8, 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 4.8. The balance between different policy instruments can change the carbon pricing revenues available for recycling

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



Note: 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 4.4, but using the *Alternative policy mix* scenario instead of *NZE Ambition* scenario.
Source: OECD ENV-Linkages model.

5 Discussion

This paper shows that transitioning towards carbon neutrality is feasible from an economic and fiscal perspective. The modelling analysis shows that such an ambitious policies do entail costs, however. The transition would imply a small slowdown of global economic growth in the time period between 2019 and 2050 (0.2 percentage points) and a decrease in net public revenues – the difference between tax revenues and subsidies expenditures – by 1.8% in 2050, although with large regional differences. Governments can choose and design their policy package according to their economic and energy context, within the context of the need to effectively decarbonise the entire economy of emissions and largely maintaining the resilience of the fiscal system.

This paper also sheds light on the mechanisms through which the transition affects public finances. Impacts on public finances result from the net effect of two opposing mechanisms. Some instruments provide more fiscal space. This is the case for instruments such as carbon pricing, which increase public revenues, or for the removal of fossil fuel support, which reduce public expenditures. Other instruments lead to a reduction of net public revenues. This effect takes place for instruments that are more costly, such as subsidies. All instruments entail an erosion of the tax base. Indeed, 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. For instance, this tax base erosion reduces by around half the potential for net public revenues of carbon pricing.

The results on public finances and economic growth outlined in the paper need to be compared to the socio-economic benefits from the reduced climate damages (the cost of inaction). While these are difficult to quantify, let alone include in a general equilibrium framework, it is important to keep in mind that achieving net-zero emissions would result in positive effects on the environment, human health and the economy, and reducing the risk of tipping points. Furthermore, the transition to a carbon neutral economy has significant co-benefits from improved air quality and interactions with the transition to a more resource-efficient and circular economy. Interactions with loss of ecosystem services and biodiversity are also likely significant, albeit less known. Quantification of such linkages is important but far from straightforward.

The results presented in this paper need to be interpreted with care as they are subject to uncertainty and depend on modelling assumptions, including baseline developments, 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 by region.

While the modelling approach presented in this paper includes some degrees of technological progress, these are limited and do not include explicitly the possibility of innovation or further development of technologies that are not yet marketed. 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. The fiscal consequences of policies to boost low-carbon innovation are not straightforward, however, not least due to the interaction effects with other policy instruments, and beyond the scope of the current analysis.

The scenario presented 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 (2021[43]) and reform of market-distorting subsidies beyond fossil fuels. The design of specific policies could also be changed. For example, the policy package presented 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. Additionally, the scope of the policy instruments could be changed, for instance to include non-CO_2 greenhouse gases.

While not the focus of this paper, climate policies can also have significant effects on other aspects of government budgets. Achieving net-zero emissions globally would imply a substantial reduction of climate damages and therefore lower public expenditures related to dealing with climate impacts, such as the destruction of infrastructure from extreme weather events, and related to adaptation to climate change, such as building sea walls to combat sea level rise. Reducing climate damages would thus have implications on public expenditures, as it would decrease the need for public finances to adapt to the adverse effects of climate change (de Mello and Martinez-Vazquez, 2022[33]). Climate policies may however significantly reduce public revenues from fossil fuel extraction activities.[29] These are often public or semi-public enterprises, and fossil fuel rents (beyond the fiscal treatment of fuel production and consumption that is covered in the analysis) often accrue to government budgets.

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, 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, but 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. The global analysis presented here can form the basis for ensuring that the international context of such country studies is properly considered.

A possible extension of this analysis could investigate trade-related issues related to the implementation of different policy instruments across countries. At first glance, countries that adopt policies that are less cost-effective risk losing comparative advantages, with negative consequences for the domestic economy, and for net public revenues. Furthermore, the current modelling analysis assumes a cap on emissions for all periods, which ensures that no carbon leakage can take place. In reality, carbon leakage may occur until the moment emission targets need to be reached, i.e. the target year of the NZE ambition.[30] These competitiveness and carbon leakage effects depend also on the speed with which countries adopt mitigation actions. The analysis of the competitiveness and carbon leakage implications of the transition to a carbon neutral economy is left for future research and could tie into a broader discussion on the interlinkages between trade and climate change (Dellink et al., 2017[44]).

Finally, future work should focus on environmental justice in the context of the transition. Achieving the net-zero transition without worsening inequality is vital for social policy objectives and public acceptance. In principle, greening of the fiscal system can contribute to increase income equality and reaping a triple dividend of economic, environmental and social gains if feasible, but this is far from being a given (Vona, 2021[45]). Flanking policies to smoothen labour market consequences of the net-zero transition may also require additional public finance, putting further pressure on the fiscal system. More research is needed to tease out how different household groups are affected by the various policy instruments.

[29] The additional investments to reduce emissions in state-owned enterprises are included in the analysis, for instance in the policy instruments to decarbonise the power sector. Similarly, tax payments by state-owned enterprises are accounted for. What is missing from the calculation is the rent accruing to the government from public ownership.

[30] To be precise, carbon leakage abroad from domestic policy can occur at any moment a foreign country does not cap its economy-wide emission levels. In principle, even under a global net-zero emissions scenario this does not preclude that carbon emissions are transferred abroad but compensated there through additional sequestration efforts. As gross emissions would increase in such a situation, this is labelled as carbon leakage under some definitions.

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Annex 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. It is based on the GTAP 10 database (Aguiar et al., 2019[27]) and GTAP-Power satellite account (Chepeliev, 2020[46]). 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[47]) 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 region	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[27]) for 2014. The Baseline scenario follows the projected population trends of the World Population Prospects (United Nations, 2018[48]) ("medium scenario"). For OECD countries and a number of emerging economies, the macroeconomic projections follow the OECD's short-term economic forecasts (OECD, 2021[49]) and the long-term projections of OECD Economics Department (Guillemette and Turner, 2021[18]).[31] For regions that are not covered by the OECD databases, short-term economic forecasts of the International Monetary Fund (IMF, 2020[50]) 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[28]).

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[51]), 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 (International Energy Agency, 2021[16]). 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.

[31] 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 modelling

Process CO_2 emissions are emissions produced during industrial processes other than fuel combustion emissions. For instance, the calcination of carbonates during cement production results in the release of process CO_2 emissions to the atmosphere. Adapting from Charkovska et al., (2019[52]), ENV-Linkages considers as process CO_2 emission the following activities:

- Mineral products, and particularly cement but also soda ash, lime, asphalt, limestone and glass production (IPCC category 2.A – GTAP sector nmm)
- Chemicals, including ammonia, carbide, ethylene (IPCC category 2.B – GTAP sector chm)
- Iron and steel production and ferroalloys (IPCC category 2.C.1 and 2.C.2 – GTAP sector i_s)
- Non-ferrous metal production, including aluminium, lead and zink (IPCC category 2.C.3 and 2.C.5 – GTAP sector nfm)
- Production of pulp and paper (IPCC category 2.D.1 – GTAP sector ppp)
- Refinery plants (IPCC category 2.G – GTAP sector p_c).

