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LONG TERM SCENARIOS: INCORPORATING THE ENERGY TRANSITION

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Long-term scenarios: incorporating the energy transition

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Selected series from the baseline scenario are available at https://stats.oecd.org/Index.aspx?DataSetCode=EO114_LTB

Other series, as well as data for the alternative scenarios, are available upon request by writing to EcoOutlook@oecd.org.

The following papers present previous versions of long-run scenarios:

Guillemette, Y. and D. Turner (2021), "The Long Game: Fiscal Outlooks to 2060 Underline Need for Structural Reform", *OECD Economic Policy Papers*, No. 29, OECD Publishing, Paris.

Guillemette, Y. and D. Turner (2018), "The Long View: Scenarios for the World Economy to 2060", *OECD Economic Policy Papers*, No. 22, OECD Publishing, Paris.

OECD (2014), “Growth Prospects and Fiscal Requirements over the Long Term”, in OECD Economic Outlook, Volume 2014 Issue 1, OECD Publishing, Paris.

Johansson Å. et al. (2013), “Long-Term Growth Scenarios”, *OECD Economics Department Working Papers*, No. 1000, OECD Publishing, Paris.

The following are background papers with methodological details on the long-term global model:

Guillemette, Y. (2019), “Recent improvements to the public finance block of the OECD’s long-term global model”*, OECD Economics Department Working Papers*, No. 1581, OECD Publishing, Paris.

Guillemette, Y., A. de Mauro and D. Turner (2018), “Saving, Investment, Capital Stock and Current Account Projections in Long-Term Scenarios”, *OECD Economics Department Working Papers*, No. 1461, OECD Publishing, Paris.

Guillemette, Y. and D. Turner (2017), “The fiscal projection framework in long-term scenarios”, *OECD Economics Department Working Papers*, No. 1440, OECD Publishing, Paris.

Guillemette, Y. et al. (2017), “A revised approach to productivity convergence in long-term scenarios”, *OECD Economics Department Working Papers*, No. 1385, OECD Publishing, Paris.

Cavalleri, M. and Y. Guillemette (2017), “A revised approach to trend employment projections in long-term scenarios”, *OECD Economics Department Working Papers*, No. 1384, OECD Publishing, Paris.

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Abstract/Résumé

Long-term scenarios: incorporating the energy transition

This paper describes the latest update of the OECD’s long-term scenarios, which are done every 2-3 years to quantify some of the most important long-term macroeconomic trends and policy challenges facing the global economy. For the first time, this update incorporates the effect of the low-carbon energy transition. The study first presents a baseline projection that acts as a business-as-usual scenario against which the economic effects of the transition can be gauged. Next, it outlines extensions to the OECD global long-term model (LTM) to consider energy use and associated CO_2 emissions and describes an alternative stylised scenario in which OECD and non-OECD G20 countries successfully transition to low-carbon energy in a way broadly consistent with a net-zero target for greenhouse gas emissions by 2050. These extensions rely on a variety of sources, but most crucially on simulations of CO_2 mitigation costs with the OECD’s ENV-Linkages model. Finally, the model’s extensions are used to explore some fiscal implications of the energy transition, in particular how the negative economic effects of carbon mitigation could be alleviated by fiscal or other structural reforms.

Keywords: long-term projection, long-term scenario, fiscal sustainability, fiscal pressure, energy transition, CO_2 emissions, CO_2 mitigation costs, revenue recycling

JEL Classification: O4, H68, J11, Q43

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Scénarios long-terme : incorporer la transition énergétique

Ce document décrit la dernière mise à jour des scénarios à long terme de l'OCDE, qui sont effectués tous les 2-3 ans pour quantifier certaines des tendances à long terme et défis macroéconomiques les plus importants auxquels l'économie mondiale est confrontée. Pour la première fois, cette mise à jour intègre l'effet de la transition énergétique bas carbone. L’étude présente d'abord une projection de référence qui agit comme un scénario de statu quo par rapport auquel les effets économiques de la transition peuvent être évalués. Ensuite, il décrit les extensions du modèle global à long terme (LTM) de l'OCDE pour prendre en compte la consommation d'énergie et les émissions de CO_2 associées et décrit un scénario stylisé alternatif dans lequel les pays de l'OCDE et ceux du G20 non-membres de l'OCDE réussissent la transition vers une énergie à faible émission de carbone d'une manière largement compatible avec un objectif de zéro net pour les émissions de gaz à effet de serre d'ici 2050. Ces extensions reposent sur une variété de sources, mais surtout sur des simulations des coûts d'atténuation du CO_2 avec le modèle ENV-Linkages de l'OCDE. Enfin, les extensions du modèle sont utilisées pour explorer certaines implications fiscales de la transition énergétique, en particulier comment les effets économiques négatifs de l'atténuation des émissions de carbone pourraient être atténués par des réformes fiscales ou structurelles.

Mots-clés : projection à long terme, scénario à long terme, soutenabilité budgétaire, pression budgétaire, transition énergétique, émissions de CO_2, coûts d'atténuation de CO_2, recyclage du revenue

Classification JEL: O4, H68, J11, Q43

Main findings

Baseline economic scenario

- Trend annual real GDP growth for the combined OECD+G20 area gradually declines from around 3% pre-COVID to 1.7% by 2060, mainly due to falling working-age population growth and a deceleration of trend labour efficiency growth in emerging-market economies. China and India continue to account for most of global growth, with India's contribution surpassing China's in the late-2030s.
- Real GDP per capita growth in the OECD area remains around 1½ per cent per annum, well below historical norms. Real GDP per capita growth is projected to slow in most of the G20 emerging-market economies, except those where recent performance has been relatively weak (including Argentina, Brazil and South Africa).
- Without policy changes, maintaining current public service standards and benefits while keeping public debt ratios stable could increase fiscal pressure in the median OECD country by 6¼ percentage points (pp) of GDP between 2024 and 2060. The increase in fiscal pressure could exceed 9 pp of GDP in nine OECD countries.
- Improvements in energy efficiency and decarbonisation of the energy mix continue along recent trends. Global CO_2 emissions from energy use remain around current levels, failing to meet the UN Paris agreement's ambition of limiting warming to 1.5°C.

Energy transition scenario

- In the energy transition scenario, all countries accelerate their transition as of 2026, eliminating coal as an energy source by 2050 and lowering shares of oil and gas in primary energy to 5% and 10%, respectively. This scenario is broadly consistent with the objective of limiting global warming to 1.5°C.
- Abstracting from gains due to avoidance of environmental damages, this acceleration of the energy transition is modelled as a negative supply shock. Global growth slows by about 0.2 pp per annum initially and 0.6 pp toward the end of the transition period. The slowdown is more modest in the OECD area, but sharper in the G20 emerging-market area given higher carbon intensity. By 2050, cumulative mitigation costs are projected at 3.7% of baseline GDP for the OECD area and 11% of GDP for the G20 emerging-market economies. The sharp, front-loaded increase in investment necessary for the energy transition could lower annual private consumption growth by 0.2-0.3 pp in the first decade of the transition.
- The installed base of low-carbon electrical capacity must scale up by a factor of 2½ to 25 by 2050, depending on the country. Annual investment in new low-carbon electrical capacity must rise to an average of 1% of GDP in OECD countries and 2½ per cent of GDP in G20 emerging-market economies in the second half of this decade. Substantial investment must be maintained through 2050, adding to fiscal pressure or to government debt, to the extent government finance them.
- The CO_2 emissions reductions implied by the energy transition scenario could be achieved through effective carbon rates (including carbon taxes, fuel excise taxes and emissions trading schemes) of around EUR 200 as of 2026 in all regions, rising to EUR 600 by 2050, or equivalent non-price measures. This could bring in around 3¼ per cent of GDP in additional government revenue in the OECD area over the 2025-2030 period, declining thereafter along with CO_2 emissions.

- Using the additional fiscal revenue to lower labour tax wedges is one possible option to make the transition more politically feasible. Through positive effects on employment, this tax shift strategy could more than completely offset the decline in output otherwise associated with the first 10 years of the energy transition, leaving living standards in 2035 higher than in the baseline scenario in the euro area and most individual OECD countries. Deploying the extra revenue into a combination of higher R&D expenditure and support for childcare would have similar effects.
- Other structural reforms could also help to offset the output costs of CO_2 mitigation. Simulations show that, for the OECD area as a whole, product market liberalisation toward best practices could more than fully offset mitigation costs through 2050. In G20 emerging-market economies, improving governance to the first quartile of OECD countries would have the same effect.

Long-term scenarios: incorporating the energy transition

1. Introduction

1. This paper describes the latest OECD long-term scenarios, which are updated every two to three years to quantify some of the most important long-term macroeconomic trends and policy challenges facing the global economy. For the first time, this update begins to incorporate some of the effects of the low-carbon energy transition. It is organised in three parts:

- Section 2 updates the long-run projections for OECD and non-OECD G20 countries that were last done in 2021 (Guillemette and Turner, 2021[1]).[1] These and the resulting fiscal pressure indicators follow the approach of previous vintages: they assume no policy change and do not account for the needed acceleration in transitioning to low-carbon energy.[2] The baseline projection acts as a reference scenario against which some economic effects of this transition can be gauged. The economic costs associated with climate change (environmental damages, local air pollution, adaptation, etc.) are not taken into account.
- Section 3 outlines extensions to the OECD global long-term model (LTM) to consider energy use and associated CO_2 emissions and describes an alternative stylised scenario in which OECD and non-OECD G20 countries successfully transition to low-carbon energy in a way broadly consistent with a net-zero target for greenhouse gas (GHG) emissions by 2050. These extensions rely on a variety of sources, but, most crucially, on simulations of CO_2 abatement cost curves with the OECD's ENV-Linkages model. The analysis focuses on the aggregate GDP costs of mitigating CO_2 emissions from energy use. As in the baseline scenario, the economic benefits of attenuated climate change as a result of the faster energy transition are not taken into account.
- Section 4 uses the model's extensions to explore some fiscal implications of the energy transition, in particular how the negative economic effects of carbon mitigation could be alleviated during the transition phase by using fiscal revenue from carbon pricing to lower labour taxation.

2. Relative to many other models and studies that address the energy transition, the main value added of this study is to provide results at the country level using a common, relatively simple and tractable framework. Annex A summarises the main features of the LTM, provides references with more details and lists a number of important caveats inherent in the use of such a stylised tool. Recent extensions to this framework to study the energy transition are explained in Annex B.

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[1] Previous versions of long-term scenarios include Johansson et al. (2013[35]), OECD (2014[36]), Guillemette and Turner (2018[4]) and Guillemette and Turner (2021[1]).

[2] A previous vintage of these long-run projections served as basis for the International Panel on Climate Change's (IPCC) Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017[13]).

2. The baseline scenario: a continued slowdown in global growth

3. The baseline economic scenario uses as a starting point the final period of the projection of the latest *OECD Economic Outlook*, currently the year 2025 from the Autumn 2023 edition (N° 114). Any demand misalignment relative to potential GDP – negative or positive output gap – remaining in 2025 is assumed to close gradually thereafter. In all major areas, output gaps are essentially closed by 2028/29.

4. Because it is intended as a point of reference for the discussion of other scenarios involving shocks or policy reforms, and as in previous vintages of this exercise, the baseline scenario assumes essentially no change to initial policy and institutional settings over the long-term projection period, except where already-legislated reforms will have a known impact on the policy indicators included in the framework, such as future changes to statutory retirement ages. In addition, every country is assumed to undertake, as of 2026, a gradual fiscal adjustment sufficient to eventually stabilise government debt as a share of GDP at its projected 2025 level, an assumption which serves to illustrate the magnitude of future fiscal pressure. As mentioned in the introduction, the economic costs of environmental damages, local air pollution and adaptation to climate change are ignored, making the results in this section comparable to previous vintages of the exercise.

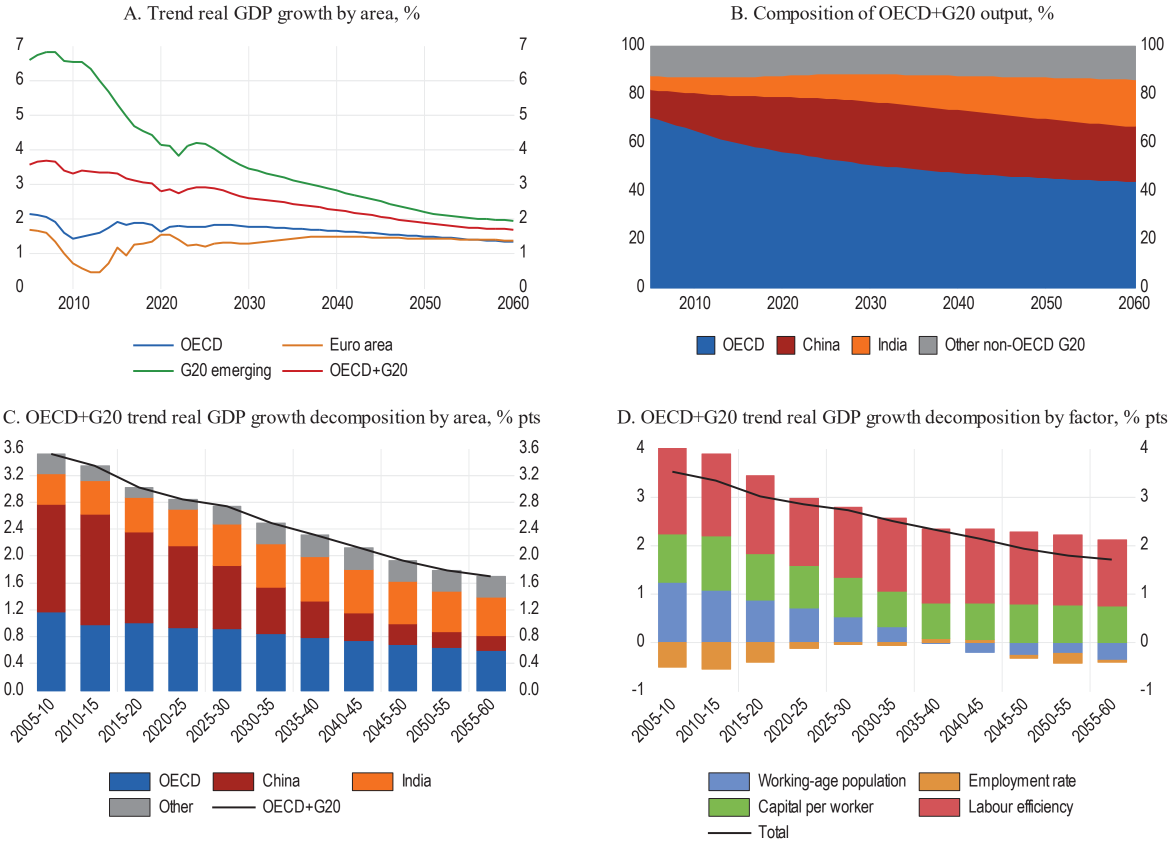
2.1. Trend growth continues to slow in both advanced and emerging-market economies

5. From around 1.8% currently, similar to the pre-COVID period, OECD trend annual output growth is projected to decelerate to 1.7% by 2035, before slowing down further to 1.3% by 2060 (Figure 1, Panel A). This development is largely driven by slowing working-age population growth, which is expected to turn negative from the mid-2030s, stabilising only in the early 2040s around -0.2% per annum. Were it not for the assumed pick-up in labour productivity growth, then, OECD trend output growth would decelerate even more in the coming decades.

6. The potential growth rate of G20 emerging-market economies falls more markedly, from around 4½ per cent per annum prior to 2020 to around 3% by the mid-2030s and just below 2% by 2060. As for OECD countries, this development is partly a consequence of slowing working-age population growth. Unlike in advanced economies, however, it also stems from slowing trend labour efficiency growth, as the baseline scenario assumes gradual convergence in trend labour efficiency growth across countries. Although decelerating, trend output growth in G20 emerging-market economies remains higher than in advanced economies throughout the projection period, implying that emerging-market economies make up a rising share of global output (Figure 1, Panel B). While the contributions from China and India already dominate global growth, India is projected to surpass China in this respect in the late-2030s, in part because China's working-age population is projected to start shrinking then and by as much as 1¼ per cent per annum by the end of that decade (Figure 1, Panel C).

7. When combining the OECD and non-OECD G20 areas, resulting in an aggregate (OECD+G20) that covers approximately 83% of global GDP today at purchasing power parity (PPP) exchange rates, trend output growth nearly halves between the pre-pandemic period and 2060. This decline is mostly driven by slowing – and eventually negative – working-age population growth, and to a lesser extent by declining contributions from both capital per worker and trend labour efficiency (Figure 1, Panel D). These trends are not immutable and could be offset by policy changes that the baseline scenario leaves out by design.

Figure 1. The baseline scenario in a snapshot



A. Trend real GDP growth by area, %

B. Composition of OECD+G20 output, %

C. OECD+G20 trend real GDP growth decomposition by area, % pts

D. OECD+G20 trend real GDP growth decomposition by factor, % pts

8. Expressed in United States dollars at 2015 PPPs, the baseline scenario implies the following for the relative sizes of economies covered in this exercise:

- China remains the single largest economy throughout the projection period.
- The G20 emerging-market area surpasses the OECD before the end of this decade.
- India surpasses the euro area in the early 2030s and the United States in the mid-2040s.
- Indonesia surpasses Germany in the mid-2020s and Japan in the mid-2030s.

The relative ranking of economies and its change over time is much different when expressed in a common currency at market exchange rates, but projections of market exchange rates involve another layer of uncertainty and are only used in this paper to aggregate certain concepts, such as fiscal outcomes.

2.2. Living standards continue to progress along recent trends

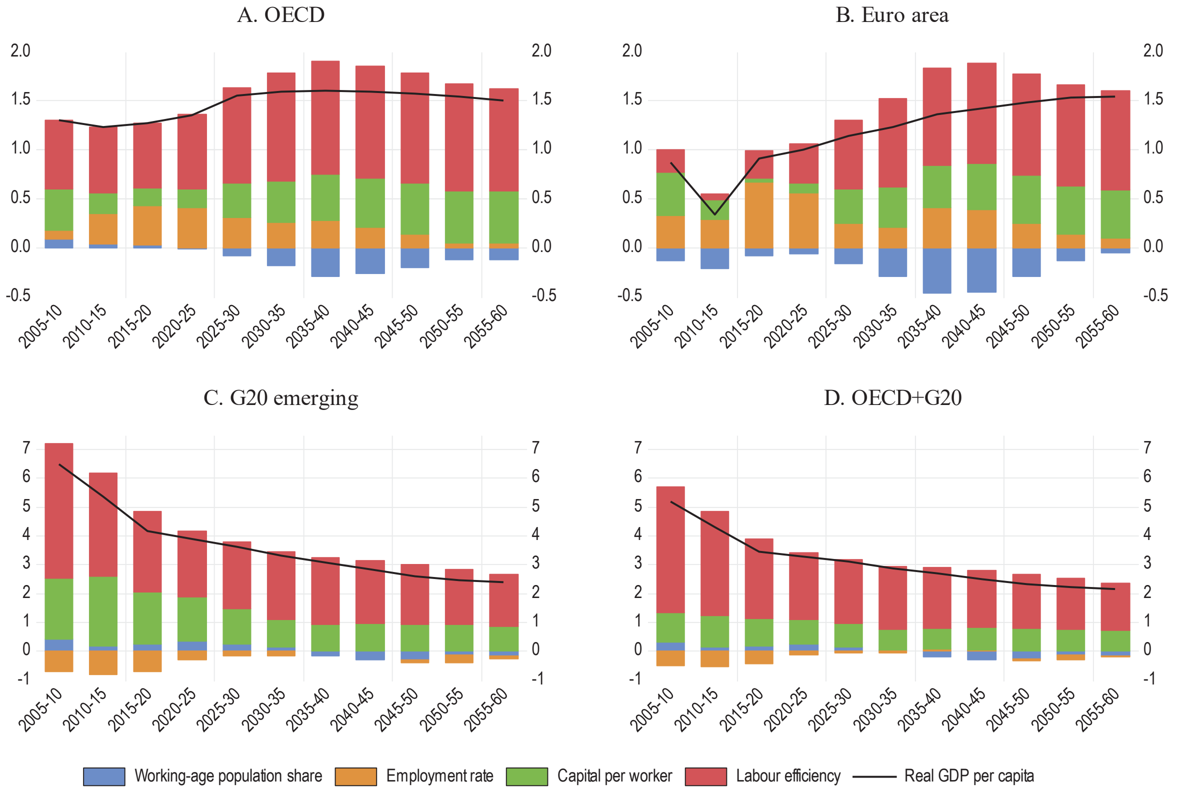
9. Slowing headline GDP growth can simply reflect slowing working-age population growth and does not necessarily imply slowing progress in living standards. GDP per capita provides a better assessment of the relative performances of economies and implications for living standards. On this metric, OECD-area real GDP per capita growth remains broadly stable over the projection period (Figure 2, Panel A and Table 1). This is due to a modest recovery in labour productivity (via both labour efficiency and capital intensity) offsetting the declining growth contribution of labour quantity:

- The declining contribution from labour is mostly explained by ageing: the overall share of the population that is of working age (15-74) has already started declining in the OECD area and, despite rising female employment, the growth contribution of the aggregate employment rate declines as the share of older cohorts (which have lower employment rates) in the working-age population rises. This implies a marked turnaround in the overall labour input (combining both employment rate and working-age population share), from recently contributing as much as ½ percentage points per annum to growth in OECD living standards, it turns neutral by the late-2030s and eventually subtracts one tenth of a percentage point from annual GDP per capita growth (Figure 2, Panel A). The demographic drag is similar in the euro area but happens as soon as 2030-35 (Figure 2, Panel B). Some OECD countries are exceptions though, thanks to rapidly rising female employment rates (e.g., Estonia) and/or higher fertility (e.g., Israel) contributing to keeping the growth contribution of labour quantity positive throughout most of the projection period (Table 1).

- The modest recovery in OECD productivity growth reflects different trends and assumptions: an assumption that frontier growth in trend labour efficiency continues at the post-Great Recession trend of around 1% per annum; continued catch-up in some countries where levels lag behind leaders (notably Eastern European countries and Baltic states); and a recovery in productivity growth in those countries where it has recently been particularly weak, so that they do not fall further behind the frontier. By design, differences across countries in trend labour efficiency growth lessen toward the end of the projection period as gradual convergence to frontier growth is assumed (but full convergence does not occur even by 2060).

