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FISCAL TOOLS TO REDUCE TRANSITION COSTS OF CLIMATE CHANGE MITIGATION

Fiscal tools to reduce transition costs of climate change mitigation

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Abstract

What will be the cost to the economy of a green transition to reduce greenhouse gas emissions? Current estimates differ depending on the study methodology and the assumptions made, in combination with the uncertainty inherent in forecasting future greenhouse gas emissions and temperature increases. This paper takes a different approach. In addition to proposing business as usual scenarios, we replicate widely-used mitigation scenarios for future carbon emissions (as the Paris agreement path for example). Considering the path of emissions and temperature increases of these scenarios as given, we then solve for the combinations of fiscal tools (especially carbon price measures and tax incentives for green investments) that can minimize the transition costs for the economy. The present study extends that conducted by Catalano et al. [2019] by exploiting a global overlapping generations model in the spirit of Kotlikoff et al. [2019] combined with a climate module. We show that the estimated economic costs of a carbon transition vary significantly depending on the fiscal tools applied to reduce greenhouse gas emissions. Due to the costs of adjustments to the structure of production required by a green transition, a policy of debt financing would minimize transition costs.

Keywords: Climate; Global Warming ; Government Policy; International Economics; Fiscal Policies and Behavior of Economic Agents
JEL Classification: Q54; Q58; F0; H2; H3

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1 Introduction

The estimated economic costs of reducing greenhouse gas emissions vary widely. For example, the United States (US) Trump administration withdrew from the Paris Agreement on Climate Change, claiming that it would be too costly for the US economy. In his June 1, 2017 statement, President Trump stated that the cost to the US economy would be "close to $3 trillion in lost GDP and 6.5 million industrial jobs" (Trump, 2017). These figures were based on the results of computable general equilibrium model (CGEM e.g. NERA 2017) simulations.[1] Other studies, based on empirical studies of experience of actual implementation of carbon taxes in European countries over the last 30 years find no significant aggregate macroeconomic effect (Metcalf and Stock [2020]). Therefore, it is difficult to make a reliable assessment what the costs might be.[2]

This is a serious problem, and more especially since climate scenario analysis has become a fundamental tool to assess the risks posed by global warming and climate change to real activities and financial institutions. For example, both the Bank of England and the European Banking Authority are undertaking stress testing of the financial system in three global temperature development scenarios.[3] The Netherlands Central Bank (Vermeulen et al. [2018]) was an early adopter of scenario based stress testing applied to the Dutch financial system. It considers four global energy transition scenarios which produce short-run economic losses based on policy measures, technological breakthroughs, or falls in consumer and investor confidence. The macroeconomic impacts are assessed in terms of GDP growth, inflation, stock prices, and interest rates.

In academic research, the most widely used models to assess climate change are integrated assessment models (IAM). These models date back to the early 1990s (Nordhaus [2018]) and integrate and allow for interactions between economic modules and climate modules. Economic growth leads to higher levels of emissions which in turn, lead to higher temperatures and climate shocks which affect the economy via their impacts on productivity and capital stock. IAM are used also by the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) to explore some of the relationships between economic developments and climate. Of course, IAM differ and even the most sophisticated have some limitations.[4]

Traditional IAM are relatively less well developed in terms of modeling the economy. For example, Nordhaus [2017] acknowledged that “the economic projections are the least precise parts of IAMs and deserve much greater study than has been the case up to now”. This limitation applies to their use to model policies, especially fiscal policies. IAM generally allow for carbon taxes but do not include a fiscal module and generally ignore the effect of climate change on fiscal revenues although there are some exceptions such as Catalano et al. [2019] and Barrage [2020a].

The present paper uses a global overlapping generations (OLG) model in line with Kotlikoff et al. [2019] augmented by a climate module Anthoff et al. [2014]) to assess the role of budget policies in estimating the economic costs related to the transition to a lower greenhouse gas emissions environment. A global OLG model is particularly well suited to addressing these problems since it is a long-run growth model which

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[1] "The U.S. economy could lose about 6% of its GDP on average between 2034 and 2040 amounting to a loss of greater than $2 trillion annually and a cumulative loss of $14 trillion." NERA (2017) page 7.

[2] Both CGEM and empirical approaches have limitations. Results from CGEM can be difficult to interpret (CGEM tend to have too many parameters and equations to offer reliable guidance to the economic intuition). Their results generally depend on calibrations, whose details can be of the essence. On the other hand, empirical studies tend to be backward looking, to focus mainly on carbon taxes and therefore failing to capture overall emission policies. Countries generally do not have only carbon taxes, but regulate emissions also via performance standards, caps, incentives and the like. These different policies have a combined effect on the implicit cost of greenhouse gas emissions or else on the actual amount of emissions. The introduction of a carbon tax per se might not lead to a significant reduction in emissions if for example replaces or adds to a cap and trade mechanism.

[3] The BoE intends to launch a first "exploratory scenario" in 2021. For a discussion on this, see: https://www.bankofengland.co.uk/paper/2019/biennial-exploratory-scenario-climate-change-discussion-paper. The EBA has indicated the work plan it intends to follow on the climate issue and in particular that "as part of the regular risk assessment of EU banks, a sensitivity analysis for climate risks could be undertaken in the second half of 2020 for a sample of volunteering banks.", see https://eba.europa.eu/eba-pushes-early-action-sustainable-finance. The ECB has also started to develop a model for assessing climate risks.

[4] 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 oft-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]).

incorporates fiscal and intergenerational issues. It also includes different projected population dynamics for different world areas, and is able to account also for technology evolution. The model can be used to propose economic scenarios of the evolution of greenhouse gas emissions and temperature increases consistent with the most widely used IPCC scenarios (i.e. Paris Agreement, business as usual, and most likely) and to assess the fiscal tools that can best reduce greenhouse gas emissions while minimizing economic disruptions.

The paper focuses on fiscal policies to mitigate pollution. There is quite wide agreement that carbon taxes combined with green subsidies are the most efficient policy to achieve a reduction in greenhouse gas emissions (Barrage [2020b]). Our baseline approach considers a combination of carbon taxes and green subsidies assuming a balanced budget. In an extension to the model, we assess the impact of an expansionary fiscal policy of allowing public debt to increase. Overall, our results show that the estimated economic costs of a carbon transition vary significantly depending on the fiscal tools used and the implementation of fiscal policy.

Our model does not consider the issue of adaptation spending i.e. public investment to adapt to climate change or remedial post-disaster relief spending. In that context, Catalano et al. [2019] show that an expansionary fiscal policy might be optimal in the sense that the higher public debt incurred in the short term via deficit financed adaptation policies could lead to a lower debt burden in the future compared to lower adaptation spending. Incorporating adaptation spending in our model would increase the need for carbon taxes since it would involve the financing of a larger amount of climate related spending (Barrage [2020a]).

The paper is organized as follows. 2 presents the economic model. Section 3 describes model calibration and defines the scenarios. Section 4 discusses the baseline results. Section 4 suggests some extensions based on a combination of carbon taxes and other fiscal tools. Section 6 provides a robustness analysis of the baseline scenarios. Section 7 concludes.

2 The model

2.1 Economic module

In order to quantify the effects of fiscal policies on emissions and thus on transition risks, we are building a two-stage model. A macro level that describes the determinants of growth and a sectoral level that allows us to disaggregate the CO2 emissions by sector, ensuring a consistent general equilibrium analysis. At the macro level, we use a multi-country overlapping generations (OLG) model for a number of areas/countries, i.e. advanced countries such as the United States, Germany, Italy, France, and emerging countries such as China, India, Africa. The remaining countries are gathered in a unique area called rest of the world (ROW). The model includes long-term demographic and human capital projections for the different countries that affect labour and capital accumulation through different agents' saving behaviours 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 (as in Catalano et al. [2019]). The core sectors in the macro model are households, firms and government for each country r. Once the macro model is defined, we move to the sectoral level following van der Mensbrugghe [2011] (section 2.1.6). Each sector/market is analysed in equilibrium and from it we obtain disaggregated CO2 emissions and feedback on the macro/regional level. All variables are defined in real terms by using the consumption goods price of the US as *numeraire*. The export price comes from the sectoral model in section 2.1.6 that describes the sectoral disaggregation into heavy manufacturing, light manufacturing, services, crops, livestock and the energy sectors.

2.1.1 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 the birth year, is denoted by $P_{t,s,r}$, with a survival rate defined as $\chi_{t,s}$.

The households' life-cycle stream utility is given by

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

where c denotes consumption goods and l is the individual labor supply (measured in efficiency units relative to the time endowment e).[5] T is longevity (101 years of life for each cohort at birth), ρ denotes the rate of time preference which is cohort invariant, and ξ defines the intertemporal elasticity of substitution, $\chi_{t,s}$ 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

$$u(c_{t,s}, e_{t,s} - l_{t,s}) = \left[c_{t,s}^{(1-\frac{1}{\epsilon})} + \alpha\left(e_{t,s} - l_{t,s}\right)^{(1-\frac{1}{\epsilon})}\right]^{\frac{1}{1-\frac{1}{\epsilon}}} \tag{2}$$

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

$$\begin{cases} l = 0 & if \quad s \leq T_i \\ 0 \leq l \leq e & if \quad T_i < s < T_r \\ l = 0 & if \quad s \geq T_r, \end{cases} \tag{3}$$

where T_i denotes the age of individuals at the end of each phase i of schooling/education that is 14-year-old for the education level $i = LS$ (primary education level), 19-year-old for $i = HS$ (secondary level), and 24 for $i = TS$ (tertiary education level). T_r indicates the retirement age, i.e. the years of contribution needed to obtain a pension. Equation (3) presents consumption and labor supply constraints during the life-cycle.

The households' saving is represented in real wealth dynamic budget constraint:

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

where $a_{t,s}$ denotes the wealth in time t of the cohort born in the period s; r_t and $pens_{t,s}$ are respectively the real interest rate and the average pension at time t for the cohort aged t,s; $\tau_{a,t}$ is the exogenous tax rate on household wealth and $\tau_{c,t}$ is the VAT rate. The term $\bar{w}_{t,s} h_{t,s} l_{t,s}$ represents the post tax real labor income, with $\bar{w}_{t,s} = (1 - \tau_{l,t}) w_{t,s}$ and $\tau_{l,t}$ denoting the exogenous tax labor income rate. The human capital $h_{t,s}$ is a specific education index as discussed in section 3. The terms $\pi_{t,s}$ and $\pi^k_{t,s}$ indicate profits share from ownership of macro and sectoral firms by cohort t,s [6] (see sections 2.1.2 and 2.1.7).

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

$$e_{t,s} - l_{t,s} = \left(\frac{[w_{t,s} h_{t,s} + \mu_{t,s}](1 - \tau_{l,t})}{p_t \alpha (1 + \tau_{c,t})}\right)^{-\epsilon}, \tag{4}$$

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:

$$\frac{c_{t+1,s}}{c_{t,s}} = \left[\frac{(1+\tau_{c,t}) p_t}{(1+\tau_{c,t+1}) p_{t+1}} \frac{1 + r_{t+1} - \tau_{a,t}}{1+\rho}\right]^{\xi} \left[\frac{1 + \alpha\epsilon(v_{t+1,s})^{1-\epsilon}}{1 + \alpha\epsilon(v_{t,s})^{1-\epsilon}}\right]^{\frac{\epsilon-\xi}{1-\epsilon}}, \tag{5}$$

---

[5] 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 $\dot{h}$, i.e. $e_{t+1} = e_t(1 + \dot{h})$. We assume that human capital stabilizes in the far long run. These conditions overcome inconsistencies about "growth compatible preferences". See Borsch-Supan et al. [2006] for a discussion.

[6] Profit shares are defined in terms of population share of aged cohorts t,s over whole population $\frac{P_{t,s,r}}{P_{t,r}}$

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 is given by:

$$\frac{c_{t+1,s}}{c_{t,s}} = \left[\frac{(1+\tau_{c,t})p_t}{(1+\tau_{c,t+1})p_{t+1}} \frac{(1+r_{t+1}) - \tau_{a,t}}{1+\rho}\right]^{\xi}. \tag{6}$$

2.1.2 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:

$$Y_{r,t} = Z_{r,t}K_{r,t}^{\beta}L_{r,t}^{1-\beta}, \quad Z_{r,t} = (1 - D_{r,t})TFP_{r,t}, \tag{7}$$

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] :

$$D_{r,t} = 1 - \frac{1}{1 + \pi_{r,1}T_t^A + \pi_{r,2}(T_t^A)^2}, \tag{8}$$

with $\pi_{r,1}$ and $\pi_{r,2}$ denoting the coefficients of the quadratic polynomial of damage function, with T_t^A representing the change, since 1900, in global mean surface temperature measured in Celsius.[7] The endogenous growth process is modelled linking physical capital per worker and human capital à la Romer [1990] as follows:

$$TFP_{r,t} = \left(\frac{K_{r,t}}{N_{r,t}}\right)^{g} H_{r,t}^{z}, \tag{9}$$

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.[8]

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

In each region a continuum of firms, $n \in [0, 1]$, is divided into segments of specialized firms active on a specific foreign area n_v, $v = 1, ..., r, ..., R$. Aggregate capital stock in country r is therefore the integral of individual capital firm endowment $K_{r,t}(n)$, :

$$K_{r,t} = \sum_v \int^{\theta_v} K_{v,t}(n)dn = \sum_v K_{r,v,t} = \sum_v \theta_v K_{r,t}, \tag{10}$$

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, labour is internationally fixed. In the following we suppress the index r for sake of semplicity. Firm's profits in each region are given by:

$$\pi_t = p_tY_t - (r_t + \delta_t)K_t - w_tL_t \tag{11}$$

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 focs are the following:

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

[8] 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 $Y_t = H_t^{z+1-\beta}K_t^{g+\beta}N_t^{1-\beta-g}$, there are constant returns to scale in capital K_t and labour 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 (see section 3 for details). 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.

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

2.1.3 Government

In each country, the public sector is divided in three areas, namely the social security, the education department and public spending in goods and services. The government raises funds through public debt and taxes paid by workers at the exogenous labor income tax rate τ_l, VAT rate τ_c, capital tax rate τ_k and tax rate on wealth τ_a. Government uses revenues to finance education expenditure, sg, and current pension and social transfers to retired people, $\zeta pens$, where $\zeta_t = \sum_i \sum_{s=T_r+1}^{T} P_{t,s,i}$ denotes the retired population and $pens_t$ is calibrated to match data of pension expenditure to GDP (see section 3). Government issues new debt in order to finance deficit:

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

where $\tau_{a,t}A_t$, $\tau_{l,t}wL_t$ and $\tau_{c,t}p_tC_t$ denote respectively revenues from aggregate savings taxation, labour taxation and VAT (see section 2.1.4 for aggregate wealth and labour). We assume $G_t = \gamma Y_t$ 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 exogenous public investment, which are defined respectively in sections 2.1.5 and 2.1.6.

2.1.4 Aggregation

In each country r for each cohort s and education level i, the total labor supply $L_{r,t}$ is equal to

$$
L_{r,t} = \sum_{i \in I} \sum_{s=s_{0,i}}^{T_r} l_{t,s,i,r} h_{t,s,i,r} P_{t,s,i,r}, \tag{14}
$$

the aggregate amount of labor input is

$$
N_{r,t} = \sum_{i \in I} \sum_{s=s_{0,i}}^{T_r} l_{t,s,i,r} P_{t,s,i,r}, \tag{15}
$$

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_r denotes the contribution years required in year t to obtain a pension.

