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Abstract

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JEL Classification: C51, C53, C54, C55, C68, F41, Q51, Q5

Keywords: climate change, Net-Zero Emissions, Green Infrastructure, Macroeconomics, DSGE, CGE, G-Cubed

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Background paper prepared for the October 2020 IMF World Economic Outlook. The views expressed in this paper are those of the author(s) and do not necessarily represent the views of the IMF, its Executive Board, or IMF management. This paper provides a detailed presentation of the simulation results from the October 2020 IMF World Economic Outlook chapter 3 and an additional scenario with carbon pricing only for comparison with the comprehensive policy package where green investments were also included. This paper has greatly benefited from continuous discussions with Oya Celasun and Benjamin Carton on the design of simulations; contributions from Philip Barrett for part of the simulations; and research support from Jaden Kim. We also received helpful comments from other IMF staff. All remaining errors are ours. McKibbin and Liu acknowledge financial support from the Australian Research Council Centre of Excellence in Population Ageing Research (CE170100005). A version of this paper appeared as IMF Working Paper 2021/195

Mitigating Climate Change:
Growth-Friendly Policies to Achieve Net Zero Emissions by 2050[1]

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I. INTRODUCTION

Global warming continues apace. The increase in the earth's average temperature since the industrial revolution is estimated at 1°C and is believed to be accelerating. Each successive decade since the 1980s has been warmer than the previous one, the past six years (2015–2020) were the warmest ever reported, and 2020 was the hottest year on record, tying 2016. Rising pressure on Earth systems is already evident from more frequent weather-related natural disasters.[2] Global sea levels are rising, and evidence is mounting that the world is closer to abrupt and irreversible changes—so-called tipping points—than previously thought (Lenton and others 2019).

The window to keep temperature increases to safe levels is rapidly closing. Scientists have warned that temperature increases relative to preindustrial levels need to be kept well below 2°C—and ideally 1.5°C—to avoid reaching climate tipping points and imposing severe stress on natural and socioeconomic systems (IPCC 2014, 2018a). The objective of limiting temperature increases by 2100 to 1.5–2°C was endorsed worldwide by policymakers in the 2015 Paris Agreement. Sizable and rapid reductions in GHG emissions are needed for this goal to be met; specifically, net GHG emissions need to decline to zero by mid-century (IPCC 2014, 2018a). Achieving this goal means that GHG emissions must be eliminated or that any remaining GHG emissions must be removed from the atmosphere by natural (for example, forests, oceans) or artificial (for example, carbon capture and storage) sinks. Even with such drastic reductions, temperatures may temporarily overshoot the target until the stock of accumulated GHG in the atmosphere is sufficiently reduced by absorption by carbon sinks.

Tangible policy responses to reduce greenhouse gas emissions have been grossly insufficient to date.[3] While the Covid-19 crisis has reduced emissions, it is already evident that this decline will only be temporary. Under unchanged policies, emissions will continue to rise relentlessly, and global temperatures could increase by an additional 2–5°C by the end of this century,

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[2] See also Chapter 2 of the April 2020 *Sub-Saharan Africa Regional Economic Outlook*, Chapter 3 of the October 2017 *World Economic Outlook*, and Kahn and others (2019).

[3] For most countries, the Nationally Determined Contributions pledged under the Paris Agreement are deemed insufficient to meet either the 1.5°C or the 2°C target, and, judging by current policies, unlikely to be met in the first place (see Climate Action Tracker Warming Projections Global Update—December 2019). Views about the shortfalls of stated polices have been echoed by others, such as the International Energy Agency, which points out that significantly more ambitious policies are needed to reach the targets (IEA 2019).

reaching levels not seen in millions of years, imposing growing physical and economic damage, and increasing the risk of catastrophic outcomes across the planet.[4]

A growing number of countries are announcing commitments to reach net-zero emissions by mid-century. To this day, 58 countries accounting for 53.3% of global GHG emissions have communicated a net-zero target, including some of the largest emitters (the European Union, Japan, Korea, China, and the US).[5] This paper focuses on reducing net carbon emissions to zero by 2050 in each country/region. It examines how mitigation policies can be designed in a growth- and employment-friendly way. It considers a comprehensive policy package, complementing carbon pricing with upfront green supply policies, specifically green public investment and subsidies to renewables production partly financed through debt financing. The initial green fiscal stimulus is key to supporting economic activity in the short run. As the economy embarks on its transition to a low-carbon path, it allows to offset the carbon tax's financial costs. In addition to the initial lift to aggregate demand, it boosts productivity in low-carbon sectors, increasing profitability and triggering more significant private investment in these sectors. This policy also creates more employment in low-carbon sectors, supporting the employment transition out of high-carbon sectors. Finally, reducing emissions through a range of alternative approaches reduces the needed level of the carbon price and, hence, associated transitional economic costs.

Such a policy aims to smooth the macroeconomic output costs in the short to medium term—the horizon most relevant to policymakers—and at easing the response to carbon taxation by putting in place key infrastructure and scaling up low-carbon sectors (thereby reducing adjustment costs). The comprehensive policy package is compared with a scenario that relies entirely on carbon pricing, highlighting the latter's less favorable output and employment outcomes. In the current economic recession related to the Covid-19 crisis, many have pointed out that the fiscal stimuli implemented in the recovery phase could be an opportunity. They

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[4] Absent climate change mitigation policies or massive migration, one-third of the global population could experience mean annual temperatures above 29°C by 2070. Such temperatures are currently found in only 0.8 percent of Earth's land surface, mostly in Africa, and are projected to cover 19 percent of land by 2070 (Xu and others 2020). The economic costs of rising climate risks are explored in Fernando et al (2021).

[5] Net-zero Target Status | Explore Net-Zero Targets | Climate Watch Data

can support the recovery from the economic crisis and put the global economy on a greener and more sustainable path by boosting green and resilient infrastructure investment.[6]

Simultaneously, the results highlight that carbon pricing is a critical element of a policy package to net-zero emissions. Green supply policies (of plausible magnitude) are in and of themselves unlikely to be sufficient to curb emissions to net-zero. While both green supply policies and carbon pricing increase the relative price of high- to low-carbon activities, one key channel through which carbon pricing is more effective at curbing emissions is raising the cost of energy and incentivizing energy efficiency.

Contrary to most of the literature, we assume that each country/region sets an independent carbon price designed to reduce emissions to net-zero by 2050, after considering the emissions reduction effect of the green fiscal stimulus. Having country-specific carbon prices is consistent with the lack of appetite for global coordination on carbon pricing. The only exception is a group of selected oil-exporting and other economies where policies only target to keep emissions at current levels; indeed, the economic activity in this group is already significantly affected by other regions' mitigation efforts.

Policy simulations are implemented using the G-Cubed global macroeconomic model (McKibbin and Wilcoxen 1999, 2013; Liu and others 2020). The model features ten countries/regions, detailed energy sectors, forward-looking agents, real and nominal rigidities, and fiscal and monetary policies. Because it has many short-term Keynesian features, it is well suited to examine the effects of mitigation policies on the macroeconomic dynamics in the short and medium term, in addition to looking at long-term effects. The model focuses on carbon emissions from fossil fuel consumption, which is the primary driver of human-made greenhouse gas emissions (IPCC 2014, 2018a). Other sources of greenhouse gas emissions beyond domestic fossil fuel CO2 emissions (forestry, agriculture, methane leaks, industrial process emissions, F-gases, international aviation/maritime emissions) are not covered.

Other policy options, such as the further development and adoption of negative emission technologies (e.g., carbon capture and storage), are assumed to contribute to reaching net-zero

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[6] For discussions on this, see Batini and others (2020), Black and Parry (2020), Hepburn and others (2020), and Bhattacharya and Rydge (2020).

emissions by offsetting some of the remaining emissions in 2050. However, they are not explicitly modeled in the paper.

The findings of the paper can be summarized as follows. First, an initial green investment push combined with initially moderate and gradually rising carbon prices can deliver the needed emission reductions at reasonable output effects. The policy package has a net positive impact on global output for the initial 15 years, raising output on average by about 0.7 percent of baseline global GDP each year. After 15 years, the drag from the carbon tax is more significant, resulting in small net output losses of about 1 percent of baseline GDP by 2050. The estimated transitional GDP costs in this paper are within the range of other studies (0.5–6.5 percent of GDP by 2050), albeit on the lower side of estimates. The lower costs reflect the support to economic activity from green infrastructure investment and higher substitutability between high- and low-carbon energy in G-Cubed than in engineering-based models (see Chapter 6 of IPCC 2014). These are moderate output losses in the context of the expected 120 percent cumulative global GDP growth over the next 30 years and the avoidance of severe damages from climate change in the second half of the century. Second, preannounced and gradually rising carbon prices are an essential policy to deliver the quick and substantial reductions in carbon emissions required to reach net-zero emissions by 2050. Most of the emissions reductions are driven by the carbon tax, reflecting its strong incentivizing of energy efficiency. Third, the economic costs of the low-carbon transition differ across the world. Countries with fast economic and population growth (such as India, and to a lesser extent China), those with heavy reliance on high-carbon energy (such as China), and most oil producers bear more significant transition costs. However, for fast-growing countries, these costs remain small given the projected growth of these economies over the next 30 years (even under mitigation). These costs also need to be weighed against substantial avoided damage from climate change and co-benefits from climate change mitigation, such as reduced local pollution and mortality rates. For fossil fuel producers, the required diversification of their economies will be difficult, but many of them also stand to benefit from global climate change mitigation.

Last but not least, limiting temperature increases to safe levels will require net-zero strategies by most countries. Neither the group of advanced economies nor the group of the five largest economies (US, EU, China, India, and Japan) mitigating alone would bring global emissions close to net-zero and keep temperature increases to safe levels. The need for global action is because emissions are expected to grow strongly in emerging markets and developing economies over the next three decades. A joint effort by all countries is thus critical to avoid the worst predicted outcomes of climate change.

The paper is organized into seven sections. Section II reviews the debate and relevant literature on achieving net-zero emissions. Section III presents the modeling approach and baseline projections. Section IV explains the design of the policy scenarios. Results are discussed in Section V for the complete participation scenario and Section VI for the partial participation scenario. Section VII concludes.

II. ACHIEVING NET-ZERO EMISSIONS BY 2050

At the time of writing this paper, there appear to be no published economic studies explicitly modeling worldwide net-zero emissions by mid-century. But many studies examine the economic impacts of various emissions transformation pathways. It is possible to implicitly link 1.5-2°C pathways to net-zero emissions around mid-century. Clarke et al. (2014) provide a comprehensive analysis of the economic impacts of achieving various goals through a uniform carbon price based on 31 models (primarily integrated assessment models) with almost 1,200 scenarios. The study organizes transformation pathways by cumulative CO2-eq concentration (ppm) in 2100 (430-480, 480-530, 530-580, 580-650, 650-720, 720-1000, and above 1000), where 430-480 ppm corresponds to an increase of 1.5-1.7°C in temperature relative to preindustrial levels, and 480-530 ppm to an increase of 1.7-2.1°C. Rogelj et al.(2018) indicate that all 1.5°C pathways see global carbon emissions embark on a steady decline to reach (near) net-zero levels around 2050, with 1.5°C-low-overshoot pathways achieving net-zero carbon emissions around 2045-2055 and 1.5°C-high-overshoot pathways around 2049-2059. Therefore, we can broadly interpret the available numerical results for achieving 430-480 and 480-530 ppm CO2-eq goals by 2100 as the impacts of net-zero emissions around mid-century.

Clarke et al. (2014) present several takeaways based on their multi-model analysis.

First, carbon prices tend to increase over time and with mitigation stringency and vary significantly across studies. Carbon prices in 2050 (in terms of 2010 USD per ton of CO2) required to reach 480-530 ppm range from about $40 to $800 across 60 studies (with the median slightly below $200). For achieving 430-480 ppm, carbon prices vary from about $75 to $950 among 34 studies (with the median slightly above $200).