Figure 2. Trend labour efficiency remains the main growth engine in the baseline scenario

Trend real GDP per capita growth, per cent


A. OECD

B. Euro area

C. G20 emerging

D. OECD+G20

Table 1. The sources of potential real GDP per capita growth in the baseline scenario

Per cent per annum

	Potential GDP per capita				Trend labour efficiency				Capital per worker				Potential employment rate				Working-age population share			
	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60
Australia	1.9	1.0	1.0	1.5	0.6	0.2	0.4	1.1	0.5	0.6	0.2	0.5	0.7	0.2	0.4	0.1	0.1	0.0	-0.1	-0.1
Austria	1.7	0.7	0.9	1.4	0.7	0.1	0.5	1.0	0.5	0.2	0.3	0.5	0.4	0.5	0.2	0.2	0.1	0.0	-0.2	-0.3
Belgium	1.6	0.9	1.1	1.3	0.3	0.1	0.2	0.8	0.8	0.5	0.5	0.5	0.6	0.3	0.5	0.2	-0.1	0.0	-0.1	-0.2
Canada	1.7	0.5	0.5	1.4	0.6	0.2	0.3	1.0	0.4	0.4	0.1	0.5	0.6	-0.1	0.3	0.1	0.2	0.0	-0.2	-0.2
Chile	3.1	1.8	1.1	2.4	0.2	-0.7	0.2	1.6	1.5	1.3	0.6	0.8	0.9	0.8	0.4	0.2	0.5	0.3	-0.1	-0.2
Colombia	2.7	2.3	1.9	2.6	1.5	0.6	1.4	1.8	0.4	1.1	0.6	1.0	0.1	0.0	-0.3	-0.1	0.7	0.7	0.1	-0.1
Costa Rica	3.1	2.4	2.3	2.1	1.4	1.3	1.5	1.5	0.5	0.9	0.7	0.9	0.4	-0.2	-0.2	-0.1	0.9	0.4	0.3	-0.2
Czechia	3.6	1.8	1.6	1.7	2.6	1.3	1.1	1.3	0.5	0.3	0.5	0.6	0.3	0.6	0.4	0.0	0.2	-0.3	-0.3	-0.3
Denmark	1.0	0.8	1.2	1.3	0.4	0.6	0.9	0.9	0.6	0.3	0.1	0.3	0.1	-0.1	0.6	0.2	0.0	0.0	-0.3	-0.1
Estonia	6.0	2.1	2.5	1.9	2.8	0.2	1.1	1.1	2.8	1.0	0.6	0.6	0.2	1.3	0.8	0.3	0.2	-0.4	0.0	-0.2
Finland	2.2	0.6	0.9	1.6	1.2	0.1	0.2	1.0	0.3	0.2	0.3	0.5	0.7	0.4	0.7	0.2	0.0	-0.1	-0.2	-0.1
France	1.1	0.5	1.0	1.4	0.4	0.1	0.4	1.0	0.5	0.3	0.3	0.5	0.2	0.1	0.4	0.1	-0.1	-0.1	-0.2	-0.2
Germany	1.2	1.0	0.7	1.4	0.6	0.4	0.5	1.0	0.2	0.0	0.2	0.4	0.3	0.9	0.2	0.2	0.1	-0.3	-0.2	-0.2
Greece	2.5	-1.2	2.7	1.9	0.9	-1.4	1.3	1.3	0.8	-0.2	0.3	0.7	1.1	0.7	1.1	0.5	-0.3	-0.2	-0.1	-0.5
Hungary	3.6	2.2	2.8	1.8	2.0	0.6	1.3	1.2	1.0	0.4	0.4	0.7	0.4	1.2	1.4	0.1	0.1	-0.1	-0.3	-0.2
Iceland	2.6	1.0	0.9	1.4	1.5	1.0	0.8	1.0	0.8	-0.1	0.1	0.5	0.0	-0.1	0.0	0.0	0.3	0.2	0.1	-0.1
Ireland	3.2	4.0	2.5	1.0	1.3	3.6	1.3	0.7	1.1	0.6	0.0	0.3	0.5	0.0	1.0	0.3	0.3	-0.1	0.2	-0.3
Israel	1.5	2.0	2.2	1.6	0.8	1.1	1.3	0.9	0.3	0.2	0.6	0.5	0.4	0.7	0.2	0.1	0.0	-0.1	0.0	0.1
Italy	0.2	-0.2	1.1	1.5	-0.5	-0.3	0.7	1.1	0.4	0.0	0.2	0.4	0.6	0.3	0.2	0.4	-0.3	-0.1	0.0	-0.4
Japan	0.6	0.7	1.2	1.8	0.4	0.3	0.6	1.3	0.4	-0.1	0.0	0.5	0.2	0.8	1.0	0.3	-0.4	-0.4	-0.4	-0.3
Korea	4.1	2.7	2.1	1.6	1.9	1.1	0.9	1.1	1.4	0.9	0.6	0.6	0.5	0.4	0.6	0.7	0.3	0.3	-0.1	-0.7
Latvia	7.8	2.6	2.9	1.8	2.7	0.8	1.5	1.2	3.4	1.6	0.9	0.7	1.4	0.7	0.5	0.1	0.3	-0.4	0.0	-0.2
Lithuania	7.5	3.7	2.9	1.6	4.1	1.3	0.9	0.9	2.7	1.2	1.1	0.7	0.3	1.4	1.0	0.2	0.3	-0.2	0.0	-0.2
Luxembourg	2.5	-0.1	0.8	0.8	0.7	-0.6	0.5	0.7	0.1	-0.1	0.0	0.4	1.7	0.4	0.4	-0.1	0.0	0.2	-0.1	-0.2
Mexico	0.6	0.6	1.4	2.5	-0.3	-0.3	0.3	1.5	-0.1	-0.1	0.1	0.8	0.5	0.5	0.4	0.2	0.6	0.6	0.5	-0.1
Netherlands	1.5	0.8	1.1	1.4	0.7	0.2	0.4	0.9	0.2	0.1	0.1	0.4	0.6	0.4	0.9	0.3	0.0	0.1	-0.3	-0.1
New Zealand	2.1	1.2	1.6	1.8	0.5	0.4	0.5	1.1	0.4	0.3	0.8	0.7	0.9	0.4	0.5	0.2	0.3	0.1	-0.1	-0.1
Norway	1.9	1.0	1.0	1.0	1.5	0.5	0.5	0.7	0.5	0.3	0.5	0.4	-0.3	0.0	0.0	0.1	0.2	0.2	-0.1	-0.2
Poland	3.8	3.6	3.4	1.5	2.0	1.6	1.8	1.0	0.6	0.9	1.0	0.8	0.9	1.1	0.9	0.0	0.4	-0.1	-0.3	-0.3
Portugal	0.8	0.8	1.9	1.8	-0.2	0.1	0.9	1.2	1.5	0.6	0.5	0.6	-0.3	0.1	0.7	0.4	-0.2	-0.1	-0.2	-0.4
Slovakia	6.2	2.5	1.9	1.5	4.7	1.4	1.3	1.2	0.6	0.4	0.5	0.7	0.4	0.8	0.4	0.0	0.5	-0.1	-0.3	-0.4
Slovenia	2.9	1.3	2.3	1.5	1.5	0.9	1.8	1.2	1.0	0.1	0.4	0.6	0.4	0.7	0.3	0.0	0.0	-0.3	-0.2	-0.3
Spain	1.5	0.4	0.9	1.3	-0.1	0.1	0.4	1.0	0.6	0.6	0.0	0.4	1.1	-0.1	0.4	0.3	-0.2	-0.2	0.1	-0.5
Sweden	2.1	1.0	1.4	1.5	1.6	0.6	0.6	0.9	0.5	0.3	0.5	0.5	-0.2	0.3	0.4	0.2	0.4	-0.1	-0.1	-0.1
Switzerland	1.2	0.8	0.7	1.0	0.5	0.4	0.7	0.9	0.4	0.1	0.3	0.4	0.1	0.3	0.0	0.0	0.2	-0.1	-0.2	-0.3
Türkiye	3.4	3.9	3.1	2.0	1.5	1.5	1.3	0.9	1.5	1.1	0.8	0.7	-0.3	1.0	0.8	0.5	0.6	0.4	0.2	-0.2
United Kingdom	1.4	0.5	0.9	1.5	0.6	-0.1	0.3	0.9	0.5	0.5	0.6	0.6	0.0	0.2	0.0	0.1	0.2	-0.1	0.0	-0.2
United States	1.3	1.1	1.4	1.0	1.1	0.9	1.1	0.8	0.7	0.3	0.3	0.4	-0.6	-0.2	0.1	0.0	0.2	0.1	-0.1	-0.1
Euro area	1.3	0.6	1.1	1.4	0.5	0.2	0.6	1.0	0.4	0.2	0.2	0.5	0.4	0.4	0.4	0.2	-0.1	-0.1	-0.1	-0.3
OECD	1.6	1.2	1.5	1.6	0.9	0.7	0.9	1.1	0.5	0.2	0.3	0.5	0.1	0.3	0.4	0.2	0.1	0.0	0.0	-0.2

Table 1. The sources of potential real GDP per capita growth in the baseline scenario *(cont'd.)*

Per cent per annum

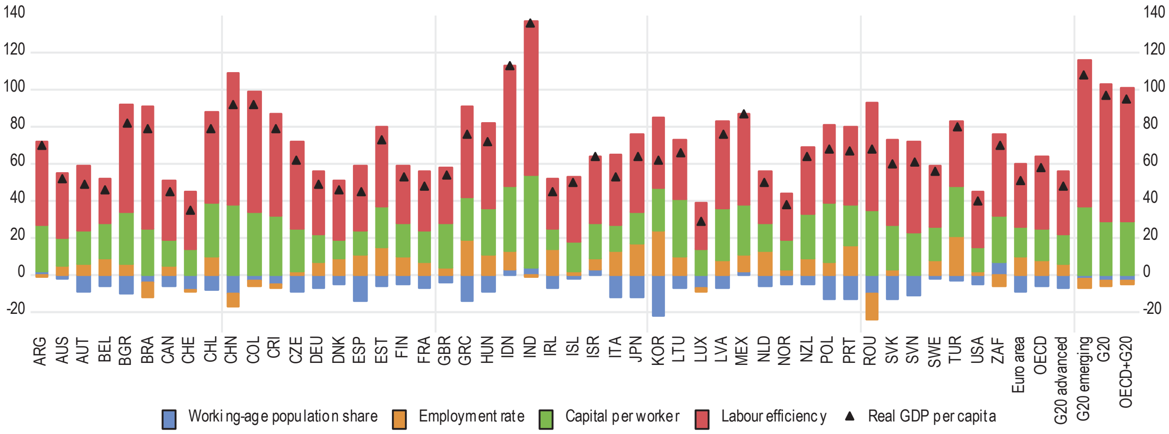
	Potential GDP per capita				Trend labour efficiency				Capital per worker				Potential employment rate				Working-age population share			
	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60	2000-07	2007-20	2020-30	2030-60
Argentina	2.0	0.9	0.4	2.2	1.0	0.3	-0.2	1.6	-0.5	0.1	0.2	0.8	1.2	0.2	0.1	-0.1	0.3	0.2	0.3	0.0
Brazil	2.1	1.2	1.1	2.4	1.9	0.9	0.9	2.0	-0.5	0.1	0.0	0.8	0.0	-0.3	0.1	-0.2	0.6	0.5	0.2	-0.2
Bulgaria	6.1	3.1	3.6	1.9	2.6	1.6	2.5	1.4	0.9	0.9	0.6	0.8	2.4	0.8	0.7	0.1	0.1	-0.2	-0.1	-0.3
China	9.9	7.3	4.3	2.1	6.4	4.2	2.6	1.8	3.5	3.6	2.0	0.9	-0.8	-0.5	-0.5	-0.1	0.9	0.0	0.2	-0.4
India	5.2	4.9	4.5	3.5	3.4	3.4	2.5	2.2	2.1	2.6	1.6	1.3	-0.9	-1.7	0.0	-0.1	0.6	0.6	0.4	0.0
Indonesia	3.2	4.0	3.5	3.0	2.6	2.4	1.9	1.7	0.4	0.9	0.8	0.9	-0.1	0.5	0.4	0.3	0.3	0.2	0.4	0.0
Romania	6.5	3.3	3.5	1.5	4.8	2.0	2.4	1.4	1.4	1.3	1.3	0.8	0.0	0.2	-0.1	-0.4	0.3	-0.2	-0.1	-0.3
South Africa	2.7	0.4	-0.1	2.3	1.9	0.2	-0.4	1.6	0.0	0.4	0.1	0.8	-0.3	-0.3	-0.2	-0.1	1.2	0.1	0.3	0.1
G20 advanced	1.3	0.9	1.2	1.3	0.8	0.5	0.7	1.0	0.5	0.2	0.3	0.4	0.0	0.2	0.3	0.1	0.0	-0.1	-0.1	-0.2
G20 emerging	6.5	5.1	3.8	2.8	5.1	3.5	2.3	2.1	1.3	2.2	1.4	0.9	-0.6	-0.8	-0.2	-0.1	0.7	0.2	0.3	-0.2
G20	5.4	4.3	3.3	2.5	4.7	3.6	2.3	2.0	0.7	1.1	0.9	0.8	-0.5	-0.6	-0.1	-0.1	0.5	0.2	0.2	-0.2
OECD + G20	5.3	4.2	3.2	2.5	4.5	3.4	2.2	1.9	0.8	1.0	0.8	0.8	-0.4	-0.5	-0.1	0.0	0.5	0.2	0.2	-0.2

Note: For potential GDP per capita (first four numeric columns), the table reports average geometric growth rates in percentage points per annum. For the components (all other numeric columns), it reports growth *contributions* to potential GDP per capita according to the production function, so that the four components sum to the total, except for a rounding error (see the section 'Decomposition of per capita real GDP growth' in Annex A). Because of missing historical data, initial years for the decomposition are 2001 for Colombia and South Africa, 2002 for Lithuania, Romania and G20; and 2003 for Euro area and OECD+G20. 'G20 advanced' includes Australia, Canada, Germany, France, the United Kingdom, Italy, Japan, Korea and the United States. 'G20 emerging' includes Argentina, Brazil, China, India, Indonesia, Mexico, Russia, Saudi Arabia, Türkiye and South Africa. The OECD+G20 aggregate includes all OECD and non-OECD G20 countries.

10. Real GDP per capita growth is projected to slow in most of the G20 emerging-market economies, except those where post-Great Recession performance has been relatively weak (including Argentina, Brazil and South Africa).

- In G20 emerging-market economies, the labour quantity component has until recently been a substantial drag on growth and this trend gradually re-asserts itself over the projection period, subtracting between ¼ and ½ percentage points to annual growth in living standards after 2040, with China being the main contributors (Figure 2, Panel C and Table 1). One important demarcation factor is the female employment rate, which is projected to decline in Brazil and China, based on a continuation of recent cohort trends, whereas in other large emerging-market economies it remains approximately stable at relatively low levels (Argentina, India and South Africa) or rises modestly (Indonesia).[3] Encouraging female employment could make a positive contribution to living standards in these countries in the decades ahead.
- Given small, and in some cases negative, labour quantity contributions, labour productivity growth, particularly the labour efficiency component, is the main factor explaining the more optimistic GDP per capita trajectory of G20 emerging-market economies when compared to G20 advanced economies (Figure 3). Strong, albeit slowing, productivity growth in India, China and Indonesia reflects recent performance and leads to noticeable catch-up in GDP per capita in those countries when benchmarked against the United States (Figure 4). Nevertheless, in India, GDP per capita is still less than 40% of the US level in 2060 and in China it is about half. In the other large G20 emerging-market economies (Argentina, Brazil and South Africa), despite the assumed gradual acceleration, relatively weak productivity growth performance in recent years implies more modest convergence to US living standards over the projection period.

Figure 3. Change in level of real GDP per capita from 2023 to 2060, %



Note: The numbers shown are based on a log decomposition, so $100 * log(a^{2060}/a^{2023})$ where a is the relevant component. This is done to ensure that the sum of components add up exactly to the total change. This calculation is approximately equal to a per cent change for small changes, less so for large ones.

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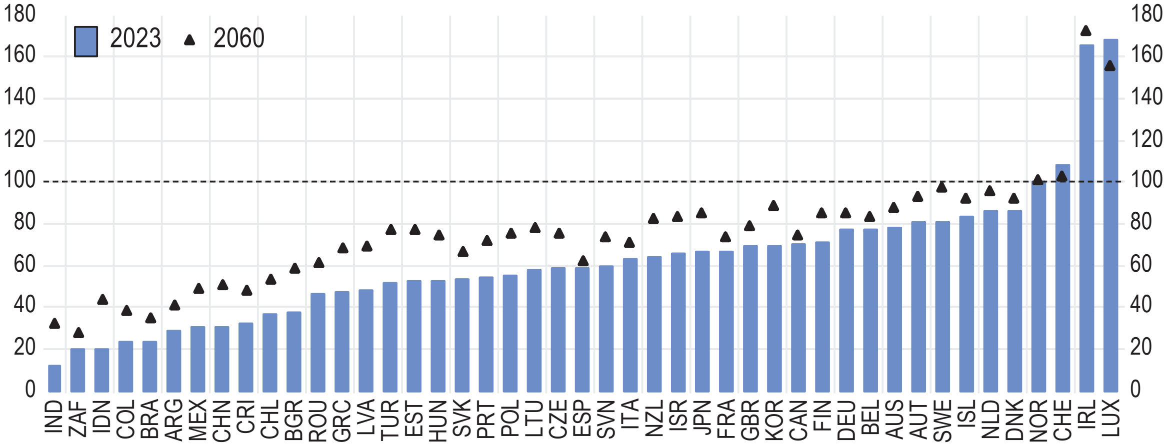
[3] Low female employment rates in India appear to be due to a number of factors, among which a lack of job growth in female-friendly sectors (e.g., manufacturing), cultural expectations and social stigma, safety concerns, lack of family policies and poor infrastructure (OECD, 2014[37]). Brussevich, Dabla-Norris and Li (2021[40]) have documented similar labour market barriers for women in China. There is, however, evidence of a U-shaped labour market participation curve with respect to income and education. This represents an upside risk to the projected evolution of female employment rates in G20 emerging-market economies.

Figure 4. Convergence in living standards is limited in the baseline scenario

Real GDP per capita at 2015 Purchasing Power Parities, USA = 100



11. Limited progress on living standards in emerging-market economies relative to the US benchmark is not inevitable but reflects the baseline scenario assumption of no policy change. However, emerging-market economies could accelerate gains in living standards with reforms to improve some of the fundamental drivers of growth (Ruch, 2020[2]; Kilic Celik, Kose and Ohnsorge, 2020[3]). In a previous set of long-run scenarios, a reform simulation exercise was considered for Brazil, China, India, Indonesia, Russia and South Africa, the so-called BRIICS countries. It showed that by improving governance, educational attainment and trade openness to median OECD levels over the next 40 years, these countries could boost their living standards by 30% to 50% relative to baseline (Guillemette and Turner, 2018[4]).

12. More generally, progress in growth-enhancing institutional and policy settings represents an upside risk to the long-run projections of this section for all countries. Another upside risk is faster technological progress, whether from advances in biotechnology, artificial intelligence, industrial automation, or other fields. The assumed rate of equilibrium labour efficiency growth in the baseline scenario (1% per annum) is in line with recent outturns, but relatively low in a longer historical context. In an alternative scenario where this assumption is raised to 2%, living standards in 2060 are about one third higher than in the baseline scenario (Guillemette and Turner, 2021[1]).

13. On the other hand, downside risks include rising income inequality within countries, as well as rising trade protectionism, noting that income distribution and trade openness are among determinants of labour efficiency growth in the framework used here. Another downside risk is climate change, both via environmental degradation and via policies that are necessary to drive the transition toward a low-carbon economy. While the latter are necessary to avoid the former, they are likely to weigh on global growth in the decades ahead. Section 3 attempts to incorporate some of the impact of the energy transition into growth prospects, building on the baseline projections just described.

2.3. Substantial fiscal pressure builds up in the baseline scenario

14. Much research has demonstrated that fiscal sustainability is a concept fraught with uncertainties (Blanchard, Leandro and Zettelmeyer, 2021[5]). There are no specific thresholds for any one fiscal indicator (government debt, fiscal balance, interest rate, etc.) beyond which a country's fiscal position can reliably be characterised as unsustainable. Sustainability depends on what happens in the unknowable future, including market perceptions, which can shift rapidly. The present study therefore does not attempt such categorisation. Instead, it uses an indicator of long-run fiscal pressure that is premised on the idea that

governments would seek to stabilise public debt ratios at projected 2025 levels (see Box 1 for details on the fiscal pressure indicator).

Box 1. Projections of public expenditure in the LTM and the fiscal pressure indicator

Public expenditure projections in the LTM are based on simple reduced-form equations that rely either on coefficients estimated from historical data (health) or on stylised assumptions (pension and other primary expenditure). These equations imply a "business-as-usual" future in which no major policy changes are undertaken. Country specificities in health, pension and other programme designs are generally not taken into account other than in initial expenditure levels, except as specified below.

Public health and long-term care expenditure

Projected growth in nominal per capita public expenditure on health care (including long-term care) is a function of real GDP per capita growth (income effect), changes in the share of the population aged 65 and over (population ageing effect), the GDP inflation rate and the excess of inflation in the health-care sector over the broader economy (Baumol effect). This latter effect reflects the cost-pressure phenomenon observed in labour-intensive sectors where labour productivity grows more slowly than in other sectors. It is related in the model to the projected rate of aggregate labour productivity growth, as faster productivity growth implies a stronger Baumol effect. The possible long-run impact of the COVID-19 pandemic on health expenditure is not taken into account. See section 4 in Guillemette (2019[6]) for additional methodological details.