Aggregate wealth is given by

$$
A_{r,t} = \sum_{i \in I} \sum_{s=s_0}^{T} a_{t,s,i,r} P_{t,s,i,r}. \tag{16}
$$

Aggregate capital evolves according to the following equation:

$$
K_{r,t+1} = (1-\delta_{r,t}) K_{r,t} + I_{r,t} + I^*_{r,t} + \Psi(I_r, K_r) \tag{17}
$$

where $I^*_{r,t}$ and $I_{r,t}$ denote respectively public and private investments, and $\Psi(I_r, K_r)$ the aggregate investment adjustment cost of all sector-specific adjustment costs (see section 2.1.5). In each country r, we define the net foreign asset position as

$$
F_{r,t} = A_{r,t} - q_{r,t} K_{r,t} - B_{r,t}, \tag{18}
$$

where $F_{r,t}$ denotes the amount of foreign assets, $A_{r,t}$ the aggregate wealth in eq. (16), $q_{r,t}$ the value of capital (q-Tobin) defined in section 2.1.5 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 assets are equal to zero $F_{r,t} = 0$, and the capital stock is equal simply to aggregate wealth $K_{r,t} = \frac{A_{r,t} - B_{r,t}}{q_{r,t}}$.

2.1.5 Investment allocation

A financial intermediate sector disaggregates the capital at the macro-level (section 2.1.2) for each region $K_{r,t}$ in capital stocks $K_{j,r,t}$ used for the j-sector production. Given the capital stock dynamics an investment flow $I_{r,t}$ is determined for each region. The financial intermediate firm buys at price $q_{t,r}$ the investment goods $I_{r,t}$, and sells a disaggregated investments goods, $I_{j,r,t}$ at the different sectors j at price $q_{j,r,t}$. Therefore, the objective function is the expected discount streams of profits:

$$V_{r,t} = \pi^k_{r,t} + \hat{\lambda}_{r,t+1} V_{r,t+1} \tag{19}$$

where $\hat{\lambda}_t \equiv \sum_s \beta^s \lambda_{t,s} \frac{P_{t,s}}{P_t}$ is the weighted discount factor of all living cohorts aged t, s at time t. Profits $\pi^k_{r,t}$ are defined as follows:

$$\pi^k_{r,t} = \sum_j q_{j,r,t} I_{j,r,t} - q_{r,t} I_{r,t} + \sum_j r_{j,r,t} K_{j,r,t}, \tag{20}$$

where $r_{j,r,t}$ is the return on sectoral capital $K_{j,r,t}$.

The value function in equation (19) is maximised subject to:

$$I_{r,t} = \left[\sum_j \gamma_{j,r,t} (I_{j,r,t})^{1-\eta} \right]^{1/(1-\eta)}, \tag{21}$$

and

$$K_{j,r,t+1} = (1 - \delta_{r,t}) K_{j,r,t} + I_{j,r,t} + I^*_{j,r,t} + \psi(I_r, K_r), \tag{22}$$

with $\gamma_{j,r,t}$ and η denoting respectively the share and the elasticity of the investment CES function (eq. 21), and $I^*_{j,r,t}$ denoting public investment in sector j in the law of motion for the j-sector capital stock (eq. 22), such that $inv_t = \sum_j q_{j,r,t} I^*_{j,r,t}$ (see equation (13)). The investment adjustment cost $\psi(I_r, K_r)$ is defined as $\psi(I_r, K_r) = \frac{\phi}{2} \frac{I^2_{j,r,t}}{K_{j,r,t}}$, with $\phi \geq 0$.

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 aggregate capital $q_{t,r}$:

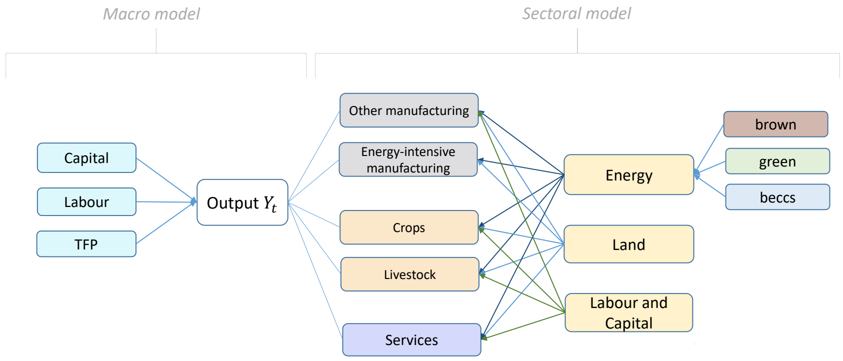
$$q_{t,r} = \left[\sum_j \gamma_{j,t,r} q^{1-\eta}_{j,t,r} \right]^{1/(1-\eta)}. \tag{25}$$

2.1.6 The quantity nesting system

In this section we describe how we nest the sectoral model (see van der Mensbrugghe [2011]) into the macro-growth model. Figure 1 depicts the structure. The model used to allocate resource among sectors aims at defining the CO2 emissions for each sector and region thus taking into account the heterogeneity in transition process among areas, as described in section 4. The energy sectors included into the model are: *oil*, *gas* and *coal* as brown energy sources with low CO2 emission efficiency; and *green*[9] and *beccs*[10] as high and negative emissions efficiency, respectively.

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

Figure 1: OLG model: production



Analytically, the sectoral model is composed of four objects: (1) 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 maximization of the conditions in point (2); (4) aggregated price functions that level up from the bottom to the upper level of the hierarchy of the production structure. In this section we describe the point (1) and some details of point (3). For further details on the other points see the appendix C.

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. The macro and sectoral systems are therefore conceivable as a dual system consistent with the general equilibrium approach. In the following we show the sectoral model starting with the supply side and then providing description for the demand conditions. General equilibirum conditions are satisfied in each sector matching supply and demand through price determination (see section C for details).

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

$$Y_{r,t} = [\gamma_y (XD^s_{r,t})^{\sigma_y} + (1-\gamma_y)(VA_{r,t})^{\sigma_y}]^{1/\sigma_y}. \tag{26}$$

The sector minimizes costs defined as

$$py_{r,t}Y_{r,t} - pd_{r,t}XD^s_{r,t} - pva_{r,t}VA_{r,t} \tag{27}$$

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

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[9] 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.

[10] 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

$$XD_{r,t} = \gamma_y \left(\frac{py_{r,t}}{pd_{r,t}} \right)^{\sigma_y} Y_{r,t} \tag{28}$$

$$VA_{r,t} = (1-\gamma_y) \left(\frac{py_{r,t}}{pva_{r,t}} \right)^{\sigma_y} Y_{r,t} \tag{29}$$

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 obtaine the definition for the gdp deflator used into 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). For the sake of simplicity we omit the regional index in the following.

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

$$VA_t = [\gamma_{va,1} MA_t^{\sigma_{va}} + \gamma_{va,2} AG_t^{\sigma_{va}} + (1-\gamma_{va,1}-\gamma_{va,2}) SERV_t^{\sigma_{va}}]^{1/\sigma_{va}}. \tag{31}$$

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 level manufacturing (LMA):

$$MA_t = [\gamma_{ma} HMA_t^{\sigma_{ma}} + (1-\gamma_{ma}) LMA_t^{\sigma_{ma}}]^{1/\sigma_{ma}}. \tag{33}$$

From the demand side, in each region r, 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 and imported goods:

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

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 from region r is distributed to each region $r' \neq r$ as follows

$$WTF_{r,t}^{d,r'} = \beta_w \left(\frac{pmt_{r',t}}{pm_t} \right)^{\sigma_w} XMT_t, \tag{36}$$

where pm is the total price of imports in region r. Exports towards different regions $r' \neq r$ are defined as follows:

$$WTF_{r,t}^{s,r'} = \beta_w \left(\frac{pmt_t}{pe_t} \right)^{\sigma_x} ES_t(1-w_{mg}), \tag{37}$$

where exports of region r are defined as follows

$$ES_t = \gamma_{es} \left(\frac{pe_t}{p_t} \right)^{\sigma_x} Y_t(1-w_{mg}), \tag{38}$$

with $(1-w_{mg})$ denoting trade related transportation costs (see appendix C for the computation of CO_2 emissions emerging from trade).

2.1.7 The bottom layer of the sectoral model: maximizing profit, minimizing CO2

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. Profits at time t are defined as the difference between the revenues from production and the total costs:

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

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:

$$KT(j)_t = B(j)_t \left[\sum_k \gamma_{k,t}\left(\theta_{k,t}K(j)_{k,t}\right)^{\rho_j} + \sum_k \gamma_{k,t}\left(\theta_{k,t}L(j)_t\right)^{\rho_j}\right]^{\frac{1}{\rho_j}}. \tag{40}$$

Finally, the term $(p(j)_{k,t} + \tau_{co2,t})CO2(j)_{k,t}$ indicates the total cost of $CO2$ emissions[11] and includes a positive carbon price τ_{co2} for energy sources with positive emissions.

Firm's profit maximization are subject to CES technological constraint:

$$Q(j)_t = A(j)_t \left[\sum_k \gamma_{k,t}\left(\theta_{k,t}CO2(j)_{k,t}\right)^{\rho_j} + \sum_k \gamma_{k,t}\left(\theta_{k,t}KT(j)_{k,t}\right)^{\rho_j} + \sum_k \gamma_{k,t}\left(\theta_{k,t}LA(j)_t\right)^{\rho_j}\right]^{\frac{1}{\rho_j}} \tag{41}$$

where $Q(j)$ is sector production, $A(j)$ a sector productivity index, γ and θ are technological parameters, the parameter ρ is related to the CES elasticity of substitution $\sigma = \frac{1}{1-\rho}$.

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

$$\sum_j CO2(j)_{r,t} = CO2_{r,t} <= \overline{CO2}_{r,t}. \tag{42}$$

The emissions constraint is calibrated by area considering the global constraint defined by the Paris Agreements and allocating it by country on the basis of country-specific emission quotas on total emissions in 2020. These quotas 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:

$$V(j)_t = \lambda_t \pi_{j,t} + \phi_{co2}(\overline{CO2}_t - CO2_t), \tag{43}$$

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

$$CO2(j)_{k,t} = \frac{1}{A(j)_t}\gamma_{k,t}\theta_{k,t}^{\sigma_j - 1}\left(\frac{p(j)_{k,t} + \tau_{co2}}{p(j)_t}\right)^{-\sigma_j} Q(j)_t, \tag{44}$$

$$KT(j)_{k,t} = \frac{1}{A(j)_t}\gamma_{j,t}\theta_{k,t}^{\sigma_j - 1}\left(\frac{ct(j)_{k,t}}{p(j)_t}\right)^{-\sigma_j} Q(j)_t, \tag{45}$$

$$LA(j)_{k,t} = \frac{1}{A(j)_t}\gamma_{j,t}\theta_{k,t}^{\sigma_j - 1}\left(\frac{pland(j)_{k,t}}{p(j)_t}\right)^{-\sigma_j} Q(j)_t. \tag{46}$$

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[11] We translates energy inputs into emissions defined in tons.

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[12].

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

$$K(j)_{k,t} = \frac{1}{B(j)_t}\gamma_{j,t}\theta_{k,t}^{\sigma_j-1}\left(\frac{r(j)_{k,t}+\delta_j}{ct(j)_{k,t}}\right)^{-\sigma_j} KT(j)_{k,t} \tag{47}$$

$$L(j)_{k,t} = \frac{1}{B(j)_t}\gamma_{j,t}\theta_{k,t}^{\sigma_j-1}\left(\frac{w(j)_{k,t}}{ct(j)_{k,t}}\right)^{-\sigma_j} KT(j)_{k,t} \tag{48}$$

Using (40) we get the average prices:

$$ct(j)_{k,t} = \frac{1}{B(j)_t}\left[\sum_k \gamma_{k,t}\left(\frac{r^k(j)_{k,t}}{\theta_{k,t}} + \frac{\gamma_t w(j)_{k,t}}{\theta_{k,t}}\right)^{1-\sigma_j}\right]^{\frac{1}{1-\sigma_j}}, \tag{49}$$

$$p(j)_t = \frac{1}{A(j)_t}\left[\sum_k \gamma_{k,t}\left(\frac{p(j)_{k,t}+\tau_{co2}}{\theta_{k,t}} + \frac{\gamma_{j,t} ct(j)_{k,t}}{\theta_{k,t}}\right)^{1-\sigma_j}\right]^{\frac{1}{1-\sigma_j}}. \tag{50}$$

Prices $p(j)_{k,t}$ are defined into appendix C.

2.2 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 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 á la Nordhaus (see equation (8)).

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:

$$M_{t,r} = \frac{M_{t,r}}{E_{t,r}}\frac{E_{t,r}}{Y_{t,r}}\frac{Y_{t,r}}{P_{t,r}}P_{t,r} \tag{51}$$

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. Parameters are taken from Forster et al. [2007].

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

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[12] $\tau_{co2,t} = \frac{\phi_{co2} p_t}{u_c}$ is the carbon price with p_t and u_c being the consumption basket (dollars) price and average marginal consumption units. All the firms are owned in equal shares by the cohorts living in each period.

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. Gases concentration are modelled as: [13]:

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

with

$$C_{t,j} = \sum_{j=1}^{5} \alpha_j Box_{j,t} \tag{54}$$

where α_i denotes the fraction of emissions M (in million metric tonnes of carbon) that is allocated to Box_j ($\alpha_i = 0.13, 0.20, 0.32, 0.25, 0.10$, 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 also also contains 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 the global temperature. 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 $3.0°C$ for a doubling of carbon dioxide equivalents, so:

$$T_t = (1 - 1/\psi)T_{t-1} + 1/\psi \frac{cs}{5.35ln2} RF_t \tag{56}$$

where cs is climate sensitivity, set to 3.0 (with a gamma distribution with shape=6.48 and scale=0.55). 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.[14] 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.

3 Calibration and scenario definition

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

3.1 Calibrating the macro model

We solve the model on a yearly base until 2281, for a 470 years, starting from an initial steady state 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 in 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 1970-2018 and is allowed to produce projections from 2019 to 2100.

Based on the data, a number of trends are calibrated: demographics, human capital, technical obsolescence (via the depreciation rate), labour and capital share, trade integration and capital flows. In

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[13] 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]

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

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: primarey (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 labour 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 discount rate time preference (see section A for details).

3.2 The sectoral calibration

We calibrate the sectoral module along the different layers of which it is composed (see sections 2.1.7 and appendix C). To do this, we use different criteria and data sources. Figure 2 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, with the exception of the Rest-of-the-World region, 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 distribution of manufacturing, agriculture and services in the different countries, while panel f shows the huge loss of CO2 efficiency in India and China related to the livestock sector.

3.2.1 Scenarios definitions

We use the model to calibrate four scenarios. We consider a scenario (called "d0") in which we assume that climate damage linked to rising global temperatures has no effect on the socio-economic system and natural resources (i.e. the physical risk of climate change is eliminated, for example through a comprehensive adaptation policy). This scenario is mainly used as a benchmark for the scenarios at the core of our analysis. Among the latter, the Business-as-usual (BAU) scenario entails a climate damage increasing over time due to global warming for all countries. This scenario reproduces the current situation with European countries at the forefront, i.e. more committed to reducing climate impact, but still not enough to achieve the objectives of the Paris Agreement. We also include the case of an even more damaging BAU (called "BAUx6"), calibrating the intensity of the climate damage as in Kotlikoff et al. [2019]. BAU and BAUx6 represent the most risky scenarios that can occur without strong and globally shared mitigation action.

On the contrary, the fourth scenario called "Paris Accords" (or more simply "PARIS") is the one that provides for the least possible climate damage as it envisages achieving the objectives of the Paris Accords, with a temperature increase of about 2°C by 2100. The mitigation action is implemented with the introduction of a carbon pricing that increases the cost of energy produced with fossil fuels (which in the model consist of coal, oil and natural gas) and encourages the use of green sources. In this scenario, we assume that, in order to potentially mitigate the negative macroeconomic consequences of a carbon price increase, policymakers will use carbon tax revenues to increase incentives for firms to green investments, thereby further reducing CO2 emissions. To limit global-mean temperature, global CO2 emissions eventually have to become zero at a global scale (Knutti and Rogelj [2015]). Of course, the challenges of ambitious mitigation pathways vary from region to region in intensity and timing. This implies that carbon neutrality would be achieved in 2050 in Europe and in 2070 in the rest of the countries.