Second, aggregate mitigation costs are positively related to carbon taxes and tend to increase over time and with mitigation stringency. Global GDP loss in 2050 (relative to the baseline) for reaching 480-530 ppm varies from about 0.5 to 6.5% across 44 studies (with the median of about 2.5%). For reaching 430-480 ppm, GDP losses vary from about 1.5-10% among 17 studies (with the median of about 3.5%). Global consumption losses in 2050 in reaching 480-530 ppm vary from about 0.5 to 5.5% across 40 studies (with the median of about 3%). For achieving 430-480 ppm, global consumption losses range from about 1.5 to 10% across 14 studies (with the median of about 3.5%). The large majority of studies report a factor of 1.5 to 3 times higher global consumption and GDP losses and 2 to 4 times higher abatement costs for scenarios reaching 430-530 ppm compared to the 530-650 ppm range.

Third, mitigation costs are heavily influenced by availability, cost, and performance of mitigation technologies, and the influence of technology on costs generally increases with mitigation stringency. Most models can produce scenarios leading to 550 ppm CO2-eq by 2100, even under limited technology assumptions. However, many models cannot solve for scenarios leading to 450 ppm CO2-eq by 2100 with limited technology portfolios, particularly when assumptions limit the use of bioenergy with carbon capture and storage.

Fourth, delaying near-term global mitigation can significantly affect aggregate mitigation costs. If near-term global mitigation is limited, the increase in mitigation costs is significantly and positively related to the gap in short-term mitigation with respect to no-delay scenarios. Costs are lower in the near term but increase more rapidly in the transition period following the delayed mitigation and higher in the longer term. Future mitigation costs are higher because delays in near-term mitigation not only require deeper reductions in the long run to compensate for higher emissions in the short term but also produce a larger lock-in in carbon infrastructure, increasing the challenge of accelerated emissions reduction rates.

Fifth, fragmented action can also increase global mitigation costs not only because of misallocation of mitigation across countries, but also through emissions leakage and trade-related spillover effects. The range and strength of the adverse effects depends on the type of policy intervention and the stringency of the mitigation effort. The smaller the proportion of global emissions included in a climate regime, the higher the costs and the more challenging it becomes to meet any long-term goal. In general, when some countries act earlier than others, the increased costs of fragmented action fall on early actors. However, aggregate economic costs can also increase for late entrants, even considering their lower near-term mitigation.

III. MODELING APPROACH AND BASELINE PROJECTIONS

A. The Modeling Approach

The model used for this project is the G-Cubed model (McKibbin and Wilcoxen 1999, 2013). A number of changes were implemented specifically for this project compared to the most recent published model in Liu et al (2020). The key changes to the model for this project are: (1) The database was significantly updated to include data from GTAP10 and the latest data from the IMF International Financial Statistics, the World Bank World Development Indicators, the OECD Economic Outlook, the United Nations World Population Prospects 2019, and the US Energy Information Administration; (2) The gas extraction and gas utilities sectors were merged into one gas sector; (3) A new sector for construction was added to the model; (4) A capacity for modeling government infrastructure investment following Calderon et al. (2015) was implemented. In particular green infrastructure projects were incorporated.

There are 10 regions and 20 sectors in the version of the model (version GGG20v154) used in this paper (Table 1).

Table 1: Regions in the G-Cubed Model

Region Code	Region Description
AUS	Australia
CHN	China
EUW	Europe
IND	India
JPN	Japan
OPC	Oil-Exporting Developing Countries
OEC	Rest of the OECD
ROW	Rest of the World
RUS	Russian Federation
USA	United States

The coverage of each region in the above table is presented below:

(a) Europe: Germany, France, Italy, Spain, Netherlands, Belgium, Bulgaria, Croatia, Czech Republic, Estonia, Cyprus, Lithuania, Latvia, Hungary, Malta, Poland, Romania, Slovenia, Slovakia, Luxemburg, Ireland, Greece, Austria, Portugal, Finland, United Kingdom, Norway, Sweden, Switzerland, Denmark

(b) Rest of the OECD: Canada, New Zealand, Iceland, Liechtenstein

(c) Oil-Exporting Developing Countries: Ecuador, Nigeria, Angola, Congo, Iran, Venezuela, Algeria, Libya, Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen

(d) Rest of the World: All countries not included in other groups.

The sectors in the model are set out in table 2.

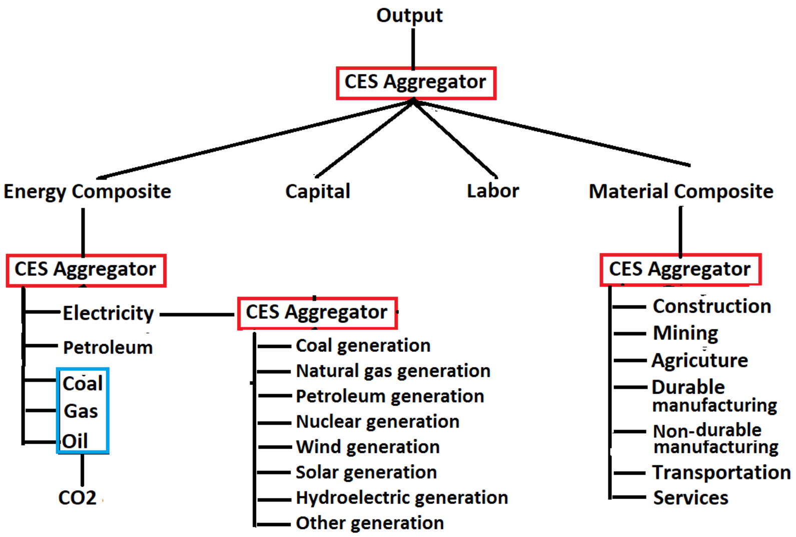
Table 2: Sectors in the G-Cubed Model

Number	Sector Name	Note
1	Electricity delivery	Energy Sectors Other than Generation
2	Gas extraction and utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Construction	Goods and Services
7	Other mining	
8	Agriculture and forestry	
9	Durable goods	
10	Nondurable goods	
11	Transportation	
12	Services	
13	Coal generation	Electricity Generation Sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

The G-Cubed sectors 1-12 are aggregated from the 65 sectors of GTAP 10. We then further disaggregate the electricity sector into the electricity delivery sector (sector 1) and 8 electricity generation sectors (sectors 13-20).

The structure of the core model is set out in McKibbin and Wilcoxen (2009, 2013). An illustration of the production structure is contained in Figure 1. CO2 emissions are measured through the burning of fossil fuels in energy generation.

Figure 1: Production Structure in the G-Cubed Model



Several key features of the standard G-Cubed model are worth highlighting here.

(1) The model completely accounts for stocks and flows of physical and financial assets. For example, budget deficits accumulate into government debt, and current account deficits accumulate into foreign debt. The model imposes an intertemporal budget constraint on all households, firms, government, and countries. Thus, a long-run stock equilibrium obtains through the adjustment of asset prices, such as the interest rate for government fiscal positions or real exchange rates for the balance of payments. However, the adjustment towards the long-run equilibrium of each economy can be slow, occurring over much of a century.

(2) Agents in G-Cubed must use money issued by central banks for all transactions. Thus, central banks in the model set short term nominal interest rates to target macroeconomic outcomes (such as inflation, unemployment, exchange rates, etc.) based on Henderson-McKibbin-Taylor monetary rules. These rules approximate actual monetary regimes in

each country or region in the model. These monetary rules tie down the long-run inflation rates in each country as well as allowing short term adjustment of policy to smooth fluctuations in the real economy.

(3) Nominal wages are sticky and adjust over time based on country-specific labor contracting assumptions. Firms hire labor in each sector up to the points that the marginal product of labor equals the real wage defined in terms of the output price level of that sector. Any excess labor enters the unemployed pool of workers. Unemployment or the presence of excess demand for labor causes the nominal wage to adjust to clear the labor market in the long run. In the short-run unemployment can arise due to structural supply shocks or changes in aggregate demand in the economy.

(4) Rigidities prevent the economy from moving quickly from one equilibrium to another. These rigidities include nominal stickiness caused by wage rigidities, lack of complete foresight in the formation of expectations, cost of adjustment in investment by firms with physical capital being sector-specific in the short run, monetary and fiscal authorities following particular monetary and fiscal rules. Short term adjustment to economic shocks can be very different from the long-run equilibrium outcomes. The focus on short-run rigidities is important for assessing the impact over the initial decades of demographic change.

(5) The model incorporates heterogeneous households and firms. Firms are modelled separately within each sector. There is a mixture of two types of consumers and two types of firms within each sector, within each country: one group bases their decisions on forward-looking expectations and the other group follows simpler rules of thumb which are optimal in the long run, but not necessarily in the short run.

(6) The fiscal rule in the model varies across model versions. In the version of the model in this paper we assumed an exogeneous budget deficit (we exogenously change budget deficits according to the revenue generated by carbon taxes or lost through various subsidies or changes in infrastructure spending) with lump sum taxes on households adjusted to ensure fiscal sustainability. In the long run the changes in interest servicing costs from any changes in revenue or expenditure that is exogenously imposed is offset through a lump sum taxed on households. Thus, the level of government debt can

permanently change in the long run with the change in debt to GDP equal to the ratio of the long run fiscal deficit to the long run real growth rate of the economy.

Several caveats apply to our study. First, we only examine the impact of reducing CO2 from fossil energy use. To the extent that a country has significant baseline shifts in land-use emissions, non-CO2 GHGs, and the like, the stringency of the target we estimate could be higher or lower than would apply in practice. Likewise, countries may have abatement costs for other sources that are importantly higher or lower than those for energy-related CO2. Second, we assume countries achieve net-zero emissions mainly with a stylized policy: a CO2 price that applies to all fossil fuels with the revenue either used to reduce the fiscal deficit or used to fund other policies in the combined policy package.[7] If countries adopt much less efficient policies or use carbon revenue differently, the macroeconomic outcomes would be different.

B. The Baseline Scenario

The baseline scenario does not assume that the Paris commitments are necessarily implemented as judging by current policies these are unlikely to be met in many countries (see Climate Action Tracker Warming Projections Global Update—December 2019). Instead the baseline relies on projections of population, projections of sectoral productivity growth rates by sector and by country, and projections of energy efficiency improvements based on historical experience. The key inputs into the baseline are the initial dynamics from 2018 to 2019 (the evolution of each economy from 2018 to 2019) and subsequent projections from 2019 onwards for sectoral productivity growth rates by sector and by country. We solve the model from 2019 adjusting various constants in the model so that the model solution for 2019 replicates the database for 2019 (the latest data we have). Sectoral output growth from 2019 onwards is driven by labor force growth and labor productivity growth.

For labor force, we use the working-age population projections from the UN Population Prospects 2019 to calculate the economy-wide labor growth rates for each region. For labor productivity, we use a catch-up model to generate labor productivity growth rates (defined in terms of labor-augmenting technological progress). We assume that the United States is the world frontier in productivity in each sector, where the productivity increases at a constant rate

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[7] The exception to this is in the carbon tax only scenario where we assume the tax revenue is lump sum rebated to households.

of 1.4 percent every year for all sectors (the average for US productivity growth) except renewable sectors which we assume grow more quickly at an additional rate of 5 percent (6.4 percent in total). For all other economies, the sectoral productivity projections follow the Barro approach estimating that the average catchup rate of individual countries to the worldwide productivity frontier is 2% per year. We use the Groningen Growth and Development database to estimate the initial productivity level in each sector of each region in the model, and then take the ratio of the initial productivity to the equivalent sector in the US. Given this initial gap, we use the Barro catchup model to generate long-term projections of the productivity growth rate of each sector within each country. Where we expect that regions will catch up more quickly to the frontier due to economic reforms or more slowly to the frontier due to institutional rigidities, we vary the catchup rate over time. The calibration of the catchup rate attempts to replicate recent growth experiences of each country and region in the model.