Public pension expenditure

Public pension expenditure is projected on the basis of the projected change in the ratio of retirees to workers and an assumption regarding the evolution of the average benefit ratio (the ratio of the average public pension benefit to the average wage). The evolution of the ratio of retirees to workers depends on the evolution of the population age structure and on projected employment rates by age and sex according to a cohort model, which takes into account already-legislated future changes in statutory retirement ages (see Annex A). Based on the observation that the average benefit ratio at the EU level has remained broadly stable over the past two decades, country-specific average benefit ratios are assumed to remain constant over the projection period, except in a few countries where significant pension reforms have recently been enacted (Greece, Italy, Portugal and Spain). In reality, some other countries have introduced affordability rules or other mechanisms in their public pension systems that may imply declines in average benefit ratios over time. See section 3 in Guillemette (2019[6]) for additional methodological details.

Other current primary expenditure

Other current primary expenditure (i.e. excluding health and pensions) is projected based on the assumption that governments will seek to provide a constant level of public spending per capita in real terms. Under some reasonable assumptions, the evolution of this expenditure category relative to GDP becomes a function of the projected evolution of the population-to-employment ratio, as expenditure (numerator) is tied to population whereas GDP (denominator) is tied to employment. See section 3.1.2 in Guillemette and Turner (2017[7]) for more details.

The fiscal closure rule and the fiscal pressure indicator

In a long-term model solved over many decades, it is necessary to ensure that the government debt-to-GDP ratio eventually stabilises. To this end, the assumption is that the government acts to stabilise the debt ratio at its initial value (i.e., the projected value for the last year of the short-run horizon of the latest *OECD Economic Outlook*, currently 2025). It does so by adjusting the ratio of underlying primary revenue to potential GDP (i.e., cyclically-adjusted and excluding one-off operations), which can be interpreted as an overall tax rate on the economy and is referred to as fiscal pressure in the main text. The resulting concept – required change in structural primary revenue over the long run – has several advantages:

- It compares a flow to a flow (revenue to GDP) rather than a stock to a flow (e.g., debt to GDP);
- By relying on structural concepts (i.e., cyclically-adjusted primary revenue and potential GDP), it abstracts from cyclical/temporary impacts on initial fiscal positions, although there are large uncertainties around such cyclically-adjusted estimates;
- It is forward-looking, so it accounts for projected trends in interest and growth rates, for instance;

The exact fiscal adjustment measure used in this paper is the required change in structural primary revenue over the period 2024 to 2060. This change in fiscal pressure can then be decomposed into 1) an initial structural fiscal gap, reflecting any disequilibrium between the initial structural primary balance and the one consistent with keeping the debt ratio stable at the current *r* – *g* differential, 2) the projected change in *r* – *g*, 3) the projected changes in the expenditure categories outlined previously in this box, and 4) a residual category called 'other factors'. This residual component includes projected changes in net capital outlays as well as cyclical effects. For presentational purposes this residual component is combined with the 'other current primary expenditure' component explained previously.

The long-run fiscal adjustment is assumed to begin in 2026 on the basis of the projected structural fiscal position for 2025 in the Autumn 2023 *OECD Economic Outlook*. A cap on overall fiscal consolidation of one percentage point of potential GDP (measured on the underlying primary balance) in any single year is imposed to reflect political economy constraints. One percentage point is somewhat arbitrary, but larger fiscal adjustments have rarely been sustained for more than two or three years. This assumption may contradict current government plans and may not be consistent with national or supra-national fiscal objectives, targets or rules. No allowance is made for Keynesian effects of consolidation on demand. The difference between actual and cyclically-adjusted revenue is pinned down by the output gap (which is assumed to close gradually within a few years) and a semi-elasticity coefficient estimated in previous OECD work (Price, Dang and Botev, 2015[8]).

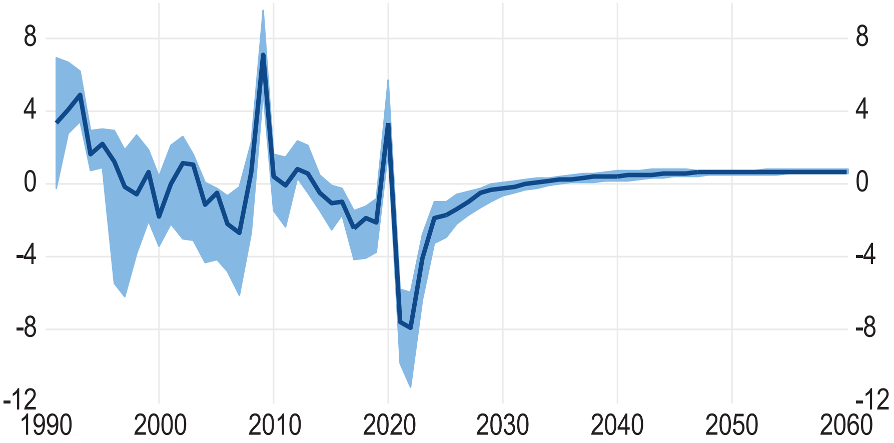
15. Future trends in interest and growth rates are crucial determinants of the future evolution of public debt ratios, as the simplified debt dynamics equation makes clear:

$$\Delta d_t = (r_t - g_t) \cdot d_{t-1} - pb_t \qquad [1]$$

where d_t is the debt-to-GDP ratio in year *t*, r_t is the implicit average nominal interest rate paid on government debt, g_t is the nominal growth rate of output and pb_t is the primary fiscal balance. Any increase in the *r* – *g* differential puts upward pressure on debt-to-GDP ratios and vice versa. Despite recent increases in market interest rates, the *r* – *g* differential remains negative at the moment in almost all OECD countries (Figure 5). This is largely because, as just mentioned, *r* is a weighted average of the interest rates at which existing debt was issued in the past and converges toward market rates only gradually as government debt is rolled over. Meanwhile, supply chain issues, labour-market tensions and recent energy price increases have recently put upward pressure on the price component of *g*. Looking forward, neutral short-term interest rates gradually converge toward potential growth rates in the LTM, implying that implicit average interest rates on public debt do the same. As a result, initial negative *r* – *g* differentials tend to converge toward a small positive value, this value being a function of 1) the share of government debt that is long-term, 2) the assumed common term premium on long-term interest rates, and 3) country-specific fiscal risk premia.[4]

Figure 5. The *r – g* differential crucial to debt dynamics normalises in the baseline scenario

% pts difference between implicit average nominal effective interest rate on government debt and nominal GDP growth across OECD countries, median and interquartile range



16. Most OECD governments confront a long-run fiscal challenge attributable to the combination of weak initial structural fiscal positions, rising financing costs, slowing growth and upward pressure on expenditure due to population ageing and the rising relative price of government-provided services. The size of this challenge can be illustrated with the long-run fiscal pressure indicator (Box 1) and broken down into the following components (Figure 6, Panel A):

- *Initial structural fiscal gap*. This component measures the distance between the structural primary balance projected in the latest *OECD Economic Outlook* for 2024 and that which would be consistent with keeping the public debt ratio stable at the projected *r* – *g* differential for that same year. The median OECD country would need to raise 1.2 pp of GDP of additional revenue to stabilise its public debt ratio, but with substantial variation across countries. Seven countries, including the United States, show an initial structural fiscal gap of 2½ pp of GDP or more.
- *Change in r – g*. Looking forward, the progressive increase in *r* – *g* discussed previously is set to add an additional 1.4 pp of GDP in fiscal pressure in the median OECD country by 2060. This component is based on net interest payments, thus also accounts for higher interest receipts, which explains why it is negative in a few countries with more government financial assets than liabilities (e.g., Luxembourg and Sweden).
- *Change in health and long-term care expenditure*. Under a business-as-usual hypothesis in which no major reforms to government programmes are undertaken, public health and long-term care expenditure is projected to increase by 2.1 pp of GDP in the median country between 2024 and 2060. Recent evidence points to a post-2009 shift in the nature of technological change that has increased the rate of cost-saving innovation in health care (Smith, Newhouse and Cuckler, 2022[9]). If sustained, this trend represents a downside risk to long-run health expenditure projections. On the other hand, the projections assume no additional impetus to health spending in the wake of the

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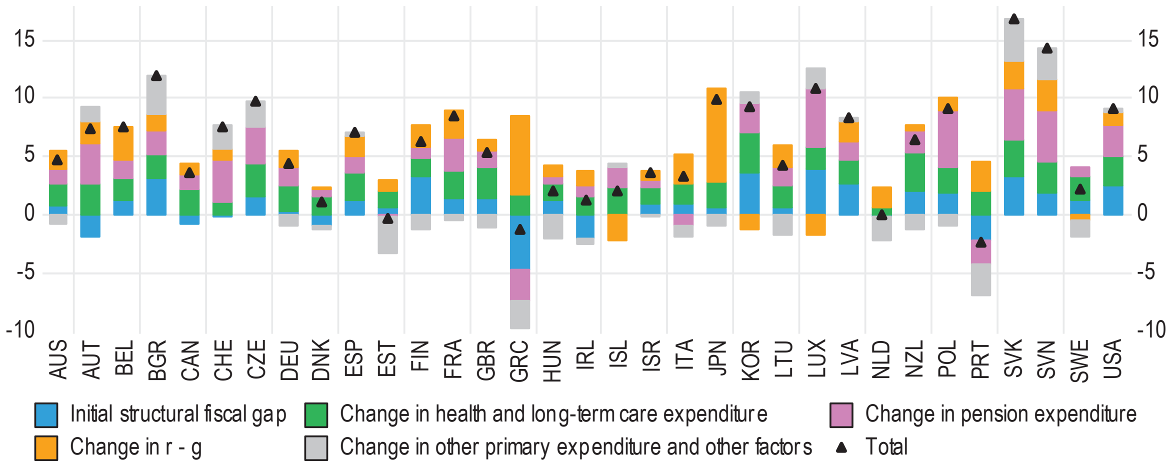
[4] In addition, because the neutral short-term rate for the euro area is set with respect to euro area potential growth, *r* – *g* differentials become slightly positive in euro area countries where potential growth eventually declines below the euro area average. See section 5 of Guillemette (2019[6]) for methodological details on interest rate projections.

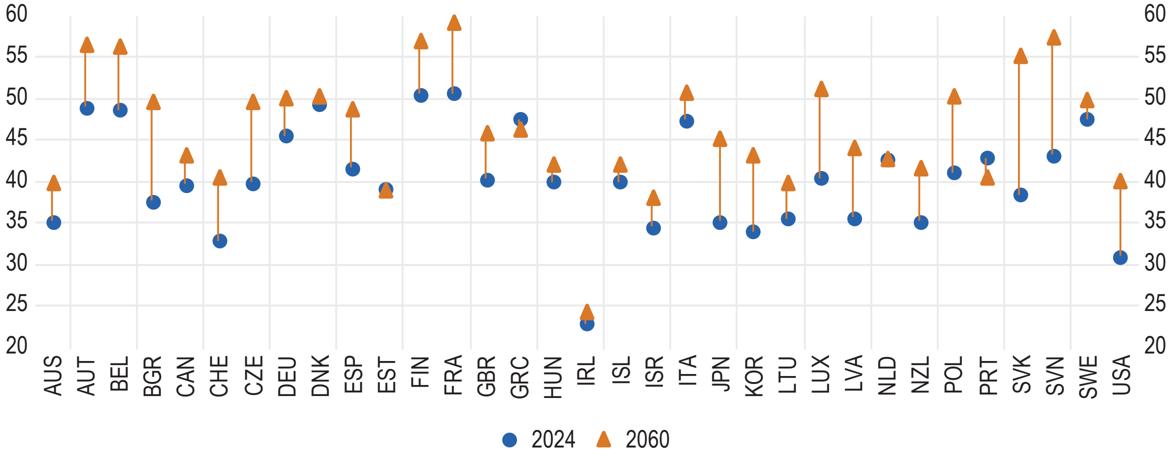
COVID-19 pandemic (for instance to build more spare capacity in intensive care units or raise pay levels for workers in public care homes), so any such adjustment would come in addition.

Figure 6. Potential future fiscal pressure to keep public debt ratio at current level in the baseline scenario

A. Change in fiscal pressure between 2024 and 2060, % pts of potential GDP



B. Fiscal pressure in 2024 and 2060, % of potential GDP



Note: The charts show how the ratio of structural primary revenue to GDP must evolve between 2024 and 2060 to keep the gross debt-to-GDP ratio stable near its current value over the projection period (which also implies a stable net debt-to-GDP ratio given the assumption that government financial assets remain stable as a share of GDP). The underlying projected growth rates, interest rates, etc., are from the baseline long-term scenario. In Panel A, the necessary change in structural primary revenue is decomposed into specific spending categories. In Panel B, blue dots show structural primary revenue in 2024 and arrows show the change during the 2024-to-2060 period. See Box 1 for more details.

- *Change in pension expenditure*. Public pension expenditure is projected to increase by 1½ pp of GDP in the median country between 2024 and 2060, but cross-country variability is much higher than in the case of health expenditure projections. Projected increases in public pension expenditure tend to be lower in countries that have legislated increases in statutory retirement ages, especially those that have linked these to future gains in life expectancy (e.g., Portugal), whereas they tend to be higher in countries with particularly unfavourable demographics (e.g., Slovakia). At the same time, part of the higher expenditure on public pensions would feed back to treasuries in the form of higher taxes on social benefits and consumption taxes on spending out of pension income. On average, this extra revenue might add up to a quarter of the projected increase in government spending on public pensions (Crowe et al., 2022[10]).

- Projected changes in other primary expenditure (current primary expenditure other than health, long-term care and pensions as well as net capital outlays) and other factors (mainly the fading of initial cyclical effects) subtract 0.4 pp of GDP to long-run fiscal pressure in the median country. However, this projection excludes potential new sources of expenditure pressure, for instance the energy transition, climate change adaptation and defence.

17. Altogether, fiscal pressure the median country is projected to increase by 6¼ pp of GDP between 2024 and 2060. Accordingly, this is the amount by which the median country would need to raise taxes to prevent gross government debt ratios from rising over time. The effort would exceed 9 pp in nine countries, including the United States, in some cases taking overall taxation levels beyond 55% of GDP (Figure 6, Panel B). Using this fiscal pressure indicator as a fiscal challenge metric, all OECD governments would need to raise taxes in this scenario, save for Estonia, the Netherlands (both having little to no public net debt) as well as Greece and Portugal (both having made substantial fiscal consolidation efforts in recent years).

18. The results of this section do not imply that taxes will, or should, rise in the future. Raising taxes is only one of many possible avenues to meet the fiscal challenge. While this strategy appears feasible in some countries where tax levels are relatively low, in other countries it may be impractical and possibly counterproductive. Another avenue would be reforming health and pension systems to increase efficiency and prevent expenditure from rising as much as projected in this stylised exercise. Additional debt finance could also be undertaken in some countries. No strategy is inherently superior and some combination of them would be prudent. Moreover, considerations missing from the framework, such as distributional issues, should also figure in the decision process. If the choice is made to meet the fiscal challenge by raising taxes, then consideration should be given to using tax instruments that are friendliest to growth, inclusiveness and sustainability. Crowe et al. (2022[10]) and Rouzet et al. (2019[11]) discuss policy options available to alleviate the fiscal pressures associated with ageing in more depth.

3. Incorporating an ambitious transition toward low-carbon energy sources

19. This section outlines the energy-related extensions to the LTM and assesses how an acceleration of the global transition toward low-carbon energy sources might affect long-run output trajectories. The projections described in the previous section serve as basis for projecting energy consumption and associated CO_2 emissions in this section, for both the baseline scenario – in which the transition is too slow to meet a global net zero GHG emissions objective by 2050 – and a transition scenario – in which it accelerates in a way consistent with the net zero 2050 objective. While many different configurations of individual country energy mixes, energy use, etc., could be consistent with this objective, the specific assumptions implemented here are chosen for reasons of simplicity and similarity of treatment, so that results are comparable across countries and hopefully illustrative in terms of broad orders of magnitude. They do not necessarily adhere to individual country commitments, targets or constraints, but can be refined when the model is applied to individual country analyses.

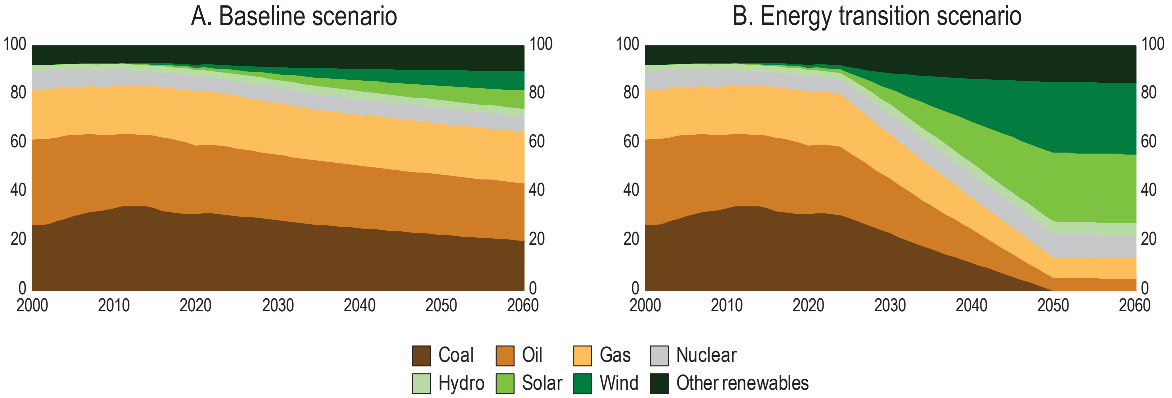
3.1. Decarbonisation of the energy mix accelerates in the transition scenario

20. The energy mix in individual countries is represented in the model as shares of total primary energy coming from eight sources (coal, oil, gas, nuclear, hydro, solar, wind and a residual category called other renewables). Total primary energy covers all energy use, including power generation, transport, heating and cooling. Different energy transition scenarios are then expressed as assumptions regarding how these

primary energy shares might evolve over time. Decarbonising the energy mix involves substituting low-carbon energy sources (including nuclear power) for carbon-based ones (coal, oil and gas). In the baseline scenario, the speed at which this occurs in the future remains in line with recent history. This is done at the country level and implies energy substitution that is clearly insufficient to reach a net-zero GHG objective by 2050 (see section 2.1 in Annex B for the technical details). At the OECD+G20 level, the share of carbon-based energy falls from 81% in 2023 to 68% in 2050 (Figure 7, Panel A and Figure 8).

Figure 7. Energy mixes in baseline and energy transition scenarios for OECD+G20 area

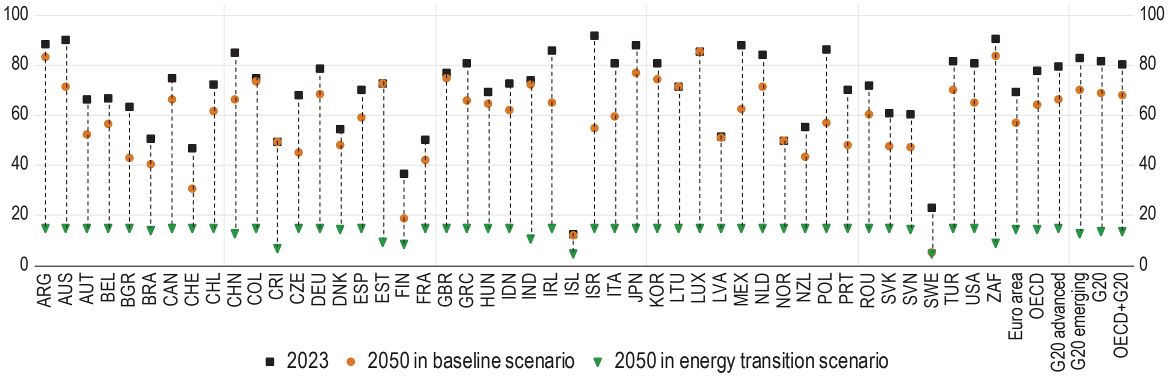
Per cent of total primary energy supply



Source: Historical data are from the IEA's World Energy Balances database.

Figure 8. The share of fossil fuels in primary energy declines sharply in the transition scenario

Per cent of total primary energy supply from carbon-based sources



Note: Carbon-based sources include coal, oil and gas. In the energy transition scenario, coal is assumed to be eliminated by 2050, while the share of oil in primary energy is assumed to decline to 5% and that of gas to 10%, except when these shares are already below these targets at the start of the projection period, in which case they remain constant.
Source: Historical data are from the IEA's World Energy Balances database.

21. For the stylised energy transition scenario, energy decarbonisation is assumed to accelerate greatly from 2026 onward. Coal is eliminated from the energy mix by 2050 at the latest (depending on the country), whereas oil and gas shares decline to, respectively, 5% and 10% of primary energy supply by 2050 in most countries. These are replaced by low-carbon energy sources, primarily solar and wind, the allocation varying by country following stylised projection rules that attempt to take the physical constraints

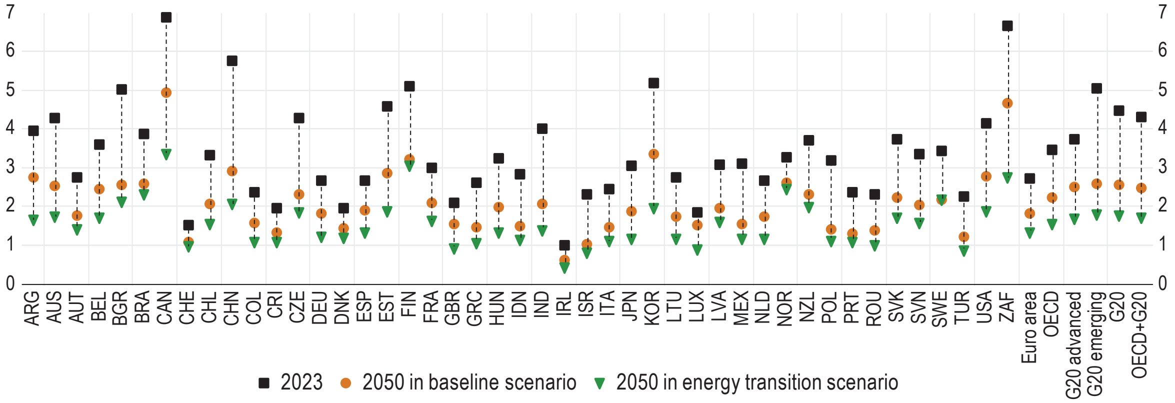
and revealed preferences of individual countries into account, albeit imperfectly (see section 2.1 in Annex B for how this is done). Carbon-based energy sources thus represent about 15% of primary energy supply in 2050 in all regions and in most individual countries, save for a few exceptions (Figure 7, Panel B and Figure 8). This outcome is broadly consistent with the global net-zero 2050 scenario (NZE) of the International Energy Agency (IEA), in which the 2050 emissions objective is met despite still substantial use of carbon-based energy, thanks to greater use of carbon capture and storage (CCS) technology as well as expanded natural carbon sinks (IEA, 2021[12]).