Our BAU scenario is in line with the IPCC's SSP2 (Middle of the Road), which assumes development patterns (e.g., final energy intensity improvement rates) that have been observed over the past century, consistent with "middle-of-the-road" expectations. The SSP2 baseline includes a strong increase in global total GHG emissions (to around 43% and 107% compared to 2010 levels in 2050 and 2100 respectively). However, alternative scenarios achieve a radiative forcing of about 4.5 W/m2 in 2100 resulting in 2050 GHG emissions being about the same level as in 2010, and 61% lower in 2100. Further scenarios, reducing end-of-century forcing to about 2.6 W/m2 results in levels of -49% in 2050 and -105% in 2100, respectively, relative to 2010 levels. In our scenarios, the radiative forcing varies between 7.5 and 3.8 depending on the mitigation effort and the intensity of climate damage (see section 4).

In order to evaluate alternative paths to those included in our main scenarios, the robustness analysis provided in section 6 evaluates the possibility of different parameter settings. The BAU scenario shares with the other alternative scenario a set of assumption about demographic, technological and energy mix affecting the development of areas defined in the model. Table 4 discusses such factors.These imply, for example, a convergence of India and China towards the economic structure of advanced economies (see section "development phase") and Africa changing specialization from agriculture to manufacturing (we refer mainly to the LIMITS project[15]). Moreover, we consider different population evolutions as in UN probabilistic projections. In addition, we consider several policy options to support the transition to a low-carbon economy, such as the possibility of using carbon tax revenues to incentivise green private investment, or to reduce other taxes such as those on labour incomes and support demand, or the possibility of increased public investment, especially in research and development.

4 Results

In this section we show the results of our main scenarios, namely D0, BAU, BAUx6 and PARIS, as described in section 3.2.1. They include different levels of radiative forcing and temperature rise. The BAU scenario includes a radiative forcing above 7 W/m2 in 2100 reaching a temperature rise of 5°C, while the PARIS scenario allows a radiative force below 4 W/m2 and a temperature increase of around 2°C in 2100. The scenario BAUx6 is characterized by a level of radiative forcing of about 5.8 W/m2, which is lower than the BAU scenario due to a greater reduction in future productivity and emissions resulting from more intense climate damage. As a result, the temperature increase is lower than in the BAU scenario, with an increase of about 4.6°C in 2100 (Fig. 3). Compared to D0 and BAU, in the PARIS scenario, before the entry into force of the carbon pricing, emissions are higher due to the famous Green Paradox: the "use it or lose it" approach, i.e. countries could be incentivised to increase CO2 emissions in the short and medium term before the restrictions on emissions start to be binding. There is also an anticipation effect in the BAU scenario, which leads to higher emissions and temperatures than in D0: economic agents bring forward brown energy consumption in expectation of climate damage which, unlike in D0, will have an impact in the future, compromising the economic system and future output (Fig. 3, panel c).

For all economies, the effect of climate change occurs with a decrease of 40% of GPD in 2100 on average. In terms of long-term economic growth, the D0 scenario provides the best performance in all countries, as climate damage does not affect either the socio-economic system or the environment. On the contrary, the greatest long-term loss of GDP is the one recorded in the BAUx6 scenario with the greatest climate damage and no additional mitigation effort compared to current measures. In figure 4 we show the disaggregated emissions profile resulting from the effects of the carbon pricing policies.

The effect of improved energy efficiency and carbon taxation in the PARIS scenario would be significant with a decrease in GDP by more than 10% on average in about 4 years (Fig. 5). The shock to energy prices triggers inflation that affects all economies similarly in the medium term. The benefits in terms of higher growth could be appreciated after 2040, when GDP levels are higher. In the long term, the incentives are beneficial for emerging countries and in particular for China.For emerging countries such as India and Africa, growth is less affected by transition processes because their less mature economies have a higher inertia as they are more inclined to adopt green technologies earlier than other countries. In figure 6 we compare the transition process in the BAU and PARIS scenario in terms of carbon intensity (brown energy sources). In the BAU scenario the share of green energy is still 30% of the entire energy package in 2100.

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[15] LIMITS stands for Low Climate Impact Scenarios and the Implications of Required Tight Emission Control Strategies funded by the European Union

The PARIS scenario produces the best results in terms of emission reductions and GDP growth in the long term. The adoption of carbon pricing would lead to a sharp decrease in gross emissions until a negative value is reached in 2070, also thanks to carbon capture and storage technologies, such as BECCS (i.e. the combination of biomass combustion with carbon capture and storage, which places the carbon that installations remove from the atmosphere in geological reservoirs). The BAU scenario is in an intermediate position compared to the other scenarios and in some cases produces higher GDP growth in the medium term because it does not entail the recessionary effects due to the transition, i.e. carbon pricing and stranded assets for brown energy sources as is the case in the PARIS scenario in the short and medium run. Indeed, the increase in the carbon price at regional and global level leads to a permanent increase in the level of brown energy prices (i.e. price of coal, oil and gas) and a depreciation of the "brown" capital stock. The increase in energy costs increases production costs, resulting in reduced profits. This in turn drives down investment and equity prices. As a consequences, firms increase the prices they charge to consumers and households' disposable income decreases thus implying lower consumption. Lower consumption and lower investment leads to a decrease in GDP, at least in the short and medium run. In fact, the positive effects of the redistribution of resources towards the green sectors are not immediate, nor sufficient in the medium term to offset the depressive effect of the devaluation of "brown" capital. The progressive disinvestment from fossil fuels should be accompanied by very large private investments in renewable to ensure that these alternative forms of energy can provide essential services in a short time frame. In addition, the negative impact on consumption could be reduced by returning the carbon tax revenue to households, for example by reducing taxation on labour income (see section 6). Indeed, the effects on GDP, inflation and interest rates will vary widely depending on how the carbon price revenue is returned to the economy.

For almost all countries, inflation increases in double digits and then falls rapidly thanks to the beneficial effects of green incentives. As inflationary pressures decrease, interest rates begin to recover, returning to pre-shock values within a period of about four to five years. Figure 7 shows the adjustment of carbon prices in all the economies for both BAU and PARIS. The time path is common for all countries. We observe a sudden increase at impact, with the highest level in the US and China. The levels of carbon pricing increase steadily until 2050-70 when the peak is reached. The increase is consistent with the gradual reduction of brown energy share in total energy use. Once the full transition is achieved the carbon pricing starts to decrease.

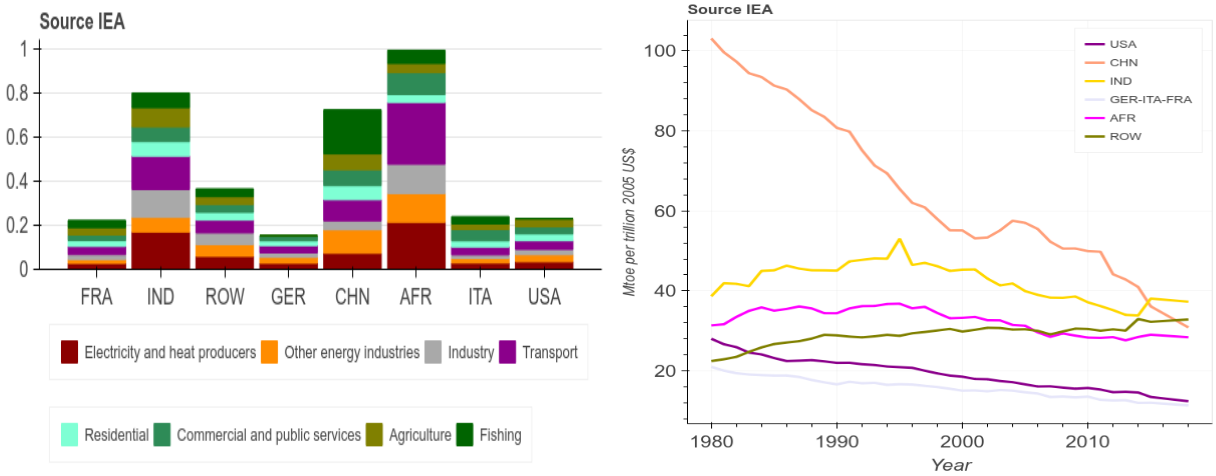
The figure 8 shows the dynamics of debt. The most significant facts are the huge increase in debt in the BAUx6 scenario and the initial increase in the PARIS scenario. In the PARIS scenario, it is assumed that revenues from carbon pricing are used to increase incentives for firms to invest green (balanced budget assumption). Therefore, the initial increase in debt is the result of the fall in GDP in the years immediately following the introduction of the carbon tax. Nevertheless, thanks to low interest rates and the increase in GDP in the medium/long term, there is a beneficial effect on the stability of the public financial position.

The Tobin's q incorporates the market value of firms, reflecting intangible attributes, such as improving corporate environmental performance, which are not captured by short-term accounting-based measure (like *return on assets*, ROA). This means that the Tobin's q allows to take into account firm's future profitability under perceived external conditions, such as the perspective of climate change legislation. Thus, while the short-term measure emphasizes contemporaneous performance, the long-term measure concerns firms' future performance (Peloza [2009]). The transition to a low carbon economy is a source of both significant risk and opportunity for the firm. In general, the risks are expected mainly in the short term, while the opportunities in the long term. Delmas et al. [2015] investigate the relationship between environmental and financial performance under increasing likelihood of environmental regulation, using data for 1,095 U.S. corporations from 2004 to 2008. They find that during this period, improving corporate environmental performance causes a decline in the short-term financial performance indicator but an increase in the potential long-run value of firms, manifested by an increase in Tobin's q.

Figure 2: Energy intensity and CO2 emissions by countries and sectors

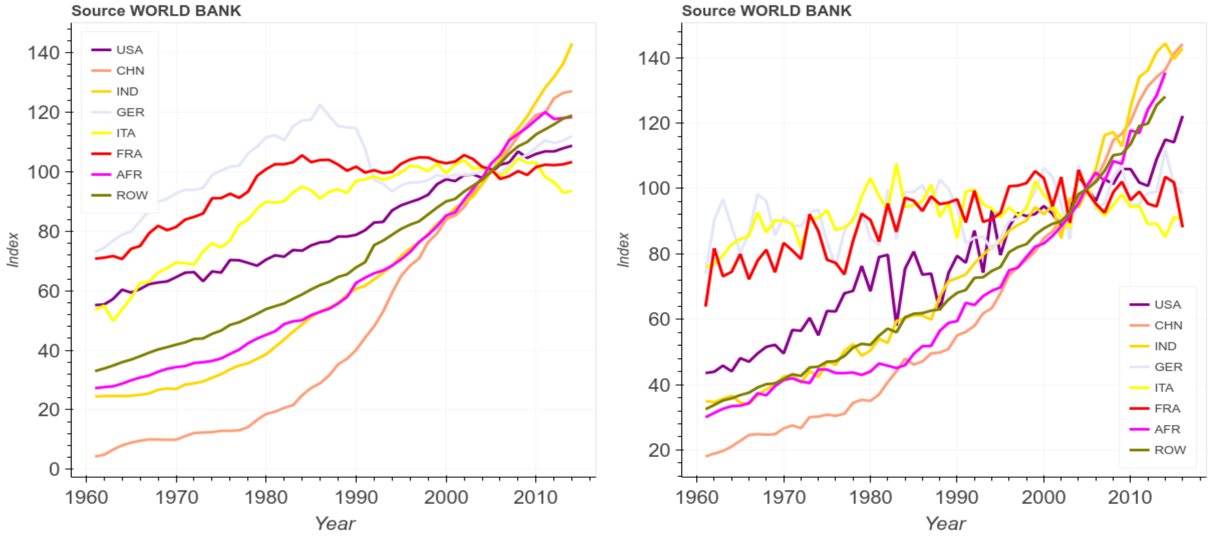
(a) normalized (AFR=1) CO2 ratio 2017/1990 by sector and country

(b) Energy intensity of GDP



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

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



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

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

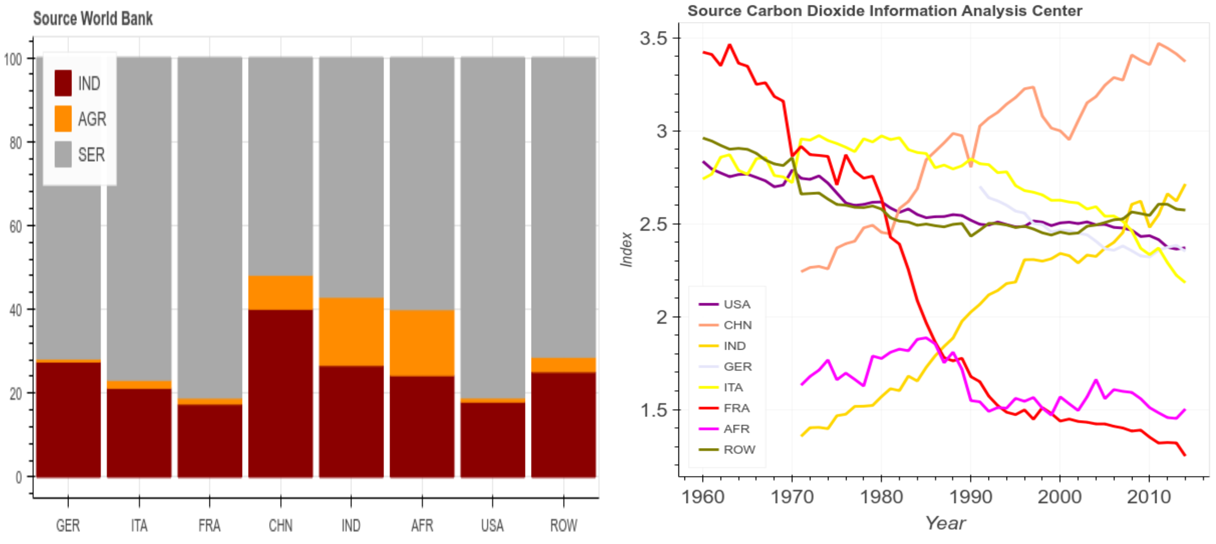
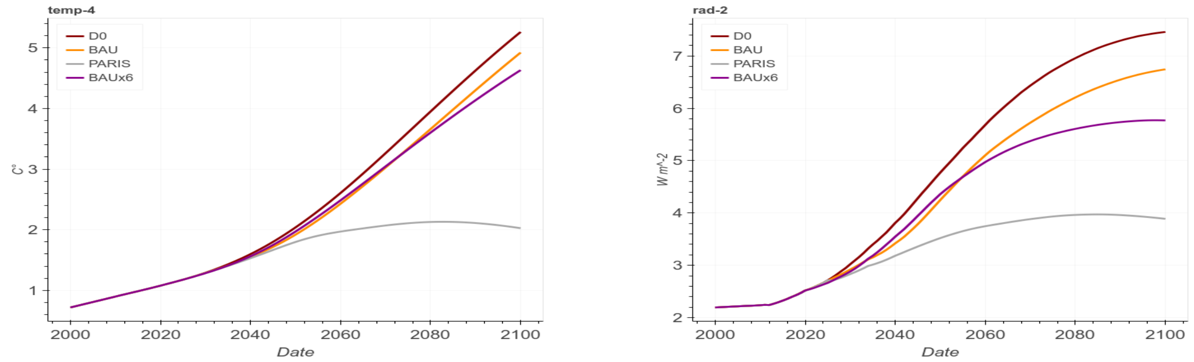


