Green energy transition: decarbonisation of developing countries and the role of technological spillovers

Abstract

The green energy transition is necessary within the next few decades to mitigate climate change. In the paper, I explore the effectiveness of carbon pricing and the role of technological spillovers in achieving decarbonization, with a particular focus on the challenges faced by developing countries. I develop a two-region integrated assessment model that incorporates fossil fuel and renewable energy sources to investigate the quantitative impact of spillovers on decarbonization in developing countries. The findings indicate that technological spillovers in developing countries contribute to the replacement of fossil fuels with renewable energy inputs. The study suggests that implementing carbon taxation in both advanced and developing regions, along with technological spillovers, yields the most favorable outcomes for the climate. However, the absence of carbon tax in developing countries with spillovers still delivers slightly better environmental results compared to taxing both regions without spillovers. The results emphasize the importance of considering spillovers and carbon taxation when designing effective policies to achieve environmental goals.

Keywords: Green energy transition, developing countries, carbon justice, integrated assessment model, social cost of carbon

JEL classification: C61, C69, E17, E27, O00, O13, O44, Q50

1 Introduction

The green energy transition is necessary within the next few decades to mitigate climate change. In simple terms, first, there should be some form of carbon pricing to internalize the climate externality. In its turn, increasing the relative price of fossil fuels leads to a higher demand for renewable energy sources. Second, more demand incentivizes innovation in renewable technologies with subsequent further increase in their productivity. These processes create the green energy transition leading to the decarbonization of the energy inputs.

This decarbonization mechanism seems to be working for the advanced countries[1]. Many advanced countries have some form of carbon pricing in place e.g. carbon tax, cap and trade etc.; a significant reduction in prices for renewable energy sources is observed together with the rise in the share of renewable energy in primary energy consumption (Känzig and Konradt (2023)). Application of the same decarbonization mechanism to the developing countries does not seem to be straightforward for two reasons. First, carbon pricing in developing countries is controversial due to concerns about carbon justice. Second, as economic growth literature Aghion and Howitt (1997) points out, developing countries are not innovating, but rather adopting already existing technology to catch up to the technological frontier through global technological spillovers.

Difficulties with carbon pricing together with the key role of technological spillovers for growth in developing countries create two counteracting forces. On the one hand, in the absence of carbon pricing in developing countries, there is no economic incentive for them to switch from fossil fuels to renewable energy sources. On the other hand, in the case of decarbonization in advanced countries, renewable energy sources are becoming more prevalent and generating more spillovers, substituting for fossil fuel technologies in developing countries even without carbon pricing. Given that developing countries do not have well-established energy infrastructure that relies on fossil fuels, they may have a chance for an easy transition to renewable energy for sustaining growth as discussed in Fay et al. (2015).

This motivates the research questions of the present paper. It investigates the role and the quantitative impact of technological spillovers on decarbonization in developing countries. Specifically, it aims to determine (i) whether a "renewable energy path" can be established in the presence of spillovers without carbon taxation and (ii) whether a "fossil fuel path" could emerge if there are high spillovers in fossil fuels.

To address these questions I develop a two-region integrated assessment model of the global economy and climate with two energy sources, specifically fossil fuel and green energy. The setup incorporates advanced and developing economies, with an advanced economy featuring exogenous growth in energy inputs and a developing economy relying on technological spillovers

[1]The term "advanced countries" refers to the high-income (HI) and upper-middle-income (UMI) countries. The term "developing countries" refers to the low-income (LI) and lower-middle-income (LMI) countries from the World Bank country classification by income level. The list of the countries in each income group can be found in the Section C.

for the growth in both energy inputs.

The model introduced in this paper follows the spirit of DICE model as in Nordhaus (2017), but also relies on Golosov et al. (2014) and Dietz and Venmans (2019) in terms of the economic block of the integrated assessment model (IAM) and on Folini et al. (2024) in terms of the climate block. The first novelty of the model presented in the paper comes from coupling fossil fuels and renewable energy sources in the economy with the three-reservoir carbon cycle and with two-reservoir temperatures in the climate emulator. The second novelty is that the model explicitly features developing economies and technological spillovers in energy. To solve the model I rely on a novel deep learning algorithm for global solutions suggested by Azinovic et al. (2022a). This method is especially suitable for large-scale highly non-linear dynamic optimization problems and this paper is the first one to apply it to the multi-region integrated assessment models which make up for the third, computational, novelty of the paper.

The main finding of the paper is that the presence of technological spillovers in developing countries leads to faster growth of renewable energy and slower growth of fossil fuels resulting in the higher share of renewable energy input in the energy mix. This result highlights the positive impact of spillovers on decarbonization efforts. Additionally, the study suggests that implementing carbon taxation in both advanced and developing regions in conjunction with technological spillovers still yields the most favorable outcomes for the climate. However, it is worth noting that the absence of carbon tax in developing countries with spillovers still delivers slightly better environmental results compared to taxation of both regions without spillovers.

These results emphasize the importance of considering both spillovers and carbon taxation in designing effective strategies for achieving environmental goals. They motivate further work in extending the model presented below with endogenous growth and endogenous spillover rates to understand how advanced economies can influence the decarbonization process in developing countries through technological spillovers.

The remainder of the paper is organized as follows. Section 2 presents some stylized empirical evidence that motivates the research, Section 3 provides a brief literature overview on the topic, Section 4 outlines the model, parametrization, and the solution method employed, Section 5 presents the findings of the paper and Section 6 concludes.

2 Empirical motivation

Throughout history, economically advanced countries have been the main contributors to climate change being responsible for almost 90% of cumulative carbon emissions (see Figure 1).

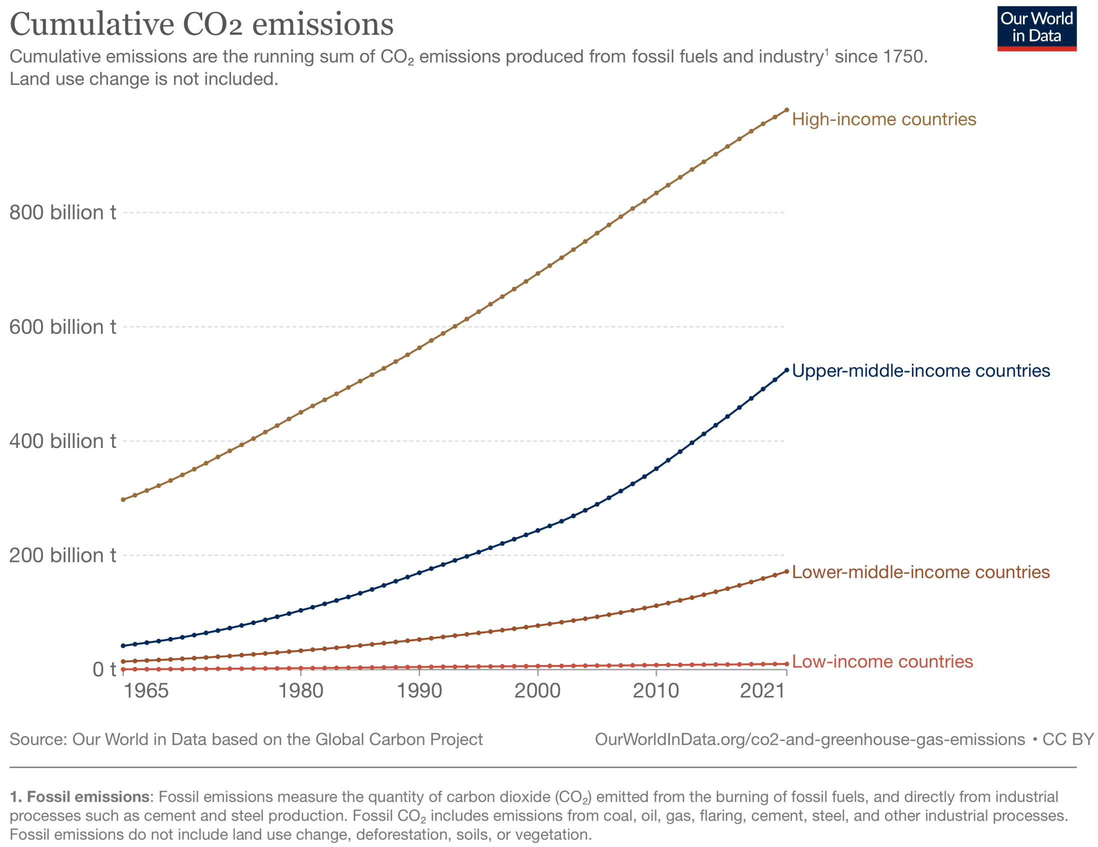
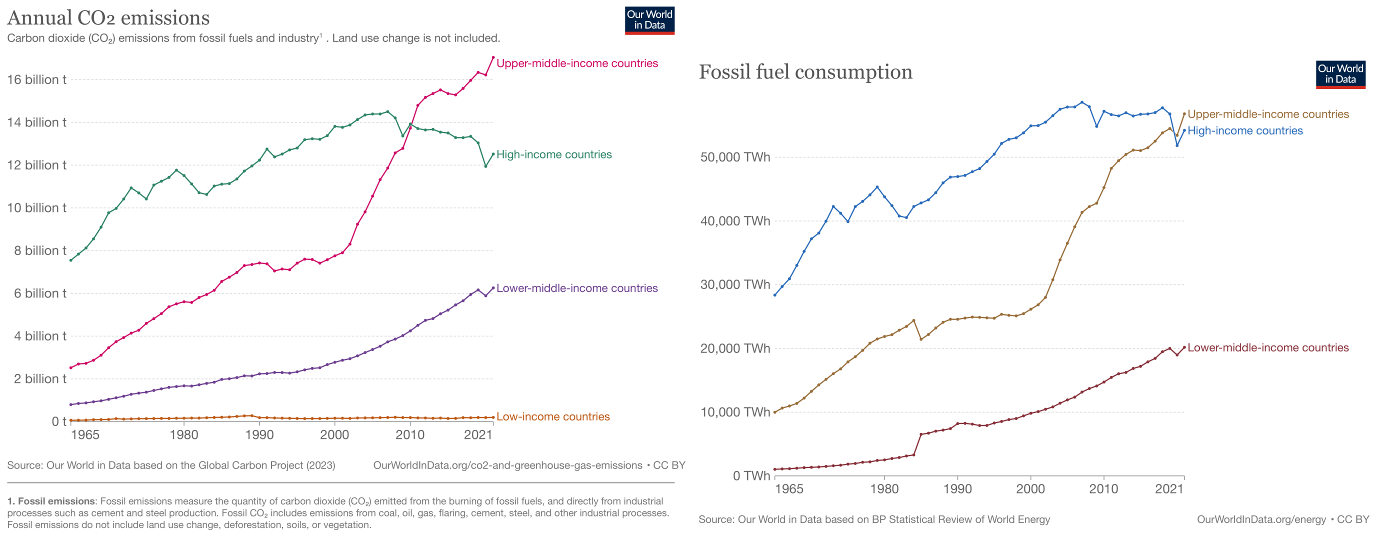


Figure 1: Cumulative CO2 emissions by income group. Source: OWID

Thus, they have been at the forefront of discussions on decarbonization and green energy transition. As a result of these efforts, a number of the advanced countries have some form of carbon initiative implemented or in progress and there is evidence of the green energy transition process happening in these countries.

Developing countries being accountable for the remaining 10% in cumulative carbon emissions (see Figure 1) may not seem to be a priority in discussions regarding immediate decarbonization efforts at least for two reasons. First, their current emissions account only for less than 20% of annual global emissions (Figure 2a), making them incapable of playing a decisive role in the world's decarbonization. Second, the climate justice principle claims that advanced countries, which benefited the most from carbon emissions during the industrialization process, have a greater responsibility to mitigate climate change. According to this principle, it is considered unfair to demand developing countries equal participation in decarbonization and green energy transition. Indeed, this reflects in the empirical evidence on the adoption of decarbonization measures by developing countries. Among fifty-four LMI countries, only two of them (Indonesia and Ukraine) have already implemented some form of the carbon tax, with eight other countries considering carbon pricing measures. LI countries do not have any decarbonization initiatives in place or under consideration.

At the same time, according to the data from 1965 to 2021, fossil fuels comprise more than 90% of the current energy mix and its consumption in developing countries has been growing at an average rate of 6% per year (Figure 2b).



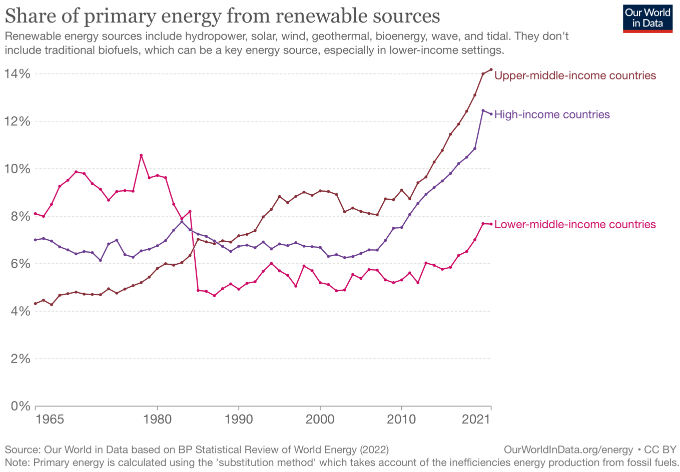
(a) Annual CO2 emissions. Source: OWID

(b) Fossil fuel consumption. Source: OWID

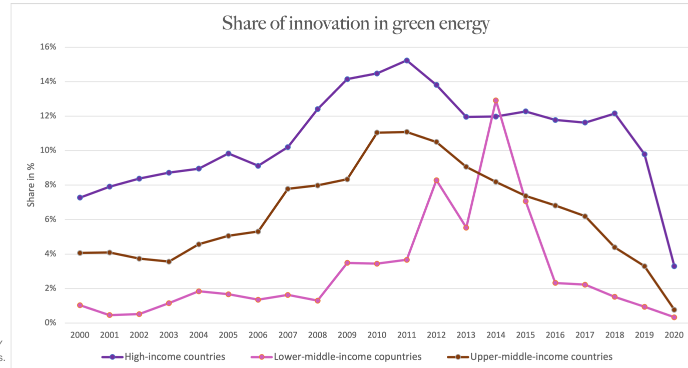
Figure 2: Annual CO2 emissions by country income group (left) and fossil fuel share of primary energy consumption (right) for the different income groups of countries.