3.2. Energy efficiency continues to improve in the baseline scenario and accelerates in the transition scenario

22. Together with the energy mix, the evolution of total energy consumption is the other crucial determinant of CO_2 emissions from energy use. Total primary energy consumption per capita is projected based on the evolution of GDP per capita and that of the energy mix itself (see section 2.2 in Annex B for how this is done). Higher GDP per capita leads to higher energy consumption per capita, but less than one-for-one, leading to important gains in energy efficiency (measured as primary energy consumed per unit of output), even in the baseline scenario (Figure 9). This is consistent with recent history, as energy efficiency has improved substantially in many countries in recent years. It also implies that, all else equal, countries where growth is projected to be relatively strong in the decades ahead show higher gains in energy efficiency than countries where growth is weaker. The evolution of energy consumption in the LTM is also a function of the evolution of the energy mix itself, not as a causal mechanism, but to ensure that energy efficiency gains are larger in the energy transition than in the baseline scenario. It is natural to suppose that in a scenario where policy discourages carbon emissions, reductions would occur on both carbon and energy intensity margins simultaneously.

Figure 9. Energy efficiency improves substantially in both scenarios

Megajoules of primary energy per unit of GDP in USD at 2015 PPPs



Note: Iceland is not shown as it is an outlier due to the large share of geothermal heat in its energy mix.
Source: Historical data on energy are from the IEA's World Energy Balances database.

23. At the OECD+G20 level, energy consumed per unit of output declines by about 40% by 2050 in the baseline scenario, and by about 60% in the energy transition scenario, relative to 2023. Said otherwise, energy efficiency is roughly one third better in the energy transition than in the baseline scenario by 2050. The 60% improvement in energy efficiency in the transition scenario by 2050 is similar to that of the IEA's NZE scenario. Initial cross-country differences in energy efficiency levels are partly preserved in the

projections, as these reflect differences in industrial mix, geography, etc. that are implicitly assumed to persist.

3.3. Gross CO_2 emissions from energy use decline much more in the transition scenario

24. CO_2 emissions from energy use are projected at the country level for both scenarios. This is done by, first, combining projections of total energy use from the previous subsection with the energy mix assumptions of section 3.1 to project energy supply from individual sources; second, applying CO_2 emissions coefficients specific to each energy source; and third, aggregating the resulting CO_2 emissions over energy sources (see section 2.3 in Annex B for methodological details). These projections cover energy use only and no other source of GHG emissions (such as industrial processes or agriculture), but CO_2 emissions from burning fossil fuels account for approximately 70% of global GHG emissions. In turn, the OECD+G20 area covered by the LTM accounts for about 85% of today's global CO_2 emissions.

25. The baseline scenario is relatively optimistic in that annual CO_2 emissions from energy use are projected to decline in all broad areas and most individual countries by 2050 (Figure 10, Panel A). The exceptions are 1) low or middle-income countries where population and/or output per capita is projected to grow at a relatively rapid clip (e.g., India and Indonesia); 2) those where the energy mix is already light on fossil fuels and limited additional progress can be made (e.g., Iceland); or 3) those where energy decarbonisation has been progressing relatively slowly (e.g., Argentina), given that the contribution of energy decarbonisation (in red) reflect country-specific recent historical trends, as explained previously. Progress on energy efficiency (in green) is the main driver of the decline in CO_2 emissions in most countries. The projected decline in global CO_2 emissions in this scenario is relatively optimistic when compared to most other business-as-usual scenarios, such as the International Panel on Climate Change (IPCC) Shared Socioeconomic Pathways (SSPs) (Box 2). Nevertheless, the projected decline in emissions would fall well short of what is needed to substantially lower the risk of catastrophic climate change.

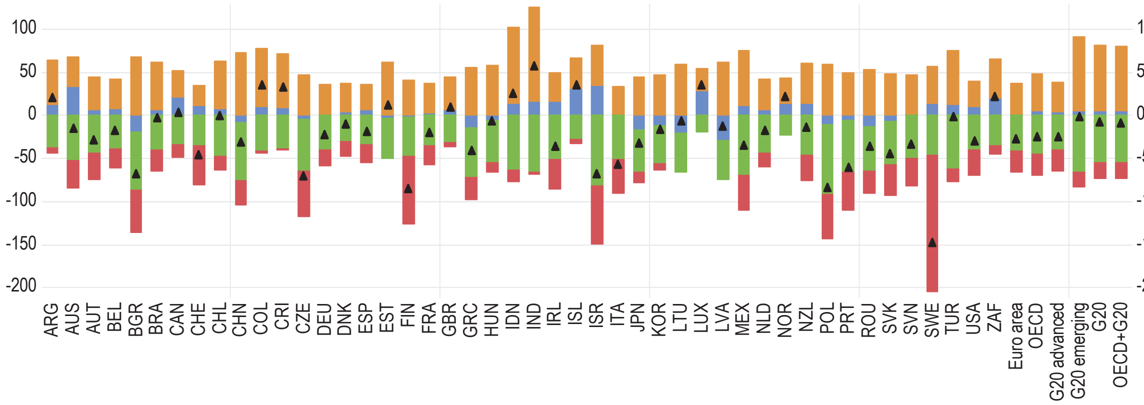
26. The energy transition scenario implies much larger declines in CO_2 emissions by 2050, with this time no exception across the countries covered (Figure 10, Panel B).

- Greater decarbonisation of the energy mix makes the largest difference to projected emissions in 2050 relative to the baseline scenario. Given that the share of carbon-based energy is assumed to decline to around 15% by 2050 in all countries, cross-country differences in energy decarbonisation are due primarily to differences in initial energy mixes. For instance, countries that start with higher shares of coal show greater decarbonisation given that coal is assumed to be eliminated by 2050 (see section 3.1).
- Energy efficiency improves more in this scenario than in the baseline scenario given the assumed link between decarbonisation of energy and energy use (see section 3.2).
- GDP per capita growth puts upward pressure on CO_2 emissions everywhere, but slightly less than in the baseline scenario given that carbon mitigation efforts have a cost in terms of output (see section 3.4).
- Population growth being completely exogenous in the LTM, its contribution to the evolution of CO_2 emissions is identical to that of the baseline scenario.

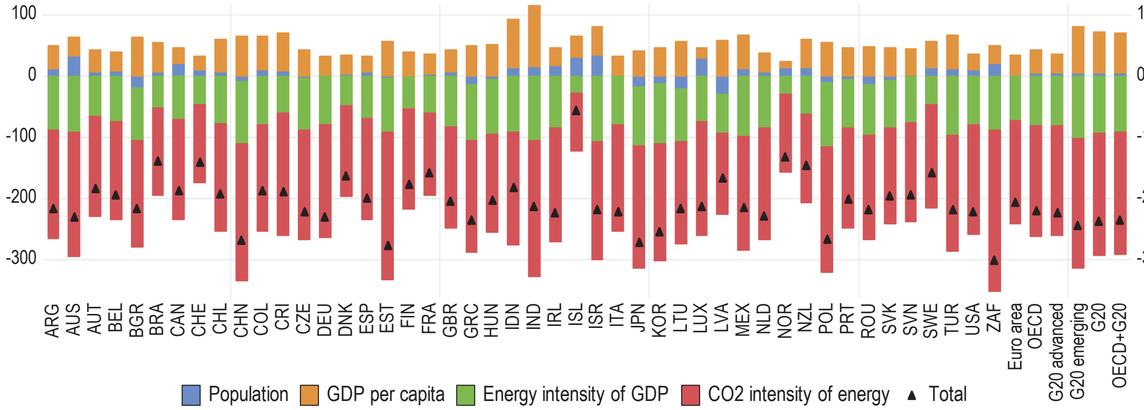
In terms of *net* CO_2 emissions at the global level in 2050, this study's energy transition scenario is comparable to the IPCC's SSP2 1.9 and therefore broadly consistent with the objective of limiting global warming to 1.5°C (Box 2). One notable difference, however, is that SSP2 1.9 envisages negative emission technologies (such as carbon capture and storage) making a larger contribution to energy decarbonisation. The same is true of the IEA's NZE scenario, in which net CO_2 emissions decline to zero by 2050, but with negative emissions of 9½ gigatonnes of CO_2 in 2050, equivalent to nearly 30% of 2020 emissions.

Figure 10. Change in annual gross CO_2 emissions from energy use, 2023-50 (log decomposition)

A. Baseline scenario



B. Energy transition scenario



Note: The decomposition shown in the charts is based on the identity $c \equiv p + y / p + e / y + c / e$, where c is CO_2 emissions from energy use, e is primary energy, y is real output and p is population, all variables being expressed in logs.
Source: Historical data on CO_2 emissions are from the Global Carbon Project via Our World in Data and historical data on energy are from the IEA's World Energy Balances database.

Box 2. Comparison of global CO_2 emissions to the Shared Socioeconomic Pathways and the Global Carbon Project's carbon budget

Preliminary work has been done to extend coverage of the LTM to countries not currently included, namely non-OECD, non-G20 countries. Trend output projections for these countries are based on a simplified approach, but one broadly consistent with that taken for other economies. The methodology described in Annex B is then applied to these additional countries to project energy use and CO_2 emissions. The global projections for CO_2 emissions hence obtained can be compared to the well-known Shared Socioeconomic Pathways (SSPs) used by the International Panel on Climate Change, among others, as well as the global carbon budget estimate of the Global Carbon Project. An important additional assumption for this comparison is that the share of gross CO_2 emissions captured and stored in this paper's energy transition scenario gradually rises from a trivial value today to 6% by 2050, thus reducing global net CO_2 emissions further relative to gross emissions.

Shared Socioeconomic Pathways (Riahi et al., 2017[13])

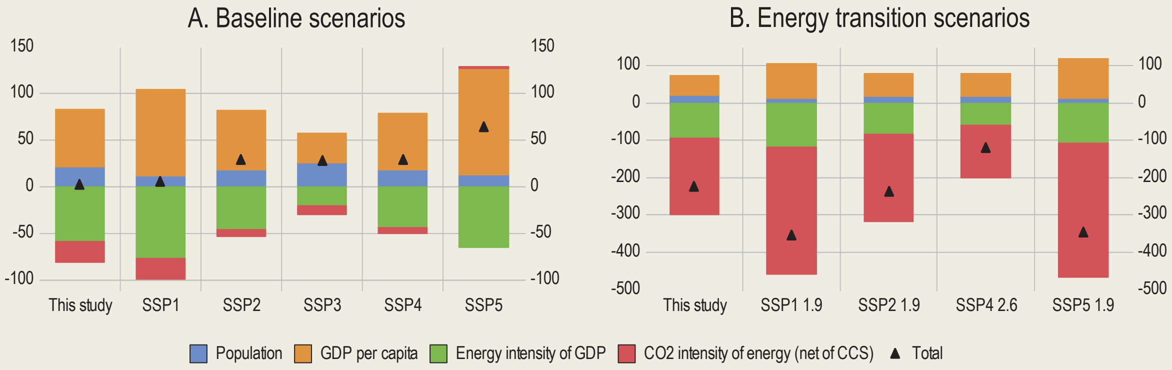
The SSPs are arranged around five narratives (labelled SSP1 to SSP5), each with a baseline scenario and associated mitigation/adaptation scenarios that are referred to by the amount of radiative forcing of the climate system in watt per square meter (W/m^2). In terms of narrative, this paper's baseline scenario is most similar to SSP2, which describes a world in which social, economic and technological trends do not shift markedly from historical patterns. Thus, it makes sense to compare the two.

The projected increase in global population used in this study is virtually identical to SSP2 and the contribution of global output expansion to CO_2 emissions is also similar (Figure 11, Panel A). However, this study's baseline scenario implies larger negative contributions from both energy efficiency and energy decarbonisation than SSP2. Overall, relative to the 2020 level, global net CO_2 emissions are almost unchanged in 2050 in this study's baseline scenario, whereas they rise some 30% in SSP2.

SSPs where radiative forcing is limited to 1.9 W/m^2 are considered compatible with the objective of limiting the increase in global temperature over pre-industrial times to 1.5°C, whereas 2.6 W/m^2 is considered compatible with limiting the temperature anomaly to 2°C. In terms of storyline, this paper's energy transition scenario is closest to SSP2 1.9, which involves all regions transitioning to global cooperation between 2020 and 2050. The projected reduction in annual CO_2 emissions between 2020 and 2050 is also closest to SSP2 1.9 (Figure 11, Panel B). The somewhat smaller contribution from energy decarbonisation in this study is partly compensated by a slightly larger contribution from energy intensity. This study's energy transition scenario is thus roughly consistent with the UN Paris Climate Agreement, assuming commensurate progress on GHG emissions other than energy-related CO_2.

Figure 11. The scenarios considered in this study are comparable to SSP2 base and SSP2 1.9

Log change in global annual net CO_2 emissions between 2020 and 2050



Note: The first bar in each panel shows the scenario discussed in this paper and refers to CO_2 emissions from energy use net of carbon capture and storage (CCS). The other bars show selected SSP scenarios for comparison and refer to net CO_2 emissions from all sources. The decomposition shown in the charts is based on the identity $c \equiv p + y / p + e / y + c / e$, where c is CO_2 emissions from energy use, e is primary energy, y is real output and p is population, all variables being expressed in logs. The numbers on the x-axis labels of Panel B refer to radiative forcing of the climate system in watt per square meter (W/m^2).

Source: Data for SSP scenarios are from Our World in Data. These scenarios are presented in Riahi et al. (2017), "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview", *Global Environmental Change*, No. 42, pp. 153-168.

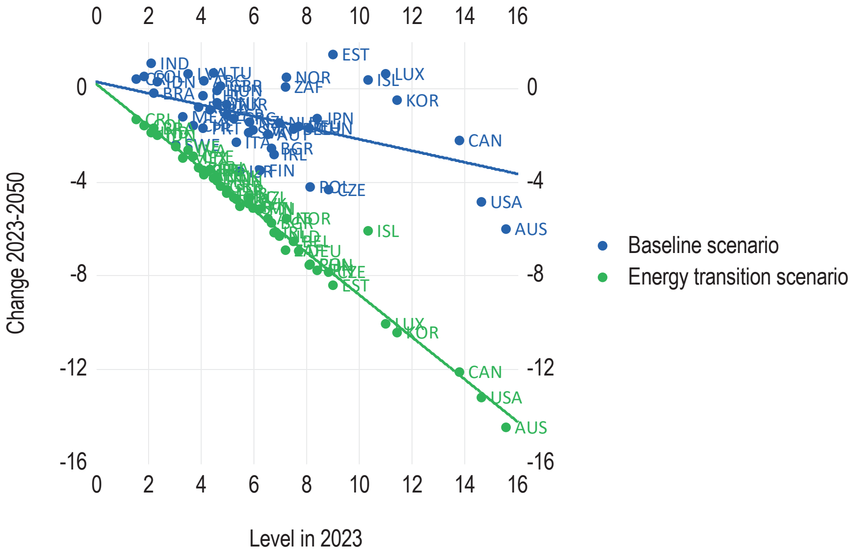
Global Carbon Budget (Friedlingstein et al., 2022[14])

According to the 2022 Annual Report of the Global Carbon Project, the remaining global carbon budget for a 50% likelihood of limiting global warming to 1.5°C is 380 gigatonnes of CO_2 ($GtCO_2$) from the beginning of 2023. The energy transition scenario in this study limits cumulative increases in global net CO_2 emissions from 2023 onward to around 520 $GtCO_2$ by 2050, with very slow increases thereafter. This projection would be somewhat higher when including other sources of CO_2 emissions and other GHGs not covered in this study. Therefore, on this metric, this study's energy transition scenario is not ambitious enough to limit global warming to 1.5°C, unless enriched with optimistic assumptions on future investments in natural carbon sinks (which are not considered here).

27. By design, cross-country convergence over time in CO2 emissions per capita is much greater in the energy transition than in the baseline scenario (Figure 12). Countries where emissions per capita are currently highest (e.g., Australia, Canada, Korea, United States) are not necessarily those where emissions fall the most in the baseline scenario, because energy mixes are assumed to continue evolving along recent country-specific trends. In the energy transition scenario, however, CO_2 emissions per capita fall most where they are initially highest. Nevertheless, some cross-country differences persist in 2050 even in the energy transition scenario, due mainly to initial differences in energy efficiency.

Figure 12. The energy transition scenario implies greater convergence in CO_2 emissions per capita

Tonnes of gross CO_2 emissions from energy use per capita, level in 2023 (x-axis) and change to 2050 (y-axis)



3.4. Impact of transition on output if all countries jointly raise carbon prices

28. Incorporating the impact of the energy transition on long-run potential output trajectories should, in principle, account for two main impact channels. The first is the direct impact of decarbonising an economy's energy sources, which, as pointed out by Pisani-Ferry (2021[15]), is akin to a negative supply shock. The second is the positive impact of avoiding environmental damages on the economy. Only the first channel is considered for the time being, but options to incorporate the damage channel are being considered for future updates.[5]

29. The magnitudes of negative supply shocks associated with an acceleration of the energy transition are based on simulations carried out with ENV-Linkages, a dynamic computable general equilibrium model maintained by the OECD (Château, Dellink and Lanzi, 2014[16]). Country-specific marginal abatement cost curves (MACCs) for energy-related CO_2 emissions are estimated with this model and incorporated in the LTM (see section 2.4 in Annex B for how this is done). The MACCS imply rising marginal abatement costs. It seems reasonable to expect that initial mitigation efforts will focus on the least costly units of CO_2 emissions and that additional mitigation will get ever more difficult, but technological developments could upset this calculus. The energy transition scenario is predicated on the conservative assumption that technology does not change quickly enough over the coming decades to significantly alter MACCs estimated today.[6] By design, the baseline scenario involves no mitigation costs. That is, only the reduction in CO_2 emissions in excess of that achieved in the baseline scenario is assumed to be costly in terms of output. Correspondingly, mitigation costs are expressed as output losses relative to the baseline scenario.

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[5] While the baseline scenario implies much larger environmental damages than the energy transition scenario, most of these would materialise beyond 2060, due to substantial inertia in the global carbon cycle and climate system. Illustrating large differences in projected environmental damages will thus also require lengthening the LTM's projection horizon. On the contrary, if the global temperature increase is to be successfully limited to 1.5 °C, virtually all mitigation costs will be borne by 2050.

[6] Technological progress is one, but not the only, determinant of the evolution of MACCs. One objective of future scenarios is to examine the sensitivity of projections to different assumptions on the evolution of MACCs over time.

30. Another important assumption is that the energy transition is incentivised by uniform carbon pricing in all countries and that the resulting revenue is redistributed to the representative household as a lump-sum transfer. Given that carbon pricing is generally considered the most efficient instrument to achieve a given amount of emissions reduction, the ensuing cost estimates can be seen as lower bounds. More realistic and socially acceptable policy packages that rely on, or include, other instruments could imply larger mitigation costs (Box 3). The global uniformity assumption is also important. Unilateral action by an individual or a group of countries would imply a loss of competitiveness relative to other countries, or the need for compensatory tariffs on trade, which could raise mitigation costs substantially.

Box 3. Mitigation costs depend on policy instruments and on global coordination

Estimates of carbon mitigation costs, including those on which LTM calibrations are based and which underlie the scenarios discussed in the main text, usually assume that some form of carbon tax is the main (or sole) policy instrument that is used to achieve the mitigation objective. However, other policy instruments will inevitably play a major role in achieving emission reductions, raising the issue as to how costs might differ with these other instruments (D'Arcangelo et al., 2023[17]).

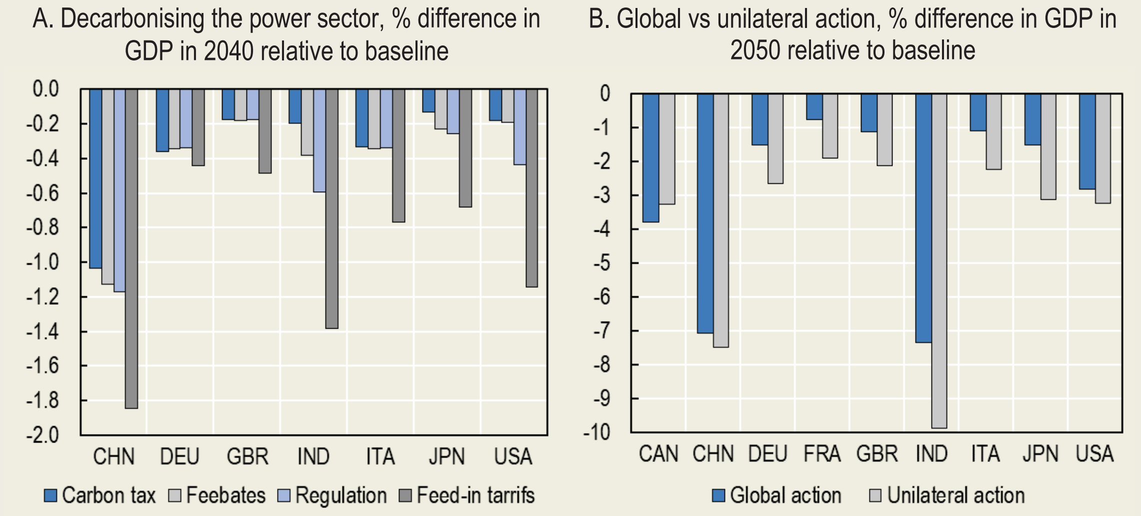
Some insights into this issue can be obtained from simulations on the ENV-Linkages model that examine the relative cost effectiveness of policy instruments to reduce carbon emissions in the power sector (see Chateau et al. (2022[18]) for more details on a similar modelling exercise). The power sector is chosen both because it is the major source of carbon emissions (roughly half of current global CO_2 emissions from fossil fuel combustion) and because electricity is a homogenous good, mostly produced for domestic production and for which there is reliable technical information about the underlying costs of production.

