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Fiscal Policies for a Sustainable Recovery and a Green Transformation

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Abstract

This paper compares the effectiveness of different fiscal policy instruments—carbon pricing, fiscal incentives for private green investments, and public green investment—in supporting a green recovery that is also fiscally sustainable. It argues that relying on carbon pricing or green investments is not sufficient to achieve the transition to a low-carbon economy in a timely and sustainable way. Carbon pricing alone would result in rapid and significant energy price increases that would be recessionary. Similarly, the level of public green investment needed to reach the Paris goals without recourse to carbon pricing would be so great that it would endanger debt sustainability. The conclusion from the simulations supports the view that a mix of supply-side policies (carbon pricing) and demand-side interventions (deficit financed green public investment) is necessary to achieve the Paris goals within the specified period and with a fiscally sustainable outcome. The paper also assesses the costs associated with transitioning to a low-carbon economy by geographic area. It finds that deficit financed public green investment by high-emitting countries only (typically advanced and emerging economies), would have positive growth impacts for those countries and enhance their fiscal sustainability, while also providing large positive spillovers to other countries, particularly to highly climate sensitive nations. In turn, the simulations show that wherever fiscally feasible it is in the best interest of all countries to increase public investment in the green economy.

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Produced by the Research Support Team

Fiscal Policies for a Sustainable Recovery and a Green Transformation*

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I. Introduction

The Covid-19 pandemic has led to unprecedented human suffering and economic decline on a global scale. While many countries are now recovering, others are still in the grip of the pandemic and most find themselves debt-ridden and facing an uncertain future with new waves of infections, rising geopolitical challenges and mounting concern over how to tackle the impending climate crisis. It is therefore urgent that every country utilize its limited fiscal resources in the most efficient way possible relying on rigorous analysis to assess the best course of action. This paper contributes to this debate by assessing the effectiveness of different fiscal policy instruments – carbon pricing, fiscal incentives for private green investments, and public green investment – in supporting a green recovery that is also fiscally sustainable. Fiscal sustainability in this context is defined broadly as a country's ability to keep its debt-to-GDP ratio on a non-explosive path.[2]

Despite deterioration of fiscal position, green investment is needed

The fiscal position of most countries has deteriorated due to the Covid-19 crisis. Both advanced and developing economies have responded to the crisis with relief measures on an unprecedented scale. General government debt to GDP has grown from about 104 percent in 2019 to about 120 percent in 2020 for the average of advanced economies, and from about 55 percent to 64 percent for emerging economies. At the same time, the low level of interest rates has allowed interest spending to remain contained in advanced economies and to grow moderately in emerging ones. Public deficits in 2021 are projected to fall as economies recover but will remain at elevated levels for the foreseeable future, according to recent World bank projections.[3]

Notwithstanding growing public debt, countries face many competing fiscal demands: (i) providing support to vulnerable population segments while recovery strengthens; (ii) rebuilding fiscal buffers at a pace contingent with recovery in order to ensure debt sustainability; and (iii) pursuing a green and inclusive transformation of the economy. The urgency of transitioning towards a green economy may not be acknowledged by all countries, which is one reason that there is considerable uncertainty over how the transition will proceed. Countries can facilitate the transition by adopting a price for carbon that reflects the true social cost of emissions. Carbon pricing will inevitably lead to an increase in energy and production costs necessary to induce a reallocation of investment toward green processes and less energy-intensive activities. Moreover, other production practices that are energy intensive and entail high greenhouse gas emissions in sectors such as agriculture, transport and building construction and management will be affected. The increase in energy prices could be eased if firms are able to improve energy efficiency. Supply-side shocks coming from higher production costs will diminish as new investment opportunities in green activities arise. While the private sector will undertake a large share of investment, public investment will be required where there are market failures such as in network and transportation infrastructures.

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[2] A country is fiscally sustainable if it has a fiscal balance in the present and in the future that is able to keep the debt as a ratio to GDP on a non-explosive path.

[3] See the June 2021 edition of the World Bank ***Global Economic Prospects***.

The rationale for borrowing today to invest for the future

Evidence shows that capital spending is often cut during times of fiscal consolidation, despite the lasting benefits for growth attributed to public investment.[4] Scaling up public investment – particularly when interest rates are near their lower bound – is essential to ensure a fast recovery from the crisis. Moreover, there is a clear argument in favor of government borrowing in order to invest in projects that will pay off in the future, as the investment will benefit future generations. Debt-financed public investment increases the capital stock and accelerates growth, generating revenue that can be used to repay the debt incurred. Without debt financing, the present generation would be disproportionately burdened via higher taxes or expenditure cuts.

Given the urgency of the climate crisis, the scaling up of public investment should be concentrated in green, sustainable activities. The rationale for debt-financed green investment in climate mitigation and resilience activities is based on the catastrophic risk that climate change poses to the economy and to public finances. Green investment has also been shown to perform better in terms of output (Hepburn C. et al. 2020) and employment (ILO, 2018) than equivalent high-carbon investment, in addition to generating health benefits due to diminished pollution and congestion. By mitigating the rise in global temperatures and strengthening the resilience of the economy, green investment helps ensure the sustainability of growth, which is necessary to manage the debt stock.

Modeling the cost of climate mitigation instruments

This paper analyzes tax and spending instruments that mitigate climate change while transitioning towards a low-carbon economy. By using an Integrated Assessment Model (IAM) with a multi-country overlapping generations structure and a climate module, results are calculated for advanced, emerging, and low-income countries and small climate-exposed economies.

The literature on the optimal level and path of a carbon taxes is very rich. Ulph and Ulph (1994) discuss the early literature. They also show that under plausible assumptions, an ad valorem carbon tax should be increasing over time. They point to the limits of the assumptions made by Sinclair (1994), who argues that the optimal path entails a decreasing carbon tax. Golosov et al (2014) characterize a constant optimal carbon tax in a dynamic stochastic general-equilibrium (DSGE) model with an externality—through climate change—from using fossil energy. Barrage (2014) relaxes some of the assumptions of Golosov et al (2014) and explores the numerical sensitivity of the optimal carbon tax–GDP ratio to the structure of preferences, depreciation, and technological progress. For a more recent analysis on the topic, see van der Ploeg and Rezai (2019). There are fewer contributions assessing optimality when there are different fiscal instruments in designing a climate mitigation strategy (Barrage 2019, Kalkuhl et al. 2013, Rausch 2013). In particular, Barrage 2019 studies optimal carbon taxes when there are other distortionary taxes. She finds that optimal carbon tax schedules are 8% - 24% lower when there are distortionary taxes, compared to the setting with lump-sum taxes.

This paper takes a different approach. It does not solve for the optimal carbon tax, which is

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[4] See chapter 2 in Schwartz, Gerd, Manal Fouad, Torben Hansen, and Geneviève Verdier, eds. 2020.

particularly dependent on the assumed value for the discount factor used to weight the welfare of the different generations. Instead, it assumes as given widely-used mitigation scenarios for future carbon emission paths (as the IPCC scenarios), and then computes the combinations of fiscal tools (especially carbon price measures and tax incentives for green investments) that achieve the given emission path, while at the same time minimizing the transition costs on economic activity. To this end the paper extends the work done in Catalano et al. [2019] by using a global overlapping generations model in the spirit of Kotlikoff et al. [2019] combined with a climate module.

More specifically, the contribution of this paper is to assess the combination of carbon taxes, green public investment and fiscal incentives for green private investment that could help achieve the Paris commitments while preserving output growth and fiscal sustainability. While carbon taxes are the proper market instrument to affect relative prices and to push savers and investors towards green activities, the political feasibility of sustained increases in energy prices seems limited. For this reason, increasing public investment in low-carbon sectors might be a more palatable approach even if costly from a budgetary perspective. In this paper, we assess the economic impact of different fiscal tools on emissions, growth dynamics and debt sustainability without considering the political implications and without addressing distributional issues, both inter-generational and intra-generational. These issues are not central to the paper and we leave them for future research.

The baseline approach considers a combination of carbon pricing and green incentives, in which the revenues from carbon pricing are recycled in the economy as incentives for green private investment. The analysis is then extended to include an expansionary fiscal policy consisting of green public investment financed via debt. Overall, the results show that the estimated economic costs of the transition to a low-carbon economy vary significantly depending on how fiscals tools are combined. In this context, Catalano et al. [2019] show that an expansionary fiscal policy is not incompatible with long-term debt sustainability. By making the economy more resilient to climate risks, spending on adaptation that raises debt in the short term would lead to a lower debt burden in the longer run, compared to a scenario with lower adaptation spending. Barrage (2020) also shows that the combination of carbon pricing and debt-financed adaptation spending is a better solution when climate related spending needs are large.

II. The Model

Overview: Characteristics of IAMS

The most widely used models to assess climate issues are integrated assessment models (IAMs) that integrate economic and climate modules allowing for their interaction. Dating from the early 1990s (Nordhaus, 2018), the modeling describes how economic growth leads to more emissions, which in turn leads to higher temperatures and climate shocks impacting the economy through productivity losses and damage to the capital stock. IAMs are utilized by the UN Intergovernmental Panel on Climate Change (IPCC) to explore some of the relationships between economic developments and climate.[5] Traditional IAMs are relatively less developed in their modeling of the economy. For example, Nordhaus [2017] recognizes that “the economic projections are the least precise parts of IAMs and deserve much greater study than has been the case up to now”. Limitations include the modeling of fiscal policy and while IAMs generally allow for carbon taxes they do not incorporate a fiscal module nor the effect of climate change on fiscal revenues. Exceptions on this regard are Catalano et al. [2019] and Barrage [2020a].

This paper uses a global overlapping generation (OLG) model referencing Kotlikoff et al. [2019] and augmented with a climate module to assess the effectiveness of different fiscal policy instruments in supporting a green recovery that is also fiscally sustainable. A global OLG model is particularly well suited to tackle these problems as it is a long-run growth model which incorporates fiscal and intergenerational issues. It incorporates separate projected population dynamics for different regions of the world, and it can also account for technological evolution. The model can design economic scenarios to match the evolution of GHG emissions and temperature increases consistent with the most widely used IPCC scenarios, and to assess the fiscal tools that can best reduce GHG emissions while minimizing economic disruptions.

Differentiation of geographic and sectoral inputs

The IAM used in this paper is developed in Catalano, Forni and Pezzolla (2018, 2019 and 2020) and it is described in detail in the Appendix. It includes a global overlapping generation (OLG) model augmented by a climate module (FUND, Anthoff et al. [2014]) to create macro-climate feedbacks along the transition to lower GHG emissions. It differentiates among four world areas, and eight economic sectors within each area. The world areas are: The United States and Europe representing the advanced countries group; China and India constituting the bulk of emerging countries; the low income group, including mainly African countries, and a mix of other low income nations; and the final group composed of small low-income countries that are highly exposed to climate shocks.[6] The model includes long-term demographic and human capital projections for the different geographic areas which affect labor and capital accumulation through savings behaviors of different agents.

At the macro level, output is a function of capital, labor, and productivity. Capital and labor, together with other inputs such as energy and land contribute to creating a more disaggregated economic structure, consisting of energy intensive manufacturing, other manufacturing, services,

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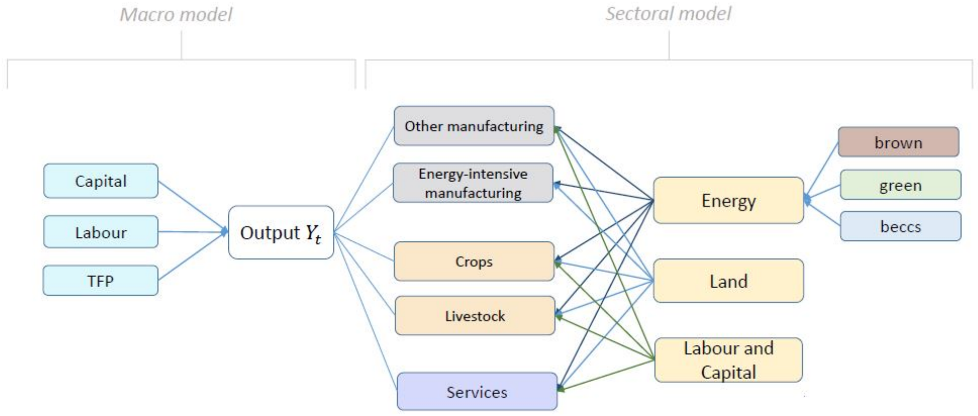
[5] As all models, also IAM have limitations. BIS [2020] for example points to the critical assumptions about the damage functions (impacts of climate change on the economy) and discount rates (how to adjust for climate-related risk) have been subject to numerous debates (Ackerman et al. [2009], Pindyck [2013], Stern [2016]). Other often-mentioned limitations include the absence of an endogenous evolution of the structures of production (Acemoglu et al. [2012], Acemoglu et al. [2015]), Pottier et al. [2014]), the choice of general equilibrium models with strong assumptions on well-functioning capital markets and rational expectations (Keen [2019]), the quick return to steady state following a climate shock (Campiglio et al. [2018]), and the often-limited role of financial markets (Espagne [2018]; Mercure and Lewney [2019]).