In addition, we assume that autonomous energy efficiency in every sector increases at a constant rate of 1 percent every year for all economies except China and India where we assume an additional rate of 2 percent (3 percent in total) assuming the two largest developing economies gain energy efficiency faster due to technological catchup.

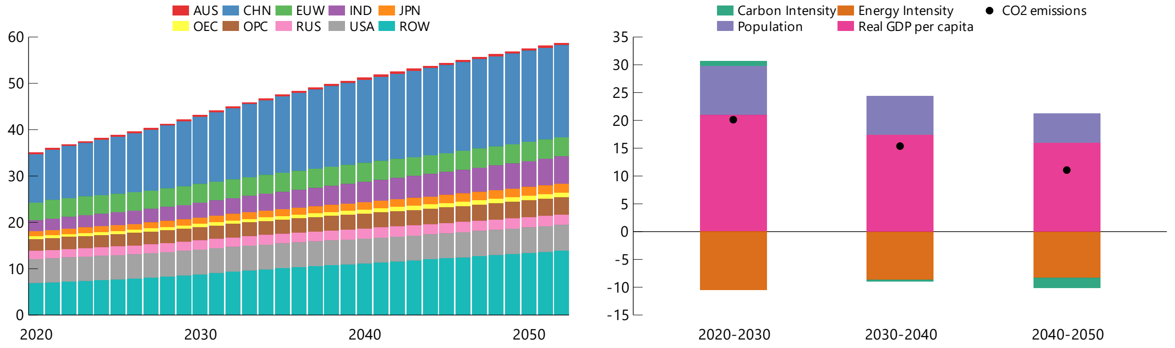
The baseline scenario abstracts from the 2020 pandemic-related fall in output and emissions, assuming that the subsequent rebound brings output and emissions levels in 2021 close to their 2019 level—the latest year for which the model has been calibrated. While this is a simplification, we expect it to be of minor significance for the results especially in the medium and long run. Black and Parry (2020), for example, finds that the required emission reductions for meeting temperature stabilization goals are essentially unchanged by the current economic crisis. But the Covid-19 crisis could lead to long-term behavioral changes that would raise or lower emissions—such as reduced use of public transportation and greater reliance on individual vehicles or greater use of digital communication, leading to reduced commuting and less travel. In line with this, the baseline assumes (somewhat above) trend increases in energy efficiency.

The baseline projects global carbon emissions to continue rising at an average annual pace of 1.7 percent and reach 57.5 gigatons by 2050 (Figure 2). Improvements in energy efficiency and some penetration of renewables—reflecting an implicit assumption of continuation of current policies and some autonomous increases (for example, reflecting consumer preferences)—cannot offset the forces of population and economic growth that are driving emissions. Projections of economic growth over the next 30 years determine the expected growth of future emissions, and therefore the scale of effort needed to keep temperature increases to 1.5–2°C. Global growth progressively declines from 3.7 percent in 2021 to 2.1 percent in 2050, reflecting a tapering off of growth in emerging market economies as they catch up toward the income levels of advanced economies. Whereas advanced economies have historically contributed the lion's share of emissions, China and India, as large and fast-growing emerging market economies, are significant emitters and are expected to continue toaccount for growing shares of carbon emissions. Their per capita emissions, however, still remain relatively small when compared with those of advanced economies.

Figure 2: Baseline CO2 Emissions, GDP, and Energy Structure

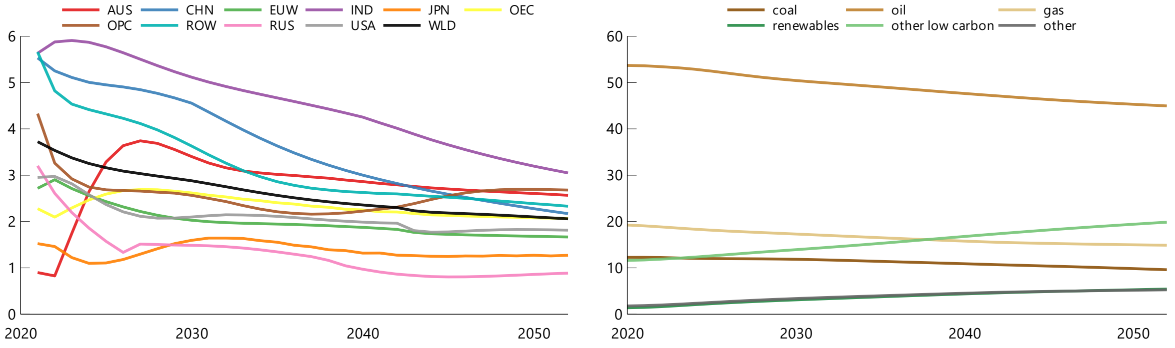
CO2 emissions *(gigatons of CO2)*

Decomposition of the change in global CO2 emissions
(contribution to CO2 emissions growth, percent)



GDP growth *(percent)*

Share of energy source in primary energy *(percent)*



Source: G-Cubed model simulations version GGG20v154

While projections are inherently uncertain, the baseline considered here is consistent with those from the IPCC (IPCC 2014, 2018a), most of which indicate that, under unchanged policies, carbon emissions will continue growing strongly, leading to temperature increases well above the safe levels agreed to in the Paris Agreement and raising the risk of catastrophic damage for the planet.

IV. NET-ZERO EMISSIONS SCENARIO DESIGN

A. Net-Zero Emissions in 2050

The goal of achieving net-zero carbon emissions by 2050 across the economy is operationalized as a reduction in gross emissions from energy use in 2050 by 80 percent, assuming that the expansion of natural emission sinks (such as forests) and some deployment of negative emission technologies (for example, carbon capture and storage technologies) will help absorb the remaining carbon emissions (IPCC 2018a,b).

In the G-Cubed model, there are fossil fuels and renewable sectors, but no carbon removal technologies. To achieve net-zero emissions by 2050 in reality, carbon removal technologies also play an important role. IPCC (2018) provides a review on carbon removal technologies, of which one main reference is Fuss (2018). We also draw on the estimates of carbon removal potentials from Fuss (2018), which are presented as follows:

Table 3: Global Carbon Removal Potentials in 2050 (Gt CO2)

Carbon removal technologies	Potentials
Afforestation and reforestation	0.5–3.6
BECCS	0.5–5
Biochar	0.5–2
Enhanced weathering	2–4
DACCS	0.5–5
Soil carbon sequestration	up to 5

We take the average of the range for each technology and sum them up (13.8Gt CO2). We make a conservative assumption that about 80% of 13.8 Gt can be achieved by mid-century, i.e., 11Gt CO2 per year. This is about 30% of global CO2 in 2018 or 20% of global baseline emissions in 2050. We assume that all regions in our model reduce their emissions by 80% by

2050 relative to 2018 as there would be little room for differentiation of mitigation efforts across countries to implement such deep reductions in emissions at the global level.[8] However, one exception is made for the grouping of selected oil-exporting and other economies (OPC), where we only require that emissions remain at the same level of 2018 by 2050, because economic activity shrinks substantially due to the fall in global oil demand.

B. Policy Tools

Broadly speaking governments can use a range of policies but we focus on two types of policies: carbon pricing and green supply policies. The first set of policies consists of raising the price of carbon through either carbon taxes or carbon emission trading programs to price the emission externality.[9] Carbon pricing reduces emissions both by raising the relative price of high-carbon energy relative to low-carbon energy, leading to a reallocation of investment and employment in that direction; and by increasing the overall energy price, which provides powerful incentives for energy efficiency. The second set of policies (green supply policies) directly aims at making low-carbon energy sources more abundant and cheaper and includes subsidies and price guarantees in the low-carbon energy sector; and direct public investment in low-carbon infrastructure and technologies. Green supply policies also reallocate economic activity from high- to low-carbon sectors by increasing the relative price of high- vs. low-carbon energy but they do not incentivize energy efficiency and can be accompanied by greater energy consumption, including of carbon-intensive sources (given the intermittency of renewable power).

The main scenario considers a comprehensive policy package designed with the goal of supporting the recovery from the Covid-19 crisis and facilitating the transition to a green economy—by lowering the policy's transitional output costs and ensuring the policy is as inclusive as possible. Specifically the policy includes (1) a green fiscal stimulus that boosts demand and supply in the economy, supporting the recovery from the Covid-19 crisis; (2) preannounced and gradually phased-in carbon price increases; and (3) compensatory transfers

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[8] The assumption that each country makes independent efforts to reduce its emissions (instead of relying on large-scale international burden sharing) is also in the spirit of the Paris Agreement which is based on countries' voluntary contributions.

[9] Regulations are also a way to implicitly raise the price of carbon. Under this category are also included the removal of fossil fuel subsidies (which can be replaced by targeted income support to the poorest households).

to households. For comparison, we also compare the results with a benchmark scenario using solely country-specific carbon pricing to achieve net zero emissions by 2050.

The layers of the comprehensive policy package and how they were implemented in the model are explained in greater detail below:

Green supply policies. These consist of an 80 percent subsidy rate on renewables (solar and wind) production and a 10-year green public investment program, starting at 1 percent of GDP and linearly declining to zero over 10 years; after that, additional public investment maintains the green capital stock created). Public investment is assumed to take place in the renewable and other low-carbon energy sectors, transport infrastructure, and services—the latter to capture the higher energy efficiency of buildings.[10]

We base our analysis on the results from Calderon, Moral-Benito and Serven (2015) who find that for every 10 percent increase in the aggregate stock of infrastructure capital, productivity in private sector output rises by 0.8%. We assume this new infrastructure once in place is sustained by spending by the government of 0.2% of GDP to offset depreciation. This locks in the productivity gains of the sectors that benefit from the green infrastructure. Rather than applying the improvement in productivity uniformly across all sectors in the economy, we assume that some sectors gain a productivity boost relative to others because of the strategic allocation of the infrastructure spending. We allocate the gains in productivity to these individual sectors. Once we assume which sectors receive the productivity boost, we scale the size of the productivity boost to those sectors in such a way that the aggregate productivity gains for the economy as a whole correspond to the results of Calderon et al. (2015). For example, suppose the infrastructure is focused mainly on the renewable energy sectors, then the productivity gains would be scaled up in these sectors so that when the shocks are weighted by the share of each sector in the economy, the aggregate productivity shocks match Calderon et al. (2015). This implies that a small sector will have a very large productivity gain if all infrastructure is allocated to that sector. Because of capital adjustment costs, which are sector specific in the model, the economy-wide output gains will be lower than if the productivity

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[10] IEA (2020a) discusses green investment opportunities in the energy and transportation sectors and in energy efficiency (for example, retrofitting of buildings). See also McCollum and others (2018) for an estimate of energy investment needs for fulfilling the Paris Agreement and achieving the United Nations Sustainable Development Goals.

was allocated across all sectors because rapid productivity growth increases the cost of private capital accumulation in the sector growing quickly.

Table 4 contains the share of total productivity gains allocated to each sector within each country. The numbers chosen are arbitrary and represent a potential scenario. They are meant to be indicative of potential policy responses in each country. There is a need for a much more detailed analysis of particular policies and the sectoral focus of infrastructure programs that could be used to calculate these types of shocks.