Figure 3: Climate Variables

(a) Surface Temperature **(b)** Radiative Forcing



(c) CO2 Emissions **(d)** CO2 Concentration

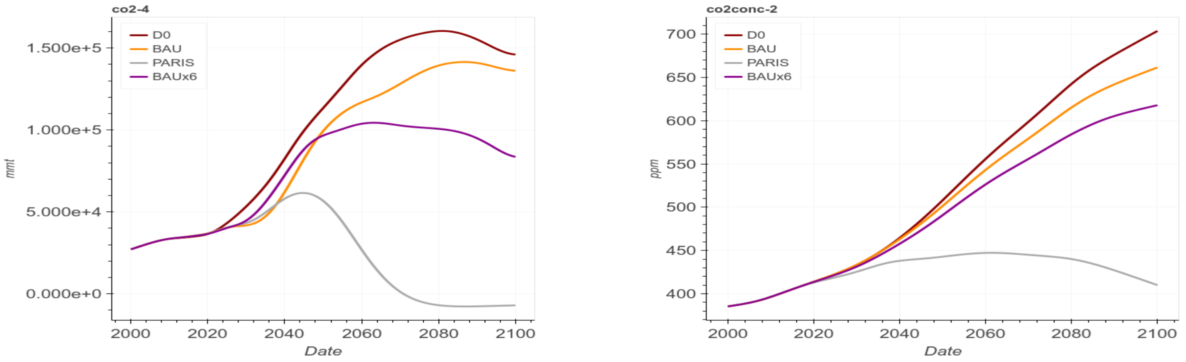
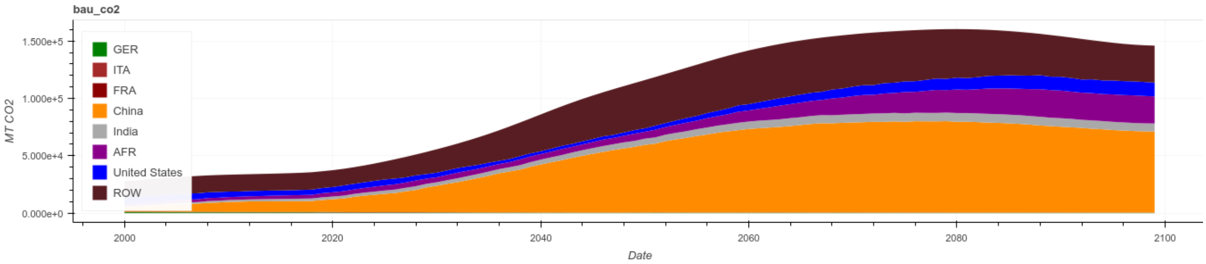


Figure 4: CO2 areas contibutions

(a) BAU



(b) PARIS

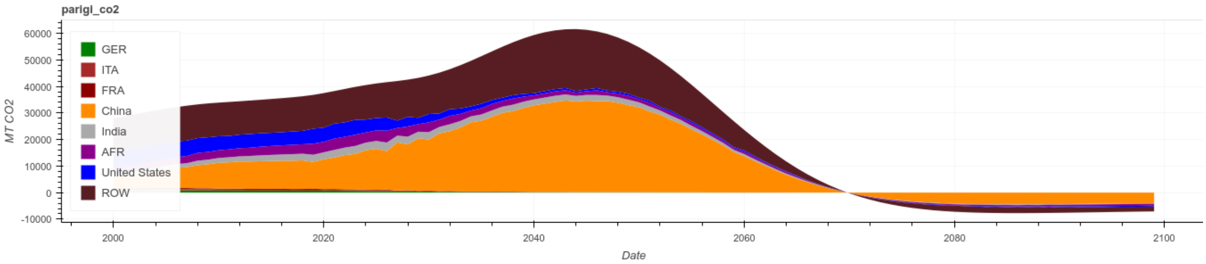
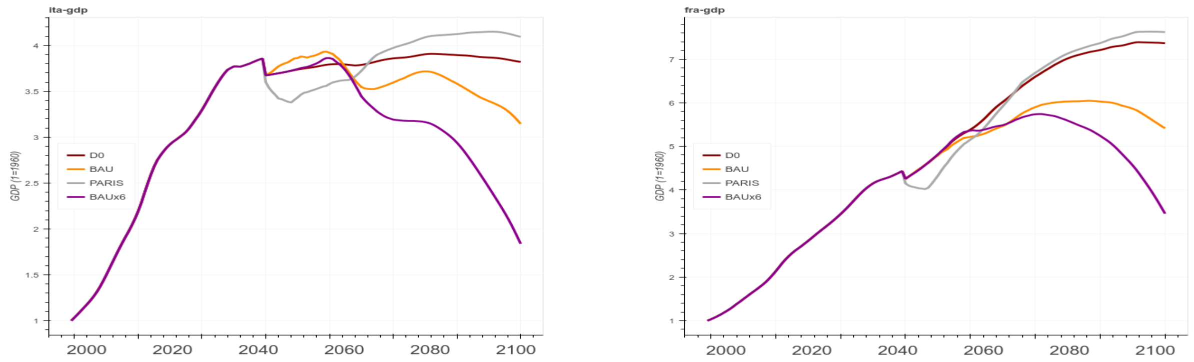
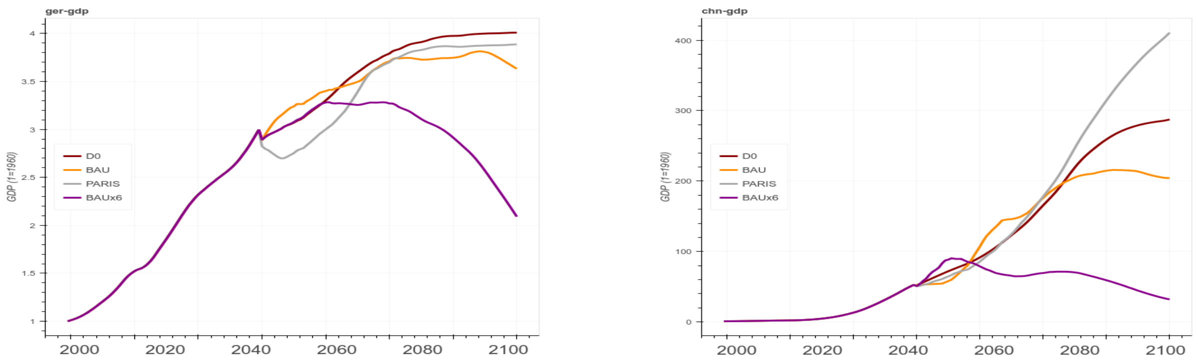


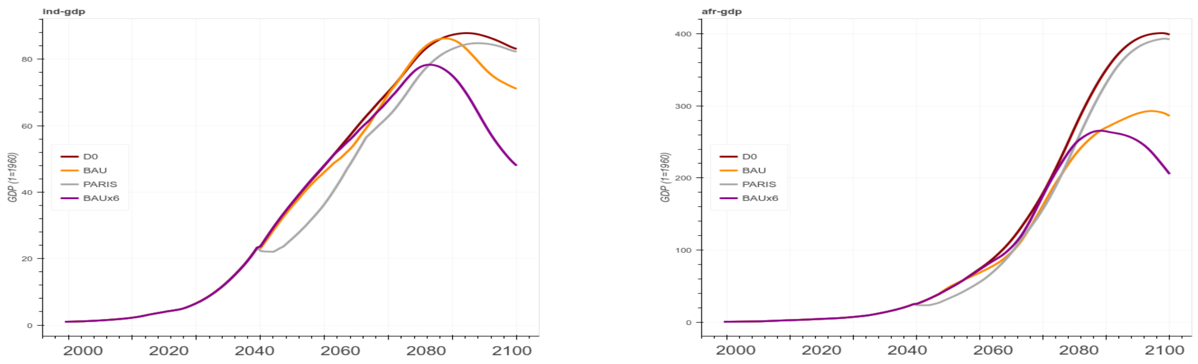
Figure 5: GDP levels


(a) ITA

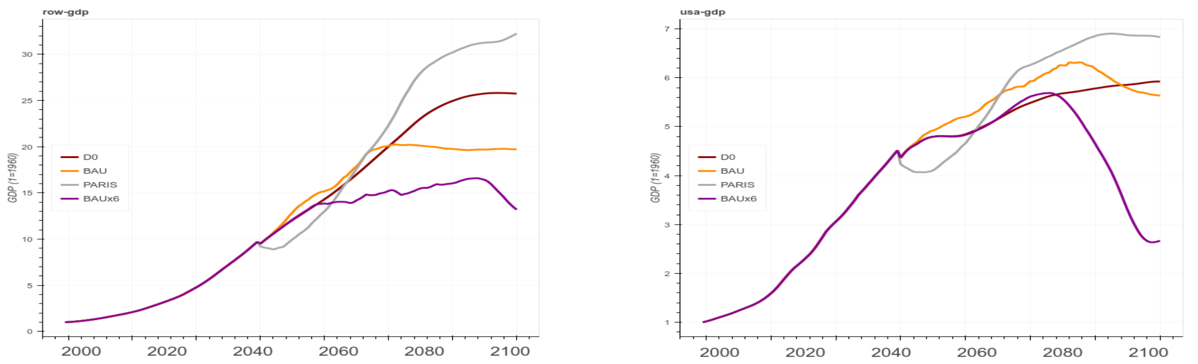
(b) FRA


(c) DEU

(d) CHN


(e) IND

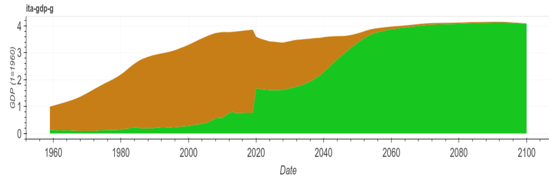
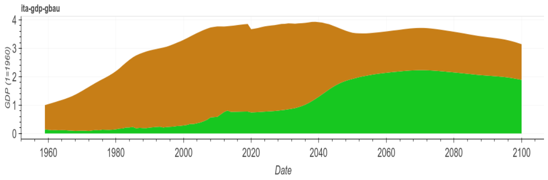
(f) AFR


(g) ROW

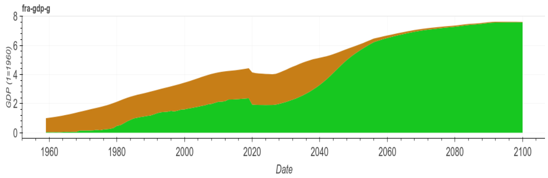
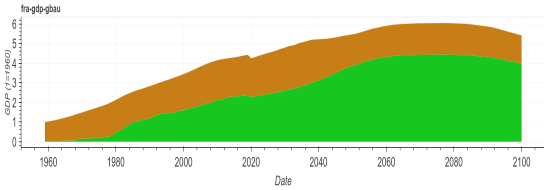
(h) USA

Figure 6: The phasing out of fossil fuels

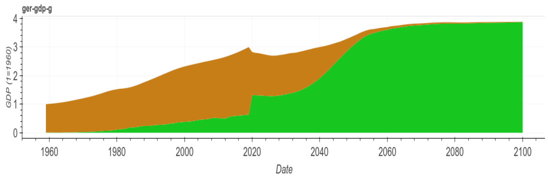
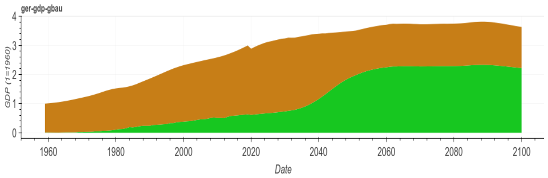
(a) ITA paris **(b)** ITA bau

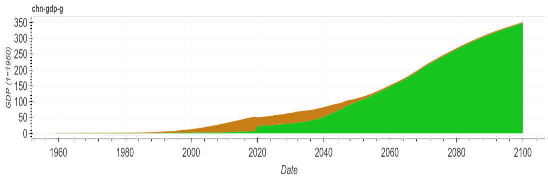
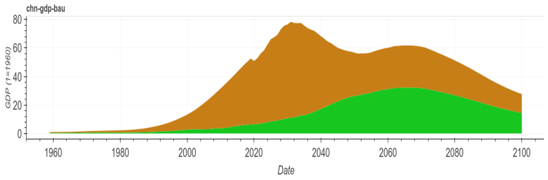
(c) FRA paris **(d)** FRA bau

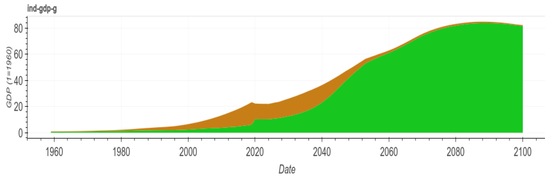
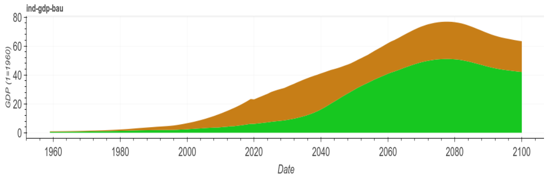
(e) GER paris **(f)** GER bau

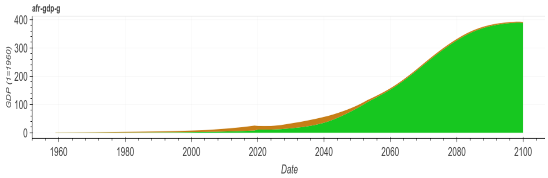
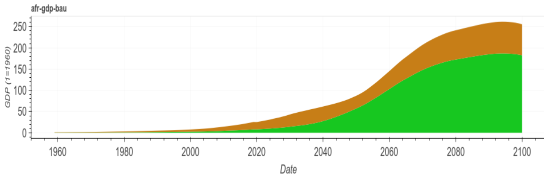
(g) CHN paris **(h)** CHN bau

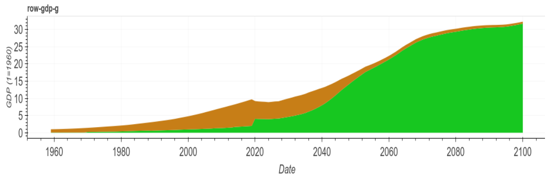
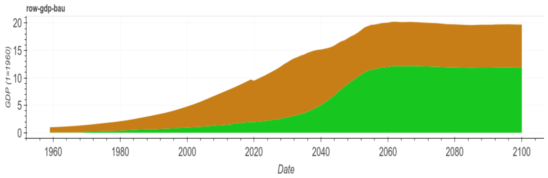
(i) IND paris **(j)** IND bau