If this growth rate persists, they could reach the current level of fossil fuel usage in high-income countries by the year 2050. This potential future amount of fossil fuel consumption coupled with the lack of decarbonization measures in developing countries becomes significant for the climate change mitigation perspectives. It brings us to the question of decarbonization and green energy transition possibilities available for developing countries.

One view on the decarbonization of developing countries can be by applying the same mechanism as for the advanced countries: internalizing climate externality by carbon pricing which creates more demand for renewable energy and incentivizes innovation in green technology ultimately leading to the green energy transition. However, the assumption about the possibility of innovation in developing countries seems to be unreasonable. The growth literature suggests that developing countries up to a certain stage of development do not innovate, they are involved in the activity of imitating the technological frontier (Aghion and Howitt (1997)). In line with this growth literature narrative, in the Figure 3 I depict the share of the primary energy from renewable energy sources that are used by different income groups of countries (Figure 3a) and the share of innovation in the green energy among the total innovation (Figure 3b).



(a) Primary energy from renewable sources. Source: OWID



(b) Renewable energy innovation. Author's elaboration based on the data from WIPO, IRENA, OWID.

Figure 3: Primary energy from renewable sources (left) and renewable energy innovation (right) for the different income groups of countries.

Lower-middle-income countries tend to increase their renewable energy usage however, their innovation rate in terms of patenting activity is the lowest among all the income groups. This indirectly suggests that the clean technologies in lower-income countries are the result of technological imitation. Thus, relying on the mechanism that involves carbon pricing to unleash the process of green energy transition does not seem a viable option for developing countries. On the one hand, carbon pricing may still seem necessary in developing countries to steer the imitation process in the right direction. On the other hand, if developing countries by imitation follow the technological portfolio of the advanced countries, the switch to clean technologies may happen just by the nature of the technology imitation process. These competing ideas pose the motivation for the present research. Specifically, I would like to quantitatively investigate the role of technological imitation in the decarbonization of developing countries and its interaction with carbon pricing.

Technological imitation is a process in which the developing (recipient) country is involved in the activity of acquiring an existing technological frontier and adapting it to the local realities. The frontier technology may be transferred in a regulated way, through the rights to use the patented technology, or in an unregulated way, through other forms of technological diffusion. The frontier technology cannot be perfectly acquired immediately and takes time to fully diffuse in the world. All the transfer and diffusion processes (regulated and unregulated) that make the imitation process possible for developing countries I call technological spillovers. [2] As an example of the technological

[2] I depart here from the definition of Grossman and Helpman (1993):

> 'By technological spillovers, we mean that (1) firms can acquire information created by others without paying for that information in a market transaction and (2) the creators (or current owners) of the information have no effective recourse, under prevailing laws, if other firms utilize information so acquired'.

spillover one can think of the solar photovoltaic (PV) technology. The technology was developed in the middle of the 20th century in the advanced economies, then intensively commercialized by China at the beginning of the 21st century, and is now being ramped up significantly in developing countries. It is hard to credibly track how this diffusion of technology was happening, probably via all forms of diffusion. For the sake of simplicity in this paper, I call this process technology spillovers.

3 A brief review of the literature

This paper is mainly related to the three strands of the literature. First, it follows the tradition of carbon pricing literature based on the economy-climate modeling pioneered by Nordhaus (1997). Second, it complements the increasing number of papers on integrated assessment modeling with a heterogeneity of regions in the spirit of Hassler et al. (2020). Third, it closely follows the literature on endogenous growth and technological spillovers within integrated assessment set-ups as in Barrett (2021).

The main purpose of the integrated assessment modeling is to quantify the welfare-maximizing carbon price that is necessary for climate change mitigation. Pioneering research of this cost-benefit analysis was done by Nordhaus (1997). His modeling framework, although criticized, evolved with time as in Nordhaus (2017) and became a cornerstone for further research of single-agent models including analytical set-ups like Golosov et al. (2014) and Traeger (2019).

However, single-agent integrated assessment models suggest universal carbon policies that are hard to implement in all countries due to the lack of agreement. This gives a rise to the multiple-agent modeling framework. This literature was pioneered by Nordhaus and Boyer (2000), with his famous RICE model which was later transformed by Hassler and Krusell (2012) into a stochastic general equilibrium version. A number of other integrated assessment models with multiple agents were developed, such as FUND (the most recent version of the model is used in Waldhoff et al. (2014)), REMIND [3], WITCH (Bosetti et al. (2007)) among others. These models were trying to address the issue of cooperation in global climate mitigation. Further, Brock et al. (2013), Brock et al. (2018) discuss the transfers and how to set a carbon policy optimally across countries with differences in income level and production possibilities. In a similar vein, Hillebrand and Hillebrand (2019) present a dynamic general equilibrium model with a heterogeneous region structure. Krusell and Smith Jr (2018) analyze gains and losses from climate change around the world and Kotlikoff et al. (2021) add inter-generational perspective to the discussion. The main take-away of this strand of the literature is that an optimal climate policy in the presence of regional heterogeneity consists of

in a way, that as technology spillovers I understand any processes of technological diffusion, with or without market transactions involved in acquiring the information.

[3] The full model description can be found on the f Potsdam Institute for Climate Impact Research

an emissions tax and a transfer policy.

A parallel strand of the literature was dedicated to single-agent models that feature endogenous technological change in the energy sector. The major contribution was done by Acemoglu et al. (2012), showing that the carbon tax should induce innovation in green technologies due to market size and price effects. Fried and Lagakos (2023) empirically evaluates the quantitative impact of these channels and confirms that a carbon tax induces large changes in innovation.

These two last strands of literature merge in Hassler et al. (2019), where a multi-regional set-up with endogenous technological change is analyzed. Continuing with this framework, Hassler et al. (2020) discuss second-best cases for carbon mitigation policies and Hassler and Krusell (2018) study the consequences of a carbon tax for oil-consuming and oil-producing regions. Barrett (2021) builds on top of these models adding a technological spillovers process for energy technology proliferation. This set-up with multiple heterogeneous regions directed technical change and technological spillovers is an important step forward. However, a possible limitation of this framework is the assumption that all the regions have equal possibilities to innovate. This assumption does not seem plausible as developing countries usually do not innovate in the energy sector and rather catch up with some lag to the current productivity frontier that is set by advanced economies Aghion and Howitt (1997). Thus it is reasonable to assume that there is no endogenous growth in energy source possible in developing countries, and the only source of growth for them is through imitation. This setup was investigated in (Acemoglu et al., 2014). The authors analytically show that the first-best solution requires coordination between Northern and Southern regions, however, it is also possible to avoid a climate disaster only with the mitigation efforts of the Northern countries. This paper provides a significant insight into the innovation and imitation dynamics between regions. However, an analytical solution of the model required significant simplifications of the climate as well and the paper does not provide a quantitative evaluation of the process. A very detailed quantitative model that deals with multiple regions and addresses the innovation and imitation dynamics between the regions is the WITCH model [4]. It includes exogenously determined energy innovation processes and their spillovers to the countries that imitate rather than innovate. However, the innovation and technological spillover processes in WITCH are not the central focus of attention and they lack tractability.

The present paper addresses the issue of decarbonization in a two-region world with a simple quantitative framework that separates innovation activity and technological spillovers in heterogeneously developed countries. The model explicitly features advanced and developing regions as in Acemoglu et al. (2014) but delivers quantitative results. It provides a tractable framework that allows to study of the technology spillover counterfactual to the baseline case in which the regions rely on their innovation processes. The framework also includes a rather detailed climate-emulator that is in agreement with CMIP5.

[4]The current vintage of the model can be found here

4 Model

4.1 Model formulation

Economy

The model builds on Nordhaus (2018), Golosov et al. (2014), Hassler et al. (2019), and Barrett (2021). The world is populated with two regions $i \in \{A, D\}$: advanced economy (A) and developing economy (D). No trade happens in the model and there are no other international markets.

Both regions have a representative consumer with identical preferences where C_t^i is the stream of consumption for region i and the world total labor evolves according to the exogenous process $L_t = L_0 + (L_\infty - L_0)\left(1 - \exp\left(-\delta^L t\right)\right)$ with the population in an advanced economy and developing economy summing up to the total labor force $L_t^A + L_t^D = L_t$. The welfare of the region i can be presented as:

$$V_t^i = \sum_{t=0}^{\infty} \phi_t^i \frac{\left(C_t^i / L_t^i\right)^{1-1/\psi}}{1 - 1/\psi} L_t^i \tag{1}$$

where ϕ_t^i is a dynamic Negishi weight of the economy defined as in Denning and Emmerling (2017), Cai et al. (2019):

$$\phi_t^i = \frac{\left(C_t^i\right)^{1/\psi}}{\sum_{i \in \{A,D\}} \left(C_t^i\right)^{1/\psi}}. \tag{2}$$

Advanced and developing economy use an aggregate production function for the final good as follows:

$$Y_t^i = \left(K_t^i\right)^{\alpha} \left(A_t^i (1 - \pi_t^i - \xi_t^i) L_t^i\right)^{1-\alpha-\nu} \left(E_t^i\right)^{\nu} \tag{3}$$

where A_t^i is the total factor productivity that grows exogenously as $A_t^i = A_0^i \left(1 + g^A\right)^t$ at the same rate g^A for both regions, K_t^i is the capital, and E_t^i is the energy input into production, π_t^i and ξ_t^i are labor shares that are used in energy production. The final good is assumed to be a numeraire.

Energy is produced in advanced and developing economies by a representative firm with the following production aggregator over two available sources of energy $E_t^{\mathrm{i,dt}}$ - dirty energy and $E_t^{\mathrm{i,cl}}$ - green energy:

$$E_t^i = \left(\kappa_{dt}^i \left(E_t^{\mathrm{i,dt}}\right)^{\rho_{CES}} + \kappa_{cl}^i \left(E_t^{\mathrm{i,cl}}\right)^{\rho_{CES}}\right)^{1/\rho_{CES}} \tag{4}$$

where $\kappa_{dt}^i + \kappa_{cl}^i = 1$. Dirty and green energy is produced via fuel-specific production technologies

$A^i_{dt,t}$ and $A^i_{cl,t}$ respectively which are linear in labor that goes into production as in Golosov et al. (2014):

$$E^{\mathrm{i}}_{t,dt} = A^i_{dt,0}\left(1+g^i_{dt}\right)^t \pi^i_t L^i_t \tag{5}$$

$$E^{\mathrm{i}}_{t,cl} = A^i_{cl,0}\left(1+g^i_{cl}\right)^t \xi^i_t L^i_t. \tag{6}$$

The growth rate of the technological progress in the dirty and green energy sources is given exogenously and differs between the regions in the baseline formulation of the model.

In the modeling set-up that features technological spillovers, there is a possibility for developing regions to benefit from the production technology from the advanced region. The technological spillovers process is a simplification of one from Barrett (2021) and states:

$$A^D_{dt,t+1} = A^D_{dt,0} + \varsigma(A^A_{dt,t} - A^A_{dt,0}) \tag{7}$$

$$A^D_{cl,t+1} = A^D_{cl,0} + \varsigma(A^A_{cl,t} - A^A_{cl,0}). \tag{8}$$

where ς is the intensity of spillovers that is assumed to be the same for both fuels at the baseline. The idea behind this spillover definition is straightforward. The developing economy starts in period zero with the initial level of the TFP in the respective energy sector. In period one the upgrade on the TFP level of the advanced economy net of its initial level is being transmitted to the developing country. Spillover intensity ς determines how much of the TFP progress in the advanced country goes in the developing country. Spillover intensity is assumed to be less than one, meaning that there is no full transmission of the TFP progress from the advanced country in one given year. Transmitting the TFP progress of the advanced economy net of the initial level is based on the assumption that the developing region never catches up with the technological level in the advanced region. More discussion on the no catch-up assumption for the developing countries is provided in Sections 4.2 and 6.

Climate externality

The climate module in the integrated assessment model under consideration consists of three reservoir carbon cycle $M = (M^{\mathrm{AT}}_t, M^{\mathrm{UO}}_t, M^{\mathrm{LO}}_t)$ and two reservoir energy balance $T = (T^{\mathrm{AT}}_t, T^{\mathrm{OC}}_t)$. The model takes the functional forms of climate part from Nordhaus (2017), and calibration from

Folini et al. (2024).

$$M_{t+1}^{\mathrm{AT}} = (1-b_{12})\, M_t^{\mathrm{AT}} + b_{12}\frac{M_{\mathrm{EQ}}^{\mathrm{AT}}}{M_{\mathrm{EQ}}^{\mathrm{UO}}} M_t^{\mathrm{UO}} + E_t^f \tag{9}$$

$$M_{t+1}^{\mathrm{UO}} = b_{12} M_t^{AT} + \left(1 - b_{12}\frac{M_{\mathrm{UQ}}^{\mathrm{AT}}}{M_{\mathrm{EQ}}^{\mathrm{UO}}} - b_{23}\right) M_t^{\mathrm{UO}} + b_{23}\frac{M_{\mathrm{EQ}}^{\mathrm{UO}}}{M_{\mathrm{EQ}}^{\mathrm{LO}}} M_t^{\mathrm{LO}} \tag{10}$$

$$M_{t+1}^{\mathrm{LO}} = b_{23} M_t^{\mathrm{UO}} + \left(1 - b_{23}\frac{M_{\mathrm{EQ}}^{\mathrm{UO}}}{M_{\mathrm{EQ}}^{\mathrm{LO}}}\right) M_t^{\mathrm{LO}} \tag{11}$$

$$T_{t+1}^{\mathrm{AT}} = T_t^{\mathrm{AT}} + c_1 F_t - c_1 \frac{F_{2\mathrm{xco2}}}{T_{2\mathrm{xco2}}} T_t^{\mathrm{AT}} - c_1 c_3 \left(T_t^{\mathrm{AT}} - T_t^{\mathrm{OC}}\right) \tag{12}$$

$$T_{t+1}^{\mathrm{OC}} = T_t^{\mathrm{OC}} + c_4 \left(T_t^{\mathrm{AT}} - T_t^{\mathrm{OC}}\right) \tag{13}$$

where $M_{\mathrm{EQ}} = (M_{EQ}^{\mathrm{AT}}, M_{EQ}^{\mathrm{UO}}, M_{EQ}^{\mathrm{LO}})$ are equilibrium carbon masses in preindustrial times, E_t emissions, and F_t is exogenous radiative forcing process. Coefficients b_{12}, b_{23} in carbon cycle and c_1, c_3, c_4 in energy balance describe diffusion processes in the reservoirs, $F_{2\mathrm{xco2}}$ is forcings of equilibrium CO2 doubling and $T_{2\mathrm{xco2}}$ is equilibrium temperature impact.