[6] The following countries are included: Eritrea, the Seychelles, Chad, Gabon, São Tomé and Príncipe, Botswana, Lesotho, Benin, Burkina Faso, Ghana, Liberia, Mali, Togo, Libya, Jordan, Bhutan, Malaysia, Timor-Leste, Antigua and Barbuda, Bahamas, Barbados, Cuba, the Dominican Republic, Haiti, Belize, Guatemala, Nicaragua, Panama, Guyana, Fiji, Papua New Guinea, Kiribati, Polynesia, Samoa, Tonga, and the Republic of Moldova (total population: 8,050,000).

crops, land, and livestock. Aggregate output is computed solving the OLG model and it is then disaggregated at the sectoral level through a system of relative prices. The energy sector includes different energy types: oil, gas and coal for brown energy producing sectors; green energy sectors[7] and BECCS[8] - respectively, high, low, and negative emissions energy sectors. The model is replicated with different calibrations for each area/sector to reflect the heterogeneity in the transition process among areas and sectors (Figure 1). Emissions and temperature changes are estimated based on economic growth projections. The estimated temperature changes have feedback effects on economic activity obtained using damage functions à la Nordhaus (see section 3 of the Appendix).

Figure 1: The structure of the economic module



Assumptions used in modeling

The model assumes that the evolution of climate change is known to all agents in advance (perfect foresight). This implies that agents know and evaluate as fully credible the path of mitigation policies announced by policy makers. Once trajectories for carbon prices, public green investments and incentives are known, all actors will optimize their economic decisions (investment in physical capital, labor supply, consumption, financial saving, etc.) in a fully intertemporal coherent way. They can anticipate both adverse and positive impacts of mitigation policies across the economic sectors that affect the discounted flows of incomes and the net present value of financial and real wealth. For example, households and firms foresee the impact of carbon price increases on the inflation rate due to its impact on energy prices. They therefore anticipate a decrease in real labor income and a real return from capital leading to a decrease in

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[7] Our green energy sources include renewable energies: geothermal energy; hydroelectric energy; marine energy; solar energy; wind energy; biomass energy; waste-to-energy; energy or cogeneration from groundwater.

[8] Bio-energy with carbon capture and storage (BECCS) is the process for extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.

investment in physical capital. On the other hand, the demand side policies related to public investment are anticipated, signaling a higher growth rate of the economy.

The assumption of perfect foresight also applies to the forecasting of public debt. Agents foresee the effects of higher domestic public debt on the market clearing conditions in the international financial markets. A shortage of saving at the world level would increase the interest rate, inducing domestic households to increase saving, in turn reestablishing equilibrium in the demand and supply of funds at the global level. However, the public debt is not always sustainable: a high level of public investment, for example, could require higher interest rates and bring about an unsustainable debt dynamic, implying that the model cannot be solved in terms of a general equilibrium path.

Indeed, in practice the model does not allow the possibility of default in equilibrium, although different countries face different levels of interest rates. The model currently assumes lower capital mobility for Emerging Economies and Low-Income Countries versus Advanced Economies. Thus, these countries face higher financing costs as compared to Advanced Economies. In similar models in the literature, sovereign risk depends on the gap between public debt level and a “safe” level (Schmitt-Grohe and Uribe, 2003 JIE). This approach is interesting, although it is difficult to calibrate as the elasticity of the interest rates to the debt level tends to be weak, is very country specific and depends heavily on the monetary policy stance. In our model, debt must be sustainable, therefore we prefer to model financing costs as long run equilibrium levels and disregard short term dynamics in the risk premium which could be due to situations of illiquidity.

III. Findings of OLG Modeling

The analysis in this paper assesses the relative effectiveness of the three fiscal instruments considered: carbon pricing, fiscal incentives to private green investment, and public green investment. In the model, carbon pricing is implemented with a carbon tax; incentives are modeled as a negative carbon tax on emissions produced by green energy sectors, while public green investment refers to public investment in the green energy production capacity.

We will first asses the use of each instrument separately, specifically carbon taxes and public green investments. We will include three climate scenarios: a high mitigation scenario consistent with reaching a rise in temperature of up to 2 degrees centigrade by the end of the century (defined as HM2 in figure 2); a low mitigation scenario, consistent with ‘business as usual’ policies, which would lead to a temperature increase of about 5 degree centigrade (scenario LM in figure 2); finally, an intermediate scenario (defined IKG in figure 2), where the only policy adopted is a substantial increase in public green investment.

In these scenarios, we assume that each country/area reduces emissions at the same rate and therefore each country’s share of emissions remains unchanged along the transition path. This assumption implies that the effort of each country is proportionally the same. Countries do not choose how fast to move towards a low-carbon transition. Although we could envisage different ‘speed’ assumptions, with some countries moving first and other lagging, that is not the main focus of the paper.

Carbon pricing alone is too costly a solution

In order to assess the effectiveness of carbon pricing as the sole instrument used for a green transition, we introduce carbon pricing in the HM2 scenario (defined as **CP** in figures 3-5). The model finds that carbon taxes – if not complemented by other mitigation policies – would have to increase substantially to achieve the Paris targets. Figure 3 shows that the required increase in the price of carbon would be very steep: it would rise rapidly in advanced economies to above $300 and would peak at almost $700 later in the century. Such a sharp climb in carbon prices would substantially delay the recovery from the Covid-19 pandemic and would lead to relatively high levels of public debt to GDP (figure 5). This latter result might seem counterintuitive, as the increase in carbon prices (achieved either via a carbon tax or by selling emission rights) should increase fiscal revenues. Indeed, the simulations point to a reduction early in the debt/GDP ratio. However, over time this effect is more than compensated by the weak economic performance. The steep increase in carbon prices required to achieve the Paris target would substantially delay the economic recovery, causing depressed GDP growth rates throughout the entire transition period (figure 4).

The carbon tax would affect the whole price system via supply chain effects. From the energy to the final goods producing sector, firms input costs would increase in proportion to the level of GHG emissions as the carbon tax is calculated on the carbon content of energy and other inputs. It is assumed that firms would pass the increase in their production costs to consumers. The relative price shifts would favor the green-energy producing sectors leading to a shift in energy mix. Because of inelastic energy demand, increased energy costs would be reflected in higher consumer prices, depressing real incomes, while the global economy is still recovering from the Covid-19 recession. At the same time, production capacity in the green energy sector would grow but slowly, due to adjustment costs and technological limits that do not allow an immediate substitution of green for brown energy production. Moreover, in this scenario, the expansion of green energy capacity relies solely on private sector investment, as this scenario assumes no public green investments or state incentives for private green investment.[9]

Green public investment alone would not meet Paris commitments.

A scenario whereby governments try to achieve the Paris targets through a strategy of relying on higher levels of green public investment alone corresponds to the scenario labelled **IKG** in figures 3-5. In this scenario, carbon prices do not increase, growth accelerates due to massive public investment, but debt/GDP reaches extremely high levels over time. Indeed, based on the model simulations, the maximum level of public investment spending consistent with debt sustainability would result in temperature increases above 3 degrees by the end of the century thus failing to meet the Paris commitments (corresponding to the scenario IKG in figure 2). These findings show that this level of public investment spending would be too expansionary and

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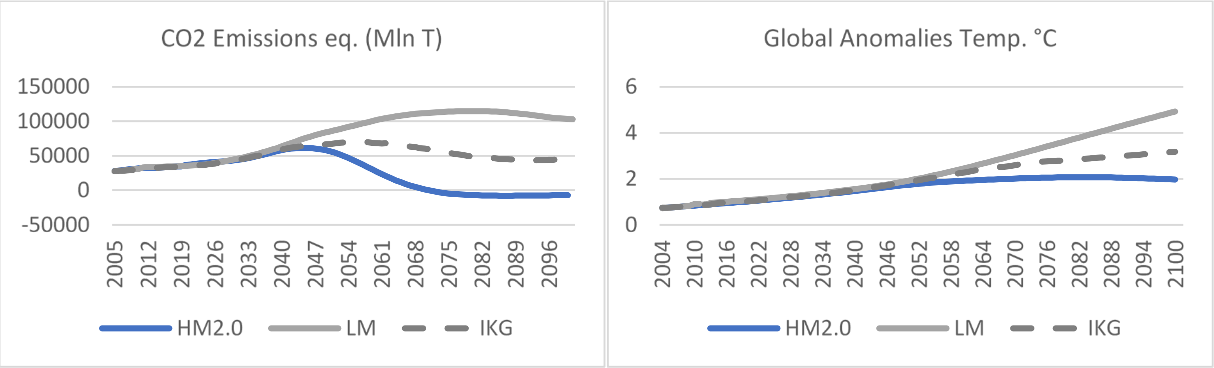
[9] In the model, carbon prices are computed to allow the model to match profiles of carbon emissions in line with the different IPCC scenario (as the Paris one, for example). These profiles, typically, entail a large initial increase of the carbon price, since there is a need to slow down immediately and considerably the flow of emissions in order to reach the Paris targets. This result is conditional on the fact that the green transition has to occur in a limited period of time, and should not be interpreted as suggesting that carbon prices (or taxes) are more recessionary than other taxes.

lead to a surge in production and demand for energy, which would be only partially met by new green energy capacity.

Figure 2 - CO2 Emissions and global temperatures anomalies in different scenarios

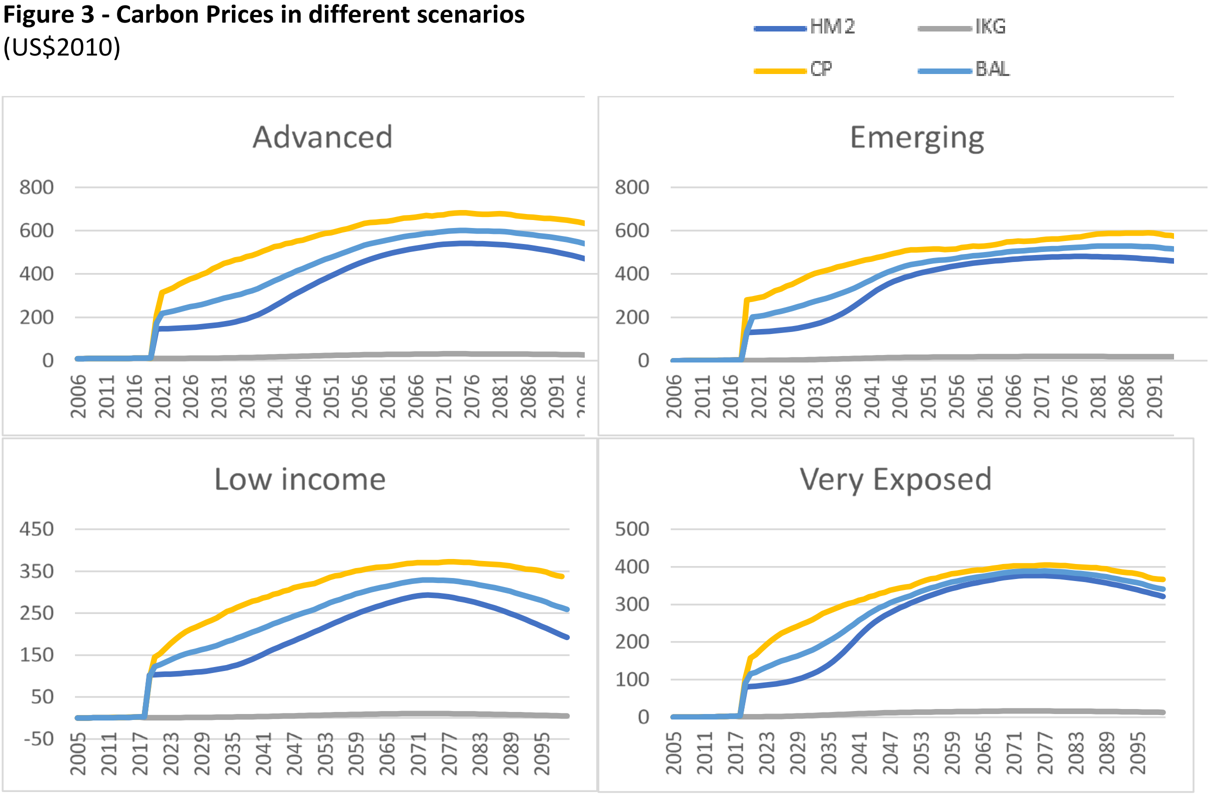


a. CO2 Emissions **b. Global temperatures anomalies**

Note. **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **IKG**: Only public green investment; **LM**: low mitigation scenario

So far, we have assumed that the revenue from carbon pricing is not returned to the economy, thereby generating a fiscal surplus; and similarly, that the public investment is financed via issuing debt, not additional taxes. Figure 3 compares two additional scenarios that evaluate the impact of returning revenue from carbon taxation to the economy. The first looked at reducing the level of taxation on labor income **(BAL)**. The second evaluated increasing government incentives for private green investments **(HM2.0)**. This second scenario appears to be a better way to achieve the Paris targets because it requires a smaller increase in carbon taxation compared to the case in which the carbon revenues are returned via labor income tax breaks. This is the case because the incentives for private green investment help to build up green energy capacity and foster the transition, while the labor income tax cuts bring about an increase in households' disposable income, which translates into higher consumption of all goods, and not just of low-carbon goods and services.