Table 4: Share of Total Productivity Gains from Public Investment Allocated to Each Sector

Sector	AUS	CHN	EUW	IND	JPN	OPC	OEC	ROW	RUS	USA
Transportation	0	0	0	0	0	0	0	0	0.2	0
Services	0.2	0	0.6	0	0.4	0.2	0.99	0.2	0.6	0.78
Coal generation	0.4	0	0.05	0	0	0	0	0	0	0
Gas generation	0	0	0	0	0	0	0	0	0	0
Oil generation	0	0	0	0	0	0	0	0	0	0
Nuclear generation	0	0	0	0	0	0	0	0	0.2	0.02
Wind generation	0.1	0.5	0.1	0.7	0.3	0.4	0.004	0.4	0	0.1
Solar generation	0.1	0.5	0.1	0.2	0.3	0.1	0.004	0.05	0	0.05
Hydro generation	0	0	0	0	0	0	0	0	0	0
Other generation	0.2	0	0.15	0.1	0	0.3	0.002	0.35	0	0.05
Total	1	1	1	1	1	1	1	1	1	1

Carbon pricing. Carbon prices are calibrated to achieve the 80 percent reduction in emissions by 2050, after accounting for emission reductions from the green fiscal stimulus and the other policies in the package. The fact that part of the emissions reductions are achieved by green public investment reduces the required level of carbon taxes to achieve the net zero emissions target. In addition, to reflect political feasibility constraints, a high annual growth rate of carbon prices (7 percent) is assumed to ensure low initial levels of the carbon price and a gradual phase-in of carbon prices.[11] The needed carbon prices start at between \$6 and \$20 a ton of CO2 (depending on the country), reach between \$10 and \$40 a ton of CO2 in 2030, and are between \$40 and \$150 a ton of CO2 in 2050.[12] In the scenario with only carbon taxes discussed below we assume the same growth rate of taxes but solve for the initial tax required to hit the 2050 targets without any additional policies.

Compensatory transfers. About 1/4 of the carbon tax revenues are recycled as cash transfers to households, in order to help protect their purchasing power from the increase in energy prices.[13]

Supportive macroeconomic policies. The policy package outlined above implies a fiscal easing that requires debt financing for the first decade.

C. Cost-Benefit Analysis

In order to reflect not only the costs but also the benefits of climate mitigation policies, the results incorporate two additional layers of analysis, namely the avoided damages from climate change and the co-benefits from climate mitigation policies.

Avoided damages from climate change. The long-term dynamics of temperatures and estimates of the avoided damages from climate change are simulated using an extension of the integrated assessment model of Hassler and others (2020) (see Barrett 2021) matched to the G-Cubed model.[14] These simulations are based on a medium climate sensitivity and the Nordhaus (2010) climate damage function. The economy-wide productivity improvements driven by avoided damages due to all the policies in the package are then imposed equally on all sectors except electricity generation in G-Cubed.

Co-benefits from climate mitigation policies. These are reductions in mortality risks and improved health from less air pollution (thanks to lower use of coal and natural gas) and

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[11] Gollier (2018a, b) finds that, contrary to the Hotelling rule (according to which greatest efficiency is achieved when the carbon tax grows at a rate equal to the interest rate), most scenarios from the Intergovernmental Panel on Climate Change (IPCC) involve a rate of growth in the carbon tax higher than the interest rate, to reflect political constraints on the initial level of carbon taxes.

[12] The range of estimates of carbon prices needed to reach a certain level of emission reduction is large (see, for instance, IPCC 2014, Figure 6.21.a, or Stiglitz and others 2014). The relatively low levels of carbon prices in our simulations reflect (1) the combination of carbon prices with other instruments (green infrastructure investment and green subsidies), which achieve part of the emission reduction; (2) the high assumed growth rate of carbon prices, which back-loads their increases; and (3) the fact that the G-Cubed model embeds more substitutability between high- and low-carbon energy (based on econometric evidence) than engineering-based models.

[13] Calculations for China and the US in IMF (2020) suggest that 1/6 to 1/4 of carbon tax revenues would allow fully protecting the purchasing power of the 20 percent poorest households.

[14] The real price of carbon is assumed to continue growing until 2080.

reduced road congestion, traffic accident risk, and road damage (associated with taxation of gasoline and road diesel). While the value of saving lives goes well beyond economic gains and quantifying the economic value of human life and health is difficult, existing valuations indicate that many countries would experience substantial economic gains from co-benefits. We apply results from Parry, Veung, and Heine (2015) who estimate a price on CO2 that would internalize domestic non-climate-related external costs associated with fossil fuels around the world. The nationally efficient CO2 price level is, on average, \$57.5 a ton (in 2010)—and ranges between \$11 and \$85 for the countries/regions in the G-Cubed model. These reflect primarily health co-benefits from reduced air pollution at coal plants and, in some cases, reductions in automobile externalities. The co-benefits differ across countries per unit of abatement and are largest for Russia and China.[15]

V. RESULTS OF FULL PARTICIPATION SCENARIOS

The goal of the simulations presented in the paper is to illustrate the main mechanisms at work and provide some order of magnitude of outcomes. The exact magnitudes in these long-term projections are unavoidably subject to substantial uncertainty. We discuss first global results and then cross-country differences.

A. Global Results

Emission reductions. Under the policy package, global carbon emissions are reduced by about 30% from the current level, at about 25 gigatons by 2030, and by about 75 percent reaching about 10 gigatons by mid-century (Figure 3).[16] This brings net emissions to zero around mid-century. While the green fiscal stimulus—especially the green public investment layer—helps reduce emissions meaningfully, its effect is much smaller than that of carbon pricing, at about 25% of carbon-tax reduced emissions. Both policies contribute to reduce the carbon intensity of energy, but in addition, carbon pricing is especially effective at increasing energy efficiency, delivering rapid and substantial emission reductions as carbon prices are ramped up. The energy mix shifts to low-carbon sectors, the share of which ramps up significantly to over 50 percent by 2030 and 80 percent by 2050. Coal disappears from the energy mix, and the shares of natural gas and oil decline significantly to 5 and 22 percent, respectively.

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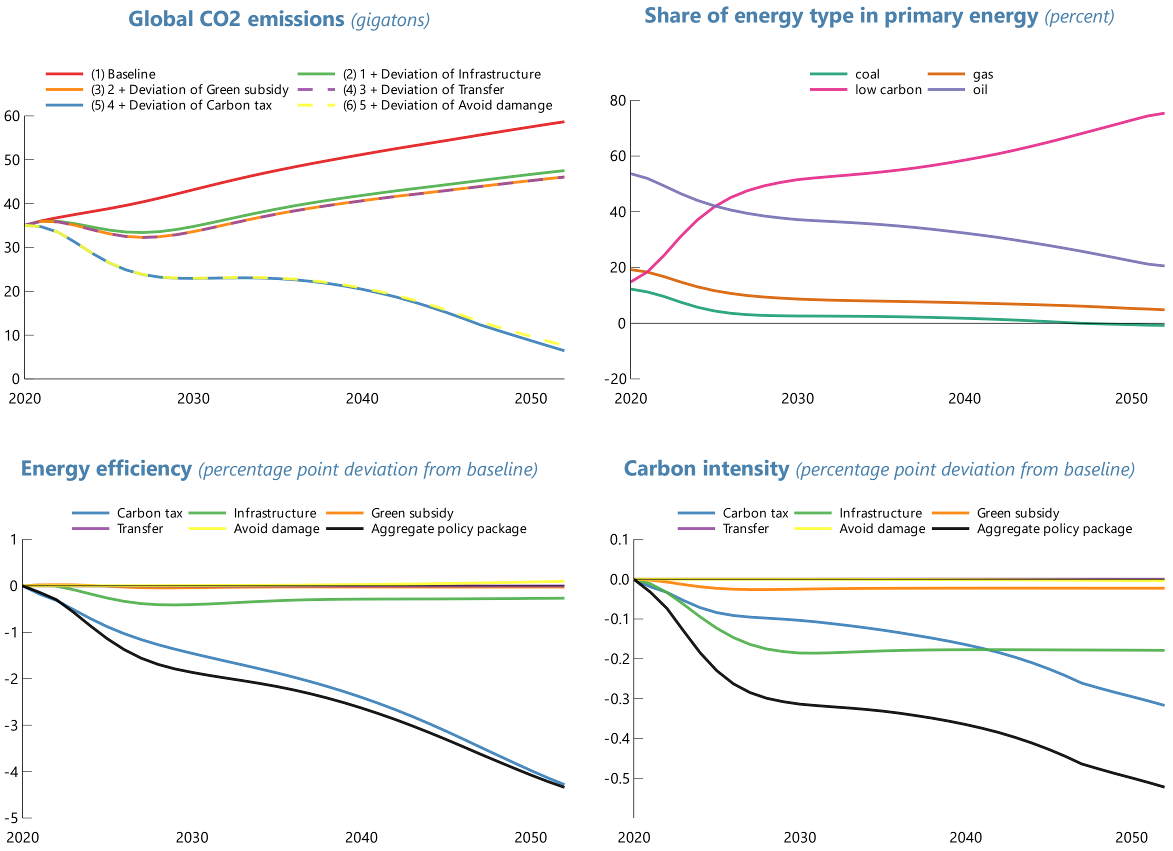
[15] See Karlsson, Alfredsson, and Westling (2020) for a review of available monetary estimates of air quality co-benefits.

[16] The reduction in global emissions is less than 80%, because OPC keeps emissions at current levels.

Figure 3: Global CO2 Emissions


Global CO2 emissions *(gigatons)*

Share of energy type in primary energy *(percent)*

Energy efficiency *(percentage point deviation from baseline)*

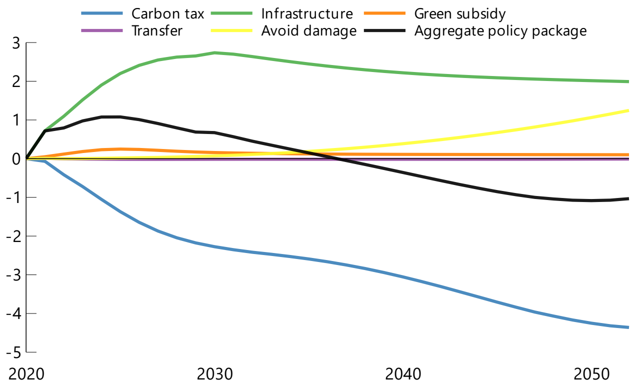
Carbon intensity *(percentage point deviation from baseline)*

Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

Economic costs. Whereas carbon pricing lowers real GDP by increasing the cost of energy, the green fiscal stimulus boosts it, both directly and indirectly (Figure 4). The green fiscal stimulus—in particular the green infrastructure layer—directly adds to GDP through higher investment spending: it initially boosts economic activity by increasing aggregate demand; over time the green infrastructure investment boosts the productivity of the low-carbon sectors, incentivizing more private investment in these sectors and increasing the potential output of the economy. It also contributes to indirectly reducing the output costs of the transition to a low-carbon economy by lowering carbon emissions and hence the level of carbon taxes needed to meet the emission reduction targets. The effects of the green fiscal stimulus are large enough to comfortably offset the economic cost of the carbon tax in the initial years, delivering an average net output gain. Thereafter, the drag from the carbon tax becomes larger as carbon prices are raised further, resulting in small net output losses.

Figure 4: Global Real GDP

(percent deviation from baseline)



Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

In addition to the economic costs and benefits from the mitigation measures themselves, the GDP gains from avoided climate damages that result from the mitigation effort need to be taken into account. These are simulated using Barrett's (2021) integrated assessment model and Nordhaus (2014) damage function. The GDP gains from avoided climate damages are still relatively small over most of the simulation horizon but they start picking up in the 2040s, reaching about 1 percent of baseline GDP.

Overall, the policy package delivers an average net output gain of 0.7 percent of baseline GDP over the first 15 years, resulting mostly from the green fiscal stimulus. Thereafter, the larger drag from the carbon tax results in small net output losses of about 0.7 percent on average between 2036-2050 and 1 percent by 2050 relative to baseline. It should be noted that even transitional output costs of 1 percent of GDP are moderate compared with an expected cumulative increase in real GDP of 120 percent over the same period in the baseline.

The climate mitigation package also generates substantial co-benefits (especially better health outcomes and lower health costs)—on the order of 0.07 percent of global GDP immediately, 0.88 percent by 2035 and 1.24 percent by 2050. Combining real GDP effects and co-benefits yields net benefits throughout the transition and makes the policy package neutral for global output by 2050.