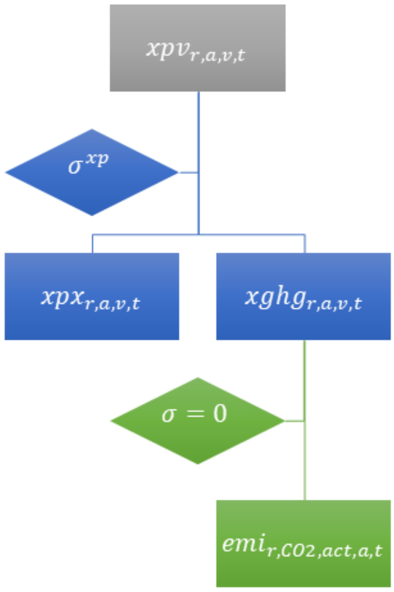
In addition, ENV-Linkages considers fugitives emissions as process emissions, including these activities:

- Coke ovens gas subsystems (IPCC category 1.B.1 – GTAP sector coa)
- Oil production (IPCC category 1.B.2.a – GTAP sector oil)
- Natural gas production and distribution (IPCC category 1.B.2.b – GTAP sectors gas and gdt)

The data on these emissions is taken from the EDGAR v6 database and allocated to GTAP sectors.

In ENV-Linkages, process CO_2 emissions are integrated within the production function, following the approach used by Hyman et al. (2002[47]) for non-CO_2 greenhouse gases (GHG). The abatement is represented by a possible substitution between greenhouse gases ($xghg$) and other sector inputs (xpx, corresponding to factors and intermediate consumption), as depicted in Figure A.1.

Figure A.1. Modelling of process CO_2 emissions abatement



Note: Each rectangle represents a variable in the model, linked one with the other by a constant elasticity of substitution functional form. The elasticity of substitution is represented within diamonds.
Source: ENV-Linkages model.

Calibration of Marginal Abatement Cost Curves

The marginal abatement cost curves (MACC) are the relation between carbon price in the model (a global homogenous carbon price focusing both combustion and process CO_2 emissions) and the level of CO_2 emissions abated compared to a zero carbon price baseline.

These MACCs for ENV-Linkages model are constructed by running a series of standard scenarios consisting in a global homogenous increase in carbon pricing to specific targets between 0 and 500 USD (constant 2014 USD), linear between 2021 and 2050 and depicting the curve formed by the carbon price and emission reduction in 2050.

Formally, the analytical expression for marginal abatement car be derived from the model's equations:

$$uc^{1-\sigma^{xp}} = a^{ghg}\left(\frac{pxghg}{\lambda^{ghg}}\right)^{1-\sigma^{xp}} + a^{xp}\left(\frac{pxp}{\lambda^{xp}}\right)^{1-\sigma^{xp}}$$

$$\frac{xghg}{xpv} = a^{ghg}\left(\lambda^{ghg}\right)^{\sigma^{xp}-1}\left(\frac{uc}{pxghg}\right)^{\sigma^{xp}}$$

These two equations serve as a basis to derive the abatement share between a scenario without tax (labelled with 0 superscript) and scenario with tax (labelled without superscript):

$$1 - \frac{xghg/xpv}{xghg^0/xpv^0} = 1 - \left[\frac{1 + \theta^{xp}/\theta^{ghg}\,(pxp/pxghg)^{1-\sigma^{xp}}}{1 + \theta^{xp}/\theta^{ghg}\,(pxp^0/pxghg^0)^{1-\sigma^{xp}}}\right]^{\frac{\sigma^{xp}}{1-\sigma^{xp}}}$$

Where $\theta^{ghg} = a^{ghg}(\lambda^{ghg})^{\sigma^{xp}-1}$ and $\theta^{xp} = a^{xp}(\lambda^{xp})^{\sigma^{xp}-1}$ are constants. $pxghg^0$ is the initial price for GHG used in the calibration, and for simplicity we'll consider $pxp^0 = pxp = 1$ as it does not significantly change the results. So, for any given θ^{xp}/θ^{ghg} (usually $\theta^{xp}/\theta^{ghg} \gg 1$), the shape of the abatement curve is parameterized by (i) the level of initial carbon pricing used for calibration $pxghg^0$; and (ii) the elasticity of substitution σ^{xp}.

If MACC data was easily available, the optimal strategy would be to estimate these parameters using econometrics techniques. However, the lack of available information on process CO_2 abatement makes it difficult to execute. Therefore, the calibration strategy is to assume an arbitrary low initial price for CO_2 emissions[32] and calibrate the elasticity of substitution using the available information in the literature on sectoral abatement potentials. This potential abatement is defined as the maximum amount of process CO_2 that could be abated with a very high carbon price, without considering the abatement possibilities using disruption technologies like CCS or hydrogen. When no information is available specific to process CO_2 emissions, information on all CO_2 emissions from the sector is used, and excluding measures related to energy efficiency and/or demand effects. The retained abatement potential are summarized in Table A.3.

Table A.3. Abatement potentials retained for the calibration of process CO_2 MACCs

Sector	Abatement potential approximated	Sources of information used for approximation	Elasticity of substitution
Non-metallic minerals (Cement)	30%	McKinsey (2020[53]) International Energy Agency (2018[54])	Old vintage: 0.01 New vintage: 0.02
Iron & Steel	45%	Sun et al. (2022[55]) Yu et al. (2018[56])	Old vintage: 0.05 New vintage: 0.1
Chemicals (Ammonia)	15%	The Royal Society (2020[57])	Old vintage: 0.1* New vintage: 0.15*
Refineries	0%	(Byrum, Pilorgé and Wilcox, n.d.[58]) (Johansson et al., 2012[59]) (Chan et al., 2016[60])	Old vintage: 0 New vintage: 0
Fugitive emissions (coal, oil and gas)	100%	(Laconde, 2018[61])	Old vintage: 0.8 New vintage: 0.8
Waste management	100%	(Bogner et al., 2008[62])	Old vintage: 0.8 New vintage: 0.8

Note: * For chemicals, the large number of different chemicals produced by the sector make difficult to determine an aggregate elasticity of substitution based on figures for Ammonia only. Therefore, the default ENV-Linkages value is retained instead of the calibrated one.
Source: Authors' calculations.

Elasticities of substitution for both vintages are in the end calibrated such that the model reproduces the abatement potential listed in Table A.1 for high carbon prices in 2050 (1000 USD) in a standard scenario setup with linearly increasing carbon prices.

[32] A value of $10 as a balance between the disequilibrium introduced in social accounting matrix data if the initial price is high and a very steep marginal abatement cost curve when the initial price is very low.

Annex 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.
2. 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.
3. 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 (International Energy Agency, 2021[16]), 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 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 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[17]) 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[63]). 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 Net Zero Tracker database (Hale et al., 2022[13]) 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 CO_2 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[34]), in a 2°C compatible pathway. CCUS and NETs usage is provided by IEA (2021[5]), 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 CO_2 emissions for this group of regions is set as a linear interpolation between CO_2 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.