Emissions from industrial activity and exogenous emissions are accumulated as follows:

$$E_t^f = \sigma_t \left(E^{\mathrm{a,dt}} + E^{\mathrm{d,dt}}\right) + E_t^{\mathrm{Land}} \tag{14}$$

where σ_t is the emission coefficient from dirty energy sources as in Nordhaus (2017) and follows:

$$\sigma_t = \sigma_0 \exp\left(\frac{g_0^\sigma}{\log(1+\delta^\sigma)}\left((1+\delta^\sigma)^t - 1\right)\right). \tag{15}$$

and E_t^{Land} are exogenous emissions as in Nordhaus (2017) that follow:

$$E_{\mathrm{Land},t} = E_{\mathrm{Land},0} \exp\left(-\delta^{\mathrm{Land}} t\right). \tag{16}$$

Damages and resource constraint

The final output of the economy is subject to damages due to temperature increase:

$$Y_t^{\mathrm{Net},i} = \Omega^i\left(T_{\mathrm{AT},t}\right)\left(K_t^i\right)^\alpha \left(A_t^i(1-\pi_t^i-\xi_t^i)L_t^i\right)^{1-\alpha-\nu}\left(E_t^i\right)^\nu \tag{17}$$

where the climate damages are supposed to be different for both of the regions and are considered as:

$$\Omega^i\left(T_{\text{AT},t}\right)=\psi_1^i T_t^{\text{AT}}+\psi_2^i\left(T_t^{\text{AT}}\right)^2. \tag{18}$$

Final output net of damages is used for the consumption and investment which gives the resource constraint:

$$Y_t^{\text{Net},i}+(1-\delta)\,K_t^i=C_t^i+K_{t+1}^i \tag{19}$$

.

I present the full write up of the model with the Bellman equation in Section A.1.

4.2 Parametrization

To parametrize the model, I partially rely on the values available from the literature and partially use the World Bank, Penn World Table (PWT 10.01), and "Our world in data" (OWID) data sources from the period of 1990-2021 to discipline certain parameters.

For the conventional parameters such as capital and energy elasticity in the production function, depreciation rate of capital, pure rate of time preferences and intertemporal elasticity of substitution I take standard values from the literature:

Calibrated parameter	Symbol	Value	Source
Pure rate of time preferences	ρ	0.015	Nordhaus (2017)
Capital elasticity	α	0.3	Nordhaus (2017)
Energy elasticity	ν	0.04	Golosov et al. (2014)
Intertemporal elasticity of substitution	ψ	1.5	Cai and Lontzek (2019)
Capital depreciation rate	δ	0.1	Nordhaus (2017)

Table 1: Economic parameters

The initial TFP level of each region is pinned down by the data on output, capital, labor, and energy for each region in 1990. Table 2 shows the values for the initial TFP levels as well as assumed TFP growth rates for each region.

Advanced economy		Developing economy	
A_0^A	0.0115	A_0^D	0.00251
g^A	0.025	g^D	0.025

Table 2: TFP parameters.

I assume a 2.5% growth rate in the world TFP that is the same for both regions. The assumption of homogeneous growth in the world may be criticized for two opposite reasons. On the one hand, in line with the idea of catching up on growth, developing countries may exhibit higher growth rates than advanced economies Patel et al. (2021). On the other hand, the presence of poverty traps and middle-income traps can hinder growth and development, contributing to a slower growth rate in the developing world Kraay and McKenzie (2014). However, there is no unequivocal evidence, putting forward one of these theories. Thus for the sake of simplicity, I stick to the homogeneous growth rate in the world. This way effectively I assume no possibility for a full catch-up for developing countries. It may seem like a restrictive assumption, however, there is one more reason to make it. The assumption of no possibility for a full catch-up is consistent with the modeling setup. The model considers a social planner solution with the relative weights of the regions in the value function determined by dynamic Negishi weights. The nature of Negishi weights is to preserve the distribution of welfare across regions to exclude income effects and capture only technological effects. Keeping the welfare distribution stable is another way to assume no full catch-up for the developing world. More discussion on how the assumption of no full catch-up for developing countries can affect the results of the paper is provided in the Section 6.

For the CES energy aggregate, I take the elasticity of substitution between dirty and green energy as 1.11 which implies parameter $\rho^{CES} = 0.1$. The reason for this choice is based on the recent evidence that found the elasticity of substitution between green and dirty sources tends to be higher than unity (Papageorgiou et al. (2017)) with some papers finding it to be much higher than unity (Jo (2020)). I stick to the conservative approach assuming low but greater than unity elasticity having in mind that higher elasticity can make all the effects more prominent.

Another issue if the elasticity of substitution can be considered the same in both regions. There is no clear answer to that, as the nature of the dominant energy technology in advanced and developing countries is fundamentally different. The main difference is that most of the countries that I consider in the advanced group are relying on a centralized energy infrastructure while developing countries are utilizing scattered small-scale mostly traditional energy sources. This difference makes it unclear if the elasticity of substitution can be higher or lower in advanced economies in comparison to developing ones. On the one hand, due to centrally functioning energy infrastructure advanced regions can be more responsive to change in energy prices and thus be more flexible in substituting dirty energy sources with green ones. On the other hand, developing countries may benefit from the absence of any infrastructure and be able to implement green high-power energy systems from scratch. Given the inconclusiveness of the argumentation for the baseline version of the model, I assume the elasticity of substitution between energy sources to be constant for both regions. A promising further avenue of the research includes the uncertainty quantification of the decarbonization paths based on a plausible range of the elasticity of substitution.

To determine the weights of the energy CES aggregator $\kappa^i_{dt}, \kappa^i_{cl}$ I employ the approach from

Golosov et al. (2014) using relative prices of fossil fuel energy to renewable energy given by:

$$\frac{p^i_{dt}}{p^i_{cl}} = \frac{\kappa^i_{dt}}{\kappa^i_{cl}} \left(\frac{E^{i,dt}_t}{E^{i,cl}_t}\right)^{\rho^{CES}-1} . \tag{20}$$

As proxies for energy prices, I use Levelized Cost of Electricity (LCOE) values from IEA and IRENA databases. Although there are no accurate LCOE estimates available for the starting year 1990, I produce some back-of-the-envelope estimations to get approximate reasonable values. For fossil fuel and renewable energy usage, I rely on the World Bank data on energy usage for the year 1990.

The growth rates of the energy sources as well as the initial TFP levels for the energy sources are chosen to target the fossil fuel energy and renewable energy consumption paths provided in the data by the World Bank. Specifically, the initial TFP level in the fossil fuel and renewable energy is pinned down by the consumption of the energy and labor shares in energy sectors in 1990 for each region (more details on it are in the Section B.4). The growth rates of TFP in energy sectors are chosen to match the evolution of the energy consumption as shown in the Figure 6.

Advanced economy				Developing economy			
$A^A_{dt,0}$	0.0458	$A^A_{cl,0}$	0.0227	$A^D_{dt,0}$	0.00712	$A^D_{cl,0}$	0.0232
g^A_{dt}	0.012	g^A_{cl}	0.014	g^D_{dt}	0.01	g^D_{cl}	0.001
κ^A_{dt}	0.75	κ^A_{cl}	0.25	κ^D_{dt}	0.82	κ^D_{cl}	0.18

Table 3: Energy parameters.

As a baseline speed of spillovers, I take the estimate of the full technology adoption happening in 11 years which implies $\varsigma = 0.09$ following Barrett (2021). Eaton and Kortum (1999) estimated that on average it takes the technology 11 years to be fully adopted internationally. This implies that about 9% of the technological frontier is adopted annually. This estimate was later confirmed by Comin and Hobijn (2010) which estimated the length between 5 and 16 years for the technological adoption. Dechezleprêtre et al. (2013) showed that there is no difference in technological adoption for green technologies in comparison to other types of technology. Thus I use these results and set the intensity of spillovers equal for both fossil fuel and renewable energy. Relying on these estimates may be considered as an upper bound of the spillover intensity. Indeed, the estimates of technological adoption include not only spillovers, in a sense of the definition of Grossman and Helpman (1993), but also a targeted technology transfer. Excluding this intentional technological adoption can result in a lower spillover intensity estimate.

It is important to have damage function different for both regions. It is well-documented in the literature that developing countries are subject to higher damages than advanced economies (see for example OECD review). I assume the standard quadratic damages for the advanced economies as in Nordhaus (2017) and high damages for the developing region as in Weitzman (2012). The summary of damage coefficients is given in Table 4.

Advanced economy Nordhaus (2017)				Developing economy Weitzman (2012)			
ψ_1^A	0.0	ψ_2^A	0.0236	ψ_1^D	0.0	ψ_2^D	0.0746

Table 4: Damages parameters.

The parameters that characterize the climate system come from Folini et al. (2024) with the difference that starting value for the carbon masses as well as the temperature of the atmosphere and the ocean are adjusted for 1990 as a starting year (see Section B).

Exogenous processes that are present in the model, such as labor evolution, industrial emission intensity, exogenous emissions, and radiative forcing inherit functional forms from Nordhaus (2017). The emission intensity process I calibrate to match the RCP6.0 scenario (see Figure 4).

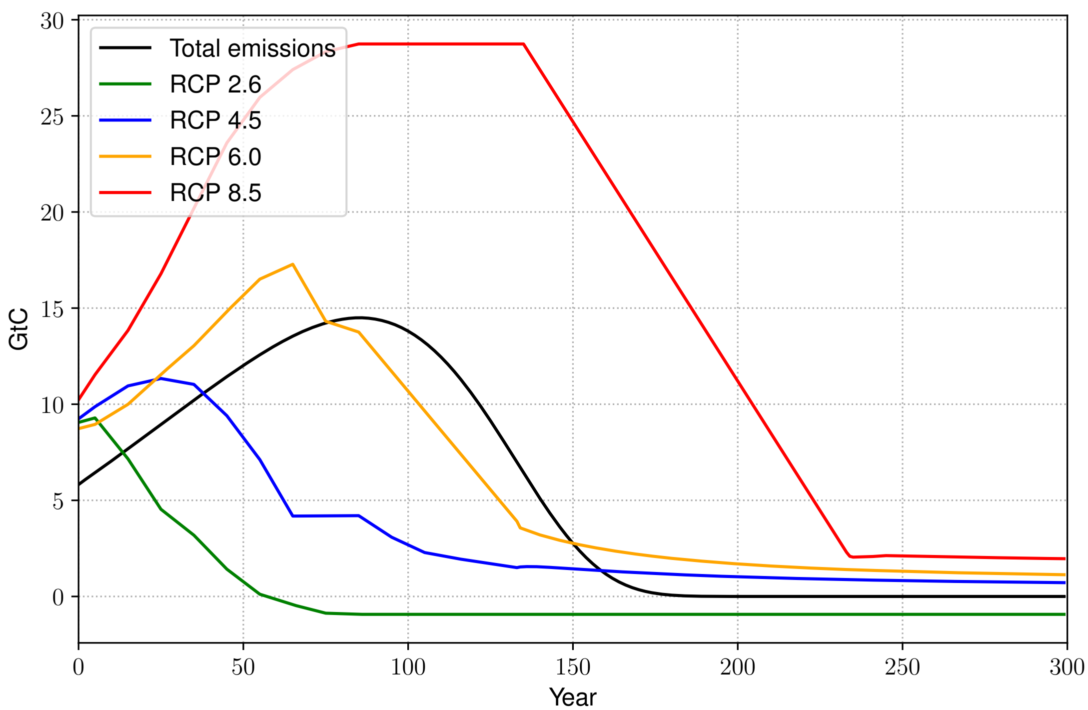
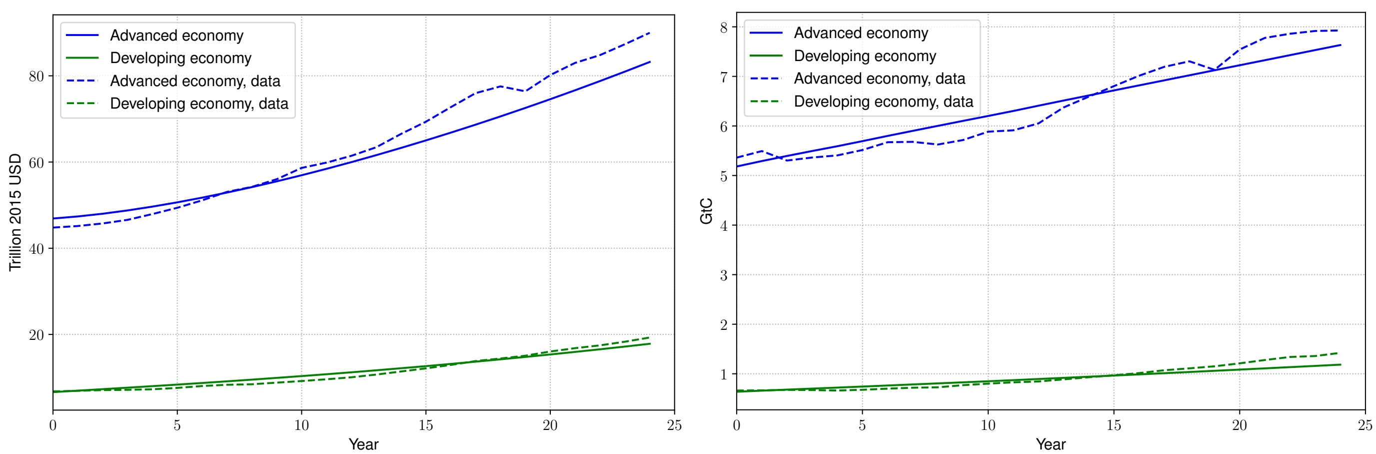


Figure 4: Total industrial emissions

In the Figure 5 and Figure 6, I depict how the business-as-usual solution of the model without spillovers (in green) and with spillovers (in red) matches the data that was used for the calibration.