The estimated transitional GDP costs (1 percent of baseline GDP by 2050 and 0 when taking into account co-benefits) are within the range of other studies (0.5-6.5 percent of GDP by 2050), albeit on the lower side of estimates—reflecting the support to activity from green infrastructure investment and higher substitutability between high- and low-carbon energy in G-Cubed than in engineering-based models (see Chapter 6 of IPCC 2014). However, our scenario differs from the literature by showing that a climate mitigation policy package can be growth-friendly in the short term—the horizon that policymakers worry about—by combining the introduction of a carbon tax with a substantial green infrastructure stimulus.

Private investment. The policy package leads to a reallocation of investment from high-carbon sectors (e.g., fossil fuel energy, manufacturing) to low-carbon sectors (e.g., renewables, other low-carbon energy, and services) (Figure 5). The reallocation is accompanied by a sharp global contraction of private investment though because the carbon tax acts as a negative wealth shock for forward-looking agents and reduces the long-term desired capital stock. The expanding low-carbon sectors are also less capital intensive than the contracting sectors, further reducing demand for capital investment. Finally, the renewable energy sector is smaller than the fossil fuel sector and takes time to expand due to capital adjustment costs, although green infrastructure investment and subsidies help incentivize private investment in renewables and other low-carbon energy sectors. Decomposing the effects of the policy package on private investment shows that the green infrastructure investment and subsidies indeed play a key role in boosting private investment in low-carbon sectors, while the carbon tax effect is relatively small. In contrast, the carbon tax is more effective at reducing private investment in high-carbon sectors, with a smaller role from the green supply policies.

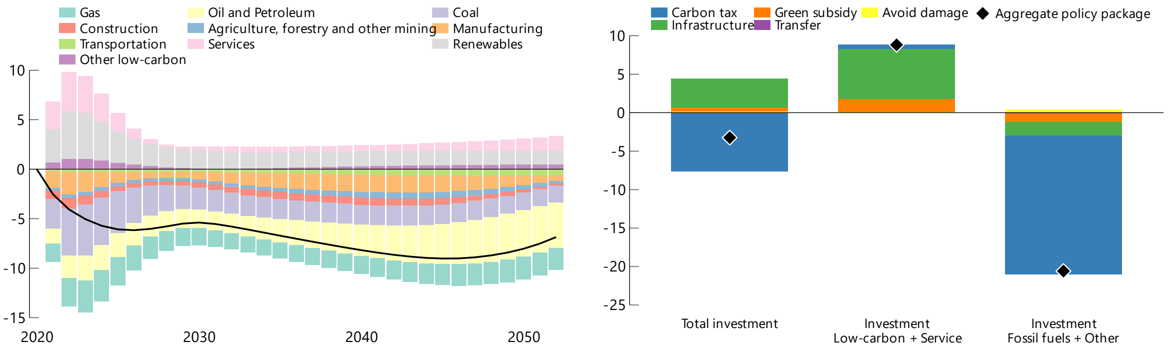
Figure 5: Global Private Investment by Sector

Global private investment by sector

(contribution to deviation of total private investment from baseline, percent)

Annual global private investment, 2020-2030

(percent deviation from baseline)

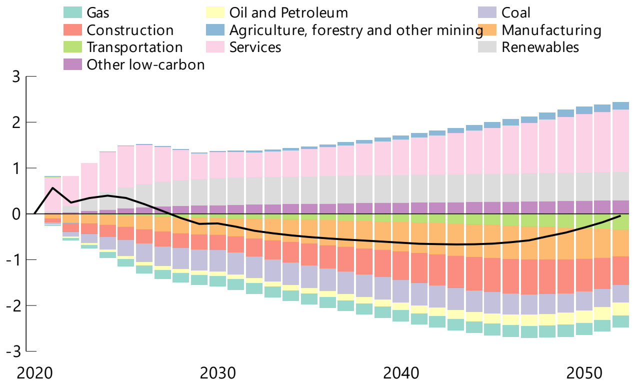


Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

Employment. The effects of the climate change mitigation policy package on global employment are similar to the effects on output (Figure 6). Employment is boosted initially reflecting both the boost to output and the fact that expanding low-carbon sectors, such as renewable energy, retrofitting of buildings[17], electric car production, and the services sector, are typically more labor intensive than the shrinking high-carbon sectors (such as fossil fuel energy, transportation, heavy manufacturing). Global employment would be higher by a total of 12 million people on average each year between 2021 and 2027, followed by a small decline relative to the baseline employment path during the transition until the economy reaches a higher output and growth path. Despite the small decline relative to the baseline, employment keeps growing strongly throughout the period. However, the policy package scenario entails a substantial reallocation of about 2 percent of jobs from high- to low-carbon sectors, which could cause difficult transitions for some workers and require reskilling and government support. In the long run, the global economy will return to full employment by assumption through the adjustment of real wages but the distribution of employment across sectors is permanently changed by the policy package.

Figure 6: Global Employment by Sector

(contribution to deviation of total employment from baseline, percent)



Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

Private consumption. Global consumption increases by about 2.5% relative to the baseline over the first ten years, and then slowly declines to the baseline level by 2050 (Figure 7). Most

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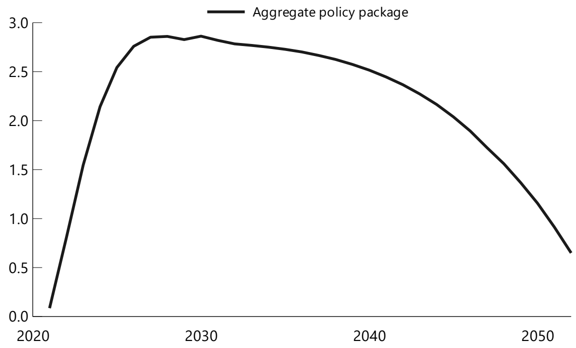
[17] Note that the construction sector is based on the definition in the GTAP database where construction is defined as "building houses factories offices and roads". It does not include maintaining and retrofitting of buildings.

regions gain higher consumption while fossil fuel exporters experience consumption losses due to fossil fuel export revenue declines. The positive impacts in the non-fossil-exporters dominate the negative impacts in the fossil exporters, leaving positive global consumption impacts. In the non-fossil-exporters, both types of consumers (forward-looking and backward-looking) increase their consumption above the baseline. Forward-looking consumers (who base their decisions on lifetime total wealth) increase consumption because the real interest rates decline below the baseline level in the long run (although higher than the baseline level in the first ten years due to public spending), and thus increase human wealth (the present value of lifetime after-tax labor income) and total wealth. Backward-looking consumers (who base their decisions on current-period after-tax income) increase consumption in the first ten years because real wages increase (due to productivity gains from public investment), the firm dividends increase, government transfers increase (from carbon tax revenues), and thus after-tax incomes increase. Their consumption starts to decrease after ten years because the productivity driven by public investment stops increasing and hence the real wage stops increasing.

Figure 7: Global Private Consumption

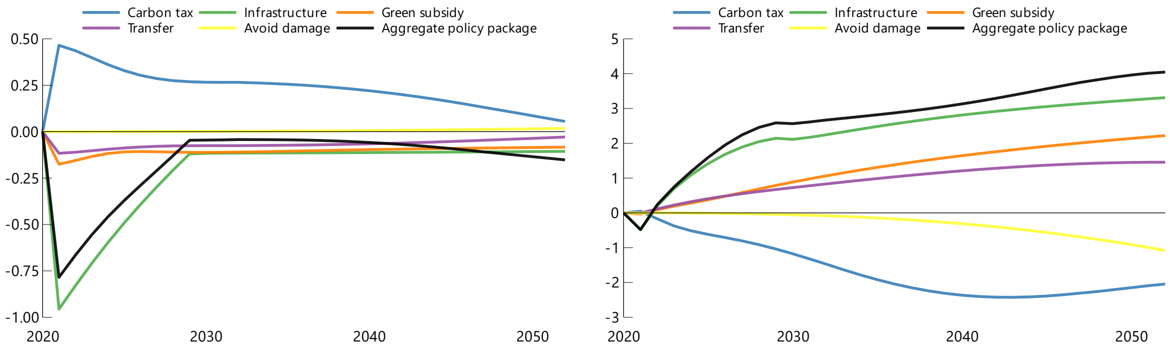
(percent deviation from baseline)



Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

Fiscal costs. The policy package initially worsens the fiscal balance and requires debt financing, given that the carbon revenues are smaller than the initial spending on infrastructure, subsidies, and compensatory transfers to households. Thereafter, carbon tax revenues are broadly sufficient to finance the additional green infrastructure and transfers to poor households (Figure 8). The debt-to-GDP ratio increases by about 3 percentage points over the first decade, and an additional 1 percentage point until 2050. This is a relatively small increase in the debt ratio over 30 years and one that is likely to more than pay for itself in the second half of the century, considering that climate damages under unchanged policies are projected to increase substantially. Using the Barrett's (2021) integrated assessment model, IMF (2020) shows that the projected net output gains from the policy package considered increase rapidly after 2050, ranging between 4.7 percent of global GDP with the Nordhaus damage function and 13.2 percent of global GDP with a more severe damage function from Burke Hsiang Miguel (2015) by 2100.[18]

Figure 8: Global Fiscal Impact



Ratio of the global fiscal balance to real GDP *(percentage point deviation from baseline)*

Debt to real GDP *(percentage point deviation from baseline)*

Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

To sum up, a comprehensive policy package combining preannounced and gradually phased-in carbon pricing with an initial green fiscal stimulus helps reduce the transitional output costs of climate mitigation, even boosting output over more than a decade. The green fiscal easing is key to boost growth and employment when carbon taxes are first introduced and facilitates the ramping up of private investment in low-carbon sectors. At the same time carbon taxes are essential to generate the needed rapid and substantial declines in emissions, in particular through discouraging investment in fossil fuel sectors and incentivizing energy efficiency. These results provide interesting insights for the recovery from the Covid-19 crisis, suggesting that fiscal packages can both support the economy in its recovery from the crisis while putting the economy on a greener, more sustainable growth path. From a macroeconomic and public finance perspective, the next decade is the best time for governments to invest and borrow

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[18] These estimates are likely to understate benefits from mitigating climate change as they imperfectly take account of—or do not incorporate—some of the damages related to temperature increases, such as a higher frequency and severity of natural disasters, a rise in sea levels, and the risk of more catastrophic climate change.

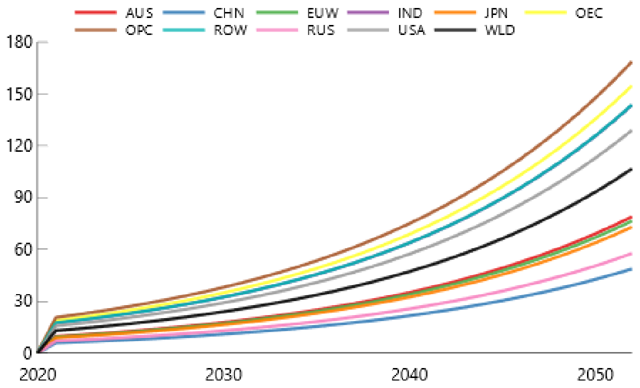
given that interest rates for many large emitters are likely to stay low for long, suggesting that an aggressive investment policy would be affordable and desirable. But as the recovery takes hold, it will be important to start phasing-in increases in carbon prices, as we are unlikely to reach net zero emissions without carbon pricing.

B. Cross-Country Differences

While the policy package achieves the same percent of emissions reduction across countries (excluding OPC), carbon tax rates differ significantly across regions (Figure 9). The rate ranges from \$48.8 in China to \$168.7 in OPC per ton of CO2 by 2050.There are a number of reasons for the differences in carbon prices. First, the same percentage of emissions reduction (80%) relative to the current levels leads to different reduction percentages relative to the baseline across regions due to different emissions levels in the baseline. The reduction percentage relative to the baseline ranges from 82-92% in 2050 (excluding OPC), indicating different levels of stringency relative to the baseline. Second, green investment contributes to different levels of emissions reduction across regions, ranging from 10-30% in 2050 (excluding OPC) relative to the baseline. These differences result in the distribution of the reduction percentage required for carbon taxes, ranging from 62-75% in 2050 (excluding OPC) relative to the baseline. Another more important reason is the economic difference across regions, including carbon intensity of each fossil fuel (tons of carbon per dollar of output), energy structure, the baseline price levels of fossil fuels, and the sectoral patterns of production and consumption. In particular, a higher share of coal in fossil fuels tends to require a lower carbon tax to achieve similar percentage reductions of emissions because coal has much higher carbon intensity than gas and oil. Given the same growth rate of carbon taxes, emissions in regions with abundant coal decrease much faster before coal runs out than afterwards. China’s tax rate is the lowest because China runs out of coal around 2045 and its emissions decrease fast over the entire period. Europe and Australia have relatively low carbon taxes also partly because they have abundant coal. ROW and India also have plenty of coal, but they run out of domestic coal around 2030-2035 and then emissions decrease slowly although carbon taxes keep rising at the same growth rate.