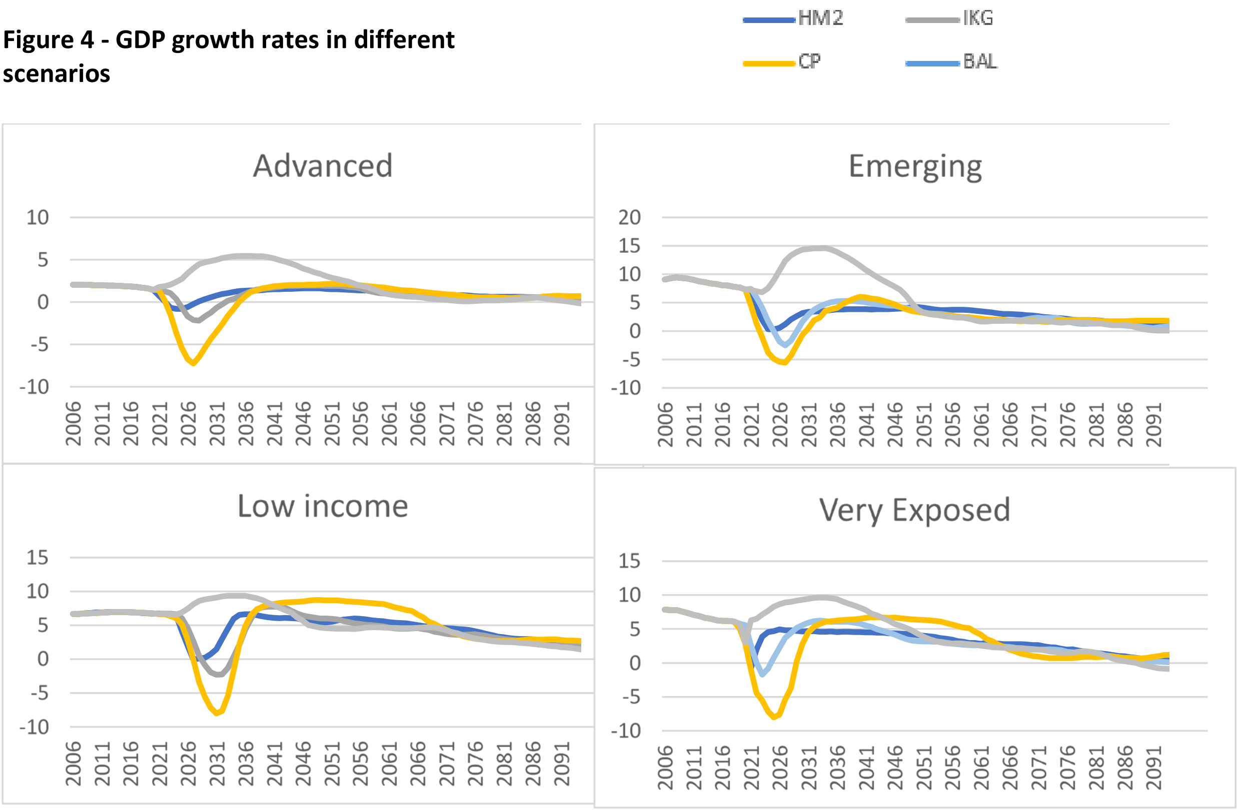
Figure 3 - Carbon Prices in different scenarios
(US$2010)



Note. **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **IKG**: Only public green investment; **CP** 2° increase in temperatures, only carbon pricing; **BAL**: 2° increase in temperatures, with carbon revenues rebated in lower labor income taxes

Moreover, the lower carbon tax level in the HM2.0 scenario supports a faster recovery from the Covid-19 recession compared to the BAL scenario (figure 4). This in turn implies that, since both scenarios assume that the carbon revenues are returned to the private sector, the MH2.0 scenario entails a lower debt/GDP profile in the long run (figure 5).

Figure 4 - GDP growth rates in different scenarios

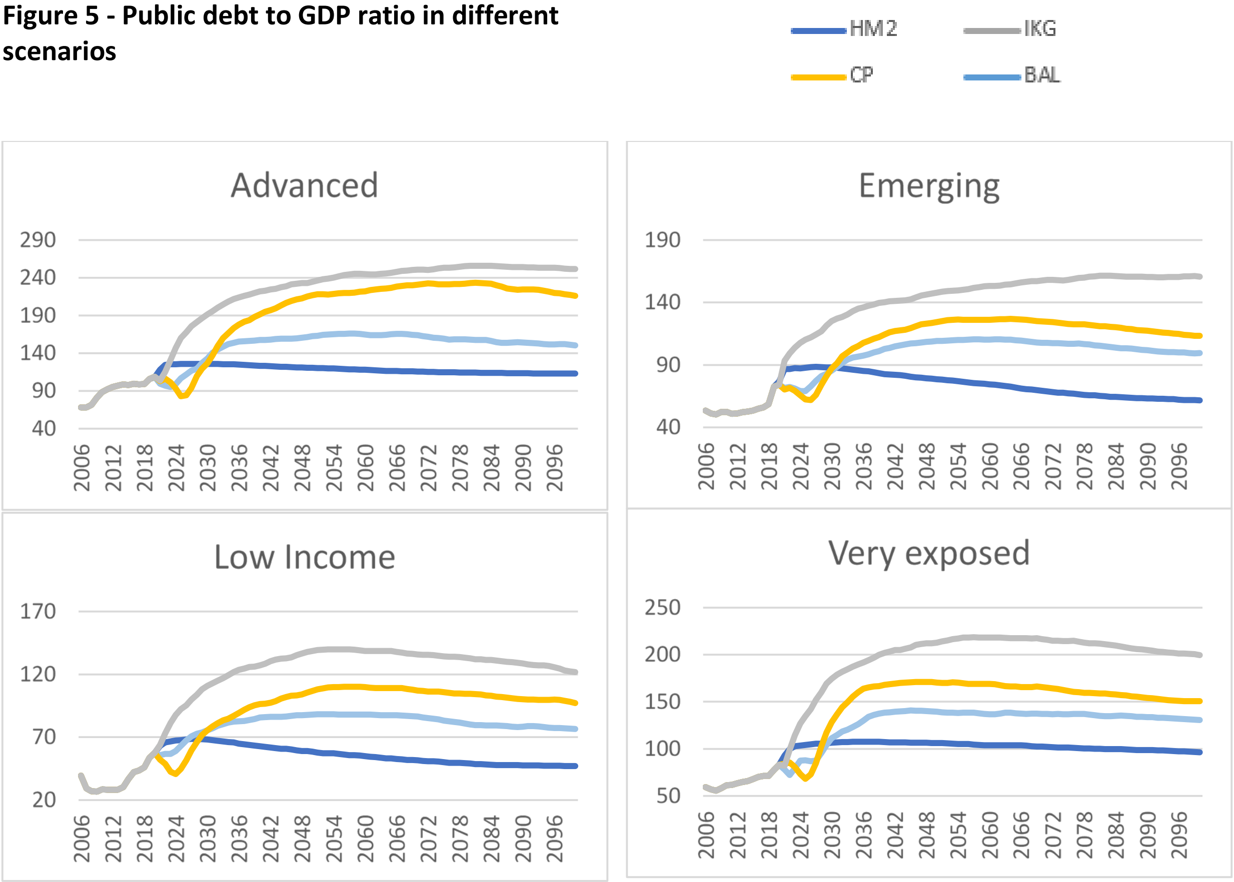


Note. **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **IKG**: Only public green investment; **CP**: 2° increase in temperatures, only carbon pricing; **BAL**: 2° increase in temperatures, with carbon revenues rebated in lower labor income taxes

Fiscal instruments are complementary and should be deployed jointly.

Overall, the results show that relying only on carbon pricing would not be optimal – in fact, it is likely to delay substantially the recovery and eventually lead to very high debt to GDP levels. Similarly, a policy of public green investments only – without a carbon tax – would not be sufficient to reduce emissions to achieve the Paris target; it would boost growth in the short run, but at the cost of extremely high debt levels. These conclusions support the view that fiscal instruments are complementary and should be deployed jointly. Carbon pricing would increase the profitability for private investors in green energy and technologies, while returning the revenues from a carbon tax through green incentives would further enhance a virtuous cycle from effective carbon pricing. Given the level of carbon pricing required and the costs of expanding the green energy capacity of the global economy, the policies modeled in these scenarios would still delay the recovery (see scenario HM2 in figure 4). Would a debt-financed additional increase in public green investments provide sufficient stimulus for the recovery while at the same time speeding up the green transition? In the next section, we will address the trade-off between increasing green public investment financed with debt and long-term fiscal sustainability.

Figure 5 - Public debt to GDP ratio in different scenarios



Note. **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **IKG**: Only public green investment; **CP**: 2° increase in temperatures, only carbon pricing; **BAL**: 2° increase in temperatures, with carbon revenues rebated in lower labor income taxes

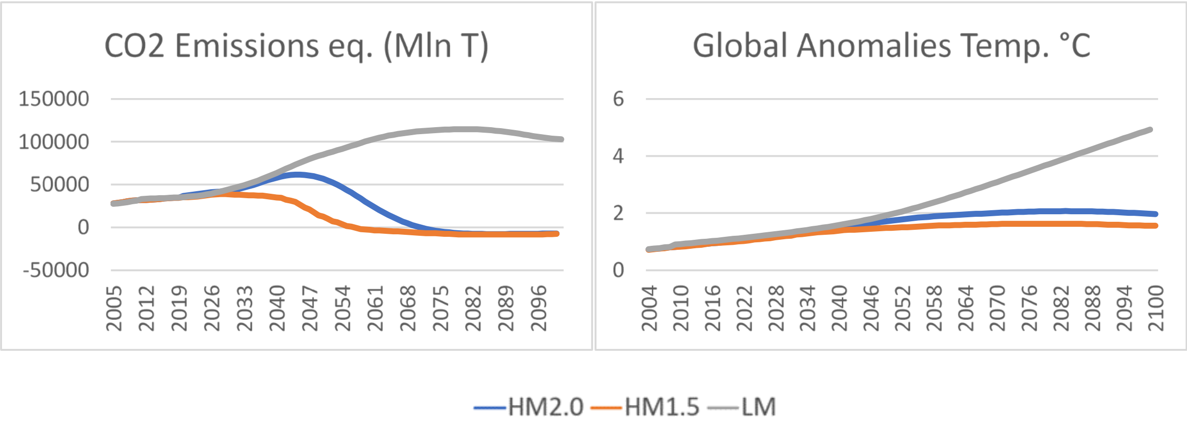
IV. The Case for Debt Financed Green Public Investment

Scaling up green public investment could support demand throughout the recovery while at the same time fostering the transition to a green economy. Increasing public investment in a low-cost borrowing environment could provide the appropriate demand side push complementing the negative supply side effect brought about by higher carbon prices. However, if additional public investment is financed with debt, long term fiscal sustainability may become an issue and will need to be assessed. This is the focus of this section.

Figures 6-12 evaluate several different scenarios. The first scenario (**HM2.0**), as in the previous section, represents a world in which all countries strive to reach at most 2 degrees increase in global temperatures by 2100 – the Paris commitments. To this aim, countries use carbon pricing and recycle revenues as fiscal incentives for private investments in green activities. Note that each country starts from unique levels of emissions and therefore requires different increases in carbon prices to reach the Paris commitments. In the case of advanced countries, carbon prices need to increase to US $140 by 2030 and to about $500 by 2070. After a contraction in 2020, growth recovers but remains below historical levels for about a decade. In the HM2.0 scenario, without additional green public investment, the increase in carbon prices and energy costs keep growth below historical levels for about a decade.

Figure 6 - CO2 Emissions and global temperatures anomalies in different scenarios

a. CO2 Emissions **b. Global temperatures anomalies**



Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **LM**: low mitigation scenario

Long-term fiscal sustainability with additional public green investment

The second scenario (**HM1.5)** prescribes that governments invest an additional 1 percent of GDP per year in green investment for five consecutive years, financed with debt.[10] This delivers the more ambitious climate objective of containing global warming to 1.5 degrees by the end of the century. As in the previous scenario, carbon tax revenues continue to fund incentives for private green investments. The difference is that in scenario HM1.5 the additional public green investment boosts the production of renewable energy and thus achieves lower temperatures. GDP growth rates are initially higher in all regions. In the long term, towards the end of the green transition, carbon prices tend to align in the two HM scenarios (figure 7) and growth rates tend to converge (Figure 8). However, the level of GDP remains higher because of both the initial push of public green investment and the lower increase in global temperatures which limits some of the deleterious effects of climate change with corresponding positive implications for economic growth and debt sustainability for all countries.