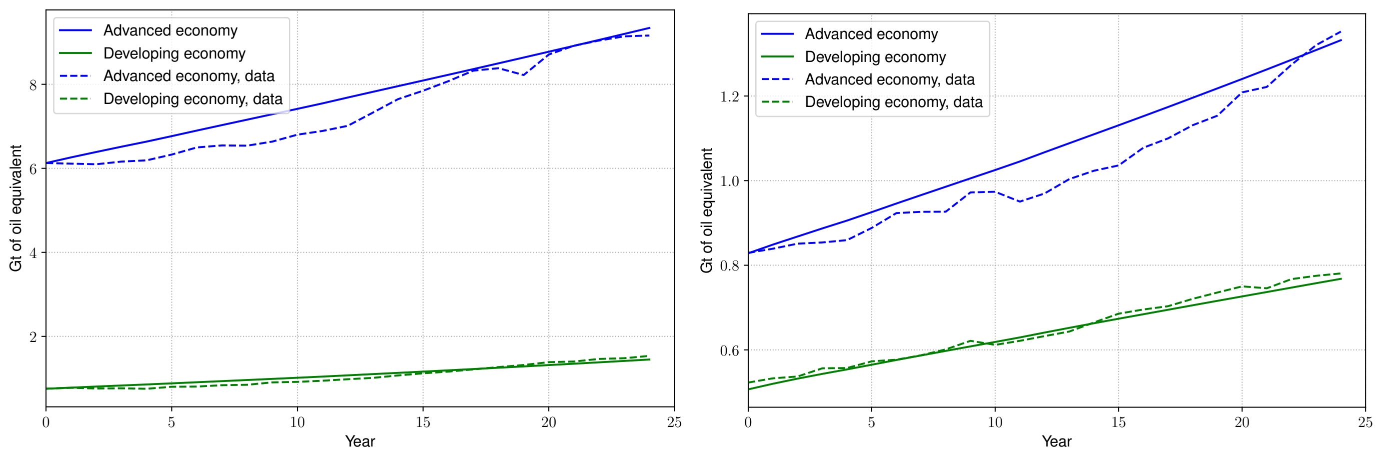
We can see that from the data we cannot infer any information about the presence or absence of the spillovers. In both cases, the actual paths of the data are matched fairly well. This observation makes the point for the relevance of the present study. Based on the data we cannot credibly say what is the driving force for the growth in energy sectors for developing countries. We can model it both ways. However, in line with the growth literature, it seems reasonable to assume that developing countries imitate the technology, rather than innovate themselves. Thus it may be misleading to make policy choices based on the models that assume the presence of innovation in developing countries. Section 5 explicitly compares the results of the model assuming its growth in every region with the model that allows for spillovers. It shows, that in the presence of spillovers, carbon taxation policy may not be necessary for developing countries.



(a) GDP

(b) Emissions

Figure 5: GDP (left) and emissions (right) for advanced and developing economies, BAU scenario, computed and actual values. Year zero on the graphs corresponds to a starting year 1990.



(a) Fossil fuel energy

(b) Renewable energy

Figure 6: GDP (left) and emissions (right) for advanced and developing economies, BAU scenario, computed and actual values. Year zero on the graphs corresponds to a starting year 1990.

More details on parametrization is presented in the appendix Section B.

4.3 Solution method: Deep Equilibrium Nets

The solution to the problem is based on the deep equilibrium nets as in Azinovic et al. (2022b). The details of the implementation of the DEQN solution to the problem from Section 4 can be found in Section A.1.

Deep Equilibrium Nets (DEQN) algorithm is a simulation-based global[5] solution method relying on deep neural networks[6] to compute an approximation of the *optimal policy function* $\mathbf{p} : \mathbf{X} \rightarrow \mathbf{Y} \subset \mathbb{R}^{\mathbf{K}}$ to a dynamic model under the assumption that the underlying economy can be characterized via discrete-time first-order equilibrium conditions, that is,

$$\mathbf{G}(\mathbf{x}, \mathbf{p}) = \mathbf{0} \; \forall \mathbf{x} \in X, \tag{21}$$

This way an unknown policy function is approximated with a neural network, that is, $\mathbf{p}(\mathbf{x}) \approx \mathcal{N}(\mathbf{x})$, and where the ν's are ex-ante unknown coefficients of the neural network that have to be determined based on some suitable loss function measuring the quality of a given approximation at a given state of the economy. This method ensures that the equilibrium conditions are satisfied throughout the entire state space, rather than just at a certain domain.

The DEQN method is especially suitable for solving integrated assessment models (IAMs) like the one presented in Section 4 as they are known to be subject to the curse of dimensionality

[5] A *global solution* adheres to the model equilibrium conditions throughout the entire state space, that is, the computational domain, whereas a *local solution* is only concerned with the local approximation around a point, typically the deterministic steady state of the model.

[6] See, e.g., Goodfellow et al. (2016) for a textbook treatment of neural networks.

(Bellman, 1961). One advantage is that this solution method can operate in high-dimensional state space and handle strongly nonlinear functions, such as those found in IAMs that consider the impacts of climate change on the economy and the environment (see, e.g., Cai and Lontzek (2019), and references therein). Another advantage is that DEQN can capture the non-stationary nature of the models as well as irregular geometries of the set of states visited during a simulation, which is important for IAMs that model complex systems with multiple feedback loops [7]. The details of the DEQN application to the IAMs can be found in Folini et al. (2024).

5 Results

This section presents the results. To answer the research question of the paper I consider two baseline scenarios and three cases of interest.

Baseline scenarios

- 'Business-as-usual' (BAU): no carbon taxation, damages are not internalised by the social planner in both regions;
- 'Optimal': optimal carbon taxation, damages are internalised by the social planner in both of regions;

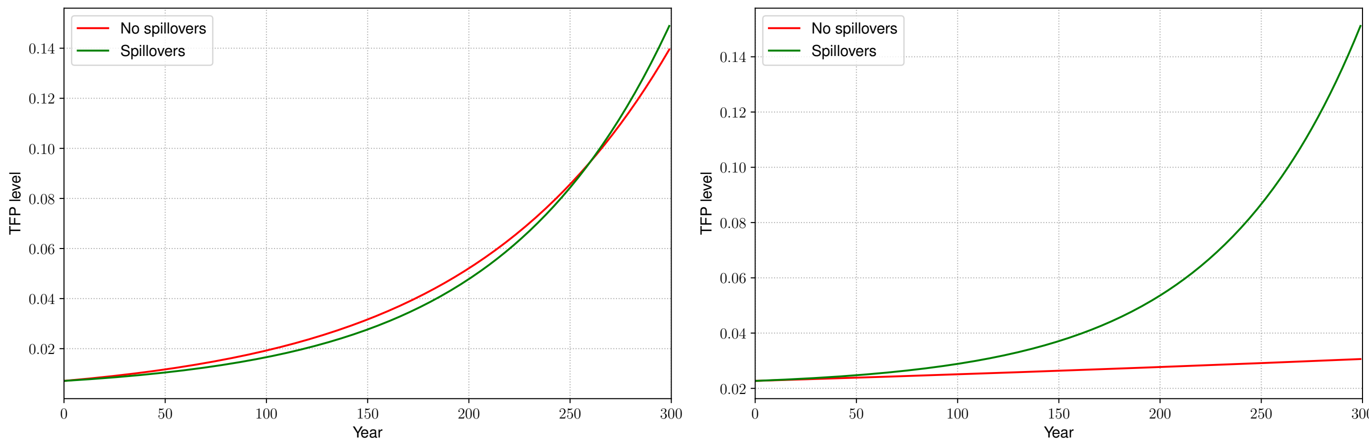
Cases of interest

- 'Second-best': carbon tax for advanced regions only, damages are internalised by the social planner in advanced region, developing region follows 'business-as-usual' scenario;
- 'Optimal' + technological spillovers: optimal carbon taxation, damages are internalised by the social planner in both of regions and the growth in energy source in developing region happens only through spillover effects;
- 'Second-best' + technological spillovers: carbon tax for advanced regions only, damages are internalised by the social planner in advanced region, developing region follows 'business-as-usual' scenario and the growth in energy source in developing region happens only through spillover effects;

'The main difference between the modeling setup with and without spillovers lies in the TFP process for the energy sources. In case of no spillovers, both advanced and developing countries rely on the exogenous growth rate that is specific to the region. In the case of spillovers, I assume,

[7] Neural networks are universal function approximators (Hornik et al., 1989); that is, they can resolve highly nonlinear features and can handle a large amount of high-dimensional input data. See, e.g., Goodfellow et al. (2016) for an introduction to deep learning.

that the growth rate in the energy sector of a developing region is dependent on the growth rate of the advanced region as shown in Eq. (7). Figure 7 depicts a difference between the TFP level of both energy sources with and without the spillovers. We can see, that the presence of spillovers in the fossil fuel sector does not change the TFP path significantly. However, in the case of renewable energy sources presence or absence of spillovers plays a crucial role.



(a) TFP process for fossil fuels

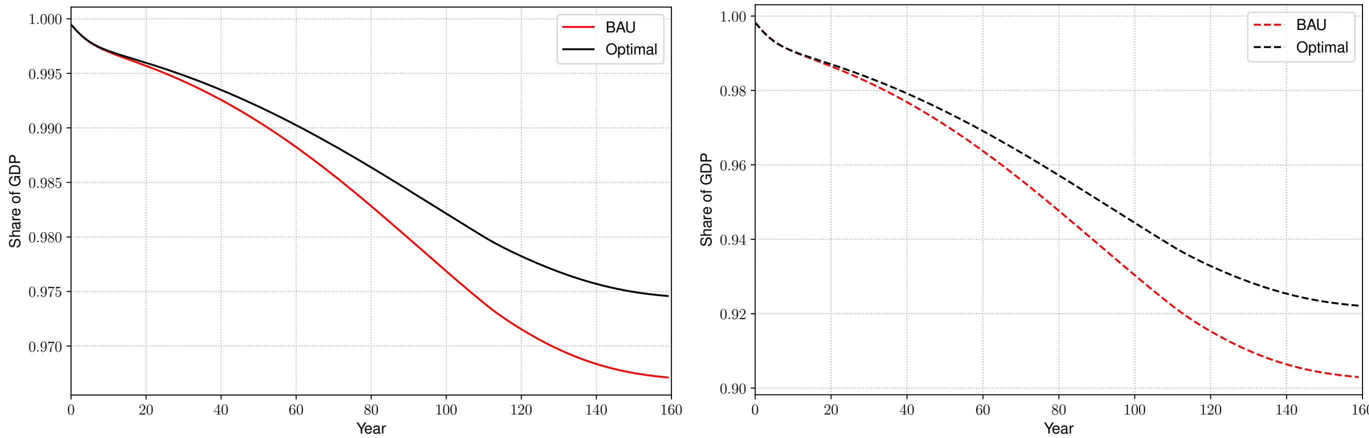
(b) TFP process for renewable energy

Figure 7: TFP level for the fossil fuels (left) and renewable energy (right) with and without spillovers for developing economies, BAU scenario. Year zero on the graphs corresponds to a starting year 1990.

5.1 Results without technological spillovers

First we compare the business-as-usual case with the optimal taxation case when the social planner internalises the damages in both regions, which we can interpret as a case of optimal taxation. In this section, we do not take technological spillovers into account.

From the Figure 8 we can see that optimal taxation reduces damages in advanced countries from 3.5% of GDP loss to 2.5%. Similar way, damages in developing countries are reduced by an optimal intervention from almost 10% of GDP loss only to 8%. The difference in damages comes from the assumption of heterogeneity of damages affecting the regions.

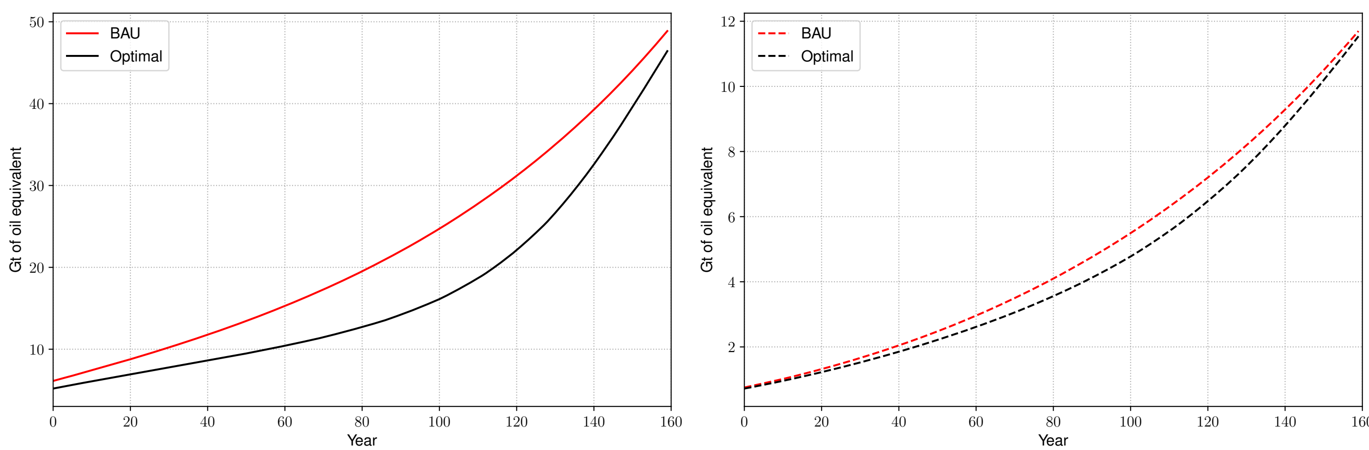


(a) Damages in advanced countries

(b) Damages in developing countries

Figure 8: Damages in advanced countries (left) and developing countries (right) under BAU and optimal taxation schemes. Year zero on the graphs corresponds to a starting year 1990.