Figure 9: Carbon Tax Rates by Region in the Policy Package

($ per ton of CO2)

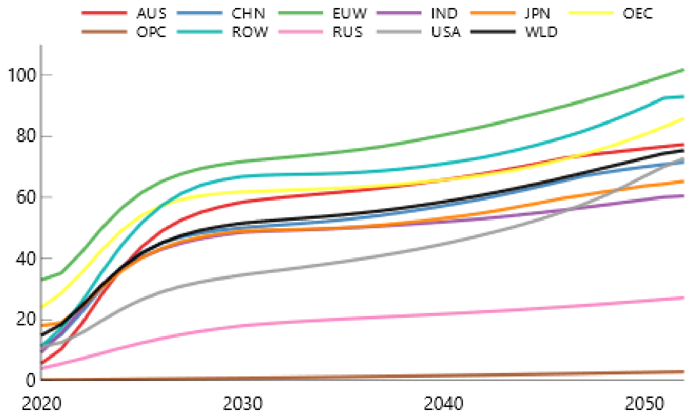


Source: G-Cubed model simulations version GGG20v154.

The share of low carbon energy in primary energy significantly increases in the first ten years (Figure 10) in most regions (except OPC) but differs across regions. There are several reasons for these difference across regions. First, the share of low carbon energy along the baseline differs substantially across regions. Second, the impacts of public investment on low carbon energy productivity are different across regions. After green investment phases out in 2030, the share of low carbon energy keeps increasing but more slowly. Coal disappears in most regions at some time points over 2025-2035 except China which continues to use coal around 2045 and Australia around 2050.

Figure 10: Share of Low Carbon in Primary Energy by Region

(percent)

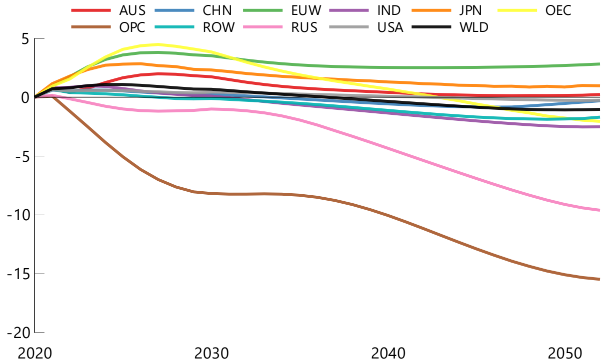


Source: G-Cubed model simulations version GGG20v154

While the transitional output costs associated with the policy package are relatively moderate in global terms, they are very different across countries (Figure 11).

Figure 11: Regional Real GDPz

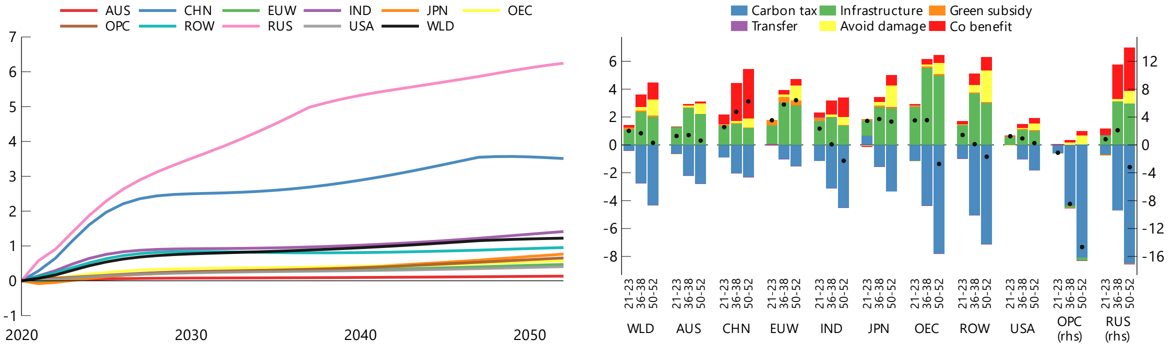
(percent deviation from baseline)



Source: G-Cubed model simulations version GGG20v154

The impacts of the policy package on GDP depend on the overall effect of carbon taxes and green investment. The impact of green investment by 2030 ranges from 1-6% across regions (excluding OPC) relative to the baseline, which depends on the effect of public investment on low-carbon sector productivity (Figure 12). The impact of carbon taxes ranges from -0.8% to -7.8% by 2030, and from -1.5 to -18% by 2050.

Figure 12: Co-Benefits by Region


Regional co-benefits *(percent of baseline GDP)*

Real GDP and co-benefits, three-year average *(percent deviation from baseline)*

Source: G-Cubed model simulations version GGG20v154

Some of the advanced economies experience smaller economic costs throughout the transition—or even gain, as in the case of Europe. The more renewables there are already in the economy, the higher the initial capital stocks, so the more they can be ramped up without incurring large adjustment costs. Europe starts with a large renewable sector, implying that the adjustment costs per unit of additional investment are much lower than for other countries.

In contrast, the United States and China have a large amount of fossil fuel capital relative to non-fossil-fuel capital, and the investment reductions from these industries offset the investment in renewables, which face larger adjustment costs to ramp up.

Countries with fast economic or population growth (India, especially; China, to a lesser extent) and most oil producers experience larger economic costs by forgoing cheap forms of energy compared to the no policy scenario, such as coal or oil. These output costs nevertheless remain small relative to baseline growth for most (with the exception of oil producers). For example, with the policy package, India's GDP would be 277 percent higher in 2050 than today, only moderately below what it would have been with unchanged policies (287 percent). But more importantly, these economic costs also need to be weighed against avoided damage from climate change and co-benefits from climate change mitigation.

The countries for which economic costs are larger are also the ones that would enjoy immediate substantial co-benefits from acting to curb carbon emissions. These are on the order of 0.7 percent of GDP immediately and 3.5 percent of GDP by 2050 for China, and 0.3 percent immediately and 1.4 percent by 2050 for India.[19] Combining real GDP effects and co-benefits yields net benefits throughout the transition for China and smaller transitional costs for India, Russia, and others.[20]

The benefits from mitigating climate change are also expected to be particularly large for some of the countries with higher transitional costs. India is among those likely to suffer the greatest damage from global warming in the second half of the century, reflecting its initially high temperatures. Simulations in IMF (2020) show that for India, the net gains from climate change mitigation—relative to inaction—could be up to 60–80 percent of GDP by 2100.

Fossil fuel exporters are bound to experience the largest economic losses from the transition of the global economy to a low-carbon path (see Mirzoev and others 2020 for a discussion of carbon transition risks in Gulf Cooperation Council countries). Even without a domestic carbon

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[19] Based on quasi-experimental evidence from China, Ebenstein and others (2017) finds that an increase of 10 micrograms a cubic meter in PM10 (particulate matter under 10 micrometers in size) reduces life expectancy by 0.64 year and, consequently, bringing all of China into compliance with its Class I standard for PM10 would save 3.7 billion life-years. In addition to the benefit of reduced mortality, studies also show significant benefits from reduced morbidity (that is, lower health care spending) in response to environmental policies. For example, reducing PM2.5 (particulate matter under 2.5 micrometers in size) concentration in China from the prevailing average to the World Health Organization–recommended level (which is about one-sixth the current average level) would reduce health care spending by $42 billion relative to 2015 spending levels, or about 7 percent of national annual health care spending (see, for example, Barwick and others 2018).

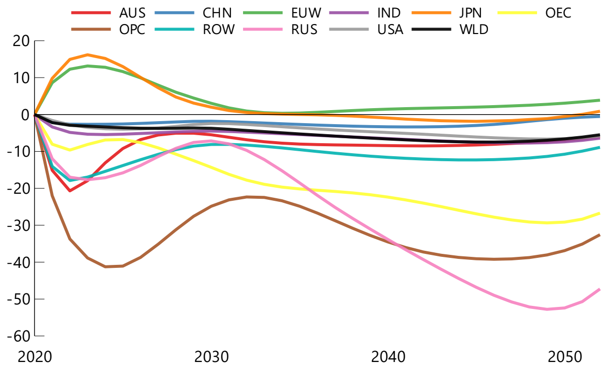
[20] Bento, Jacobsen, and Liu (2018) also points out that the costs of implementing a carbon tax are substantially lower with a large informal sector as the carbon tax lowers the relative distortion between the formal and informal sectors—since even the informal sector must buy energy from the formal sector, these mechanisms can lead to welfare-enhancing expansion of the formal sector.

tax, the fall in global demand for fossil fuels would significantly lower these economies' fiscal revenues and economic activity. Moreover, the industrial structure in many fuel exporters is reliant on cheap energy, making the required restructuring and diversification of these economies more difficult and painful. Many oil exporting countries have recognized the challenges that are being created by the energy transition and are actively seeking to diversify their economies away from the reliance on oil.[21] Many oil exporters, however, also stand to gain from global climate change mitigation measures. For example, rising temperatures will make oil-exporting countries in the Middle East, where water scarcity is already a growing concern, even hotter.

Investment differs significantly across regions depending on each region's energy structure because the policy package induces investment from high-carbon sectors to low-carbon sectors (Figure 13). As mentioned above, green public investment has a strong positive effect on low-carbon investment, while carbon taxes have a strong negative effect on high-carbon investment. The net effect differs across regions. In Europe and Japan, the positive effect in low-carbon sectors moderately dominates the negative effect in high-carbon sectors. In fossil-exporting regions, the negative effect in high-carbon sectors is much stronger, leading to net negative investment.

Figure 13: Private Investment by Region

(percent deviation from baseline)



Source: G-Cubed model simulations version GGG20v154

Most regions benefit from higher consumption over the entire period by 2050 except OPC and Russia which suffer from fossil revenue losses (Figure 14). For non-fossil-exporters, the

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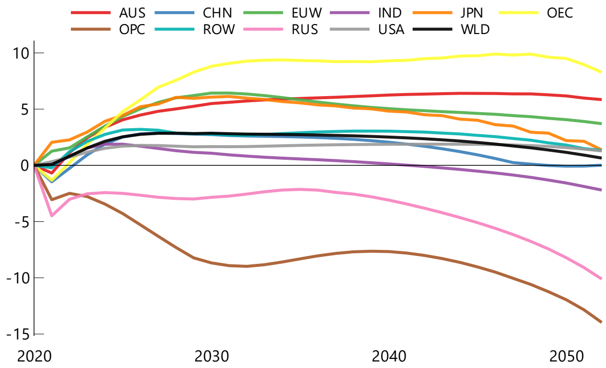
[21] Policies that seek to strengthen the non-oil sector through better business regulation, greater credit availability, and reforms to the labor market and increase sources of non-oil revenue for the government are being implemented.

magnitude of consumption benefits differs across regions, reflecting the overall effects of the consumption change of the two types of consumers. The difference in consumption outcomes depends mainly on the differences in the impacts of the policy package on the real interest rates, the real wages, the firm dividends, and the government transfers. For example, Europe and OEC have higher increases in real wages than Japan, but their interest rates in the first ten years also increase more than in Japan, leading to lower human wealth in Europe and OEC. But the effects of backward-looking consumers dominate those of forward-looking consumers, so Europe and OEC have higher consumption gains than Japan. The United States and China have quantitatively similar consumption gains which are less strong than Europe and OEC.