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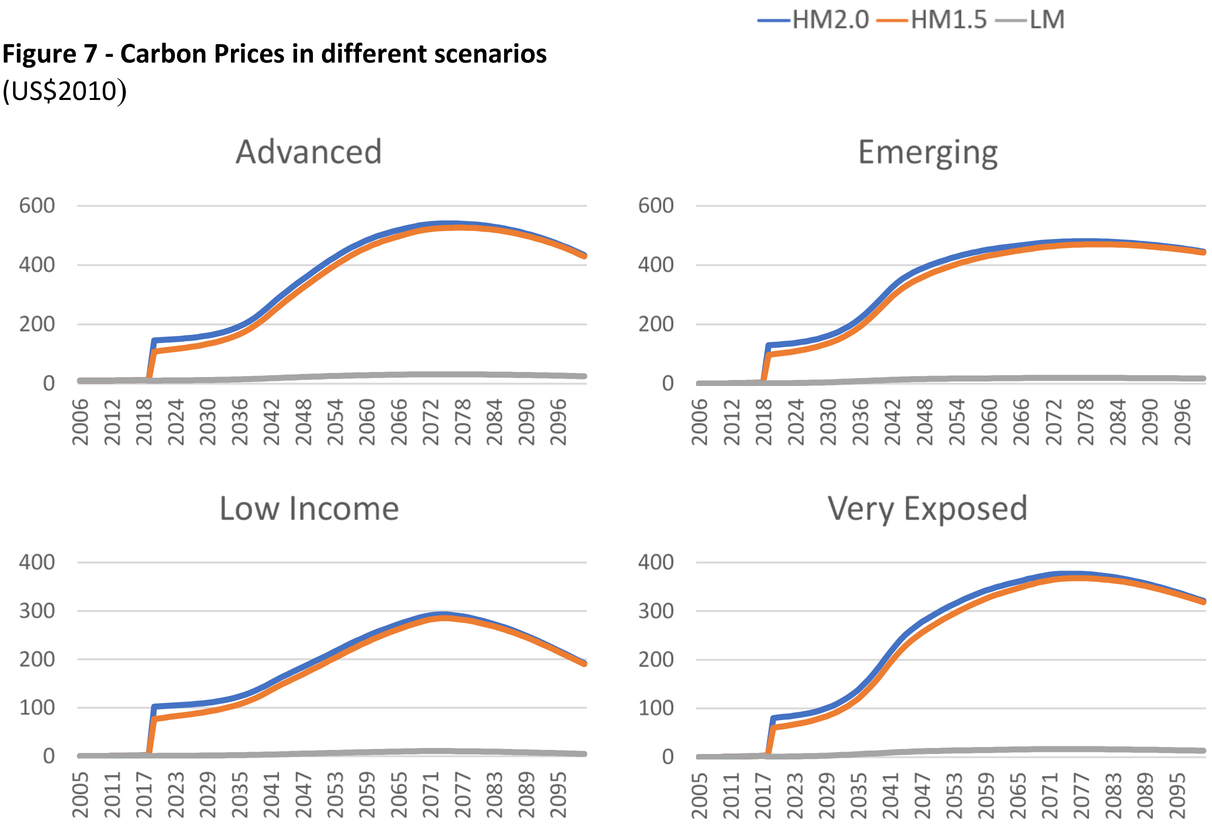
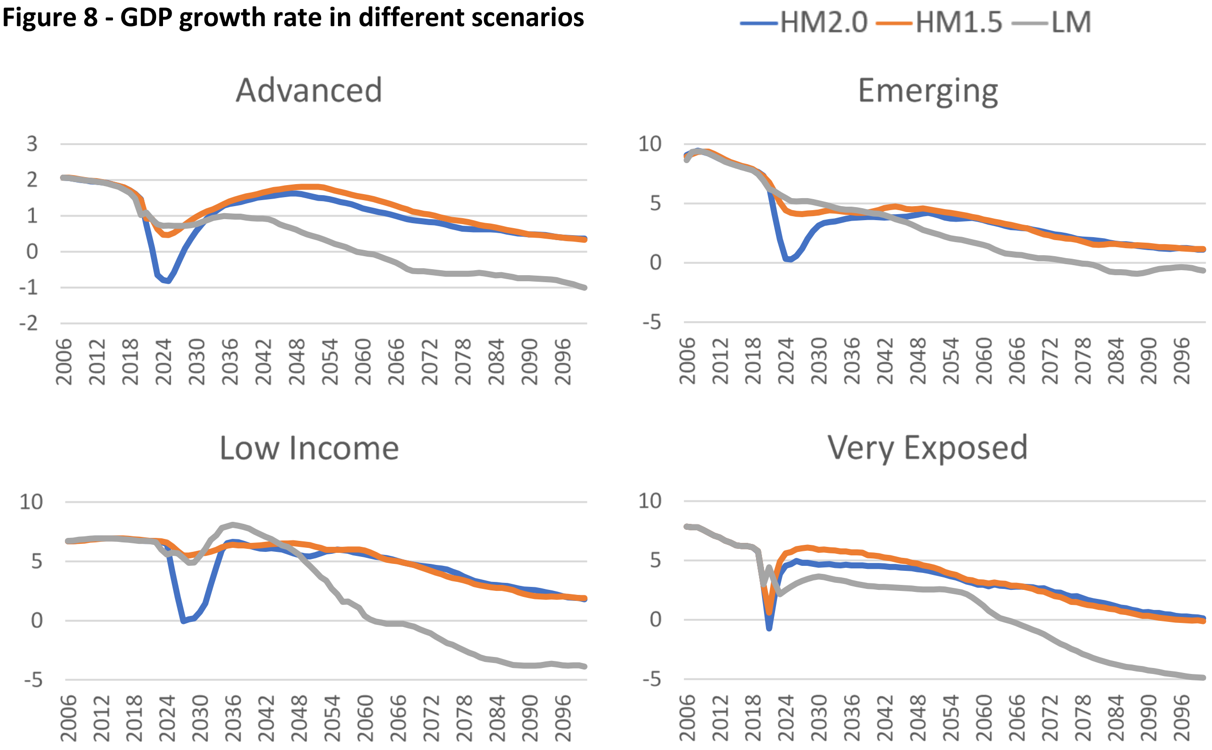
[10] Based on our estimates, this figure of 1 percent for five years is about the amount of public green investment that would be necessary to achieve a lower increase in the end-of-the-century temperatures by 0.5 degree. For the EU countries, this is also not far from what foreseen by the Next Generation Recovery plan from Covid-19.

Figure 7 - Carbon Prices in different scenarios
(US$2010)



Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **LM**: low mitigation scenario

Figure 8 - GDP growth rate in different scenarios



Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **LM**: low mitigation scenario

Low mitigation is not a good outcome.

The Third scenario **(LM)** considers a low mitigation exercise in which carbon prices do not significantly increase from current levels and temperatures rise substantially with negative impacts on productivity and an increase in climate-related disasters. In this scenario temperatures rise by about 5 degrees by the end of the century (figure 6) with carbon emissions soaring due to the absence of an effective carbon pricing strategy.[11] In the LM scenario, avoiding the green transition leads to higher growth rate in the short-run (slightly so compared to the HM1.5, thanks to the support from green public investment in the latter), but a substantially lower one in the long-run as the increase in temperatures starts to take a severe toll on economic activity.

What happens to debt sustainability?

In both high-mitigation scenarios, the debt/GDP ratio shows a spike in 2020 due to the Covid-19 crisis and to the impact on activity of the increase in carbon pricing (figure 9). Adding debt financed green public investment in HM1.5 leads to a slightly higher debt dynamic in the short

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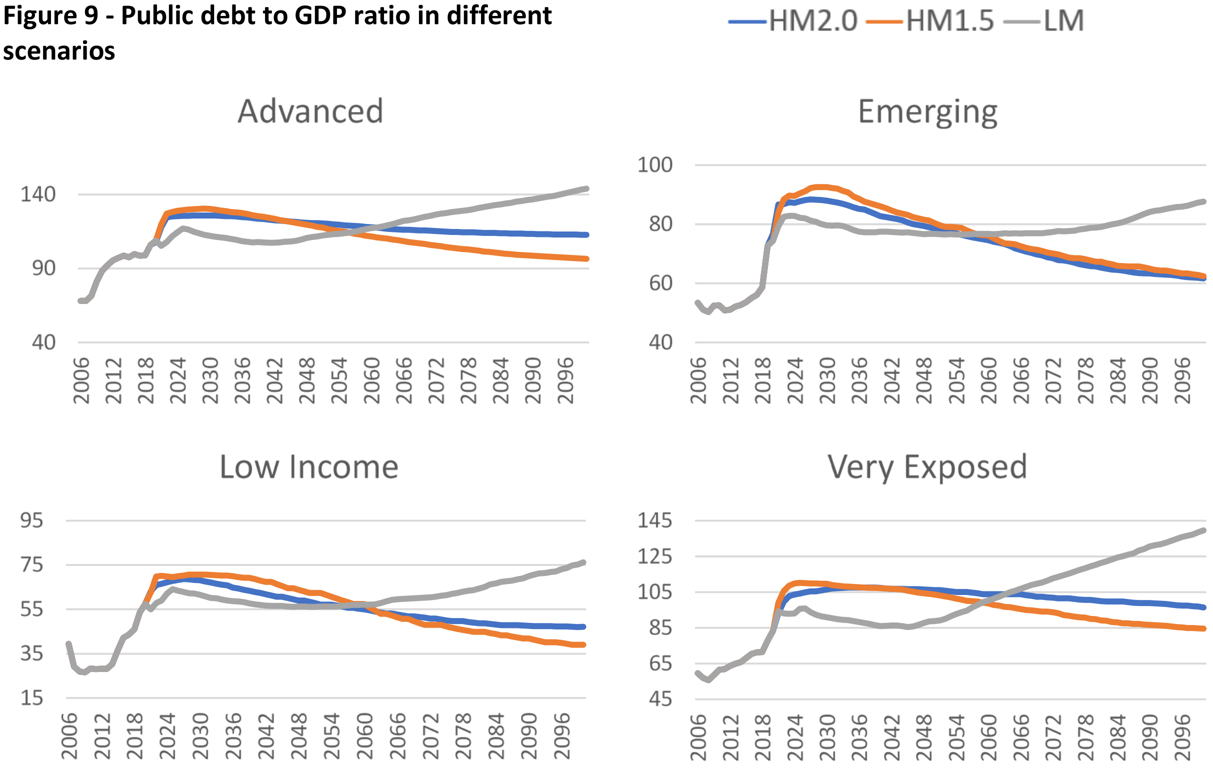
[11] In the long-run, CO2 emission falls (the profile of emission has a hump shape profile) as the high temperatures start having a severe negative impact on economic activity, therefore in turn reducing emissions.

run compared to HM2.0, but to a lower level of debt/GDP in the long run. Indeed, the simulations show that in the long term the debt/GDP is sustainable under both HM scenarios, more so in the HM1.5, while fiscal sustainability is at risk under the LM scenario. The debt/GDP ratio, after the initial spike, grows further in the HM1.5 scenario for a few years to finance the 1 percent of GDP additional green public investment, while it remains rather stable at high levels in the HM2.0 scenario (figure 9). The additional public spending in green investments leads to a slightly higher debt dynamic in the short run, but to a lower level of debt/GDP in the long term. In the LM scenario, debt/GDP falls in the short-run thanks the post-pandemic recovery, which is stronger as the LM scenario does not entail an increase in carbon prices, but then moves to an upward trajectory by the middle of the century. Fiscal sustainability is not attained in the LM scenario, as the economic impacts of rising temperatures and climate shocks eventually translate into higher spending, to pay for the impact of climate change, and in reduced tax revenue due to slower growth.

Figure 9 - Public debt to GDP ratio in different scenarios



Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **LM**: low mitigation scenario

The profiles of debt/GDP differ across country/areas, reflecting several characteristics - two of the most important being interest rate variation and exposure to climate risks. For example, in advanced economies, the debt/GDP in HM1.5 falls below the level in HM2 between the years 2035 and 2050, while for emerging and low-income countries this happens later, in part since equilibrium interest rates are higher in these latter economies. While financial markets are assumed to be open, capital mobility is not perfect in low-income countries, therefore demand for funds to finance projects with high returns is not matched by supply leading to higher interest rates. In small and climate-exposed economies, debt/GDP in the HM1.5 scenario falls below the level in the HM2.0 rather sooner - by 2035. This is a result of the additional public green investment implemented by all countries in the HM1.5 scenario which mitigates global temperature increases and reduces climate shocks, which is particularly relevant for the most climate-exposed countries. Indeed, their GDP profile is significantly higher in the HM1.5 scenario as compared to the HM2.0 one (figure 8), and this leads to a significantly sounder debt/GDP long-term dynamic (figure 9).

This section has presented simulations that suggest that a carbon tax whose revenues are returned in the form of green incentives, combined with deficit financed public investments in green activities, can be effective in achieving the Paris Agreements goals and in supporting the recovery of the global economy, while at the same time protecting long-term fiscal sustainability. An important point that emerges from the simulations is that it is in the interest of each individual country group to increase debt-financed green public investments as this would support the recovery, reduce GHG emissions and therefore temperature increases, with its negative effects on activity, and in turn improve debt sustainability.

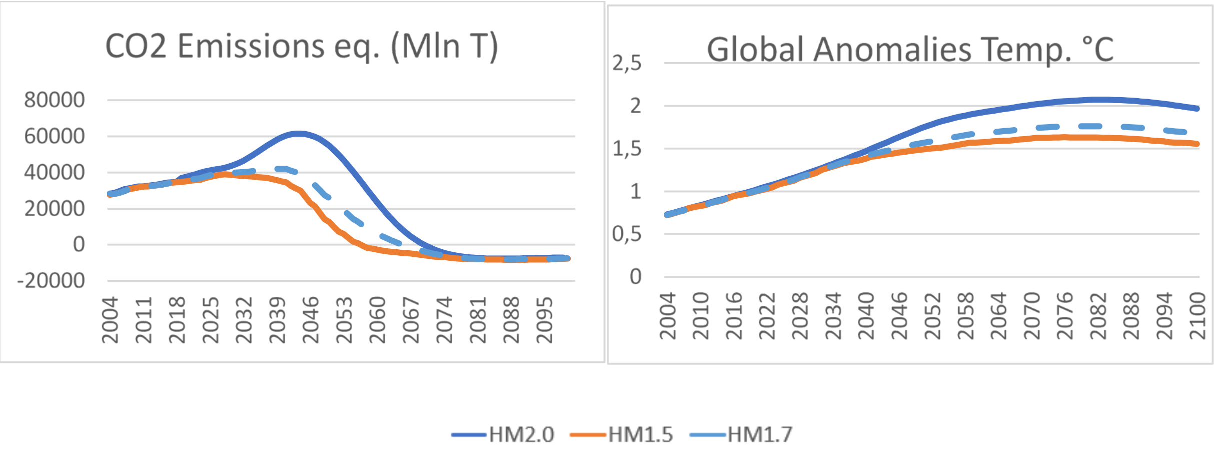
V. International Spillovers

Financing constraints aside, low-income countries would also benefit from green public investment.