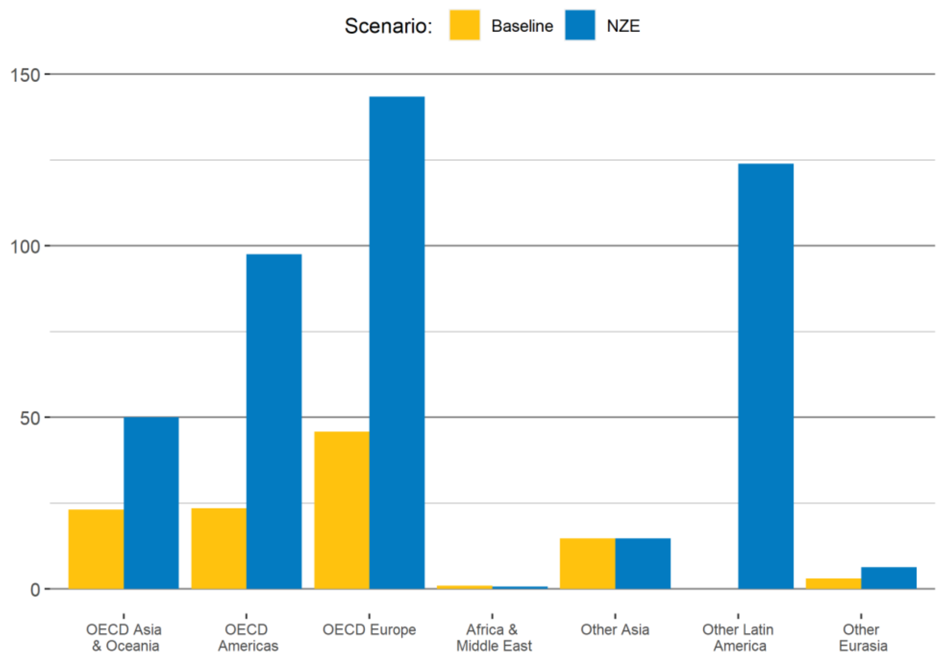
Resulting carbon prices

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.

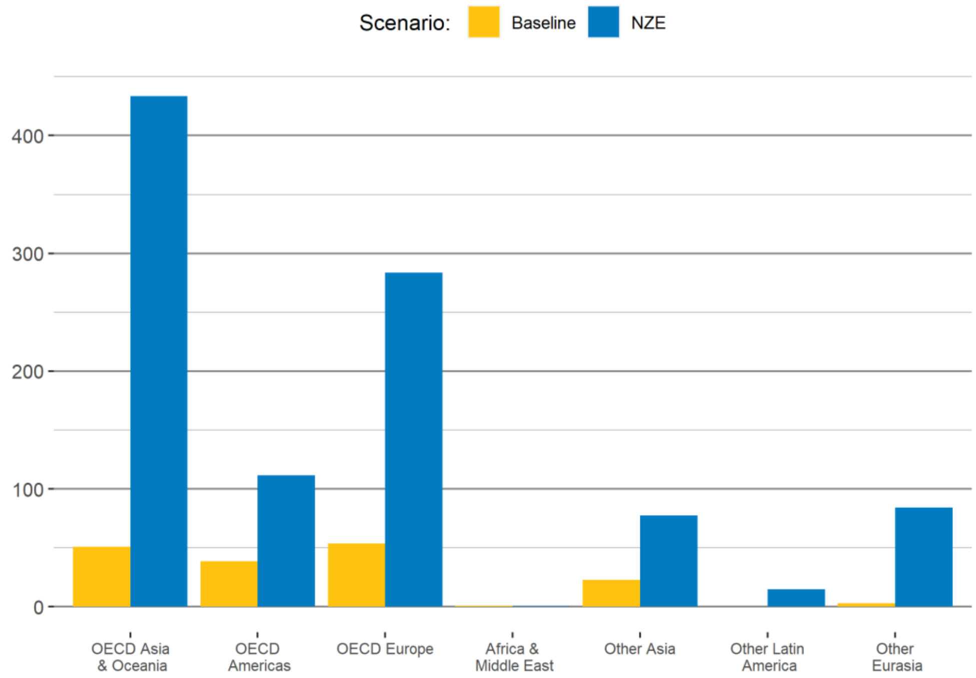
Figure B.1. The NZE Ambition scenario requires high carbon prices to reach emission targets in 2050

Average carbon price on CO_2 emissions (constant 2014 USD)

Panel A. 2030



Panel B. 2050



Source: OECD ENV-Linkages model.

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[25]) 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.

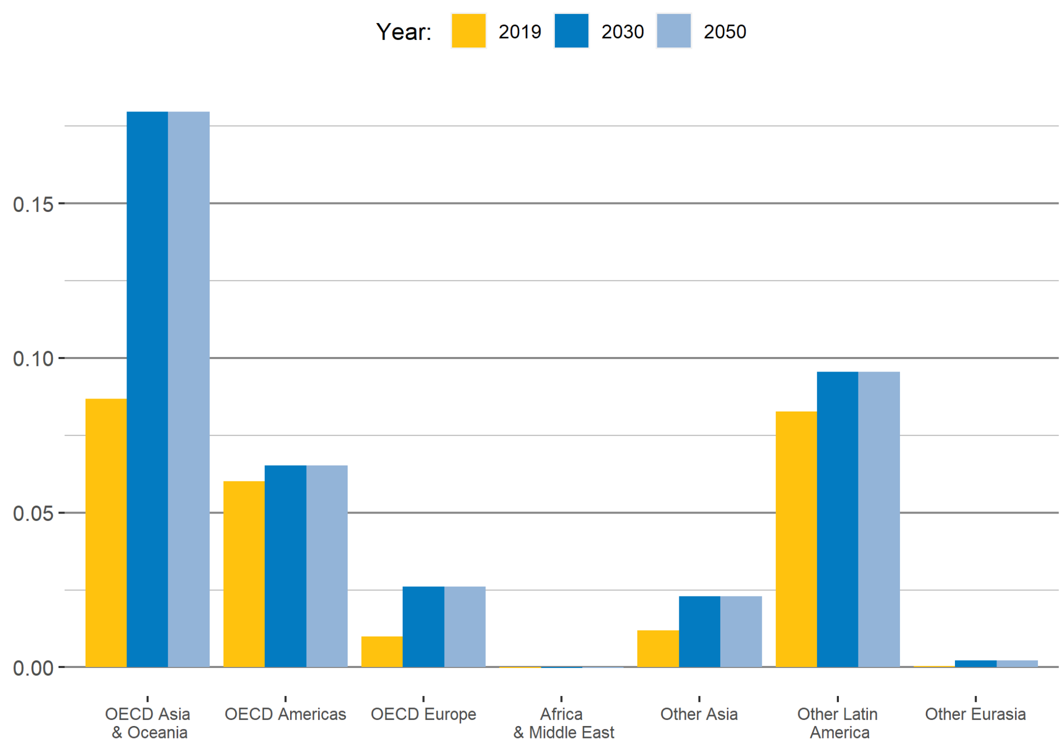
Finally, the dataset is extended with additional data gathered from the IEA Fossil Fuel Support Database (IEA, 2021[26]) for the years 2014 and 2019. This is because the OECD Inventory currently covers fossil fuel support in 50 OECD countries, G20 and Eastern Partnership (EaP) economies. The IEA Database 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.