Figure 14: Private Consumption by Region

(percent deviation from baseline)

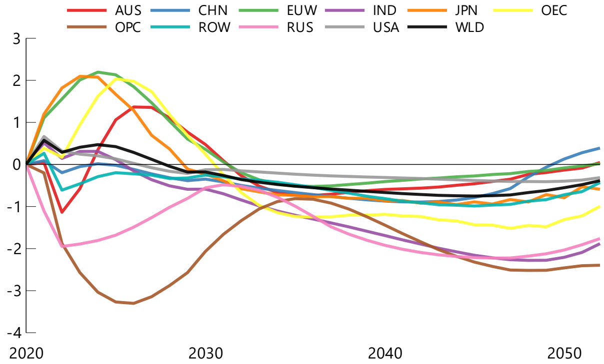


Source: G-Cubed model simulations version GGG20v154

The differences in employment across regions are similar to the differences in private investment (Figure 15). There are two exceptions which experience investment decreases but employment increases: one is the rest of OECD and the other is the US (to a lesser extent). This outcome is because almost all productivity gains from public investment are allocated to the service sector in OEC and to a lesser extent in the US (by assumption), and the service sector is much more labor-intensive than other sectors. Although the investment boom in the service sector does not offset the investment decline in other sectors, the employment expansion in the service sector sufficiently dominates the negative employment impact in other sectors. This exceptional case illustrates that private investment and employment can go in opposite directions. More generally, the more the productivity gains allocated to the labor-intensive sectors, the larger the discrepancy between private investment and employment. From the employment perspective, it is important for policymakers to consider the sectoral distribution of public investment.

Figure 15: Employment by Region

(percent deviation from baseline)



Source: G-Cubed model simulations version GGG20v154

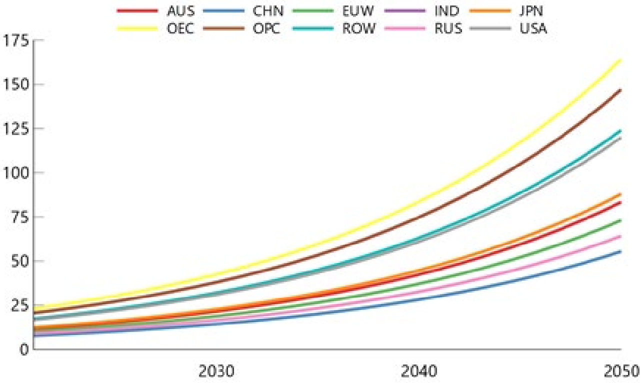
C. Policy Package vs. Carbon Tax Only

To better understand the role of green public investment in the policy package, we compare the package results with an alternative policy that achieves the same gross emissions reduction of 80 percent by mid-century but only through levying carbon taxes. We assume that the rate of growth of the carbon tax is the same as the previous scenario at 7% per year. As with the package scenario, we search for an initial tax rate in each region such that the 80% target is achieved by 2050 in all regions except OPC. Carbon tax revenues are assumed to be redistributed to households as lump-sum transfers.

With all abatement falling on the carbon tax, the required carbon taxes to achieve the same amount of emissions reductions are higher. The initial level and path of carbon taxes for each region are shown in Figure 16.

Figure 16: Carbon Taxes by Region in the Carbon-Tax-Only Scenario

($ per ton of CO2)



Source: G-Cubed model simulations version GGG20v154

Under a carbon-tax-only policy, reducing gross emissions by 80 percent by mid-century requires carbon taxes that are on average 21 percent higher than in the comprehensive policy package scenario (Table 5).[22]

Table 5: CO2 Taxes by 2050 in the Policy Package and Carbon-Tax-Only Scenarios

Region	Package	Tax only	Ratio
AUS	79.0	95.4	1.21
CHN	48.8	63.5	1.30
EUW	76.5	83.7	1.09
JPN	73.0	100.7	1.38
IND	143.6	168.3	1.17
OEC	154.8	188.0	1.21
OPC	168.7	168.4	1.00
RUS	57.8	73.6	1.27
USA	129.0	137.4	1.06

The effect on global GDP is negative throughout the transition, increasing progressively to reach 5 percent of baseline GDP by 2050 (Figure 17). The difference in the GDP impacts between the two scenarios is jointly driven by the absence of productivity gains from public investment and by the more ambitious carbon taxes required to achieve the same level of emissions reduction. Without public investment, there are no GDP gains through demand in the short run or via productivity in the medium run. The difference in the investment response more directly captures the role of productivity gains from public investment. Productivity gains from public investment can potentially boost private investment by 5-10% relative to the baseline over the entire period. The public investment also causes significant differences at the sectoral level across the two scenarios. In particular, there is a huge difference in renewable and other low-carbon sectors, and also in the service sector given the service sector also gains

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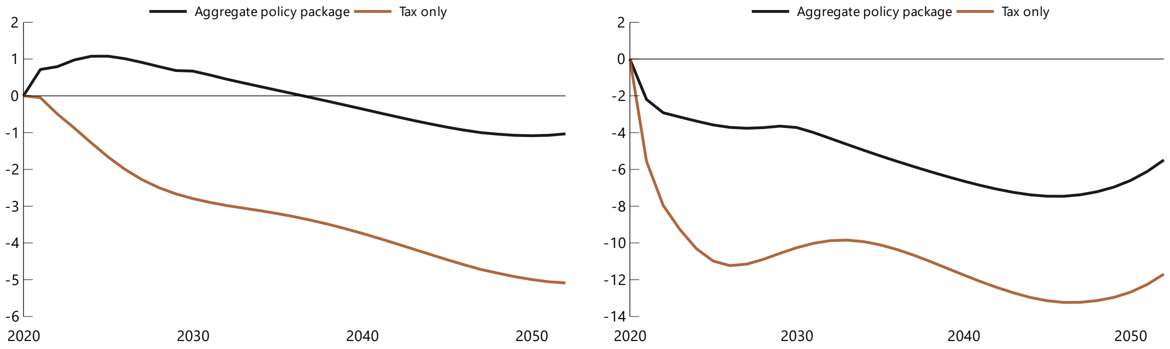
[22] This number is a simple average of the percent deviation between the carbon tax in the two scenarios across eight regions (excluding OPC and ROW).

productivity from public investment. On the other hand, fossil fuels shrink much less dramatically in the tax-only scenario.

Figure 17: GDP and Investment: Policy Package vs. Carbon Tax Only

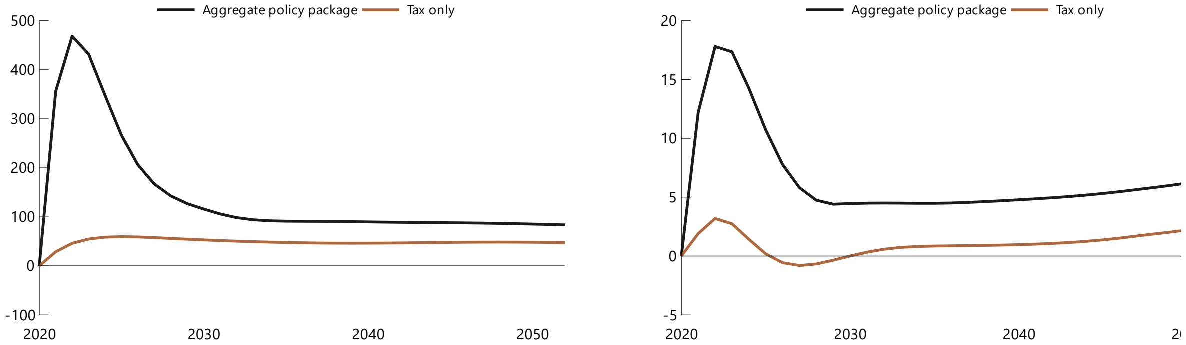
Global real GDP *(percent deviation from baseline)*

Global investment *(percent deviation from baseline)*



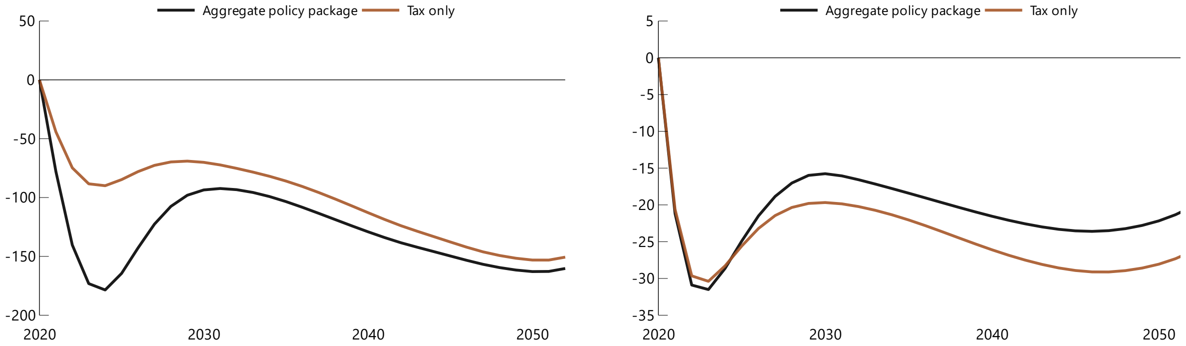
Global investment; renewables and other low carbon *(percent deviation from baseline)*

Global investment; renewables, other low-carbon, and services *(percent deviation from baseline)*



Global investment; coal, gas, and oil *(percent deviation from baseline)*

Global investment; coal, gas, oil, agriculture, construction, manufacturing, and transportation *(percent deviation from baseline)*



Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

The differences in GDP loss across countries under the policy package and the tax only scenario is similar to the global outcomes (Table 6). All countries have lower GDP losses in the policy package. For some countries (AUS, EUW, JPN) the GDP changes are positive in the policy package over the entire period as compared to negative in the carbon tax only scenario. As mentioned above, the results are sensitive to how the revenue from the carbon tax is used.

Table 6: Change in GDP in the Policy Package and Tax-Only Scenarios (percent deviation from baseline)

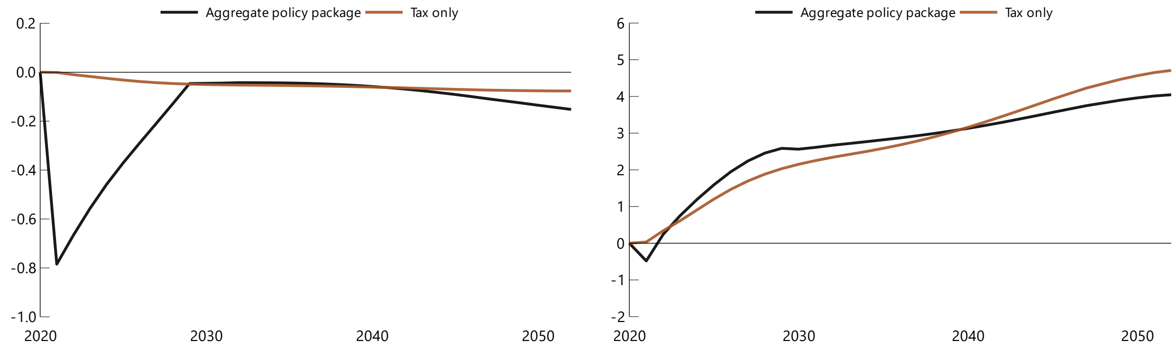
Scenario	Year	AUS	CHN	EUW	JPN	IND	OEC	OPC	ROW	RUS	USA
Package	2020	0.37	0.46	1.40	1.66	0.63	1.43	-1.17	0.40	-0.08	0.46
	2030	1.25	0.03	2.71	1.84	-0.24	2.81	-8.12	-0.42	-1.20	0.31
	2050	0.21	-0.88	2.43	0.82	-2.53	-2.18	-15.39	-1.77	-9.59	-0.31
Tax only	2020	-1.11	-1.19	0.02	0.54	-1.22	-1.45	-1.09	-1.07	-1.76	0.02
	2030	-2.44	-2.27	-0.92	-1.53	-3.30	-4.27	-7.58	-6.51	-9.96	-0.95
	2050	-3.39	-3.44	-1.66	-3.87	-5.44	-9.56	-17.18	-8.70	-21.36	-2.07

It is worth noting that the GDP losses from carbon taxes in G-Cubed tend to be larger than the GDP losses reported in many other CGE models for a similar carbon tax. This reflects the way investment is modelled in G-Cubed. The assumption of quadratic adjustment costs in a putty clay investment model implies that a rise in carbon prices has larger investment effects on capital intensive fossil fuel and fossil fuel intensive sectors. Investment falls sharply in those sectors which tends to reduce GDP. Investment in other sectors such as renewables incurs sharply rising adjustment costs which does not generate the level of investment that is lost from existing fossil fuel intensive sectors. Thus, the GDP losses reflect the investment changes that are not well captured in CGE models in which capital can freely flow across sectors. G-Cubed attempts to model the stranded physical assets that result from changes in climate policy. However there are also a number of channels which could reduce the cost of carbon pricing and are not included in G-Cubed, such as the productive recycling of revenues (productive investment or lower distortionary taxes instead of lump-sum transfers to households), reduced informality in developing economies as carbon taxation is more difficult to avoid than most other taxes (Bento, Jacobsen, and Liu 2018), and induced technical change in low-carbon technologies.