Who should pay for the transition to a green economy? The international distribution of these costs is the final issue addressed in this paper. Given that the major emitters are overwhelmingly represented by advanced and emerging economies with more financial capacity, they can better afford to pay the cost of reducing emissions more aggressively. Several of the low-income and vulnerable countries simply cannot afford to increase public green investment and may have other objectives competing for their scarce resources. An alternative scenario in which only advanced and emerging economies increase public investments (HM1.7 in figures 10-12), is therefore evaluated. Although low-income and vulnerable countries carry a limited weight in terms of emissions, the CO2 emission path in this last scenario is higher than in the HM1.5 (figure 10), leading to temperatures increases of 1.7 degree. The results show that greater spending on green public investment in advanced and emerging economies, not only boosts domestic demand and induces positive trade spillovers for low-income and vulnerable countries but has the added benefit of mitigating temperature increases. Figure 12 shows that while low-income and vulnerable economies have a weaker recovery in the short run compared to advanced and emerging countries, due to the lack of green public investment, they also have a smaller increase in public debt (figure 11).

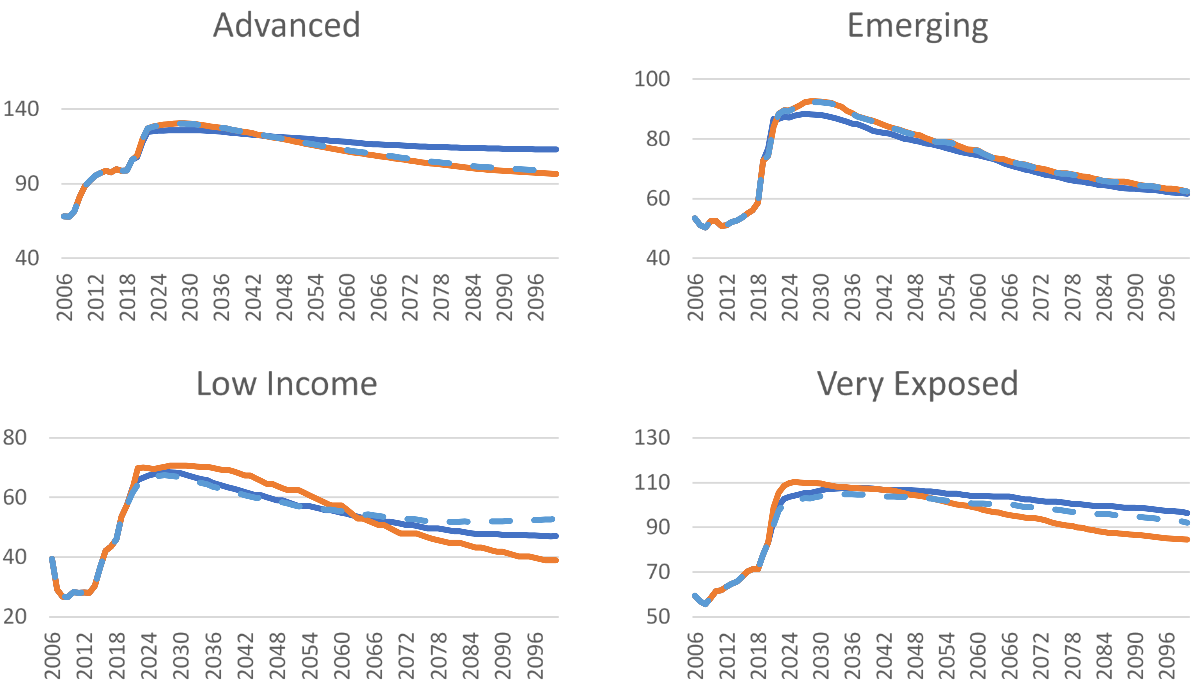
Financing constraints aside, the model shows that low-income and vulnerable countries would indeed benefit from increasing their own green public investment although that would require the introduction of measures to help easing the financing constraints. Although this would lead to an initial increase in debt/GDP, long-term debt dynamics would improve. This can be seen in the long-term profile of debt/GDP in the HM1.5 and HM1.7 scenarios in Figure 11. This is the case because green public investments would support the recovery, ensure a higher growth path, and further contribute to keeping temperatures contained, which would especially benefit those countries that are highly exposed to climate risks.

Figure 10 – CO2 Emissions and global temperatures anomalies in different scenarios



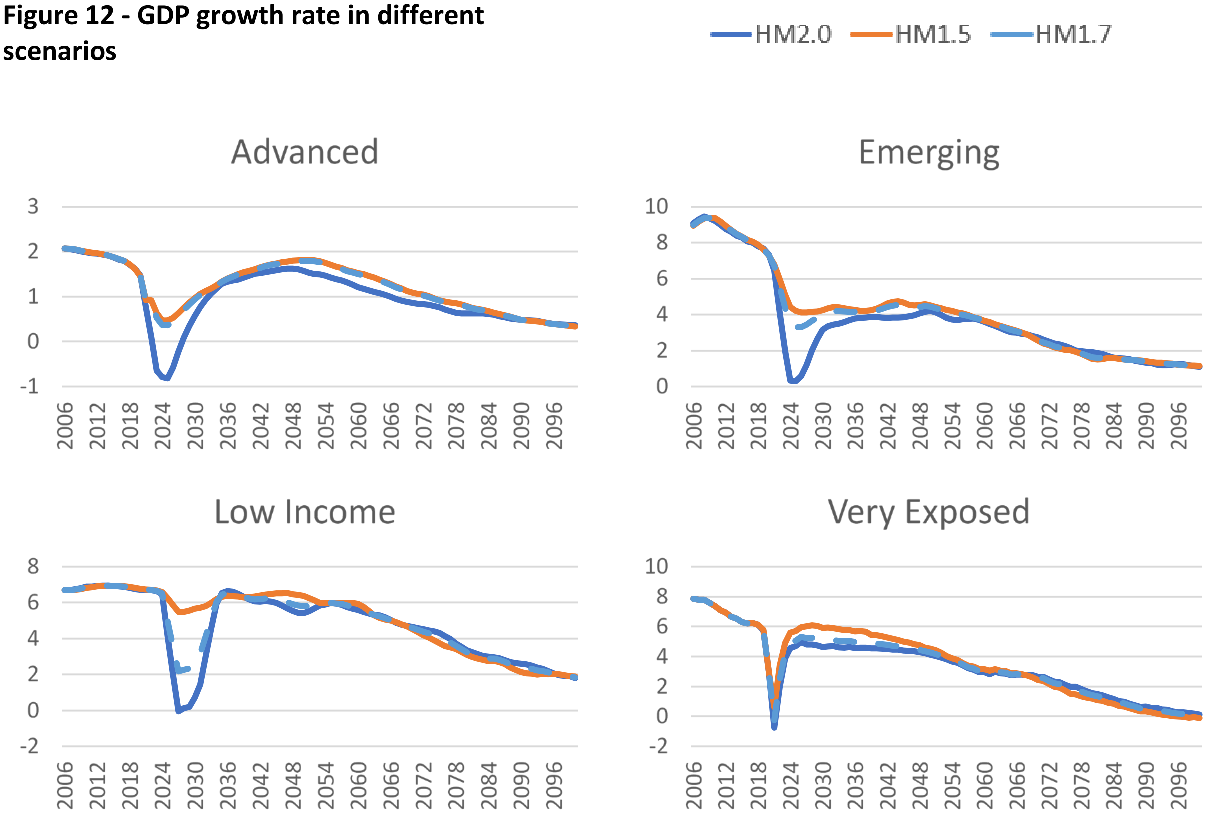
Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **HM1.7**: 1.7° increase in temperatures, with carbon revenues rebated in green incentives and only AE and EME increasing green public spending.

Figure 11 - Public debt to GDP ratio in different scenarios



Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **HM1.7**: 1.7° increase in temperatures, with carbon revenues rebated in green incentives and only AE and EME increasing green public spending.

Figure 12 - GDP growth rate in different scenarios



Note: **HM2**: 2° increase in temperatures, with carbon revenues rebated in green incentives; **HM1.5**: 1.5° increase in temperatures, with carbon revenues rebated in green incentives and all countries increasing green public spending; **HM1.7**: 1.7° increase in temperatures, with carbon revenues rebated in green incentives and only AE and EME increasing green public spending.

VI. Robustness and Caveats

The results of long-term scenario analysis should be interpreted with caution. The long-term horizon per se is a source of uncertainty, as model simplifications and approximation that might not lead to large errors within a short horizon could compound over time and lead to large deviations in the long-run. One such element is related to interest rates. The OLG model used in this paper is an equilibrium model, which under baseline UN population projections and technology assumptions, leads to low equilibrium risk-free interest rates for a prolonged period of time. As more countries in the world significantly increase their borrowing levels for purposes largely unrelated to green spending needs, borrowing costs can rise. Borrowing costs can rise also if risk-premiums, which are not modeled in this paper, increase. A different dynamic of borrowing costs would require to reconsider the debt sustainability results. A similar argument works for the intensity of the climate damages. Assuming more intense effects of rising temperatures on the economy would weaken the growth prospects going forward, although it would make an even more urgent case for a rapid increase in green public investment.

More generally, while the results relative to the levels of the variables, especially GDP growth and public debt/GDP, should be taken with caution, more trust should be given to the comparisons across different scenarios. Slightly different calibrations are not going to change the key finding that a combination of carbon pricing and public green investments is a superior option in terms of growth outcomes and debt sustainability in the long-run; or the finding that very exposed countries would greatly benefit from additional public green investments on the part of advanced and emerging countries. Finally, as shown in Catalano et al. (2020), the results from the model are robust to changes in parameter values and modeling assumptions.

VII. Conclusions

This paper has presented simulations suggesting that carbon pricing, fiscal incentives for private green investments and debt-financed green public investments should be combined to speed up the recovery from the Covid-19 induced recession and hasten the transition to a green global economy. Debt-financed public investment in green activities has three main advantages: 1) speeding-up the recovery from the Covid-19 recession; 2) reducing carbon emissions to levels committed to under the Paris Agreement; and 3) improving the long-run debt dynamics in all countries and especially in those more exposed to climate shocks, notwithstanding the initial increase in debt necessary to finance the investment increase.

Indeed, the simulations show that, even if the additional public green investment is financed with debt, it improves long-run debt sustainability in all countries especially if all countries participate in the effort. By limiting climate related damages, especially in those countries more exposed to climate shocks, the additional public investment improves fiscal sustainability and fiscal space in all countries. If the additional public green investment is implemented only in high-emitting countries (typically advanced and emerging), it would enhance fiscal sustainability domestically and have large positive spillovers, especially for those countries most exposed to climate shocks.

Appendix

The model

In order to quantify the effects of fiscal policies on emissions and thus on transition and physical risks, we have built a two-stage model. At the macro level, it describes the determinants of growth (Section 1). And at the sectoral level, it allows to disaggregate emissions by sector, ensuring a consistent general equilibrium solution (Section 2). The model is completed with a climate module (Section 3) and calibrated for each area (Section 4).

At the macro level, we use a multi-country overlapping generations model (following the original contribution of Auerbach and Kotlikoff, 1987) for four economic areas: advanced countries; emerging countries; low income countries and small economies very exposed to climate shocks. In this appendix, we describe the main elements of the model for each area. The model includes United Nations long-term demographic and human capital projections for the different countries. Population dynamics in turn affects labor supply, and capital accumulation through agents' saving behaviors and interest rate levels. The approach based on the overlapping generations makes it possible to analyze the determinants of capital accumulation in a general equilibrium growth model, i.e. the extent to which cohorts save, consume, work and thus affect capital accumulation. The core sectors in the macro model are households, firms and government for each country r.

Once the macro model is defined, we solve for the sectoral disaggregation following van der Mensbrugghe [2011]. Each sector/market is analyzed in equilibrium. From the sectoral dynamics, we obtain disaggregated CO2 emissions and in turn feedback effects on the macro economy at the regional level using a climate module (FUND, Anthoff et al. [2014]). All variables are defined in real terms by using the consumption basket price of the US as *numeraire*.

1. Macro-Economic module

1.1 Households

The economy is populated by individuals divided into 101 age cohorts, with ages ranging from zero to a maximum of 100 years, split in 3 education levels (primary, secondary and tertiary). We feed the model with United Nations [2019] long-term population projections, as in Borsch-Supan et al. [2006]. This implies that cohorts are different in size, based on the age distribution resulting from UN population projections, which provides cohort dimensions for each age group, from 0 to 100+. Therefore, demography is taken as exogenous. In each country r and period t the size of population of age $t - s$, with s being the birth year, is denoted by $P_{t,s,r}$, with a survival rate (that is the ratio between the size of cohort s and s+1) defined as $\chi_{t,s}$.