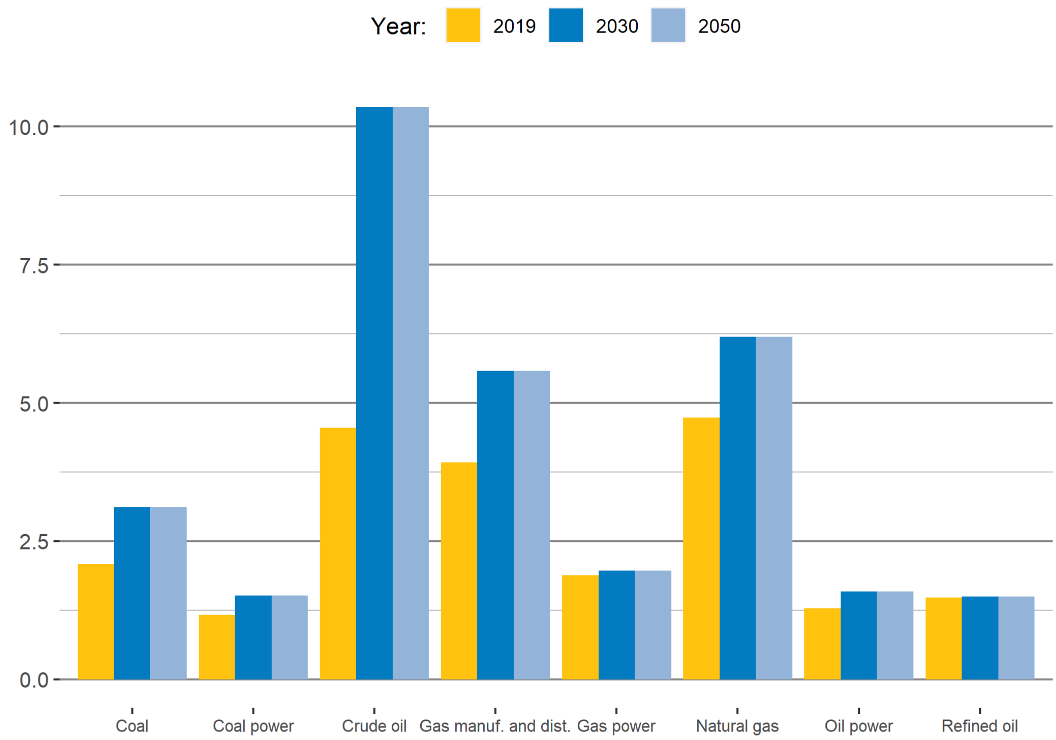
Figure B.2. The *NZE Ambition* scenario increases net tax rates on fossil fuel production and transformation

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

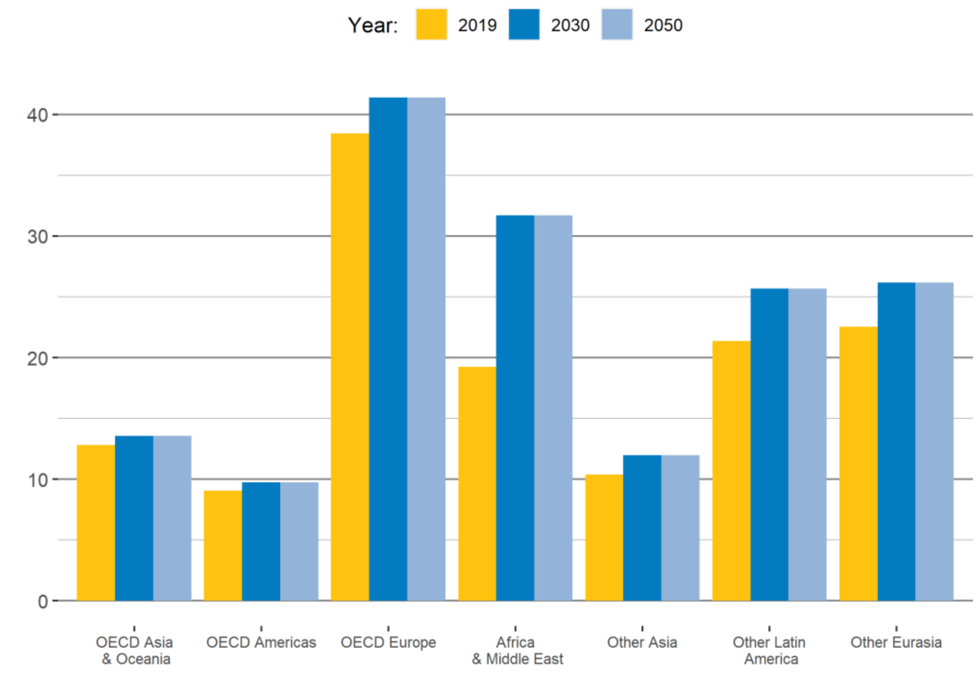


Note: The figures presented are the arithmetic average of fossil fuel production net tax rate, weighted by the sector output in 2019.
Source: OECD ENV-Linkages model based on OECD (2022[25]) and IEA (2021[26]) data.

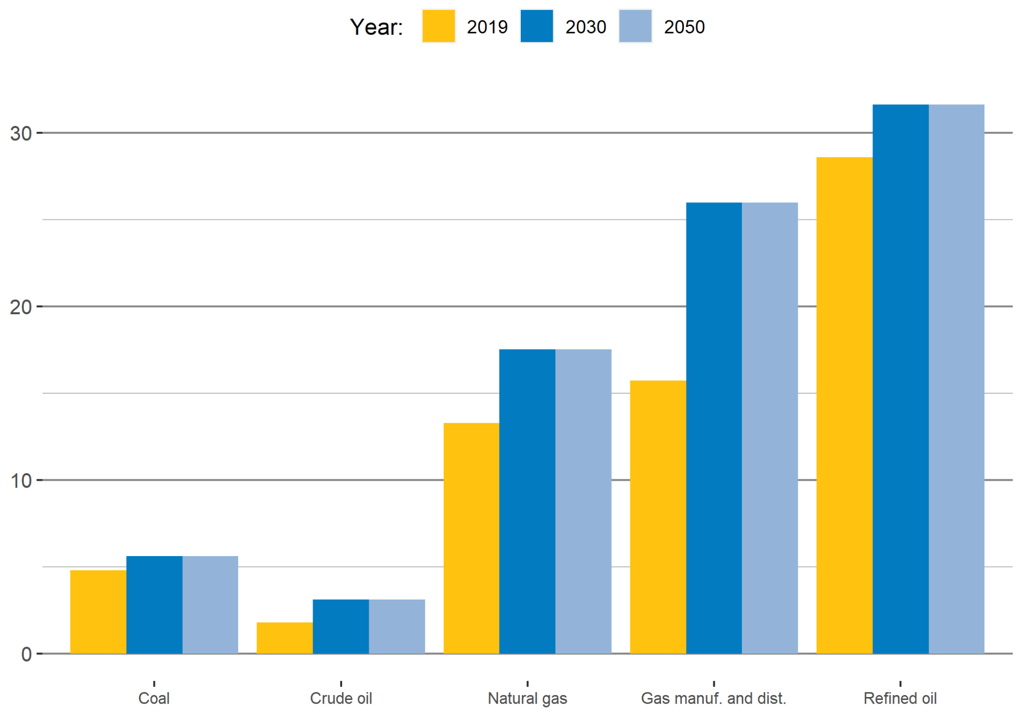
Figure B.3. The *NZE Ambition* scenario increases net tax rates on fossil fuel consumption

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



Note: The figures presented are the arithmetic average of fossil fuel consumption net tax rate, weighted by demand in 2019.
Source: OECD ENV-Linkages model based on OECD (2022[25]) and IEA (2021[26]) data.

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:

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

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 decarbonation 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 $g^{\lambda^e}_{r,e,a,t}$ 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[64]) that allows to reach the global objectives of the IEA's NZE scenario (International Energy Agency, 2021[5]), 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 (International Energy Agency, 2021[5]).

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

1. 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.
2. 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.
3. 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.