The second difference between G-Cubed and other modelling approaches is the relatively small carbon prices that can achieve a given level of abatement. The lower carbon prices reflect two key issues. The first is the aggregate effects on GDP through investment discussed above. Lower GDP reduces emissions and therefore requires a smaller carbon tax. The second important issue is the role of substitutability in production and consumption in G-Cubed. As relative prices change, firms and households can adjust their production and consumption activities to substitute away from more expensive carbon intensive goods to less expensive goods. This not only occurs in relation to fossil fuels but across the entire economy. The elasticities of substitution in production and consumption in G-Cubed are estimated rather than calibrated. They reflect the historical experience of ease of substitution in response to price changes. It is an open question whether future substitution will reflect the historical experience or may be much harder (as apparently assumed in many models).

The fiscal impacts of the two alternative policy packages are clear in Figure 18. In the carbon tax only scenario the fiscal balances are only slightly affected as the revenue is recycled to households with the fiscal position only impacted by changes in economic outcomes that affect other revenue and expenditure items. Under the complete package the green infrastructure program initially worsens the fiscal balance leading to higher short-term debt. Over time the higher productivity growth from the infrastructure spending eventually leads to a lower debt to GDP ratio.

Figure 18: Fiscal Impacts: Policy Package vs. Carbon Tax Only



Fiscal balance to real GDP *(percentage point deviation from baseline)*

Debt to real GDP *(percentage point deviation from baseline)*

Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

VI. RESULTS OF PARTIAL PARTICIPATION SCENARIOS

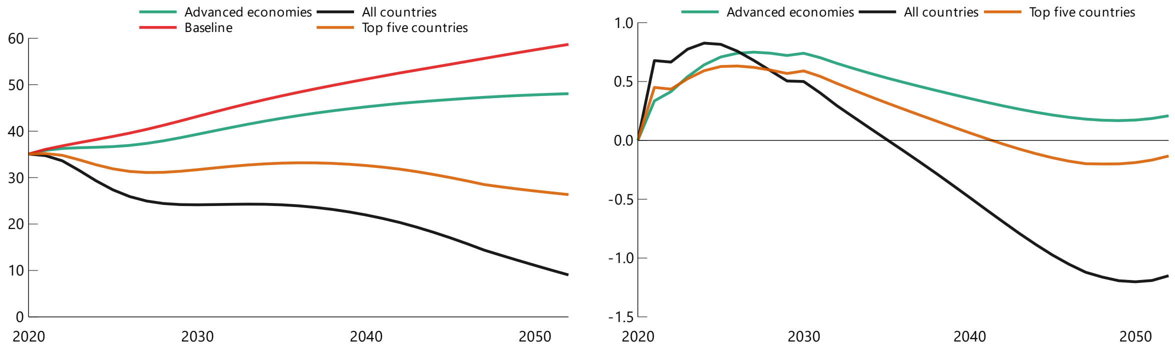
It is sometimes argued that countries that have contributed the bulk of the stock of global carbon emissions—advanced economies—should shoulder a greater part of the mitigation burden.

In order to examine the impact of partial participation on emissions and macroeconomic outcomes, we run two scenarios, one where only advanced economies implement the comprehensive policy package and another one where the largest five economies (USA, EUW, CHN, IND, JPN) implement the package.

In a scenario in which advanced economies are the only ones that reduce their gross carbon emissions by 80 percent by 2050, global emissions still increase to 48 gigatons by 2050, well above current levels (Figure 19). Advanced economies acting alone are not able to keep global temperatures at safe levels, as their share in global emissions is set to drop to 23 percent in 2050 from 32 percent of global emissions under unchanged policies. And in a scenario in which only advanced economies enact mitigation policies, the decline in their emissions would be partially offset by an increase in other countries' emissions relative to the baseline. This reflects two types of "leakages": first, lower demand from advanced economies for fossil fuels depresses global fossil fuel prices and so increases their consumption by other countries; and second, some carbon-intensive activities previously carried out in advanced economies are likely to relocate to countries where carbon is not taxed.

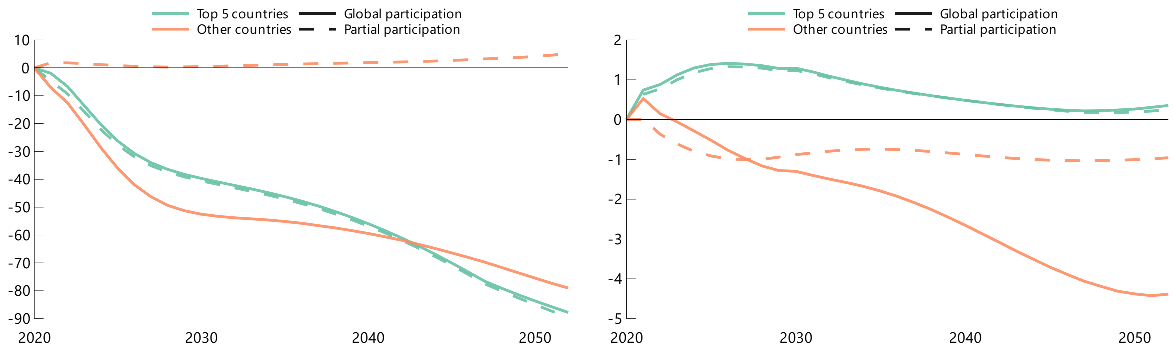
The non-participating countries experience negative impacts on GDP for two reasons. In the layer of carbon taxes, fossil fuel exporters suffer fossil export revenue losses and thus GDP losses, and the non-participating countries that are not fossil exporters experience higher GDP because capital flows from participating countries into those countries. In the layer of green investment, fossil fuel exporters again suffer fossil export revenue losses and GDP losses, and the non-participating countries that are not fossil exporters experience lower GDP because capital flows away into the participating countries. Overall, fossil fuel exporters suffer significant GDP losses, and non-participating non-fossil-exporting countries also suffer GDP losses to a lesser extent (the spillover effect of green investment dominates that of carbon taxes).

Figure 19: Partial Participation in Mitigation



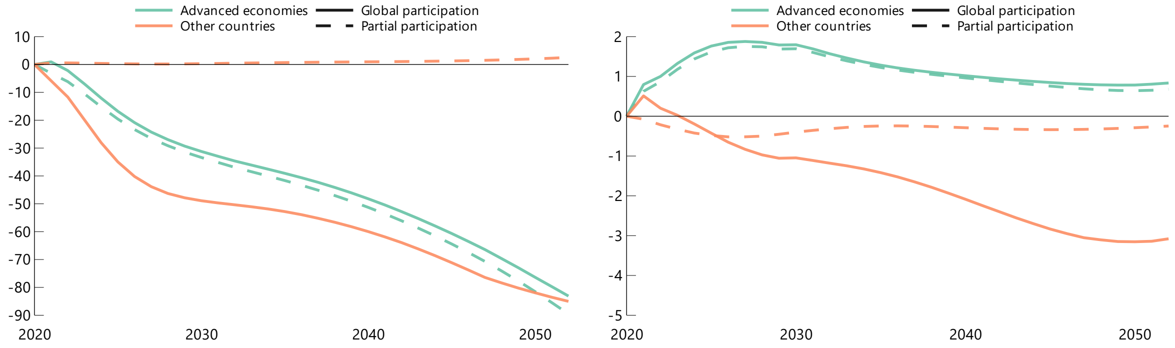
Global CO2 emissions *(gigatons of CO2)*

Global real GDP *(percent deviation from baseline)*



CO2 emissions *(percent deviation from baseline)*

Real GDP *(percent deviation from baseline)*



CO2 emissions *(percent deviation from baseline)*

Real GDP *(percent deviation from baseline)*

Source: G-Cubed model simulations version GGG20v154 and IMF staff calculations.

Notes: 1/ Top 5 countries consist of CHN, USA, EUW, IND and JPN.

2/ Advanced economies consist of AUS, EUW, JPN, USA, and OEC.

3/ The avoided damages from climate change are assumed to be the same in the partial action scenario as in the global action scenario. While a simplification, the difference would not be very large before 2050.

In the scenario where the five largest economies (the United States, Europe, China, Japan, and India) act together, they can make a large dent in global emissions over the next three decades, though still insufficient to keep temperatures to the levels of the Paris Agreement. Global emissions would be reduced by about 55 percent from baseline levels and 25 percent from current levels by mid-century, with a very similar effect on each participating country's GDP, as in the scenario of global action. This highlights the significant growth of emissions expected in the rest of the world under unchanged policies and the need for worldwide participation in mitigation efforts. Absent the possibility of significantly negative emissions in large economies—which would require more significant deployment potential of carbon capture and storage—saving the planet will require worldwide participation in mitigation efforts.

VII. CONCLUSIONS

This paper has explored a range of policy options aimed at achieving global and regional targets of net-zero carbon emissions by 2050. Achieving net-zero emissions is shown to be possible but the economic costs of the target depend very much on the policy mix used to achieve net zero emissions. It is shown that a policy of only using a carbon tax to reach the target, has significant economic costs in the short run and these continue by 2050. Whereas a well-designed policy that has a mix of policies aimed at both achieving net zero emissions by 2050 and providing fiscal stimulus through infrastructure investment to support the net-zero target at the early stages of the global economic recovery from the pandemic can have short term economic benefits with substantially reduced economic impacts by 2050.

Carbon pricing is shown to be an important driver of the scale of emissions reductions while a substantial green infrastructure program is important to support the emission reductions but also to minimize the economic costs of the structural changes required in the global economy over the next 30 years.

The impacts of the policies differ significantly across countries with fossil fuel intensive economies tending to have the largest economic costs due to the loss of revenues from exporting fossil fuels. These economies also need to undertake more substantial structural change domestically to reduce domestic emissions from energy use. We demonstrate that if there is some capacity to substitute fossil fuels with other energy sources such as renewables this negative impact can be substantially reduced. Australia is a case where despite the carbon tax policy having significant economic impacts, a well-designed infrastructure policy focusing on renewables can substantially reduce the costs of the net-zero target.

We also show that policies that exclude key countries significantly reduce the carbon abatement outcomes and are inadequate to achieve the emissions targets required to stabilize temperatures. The scale of projected emissions being generated by emerging and developing economies in future years overwhelms any substantial action by developed economies alone. Thus, a key part of achieving realistic global climate targets will be to ultimately bring emerging and developing economies into a global agreement. The scale of the transformation will likely entail substantial technology transfer and significant funding mechanisms which are not explored in the paper.

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