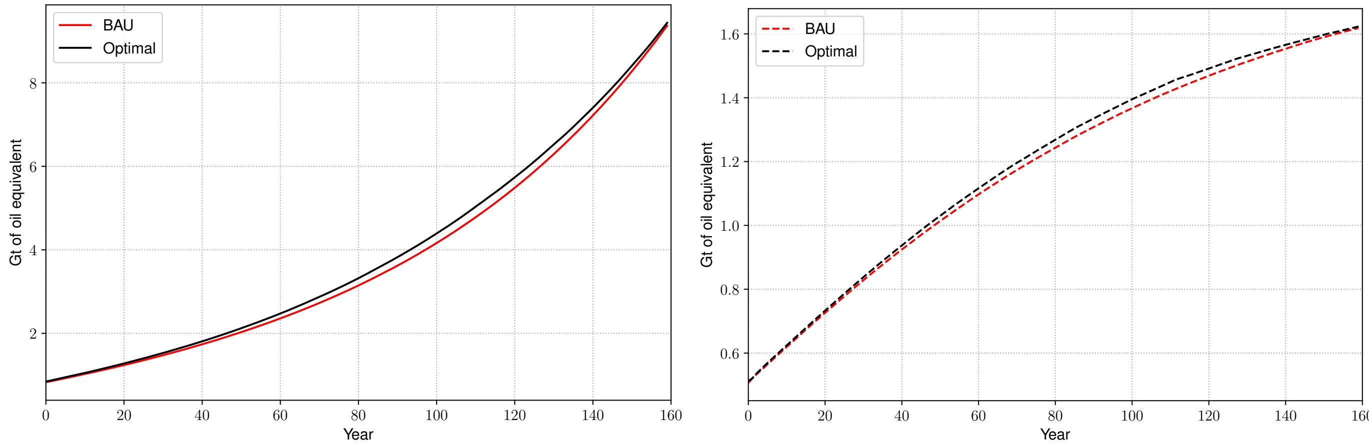
Figure 9 shows the evolution of the dirty energy sources for both regions and Figure 10 depicts the results for renewable energy sources. In both cases, the effect of the 'Optimal' taxation follows the economic intuition. Thus fossil fuel usage is being reduced in the 'Optimal' case in comparison to 'BAU' and renewable energy is slightly increased due to the substitution effect. Advanced region reduces their fossil fuel usage more than developing region in line with the initial assumptions of the model, that advanced region pollutes more.



(a) Advanced economy

(b) Developing economy

Figure 9: Dirty energy in advanced economy (left) and developing economy (right) under BAU and optimal taxation schemes. Year zero on the graphs corresponds to a starting year 1990.

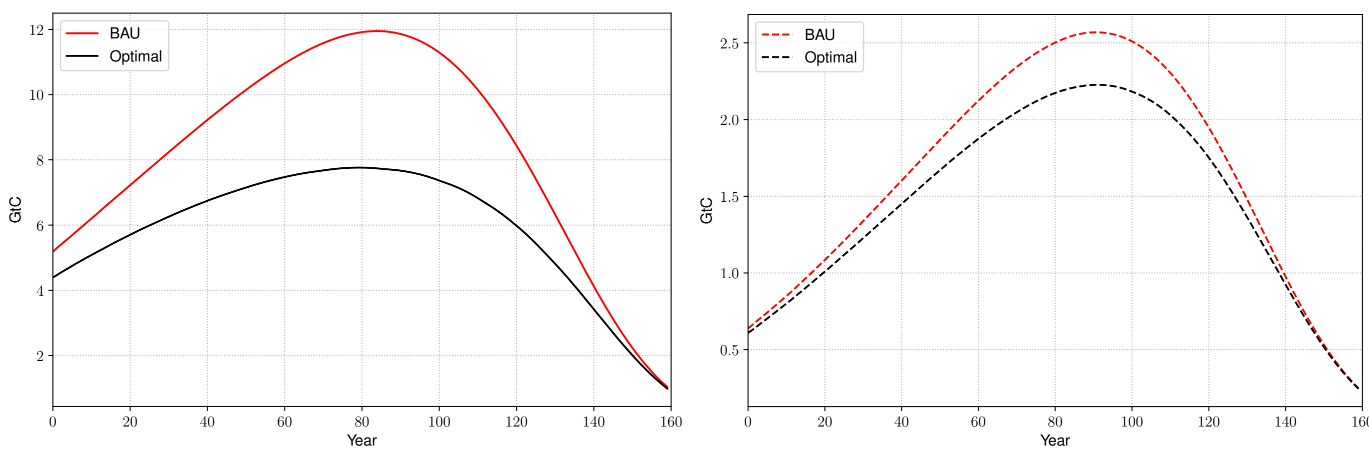


(a) Advanced economy

(b) Developing economy

Figure 10: Clean energy in advanced economy (left) and developing economy (right) under BAU and optimal taxation schemes. Year zero on the graphs corresponds to a starting year 1990.

The emissions in the Figure 11 predictably follow fossil fuels usage patterns. We can see that business-as-usual emissions are relatively high in comparison to the case of taxation.

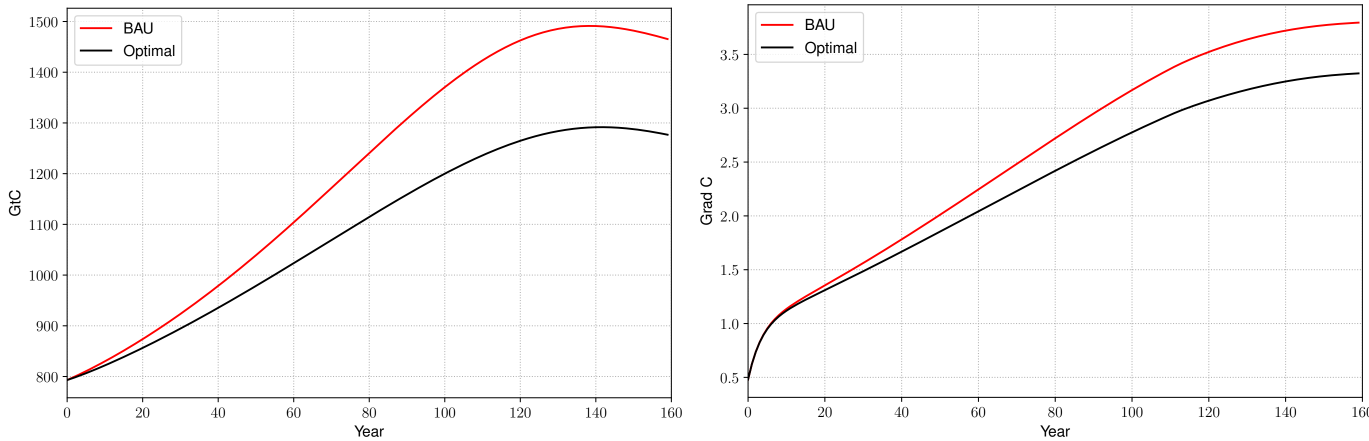


(a) Advanced economy

(b) Developing economy

Figure 11: Emissions in advanced economy (left) and developing economy (right) under BAU and optimal taxation schemes. Year zero on the graphs corresponds to a starting year 1990.

Overall, the optimal taxation scheme gives a decline in emissions of about 200GtC and 0.5C° decrease in temperature.

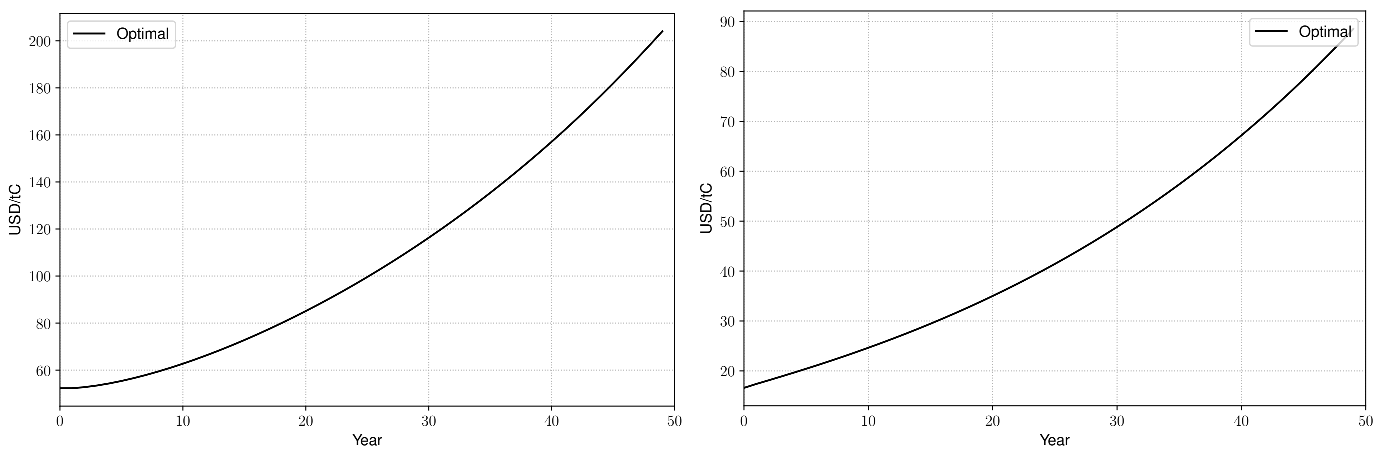


(a) Mass of the carbon in the atmosphere

(b) Temperature of the atmosphere

Figure 12: Mass of carbon in the atmosphere (left) and temperature of the atmosphere (right) under BAU and optimal taxation schemes. Year zero on the graphs corresponds to a starting year 1990.

The value of the social cost of carbon represents the optimal carbon taxation level. In the Figure 13, we can see that the optimal carbon tax for developing countries equals approximately 200USD/tC in advanced regions and 90USD/tC in developing regions at the year 2040.



(a) SCC in advanced region

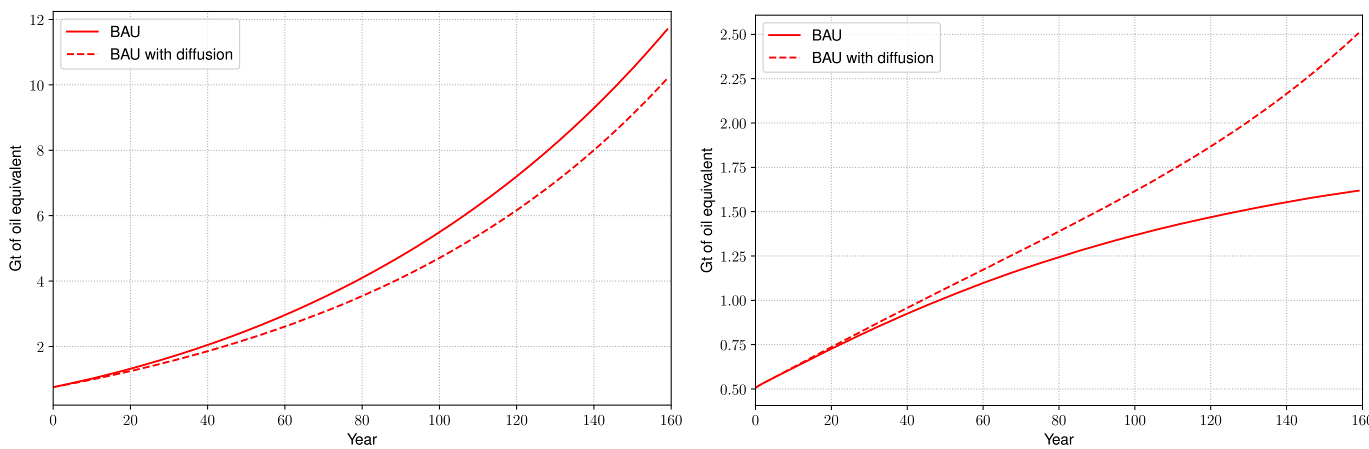
(b) SCC in developing region

Figure 13: SCC in advanced region (left) and developing region (right) under optimal taxation scheme. Year zero on the graphs corresponds to a starting year 1990.

5.2 Business-as-usual with technological spillovers

We consider now the business-as-usual case with technological spillovers. The technological evolution in the advanced economy remains the same as in the case without the spillovers. However, the developing economy gets the chance to catch up with the energy technologies used in the advanced economy. The only source of growth in energy technologies in developing regions are the technological spillovers.

We can see on Figure 14 that usage of fossil fuel energy declines moderately and renewable energy grows faster in developing economies in the presence of spillovers.



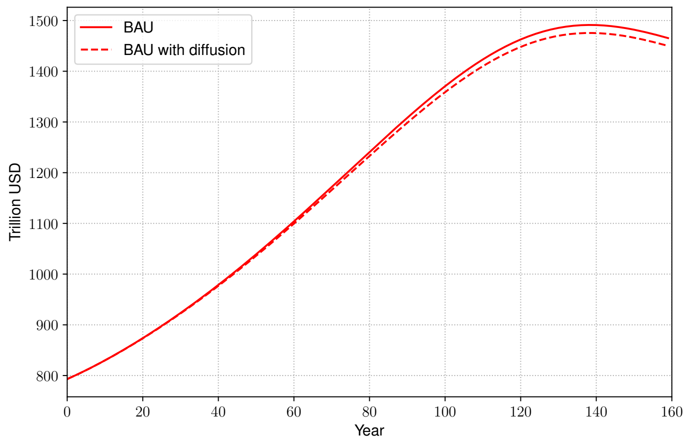
(a) Dirty energy

(b) Green energy

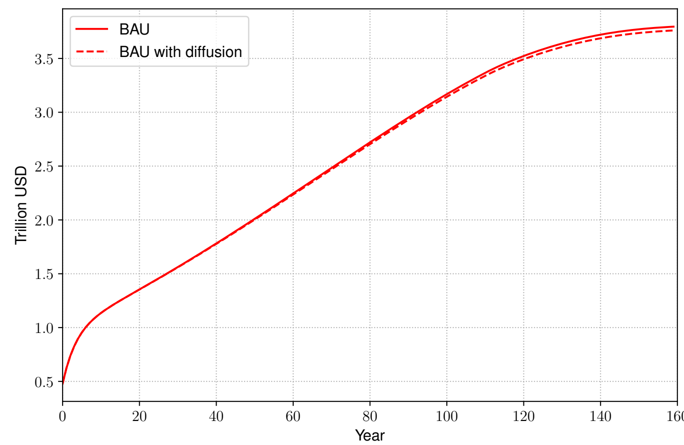
Figure 14: Dirty energy (left) and green energy (right) in developing economy. Year zero on the graphs corresponds to a starting year 1990.