In this specific case, the GDP cost of using certain alternative policy instruments – in particular, regulation on a minimum share of renewables in total power generation or feebates (a system of fees and rebates based on the carbon content of each form of power generation) – are estimated to be only marginally higher than using a carbon tax (Figure 13, Panel A). By contrast, feed-in tariffs that guarantee higher prices (relative to market prices) to producers of solar and wind power, so effectively providing a subsidy to theses renewables without impacting fossil-fuel based power generation directly, could be much more costly.

However, in the current version of ENV-Linkages, it is difficult to generalise this result for other sectors. For example, regulating the carbon content of manufactured goods would hardly be practical and, in any case, much more costly than using the price mechanism via a carbon tax, given the great heterogeneity of goods and underlying production processes and differences in the ease with which they could be decarbonised. A further complication is that, as manufactured goods are widely traded, unilateral action by one country would only lead to displacement of production.

More generally, CO_2 mitigation costs in any given country depends on whether similar actions are taken by its trade partners. Unilateral action generally implies higher GDP losses, sometimes by a factor of around two, because production cost increases faced by domestic agents imply a loss of competitiveness and international market shares relative to trade partners that do not face higher costs (Figure 13, Panel B). Major fossil fuel exporters are exceptions, however, as concerted global action would likely imply larger falls in global fossil-fuel demand and international prices, further reducing income from fossil fuel exports.

Figure 13. Mitigation costs depend on policy instruments and coordination

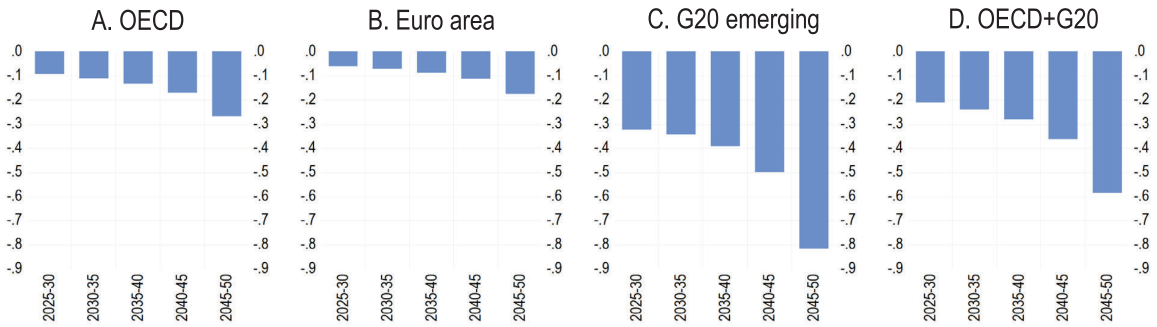


Note: Simulations are done on the OECD ENV-Linkages model. In Panel A, policies are adjusted so that 10% of the power sector remains fossil-fuel based in 2040. Countries start from different power mixes – the intended comparison is across policy instrument. In Panel B, the global action scenario assumes that carbon taxes are gradually implemented so that global CO_2 emissions from fossil fuel combustion are reduced by 70% relative to baseline in 2050 (or 40% relative to 2021). Unilateral action scenarios instead assume that countries act alone in implementing the same carbon tax as in the global action scenario.

31. For the OECD+G20 area, the acceleration of the energy transition described in previous sections is projected to reduce annual potential output growth by about 0.2 pp initially (in the 2025-30 period), this negative impact rising gradually to nearly 0.6 pp by the end of the transition (in the 2045-50 period) (Figure 14). Negative supply shocks are smaller in the OECD area and larger in emerging-market economies. That negative growth impacts become larger over time stems from the combination of CO_2 emissions falling at a fairly constant rate (in tonnes mitigated per year) with MACCs that imply rising marginal mitigation costs. While GDP growth reductions are modest initially in the OECD, impacts on private consumption could be larger given that the energy transition scenario implies large and front-loaded increases in investment (Box 4).

Figure 14. CO_2 mitigation costs vary by region

Average annual real potential output growth in the energy transition scenario, % pts difference from baseline



Note: Mitigation costs are based on simulations with the ENV-Linkages model, see section 2.4 in Annex B.

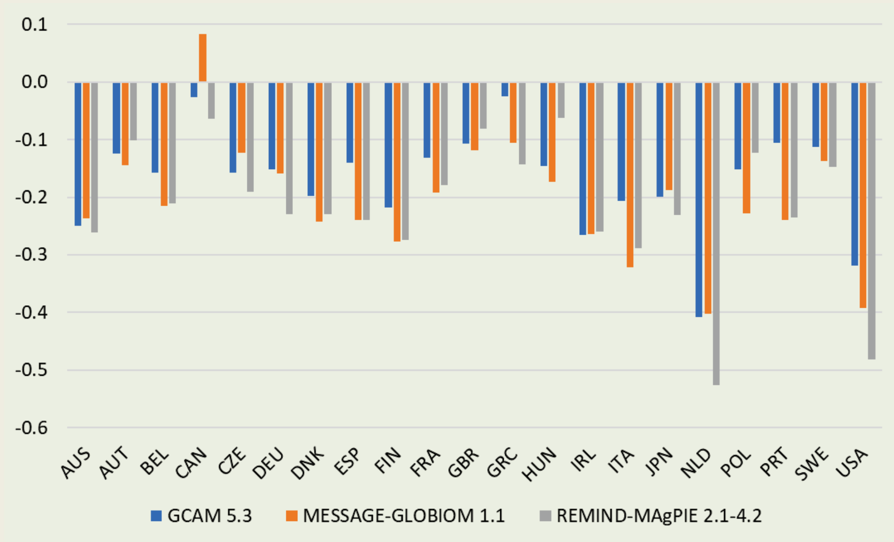
Box 4. The implications of low-carbon policies for private consumption

The focus of the discussion in the main paper is on the implications of a low-carbon energy transition for GDP, which reflects a similar focus in the LTM. However, the policies required to achieve this transition may have different impacts on other expenditure aggregates, which are not explicitly identified in the LTM and may not follow GDP proportionately. This is especially the case for private consumption. A scenario with a substantial energy transition by 2050 almost surely involves a significant increase in the share of global GDP devoted to investment, thus reducing global consumption possibilities. The resulting differential between the growth rate of GDP and private consumption is likely to be most apparent early in the transition, as the investment share is built up.

The possible magnitude of this effect can be gleaned from simulations on the NiGEM macroeconomic model, whereby outputs from three Integrated Assessment Models used by the Network for Greening the Financial System's (NGFS) to study a net zero 2050 scenario are fed into NiGEM. The simulations broadly suggest that, for most countries which are not net exporters of fossil fuels, annual consumption growth may be reduced by 0.2-0.3 pp more than GDP growth in the first decade of the transition (Figure 15). This result should be understood in the context of already weak growth in potential GDP per capita, around 1.1% for the OECD area in the first decade of the energy transition scenario described in the main text. This consumption effect is broadly consistent with the back-of-the envelope exercise of Pisani-Ferry (2022[19]), who calculates that if the investment share must increase by about 2 pp of GDP to achieve net zero, and this increase is phased in over a 10-year period, then it might be associated with a "decrease in real consumption growth of 0.3 percentage points per year".

Figure 15. Consumption declines more than GDP in the first decade of a net zero scenario

% pts difference in average annual growth of private consumption relative to GDP



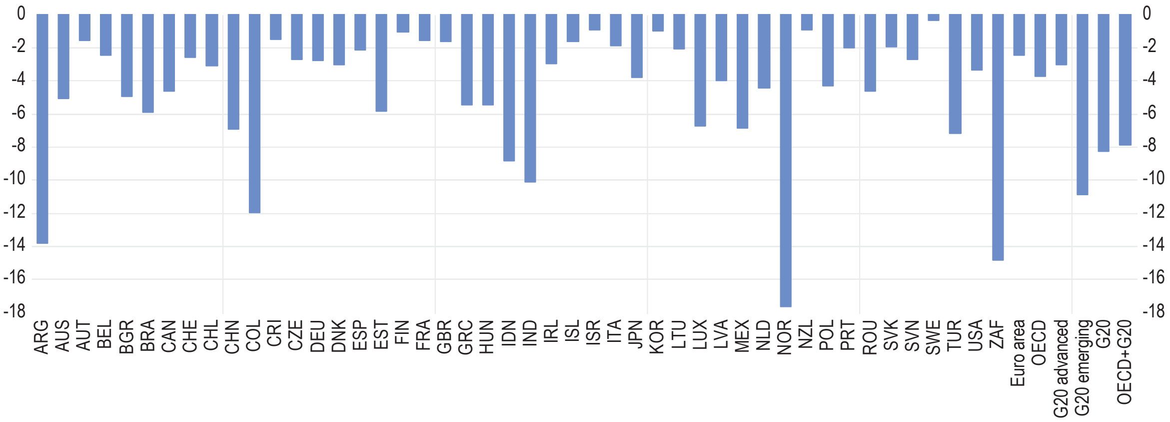
Note: The figure shows the difference in the annual average growth rate of real private consumption versus real GDP in the first decade of the NGFS' net zero 2050 scenario (2021-2031). The simulations are all run on the NiGEM model, with the three variants (represented by the three bars for each country) representing inputs from three Integrated Assessment Models. The selection of countries is limited as the consumption aggregate is not available for all countries in NiGEM.
Source: OECD calculations based on the NGFS' scenarios database v2.0.

Over the longer term, the model simulations suggest that, for most countries, consumption and GDP paths become less divergent as the net-zero GHG objective is approached. However, net fossil fuel exporters experience large declines in their terms of trade, implying that consumption falls by much more than GDP (even though such countries also experience the largest falls in GDP).

32. By 2050, cumulative mitigation costs associated with the energy transition (measured as the *level* difference in GDP relative to baseline) amount to 3.7% of baseline GDP for the OECD area and 11% of GDP for the G20 emerging-market area (Figure 16). Globally, cumulative mitigation costs work out to about 8% of GDP by 2050 (based on the OECD+G20 area). By comparison, in the SSPs described in Box 2, global GDP in 2050 is about 3-4% lower in the most closely comparable scenario (SSP2 1.9) than in the relevant baseline (SSP2 base). Likewise in the Network for Greening the Financial System (NGFS) simulations: by 2050 global GDP is around 3% lower in the 'net zero 2050' scenario than in the 'current policies' scenarios on the basis of the MESSAGEix-GLOBIOM 1.1 model, and about 4½ per cent lower on the basis of the REMIND-MAgPIE 2.1-4.2 model (NGFS, 2022[20]). Overall, mitigation costs are thus somewhat larger in ENV-Linkages than in other models.

Figure 16. Cumulative mitigation costs in the energy transition scenario vary across countries

Level of potential output in 2050, % difference from baseline



Note: Mitigation costs are based on simulations with the ENV-Linkages model, see section 2.4 in Annex B.

33. Mitigation costs are somewhat higher because, unlike many other models used to study the energy transition, the current version of ENV-Linkages:

1. Does not account for the reduction in climate damages on the economy resulting from mitigation actions.
2. Does not assume changes in preferences during the transition period (such as for smaller cars/ houses or greener diets) that allow for costless adaptation. In ENV-Linkages, reallocation of consumption/production is always the consequence of price changes and implies welfare losses.
3. Features some rigidity in capital reallocation, implying costly capital adjustments to carbon mitigation actions during the transition period.
4. Does not assume that mitigation costs decline over time, for instance because of technology.

Given great uncertainty around these features, the usefulness of modelling exercises may reside more in establishing a plausible cross-country distribution of mitigation sensitivities rather than global cost estimates. On this score, models tend to broadly agree: emerging-market economies are generally more negatively affected by the global energy transition than advanced economies, with Africa and the Middle East particularly hard hit. This is because of a combination of negative terms-of-trade effects (for oil and gas exporters), more energy-intensive industry mixes and higher carbon intensity of energy (i.e., greater distance from the net-zero objective). These differences underline the potential importance of the Loss and Damage Fund agreed at COP27.

4. Some implications of the energy transition for fiscal sustainability

34. This section uses the LTM model to illustrate and quantify a few of the potential fiscal implications of the energy transition.

4.1. The energy transition requires substantial investment in electricity generation

35. As shown in section 3.1, the stylised energy transition scenario involves a shift away from fossil fuel-based primary energy sources to low-carbon sources, either nuclear power or renewables. Save for a few exceptions, such as geothermal heat, these low-carbon energy sources all involve generating electricity. The energy transition thus requires building substantial new capacity to generate electricity. Building electrical capacity is just one of many types of investment that will need to accompany the energy transition, but it is one that has traditionally involved a high degree of public sector financing, so future investment needs, even partial, are a useful addition to fiscal sustainability analyses.

36. The projections and assumptions described previously for total primary energy consumption and for energy mixes allow indicative projections to be made for the additional electrical capacity needed over time in both baseline and energy transition scenarios (see section 2.5 in Annex B for how this is done). Combining these projections with cost estimates for building new electricity plants of various types allow future capital investment needs to be projected as well. These projections are highly uncertain, one reason being uncertainty as regards which low-carbon technologies will replace fossil fuels in different countries and in what proportions, and another being uncertainty as regards how the costs of different technologies will evolve.[7]

37. In the energy transition scenario, the installed base of low-carbon electrical capacity is projected to increase by a factor of 2½ to 25 by 2050, depending on the country (Figure 17). This factor is lower in countries where low-carbon sources already account for a large share of primary energy (e.g., Iceland) and higher in country with high carbon intensity. New solar capacity dominates in the projections, in part by assumption (as its cost has tended to decline faster than other technologies), but also because of its relatively low capacity factor, implying the need for a larger installed base than other renewable technologies for a given amount of annual electricity generation (see section 2.5 in Annex B for more details). As just mentioned, these projections are highly stylised, but nevertheless illustrate the size of the challenge in scaling up electricity production from low-carbon sources.

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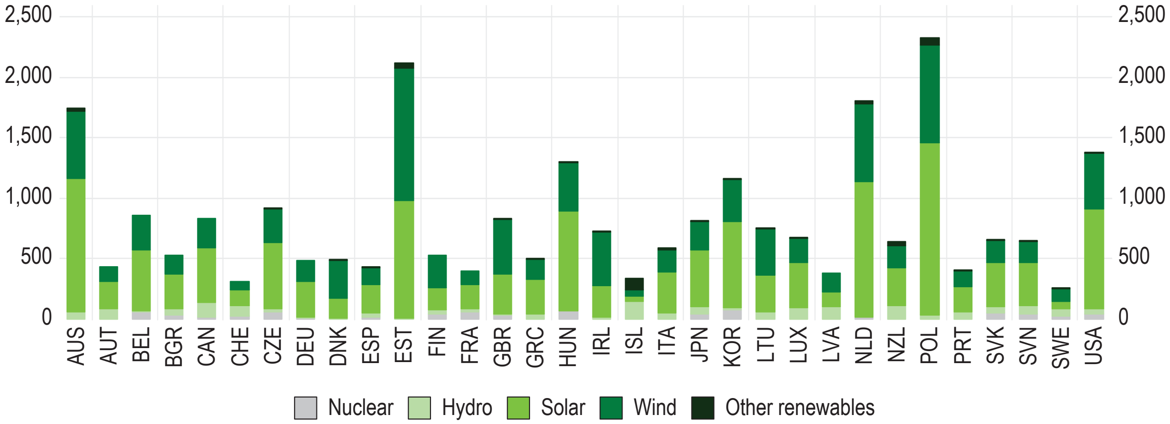
[7] Since projections use global average costs per gigawatt of new capacity and since costs are generally lower in emerging-market economies than advanced economies, the projections likely underestimate investment needs in advanced countries and overestimate them in emerging-market countries, all else equal. These cost assumptions can be refined (and made country specific) when the model is used for more targeted analyses.

Figure 17. Low-carbon electrical capacity must scale up in the energy transition scenario

Low-carbon electrical capacity in 2050, index, 2020 = 100

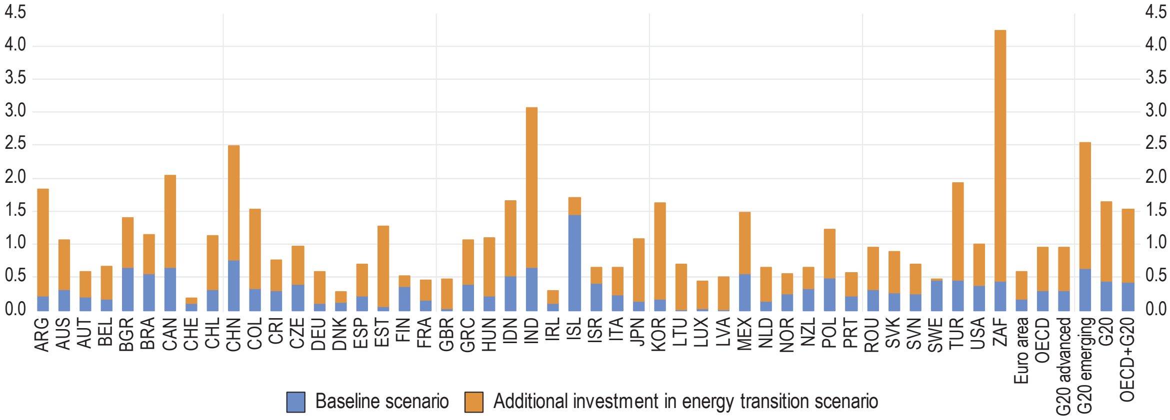


Note: Not all OECD countries are shown given missing historical data for some countries. Israel is not shown as it is an outlier given very low capacity in the base year (2020).
Source: Historical data are from the IEA's Electricity Information Statistics database.

38. Investment in new low-carbon electrical capacity rises to an average of 1% of GDP in OECD countries and 2½ per cent of GDP in G20 emerging-market economies in the second half of this decade in the energy transition scenario (Figure 18). These higher investment rates in the energy transition than in the baseline scenario would need to be maintained through 2050, although increases tend to be front loaded. This front-loading of investment is one reason why the negative impact of the energy transition on private consumption will plausibly be larger than on GDP in most countries (see Box 4). Again, differences in initial energy mixes largely explain cross-country differences in investment needs, for instance why euro area countries generally show lower investment needs than other OECD countries.

Figure 18. Investment in low-carbon electrical capacity must rise in the energy transition scenario

% of GDP, average 2026-30



Note: See section 2.5 in Annex B for details on the methodology and assumptions behind these projections.

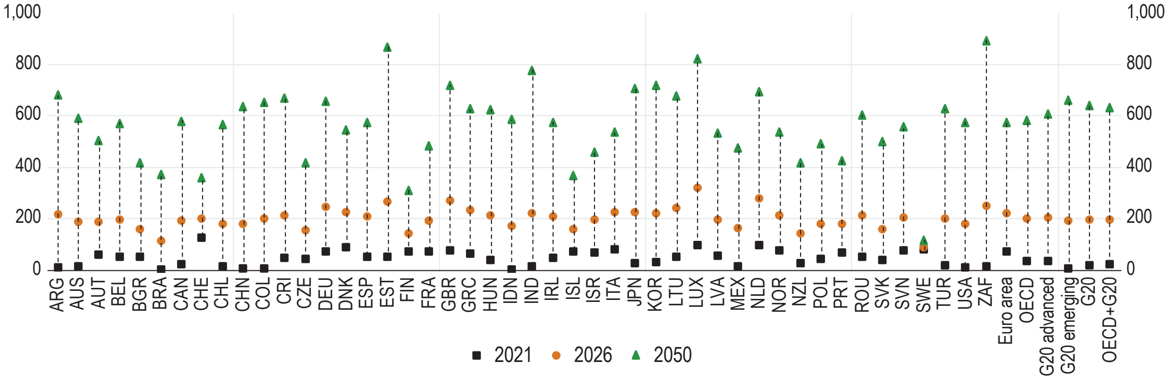
39. Projected investment needs in the energy transition scenario do not represent a pure increase in expenditure as the baseline scenario also involves some investment in new electricity generation. The increase over baseline amounts to $^{2}/_{3}$ pp of GDP in the OECD area, but as much as 1½ pp of GDP in Korea and Türkiye, for instance. If the public sector finances two thirds of these investments, then capital costs for new electricity generation could add a few tenths of a percentage point to the fiscal pressure estimates discussed previously and perhaps as much as one percentage point in some countries. The additional fiscal pressure is estimated to be more substantial in G20 emerging-market economies, such as India and South Africa, suggesting that these may require the help of advanced countries to finance new energy infrastructure.

4.2. Carbon taxation can yield substantial, but temporary, new revenue

40. While the energy transition is sure to demand additional public investment, it can also bring in substantial additional revenue. The baseline scenario assumption is that effective carbon rates (ECRs) – the sum of tradeable emission permit prices, carbon taxes and fuel excise taxes – remain at current levels, which vary from less than EUR 1 per tonne of CO_2 (Brazil) to more than EUR 120 (Switzerland) (OECD, 2023[21]). The energy transition scenario instead assumes that the transition would be incentivised by higher carbon pricing. Recent OECD work on the elasticity of CO_2 emissions to ECRs allows a calculation to be made of how much ECRs would have to increase to bring about the fall in CO_2 emissions envisioned in this scenario (D'Arcangelo et al., 2022[22]) (see section 2.6 in Annex B for how this is done). In all broad regions, effective carbon rates would need to increase to around EUR 200 as of 2026 (assuming it takes 10 years for emissions to adjust to a change in the ECR) and to around EUR 600 by 2050 (Figure 19). These results are broadly in line with other projections, for instance those of the NGFS, where the weighted global carbon price rises to USD 450-700 by 2050 in comparable scenarios compatible with the UN's Paris Agreement (NGFS, 2022[20]).