The households' life-cycle stream utility is given by:

$$U = \sum_{t=s}^{s+T} \chi_{t,s} \frac{u\left[c_{t,s}, (e_t - l_{t,s})\right]^{1-1/\xi}}{1-\frac{1}{\xi}} \frac{1}{(1+\rho)^{t,s}}$$

where *c* denotes consumption goods and *l* is the individual labor supply (measured in efficiency units relative to the time endowment *e*).[12] *T* is longevity (101 years of life for each cohort at birth), ρ denotes the rate of time preference which is cohort invariant, ξ defines the intertemporal elasticity of substitution, and $\chi_{t,s}$ is the survival rate at age *t,s*.

Utility - of the constant elasticity substitution type - at time *t* for a particular working cohort aged *t,s* is given by

$$u(c_{t,s}, e_{t,s} - l_{t,s}) = \left[c_{t,s}^{(1-\frac{1}{\epsilon})} + \alpha\left(e_{t,s} - l_{t,s}\right)^{(1-\frac{1}{\epsilon})}\right]^{\frac{1}{1-\frac{1}{\epsilon}}}$$

where ε denotes the substitutability of consumption and leisure, and α the intensity of preference for leisure relative to consumption.

Households maximize utility in equation (1) subject to:

$$a_{t+1,s} = \begin{cases} \frac{1}{\chi_{t,s}}\left(1 + r_t - \tau_{a,t}\right) a_{t,s} + \bar{w}_{t,s} h_{t,s} l_{t,s} - (1 + \tau_{c,t}) p_t c_{t,s} + \pi^k_{t,s} + \pi_{t,s}, & \text{if } s < T_r \\ \frac{1}{\chi_{t,s}}\left(1 + r_t - \tau_{a,t}\right) a_{t,s} + pens_{t,s} - (1 + \tau_{c,t}) p_t c_{t,s} + \pi^k_{t,s} + \pi_{t,s}, & \text{if } s \geq T_r \end{cases}$$

$\pi^k_{t,s}$ [13]

The optimal labor/leisure choice gives the following first order condition:

$$e_{t,s} - l_{t,s} = \left(\frac{[w_{t,s} h_{t,s} + \mu_{t,s}](1 - \tau_{l,t})}{p_t \alpha (1 + \tau_{c,t})}\right)^{-\epsilon}$$

where $[w_{t,s} h_{t,s} + \mu_{t,s}](1 - \tau_{l,t})$ denotes the effective cost of leisure and $\mu_{t,s}$ the shadow wage rate. If leisure is less than the total time endowment *e*, $\mu_{t,s} = 0$. If $e_{t,s} \leq l_{t,s}$, the shadow wage rate $\mu_{t,s} \geq 0$, i.e. it reduces leisure demand to the time endowment.

The Euler equation for the intertemporal consumption choice is:

$$\frac{c_{t+1-s}}{c_{t-s}} = \left[\frac{1 + \tau_{c,t}}{1 + \tau_{c,t+1}} \frac{1 + r_{t+1} - \tau_{a,t}}{1 + \rho}\right]^{\xi} \left[\frac{1 + \alpha\epsilon(v_{t+1-s})^{1-\epsilon}}{1 + \alpha\epsilon(v_{t-s})^{1-\epsilon}}\right]^{\frac{\epsilon-\xi}{1-\epsilon}},$$

---

[12] Labor supply *l* is measured in efficiency units relative to the time endowment *e*. We assume that *e* grows at the human capital growth rate *h*˙, i.e. $e_{t+1} = e_t(1+h)$. We assume that human capital stabilizes in the very long-run. These conditions overcome inconsistencies about “growth compatible preferences”. See Borsch-Supan et al. [2006] for a discussion.

[13] Profit shares are defined in terms of population share of cohorts *t,s* over the whole population.

where $v_{t,s} = [w_{t,s}h_{t,s} + \mu_{t,s}](1 - \tau_{l,t})$ and p_t denotes the GDP deflator. When individuals retire, $l = 0$ and leisure is equal to e. The Euler equation therefore is given by:

$$\frac{c_{t+1,s}}{c_{t,s}} = \left[\frac{(1+\tau_{c,t})p_t}{(1+\tau_{c,t+1})p_{t+1}}\frac{(1+r_{t+1})-\tau_{a,t}}{1+\rho}\right]^{\xi}$$

1.2 Firms

In each country r, the production sector is characterized by a representative firm which uses a Cobb-Douglas technology with increasing returns to scale which combines the capital stock, K_t with the effective labor input L_t:

$$Y_{r,t} = Z_{r,t}K_{r,t}^{\beta}L_{r,t}^{1-\beta}, \quad Z_{r,t} = (1-D_{r,t})TFP_{r,t}$$

where $0 \leq \beta \leq 1$ is the capital share, TFP_t the endogenous total factor productivity, and $L_t = H_tN_t$, with N_t denoting the aggregate hours worked and H_t the human capital level. As in Kotlikoff et al. [2019], the climate damage D_t alters the total factor productivity according to the time-t TFP-damage function defined as in Nordhaus [2008] and Nordhaus and Yang [1996]:

$$D_{r,t} = 1 - \frac{1}{1+\pi_{r,1}T_t^A+\pi_{r,2}(T_t^A)^2}$$

T_t^A

[14] The endogenous growth process is modeled linking physical capital per worker and human capital à la Romer [1990] as follows:

$$TFP_{r,t} = \left(\frac{K_{r,t}}{N_{r,t}}\right)^{g} H_{r,t}^{z}$$

where g and z denote the contribution of the production factors to TFP_t. In particular, g measures the capital-per-worker contribution in technology creation, and z is the contribution of human capital.[15]

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[14] The coefficients $\pi_{r,1}$ and $\pi_{r,2}$ are calibrated as in Kotlikoff et al. [2019].

[15] Growth models, which include population projections, usually acknowledge the role of human capital and increasing return to scale. Indeed, the growth rate of the economy is proportional to the total amount of knowledge/ideas in the economy. An increase in the size of the population, other things equal, raises the average aggregate human capital and therefore leads to an increase in the per-capita income. The inclusion of non-rivalrous input, such as human capital/ideas, linked to population dynamics, in the production function leads to increasing returns to scale (Romer [1990]). Given the following production function $Y_t = H_t^{z+1-\beta}K_t^{g+\beta}N_t^{1-\beta-g}$,

Productivity improvements are a result of the interaction between capital-to-labor ratio (i.e. the number of machines per unit of labor) and human capital endowment (i.e. labor quality).

TFP is therefore modeled at the aggregate level and not for each single sector. This assumption could be relaxed by assuming, for example, a different *TFP* for the brown and green energy sectors. This could ease the transition, as - in the scenarios compatible with the Paris Agreements - capital is accumulated more quickly in the green sectors and therefore *TFP* should grow faster in these sectors. However, since we model the *TFP* following the macro literature, we have not taken this approach. Modeling technological innovation in the green sector would require a more careful understanding of the factors of technological progress at the sectoral level (Acemoglu ate al 2012).

In each region a continuum of firms, $n \in [0,1]$, is divided into segments of firms borrowing capital on a specific foreign area n_v, $v = 1,...,r,...,R$. This modeling device allows us to consider market segmentation and to mimic the financial degree of openness among countries and to consider separately the domestic and foreign sources of financing. Therefore, aggregate capital stock in country r is the integral of individual capital firm endowment $K_{r,t}(n)$,

$$K_{r,t} = \sum_v \int^{\theta_v} K_{v,t}(n)dn = \sum_v K_{r,v,t} = \sum_v \theta_v K_{r,t}$$

where θ_v denotes v-segment length of uniform firms. Therefore θ_v corresponds to the share of capital stock from country $v = 1,...,r,...,R$, with R denoting the number of countries in the model. Conversely, labor is internationally not-mobile. In the following exposition, we suppress the index r for notation simplicity.

Firms' profits in each region are given by:

$$\pi_t = p_t Y_t - (r_t + \delta_t)K_t - w_t L_t \tag{11}$$

where δ denotes the depreciation rate using the capital. Firms set their optimal capital stock demand for $K_{v,t}$ and labor demand L_t. The f.o.c.'s are the following:

$$\begin{aligned} r_t &= \sum_{v=1}^{n} \theta_{v,t} \left(p_t TFP_t \beta f^{'}_{K,v,t} - \delta_{v,t} \right) \\ w_t &= p_t TFP_t (1-\beta) f'_L. \end{aligned} \tag{12}$$

1.3 Government

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there are constant returns to scale in capital K_t and labor N_t, and increasing returns to human capital, where the degree of increasing returns is measured by $z + 1 - \beta > 0$, with $z > 0$ and $0 \leq \beta \leq 1$. In particular, we estimate z, β and g. For many countries the sum of exponents is positive. Therefore, as human capital, H_t, in our model is exogenous, but it is not constant over time as it depends on exogenous population projections and education levels.

$\zeta_t = \sum_i \sum_{s=T_r+1}^{T} P_{t,s,i}$

$$\Delta B_t = r_t B_t - \tau_{l,t} w L_t - \tau_{c,t} p_t C_t - \tau_{a,t} A_t + sg_t + \zeta_t pens_t + G_t - rev_{co2,t} + inv_t, \qquad (13)$$

where $\tau_{a,t}A_t$, $\tau_{l,t}wL_t$ and $\tau_{c,t}p_tC_t$ denote respectively revenues from taxation of aggregate savings, labor and consumption taxation. We assume $G_t = \gamma Y_t$, i.e. the public spending (public consumption and investment) is a constant fraction of GDP; sg_t is public spending on education. r_tB_t denotes the real interest repayment on public debt and $\Delta B_t = B_{t+1} - B_t$ denotes public debt change. $rev_{co2,t}$ and inv_t denote respectively revenues from carbon taxation and green public investment.

1.4 Aggregation

In each country r, for each cohort s and education level i, the total aggregate wealth supply $A_{r,t}$ is equal to:

$$A_{r,t} = \sum_{i \in I} \sum_{s=s_0}^{T} a_{t,s,i,r} P_{t,s,i,r}$$

where $s_{0,i}$ is the year in which the cohort aged t,s becomes employed; $P_{t,s,i,r}$ is the population aged t,s in year t; T denotes the contribution years required in year t to obtain a pension. In the same way, given individual-cohorts labor supply we aggregate obtaining the indexes $L_{r,t}$ and $N_{r,t}$.. Aggregate capital evolves according to the following equation:

$$K_{r,t+1} = (1 - \delta_{r,t})K_{r,t} + I^*_{r,t} + \psi(I^*_{r,t}, K_{r,t}) \ (17)$$

where $I^*_{r,t}$ denote the sum of public and private investments, and $\psi(I^*_{r,t}, K_{r,t})$ the aggregate investment adjustment cost. In each country r, we define the net foreign asset position as:

$$F_{r,t} = A_{r,t} - q_{r,t}K_{r,t} - B_{r,t} \qquad (18)$$

where $F_{r,t}$ denotes the amount of net foreign assets, $A_{r,t}$ the aggregate wealth in eq. (16), $q_{r,t}$ the value of capital (q-Tobin) and $B_{r,t}$ the public debt of region r that is assumed to be held entirely by domestic agents. It is worth to note that all variables in equation (18) are defined in real terms. In the closed economy framework, the rate of return on capital in one country is equal to the marginal productivity of capital in that country (equation 12). Moreover, any country's foreign

$K_{r,t} = \frac{A_{r,t} - B_{r,t}}{q_{r,t}}$

2. Sectoral disaggregation

2.1 Investment allocation

The economy is disaggregated into sectors labelled as $j=1,\ldots J$. In each sector a homogenous good is produced with sector specific inputs such as capital goods among others (see section 2.2). Here, we focus on the intermediate sector that allocates aggregate investment set at the macro level (see section 1.2 and 1.4) to the most profitable sectors in terms of financial expected profitability. The sector is a financial intermediator that disaggregates the macro-level capital for each region $K_{r,t}$ in capital stocks $K_{j,r,t}$ used for the j-sector production. Given the aggregate capital stock dynamics, an aggregate investment flow $I_{r,t}$ is determined for each region. The financial intermediate firm buys at price $q_{t,r}$ the investment goods $I_{r,t}$, allocate it into differentiated investments goods, $I_{j,r,t}$.[16] The firm earns from the revaluation of the sectoral investment depending on the dynamics of the price $q_{j,r,t}$. The objective function of the financial intermediator is the expected discount streams of profits given by:

$$V_{r,t} = \pi_{r,tk} + \lambda\hat{}_{r,t+1} V_{r,t+1} \qquad (19)$$

$$\hat{\lambda}_t \equiv \sum_s \beta^s \lambda_{t,s} \frac{P_{t,s}}{P_t}$$

$$\pi_{r,tk} = \sum^{k}{}_{j} q_{j,r,t} I_{j,r,t} - q_{r,t} I_{r,t} + \sum^{k}{}_{j} r_{j,r,t} K_{j,r,t}$$

where $r_{j,r,t}$ is the return on sectoral capital $K_{j,r,t}$ rent-out to the production sectors. The value function in equation (19) is maximized subject to:

$$I_{r,t} = \left[\sum_j \gamma_{j,r,t} (I_{j,r,t})^{1-\eta} \right]^{1/(1-\eta)}$$

and

$$K_{j,r,t+1} = (1 - \delta_{r,t}) K_{j,r,t} + \hat{I}_{j,r,t} + \psi(\hat{I}_{j,r,t}, K_{j,r,t}) \qquad (22)$$

---

[16] Aggregate capital stock is differentiated in the form of technological compatibility in terms of production function usability in sector *j*. At the beginning of period *t,* investment is allocated across sectors, accumulated into differentiated capital stock and then it is rent-out for production. At the end of the period, the differentiated capital stocks depreciate and in the next period are used for production. Finally, total investment in the economy is given by the aggregation of sectoral investment (equation 21).

with $\gamma_{j,r,t}$ and η denote respectively the share and the elasticity of the investment CES function (eq. 21). We set the total investment flow as total sectoral investment, $\hat{I}_{j,t} = I^*_{j,t} + I_{j,t}$ with $I^*_{j,t}$ denoting public investment in sector j in the law of motion for the j-sector capital stock (eq. 22), such that $inv_t = q_{j,r,t} I_{j,r,t}{}^*$ (see equation (13)). The investment adjustment cost $\psi(I_r,K_r)$ is defined as

$$\psi(I_{j,r,t}, K_{j,r,t}) = \frac{\phi}{2} \frac{I^2_{j,r,t}}{K_{j,r,t}}$$

with $\varphi \geq 0$.