4. 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:

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

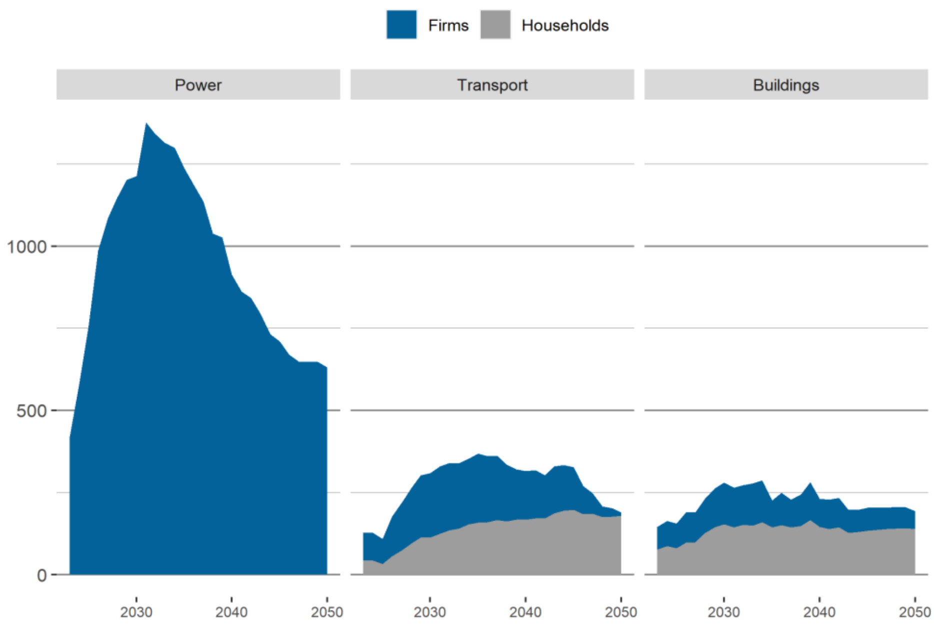
where:

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

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)



Source: OECD ENV-Linkages model, based on IEA (2021[16]). 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.

Annex C. Detailed modelling results

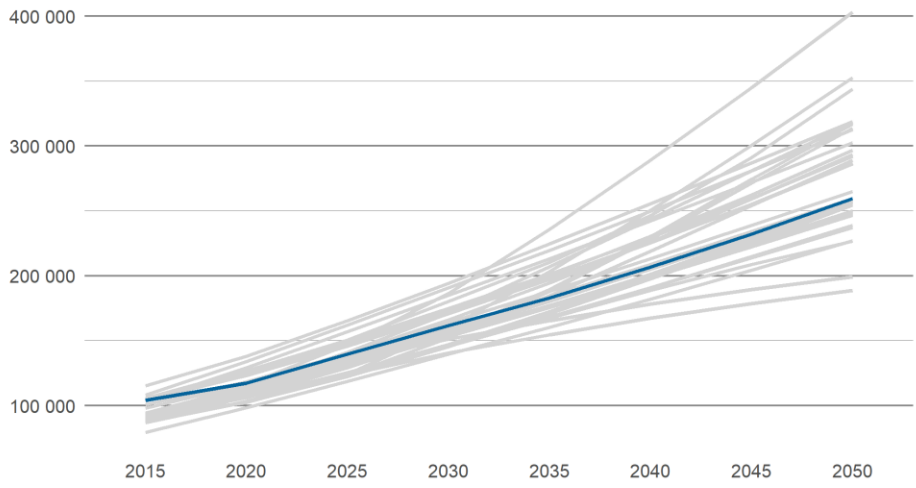
Baseline scenario

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

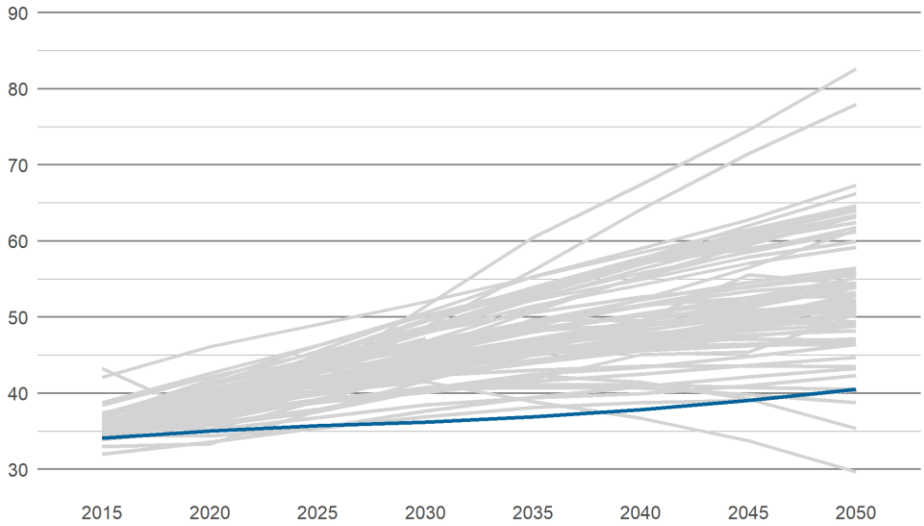
Comparing the ENV-Linkages *Baseline* with the set of scenarios presented in the 2022 IPCC Working Group III report (IPCC, 2022[40]), the *Baseline* appears in the medium range for economic growth, while in the low range for emissions (Figure C.1). This is due to the fact that the ENV-Linkages *Baseline*, as the World Energy Outlook (International Energy Agency, 2021[16]), 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)



Note: ENV-Linkages projections are shown in blue.
Source: OECD ENV-Linkages model and IPCC (2022[40]).

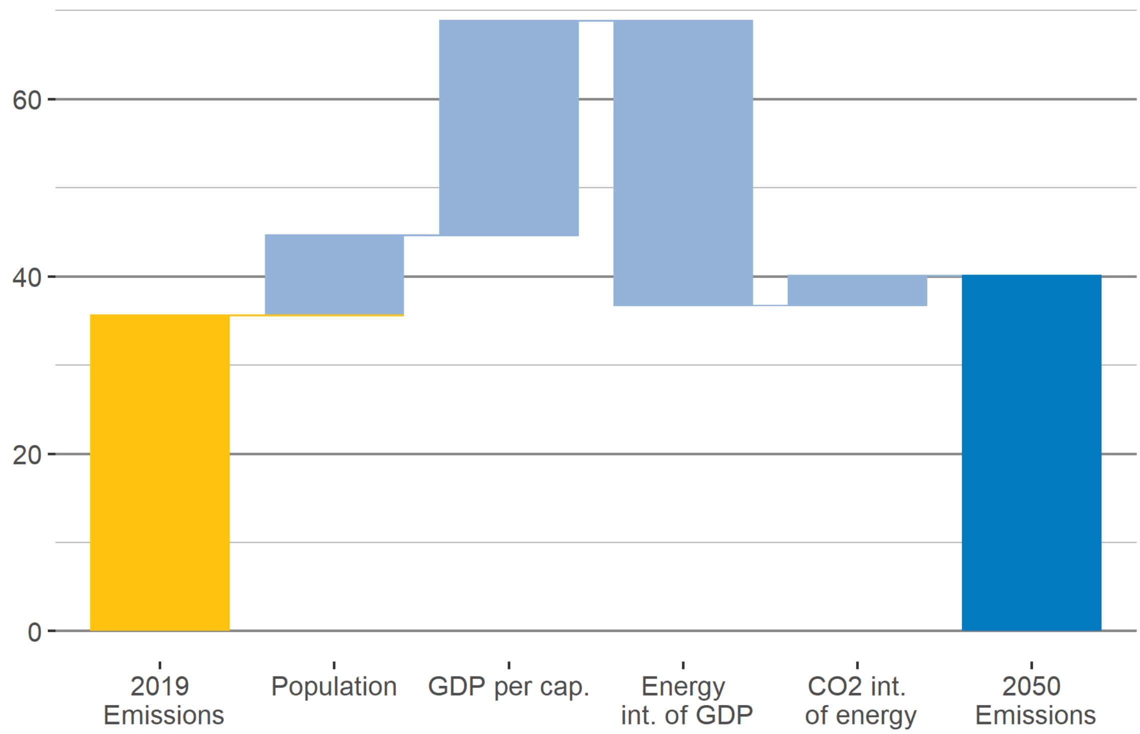
Drivers of changes in emissions

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 10 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 CO_2 emissions. This income effect adds another 36 Gt of emissions by 2060.
- 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 more than 34 Gt of emissions in 2060.
- The amount of CO_2 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)



Source: OECD ENV-Linkages model.