Figure 19. Effective carbon rates increase sharply in the energy transition scenario

EUR (of 2021) per tonne of CO_2



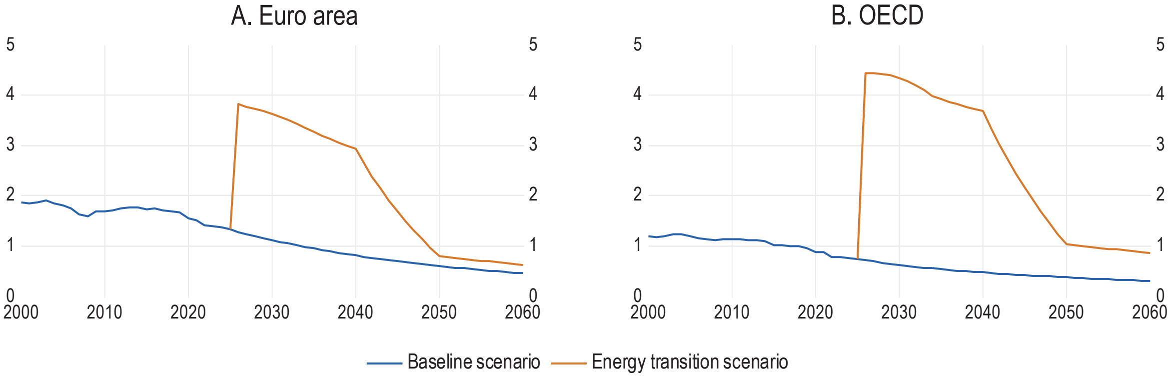
Note: In the baseline scenario, effective carbon rates are assumed to remain at their (country-specific) 2021 levels.
Source: Initial values (for 2021) are from OECD (2023), Effective Carbon Rates 2023: Pricing Greenhouse Gas Emissions through Taxes and Emissions Trading, *OECD Series on Carbon Pricing and Energy Taxation*, OECD Publishing, Paris, https://doi.org/10.1787/b84d5b36-en.

41. Such large increases in carbon pricing would rapidly bring in additional government revenue, around 2½ per cent of GDP in the euro area and 3¾ per cent of GDP in the OECD area over the 2026-2030 period (Figures 20). Revenue windfalls are much greater than these averages in some countries where reductions in CO_2 emissions in the energy transition scenario are especially large relative to baseline (Figure 21). However, they would largely be temporary. Carbon-related fiscal revenue would decline along

with CO_2 emissions after 2026, slowly at first as continued increases in ECRs partly offset falling emissions, and more rapidly later on as ECRs near their peaks (here post-2040 given the assumption of a 10-year adjustment period).

Figure 20. The fiscal windfall from carbon pricing in the energy transition scenario is large but temporary

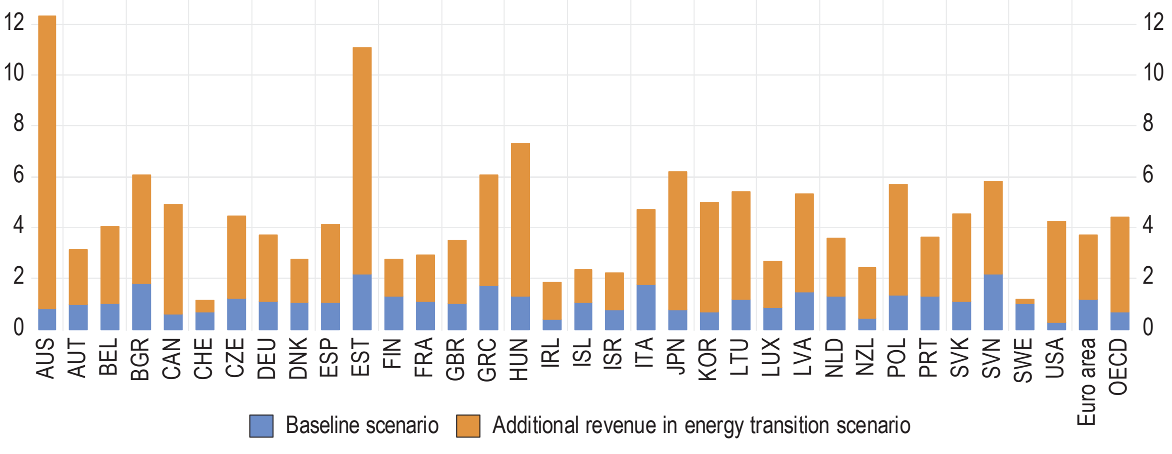
Carbon-related government revenue, % of GDP



Note: Carbon-related revenue is an estimate based on the 'energy products' tax base and the 'climate change' domain in the OECD's Environmentally Related Tax Revenue database. The energy transition scenario assumes that it takes 10 years for CO_2 emissions to fully adjust to a change in the ECR, implying immediate and large increases in ECRs at the beginning of the projection period given projected emissions trajectories. The OECD aggregate excludes Chile, Colombia, Costa Rica, Mexico, Norway and Türkiye as these countries do not have a fiscal block in the LTM.
Source: Historical data are from the OECD's Environmentally Related Tax Revenue database.

Figure 21. Higher carbon pricing could temporarily bring in substantial additional government revenue

% of GDP, average 2026-30



Note: Carbon-related revenue is an estimate based on the 'energy products' tax base and the 'climate change' domain in the OECD's Environmentally Related Tax Revenue database. Chile, Colombia, Costa Rica, Mexico, Norway and Türkiye are not shown and excluded from the OECD aggregate as these countries do not have a fiscal block in the LTM.

42. At least temporarily, higher carbon pricing could help OECD governments meet the additional fiscal pressure associated with population ageing and other factors estimated previously. Realistically, however, ECRs are unlikely to increase by as much as the above stylised calculations suggest, as these ignore the difficult political economy of rapid and large increases in energy prices. As D'Arcangelo et al. (2022[22]) explain, carbon pricing by itself would, in any case, not be sufficient to bring about the economic and societal transformations necessary for a net-zero world. Governments will need to employ a broader set of policy instruments, including regulations and subsidies. While necessary, the use of other instruments is likely to raise the output costs of the energy transition (lower efficiency), raise public expenditure (e.g., subsidies) and fail to bring in as much additional government revenue as estimated above (Fouré et al., 2023[23]). Governments should therefore seek to rely on higher carbon pricing as much as realistically feasible and seek ways to make this option more politically palatable. One such way might be to raise ECRs as part of a broader tax policy package that would shift the burden of taxation away from labour and toward carbon. This option is examined in the next section.

4.3. Using carbon-related revenue to offset the negative output effect of the transition

43. Previous versions of OECD long-run scenarios have illustrated positive impacts that labour market reforms could have on future living standards, notably lowering tax wedges (Guillemette and Turner, 2021[1]). The projected impacts of these reforms in the LTM are based on the empirical work of Gal and Theising (2015[24]) and Égert and Gal (2017[25]). These same estimates can be used to assess the impact of a tax shift strategy in which revenue from higher carbon pricing would be used to reduce labour tax wedges. Dynamics are important here because, as seen in the previous section, revenue from carbon pricing first rises, but later declines, implying that labour tax wedges could be lowered, but would eventually have to rise again. Nevertheless, seeing as higher carbon pricing is politically awkward to implement, the tax shift strategy could facilitate the phasing in of higher carbon taxes, allowing at least the initial part of the energy transition to benefit from the greater efficiency of a price-induced transition.

44. Relative to the energy transition scenario considered so far, in which additional fiscal revenue from carbon pricing was channelled back to households as a lump sum, using this extra revenue to lower tax wedges would temporarily boost employment rates.[8] At peak impact around 2035, the euro area and OECD aggregate employment rates are around 1½ pp higher than without the tax shift, more than fully offsetting the output costs associated with the first 10 years of the energy transition and leaving living standards in 2035 slightly higher than in the baseline scenario (Figure 22). The tax shift's positive impacts fully or more than fully offset carbon mitigation costs in most individual OECD countries, Luxembourg being the main exception due to relatively high mitigation costs in the energy transition scenario. The impact of a change in tax wedges on employment is assumed to be the same across countries, but those where tax wedges are particularly high might plausibly benefit more from a cut. The cumulative effect of the tax shift policy is evaluated in 2035 because, as shown previously, it would decline thereafter as declining carbon tax revenue force tax wedges back up.

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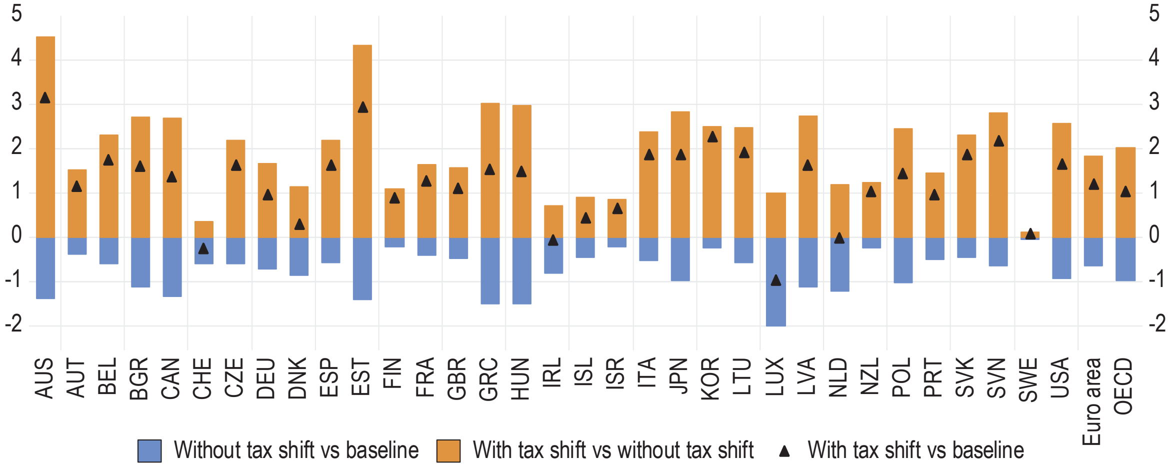
[8] The scenario assumes that a one-percentage point of GDP increase in tax revenue allows tax wedges to be lowered by about 2½ percentage points of labour costs. This assumption is based on an estimated relationship across OECD countries between tax wedges and government fiscal receipts.

Figure 22. Shifting tax burden from labour to carbon offsets most transition costs to 2035

Level of potential output in 2035, % difference between scenarios (see legend and note)



Note: Blue bars show the % difference in the level of output in 2035 in an energy transition scenario with carbon revenue rebated as lump sums versus the baseline scenario. Orange bars show the % difference in the level of output in 2035 in an energy transition scenario with carbon revenue used to lower tax wedges versus when it is rebated as lump sums. Diamonds show the % difference in the level of output in 2035 in an energy transition scenario with carbon revenue used to lower tax wedges versus the baseline scenario, which corresponds to the sum of blue and orange bars. Chile, Colombia, Costa Rica, Mexico, Norway and Türkiye are not shown as these countries do not have a fiscal block in the LTM.

45. Lowering tax wedges is only one of the ways in which extra carbon-related fiscal revenue could be redistributed to households in a fiscally neutral package. For instance, it is conceivable that the structural economic changes that are necessary for a successful energy transition might increase structural unemployment, at least for a while. Even if not, it might plausibly increase frictional unemployment. The OECD empirical work mentioned previously and used to assess the impact of lowering tax wedges suggests that active labour market policies (ALMPs), such as programmes to help workers re-train and change occupation, could help boost employment rates, with especially strong impacts on youth. Expanding ALMPs could thus help ease the transition, lowering mitigation costs.

46. This same work also suggests that in-kind family benefits, notably childcare, could help boost employment rates, with especially strong impacts on women. Other empirical work has, moreover, shown that in-kind family benefits have an outsized positive impact on household disposable income (Botev, Égert and Turner, 2022[26]), so increased spending in this area would be particularly useful if the energy transition depresses disposable income and consumption, as suggested by the analysis in Box 4.

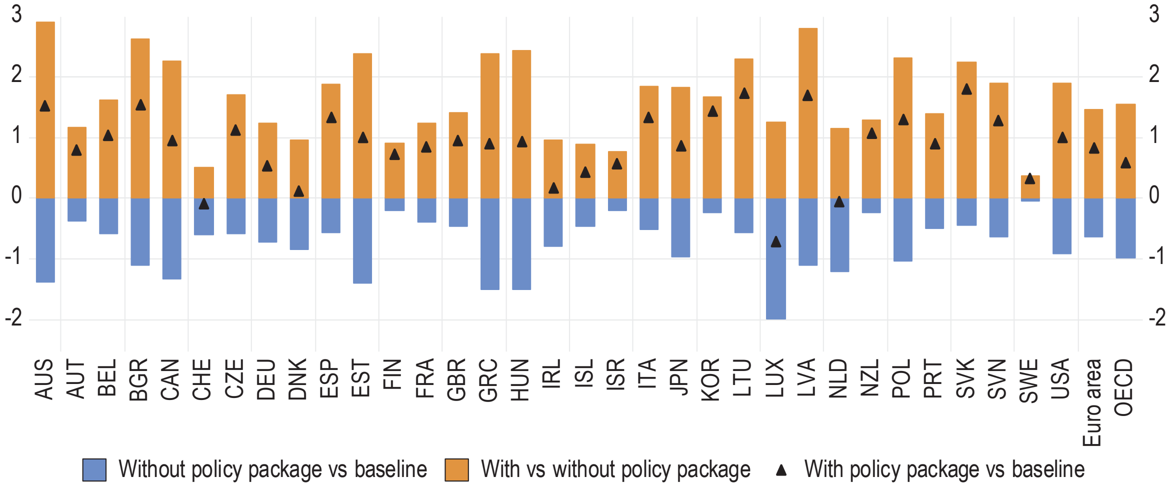
47. Mitigating climate change and adapting to its inevitable impacts will require innovation across multiple areas and governments can also play a role in supporting fundamental research and development (R&D), which tends to be underprovided in market economies. In the LTM, government expenditure on R&D raises the global stock of available knowledge, generating positive externalities and raising trend labour efficiency in all countries.

48. To illustrate the potential for a policy package that would jointly support employment and innovation, a scenario is run in which two-thirds of the additional carbon-related fiscal revenue in the energy transition scenario is used to increase government R&D expenditure and the remaining third is used to enhance support for childcare. By 2035, the OECD's aggregate employment rate is 0.6 pp higher than in the transition scenario with lump-sum redistribution of additional carbon-related revenue, while trend labour efficiency growth is 0.1 pp higher. The overall impacts on potential output are broadly similar to those of

the previous scenario: the output costs of carbon mitigation during the first 10 years of the energy transition are essentially offset in all countries except Luxembourg, where they are nonetheless lowered to less than 1% of GDP (Figure 23).

Figure 23. Using carbon-related revenue to support employment and innovation could fully offset transitions costs to 2035

Level of potential output in 2035, % difference between scenarios (see legend and note)



Note: Blue bars show the % difference in the level of output in 2035 in an energy transition scenario with carbon revenue rebated as lump sums versus the baseline scenario. Orange bars show the % difference in the level of output in 2035 in an energy transition scenario with carbon revenue used to raise government expenditure on R&D and in-kind family benefits versus when it is rebated as lump sums. Diamonds show the % difference in the level of output in 2035 in an energy transition scenario with carbon revenue used to raise expenditure on R&D and in-kind family benefits versus the baseline scenario, which corresponds to the sum of blue and orange bars. Chile, Colombia, Costa Rica, Mexico, Norway and Türkiye are not shown as these countries do not have a fiscal block in the LTM.

4.4. Other structural reforms could also help offset mitigation costs

49. Besides redistributing carbon-related revenue to households and businesses in a way that boosts growth, governments could also offset mitigation costs with structural reforms that involve little or no fiscal cost. Such reforms are desirable in all circumstances, but even more so in the context of an energy transition that might place downward pressure on GDP per capita. To illustrate, an energy transition scenario is run in which 1) OECD governments gradually liberalise product markets, so that overall PMR indicators improve to the top-5 OECD countries' average (Denmark, Germany, Netherlands, Spain and United Kingdom) by 2050; and 2) non-OECD G20 countries gradually improve their governance scores (measured by the World Bank's Rule of Law indicator) and PMR scores to the respective OECD medians, also by 2050.[9]

50. Simulation results show that, for the OECD area as a whole, reform impacts would fully offset mitigation costs throughout the projection period and leave potential output essentially the same as in the baseline scenario in 2050 (Figure 24, Panel A). In the G20 emerging-market area, mitigation costs are slightly larger than reform benefits early in the transition period, but the situation has reversed by the early-2040s (Figure 24, Panel B). It should be noted that, since energy use is linked to output, global CO_2

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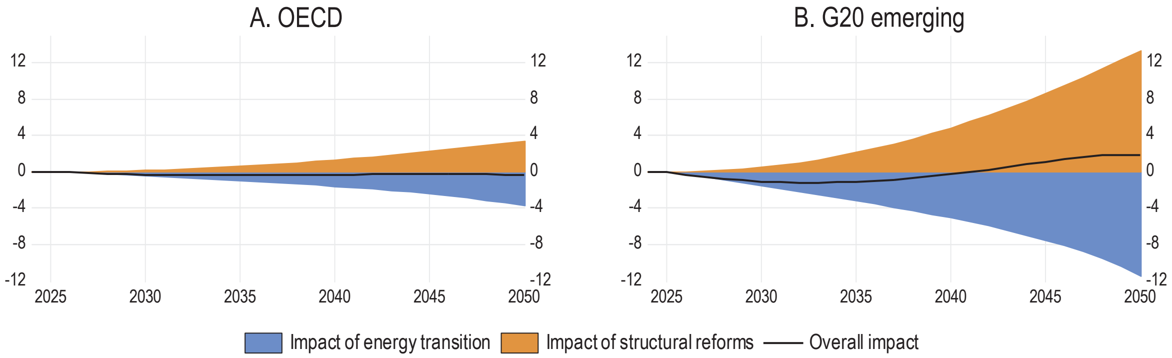
[9] See section 3 in Guillemette and Turner (2018[4]) for more details on governance and the Rule of Law indicator in the LTM.

emissions in 2050 are about 3% higher in this scenario than in the regular energy transition scenario, so some additional effort on energy decarbonisation or efficiency would be needed to achieve the same level of emissions reduction.

Figure 24. Structural reforms can fully offset mitigation costs by 2050

% difference in potential output relative to baseline scenario



Note: The structural reforms simulated are improvements in product market regulation in both OECD and G20 emerging-market economies and additional governance reforms in G20 emerging-market economies (see text for details). The blue areas are obtained by comparing the energy transition scenario without structural reforms to the baseline scenario. The yellow areas are obtained by comparing the energy transition scenario with structural reforms to that without the reforms. The lines are obtained by comparing the energy transition scenario with structural reforms to the baseline scenario.

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Annex A. The growth projection and accounting framework

1. Model coverage and aggregates

1. The OECD's long-term model (LTM) includes 48 countries: the 38 OECD member countries, eight non-OECD G20 countries (Argentina, Brazil, China, India, Indonesia, Russia, Saudi Arabia and South Africa) and two other accession or partner countries (Bulgaria and Romania).

2. In tables and figures, the 'G20 advanced' aggregate includes Australia, Canada, France, Germany, Italy, Japan, Korea, the United Kingdom and the United States. The 'G20 emerging' aggregate includes Argentina, Brazil, China, India, Indonesia, Mexico, Russia, Saudi Arabia, South Africa and Türkiye. The G20 aggregate includes both advanced and emerging members. The 'OECD+G20' aggregate includes all OECD and non-OECD G20 countries, which together amount to approximately 83% of total world GDP at Purchasing Power Parity exchange rates.

3. Future work will seek to add the rest of the world (currently 17% of global GDP) in a simplified manner as these countries will likely account for a rising share of global GDP over time as well as global greenhouse gases emissions.

2. Potential output projection

4. The backbone of the LTM is a consistent set of long-run projections for potential output which are extensions of the short-term potential output estimates prepared for the twice-yearly *OECD Economic Outlook* following the approach described in Chalaux and Guillemette (2019[27]). Potential output (*Y*) is based on a Cobb-Douglas production function with constant returns to scale featuring physical capital (*K*) and trend employment (*N*) as production factors plus labour-augmenting technological progress (*E*, hereafter referred to as trend labour efficiency[10]), so that:

$$y = \alpha(n + e) + (1 - \alpha)k$$

where lower case letters denote logarithms and α is the labour income share, assumed to be 0.67 for all countries.[11] Potential output is projected out to 2060 by modelling the trend input components as follows:

- Trend labour efficiency growth is determined differently depending on whether the model is used to produce a baseline scenario (scenario mode) or to run an alternative scenario with shocks to institutional and policy indicators (simulation mode). In scenario mode, trend labour efficiency growth is the sum of an absolute convergence component and a momentum component. The absolute convergence component depends on the remaining distance to an equilibrium level of labour efficiency, usually taken to be the United States'. The initial momentum component is calculated as a residual given the estimated trend labour efficiency growth and that predicted by

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[10] In this framework, labour efficiency (*E*) and total factor productivity (*TFP*) – that part of output not explained by factor inputs – are closely related but distinct concepts: $TFP = E^{\alpha}$.

[11] This parameter value roughly corresponds to the wage share in advanced economies and has proven to be quite stable in time. This is less true of emerging-market economies, however, and future work could consider the consequences of allowing the wage share to vary across country, over time, or both. See Chalaux and Guillemette (2019[27]) for more on this assumption.

absolute convergence. This momentum component is then assumed to gradually taper off, eventually leaving absolute convergence the sole driver of trend labour growth. In the long run, trend labour efficiency growth in all countries converges to an assumed exogenous rate of global technological progress (1% per annum). In simulation mode, the equilibrium level of labour efficiency is made to be a function of any assumed change to the particular institutional and policy environment of that country, represented by: a broad governance indicator (the World Bank's rule of law indicator); the stock of human capital (mean years of schooling in the population aged 15 and over) and its quality (average PISA scores); the extent to which product market regulation promotes competition (the OECD's PMR indicator); the stability of the macroeconomic environment (based on the level and volatility of inflation); average tariffs on imported goods; domestic and global R&D expenditure; and income inequality (the GINI coefficient). The impact of changes to these indicators on equilibrium trend labour efficiency are those estimated in Guillemette et al. (2017[28]). In both scenario and simulation modes, the speed of convergence is 2.4%, meaning that this proportion of the distance between the current level of trend labour efficiency and its equilibrium is eliminated each year.