Equation (19) is maximized over future capital stock of sector j, $K_{j,r,t+1}$, and the investment goods flow $I_{j,r,t}$. Therefore, we obtain the following FOCs:

$$q_{j,r,t} = \beta(1 + r_{t+1}) \left[(1 - \delta_j) q_{j,r,t+1} + r_{j,r,t+1} + \psi^{'}(i_{t,r,j}) \right] \tag{23}$$

$$I_{j,r,t} = \gamma_{j,r,t} \left(\frac{q_{j,r,t}}{q_{r,t}} \right)^{-\eta} I_{r,t} + (q_{j,r,t} - 1) \frac{K_{j,r,t}}{\phi}. \tag{24}$$

Equation (23) defines the price of capital goods dynamics (q-Tobin) given expected return in sector j and equation (24) states that the aggregate investment goods are allocated to sector j proportionally to relative prices. Moreover, additional investment in sector j requires $q \geq 1$. Given the value of capital in each sector j obtained from equation (23) we get the value of the aggregate capital $q_{t,r}$:

$$q_{t,r} = \left[\sum_j \gamma_{j,t,r} q^{1-\eta}_{j,t,r} \right]^{1/(1-\eta)} . \tag{25}$$

2.2 The quantity nested system

In this section we describe how we nest the sectoral model (see van der Mensbrugghe [2011]) into the macro-growth model. Figure 1 in the main text depicts the structure. The model used to allocate resource among sectors aims at defining the CO2 emissions for each sector and region thus considering the heterogeneity in the transition process across areas. The energy sectors included in the model are: *oil*, *gas* and *coal* as brown energy production sectors with low CO2 emission efficiency; and *green*[17] and *beccs*[18] as high and negative emissions efficiency, respectively.

We follow a top-down approach that regulates the sectoral allocation of the GDP defined in the macro-model. For each *r* region the economic structure defines a hierarchical price system reflecting the sectoral specialization of each region. Therefore, the macro-model receives feedbacks in the form of price signals (GDP deflator, aggregate *q*-Tobin, etc.) reflecting also the effects of carbon taxation or other mitigation policies.

Analytically, the sectoral model is composed of four objects: (1) a CES production functions nested on multiple levels; (2) for each level, the cost functions to be minimized taking into account the CES functions in point (1); (3) optimal demand functions for production inputs obtained from the maximizations in point (2); (4) aggregated price functions for each level of the hierarchy of the production structure. In this section, we describe the point (1) and some details of point (3).

While the macro-model defines output in terms of aggregate macro-inputs and from a supply side perspective, the sectoral model defines the corresponding production $Y_{r,t}$ at the sectoral level taking into account the disaggregated economic structure. Aggregate output, computed solving the OLG model, is then disaggregated at the sectoral level through a system of relative prices. In the following we show the sectoral model starting with the supply side and then providing a description for the demand conditions. General equilibrium conditions are satisfied in each sector matching supply and demand through price determination.

In each region *r*, the aggregate regional output $Y_{r,t}$ is given by a CES function of intermediate goods $XD_{t,r}$ and final goods $VA_{t,r}$:

$$Y_{r,t} = [\gamma_y (XD^s_{r,t})^{\sigma_y} + (1-\gamma_y)(VA_{r,t})^{\sigma_y}]^{1/\sigma_y}$$

The sector minimizes costs defined as:

$$py_{r,t}Y_{r,t} - pd_{r,t}XD^s_{r,t} - pva_{r,t}VA_{r,t}$$

subject to (26). Therefore, we have optimal demand functions:

$$\begin{aligned} XD_{r,t} &= \gamma_y \left(\frac{py_{r,t}}{pd_{r,t}}\right)^{\sigma_y} Y_{r,t} \\ VA_{r,t} &= (1-\gamma_y) \left(\frac{py_{r,t}}{pva_{r,t}}\right)^{\sigma_y} Y_{r,t} \end{aligned} \qquad (28), (29)$$

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[17] As green energy sources we consider renewable energies: geothermal energy; hydroelectric energy; marine energy; solar energy; wind energy; biomass energy; waste-to-energy; energy or cogeneration from groundwater.

[18] Bio-energy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.

with $py_{r,t}$, $pd_{r,t}$ and $pva_{r,t}$ denoting GDP deflator, and the prices of the bundles *XD* and *VA* respectively. Substituting the equations (28) and (29) into (26) we obtain the definition for the GDP deflator used in the macro model:

$$py_{r,t} = [\gamma_y(pd_{r,t})_{\sigma_y} + (1 - \gamma_y)(pva_{r,t})_{\sigma_y}]_{1/\sigma_y}. \tag{30}$$

The sectors producing intermediate and final goods are defined in a similar way to the aggregate sectors. Therefore, we omit the profit definitions providing only the optimal demand conditions (see appendix C in Catalano ate al 2020). For the sake of simplicity, we omit the regional index in the following.

The final good *VA* is a bundle of manufacturing *MA*, agriculture *AG* and services *SERV* goods:

$$VA_t = [\gamma_{va,1} MA_t^{\sigma_{va}} + \gamma_{va,2} AG_t^{\sigma_{va}} + (1 - \gamma_{va,1} - \gamma_{va,2}) SERV_t^{\sigma_{va}}]^{1/\sigma_{va}}$$

Agriculture production is obtained through crops (*CR*) and livestock (*LS*):

$$AG_t = [\gamma_{ag}(CR_t)_{\sigma_{ag}} + (1 - \gamma_{ag})(LS_t)_{\sigma_{ag}}]_{1/\sigma_{ag}}, \tag{32}$$

and manufacturing is divided into high energy manufacturing (HMA) and low energy manufacturing (LMA):

$$MA_t = [\gamma_{ma} HMA_{\sigma t\ ma} + (1 - \gamma_{ma}) LMA_{\sigma t\ ma}]_{1/\sigma_{ma}}. \tag{33}$$

From the demand side, in each region *r*, overall aggregate demand XA_t is defined as follows

$$XA_t = w_t H_t L_t + r_t K_t. \tag{34}$$

XA_t is satisfied by both domestic (*XD*) and imported goods (*XMT*):

$$\begin{aligned} XD_t^d &= \beta^d \left(\frac{pa_t}{pd_t}\right)^{\sigma_m} XA_t \\ XMT_t &= \beta^d \left(\frac{pa_t}{pmt_t}\right)^{\sigma_m} XA_t \end{aligned} \tag{35}$$

where *pa*, *pd* and *pmt* denote the price of the bundle *XA*, the price of the domestically produced goods *XD* and the price of imports *XMT* respectively. Import for region *r* is distributed to each region *r*' as follows:

$$WTF_{r,t}^{d,r'} = \beta_w \left(\frac{pmt_{r',t}}{pm_t}\right)^{\sigma_w} XMT_t$$

where *pm* is the aggregate price of imports in region *r* from the various *r'* regions. Exports towards different regions *r*' are defined as follows:

$$WTF_{r,t}^{s,r'} = \beta_w \left(\frac{pmt_t}{pe_t}\right)^{\sigma_x} ES_t(1 - w_{mg})$$

where exports of region *r* are defined as follows:

$$ES_t = \gamma_{es} \left(\frac{pe_t}{p_t} \right)^{\sigma_x} Y_t (1 - w_{mg})$$

with $(1-w_{mg})$ denoting trade related transportation costs.

2.3 The bottom layer of the sectoral model: Maximizing profit, minimizing CO2 emissions

In this section, we describe the bottom layer of the model and the introduction of the carbon pricing. Firms of sector *j* = *hma, lma, cr, ls, serv* produce goods *Q*(*j*) using land (LA), energy (CO2), and a capital and labor bundle *KT* (see equation 40 below). Profits at time *t* are defined as the difference between the revenues from production and the total costs:

$$\pi(j)_t = p(j)_t Q(j)_t - \sum\nolimits_j^k \left[(p(j)_{k,t} + \tau_{co2,t}) CO2(j)_{k,t} + ct(j)_{k,t} KT_{k,t} + pland(j)_{k,t} LA(j)_{k,t} \right] \qquad (39)$$

where *k* = *oil, carbon, gas, green, beccs* is the index of energy source for any sector *j*. The term *ct* denotes the average cost of input *KT* and *pland* is the sector specific price of land. KT is defined as a CES function of capital (*K*) and labor (*L*) with efficiency index *B(j)*:

$$KT(j)_t = B(j)_t \left[\sum_k \gamma_{k,t,j,1} \left(\theta_{k,t,j,1} K(j)_{k,t} \right)^{\rho_j} + \sum_k \gamma_{k,t,j,2} \left(\theta_{k,t,j,2} L(j)_t \right)^{\rho_j} \right]^{\frac{1}{\rho_j}} .$$

Finally, the term $(p(j)_{k,t} + \tau_{co2,t}) CO2(j)_{k,t}$ indicates the total cost of *CO*2 emissions[19] and includes a positive carbon price τ_{co2} for brown energy sources, while a negative one for green energy sources. Firm's profit maximizations are subject to CES technological constraint:

$$Q(j)_t = A(j)_t \left[\sum_k \gamma_{k,t,j,1} \left(\theta_{k,t,j,1} CO2(j)_{k,t} \right)^{\rho_j} + \sum_k \gamma_{k,t,j,2} \left(\theta_{k,t,j,2} KT(j)_{k,t} \right)^{\rho_j} + \sum_k \gamma_{k,t,j,3} \left(\theta_{k,t,j,3} LA(j)_t \right)^{\rho_j} \right]^{\frac{1}{\rho_j}}$$

$$\sigma = \frac{1}{1-\rho}$$

In order to set the carbon price we define an exogenous emission dynamic constraint $\overline{CO2}_{r,t}$ on total regional actual emissions:

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[19] We translate energy inputs into emissions defined in tons.

$$\sum_{j} CO2(j)_{r,t} = CO2_{r,t} <= \overline{CO2}_{r,t}$$

The emissions constraint is calibrated by region considering the global constraint defined by the Paris Agreements and allocating it to the different regions/countries on the basis of the share of country-specific emission on total emissions in 2020. These shares are then kept constant over the entire simulation horizon. The goal is to set a regional tax to affect the relative prices of the green-brown energy mix. The value of the firm to be maximized w.r.t. $CO2(j)$, $KT(j)$, $LA(j)$, $K(j)$ and $L(j)$ is:

$$V(j)_t = \lambda_t \pi_{j,t} + \varphi_{co2}(\overline{CO2_t} - CO2_t) \tag{43}$$

where φ_{co2} is the Lagrange multiplier of the binding constraint in equation (42). Maximizing (43) subject to (41) and using (42) we can get the following first order conditions:

$$CO2(j)_{k,t} = \frac{1}{A(j)_t}\gamma_{k,t,j,1}\theta_{k,t,j,1}^{\sigma_j-1}\left(\frac{p(j)_{k,t}+\tau_{co2}}{p(j)_t}\right)^{-\sigma_j} Q(j)_t,$$

$$KT(j)_{k,t} = \frac{1}{A(j)_t}\gamma_{j,t,j,2}\theta_{k,t,j,2}^{\sigma_j-1}\left(\frac{ct(j)_{k,t}}{p(j)_t}\right)^{-\sigma_j} Q(j)_t,$$

$$LA(j)_{k,t} = \frac{1}{A(j)_t}\gamma_{j,t,j,3}\theta_{k,t,j,3}^{\sigma_j-1}\left(\frac{pland(j)_{k,t}}{p(j)_t}\right)^{-\sigma_j} Q(j)_t.$$

If actual carbon emissions in region r are lower than the constraint (42), τ_{co2} is zero, otherwise it is positive. The carbon tax τ_{co2} is defined in consumption units: $\tau_{CO2,t} = \frac{\phi_{CO2} p_t}{u_c}$ is the carbon price with p_t and u_c being the consumption basket (dollars) price and average marginal consumption units. The carbon price is priced in terms of final consumption goods unit and reflects the cost in terms of real consumption. All the firms are owned in equal shares by the cohorts living in each period.