The reason for that is as follows: the main difference between the fossil fuel sectors in two regions is in the initial levels of TFP, but the levels are not being transferred through the spillovers. Thus, fossil fuel energy does not grow in response to the spillovers process because the growth rate of fossil fuels in advanced region is approximately the same as the respective growth rate in developing region. In fact, technology transfer in dirty energy through spillovers happens slower than in the exogenous case. At the same time green energy usage in developing countries increases dramatically due to the fact that the growth rate of TFP in renewable energy in advanced economy is much higher than in developing region. Thus the baseline level of the technological spillover in energy sector acts two folds: slowing down the TFP growth in dirty energy and accelerating the TFP growth in green energy in developing countries. Due to this twofold effect, in the case of business as usual, the presence of the technological spillovers slightly reduces the mass of carbon in the atmosphere and temperature.

It would be interesting to experiment with the elasticity of substitution between energy sources in developing countries as well as with the intensity of the spillovers process, to see if there is any plausible option to rely on technological spillovers and to improve the environmental state in business as usual case. Certainly, the contribution of the developing countries in climate change as well as in decarbonization so far is not considered significant and cannot substitute for the efforts of advanced economies. However, it would be beneficial to understand if there are certain circumstances in terms of the elasticity of the substitution between energy sources (which we cannot influence as a policy, but we can test if it's a plausible value that can be confirmed empirically) and spillovers intensity (which we can influence as a policy) that can result in a significant reduction of the negative climate externalities in business as usual case.



(a) Mass of the carbon in the atmosphere

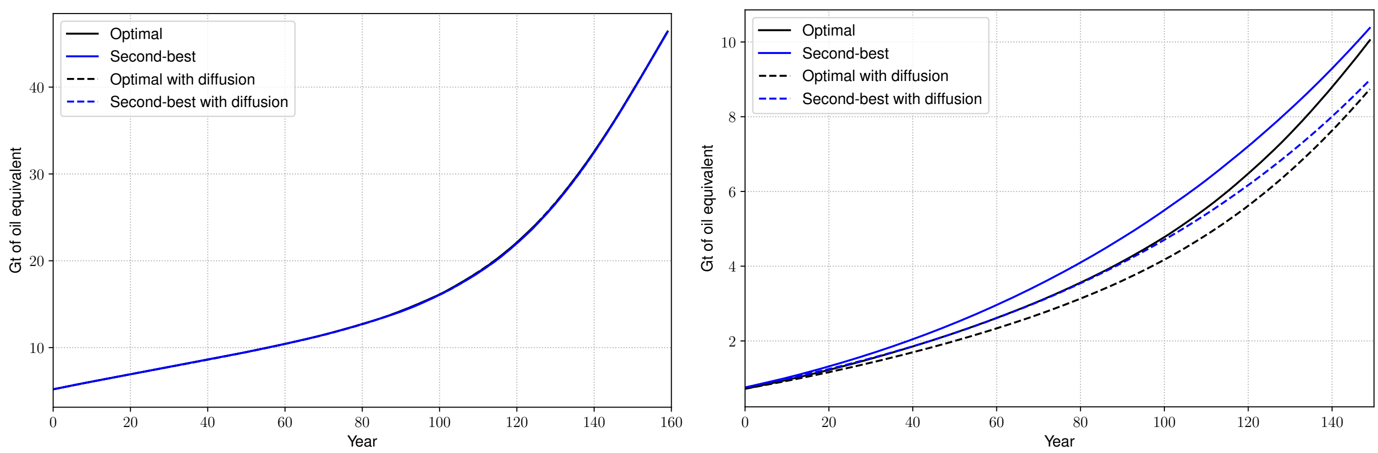


(b) Temperature of the atmosphere

Figure 15: Mass of carbon in the atmosphere (left) and temperature of the atmosphere (right). Year zero on the graphs corresponds to a starting year 1990.

5.3 Optimal taxation and second-best taxation with technological spillovers

As we saw in the previous section, the presence of technological spillovers in the business-as-usual case if anything makes climate indicators slightly better (under current assumptions about the elasticity of the substitution between energy inputs as well as the speed of spillovers). Now we aim at understanding if technological spillovers makes any difference for the optimal taxation case as well as for the second-best taxation case. Under the second-best taxation case I imply the case when only advanced region is subject to carbon taxation and developing region is evolving with unrestricted emissions.



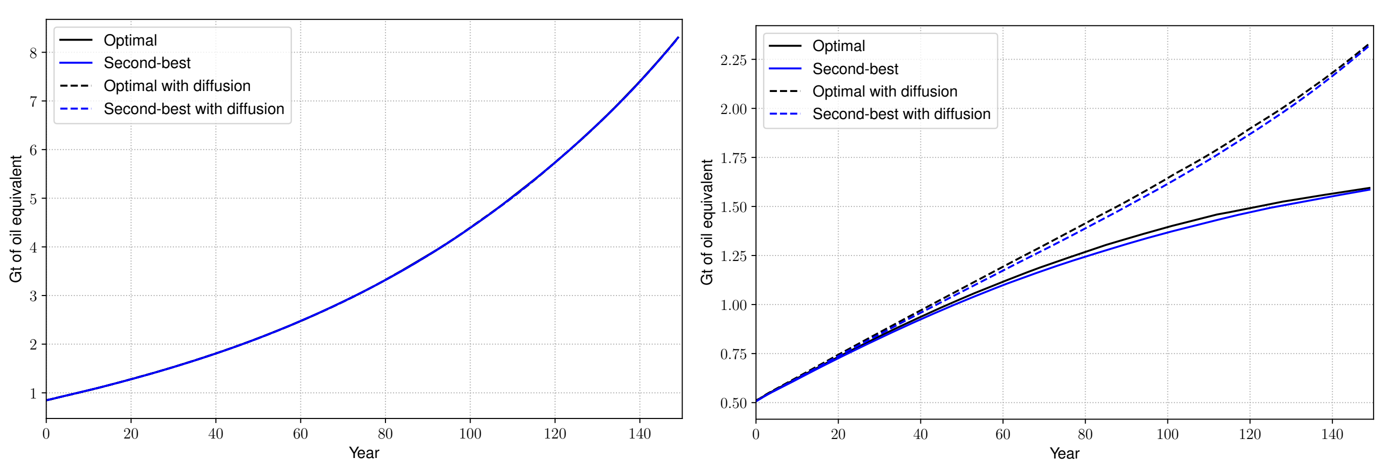
(a) Advanced economy

(b) Developing economy

Figure 16: Dirty energy in advanced (left) and developing economy (right) . Year zero on the graphs corresponds to a starting year 1990.

In the Figure 16 we see that the presence of the technological spillovers do not change fossil fuel usage for the advanced economy under any taxation scheme (see Figure 16a).

In developing countries the presence of spillovers generally decreases fossil fuel usage both in optimal and second-best cases in line with the effect of the spillovers in business-as-usual case. An interesting result that can be observed in the Figure 9b is that in case of spillovers and no carbon taxation in developing countries, the level of fossil fuel usage corresponds approximately to the level of fossil fuels with carbon taxation in developing countries. It means that the spillovers in renewable energy create a replacement effects in fossil fuels comparable in size with the effects of carbon taxation.

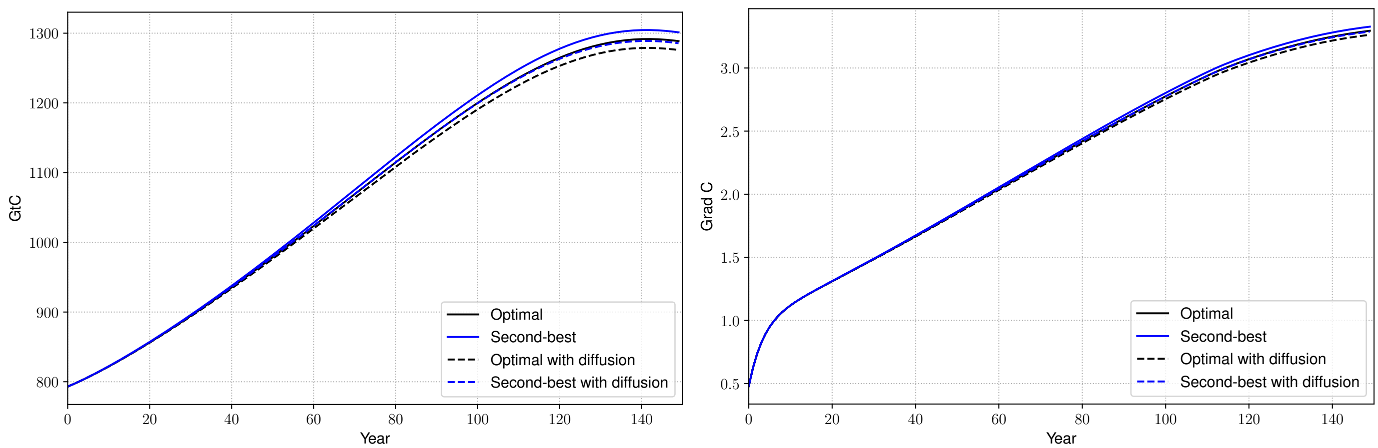


(a) Advanced economy

(b) Developing economy

Figure 17: Green energy in advanced (left) and developing economy (right). Year zero on the graphs corresponds to a starting year 1990.

Renewable energy usage, as displayed in the Figure 17, is substantially increased by the spillovers. In case of the renewable energy sources spillover effect is changing the growth rate of the TFP in renewable energy thus effecting significantly its productivity.



(a) Mass of the carbon in the atmosphere

(b) Temperature of the atmosphere

Figure 18: Mass of carbon in the atmosphere (left) and temperature of the atmosphere (right). Year zero on the graphs corresponds to a starting year 1990.

In the case of taxation in an advanced economy and spillover mass of carbon in the atmosphere as well as the temperature tends to be slightly higher than in the case of optimal abatement with spillovers. From the perspective of climate change optimal mitigation with spillovers delivers the most desirable results in terms of temperature reduction.

The panel of results provides support for the policy recommendation to put effort into taxing advanced economies to provide decarbonization efforts. Developing countries being not taxed do not wipe off the gains that can be achieved by advanced economies. Allowing the developing countries to grow without the burden of environmental taxation can be a politically desirable solution and with technological spillovers the second-best taxation option becomes as good as optimal taxation without spillovers in terms of the climate impact.

5.4 Welfare analysis

In this section, I formally compare the welfare of the economies well as the total welfare of the social planner as consumption equivalent under different scenarios. I compare the welfare gains (losses) concerning the business-as-usual case without spillovers.

Case	Advanced region	Developing region	Total welfare
Optimal	-0.1	2.77	0.95
Second-best	-0.02	2.51	0.92
BAU with spillovers	-0.37	0.73	0.03
Optimal with spillovers	-0.01	2.74	1.0
Second-best with spillovers	-0.08	2.73	0.95

Table 5: Welfare values expressed in percent deviation from the BAU case without spillovers

From the Table 5, we can see that for developing countries the most welfare improving scenario is an optimal taxation. The reason for that can be the significant size of the damages that developing region is facing and that is not being fully covered when developing region is not internalising its damages.

The welfare gains for developing region from optimal taxation with spillovers and second-best taxation with spillovers are approximately the same. At the same time total welfare is the same in case of the optimal taxation and second-best taxation with spillovers. These two results confirm the policy recommendation that second-best taxation with spillovers is a preferable option both from the point of view of the total welfare and welfare of the developing region.

6 Conclusion and discussion

The green energy transition in advanced in developing countries is necessary for successful mitigation of the climate change. However, the role of technological spillovers and its interaction with carbon taxation in the decarbonization process remains unclear. Developing countries, which represent more than half of the world's population, require energy to support their economic growth, but relying on fossil fuels could jeopardize global efforts to mitigate climate change. The present paper investigates how technological spillovers between heterogeneously developed countries affect the decarbonization perspective for less developed countries. The main finding suggests that in the presence of spillovers having carbon taxation only in advanced economies becomes preferable to taxation of both and advanced countries of spillovers are not taken into account. This highlights the importance of considering technological spillovers in the design of global climate policies.

The main result of this paper relies on two major assumptions. The first assumption concerns the way the countries were split into advanced and developing countries. In a current set-up, I assumed that advanced countries are high-income and upper-middle-income countries based on the World Bank income classification and developing countries are lower-middle-income and low-income economies. This choice was mostly driven by the empirical evidence on the innovation activity in terms of registering patents. Indeed, the set-up of the research question implies that the technology is being developed in one part of the world and adapted by the rest of the world. Both high-income and upper-middle-income countries innovate significantly, thus they were placed in the group of advanced, innovating, countries.

This split of the countries into the regions is also related to the second major assumption. By specifying the spillover process I assume the developing countries can't catch up with the advanced economies - there is always a lag in development. It is an open question whether developing countries especially the poorest ones can catch up to the level of middle-income or advanced economies. It would be possible to consider an alternative split of the world economy that puts only high-income countries in the advanced economy and the rest of the world in the developing economy. However, in this case, the context of the model presented will be significantly changed. It will be necessary to take into account that big emerging economies like China and countries of Latin America are part of the upper-middle countries and now they are driving the growth of developing regions. This would mean that innovations are not geographically anchored and spillovers can go both ways. This alternative modeling setup falls into the narrative that in general innovations around the world are produced by several big players and then spread around among other countries as well and there is a catch-up of developing countries. This alternative setup does not seem to bring additional insights to the research question of the present study, thus it was omitted.