- The evolution of trend employment is primarily the result of three sets of dynamics: the evolving size of the working-age population (defined here as ages 15 to 74); its age composition; and trends in the employment rates of different age/sex groups. The size and composition of the working age population follows the demographic assumptions of Eurostat (for most European countries) and those of the United Nations (for other countries) and are exogenous in the LTM. Trends in the employment rates of different age/sex groups are projected by applying a cohort approach to cyclically-adjusted historical employment rates. These generational trends reflect societal changes, such as rising female employment rates, but also structural changes such as higher educational attainment. Projected changes in potential employment arise from differences in the employment propensities of different cohorts combined with shifts in the demographic structure of the population. To take into account the impact of recent and future policy changes on trend employment rates, the approach also integrates OECD empirical estimates of the impacts of structural reforms (Égert and Gal (2017[25]); Gal and Theising (2015[24])). For the baseline scenario, already-legislated future changes in legal retirement ages are taken into account. Other labour market policy indicators are held constant. For more on the trend employment projection framework, see Cavalleri and Guillemette (2017[29]).
- The evolution of the productive capital stock depends on projections of public and private investment, excluding housing. Public investment as a share of GDP is assumed to gradually return to its 2015-2025 historical average, except in China where it is assumed to decline substantially given very high historical public investment ratios. Private investment as a share of GDP is a function of the economy's cyclical position, the real long-term interest rate (as the main determinant of the user cost of capital) and trend growth rates of labour efficiency and employment. The projection rules ensure that in steady state, the capital-to-output ratio is roughly stable, so that the growth contribution from changing capital intensity is modest, in line with a stylised fact from growth decompositions (Jones, 2015[30]).

3. Decomposition of per capita real GDP growth

5. A convenient expository decomposition (used in Table 1 in the main text) is to divide changes in GDP per capita, a crude metric for living standards, into productivity, capital intensity and labour utilisation components:

$$\Delta(y-p) = \alpha\Delta e + \{1-\alpha\}\Delta(k-n) + \Delta(n-pwa) + \Delta(pwa-p)$$

where *P* is total population, *PWA* is population of working age (15-74), and lower-case letters again denote logarithms. The first term on the right-hand side of this equation measures the contribution of labour efficiency growth to GDP per capita growth; the second term measures the contribution of capital intensity (capital per worker); the third picks up the contribution of the employment rate; and the last term indicates the contribution of the working-age population share, a summary indicator of the population age structure.

4. Exchange rate for currency conversion

6. When comparing levels across countries, GDP and GDP per capita are expressed in United States dollars (USD) at fixed 2015 Purchasing Power Parity (PPP) exchange rates.

5. Caveats regarding the interpretation of projections and scenarios

7. The scenarios generated with the LTM are highly stylised, conditional on a number of hypotheses and omit some important factors, such as potential economic damages from environmental degradation. They are meant to illustrate some of the forces that could shape the medium and long-term outlook for the world economy. As regards missing elements, the projections should be seen as incorporating the implicit assumption that they remain unchanged from their current states. Second, long-run scenarios are useful, but not always sufficient, to provide country-specific policy recommendations, which must take account of particular economic and policy contexts that cannot be fully incorporated into such a stylised exercise. Third, differences in economic outcomes between the baseline and alternative scenarios incorporating policy changes should not be interpreted as reflecting pure one-way causation from policies to outcomes. In reality, causation typically runs both ways, so the coefficients linking policies and outcomes incorporated in the LTM should be understood as attempts to add realism to the scenarios, in the sense of respecting estimated historical correlations. Fourth and finally, the long-run scenarios focus on GDP per capita as a measure of living standards and leave out many other dimensions of well-being. They can and should be considered in conjunction with other projection exercises – for the environment, income inequality, health, etc. – to get a full picture of the likely evolution of well-being.

Annex B. Accounting for the energy transition in the OECD global long-term model

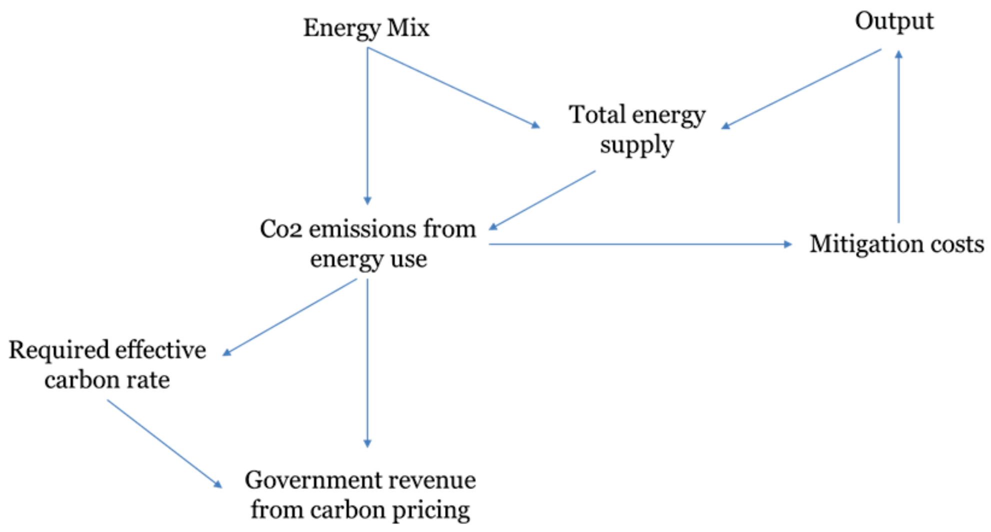
1. Introduction

1. This Annex describes recent extensions to the OECD long-term model (LTM) which add an energy transition dimension to the long-run scenarios produced with this model. The approach is aggregate, reduced form and inspired by the work of Alestra and al. (2020[31]). It has the benefit of generating results at the country level and in a consistent and transparent way for all countries. Assumptions on the future evolution of the primary energy mix are combined with simple equations that are partially estimated and partially calibrated to derive other variables of interest, including energy consumption, CO_2 emissions from energy use, mitigation costs and effective carbon rates required to follow the implied CO_2 emissions trajectories. This work is ongoing and further refinements and extensions are planned.

2. A reduced-form approach

2. In keeping with the aggregate nature of the LTM, and to keep things simple and tractable, the new energy-economy links rely on reduced-form relationships (Figure A B.1).

Figure A B.1. A sketch of the main energy-related additions to the LTM



Note: The arrows represent direction of causation in the framework.

2.1. Energy mix

3. The new energy block of the LTM starts from assumptions on the future evolution of the primary energy mix in different scenarios. These shares are set exogenously, as opposed to being endogenous to energy prices, for a few reasons. First, projecting energy prices is extremely challenging and even models with endogenous prices often do not report them, presumably because they do not appear plausible. Second, setting the mix exogenously makes it straightforward to assume trajectories that would result from non-price means, such as regulation, or direct interventions in energy supply decisions. It is becoming increasingly clear that price instruments are politically difficult to implement and may not be sufficient to effect the required changes (D'Arcangelo et al., 2023[17]). Third, it also makes it easier to account for geophysical constraints that make certain energy sources impractical or impossible to develop in some countries, which is particularly important given the country-level scale of the LTM. Fourth and finally, when governments make commitments or set targets (such as phasing out certain energy sources or reaching renewable energy goals), they usually do not make them conditional on future energy prices.

4. Assumptions on the energy mix being exogenous, any plausible trajectory can be implemented. This can be done manually on a country-by-country basis. However, given the number of countries, energy sources, scenarios and years to consider, it is useful to have a programmatic way of generating energy mix trajectories from a few summary parameters. Such an approach is described below for two scenarios:

- *Baseline*. A baseline scenario that could roughly be described as business as usual, i.e., the energy mix continues to be decarbonised at the rate recently observed. By assumption, this scenario involves no mitigation cost and provides the reference point to establish such costs in other scenarios.
- *Energy transition*. An energy transition scenario in which energy decarbonisation would accelerate from the current pace to reach a level broadly consistent with a global net zero GHG emissions target by 2050. There are many possible configurations of energy mixes across countries that would be consistent with a global net-zero target and even more when also considering the uncertain future evolution of energy efficiency, carbon capture and storage, the size of carbon sinks, etc. The idea here is to provide a plausible configuration that treats all countries in a similar manner in terms of the share of energy coming from carbon-based sources in 2050.

5. The scenarios are generated with a set of projection rules common across countries. The procedure can be broadly summarized by the following steps:

1. Using historical country-level data on primary energy from the IEA's World Energy Balances, total energy supply[12] is organized into eight categories, namely coal, oil, gas, nuclear, hydro, wind, solar and a residual category called 'other renewables' that includes renewable sources other than wind or solar (biofuels, geothermal energy, etc.). Shares of total energy supply attributable to each source are computed, leaving aside energy from non-renewable waste, heat and cross-border electricity trade owing to the difficulty of assigning it to one of the eight categories.[13] This yields a set of eight shares between zero and one, that add up to one, indicating the share of primary energy coming from source *i* in year *t* ($\Omega_{i,t}$).

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[12] Total energy supply (*TES*) is the IEA's nomenclature. It corresponds to total primary energy consumption in other nomenclatures. The precise definition is total energy supply = primary energy production + imports - exports - international marine bunkers - international aviation bunkers ± stock changes.

[13] The bias associated with this adjustment would generally be small, except for countries that rely a lot on imported electricity to meet their energy demand. Luxembourg and Lithuania are cases in point with more than 60% of final electricity consumption imported in 2021. Estonia, Hungary, Latvia and Finland all imported more than 20% of final consumption of electricity in 2021.

2. For the baseline scenario, the coal, oil and gas shares in the primary energy mix are projected through 2060 on the basis of their observed evolution over the 2009-2019 period:
    a. If they were on an uptrend between 2009 and 2019, they are assumed to remain stable in future.
    b. If they were on a downtrend over this period, which is usually the case, they are assumed to keep declining at the same average rate as that observed over the 2009-2019 period. The share of coal is allowed to decline to zero, but oil and gas shares are not allowed to decline below 5% and 10%, respectively, unless they were already lower at the start of the projection period, in which case they remain stable. These are the same floors used in the energy transition scenario (see below), on the reasonable assumption that even in an energy world dominated by renewables, there will likely remain some need for oil (e.g., for heavy transport) and gas (e.g., as a backup to renewable energy).

    Any void in the energy mix left by the decline of carbon-based energy shares is assumed to be filled by low-carbon energy, using the shares of new low-carbon energy described in step 4.
3. For the energy transition scenario, the coal share is assumed to go to zero by 2050 at the latest (and earlier if it is already the case in the base scenario given recent trends). That of oil is assumed to decline to 5% by 2050 at the latest (and earlier if it is already the case in the baseline scenario). And that of gas is assumed to decline to 10% by 2050 at the latest (and earlier if it is already the case in the base scenario). Again, the resulting void in the energy mix is assumed to be filled by low-carbon sources, according to the shares of new low-carbon energy described in step 4.
4. A set of shares is calculated, based on the same historical data as in step 1, measuring the relative importance of wind and solar energy in recent additions to low-carbon energy (which includes all renewables plus nuclear energy). These shares are assumed to evolve gradually so that solar and wind energy account for, respectively, 60% and 40% of new additions to low-carbon energy by 2060. The shares of nuclear, hydro and other low-carbon sources in new low-carbon energy are assumed to decline commensurately and proportionally to their relative importance in the energy mix at the start of the projection period. The underlying assumption is that prices of solar and wind-based energy will continue to decline in future relative to other low-carbon energy sources. Country specificities (which might make some low-carbon sources impractical) are partially taken into account by initialising the projections from historical data, but the approach could be refined (for instance by considering country-specific solar/wind potential).

6. Applying these rules to obtain projections of future energy mixes hopefully strikes a good balance between treating countries similarly, while also respecting the revealed preferences and geophysical constraints imbedded in current energy mixes. For instance, in a country with a substantial share of hydro power, the approach implies that some of the reduction in carbon-based energy is made up by new hydro power (but that the share of hydro in new low-carbon energy gradually declines in favour of wind and solar). At the same time, a country with no hydro power at the moment does not suddenly start to add hydro power, as its current absence likely implies that it is impractical or uneconomic.

7. Conditional on the exogenous energy mix shares just described, the new endogenous variables are projected using reduced-form relationships.

2.2. Energy consumption

8. Starting from historical country-level data from the IEA's World Energy Balances, total energy supply in terajoules (TJ) in year *t* (TES_t) is projected with the following equation:

$$\Delta\log\left(\frac{TES_t}{POP_t}\right) = \alpha + \epsilon_{ycap} \cdot \Delta\log\left(\frac{GDPVD_t}{POP_t}\right) + \beta_1 \cdot \Delta\Omega_{renew,t} + \beta_2 \cdot \Delta\Omega_{renew,t} \cdot \Omega_{renew,t-1} \quad [1]$$

where POP_t is population, $GDPVD_t$ is real GDP in USD at 2015 PPPs, $\Omega_{renew,t}$ is the share of total primary energy coming from renewable sources ($\Omega_{renew,t} = \Omega_{hydro,t} + \Omega_{solar,t} + \Omega_{wind,t} + \Omega_{orenew,t}$) and α is a constant which, given the functional form in first difference, acts as a time trend for the level of energy consumption per capita that is common to all countries. The equation is estimated over the period 1995 to 2021 using IEA data for 150 countries, for a total of nearly 3 900 observations. The estimation period could begin earlier but starting in 1995 provides plenty of observations and avoids relying on earlier times when energy systems may have been substantially different, with little renewables.

- The elasticity of energy consumption per capita to real GDP per capita is differentiated by income level. Coefficient estimates ($\hat{\epsilon}_{ycap}$) are 0.208 ($p < 0.01$) for low-income countries (defined as having real GDP per capita of less than USD 5 000 at 2015 PPPs), 0.417 ($p < 0.01$) for middle-income countries (between USD 5 000 and 35 000) and 0.231 ($p < 0.01$) for high-income countries (more than USD 35 000). That growth in middle-income countries is more energy intensive makes intuitive sense, as development at that stage tends to rely on infrastructure and other energy-intensive capital accumulation. Otherwise, income per capita growth is associated with only a mild increase in energy consumption per person, which also makes sense considering that labour efficiency growth is the main driver of per-capita income gains in the long run, and better labour efficiency does not necessarily require more energy.
- The share of renewables in total energy supply (a measure of the carbon intensity of overall energy supply) is included, not as a causal factor, but to ensure that improvements in the carbon intensity of energy are accompanied by gains in energy efficiency and that the two co-evolve according to their historical correlation. This is what would be expected if agents respond to a higher carbon tax by taking advantage of both margins of adjustment. $\hat{\beta}_1$ is estimated at -1.591 ($p < 0.01$), indicating that a one-percentage point increase in the share of primary energy coming from renewables is associated with a 1.6% improvement in primary energy consumption per capita. This is only true for a country starting with zero renewables, however. The coefficient on the interaction term between the change in the share of renewables and the previous period's share of renewables, $\hat{\beta}_2$, is estimated to be 1.419 ($p < 0.01$), implying that energy efficiency gains associated with a shift toward renewables gradually diminish as renewables take up a larger share of the energy mix. At 90% renewables, an additional one-percentage point increase is associated with only a 0.3% gain in primary energy use per capita.
- The estimated constant is close to zero and not statistically significant.

9. The reported coefficient estimates are highly robust to the inclusion of country and/or time fixed effects. The LTM implementation of [1] relies on (endogenous) real GDP and (exogenous) population projections already present in the model. A time trend (α) is included to make the model more flexible, but it is set to zero by default as per the above result. A zero-time trend implies that without progress in income per capita and/or a shift toward renewables, growth in energy consumption is proportional to population growth.

10. The equation omits an energy price index, for several reasons:

- Conceptually, to go along with primary energy concepts, primary energy prices should be used in the empirical analysis. It is not clear how to obtain such prices, however, given that low-carbon energy is not traded in its primary forms.
- Aggregate energy price indices from the IEA are only available for high-income countries, severely restricting country coverage and preventing the differentiation of the income effect by income level.
- The first two points notwithstanding, when restricting the country coverage and simplifying the equation to include in [1] the real aggregate energy price index for households and businesses from the IEA, its estimated coefficient is not statistically significant.
- As mentioned previously, the LTM extensions do not include nor rely on external projections of future energy prices. Substitution across energy sources is implicit in the exogenous energy mix

assumptions, and overall gains in energy efficiency are determined by [1] following historical correlations.

2.3. CO₂ emissions from energy use

2.3.1. Individual countries

11. Starting from historical country-level data from the Global Carbon Project (via Our World in Data), gross CO_2 emissions (i.e. gross of any carbon capture and storage) from energy use in year t ($CO2_t$), measured in tonnes, are projected by combining the projection of total energy supply (TES_t) from [1] with projected energy shares ($\Omega_{i,t}$), with each carbon-based primary energy type *i* having a specific emissions coefficient (e_i) expressed in tonnes of CO_2 per terajoule (TJ) of primary energy:

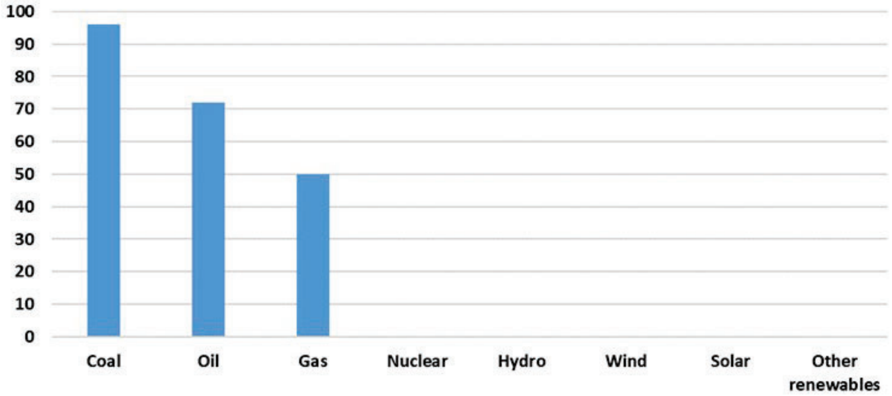
$$CO2_t = TES_t \cdot \sum_i e_i \Omega_{i,t} \quad [2]$$

In the LTM, the equation is implemented in log change to avoid any discontinuity at the jump-off point between historical data and projections.

12. Emissions coefficients are available from several sources, but they are estimated on the basis of [2] to ensure that they align well with the data sources used here. Emissions coefficients are assumed to be common across countries. The dataset spans 1965 to 2020 and 137 countries, for a total of 6 475 observations. The results are broadly consistent with those of other studies, in particular Alestra et al. (2020[31]) (Figure A B.2). In the LTM implementation, the emissions factors are held constant for the moment, but they could be allowed to decline somewhat over the projection period to reflect improving technology.

Figure A B.2. Emissions coefficients by primary energy type

Tonnes of CO_2 emitted per terajoule of primary energy



Note: The bars represent the estimated coefficients ($\hat{e}_i$) from [2].

13. The fraction of gross emissions that is captured and stored before entering the atmosphere (CCS_t) can either be set manually or, as in Krusell and Smith (2022[32]), be made a logistic function of time, calibrated so that it rises slowly at first, then more rapidly, and then more slowly again as it nears some assumed upper bound. In any case, the trajectory can be summarised in terms of the values of this fraction

in some intermediate year (like 2030) and the end of the transition period (2050). Then, CO_2 emissions from energy use, net of carbon capture and storage, are given by:

$$CO2\_NET_t = (1 - CCS_t) \cdot CO2_t \qquad [3]$$

The baseline calibration starts from a trivial share of global emissions being captured and stored in 2020 remaining below 1% throughout the projection period. In the energy transition scenario considered in the main text, carbon capture and storage is assumed to play only a marginal role, CCS_t rising to 1% by 2030 and 6% by 2050.

2.3.2. Aggregation to global level

14. Individual-country gross CO_2 emissions from energy use are aggregated at the world level (WLD_CO2_t) by summing across countries (indexed by ***c***):

$$WLD\_CO2_t = \sum_c CO2_{c,t} \qquad [4]$$

This calculation requires CO_2 emission projections for all countries, whereas the LTM covers only 48 countries. For the other countries, a simplified framework, coherent with the more detailed LTM framework, is being developed to project potential output and components. CO_2 emissions are then obtained in the same way as for OECD and non-OECD G20 countries by making assumptions about the evolution of the energy mix (as described in section 2.1) and applying [1] for total energy supply and [2] for CO_2 emissions from energy use. For the moment, emissions from non-energy sources (land use, process emissions, etc.) are ignored. Net CO_2 emissions (from [3]) are aggregated in the same way.

2.4. Mitigation costs

15. The extensions to the framework attempt to incorporate the plausible impact of reducing CO_2 emissions on the trajectory of output and, for the moment, leave out positive effects on output from avoiding environmental damage.

2.4.1. Obtaining mitigation costs from ENV-Linkages

16. Estimating a reduced-form equation for mitigation costs, defined as output losses associated with reducing CO_2 emissions from energy use, is not straightforward. A joint decarbonisation effort of the magnitude required over the coming decades has never occurred historically. The best available guides to the likely economic implications are presumably multi-sector models of the economy in which energy supply and demand are specified in detail and in which replacing brown with green capital in an accelerated fashion (usually in response to higher carbon pricing) impedes economic activity. These impediments can include frictional costs, such as labour reallocation, as well as structural ones, such as lower multifactor productivity due to substitution of green for brown capital in energy production. The approach taken here is to evaluate the trade-off (between emission reductions and output) that occur in such a model, namely the OECD's ENV-Linkages (Château, Dellink and Lanzi, 2014[16]), and summarise it into a reduced-form equation for use in the LTM.