Finally, the demands for capital and labor are defined as:

$$K(j)_{k,t} = \frac{1}{B(j)_t}\gamma_{j,t,1}\theta_{k,t,1}^{\sigma_j - 1}\left(\frac{r(j)_{k,t} + \delta_j}{ct(j)_{k,t}}\right)^{-\sigma_j} KT(j)_{k,t}$$

$$L(j)_{k,t} = \frac{1}{B(j)_t}\gamma_{j,t,2}\theta_{k,t,2}^{\sigma_j - 1}\left(\frac{w(j)_{k,t}}{ct(j)_{k,t}}\right)^{-\sigma_j} KT(j)_{k,t}$$

Using (40) we get the average prices:

$$ct(j)_{k,t} = \frac{1}{B(j)_t}\left[\sum_k \gamma_{k,t,j,1}\left(\frac{r^k(j)_{k,t}}{\theta_{k,t,j,1}} + \frac{\gamma_{t,k,j,2}w(j)_{k,t}}{\theta_{k,t,j,2}}\right)^{1-\sigma_j}\right]^{\frac{1}{1-\sigma_j}},$$

.

$$p(j)_t = \frac{1}{A(j)_t}\left[\sum_k \gamma_{k,t,j,1}\left(\frac{p(j)_{k,t} + \tau_{co2}}{\theta_{k,t,1}} + \frac{\gamma_{j,t,j,2}ct(j)_{k,t}}{\theta_{k,t,2}}\right)^{1-\sigma_j}\right]^{\frac{1}{1-\sigma_j}}.$$

3. The climate model

In this section we describe the climate module which is based on the FUND model developed by Tol [2004], Tol [2005] and later by Anthoff et al. [2014].

The application of FUND in this study is aimed at determining the level of emissions related to the economic activity and therefore the evolution of temperatures over time. The FUND model uses estimates of population, technological and economic growth rates to compute atmospheric concentrations of CO2, CH4 and N2O, the global average temperature, the impact of CO2 on the economy and the impact of climate change damage on the economy and population. Our framework combines the described OLG model with the FUND climate module. The FUND model receives as exogenous variables the technological, economic and demographic growth rates produced by the OLG model and returns emissions and temperatures that are consistent with the macroeconomic variables. In turn, using the temperature path obtained from the FUND model, we determine the climate damage on the economy through a damage function ´a la Nordhaus.

Total CO2 and GHGs emissions in the FUND climate module are defined according to the Kaya identity that calculates the total emission as the product of four factors:

$$M_{t,r} = \frac{M_{t,r}}{E_{t,r}}\frac{E_{t,r}}{Y_{t,r}}\frac{Y_{t,r}}{P_{t,r}}P_{t,r}$$

where *M* denotes emissions, *E* denote energy use, *Y* denotes GDP and *P* denotes population; *t* is the index for time, *r* for region. The equation is used to quantify current emissions and, at the same time, to determine how the relevant factors must change over time to reach a given target level of CO2 emissions in the future (see the scenario called “Paris Agreement” where the emission target is set to zero).

Concentrations are defined according to:

$$C_{t,j} = C_{t-1,j} + \gamma M_t - \zeta(C_{t-1} - C_{pre}) \tag{52}$$

where C denotes concentration and *pre* denotes pre-industrial levels.

The atmospheric concentration of carbon dioxide follows from a five-box model. The box model describes the abundance - or concentration - of a certain gas inside a box representing a selected atmospheric area (which could be for example an urban area, a country, or the global atmosphere). This type of models allows to describe carbon exchanges between the atmosphere and the carbon reservoirs available on the planet under the disturbances due to anthropogenic CO2 emissions as well as global temperature changes. The model can successfully simulate the observed changes and variations of the atmospheric CO2 concentration across different periods. Gas concentrations are modeled as:[20]

$$Box_{t,j} = \rho_i Box_{t-1,j} + 0.000471 \alpha_j M_t \tag{53}$$

with

$$C_{t,j} = \sum_{j=1}^{5} \alpha_j Box_{j,t}$$

where α_j denotes the fraction of emissions M (in million metric tons of carbon) that is allocated to Box_j ($\alpha_j = 0.13, 0.20, 0.32, 0.25, 0.10$, respectively) and ρ the decay-rate of the boxes ($\rho = exp(-1/lifetime)$), with life-times equal to infinity, 363, 74, 17 and 2 years, respectively. The lifetime t in the box is defined as the average time that a molecule of carbon dioxide remains in the box. Thus, the 13% of total emissions remains forever in the atmosphere with an infinite life span, while 10% is - on average - removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

The FUND model contains also an expression for the radiative forcing RF, which denotes an externally imposed perturbation in the radiative energy budget of the Earth’s climate system, measured in W/m^2 (watt per square meter), and defined as a function of different gasses such as

$$RF_t = f(CO2, CH4, N2O, SF6, SO2). \tag{55}$$

The functional form of (55) is based on Meinshausen et al. [1992].

Based on the computed radiative forcing, the FUND model allows to determine global temperatures. The global mean temperature T is governed by a geometric build-up to its equilibrium value (determined by the radiative forcing RF). In the base case, global mean temperature T rises in equilibrium by $3.0^\circ C$ for a doubling of carbon dioxide equivalents, so:

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[20] In the FUND model the five-box model is due to Maier-Reimer and Hasselmann [1987], and its parameters are from Hammitt et al. [1992].

$$T_t = (1 - 1/\psi)T_{t-1} + 1/\psi \frac{cs}{5.35ln2} RF_t$$

where cs is climate sensitivity, set to 3.0. The persistence parameter is $\psi = max\ (\alpha + \beta_l cs + \beta_q cs^2, 1)$ where α is set to -42.7, β_l is set to 29.[21] We set β_q to 0.001, such that the best guess "e-folding time" (i.e. time of the temperature anomalies to persist) for a climate sensitivity of 3.0 is 44 years.

4. Calibration

In this section, we describe the calibration of the macro and sectoral models.

4.1 Calibrating the macro model

We solve the model on a yearly base until 2281, for 470 years, starting from an initial steady state assumed to be in 1812. We assume a phasing-in and a phasing-out period of 101 years, at the beginning and at the end of the simulation period, during which it is assumed that the levels of demography and human capital are stable. In this way, the final steady state is endogenous to the determination of the transition during the central simulation periods, included between the periods of phasing-in and phasing-out. The model is a system of large-scale non-linear equations with a high size (101x3x7) due to age (101), education levels (3) and number of countries/areas (7). It is trained on data between 1970-2019 and is allowed to produce projections from 2020 to 2100.

Based on the data, a number of trends are calibrated: demographics, human capital, technical obsolescence (via the depreciation rate), labor and capital share, trade integration and capital flows. In order to address the demographic impact on economic growth, we use historical population data and projections provided by the (United Nations [2019]) for the period 1960-2100, with cohorts aged between 0−100 denoted by $P_{t,s,r}$ for each region r, with (t,s) denoting the age of each cohort. In order to evaluate the role of human capital accumulation and labor productivity in the economies, we build a human capital index for each country based on the education levels provided by Barro and Lee [2015]: data on education from 1950 to 2010 are grouped into three education levels: primary (LS), secondary (HS) and tertiary (TS). The depreciation rate of capital is calibrated using IMF data for total investment and capital stock, while to calibrate the capital share β we use the labor income share data provided by ILO.

We use the GDP levels for each economy to calibrate the total factor productivity. Similarly, we use data on pension expenditure and labor tax rate to calibrate the pension benefit and the historical value of debt-to-GDP, respectively. Moreover, in order to match interest rate data, we introduce changes in the rate of time preference.

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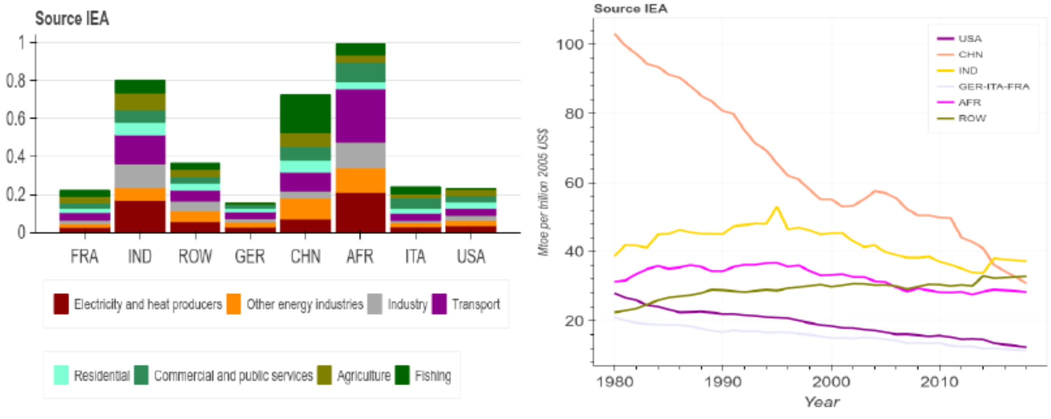
[21] The parameter is called "e-folding time", or turnover time, which is the expected time for the temperature anomalies to persist.

4.2 The sectoral calibration

We calibrate the sectoral module along the different layers of which it is composed. To do this, we use different criteria and data sources. Figure A.1 shows the dimensions along which we calibrate the model, i.e. the different countries and pollutant sectors (industry, agriculture, services). The data represent the information used to calibrate the parameters of the model. The increase in CO2 emissions has been concentrated in China, Africa and India in the transport, electricity and heating sectors, although the advanced countries have much higher historical emissions than the emerging ones (*panel a*).

Panel b shows the ratio between the calibrated total energy production and GDP of all countries included in the model. Almost all countries, have reduced their energy intensity. We also focus on livestock and crops that show an upward trend in output in non-advanced economies (*panel c and d*). Finally, *panel e* shows the composition of GDP in terms of manufacturing, agriculture and services in the different countries, while *panel f* shows the large loss of CO2 efficiency in India and China due to the growing livestock sector.

Figure A.1 Energy intensity and CO2 emissions by countries and sectors

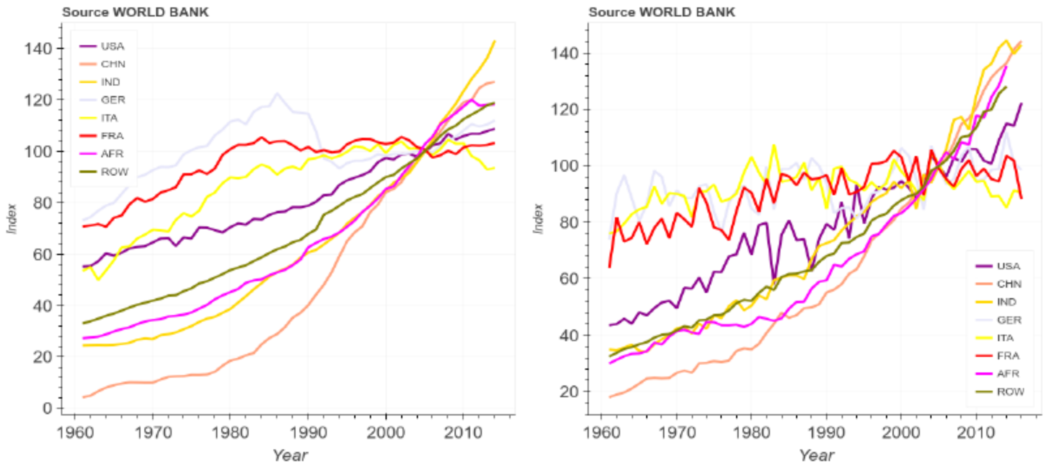


(a) normalized (AFR=1) CO2 ratio 2017/1990 by sector and country

(b) Energy intensity of GDP

Source IEA

Source IEA

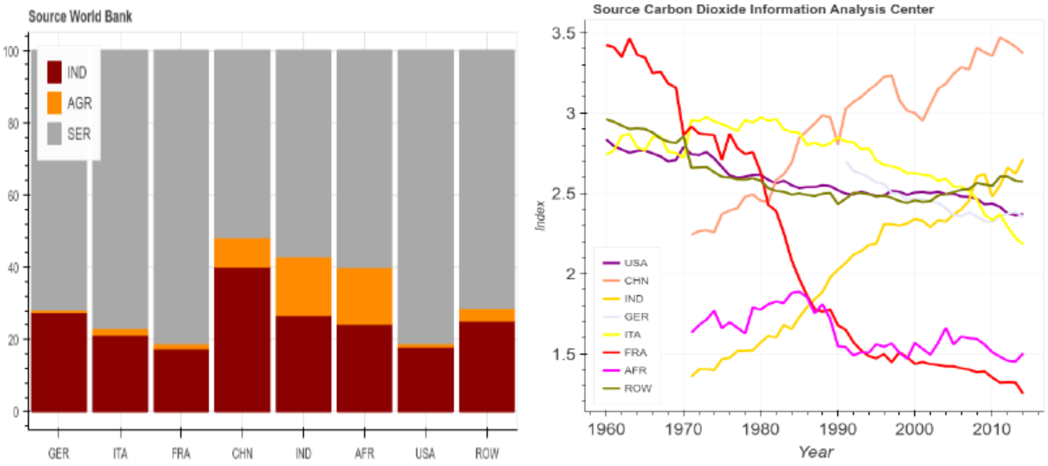


(c) Livestock production index (2004-2006 = 100)

(d) Crops production index (2004-2006 = 100)

Source WORLD BANK

Source WORLD BANK



(e) Sectors. 2016 Value added (% of GDP)

(f) CO2 intensity (kg per kg of oil equivalent energy use)

Source World Bank

Source Carbon Dioxide Information Analysis Center

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