(k) AFR paris **(l)** AFR bau

(m) ROW paris **(n)** ROW bau

(o) USA paris **(p)** USA bau

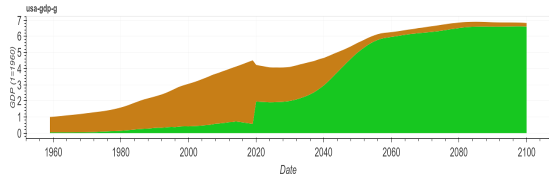
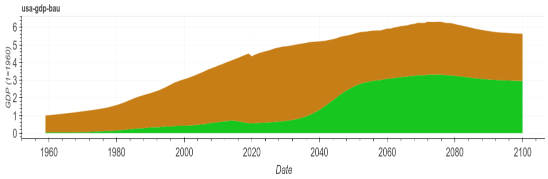
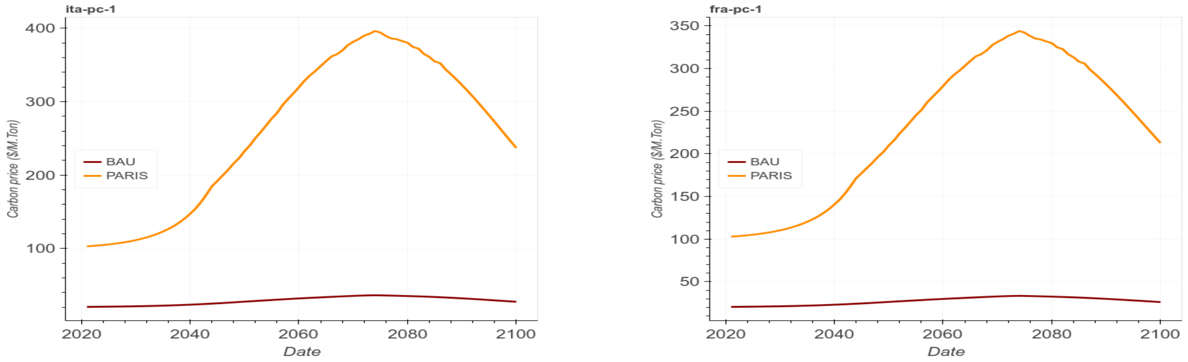
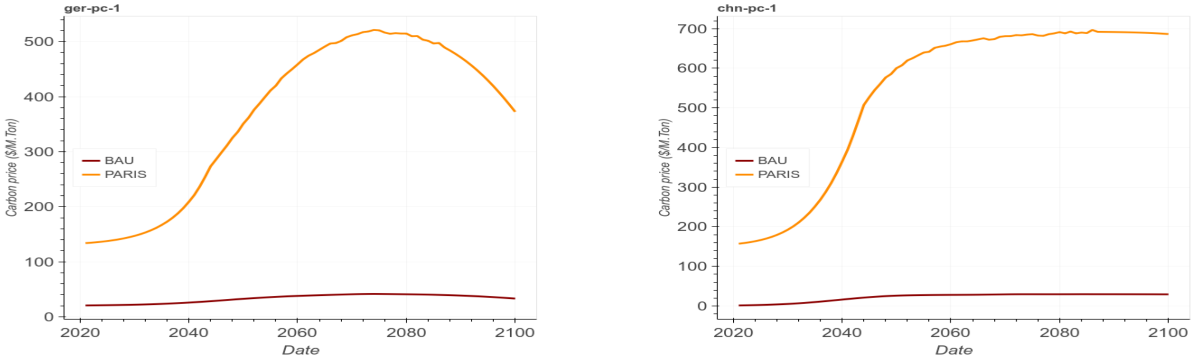
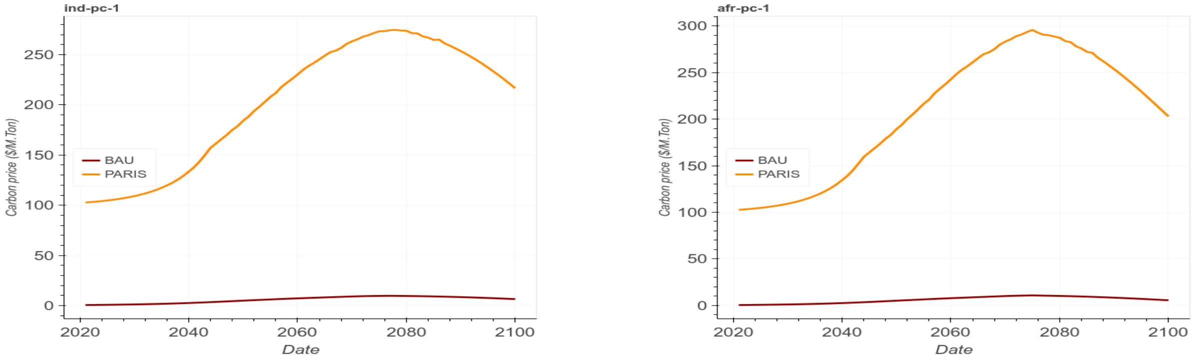



Figure 7: Carbon Price


(a) ITA **(b)** FRA


(c) GER **(d)** CHN


(e) IND **(f)** AFR

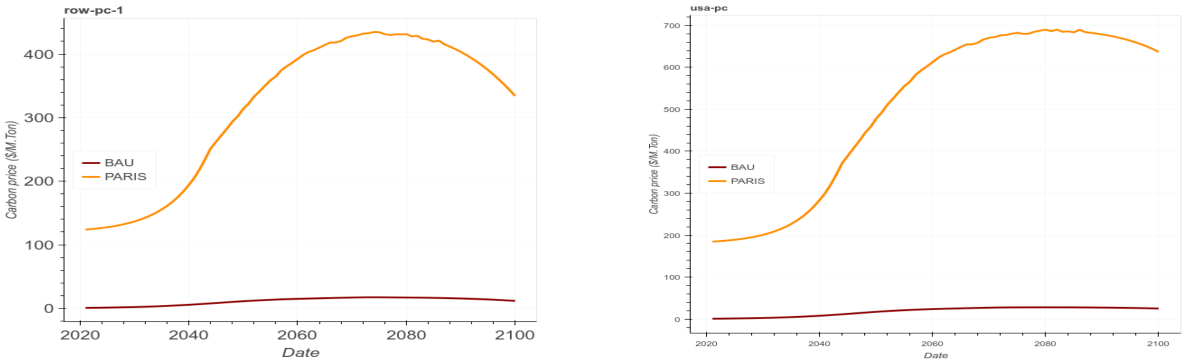
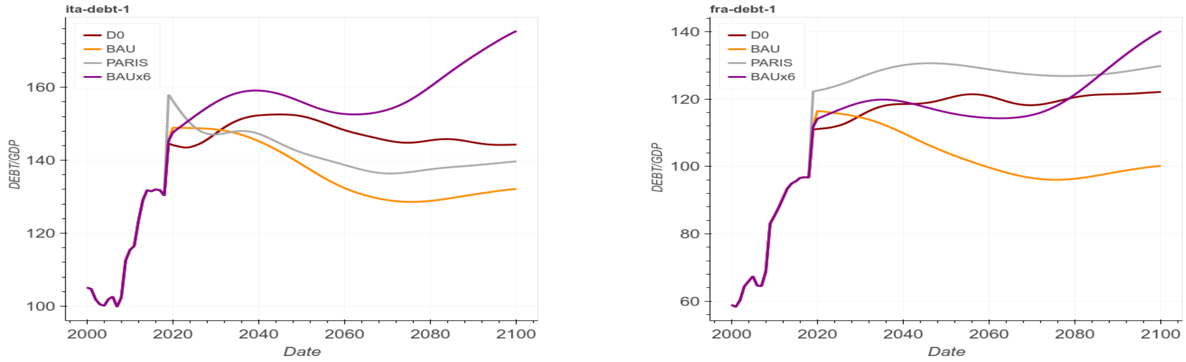
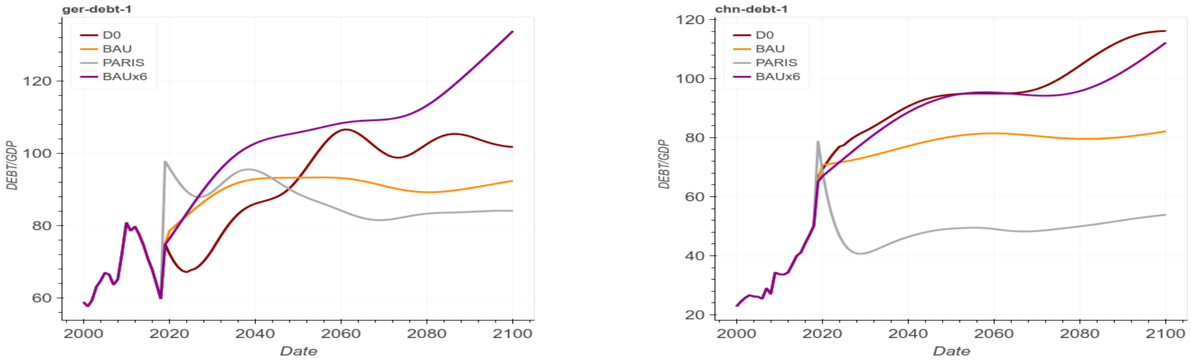

(g) ROW **(h)** USA

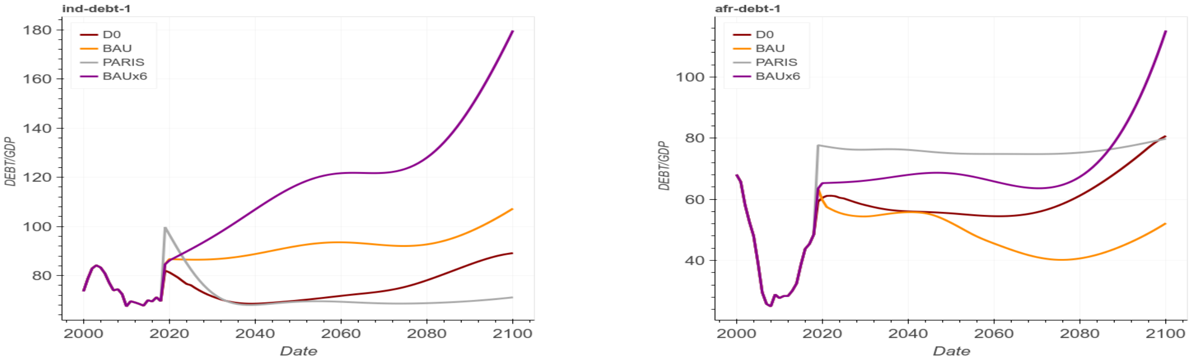
Figure 8: Debt-tp-Gdp ratio



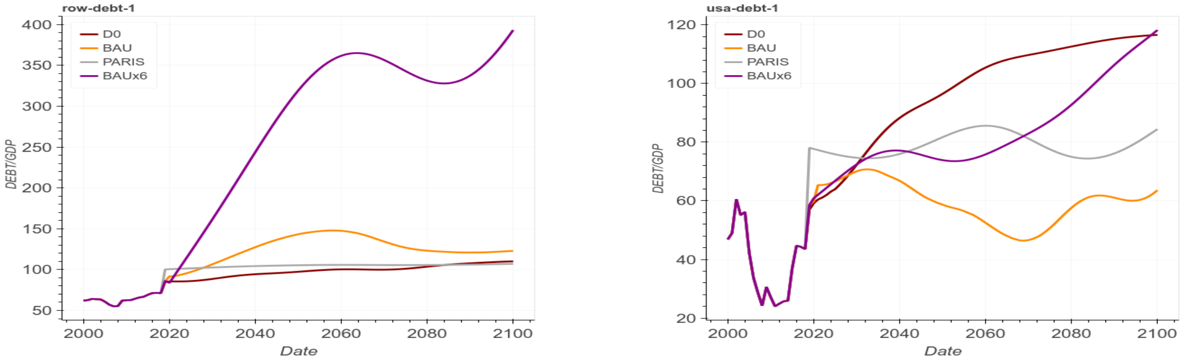
(a) ITA **(b)** FRA



(c) GER **(d)** CHN



(e) IND **(f)** AFR



(g) ROW **(h)** USA

5 The impact of fiscal policy

To offset the negative effects of the carbon pricing on the economic system, we provide additional simulations that allow us to compare the effect of different fiscal instruments and their interaction on growth. To the assumptions of the PARIS scenario, we add an increase in public investment in green energy equal to 1% of GDP for five years (PARIS2) and an additional debt-financed incentives in R&D expenditure in private sectors to increase energy efficiency through technological innovation (PARIS1). In another scenario, we assume that the carbon tax revenues are used not for green investment incentives (as in the PARIS scenario) but to cut taxes on labour income (LABTAX scenario), under balanced budget assumption, in order to mitigate the negative effects of the carbon price on consumption. Figure 9 shows that both PARIS1 and PARIS2 show significantly higher GDP levels than in the PARIS scenario, where incentives for green investments were made on a balanced budget using carbon tax revenues.

In PARIS1 and PARIS2 these expenditures are deficit-financed and thus lead to a strong initial increase in public debt (Fig. 10). However, GDP growth more than offsets the increase in debt, leading the debt-to-GDP ratio to fall sharply in the medium and long term in almost all countries. These policies to support demand in the transition phase are therefore extremely effective both in terms of long-term economic growth and debt stability.

Finally, the use of revenues to reduce taxation on labour (LABTAX) only has positive effects in the short and medium term as it supports consumption and demand. However, the absence of green incentives reduces the effects of the carbon tax on brown assets and green investments, thus undermining long-term growth. This negative impact on GDP makes the LABTAX scenario the least performing scenario in many countries, thus highlighting the importance of supporting the transition to a low-carbon economy through increased green investment.

6 Robustness

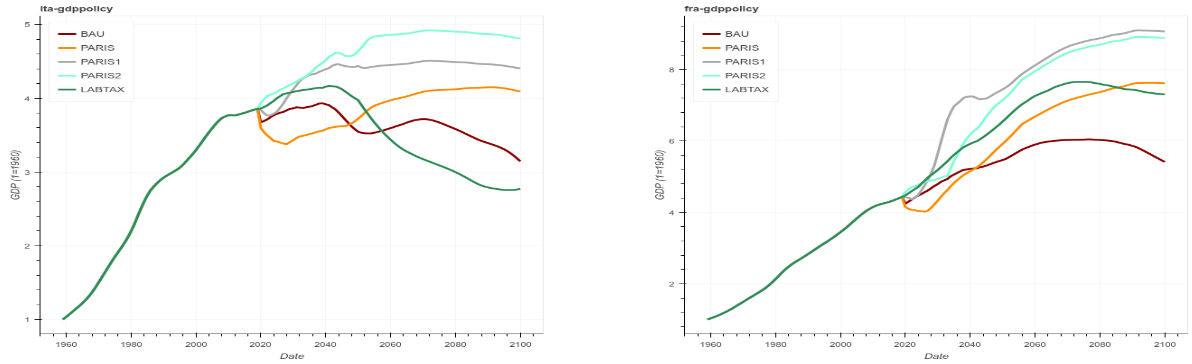
To assess the robustness of our results, we provide the model's response to changes in some relevant parameters and variables, i.e. those that influence the long-term economic growth path, especially under climate change mitigation efforts. In particular, we explore changes in demographic trends and technology around the two main policy scenarios: BAU and PARIS. As far as demographic trends are concerned, we consider the UN 95% prediction intervals of the probabilistic projections in order to provide an assessment of the uncertainty inherent in the UN medium-variant projection underlying both the BAU and PARIS scenarios. Therefore, we get BAUHP and BAULP for the upper and lower bounds of the 95% confidence intervals, respectively. Similarly, for PARIS, we get PARISHP and PARISLP.

As indicated in section 3.2.1, we have considered the case of greater climatic damage (6x damage) than the underlying damage in the BAU and PARIS scenarios (1x damage). Therefore, we get the additional two scenarios: BAUx6 and PARISx6, with damage functions equal to six times the Nordhaus [2017] function as in equation (8). These two variants are also assessed with the UN's probabilistic demographic projections. Therefore, we get the following scenarios: BAUx6HP, BAUx6LP and PARISx6HP and PARISx6LP.

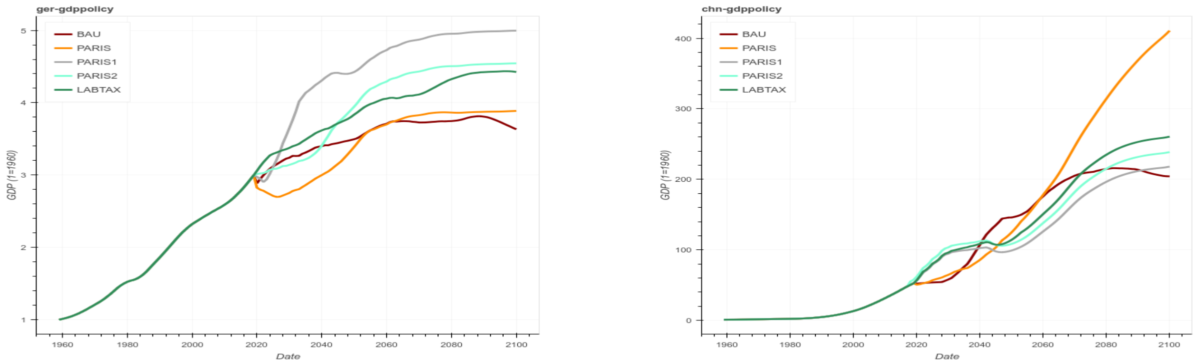
In general, with a higher population than the medium variant projections, GDP in the PARISHP case grows faster over the whole horizon than in the PARIS scenario for all countries (Fig. 11). On the other hand, in the BAUHP scenario, the positive effects of a larger population on GDP are only evident in the short to medium term, while in long-term GDP is lower than in the BAU scenario. This is because a larger population implies higher consumption and therefore higher emissions and stronger climate damage which, without any mitigation effort, undermines long-run productivity and growth in all countries. Conversely, low population growth always produces the worst performance, both in PARISLP and BAUHP.