The future avenue of research based on the built framework is twofold. First, it seems promising to conduct a global sensitivity analysis to better understand the interaction between growth rates of the energy sources in the advanced economy, technology spillovers intensity, and elasticity of substitution between energy inputs. This allows for quantitatively supported policy advice concerning the subsidies on innovation and technological transfer. Second, the model can be extended to include endogenous technological growth in energy as well as endogenous technological spillover intensity. This permits the exploration of directed technical mechanisms (market size effect and price effect) interacting with technological spillovers. In this case, an extension of the model with an alternative split of the world regions between advanced and developing countries as well as the possibility of catching up for the developing countries seems to be beneficial.

A Appendix

A.1 Recursive formulation

$$V_t\left(K_t^i\right) = \max_{K_{t+1}^i, C_t^i, \pi_t^i, \xi_t^i} \left\{ \sum_{i\in\{a,d\}} \phi^i \frac{\left(\frac{C_t^i}{\varrho_t^i L_t}\right)^{1-1/\psi}}{1-1/\psi} \varrho_t^i L_t + e^{-\rho} V_{t+1}\left(K_{t+1}^i\right) \right\} \tag{A.1}$$

$$\text{s.t.}\quad \Omega^i\left(T_{\mathrm{AT},t}\right)\left(K_t^i\right)^{\alpha}\left(\varphi_t^i A_t(1-\pi_t^i-\xi_t^i)\varrho_t^i L_t^i\right)^{1-\alpha-\nu}\left(E_t^i\right)^{\nu} + (1-\delta)K_t^i - C_t^i - K_{t+1}^i = 0 \quad \left(\lambda_t^i\right) \tag{A.2}$$

$$1-\pi_t^i \geq 0 \quad \perp \quad \lambda_t^{\pi^i} \geq 0 \tag{A.3}$$

$$1-\xi_t^i \geq 0 \quad \perp \quad \lambda_t^{\xi^i} \geq 0 \tag{A.4}$$

$$E_t^i = \left(\kappa_{dt}\left(E_t^{\mathrm{i,dt}}\right)^{\rho_{CES}} + \kappa_{cl}\left(E_t^{\mathrm{i,cl}}\right)^{\rho_{CES}}\right)^{1/\rho_{CES}} \tag{A.5}$$

$$E_t^{\mathrm{i,dt}} = A_{dt,t}^i \pi_t^i \varrho_t^i L_t^i \tag{A.6}$$

$$E_t^{\mathrm{i,cl}} = A_{cl,t}^i \xi_t^i \varrho_t^i L_t^i \tag{A.7}$$

$$b_{11}M_t^{\mathrm{AT}} + b_{21}M_t^{\mathrm{UO}} + \sigma_t\left(E^{\mathrm{a,dt}} + E^{\mathrm{d,dt}}\right) + E_t^{\mathrm{Land}} - M_{t+1}^{\mathrm{AT}} = 0 \quad \left(\nu_t^{\mathrm{AT}}\right) \tag{A.8}$$

$$b_{12}M_t^{AT} + b_{22}M_t^{\mathrm{UO}} + b_{32}M_t^{\mathrm{LO}} - M_{t+1}^{\mathrm{UO}} = 0 \quad \left(\nu_t^{\mathrm{UO}}\right) \tag{A.9}$$

$$b_{23}M_t^{\mathrm{UO}} + b_{33}M_t^{\mathrm{LO}} - M_{t+1}^{\mathrm{LO}} = 0 \quad \left(\nu_t^{\mathrm{LO}}\right) \tag{A.10}$$

$$T_t^{\mathrm{AT}} + c_1\left(F_{\mathrm{2xco2}}\log_2\left(\frac{M_t^{\mathrm{AT}}}{M_{\mathrm{eq}}^{\mathrm{AT}}}\right) + F_{\mathrm{EX},t}\right) - c_1\frac{F_{\mathrm{2xco2}}}{T_{\mathrm{2xco2}}}T_t^{\mathrm{AT}} - c_1c_3\left(T_t^{\mathrm{AT}} - T_t^{\mathrm{OC}}\right) - T_{t+1}^{\mathrm{AT}} = 0 \quad \left(\eta_t^{\mathrm{AT}}\right) \tag{A.11}$$

$$T_t^{\mathrm{OC}} + c_4\left(T_t^{\mathrm{AT}} - T_t^{\mathrm{OC}}\right) - T_{t+1}^{\mathrm{OC}} = 0 \quad \left(\eta_t^{\mathrm{OC}}\right) \tag{A.12}$$

where $i \in \{A, D\}$, $A_t^a = \varphi_t^a A_t$, $A_t^d = \varphi_t^d A_t$, A_t is a world TFP, and $\varrho_t^a L_t^a = L_t$, $\varrho_t^d L_t^d = L_t$, where L_t is a world population. $\varphi_t^a, \varphi_t^d, \varrho_t^a, \varrho_t^d$ are exogenously given processes.

We normalize consumption, capital and energy for every economy by total labor in the economy and production TFP of the world.

$$k_t^a = \frac{K_t^a}{A_tL_t},\ c_t^a = \frac{C_t^a}{A_tL_t},\ e_t^a = \frac{E_t^a}{A_tL_t},\ k_{t+1}^a = \frac{K_{t+1}^a}{A_{t+1}L_{t+1}} \tag{A.13}$$

$$k_t^d = \frac{K_t^d}{A_tL_t},\ c_t^d = \frac{C_t^d}{A_tL_t},\ e_t^d = \frac{E_t^d}{A_tL_t},\ k_{t+1}^d = \frac{K_{t+1}^d}{A_{t+1}L_{t+1}} \tag{A.14}$$

In the objective function we divide all the terms by A_tL_t and then replace $v_t = \frac{V_t}{{A_t}^{1-1/\psi}L_t}$.

$$\begin{aligned}\frac{V_t\left(K_t^a, K_t^d\right)}{{A_t}^{1-1/\psi} L_t} = \max_{k_{t+1}^a, k_{t+1}^d, c_t^a, c_t^d, \pi_t^a, \pi_t^d, \xi_t^a, \xi_t^d} & \left\{ \phi^a \frac{\left(\frac{C_t^a}{\varrho_t^a A_t L_t}\right)^{1-1/\psi} \cancel{A_t^{1-1/\psi}}}{1-1/\psi} \varrho_t^a \cancel{L_t} + \phi^d \frac{\left(\frac{C_t^d}{\varrho_t^d A_t L_t}\right)^{1-1/\psi} \cancel{A_t^{1-1/\psi}}}{1-1/\psi} \varrho_t^d \cancel{L_t} \right. \\ & \left. + \frac{e^{-\rho}}{{A_t}^{1-1/\psi} L_t} \frac{V_{t+1}\left(K_{t+1}^a, K_{t+1}^d\right)}{{A_{t+1}}^{1-1/\psi} L_{t+1}} {A_{t+1}}^{1-1/\psi} L_{t+1} \right\}\end{aligned} \tag{A.15}$$

$$v_t\left(k_t^a, k_t^d\right) = \max_{k_{t+1}^a, k_{t+1}^d, c_t^a, c_t^d, \pi_t^a, \pi_t^d, \xi_t^a, \xi_t^d} \left\{ \phi^a \frac{\left(\frac{c_t^a}{\varrho_t^a}\right)^{1-1/\psi}}{1-1/\psi} \varrho_t^a + \phi^d \frac{\left(\frac{c_t^d}{\varrho_t^d}\right)^{1-1/\psi}}{1-1/\psi} \varrho_t^d + \beta_t v_{t+1}\left(k_{t+1}^a, k_{t+1}^d\right) \right\} \tag{A.16}$$

We define the growth adjusted discount factor β_t as in

$$\beta_t := \exp\left(-\rho + (1-1/\psi) g_t^A + g_t^L\right). \tag{A.17}$$

We get a normalized problem:

$$v_t\left(k_t^i\right) = \max_{k_{t+1}^i, c_t^i, \pi_t^i, \xi_t^i} \left\{ \sum_{i\in\{a,d\}} \phi^i \frac{\left(\frac{c_t^i}{\varrho_t^i}\right)^{1-1/\psi}}{1-1/\psi} \varrho_t^i + \beta_t v_{t+1}\left(k_{t+1}^i\right) \right\} \tag{A.18}$$

$$\text{s.t.} \quad \Omega^i\left(T_{\text{AT},t}\right)\left(k_t^i\right)^\alpha \left(\varphi_t^i \varrho_t^i (1-\pi_t^i-\xi_t^i)\right)^{1-\alpha-\nu} \left(e_t^i\right)^\nu + (1-\delta)\,k_t^i - c_t^i - \exp\left(g_t^A + g_t^L\right) k_{t+1}^i = 0 \quad \left(\lambda_t^a\right) \tag{A.19}$$

$$1-\pi_t^i \geq 0 \quad \perp \quad \lambda_t^{\pi^i} \geq 0 \tag{A.20}$$

$$1-\xi_t^i \geq 0 \quad \perp \quad \lambda_t^{\xi^i} \geq 0 \tag{A.21}$$

$$e_t^i = \frac{\left(\kappa_{dt}\left(E_t^{\text{i,dt}}\right)^{\rho_{CES}} + \kappa_{cl}\left(E_t^{\text{i,cl}}\right)^{\rho_{CES}}\right)^{1/\rho_{CES}}}{A_t L_t} \tag{A.22}$$

$$E_t^{\text{i,dt}} = \pi_t^i A_{dt,t}^i \varrho_t^i L_t \tag{A.23}$$

$$E_t^{\text{i,cl}} = \xi_t^i A_{cl,t}^i \varrho_t^i L_t \tag{A.24}$$

$$b_{11} M_t^{\text{AT}} + b_{21} M_t^{\text{UO}} + \sigma_t\left(E^{\text{a,dt}} + E^{\text{d,dt}}\right) + E_t^{\text{Land}} - M_{t+1}^{\text{AT}} = 0 \quad \left(\nu_t^{\text{AT}}\right) \tag{A.25}$$

$$b_{12} M_t^{AT} + b_{22} M_t^{\text{UO}} + b_{32} M_t^{\text{LO}} - M_{t+1}^{\text{UO}} = 0 \quad \left(\nu_t^{\text{UO}}\right) \tag{A.26}$$

$$b_{23} M_t^{\text{UO}} + b_{33} M_t^{\text{LO}} - M_{t+1}^{\text{LO}} = 0 \quad \left(\nu_t^{\text{LO}}\right) \tag{A.27}$$

$$T_t^{\text{AT}} + c_1\left(F_{\text{2xco2}} \log_2\left(\frac{M_t^{\text{AT}}}{M_{\text{eq}}^{\text{AT}}}\right) + F_{\text{EX},t}\right) - c_1 \frac{F_{\text{2xco2}}}{T_{\text{2xco2}}} T_t^{\text{AT}} - c_1 c_3\left(T_t^{\text{AT}} - T_t^{\text{OC}}\right) - T_{t+1}^{\text{AT}} = 0 \quad \left(\eta_t^{\text{AT}}\right) \tag{A.28}$$

$$T_t^{\text{OC}} + c_4\left(T_t^{\text{AT}} - T_t^{\text{OC}}\right) - T_{t+1}^{\text{OC}} = 0 \quad \left(\eta_t^{\text{OC}}\right) \tag{A.29}$$

A.2 Equilibrium conditions

- Envelope theorem with respect to state variables

$$\frac{\partial v_t}{\partial k_t^i} = v_{k^i,t} = \lambda_t^i \left(\Omega^i \left(T_{\text{AT},t}\right) \alpha \left(k_t^i\right)^{\alpha-1} \left(\varphi_t^i \varrho_t^i (1-\pi_t^i-\xi_t^i)\right)^{1-\alpha-\nu} \left(e_t^i\right)^{\nu} + (1-\delta_t) \right) \tag{A.30}$$

$$\frac{\partial v_t}{\partial M_{\text{AT},t}} = v_{M_{\text{AT}},t} = \nu_t^{\text{AT}} b_{11} + \nu_t^{\text{UO}} b_{12} + \eta_t^{\text{AT}} c_1 F_{2\text{XCO2}} \frac{1}{\ln 2 M_{\text{AT},t}} \tag{A.31}$$

$$\frac{\partial v_t}{\partial M_{\text{UO},t}} = v_{M_{\text{UO}},t} = \nu_t^{\text{AT}} b_{21} + \nu_t^{\text{UO}} b_{22} + \nu_t^{\text{LO}} b_{23} \tag{A.32}$$

$$\frac{\partial v_t}{\partial M_{\text{LO},t}} = v_{M_{\text{LO}},t} = \nu_t^{\text{UO}} b_{32} + \nu_t^{\text{LO}} b_{33} \tag{A.33}$$

$$\begin{aligned}\frac{\partial v_t}{\partial T_{\text{AT},t}} = v_{T_{\text{AT}},t} = &\sum_{i\in\{a,d\}} \lambda_t^i \Omega^{i\prime}(T_t^{\text{AT}}) \left(\varphi_t^i \varrho_t^i (1-\pi_t^i-\xi_t^i)\right)^{1-\alpha-\nu} \left(k_t^i\right)^{\alpha} \left(e_t^i\right)^{\nu} \\ &+ \eta_t^{\text{AT}} (1 - c_1 \frac{F_{2\text{XCO2}}}{\text{T2xco2}} - c_1 c_3) + \eta_t^{\text{OC}} c_4 \end{aligned} \tag{A.34}$$

$$\frac{\partial v_t}{\partial T_{\text{OC},t}} = v_{T_{\text{OC}},t} = \eta_t^{\text{AT}} c_1 c_3 + \eta_t^{\text{OC}} (1-c_4). \tag{A.35}$$