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 CO_2 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.

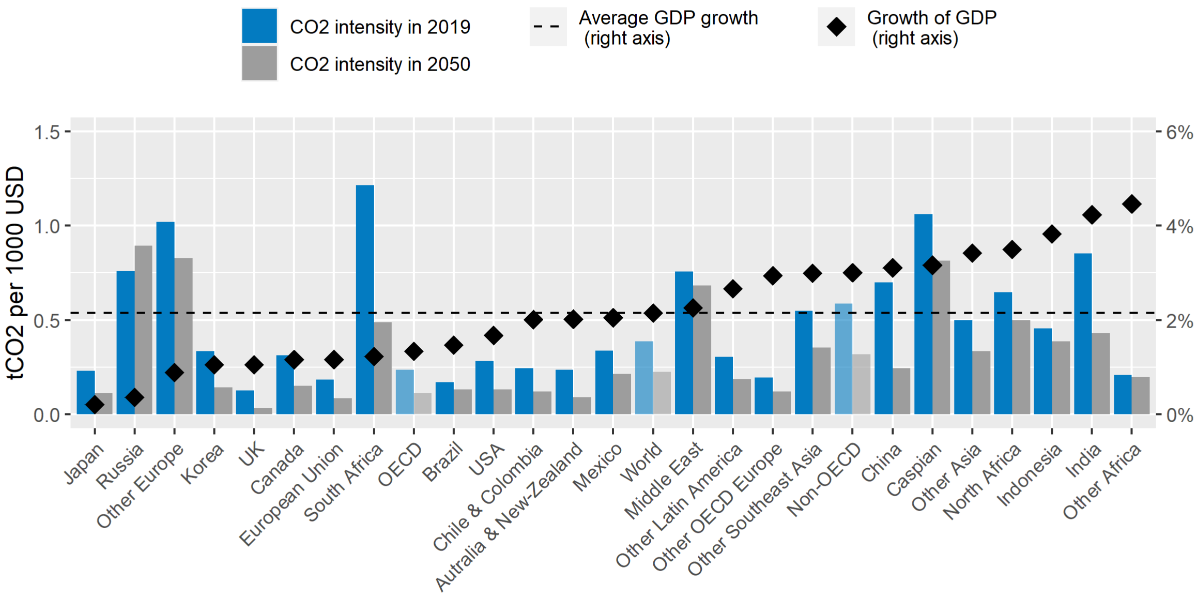
Changes in regional economic growth

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 2.6% 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 5.4%, 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 CO_2 intensity of GDP (i.e. the combination of energy intensity of GDP and CO_2 intensity of energy) in 2019. Therefore, even though in almost all countries (all except the Russian Federation) the intensity of CO_2 decreases, the CO_2 intensity of the global economy declines relatively little (thus with limited effect in driving global CO_2 emission changes, as shown in Figure C.3).

The projected changes in regional emissions highlight the need for global action to mitigate CO_2 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



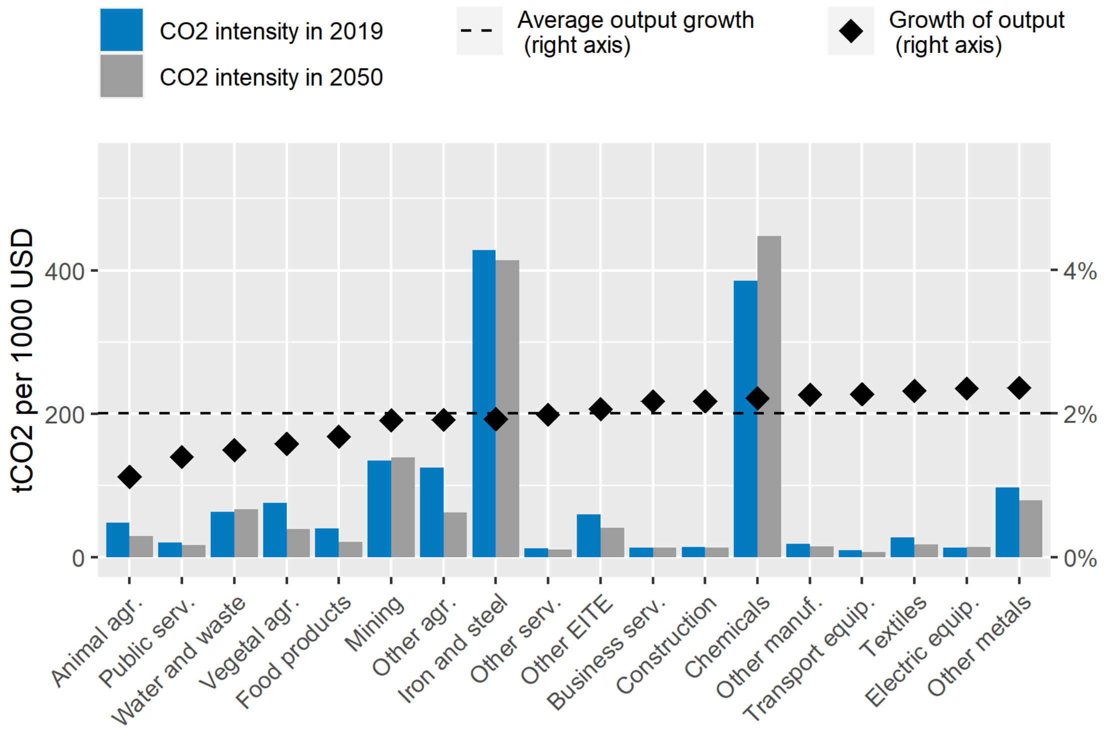
Source: OECD ENV-Linkages model.

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



Note: "agr." = "agriculture", "manuf."="manufacturing", "serv."="services, "equip."="equipment".
Source: OECD ENV-Linkages model.

NZE Ambition scenario

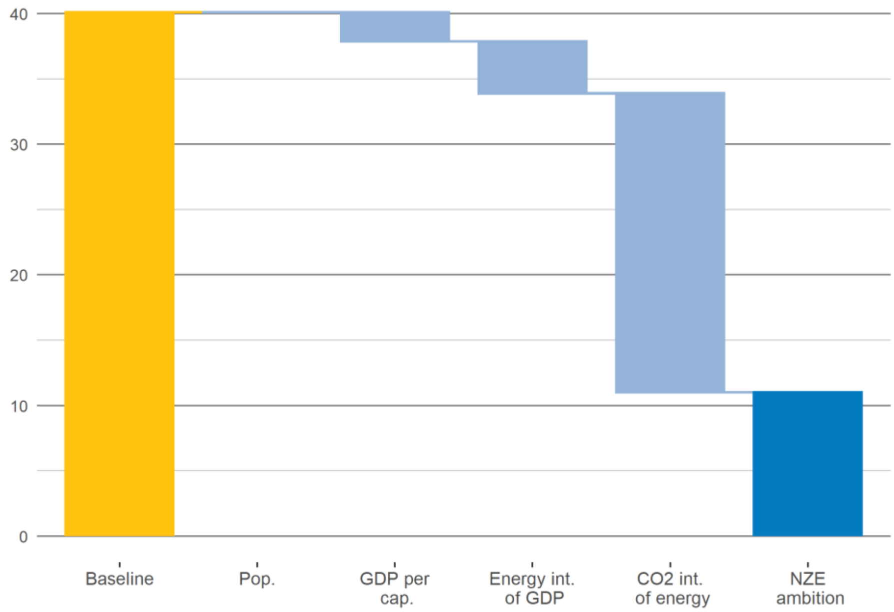
Decomposition of emission reductions in the NZE Ambition scenario

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 CO_2 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.[33] Finally, by assumption, population does not change between scenarios.