The various PARISx6 scenarios are based on the same carbon tax profile as the PARIS scenario (section 4). However, they assume greater climate damage, which should therefore imply a higher carbon tax to reach the same level of emissions and temperature as the PARIS scenario. Thus, in the absence of an adequate upward correction of the carbon tax, the increased climate damage (damagex6) inevitably results in a worse performance of the PARISx6 scenarios than the PARIS scenario.

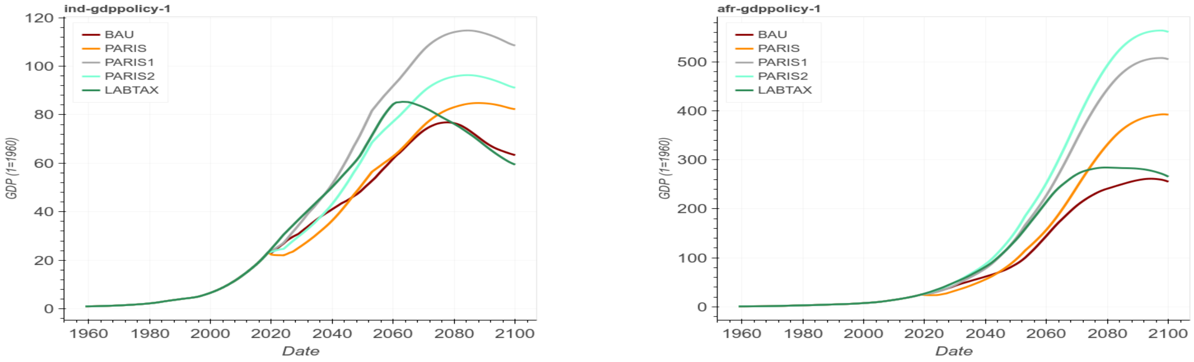
Figure 9: GDP levels


(a) ITA

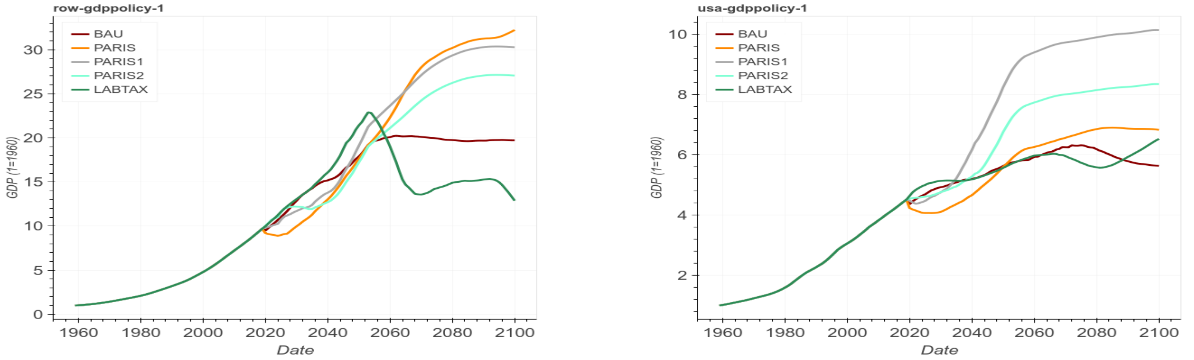
(b) FRA


(c) DEU

(d) CHN

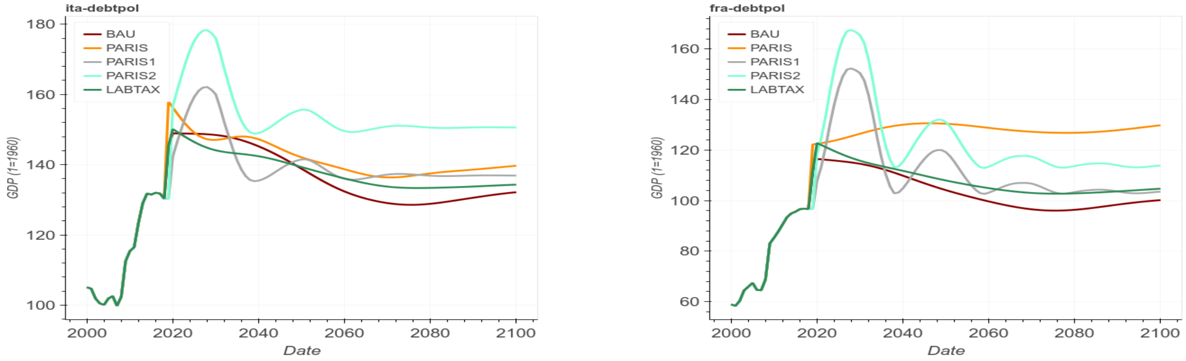

(e) IND

(f) AFR


(g) ROW

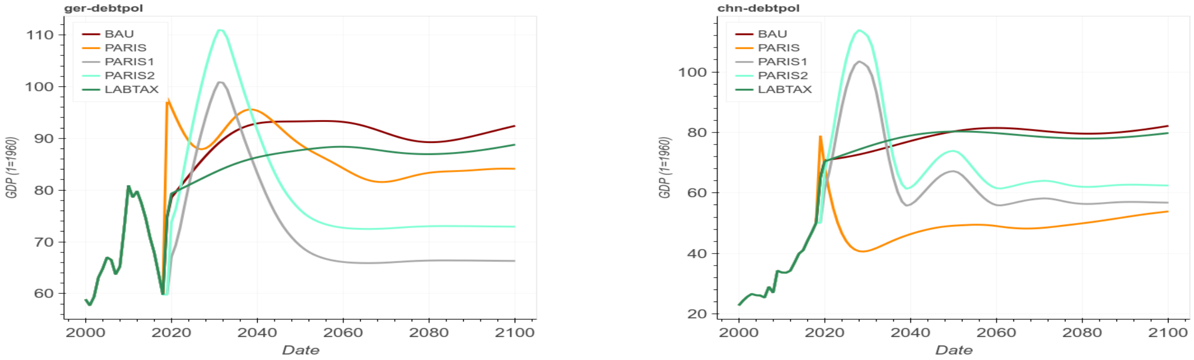
(h) USA

Figure 10: Debt-to-Gdp ratio - policy



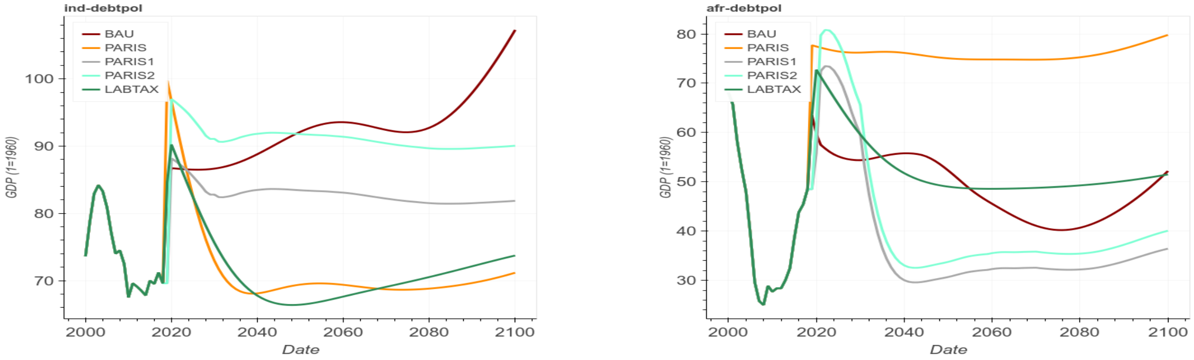
(a) ITA

(b) FRA



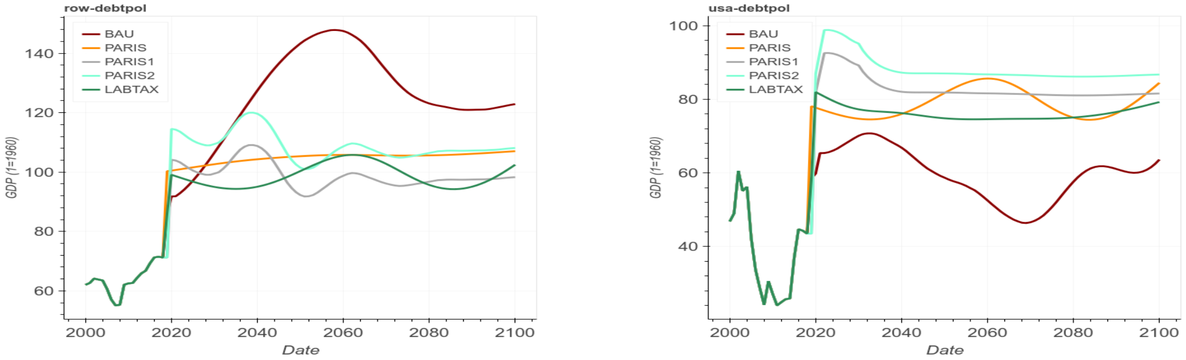
(c) GER

(d) CHN



(e) IND

(f) AFR

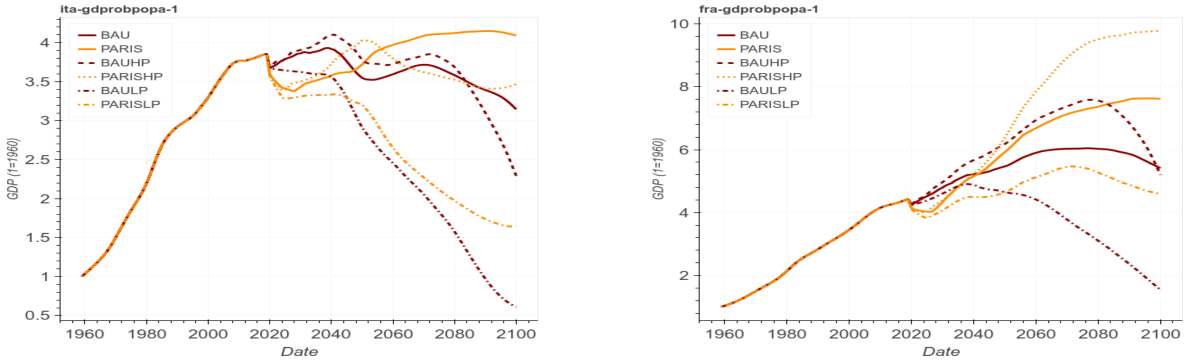


(g) ROW

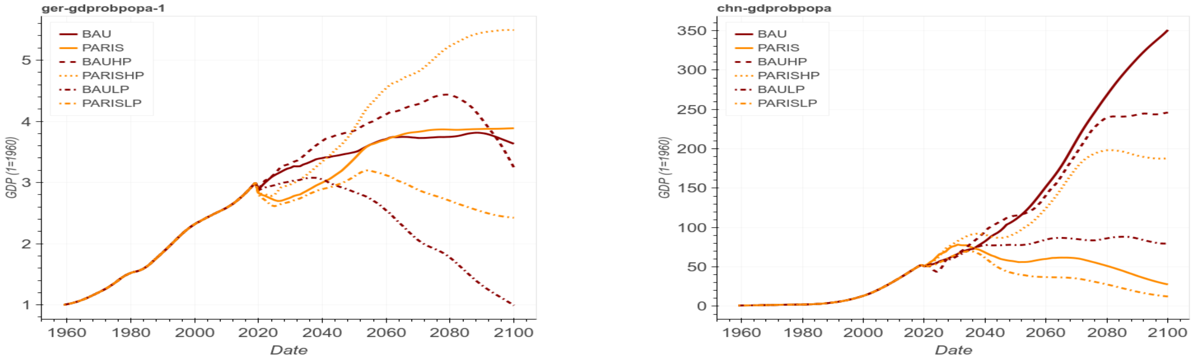
(h) USA

Figure 11: GDP levels - Robustness - popoulation

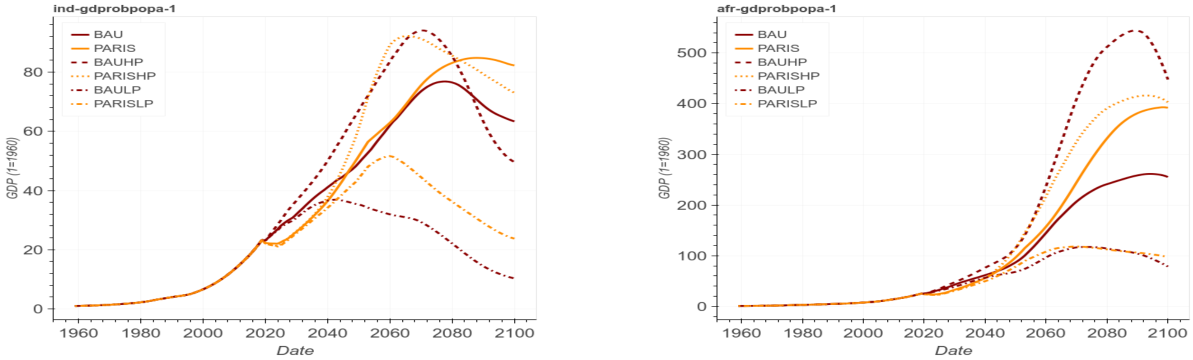
(a) ITA **(b)** FRA



(c) GER **(d)** CHN



(e) IND **(f)** AFR



(g) ROW **(h)** USA

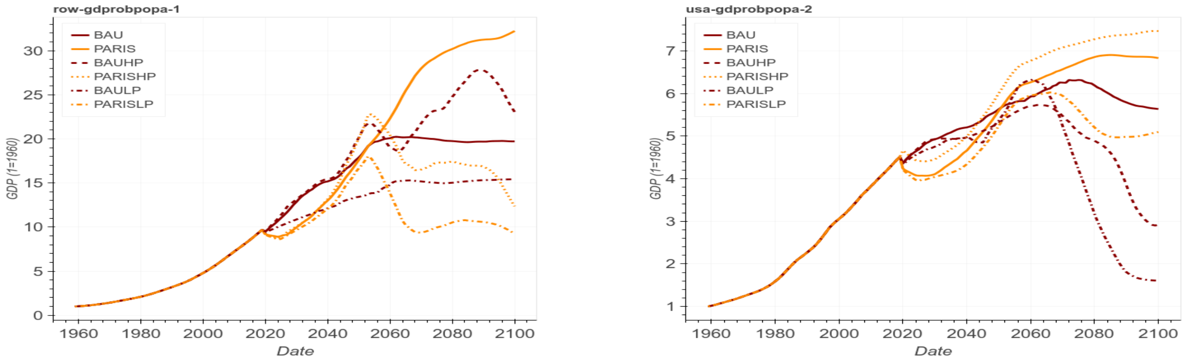
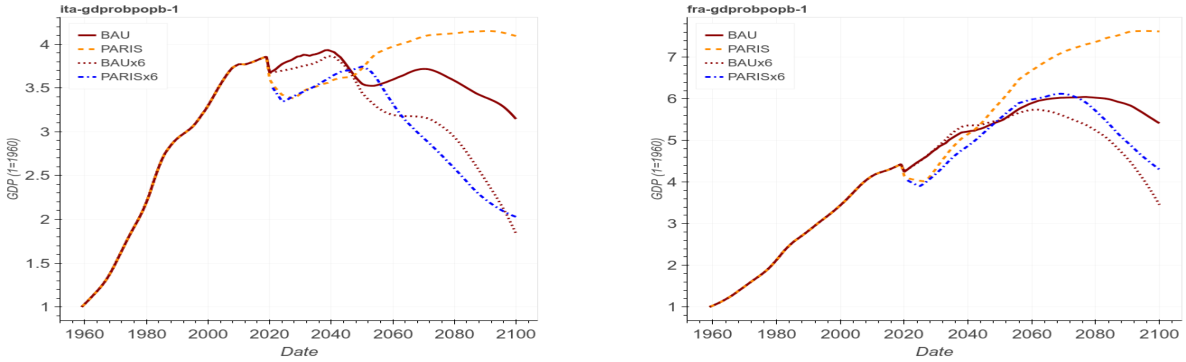
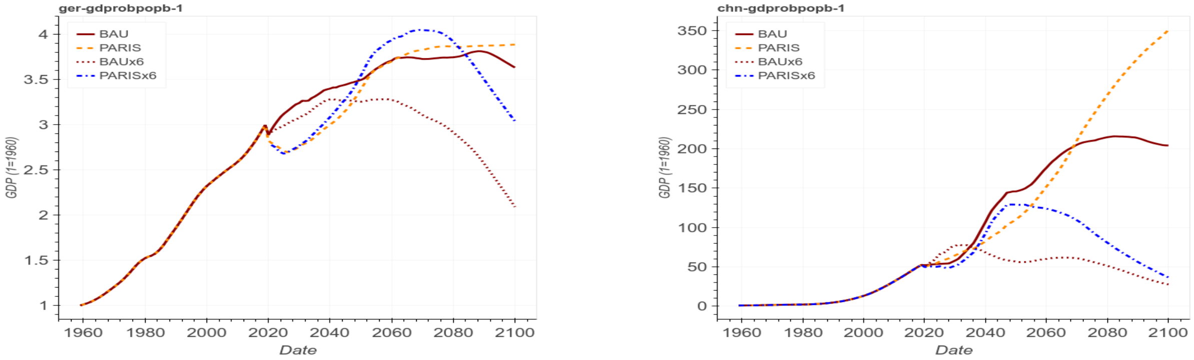