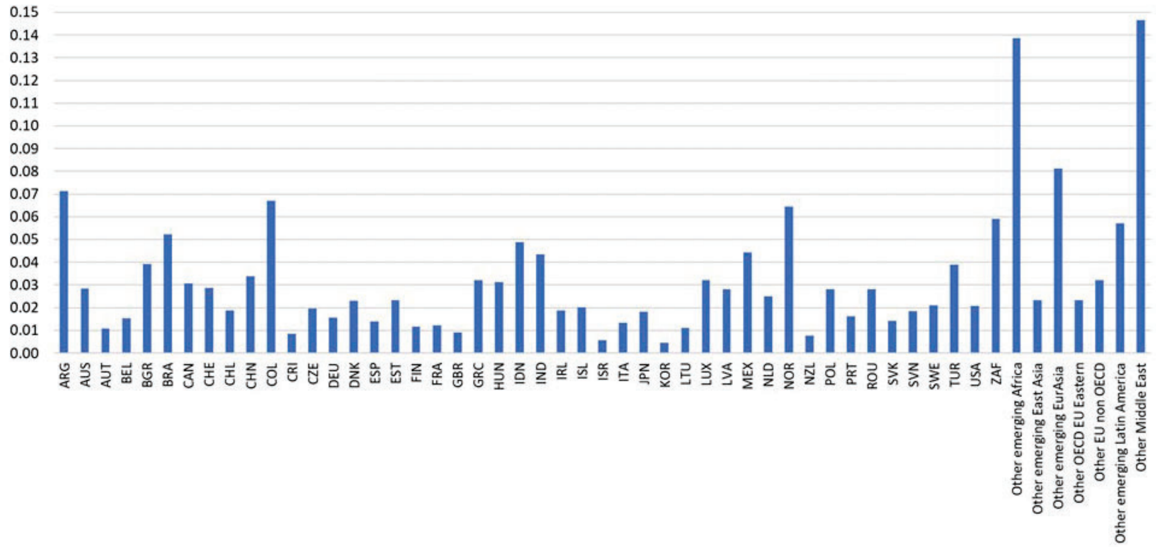
17. The first step in the analysis is to generate a set of scenarios with ENV-Linkages in which countries act simultaneously and rely on carbon taxation to reduce CO_2 emissions. Revenue collected from carbon taxes are assumed to be rebated to households as lump sums. The trade-off between output and mitigation is then estimated in the cross-scenario dimension. Output of a region/country in period t in scenario s ($GDPV_{t,s}$) is assumed to have the following functional form:

$$log\left(\frac{GDPV_{t,s}}{GDPV_{t,s=0}}\right) = m_t \cdot log\left(\frac{CO2_{t,s}}{CO2_{t,s=0}}\right) + \varepsilon_{t,s} \qquad [5]$$

where $s = 0$ indexes the reference scenario (in which there is little or no mitigation) and m_t measures the elasticity of output to carbon mitigation in period t. This equation is estimated separately for each region/country using time series data for 20 scenarios with carbon taxes ranging from zero to USD 400. As the set of scenarios s used in estimation rely on a specific policy instrument, here a carbon tax, the $\hat{m}_t$ estimates are specific to this policy instrument, as well as to other important assumptions made across the scenarios, such as the revenue rebating assumption. Elasticity estimates take into account the endogenous response of investment to carbon mitigation policies. In other words, they not only account for negative impacts of mitigation on output, but for any positive ones as well, so in this sense they are 'net' elasticities. Estimated elasticities range from less than 0.01 (e.g., Costa Rica, New Zealand) to 0.15 (emerging Africa and Middle East) (Figure A B.3).

Figure A B.3. Estimated elasticities of output to carbon mitigation in ENV-Linkages

% reduction in output (relative to baseline) associated with a 1% reduction in CO_2 emissions from energy use (relative to baseline) by 2060



Note: The figure reports $\hat{m}_{2060}$ from estimating [5] based on a set of simulations with the ENV-Linkages model. Mitigation is achieved using a carbon tax with all countries/regions in the model acting simultaneously. Because of unresolved issues with some individual countries, the coefficients for Estonia, Greece, Luxembourg and Sweden are replaced by coefficients estimated on regional aggregates.

18. Separate elasticities are obtained for each period of the underlying simulations. In principle, they might be expected to decline over time, thanks to technological improvements and network externalities associated with a green energy system, but this is not the case in the set of simulations used here. Like other similar computable general equilibrium (CGE) models, ENV-Linkages is not well suited to study technological progress.[14] The elasticities shown in Figure A B.3 are thus based on the last simulation period (the year 2060) as it features the widest range of outcomes for both CO_2 and GDP. Nevertheless,

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[14] Besides, technology is not the only determinant of mitigation costs, so even if technology is sure to progress, it does not necessarily follow that mitigation costs will decline over time.

for greater flexibility (or until ENV-Linkages can account for technological progress), the LTM allows mitigation costs to fall over time via an exogenous parameter specifying the assumed annual per cent change in mitigation costs ($coef\_dm$):

$$m_t = m_{t-1} \cdot \left(1 + \frac{coef\_dm}{100}\right) \qquad [6]$$

This decay rate for mitigation costs is assumed to be zero for the moment given a lack of empirical basis for specifying a value, but it allows alternative scenarios to be run and sensitivity analyses to be done.

2.4.2. Mitigation costs and the LTM's production function

19. At the core of the LTM is a Cobb-Douglas production function for each country with three components: trend employment, an economy-wide capital stock (excluding housing) and labour-augmenting trend labour efficiency. It is the same one used for potential output in the *OECD Economic Outlook*. Many models that consider the economic impact of the energy transition use a function with energy as an explicit factor of production. The LTM eschews this approach to keep methodological consistency with the *Economic Outlook* and avoid breaking the continuity between historical estimates and projections of trend output. Consequently, implementing mitigation costs in the LTM involves deciding how to apply the elasticities ($\widehat{m}_t$) estimated from [5] to the three components.

- Conceptually, the energy transition destroys jobs in emission-intensive sectors and creates jobs in green energy and other low-emission sectors. In the aggregate, however, trend employment is not expected to change much. Previous OECD work has found that the transition could have small or moderately negative, but also possibly positive, impacts on aggregate employment (Botta, 2019[33]; Chateau, Bibas and Lanzi, 2018[34]).
- A higher carbon price leads to sectoral reallocation as well as capital substitution. In conventional economic models with various sectors and types of capital (brown vs green), this leads to a reduction in overall allocative efficiency.[15] In an aggregate production function, the equivalent result is a decline in the productivity residual, here trend labour efficiency.
- The impact on the economy's capital stock is probably modestly negative. On the one hand, the scrapping rate increases, at least temporarily, because capital goods that are still functional (power plants, petrol cars, etc.) must be retired before their natural end-of-life. A higher scrapping rate implies a higher user cost of capital, weighing on investment. On the other hand, rapid decarbonisation necessitates substantial investment in new (greener) capital, offsetting to some extent the higher scrapping rate for old (brown) capital. A successful transition could conceivably lead to little change in the aggregate capital stock.

20. For these reasons, as well as simplicity, in the LTM carbon mitigation is assumed to directly impact potential output via the trend labour efficiency channel. Hence, the projection for trend labour efficiency growth in scenarios other than the reference one ($s = 0$) is given by:

$$\Delta\log\,(EFFLABS)_{t,s} = \Delta\log\,(EFFLABS)_{t,s=0} + m_t \cdot \Delta log\left(\frac{CO2\_NET_{t,s}}{CO2\_NET_{t,s=0}}\right) \qquad [7]$$

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[15] For instance, Fries (2023[42]) outlines a simple model with a final good produced with labour and an intermediate input, which is in turn produced using a low-carbon capital input and a fossil-based one. In this setup, when the low-carbon and fossil inputs are substitutes, introducing a carbon tax (or a low-carbon investment subsidy) pushes the ratio of low-carbon to clean capital away from the output-maximising one, reducing aggregate productivity and output. In a more fully-fledged DSGE model, Fried, Novan and Peterman (2022[43]) similarly find that a positive likelihood that the government adopts a climate policy causes investment to become relatively cleaner but output to fall.

Given that the LTM attempts to keep the capital-to-output ratio roughly stable over the long run, a decline in trend labour efficiency relative to baseline also implies some decline in capital accumulation, all else equal. Combining the direct impact on trend labour efficiency and the indirect impact on capital accumulation, the total long-run impact on potential output of a 1% reduction in net CO_2 emissions relative to baseline works out to m_t. Given the Cobb-Douglas functional form with a 0.67 labour income share, this means that two-thirds of the costs of CO_2 mitigation come through lower trend labour efficiency and one third through lower capital accumulation, approximately in line with ENV-Linkages. Despite the absence of CCS technology in ENV-Linkages, mitigation costs are made a function of net emissions in the LTM, implying that the cost of mitigation via CCS is the same as for other channels (improving energy efficiency or decarbonising the energy mix).

2.5. Green investment

21. Although the output-to-carbon mitigation elasticities obtained from ENV-Linkages and their implementation in the LTM account for the endogenous response of investment to mitigation policies, it is informative to calculate green investment needs endogenously within the LTM itself. These investment projections do not feedback into the capital stock (to avoid double counting), but they can nevertheless inform the fiscal part of the LTM given that some of the needed green investment will be financed publicly. One type of investment that can be calculated straightforwardly from the variables described previously is required investment in low-carbon electricity generation. This is just one type of investment needed to accompany the energy transition (others include investments in energy grids, energy efficiency, electric vehicles, etc.), but certainly a large part of the total.[16]

22. From projected total energy supply (explained in section 2.1) and the assumed energy mix, low-carbon electricity production of type *i* in year *t* ($LCELEC_{i,t}$) in gigawatt hours (GWh) is given by:

$$LCELEC_{i,t} = TES_t \cdot \Omega_{i,t} \cdot coef\_tj\_gwh \cdot therm\_eff_i \tag{8}$$

where TES_t is total energy supply in terajoules from equation [1], $\Omega_{i,t}$ is the share of low-carbon energy type *i* in the energy mix, $coef\_tj\_gwh$ is a coefficient to convert from terajoules (of primary energy) to gigawatt hours of electricity and $therm\_eff_i$ is an energy-specific thermal efficiency factor used in the calculation of primary-energy equivalents for non-combustible energy sources.[17] Nuclear is included among low-carbon energy types.

23. New low-carbon electricity generation capacity of type *i* in year *t* ($LCNEWCAP_{i,t}$) in gigawatt (GW) can then be computed as:

$$LCNEWCAP_{i,t} = \frac{\Delta LCELEC_{i,t} \cdot coef\_peak\_avg}{365 \cdot 24 \cdot capfactor_i} \tag{9}$$

where $capfactor_i$ is the average capacity factor of energy type *i*, which indicates how much new installed capacity (in GW) is needed for each GWh of electricity production. These factors are needed to account for the fact that some generation technologies have much more downtime than others (Table A B.1). A

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[16] Global investment on the transition away from fossil fuels reached USD 755 billion in 2021, about half of which was spent on renewable energy (BloombergNEF, 2022[38]).

[17] When calculating total energy supply, the IEA uses the physical energy content method to express electricity and heat produced from non-combustible sources into primary energy equivalent. Equation [8] performs the reverse operation by going from a primary-energy concept to an electricity concept. Based on the thermal efficiency factors used by the IEA when no country-specific information is available, the factors used here are 33% for nuclear energy, 100% for hydro and wind, 90% for solar (based on 100% for solar photovoltaic and 33% for solar thermal electricity) and 50% for other renewables. See IEA (2022[39]) for more information.

capacity factor of one would indicate that a power generation plant always provides its full installed capacity. For the moment, these capacity factors are assumed fixed in time and uniform across countries, but they could be allowed to vary in both dimensions (for instance wind and solar have different capacity factors depending on geographical location and they could improve over time with technological progress).

24. In [9], $coef\_peak\_avg$ is a coefficient that accounts for the fact that peak electricity consumption is higher than average. Given the use of the annual frequency in the LTM, ignoring this factor would imply that electricity demand was evenly spread throughout the year, which is not realistic. These country-specific factors are based on recent historical data for peak-to-average electricity consumption at the monthly frequency and generally range from 1.1 to 1.3. How electricity consumption and load management will evolve in the future in energy grids that are highly reliant on renewables remains highly uncertain. It could be that gas will play an important role in meeting peak electricity needs, or that batteries or other types of equipment will be able to store energy in off-peak hours and release it during peak times, obviating the need for extra low-carbon capacity. But it seems likely that low-carbon electricity sources will need to have higher capacity than the annual total would indicate. Using peak-to-average statistics at the monthly frequency is a conservative assumption given that peak-to-average fluctuations are even greater at the daily or hourly frequencies.

Table A B.1. Assumptions for new low-carbon electricity generation capacity

	Average capacity factor	Average cost of new capacity in 2022, USD billion per GW	Assumed differential with US GDP deflator (percentage points per annum)
Wind	0.37	1.5	-2.0
Solar	0.17	0.9	-3.5
Hydro	0.46	2.9	5.0
Nuclear	0.90	4.0	5.0
Other renewables	0.76	2.6	0.0

Note: Except for nuclear power, all capacity factors and cost estimates are based on global 2022 averages for new capacity reported by the International Renewable Energy Agency. Estimates for wind include offshore and onshore wind, weighted by new capacity. Estimates for solar include solar photovoltaic and concentrated solar power, weighted by new capacity. Other renewables include geothermal power and biofuels. For nuclear power, cost estimates are based on average overnight costs of new capacity reported by the International Energy Agency. Inflation differentials are assumptions for the projection period informed by trends in global average costs over the 2012-2022 period.
Source: Author's calculations based on IRENA (2023), *Renewable Power Generation Costs in 2022*, International Renewable Energy Agency, Abu Dhabi; and IEA/NEA (2020), *Projected Costs of Generating Electricity 2020 Edition*, OECD Publishing, Paris.

25. Low-carbon electricity capacity investment for energy source *i* at time *t* ($LCINV_{i,t}$) in billion local currency is then computed as:

$$LCINV_{i,t} = COST\_PER\_GW_{i,t} \cdot LCNEWCAP_{i,t} \qquad [10]$$

where $COST\_PER\_GW_{i,t}$ is the assumed cost per gigawatt (GW) of new capacity for energy source *i* in local currency. Initial cost estimates are based on global USD averages in 2022 (Table A B.1), which are converted to local currency using market exchange rates. These estimates could eventually be country specific when data allows (building new power plants is presumably cheaper in developing countries for instance given lower labour costs).

26. Costs per GW of new capacity can be projected in different ways. The approach chosen for the moment is to assume fixed differentials between inflation for the different technologies and the GDP deflator (Table A B.1). These differentials have recently been negative for new solar and wind capacity for instance, indicating falling relative prices. Another approach would be to rely on external models in which

prices are endogenous, making sure that the scenarios examined are coherent with those of the LTM. A third approach would be to use an experience curve, whereby the price of a technology is inversely related to its global speed of adoption. It has been estimated, for instance, that the price of solar panels declines by about 0.2% for each 1% increase in global installed capacity. Such an approach builds in a positive externality: higher investment by one country lowers the cost for other countries. The experience curve is likely to flatten out near a price floor, however, and where this floor might be is unknown. Many countries attempting to decarbonise their energy supply at once could also place upward pressure on the costs of new energy technologies if supply constraints emerge.

27. Total investment in low-carbon electricity generation capacity can be computed by summing across the technologies *i* listed in Table A B.1:

$$LCINV_t = \sum_i LCINV_{i,t} \qquad [11]$$

It can be useful to express this series as a percentage of GDP ($LCINVQ_t$):

$$LCINVQ_t = \frac{LCINV_t}{GDP_t} \cdot 100 \qquad [12]$$

where GDP is also expressed in billion local currency. These investment series provide a useful guide to investment needs in various scenarios but, as mentioned previously, investment in low-carbon electricity generation capacity leaves out many other types of investment that must accompany the energy transition.[18]

28. Both the private and public sectors will be involved in financing new green energy. From the equations just described, public investment in new renewable energy capacity could be added to the fiscal block of the LTM by making an assumption on the fraction of total investment to be financed publicly. Such an assumption could be based on the currently observed split between private and public finance of green energy projects, although it seems likely that the public sector will need to play an increasingly prominent role if ambitious emissions targets are to be achieved.

2.6. Government revenue from pricing carbon emissions from energy use

29. Another variable of interest in assessing the fiscal implications of different energy transition scenarios is government revenue associated with taxing carbon. The OECD’s Environmentally Related Tax Revenue database gathers information on government revenue from environmental taxes for OECD and many non-OECD economies. The database is arranged around different tax bases and environmental domains.[19] Focusing on the ‘energy products’ tax base and the ‘climate change’ domain yields a good proxy for government revenue from pricing carbon emissions from energy use. This stream of government revenue can be carved out of the general government primary revenue series (based on National Accounts) used in the LTM and projected separately.

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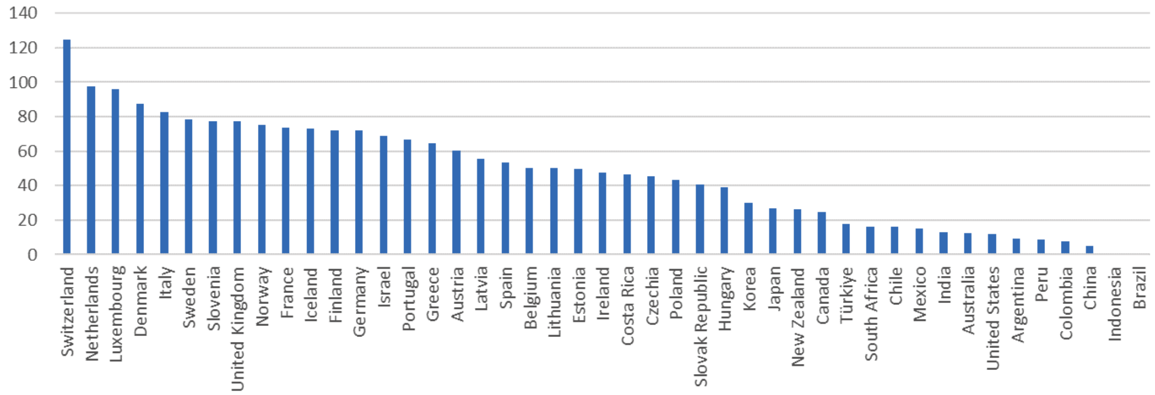
[18] For instance, the cost of decommissioning existing brown energy power plants, which is seldom pre-funded. Some of this investment could be added to the total by assigning average decommissioning costs (per GW of capacity) to each energy type and relating them to any projected (negative) changes in capacity, with an equation like [10] but this time applied to non-renewable energy types left out of Table A B.1 (but perhaps including nuclear). Another type of investment that is not covered is R&D in early technology, but projecting it is difficult, as it does not relate directly to energy consumption.

[19] See https://www.oecd.org/environment/tools-evaluation/PINE_Metadata_Definitions_2016.pdf for more information.

30. Doing so requires an indicator of the average revenue raised by government per tonne of CO_2 emitted from energy use. One approach would be to simply divide the government revenue series just described by CO_2 emissions. Another approach is to use the OECD's effective carbon rates (ECR) estimates. The ECR is the sum of tradeable emission permit prices, carbon taxes and fuel excise taxes, all of which result in a price on carbon emissions (OECD, 2023[21]). Accounting for fuel excise taxes is crucial as these still account for the bulk of estimated ECRs. Estimates are available for 45 OECD and G20 countries – almost the same coverage as the LTM (Figure A B.4). While this indicator is not strictly equivalent to government revenue per tonne of CO_2, as it is constructed differently, it exhibits a close correspondence and has the advantage of being well documented.

Figure A B.4. Effective average carbon rates, 2021

EUR per tonne of CO_2



Note: Effective average carbon rates are averaged across all energy-related CO_2 emissions, including those that are not covered by any carbon pricing instrument, and account for free allocation of allowances in emissions trading systems. See the source for additional details.
Source: OECD (2023), Effective Carbon Rates 2023: Pricing Greenhouse Gas Emissions through Taxes and Emissions Trading, *OECD Series on Carbon Pricing and Energy Taxation*, OECD Publishing, Paris, https://doi.org/10.1787/b84d5b36-en.

31. The annual change in government revenue from pricing carbon emissions from energy use in national currency ($YRCARB_t$) is conceptually equal to net CO_2 emissions (net of any carbon capture and storage) as projected in [3], multiplied by the effective carbon rate:

$$YRCARB_t = CO2\_NET_t \cdot ECR_t \tag{13}$$

where ECR_t is the effective carbon rate per tonne of CO_2 in current local currency (it is usually expressed in EUR in OECD reports). This reduced-form approach is an approximation – more accurate projections would require disaggregating final energy use into different fuels and applying the relevant taxes/levies. This approximation can nevertheless usefully enrich the fiscal block of the LTM by establishing a channel through which the energy transition affects a government's fiscal position. To avoid any discontinuity in the series at the jump-off point between historical data and projections, the equation is implemented in log change in the LTM.

32. A projection of ECR_t is needed to apply [13] in the LTM. This projection is based on empirical estimates by the OECD of the responsiveness of emissions to ECRs (D'Arcangelo et al., 2022[22]). In the baseline scenario, the ECR is assumed to remain constant in real terms. Then, for other scenarios (such as the energy transition one), the net CO_2 emissions trajectory given by [3] is compared to that of the base scenario, and the ECR that would be needed at time *t* in scenario *s* ($ECR_{t,s}$) to generate this level of mitigation is calculated as:

$$ECR_{t,s} = ECR_{t,s=0} + \frac{log\left({CO2\_NET_{t+10,s}}/{CO2\_NET_{t+10,s=0}}\right)}{coef\_co2\_ecr} \qquad [14]$$

where $s = 0$ refers to the baseline scenario and $coef\_co2\_ecr$ is the estimated semi-elasticity of CO_2 emissions to the ECR of D'Arcangelo et al. (2022[22]), namely -0.00369. This semi-elasticity is similar to those calculated implicitly from ENV-Linkages scenarios, although in ENV-Linkages they vary across countries given different industrial structures and other country characteristics.[20] This coefficient was not estimated in a dynamic model, so for LTM purposes, it is assumed that CO_2 emissions would adjust (to a change in the ECR) over a 10-year period, hence the 10-year lead in the comparison of CO_2 trajectories in [14]. The semi-elasticity of emissions to changes in ECRs is assumed to be constant in time. While this hypothesis could not be rejected in the empirical work of D'Arcangelo et al. (2022[22]), in reality the responsiveness of emissions to carbon pricing plausibly rises the longer the time horizon considered. To the extent that this is the case, then the LTM will overestimate the required increase in ECRs and associated government revenue in the energy transition scenario.

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[20] It is also very close to the point estimate of the semi-elasticity of GHG emissions to carbon taxes reported by Kanzig and Konradt (Känzig and Konradt, 2023[41]) (impulse response after four years using the control-based approach).