[33] 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 CO_2 intensity of energy and energy intensity of GDP

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



Source: OECD ENV-Linkages model.

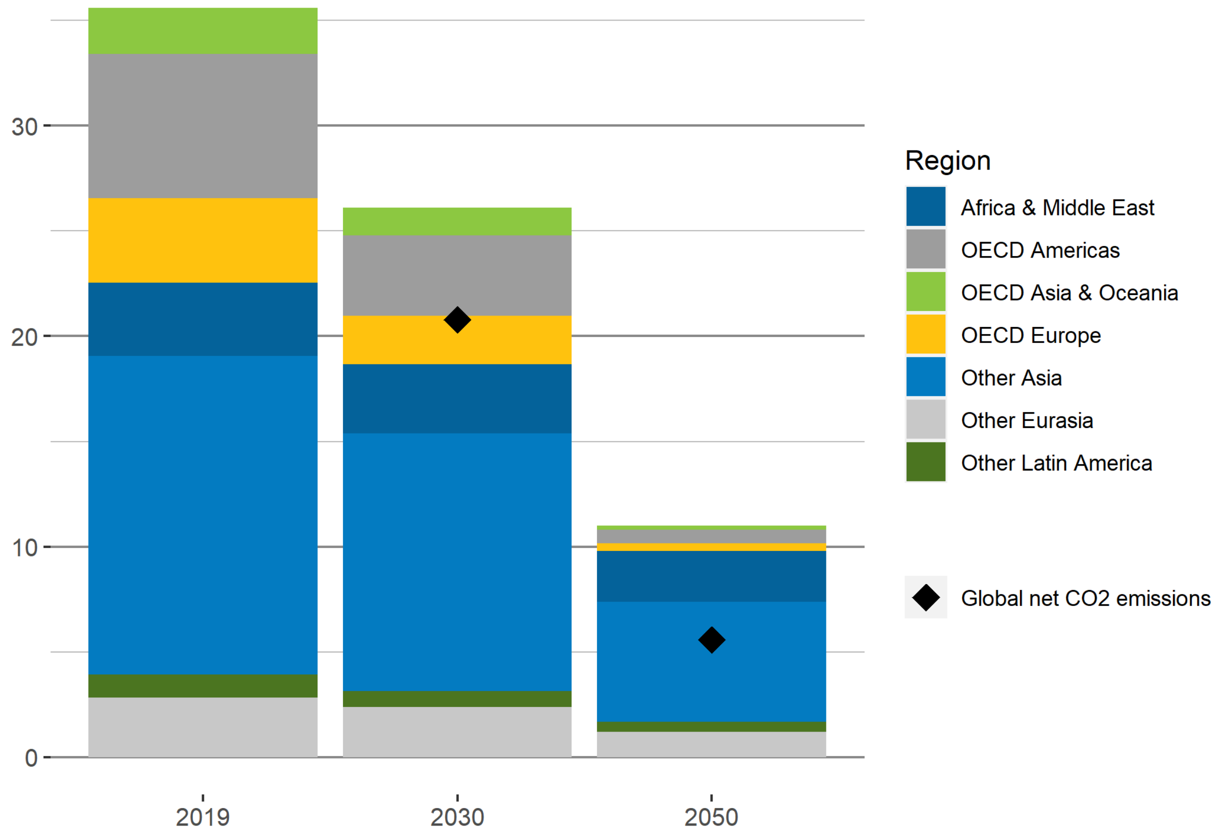
Regional emission reductions

The largest CO_2 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_2. 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

CO_2 emissions, *NZE Ambition* scenario (Gt)



Source: OECD ENV-Linkages model.

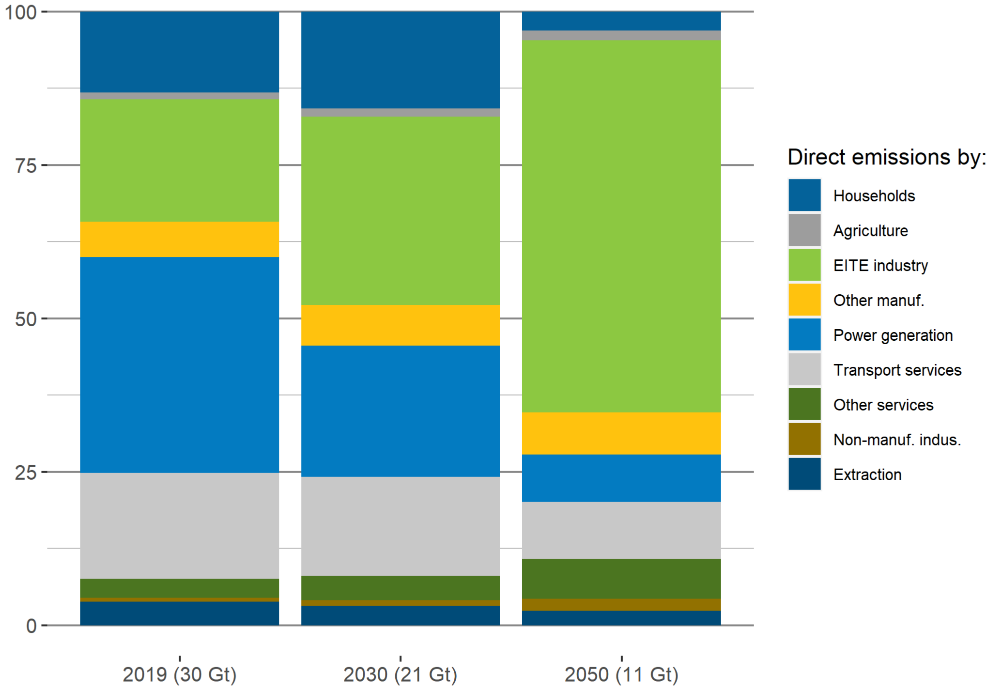
Sectoral emission reductions

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[34] 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.