Figure 12: GDP levels - Robustness - damage

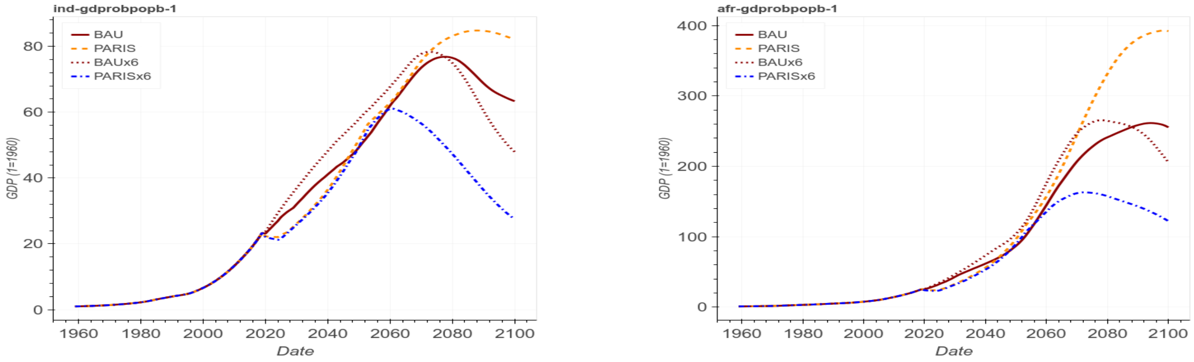
(a) ITA (b) FRA



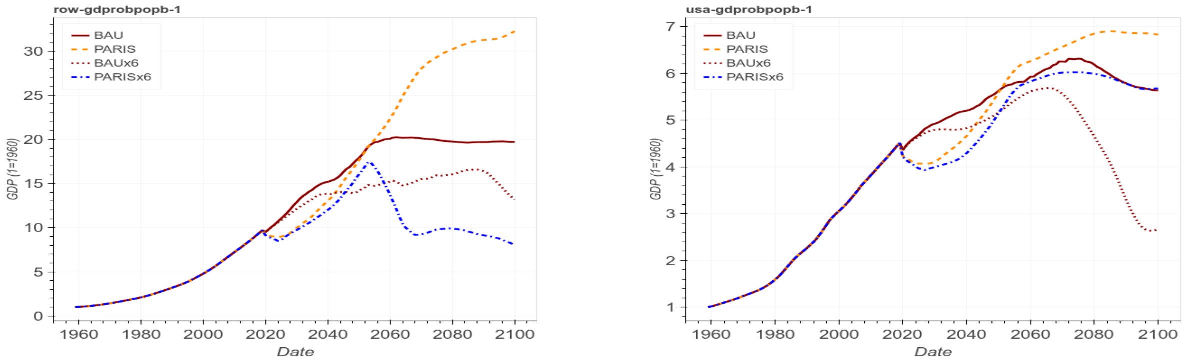
(c) GER (d) CHN



(e) IND (f) AFR



(g) ROW (h) USA



7 Conclusions

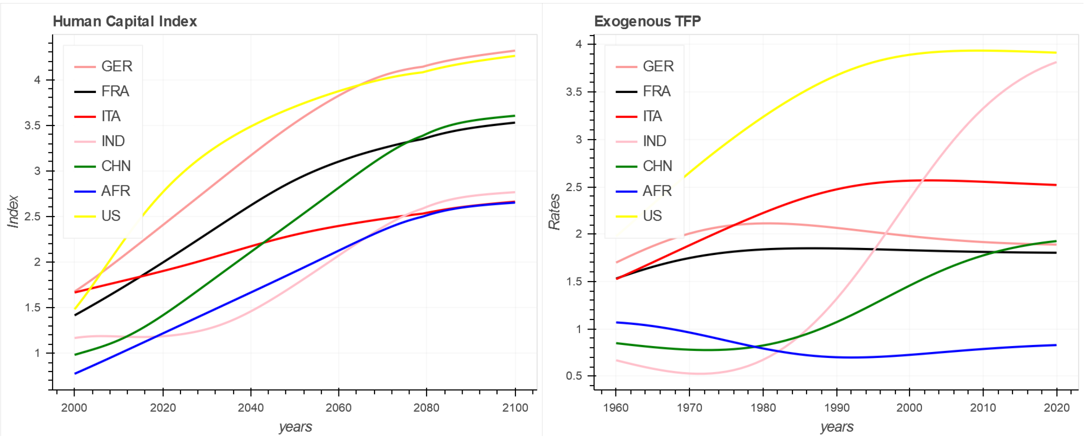
Based on the existing scientific evidence, country signatories to the Paris Agreement have committed to limiting temperature increases to below $2°C$ by 2100. The various policies being considered to achieve this rely on carbon pricing combined with incentives for private sector investment in green energy sources. Improved energy efficiency and carbon capture technologies will contribute. To analyze the economic impact of climate change at the global level, we built a model which is based on Nordhaus's IAM framework but allows a richer description of the economic environment. We used the model to analyze emissions trajectories and the impact of global warming and mitigation policies on economic growth in both the short and medium-long terms. We considered a policy which consists of adoption of carbon pricing to increase the price of brown sources of energy in both the advanced and emerging countries, and assumes that the carbon tax revenues are used to encourage private sector green investments (balanced budget case). We compared the economic impact of this policy which is in line with the objectives of the Paris Accords, with a no policy scenario i.e. no additional efforts to contain global warming compared to the current situation (business as usual scenario). A policy of carbon pricing aimed at global zero emissions by 2070 in line with the Paris Agreement scenario allows temperature increases of maximum $2°C$ and limits the impact of climate damage on long-term growth, but at the cost of a short-term recession. We compared the Paris scenario with other scenarios which combine a carbon tax with other fiscal instruments to offset the recessionary effects of taxation (fiscal expansion case). We found that policies aimed at supporting labor income and consumption are ineffective. We found also that an initial increase in public debt to finance green public expenditure (i.e. public investment and R&D spending aimed at making adoption of alternative energy sources profitable) would be more than offset by medium and long term GDP growth and would lead to a better debt/GDP dynamic.

A The macro-model calibration

In this section we report tables and figures related to the calibrated parameter of the macro model. Details on the calibration strategy are reported in Catalano and Pezzolla [Working Paper 2020]. A number of exogenous trends are assumed: demographics, human capital, technical obsolescence (via the depreciation rate), labour and capital share and goods market integration (trade and capital flows). The latter allows us to take into account the degree of integration between areas that is not captured by price determination, i.e. the institutional and behavioral factors that affect the degree of integration between economies. We use a runtime calibration strategy (1970-2018) to calibrate the values the GDP levels to the actual data for each economy using the exogenous total factor productivity as a tool. 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 discount rate time preference.

The exogenous TFP (that match historical GDP data) and the human capital H_t (computed as a Törnqvist index according to demographic projections and education levels) are shown in figure 13.

Figure 13: Calibration results



(a) Human capital index, 2000-2100

(b) Exogenous TFP

Endogenous TFP is defined as in equation (9): $TFP = \left(\frac{K}{N}\right)^g H^z$. We estimate the parameters g and z in the long-run relation

$$\log(TFP) = g\log(K/N) + z\log(H) + \epsilon_{tfp}.$$

using capital stock data provided by Berlemann and Wesselhöft [2014], and data for labour, human capital and TFP provided by Penn World Trade[16]. Fixed effects panel estimates lead to $g = 0.17$ and $z = 0.24$ (standard deviation 0.013 and 0.058 respectively), while random coefficients estimation (Swamy [1970]) leads to different values between countries, as shown in table 1. These coefficients (z^* and g^* in table 1) are obtained as deviation from the fixed effects estimates: in particular, we apply to the fixed effects coefficients the percentage difference between the random estimates for individual countries (z and g in table 1) and the average coefficient resulting from the technique of random coefficients.

Table 1: Random coefficients estimation

Countries	z^*	g^*	z	g	σ_z	σ_g
Germany	0.307	0.030	-0.093	2.898	0.004	0.132
Italy	0.016	0.001	0.005	-0.169	0.001	0.080
France	0.138	0.0115	-0.038	1.396	0.002	0.103
China	0.476	0.041	-0.047	1.928	0.002	0.136
India	0.088	0.0073	-0.018	0.873	0.000	0.060
Africa	0.816	0.082	-0.118	3.650	0.003	0.121
USA	0.014	0.048	-0.008	0.063	0.000	0.074

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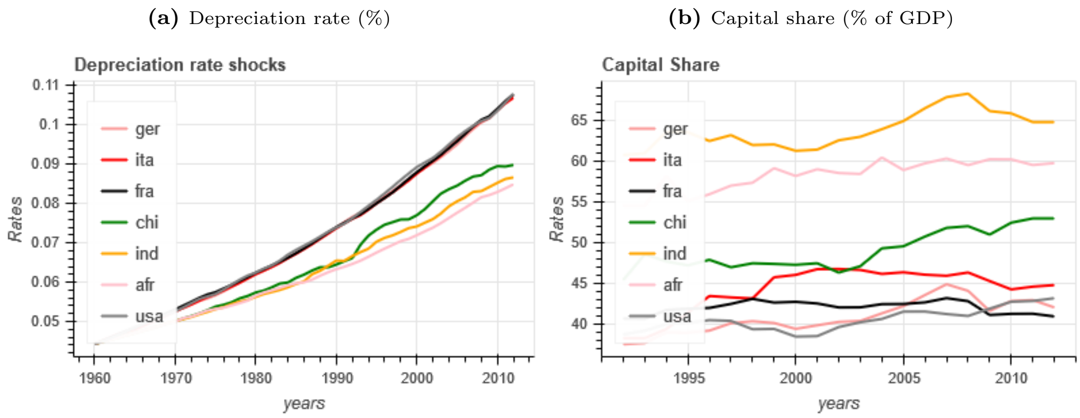
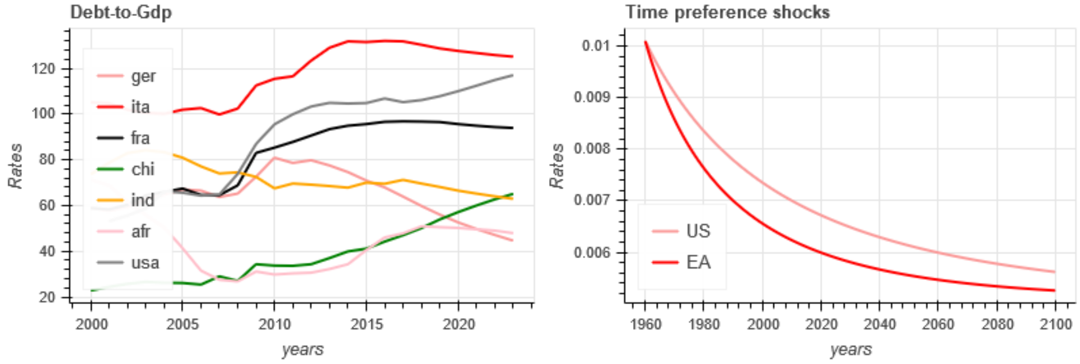
[16] Feenstra et al. [2015], available for download at www.ggdc.net/pwt.

Figure 14 shows the capital share, the depreciation rate, debt-to-GDP and the rate of time preference. To calibrate the capital share β we use the labour income share data provided by ILO.[17] We obtain a time profile of the capital share in production that is slightly increasing in the period 1991-2013 in all countries. The depreciation rate of capital is set according to IMF data for total investment and capital stock in constant 2005 international dollars. We get a depreciation rate δ that is increasing for all countries over the period 1960-2013. The debt-to-GDP ratio is calibrated in order to match data provided by IMF from 2000 to 2020, as shown in figure 14. Finally, the dynamic results for the rate of time preference, which is strictly related to demographic dynamics, is used to calibrate the capital-to-GDP ratio.

Figure 14: Parameters trends


(a) Depreciation rate (%) **(b)** Capital share (% of GDP)


(c) General government gross debt (% of GDP)) **(d)** The rate of time preference for US and EU

Government spending on education sg in equation (13) is calibrated according to WDI data, shown in table 2.

Table 2: Government expenditure on education, total (% of GDP)

Countries	%
Germany	4.81 (2015)
Italy	4.08 (2015)
France	5.46 (2015)
China	1.89 (1999)
India	3.84 (2013)
Africa(*)	4.00 (2016)
USA	4.99 (2014)

(*) Sub-Saharian Africa.
In parenthesis, the last year available.
Source: World Development Indicators

As regards the degree of integration, we assume an increasing degree of economic openness that allows to take account of the effects of slow capital and goods market integration affecting the whole simulated

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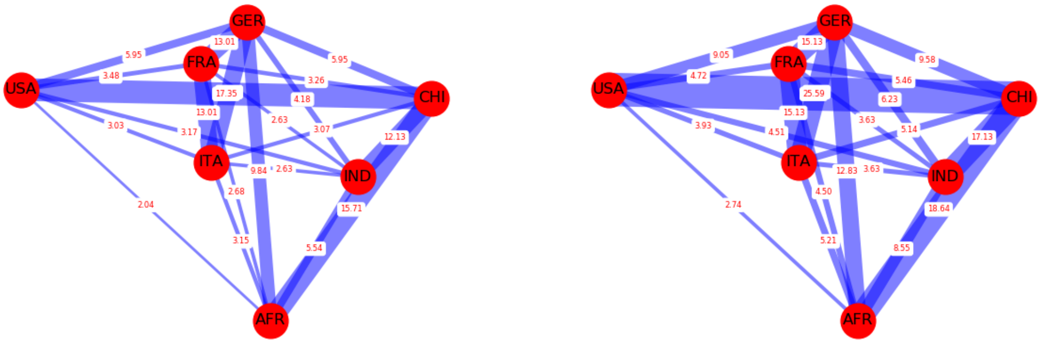
[17] For Sub-Saharian Africa we refer to Trapp, K. Measuring the Labour Income Share of Developing Countries: Learning from Social Accounting Matrices. UNU-WIDER, Helsinki, Finland (2015) 22 pp. [WIDER Working Paper No. 2015/041].

economy and obtain endogenous capital movements between countries. Figure 15 a and b shows the evolution of market integration between 2017 and 2030 (it is assumed to stabilize afterwards until 2100), based on trends in the period 2000-2017 (World Bank bilateral data). What emerges is a growing integration between emerging and advanced countries (thicker blue line), and at the same time a greater integration between European countries.