- FOCs with respect to consumption, capital tomorrow and climate variables tomorrow

$$[c_t^i] : c_t^i = \left(\frac{\lambda_t^i}{\phi^i \left(\varrho_t^i\right)^{1-1/\psi}} \right)^{-\psi} \tag{A.36}$$

$$[k_{t+1}^i] : \beta_t v_{k^i,t} - \exp\left(g_t^A + g_t^L\right) \lambda_t^i = 0 \tag{A.37}$$

$$[M_{\text{AT},t+1}] : \beta_t v_{M_{\text{AT}},t+1} - \nu_t^{\text{AT}} = 0 \tag{A.38}$$

$$[M_{\text{UO},t+1}] : \beta_t v_{M_{\text{UO}},t+1} - \nu_t^{\text{UO}} = 0 \tag{A.39}$$

$$[M_{\text{LO},t+1}] : \beta_t v_{M_{\text{LO}},t+1} - \nu_t^{\text{LO}} = 0 \tag{A.40}$$

$$[T_{\text{AT},t+1}] : \beta_t v_{T_{\text{AT}},t+1} - \eta_t^{\text{AT}} = 0 \tag{A.41}$$

$$[T_{\text{OC},t+1}] : \beta_t v_{T_{\text{OC}},t+1} - \eta_t^{\text{OC}} = 0 \tag{A.42}$$

- Budget constraints:

$$\Omega^i \left(T_{\text{AT},t}\right) \left(k_t^i\right)^{\alpha} \left(\varphi_t^i \varrho_t^i (1-\pi_t^i-\xi_t^i)\right)^{1-\alpha-\nu} \left(e_t^i\right)^{\nu} + (1-\delta)\, k_t^i - c_t^i - \exp\left(g_t^A + g_t^L\right) k_{t+1}^i = 0 \tag{A.43}$$

- KKT condition for π_t^i:

$$\Psi^{\text{FB}}\left(\lambda_t^{\pi^i}, 1-\pi_t^i\right) = \lambda_t^{\pi^i} + \left(1-\pi_t^i\right) - \sqrt{\left(\lambda_t^{\pi^i}\right)^2 + \left(1-\pi_t^i\right)^2}, \tag{A.44}$$

where

$$\begin{aligned}\lambda_t^{\pi^i} &= \lambda_t^i \nu A_{dt,t}^i \varrho_t^i L_t \kappa_{dt} \Omega^i\left(T_{\text{AT},t}\right)\left(k_t^i\right)^\alpha\left(e_t^i\right)^\nu\left(\varphi_t^i\varrho_t^i(1-\pi_t^i-\xi_t^i)\right)^{1-\alpha-\nu}\left(E_t^i\right)^{-\rho}\left(E_t^{\text{i,dt}}\right)^{\rho-1}\\ &\quad-(1-\alpha-\nu)\varphi_t^i\varrho_t^i\Big(\varphi_t^i\varrho_t^i(1-\pi_t^i-\xi_t^i)\Big)^{-\alpha-\nu}\lambda_t^i\Omega^i\left(T_{\text{AT},t}\right)\left(k_t^i\right)^\alpha\left(e_t^i\right)^\nu + \nu_t^{\text{AT}}\sigma_t A_{dt,t}^i\varrho_t^i L_t.\end{aligned} \tag{A.45}$$

- KKT condition for ξ_t^i:

$$\Psi^{\text{FB}}\left(\lambda_t^{\xi^i}, 1-\xi_t^i\right) = \lambda_t^{\xi^i} + \left(1-\xi_t^i\right) - \sqrt{\left(\lambda_t^{\xi^i}\right)^2 + \left(1-\xi_t^i\right)^2}, \tag{A.46}$$

where

$$\begin{aligned}\lambda_t^{\xi^i} &= \lambda_t^i \nu A_{cl,t}^i \varrho_t^i L_t \kappa_{cl} \Omega^i\left(T_{\text{AT},t}\right)\left(k_t^i\right)^\alpha\left(e_t^i\right)^\nu\left(\varphi_t^i\varrho_t^i(1-\pi_t^i-\xi_t^i)\right)^{1-\alpha-\nu}\left(E_t^i\right)^{-\rho}\left(E_t^{\text{i,cl}}\right)^{\rho-1}\\ &\quad-(1-\alpha-\nu)\varphi_t^i\varrho_t^i\Big(\varphi_t^i\varrho_t^i(1-\pi_t^i-\xi_t^i)\Big)^{-\alpha-\nu}\lambda_t^i\Omega^i\left(T_{\text{AT},t}\right)\left(k_t^i\right)^\alpha\left(e_t^i\right)^\nu.\end{aligned} \tag{A.47}$$

B Parametrisation

B.1 Initial values

Calibrated parameter	Symbol	Value 1990	Source
Capital in advanced economy (trill USD 2015)	K_0^A	148.03	PWT 10.01
Capital in developing economy (trill USD 2015)	K_0^D	14.31	PWT 10.01
Mass of carbon in the atmosphere (1000 GtC)	M_0^{AT}	0.723	author's elaboration
Mass of carbon in the upper ocean (1000 GtC)	M_0^{UO}	0.555	author's elaboration
Mass of carbon in the lower ocean (1000 GtC)	M_0^{LO}	1.301	author's elaboration
Temperature of the atmosphere ($C°$)	T_0^{AT}	0.64	author's elaboration
Temperature of the ocean ($C°$)	T_0^{OC}	0.15	author's elaboration

Table 6: Starting states

B.2 Parametrisation of the exogenous processes for the starting year 1990

The functional forms of the exogenous variables can be found in the **??**. However, the parametrisation of the exogenous processes was adjusted to the starting year 1990. The adjusted parameters are presented in the tables below. **Population**

Calibrated parameter	Symbol	Value 1990
Annual rate of convergence	δ^L	0.012
World population at starting year [billion]	L_0	3.03
Asymptotic world population [billion]	L_∞	11.5

Table 7: Annual parametrization for labor evolution

Carbon Intensity

Calibrated parameter	Symbol	Value 1990
Initial growth of carbon intensity per year	g_0^σ	-0.008
Decline rate of decarbonization per year	δ^σ	0.01
Initial carbon intensity (1000GtC)	σ_0	0.0002

Table 8: Annual parametrization for carbon intensity evolution

Emissions from land

Calibrated parameter	Symbol	Value 1990
Emissions from land (1000GtC per year)	$E_{\text{Land},0}$	0.00127
Decline rate of land emissions (per year)	δ^{Land}	0.023

Table 9: Annual parametrization for the emissions from land.

Exogenous radiative forcing

Calibrated parameter	Symbol	Value 1990
Forcings of non-CO2 GHG (Wm-2)	F_0^{EX}	0.25
2100 forcings of non-CO2 GHG (Wm-2)	F_1^{EX}	1.0
Number of years before 2100	T	110

Table 10: Annual parametrization for the exogenous forcing.

B.3 The climate system

The functional forms of the temperature equations can be found in the **??**. However, the starting values for the temperature equations were adjusted to the starting year 1990. The adjusted parameters are presented in the tables below.

Calibrated parameter	Symbol	Value 1990
Concentration in atmosphere (1000GtC)	$M_{\text{INI}}^{\text{AT}}$	0.723
Concentration in upper strata (1000GtC)	$M_{\text{INI}}^{\text{UO}}$	0.555
Concentration in lower strata (1000GtC)	$M_{\text{INI}}^{\text{LO}}$	1.301

Table 11: Annual parametrization for the mass of carbon.

Calibrated parameter	Symbol	Value 1990
Atmospheric temp change (°C) from 1850	T_0^{AT}	0.64
Lower stratum temp change (°C) from 1850	T_0^{OC}	0.15

Table 12: Annual parametrization for the temperature.

B.4 Energy sector

To get parametrisation for the energy sector I first compute the labor shares in energy sector under the assumption of profit maximisation and given energy consumption in the year 1990. The net output was defined as follows:

$$Y_0^i = \Omega^i\left(T_{\text{AT},0}\right)\left(K_0^i\right)^{\alpha}\left(\varphi_t^i A_0(1 - L_{dt,0} - L_{cl,0})\right)^{1-\alpha-\nu}\left(\left(\kappa_{dt}\left(A_{dt,0}^i L_{dt,0}^i\right)^{\rho_{CES}} + \kappa_{cl}\left(A_{cl,0}^i L_{cl,0}^i\right)^{\rho_{CES}}\right)^{\frac{1}{\rho_{CES}}}\right)^{\nu}.$$

I take the derivative of the net output with respect to labor shares in energy sector:

$$\frac{\partial Y_0^i}{\partial L_{dt,0}^i} = -(1-\alpha-\nu)\frac{1}{1 - L_{dt,0}^i - L_{cl,0}^i} + \nu\kappa_{dt}\frac{1}{L_{dt,0}^i}\left(\frac{E_{dt,0}^i}{E_0^i}\right)^{\rho_{CES}}$$
$$\frac{\partial Y_0^i}{\partial L_{cl,0}^i} = -(1-\alpha-\nu)\frac{1}{1 - L_{dt,0}^i - L_{cl,0}^i} + \nu\kappa_{cl}\frac{1}{L_{cl,0}^i}\left(\frac{E_{cl,0}^i}{E_0^i}\right)^{\rho_{CES}}$$

This way I get the initial shares of labor in fossil fuel and renewable energy production:

$$L_{dt,0}^{i} = \frac{\nu\kappa_{dt}\left(\frac{E_{dt,0}^{i}}{E_{0}^{i}}\right)^{\rho_{CES}}}{1-\alpha-\nu+\nu\kappa_{dt}\left(\frac{E_{dt,0}^{i}}{E_{0}^{i}}\right)^{\rho_{CES}}+\nu\kappa_{cl}\left(\frac{E_{cl,0}^{i}}{E_{0}^{i}}\right)^{\rho_{CES}}} \tag{B.1}$$

$$L_{cl,0}^{i} = \frac{\nu\kappa_{cl}\left(\frac{E_{cl,0}^{i}}{E_{0}^{i}}\right)^{\rho_{CES}}}{1-\alpha-\nu+\nu\kappa_{dt}\left(\frac{E_{dt,0}^{i}}{E_{0}^{i}}\right)^{\rho_{CES}}+\nu\kappa_{cl}\left(\frac{E_{cl,0}^{i}}{E_{0}^{i}}\right)^{\rho_{CES}}} \tag{B.2}$$

From this we get the following initial labor shares:

Calibrated parameter	Symbol	Value
Labor share FF in advanced	$L_{dt,0}^{A}$	0.045
Labor share RE in advanced	$L_{cl,0}^{A}$	0.012
Production labor share	$1-L_{dt,0}^{A}-L_{cl,0}^{A}$	0.942
Labor share FF in developing	$L_{dt,0}^{D}$	0.047
Labor share RE in developing	$L_{cl,0}^{D}$	0.001
Production initial labor share	$1-L_{dt,0}^{D}-L_{cl,0}^{D}$	0.94

Table 13: Energy sector initial labor share values

Based on the initial labor shares computed above I pin down the initial TFP values for each energy sector in each region reported in Table 3, based on the energy consumption data in 1990.

C Countries by income groups based on the World Bank Classification

Afghanistan	Guinea-Bissau	Somalia
Burkina Faso	Korea, Dem. People's Rep	South Sudan
Burundi	Liberia	Sudan
Central African Republic	Madagascar	Syrian Arab Republic
Chad	Malawi	Togo
Congo, Dem. Rep	Mali	Uganda
Eritrea	Mozambique	Yemen, Rep.
Ethiopia	Niger	Zambia
Gambia, The	Rwanda	
Guinea	Sierra Leone	

Table 14: Low income countries: economies with GNI less than $1,086 per capita

Angola	India	Philippines
Algeria	Indonesia	Samoa
Bangladesh	Iran, Islamic Rep	São Tomé and Principe
Benin	Kenya	Senegal
Bhutan	Kiribati	Solomon Islands
Bolivia	Kyrgyz Republic	Sri Lanka
Cabo Verde	Lao PDR	Tanzania
Cambodia	Lebanon	Tajikistan
Cameroon	Lesotho	Timor-Leste
Comoros	Mauritania	Tunisia
Congo, Rep.	Micronesia, Fed. Sts.	Ukraine
Côte d'Ivoire	Mongolia	Uzbekistan
Djibouti	Morocco	Vanuatu
Egypt, Arab Rep.	Myanmar	Vietnam
El Salvador	Nepal	West Bank and Gaza
Eswatini	Nicaragua	Zimbabwe
Ghana	Nigeria	
Haiti	Pakistan	
Honduras	Papua New Guinea	

Table 15: Lower-middle income countries: economies with GNI between $1,086 and $4,255 per capita.

Albania	Fiji	Namibia
American Samoa	Gabon	North Macedonia
Argentina	Georgia	Palau
Armenia	Grenada	Paraguay
Azerbaijan	Guatemala	Peru
Belarus	Guyana	Russian Federation
Belize	Iraq	Serbia
Bosnia and Herzegovina	Jamaica	South Africa
Botswana	Jordan	St. Lucia
Brazil	Kazakhstan	St. Vincent and the Grenadines
Bulgaria	Kosovo	Suriname
China	Libya	Thailand
Colombia	Malaysia	Tonga
Costa Rica	Maldives	Türkiye
Cuba	Marshall Islands	Turkmenistan
Dominica	Mauritius	Tuvalu
Dominican Republic	Mexico	
Equatorial Guinea	Moldova	
Ecuador	Montenegro	

Table 16: Upper-middle income countries: economies with GNI between $4,256 and $13,205 per capita

Andorra	Greece	Poland
Antigua and Barbuda	Greenland	Portugal
Aruba	Guam	Puerto Rico
Australia	Hong Kong SAR, China	Qatar
Austria	Hungary	Romania
Bahamas, The	Iceland	San Marino
Bahrain	Ireland	Saudi Arabia
Barbados	Isle of Man	Seychelles
Belgium	Israel	Singapore
Bermuda	Italy	Sint Maarten (Dutch part)
British Virgin Islands	Japan	Slovak Republic
Brunei Darussalam	Korea, Rep.	Slovenia
Canada	Kuwait	Spain
Cayman Islands	Latvia	St. Kitts and Nevis
Channel Islands	Liechtenstein	St. Martin (French part)
Chile	Lithuania	Sweden
Croatia	Luxembourg	Switzerland
Curaçao	Macao SAR, China	Taiwan, China
Cyprus	Malta	Trinidad and Tobago

Table 17: High income countries: economies with GNI more than $13,205 per capita

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