[34] 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 (%)

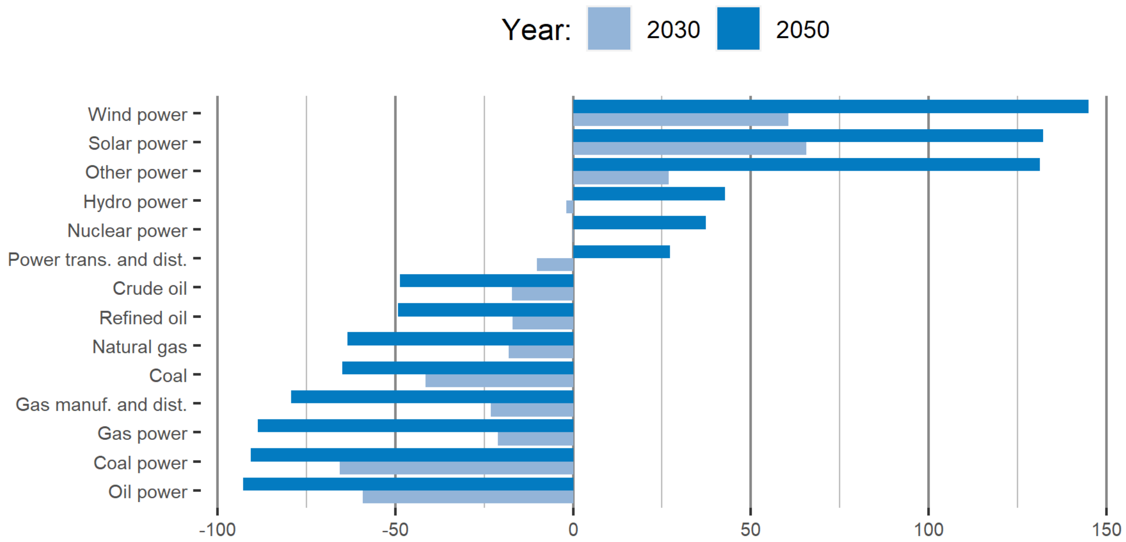


Source: OECD ENV-Linkages model.

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* (%)

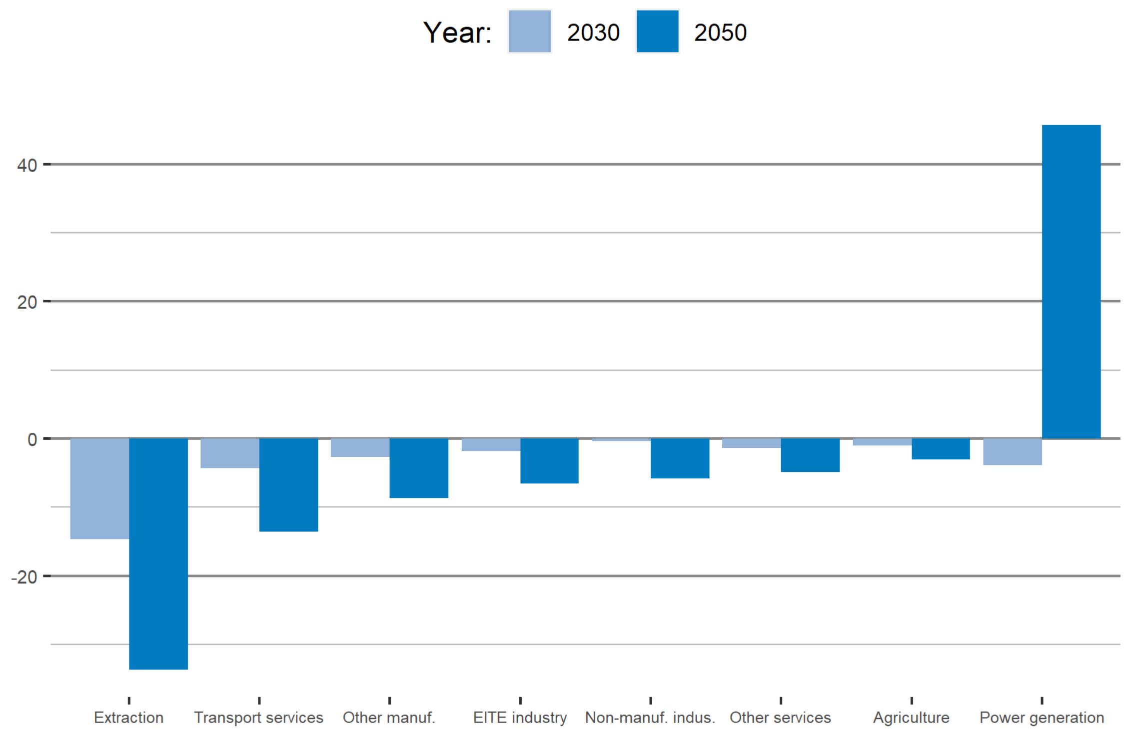


Source: OECD ENV-Linkages model.

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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Source: OECD ENV-Linkages model.

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.

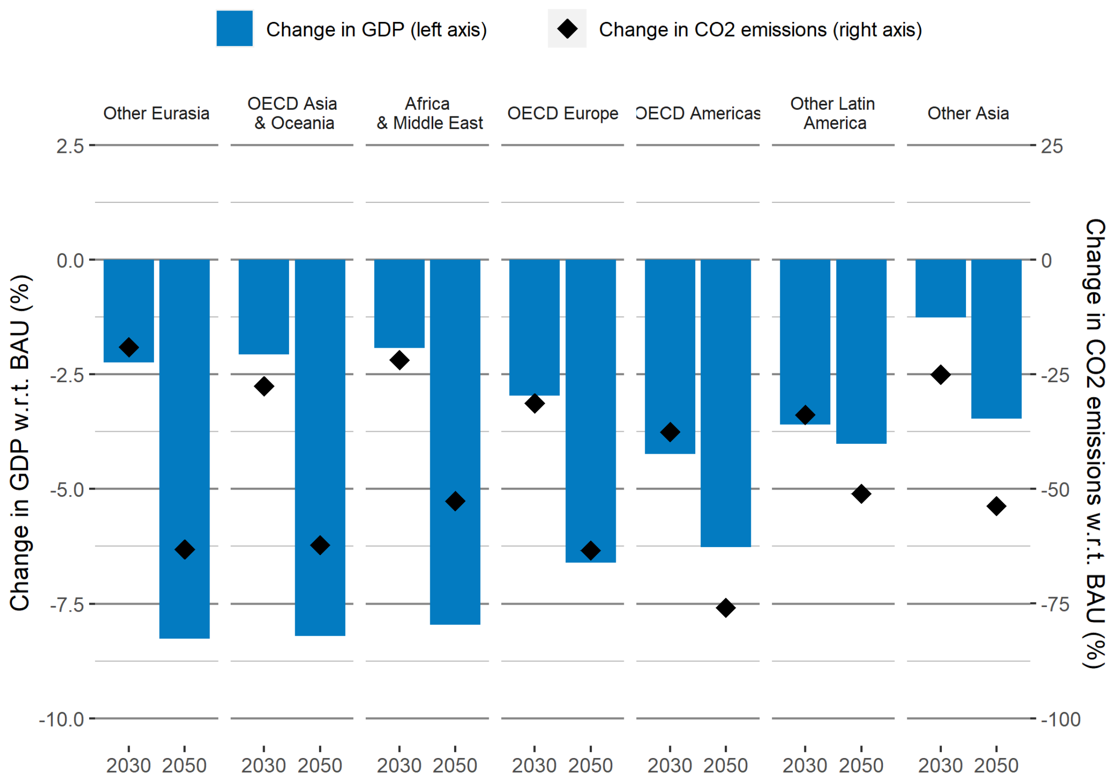
The sectors that reduce output levels the least are the services sectors, where CO_2 emissions are much smaller than in industry, and agriculture. Agriculture contributes significantly to climate change through its nitrogen and methane emissions, but the NZE transition simulated here focuses on CO_2, which can be decarbonised at least partially by energy efficiency improvements and electrification.

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.

1. 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 lower and even positive in certain regions. 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.

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



Source: OECD ENV-Linkages model.