Figure 15: Integraton matrices



(a) 2017, starting point

(b) 2100 Globalized world economy

Source: our calculations based on WITS data (World Bank)

Other parameters are reported in table 3.

Table 3: Model Parameters

		Ger	Ita	Fra	Chn	Ind	Afr	Usa
ξ	Intertemporal elasticity of substitution	.5	.5	.5	.5	.5	.5	.5
η	Labor-Consumption elasticity of substitution	.95	.95	.95	.95	.95	.95	.95
ρ	Pure time impatience rate	0.006	0.006	0.006	0.011	0.011	0.011	0.006
α	Weight of leisure utility	0.32	0.27	0.33	0.3	0.3	0.3	0.3
β	Share of capital in production	0.421	0.445	0.410	0.530	0.647	0.597	0.436
δ	Depreciation rate of capital	0.107	0.106	0.107	0.089	0.086	0.084	0.107
g	Capital spillover in TFP	0.030	0.001	0.011	0.041	0.007	0.082	0.048
z	Human capital spillover in TFP	0.307	0.016	0.138	0.476	0.088	0.816	0.014
τ_l	Labor tax rate and social contributions	0.50	0.48	0.24	0.15	0.29	0.23	0.30
τ_c	VAT rate	0.19	0.22	0.20	0.13	0.18	0.15	0.05
τ_a	Wealth tax	0.05	0.05	0.05	0.05	0.05	0.05	0.05
sg	Schooling expenditure on Gdp	0.051	0.043	0.057	0.042	0.046	0.02	0.049
γ	Goods, Services spending	0.195	0.188	0.234	0.145	0.111	0.145	0.140

B TABLES

Table 4: Scenario assumptions

DAMAGE

Scenario	Damage	Adaptation
D0	0x damage	FULL
BAU/PARIS	1x damage	NATURAL
BAUx6/PARISx6	6x damage	NATURAL

ENERGY

Scenario	PRIMARY ENERGY MIX	DEMAND
D0	Costs reduction: 15% OIL - 30%(GAS-COAL) FOSSIL; 20% GREEN	ADV .4% and EME 1% REGIONAL
BAU	Costs reduction: 15% OIL - 30%(GAS-COAL) FOSSIL; 20% GREEN	ADV .4% and EME 1% REGIONAL
PARIS	BAU + endogenous eff	BAU + endogenous eff.

DEMOGRAPHY

Scenario	Population growth	Human Capital growth
D0/BAU/PARIS	MEDIUM	MEDIUM
BAUHP/PARISHP	HIGH	HIGH
BAULP/PARISLP	LOW	LOW

EMISSIONS

Scenario	Transition time	BECCS
PARIS	2060	NORMAL
PARIS+	2050	HIGH
PARIS-	2080	LOW

POLICY

Scenario	Carbon tax	Green incentives	Green public investment	R&D	Labor tax cut
D0					
BAU					
PARIS	✓	✓			
PARIS1	✓	✓	✓		
PARIS2	✓	✓	✓	✓	
PARIS LABTAX	✓	✓			✓
PARIS NOG	✓				

DEVELOPMENT STAGES

Scenario	Net forestation	Crops (Adv/Eme)	Livestock (Adv/Eme)	Africa[1]	India[2]	China[3]
ALL	1%/yr loss until 2050*	0.46/0.6	0.10/0.24	by 2060	by 2060	by 2080
ALL	0.5%/yr loss until 2050*	0.46/1	0.10/0.40	by 2040	by 2040	by 2060
ALL	1.2%/yr loss until 2050*	0.46/0.46	0.10/0.10	by 2040	by 2040	by 2060

(*) Then, in 2100, it returns to the levels of 2010.
(1) Development phase from agriculture to manufacturing
(2) Development towards service and manufacturing.
(3) Convergence towards EU and US specialisation.

C The sectoral model

This section is organized as follows: section C.1 show the details of demand system for the volumes produced and exchanged in the several sectors. Section C.2 shows the energy demand for the five type of energy accounted into the model: gas oil, coal, green and beccs. Section C.3 refers to the price aggregation starting from the bottom layers to the top. In sections C.4 and C.5, we take into account $CO2$ from trade and from consumption.

C.1 Nested Demand system

In this section, we drop the t indices of time and r of the region, since the equations are mainly static relationships. Manufacturing, agriculture and services sector demands depends on value added levels VA

$$\begin{aligned} MA &= \gamma_{va,m}\left(\frac{pva}{pma}\right)^{sx} VA \\ AG &= \gamma_{va,a}\left(\frac{pva}{pag}\right)^{sx} VA \\ SERV &= \gamma_{va,s}\left(\frac{pva}{pserv}\right)^{sx} VA. \end{aligned} \tag{57}$$

High energy sector (HMA) and low energy macro sector (LMA) demands equation are:

$$\begin{aligned} HMA &= \gamma_{ma,h}\left(\frac{pma}{phma}\right)^{\sigma}_{ma} MA \\ LMA &= \gamma_{ma,l}\left(\frac{pma}{plma}\right)^{\sigma}_{ma} MA. \end{aligned} \tag{58}$$

Agriculture prduction is disaggregate in crops (CRO) and livestock (LIV) production

$$\begin{aligned} CRO &= \gamma_{ag,c}\left(\frac{pag}{pcro}\right)^{\sigma}_{a} gAG \\ LIV &= \gamma_{ag,l}\left(\frac{pag}{pliv}\right)^{\sigma}_{a} gAG. \end{aligned} \tag{59}$$

C.2 Energy Demand

Each sector demands a bundle of energy sources. Services energy demands are:

$$\begin{aligned} SERVEOIL &= \gamma_{ser,e}\left(\frac{pserveoil}{pserv}\right)^{-\sigma_s} SERV \\ SERVEGAS &= \gamma_{ser,e}\left(\frac{pservegas}{pserv}\right)^{-\sigma_s} SERV \\ SERVECOAL &= \gamma_{ser,e}\left(\frac{pservecoal}{pserv}\right)^{-\sigma_s} SERV \\ SERVEGREEN &= \gamma_{ser,e}\left(\frac{pservegreen}{pserv}\right)^{-\sigma_s} SERV \\ SERVEBECCS &= \gamma_{ser,e}\left(\frac{pservebeccs}{pserv}\right)^{-\sigma_s} SERV. \end{aligned} \tag{60}$$

Livestock energy demands:

$$\begin{aligned}
LIVEOIL &= \gamma_{liv,e} \left(\frac{pliveoil}{pliv}\right)^{-\sigma_v} LIV \\
LIVEGAS &= \gamma_{liv,e} \left(\frac{plivegas}{pliv}\right)^{-\sigma_v} LIV \\
LIVECOAL &= \gamma_{liv,e} \left(\frac{plivecoal}{pliv}\right)^{-\sigma_v} LIV \\
LIVEGREEN &= \gamma_{liv,e} \left(\frac{plivegreen}{pliv}\right)^{-\sigma_v} LIV \\
LIVEBECCS &= \gamma_{liv,e} \left(\frac{plivebeccs}{pliv}\right)^{-\sigma_v} LIV.
\end{aligned} \tag{61}$$

Crops energy demands:

$$\begin{aligned}
CROEOIL &= \gamma_{cro,e} \left(\frac{pcroeoil}{pcro}\right)^{-\sigma_c} CRO \\
CROEGAS &= \gamma_{cro,e} \left(\frac{pcroegas}{pcro}\right)^{-\sigma_c} CRO \\
CROECOAL &= \gamma_{cro,e} \left(\frac{pcroecoal}{pcro}\right)^{-\sigma_c} CRO \\
CROEGREEN &= \gamma_{cro,e} \left(\frac{pcroegreen}{pcro}\right)^{-\sigma_c} CRO \\
CROEBECCS &= \gamma_{cro,e} \left(\frac{pcroebeccs}{pcro}\right)^{-\sigma_c} CRO.
\end{aligned} \tag{62}$$

High manufacturing energy demands:

$$\begin{aligned}
HMAEOIL &= \gamma_{hma,e} \left(\frac{phmaeoil}{phma}\right)^{-\sigma_h} HMA \\
HMAEGAS &= \gamma hma, e \left(\frac{phmaegas}{phma}\right)^{-\sigma_h} HMA \\
HMAECOAL &= \gamma_{hma,e} \left(\frac{phmaecoal}{phma}\right)^{-\sigma_h} HMA \\
HMAEGREEN &= \gamma_{hma,e} \left(\frac{phmaegreen}{phma}\right)^{-\sigma_h} HMA \\
HMAEBECCS &= \gamma_{hma,e} \left(\frac{phmaebeccs}{phma}\right)^{-\sigma_h} HMA.
\end{aligned} \tag{63}$$

Light manufacturing energy demands:

$$\begin{aligned}
LMAEOIL &= \gamma_{lma,e} \left(\frac{plmaeoil}{plma}\right)^{-\sigma_l} LMA \\
LMAEGAS &= \gamma_{lma,e} \left(\frac{plmaegas}{plma}\right)^{-\sigma_l} LMA \\
LMAECOAL &= \gamma_{lma,e} \left(\frac{plmaecoal}{plma}\right)^{-\sigma_l} LMA \\
LMAEGREEN &= \gamma_{lma,e} \left(\frac{plmaegreen}{plma}\right)^{-\sigma_l} LMA \\
LMAEBECCS &= \gamma_{lma,e} \left(\frac{plmaebeccs}{plma}\right)^{-\sigma_l} LMA.
\end{aligned} \tag{64}$$

C.3 Price system

In this section we provide the equations for prices in sectors j. In general we have:

$$p_j^e = \left[\sum_c \gamma_c^e p_c^{e1-\sigma_j)} \right]^{-1/(1-\sigma_j)} \tag{65}$$

Prices in sectors j that use energy sources k:

$$\begin{aligned}
phma &= \left[\sum_k \gamma_k^e p_{hma}^e \right]^{-1/(1-\sigma_h)} \\
plma &= \left[\sum_k \gamma_k^e p_{lma}^e \right]^{-1/(1-\sigma_l)} \\
pliv &= \left[\sum_k \gamma_k^e p_{liv}^e \right]^{-1/(1-\sigma_v)} \\
pcro &= \left[\sum_k \gamma_k^e p_{cro}^e \right]^{-1/(1-\sigma_c)} \\
pserv &= \left[\sum_k \gamma_k^e p_{serv}^e \right]^{-1/(1-\sigma_s)} \quad .
\end{aligned} \tag{66}$$

Manufacturing and agriculture goods bundle prices:

$$pma = [\gamma_{ma}(phma)^{\sigma_{ma}} + \gamma_{ma}(plma)^{\sigma_{ma}}]^{1/\sigma_{ma}} \tag{67}$$

$$pag = [\gamma_{ag}(pcro_{t,r})^{\sigma_{ag}} + \gamma_{ag}(pliv_{t,r})^{\sigma_{ag}}]^{1/\sigma_{ag}} \, . \tag{68}$$

Value added price index:

$$pva_t = [\gamma_{va,1}(pma_{t,r})^{\sigma_{va,2}} + \gamma_{va}(pag_{t,r})^{\sigma_{va}} + (1 - \gamma_{va,1} - \gamma_{va,2})(pserv_{t,r})^{\sigma_{va}}]^{1/\sigma_{va}} \tag{69}$$

Price of imports and exports are ces aggregator defined on the bilater trade prices:

$$\begin{aligned}
pmt_t &= \left(\sum_{r,r'} \beta_w pm^{(1-\sigma_w)} \right)^{1/(1-\sigma_w)} \\
pet_t &= \left(\sum_{r,r'} \beta_w pe^{(1-\sigma_e)} \right)^{1/(1-\sigma_e)} \quad .
\end{aligned} \tag{70}$$

C.4 The CO2 sub-system

In this section we aggregate $CO2$ over energy sectors k in each region and add emissions emerging from trade:

$$\begin{aligned}
CO2_{trade,r,t} &= \gamma_{co2} w_{mg} Y_{r,t} \\
CO2_{r,t} &= CO2_{trade,r,t} + \sum_k CO2_{k,r,t}
\end{aligned} \tag{71}$$

C.5 Consumers

In order to get emission from households, we model a disaggregated consumption using the same CES strategy as in the production sectors. Households consume a basket of goods $s = 1, ...S$ that sums to the aggregate consumption level obtained in the macro model.

$$pC_s = \sum_i p_i c_i \tag{72}$$

$$C_s = \left(\sum_{i=0}^{n} \lambda_{cc,i}^{\frac{1}{\sigma_{cc}}} c_{i,s}^{\frac{\sigma_{cc}-1}{\sigma_{cc}}} \right)^{\frac{\sigma_{cc}}{\sigma_{cc}-1}} \tag{73}$$

In this way we could introduce into the model the CO2 accounting emissions in the same way as in the productive sectors.

D Equilibrium condition

In this section we show the equilibrium conditions for both the macro and sectoral model.

D.1 Macro Model conditions

The dynamic general equilibrium of the economy in the time period $[t_0, t_1]$ is defined as a set of micro variables $\{c_{t,s,i,r}, l_{t,s,i,r}, a_{t,s,i,r}\}_{t=t0}^{t1}$, aggregate variables $\{C_{r,t}, L_{r,t}, K_{r,t}, A_{r,t}\}_{t=t0}^{t1}$, wage and interest rate $\{w_{r,t}, r_{r,t}\}_{t=t0}^{t1}$ such that:

1. Households utility in equation (1) is maximised subject to equations (3) and (4)
2. Factor prices equal their marginal productivities satisfying equation (12).
3. Domestic labor and capital markets clear satisfying equations (14)-(16).
4. Public sector issues debt to satisfy eq. (13).
5. Domestic goods markets clear:

$$TFP_{r,t} K_{r,t}^{\beta} L_{r,t}^{1-\beta} + r_t F_{r,t} = \sum_i \sum_s \frac{P_{c,r,t}}{P_{r,t}} c_{t,s,i,r} f_{t,s,i,r} + q_{r,t} I_{r,t},$$

   where $I_{r,t} = K_{r,t+1} - K_{r,t}(1-\delta) - I_{r,t}^{*}$ is private sector investment with $I_{r,t}^{*}$ denoting public investment and δ the depreciation rate. $P_{c,r,t}$ and $P_{r,t}$ denote respectively the consumer price index and the GDP deflator in each country r.

6. In the open economy framework, market clearing on the international market requires that the rate of return on capital in a single country is such that the sum of all foreign assets in the system equals zero:

$$r_{r,t} : \sum_{r=1}^{R} F_{r,t} = 0 \quad \forall r = 1, ..., R \tag{74}$$

   where all net foreign asset positions $F_{r,t}$ are defined relative to the numeraire goods and R is the number of countries in the model.

7. Real world output is

$$Y_t = \sum_{r=1}^{R} Y_{r,t}. \tag{75}$$

D.2 Sectoral model equilibrium conditions

In order to close the model we provide the supply equations for land, intermediate, export and CO2 quantities to close the corresponding market in region r:

$$\begin{aligned}
LA^s_t &= \gamma_l \left(\frac{pa_t}{pland_t}\right)^{\sigma_l} LANDMAX \\
XD^s_t &= (1-\gamma_{es}) \left(\frac{pd_t}{py_t}\right)^{\sigma_x} Y_t(1-wmg) \\
WTF^s_t &= \beta_e \left(\frac{pet_t}{pe_t}\right)^{-\sigma_e} ES_t \\
CO2^s_t &= C\bar{O}2_t
\end{aligned} \tag{76}$$

where landmax is the maximum endowment of land per region r.

The price equilibrium set is obtained considering the following demand/supply matching conditions. The array of prices are $p = pland, pd, pe, r, w, pco2$ for each region and su-bsector:

$$\begin{aligned}
LA^s_t &= LA^d_t \\
XD^s &= XD^d_t \\
WTF^s &= WTF^d_t \\
K(j)^s_{k,t} &= K(j)^d_{k,t} \\
L(j)^s_{k,t} &= L(j)^d_{k,t} \\
CO2^s_t &= CO2^d_t.
\end{aligned} \tag{77}$$

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