CAN TODAY'S AND TOMORROW'S WORLD UNIFORMLY GAIN
FROM CARBON TAXATION?

Laurence J. Kotlikoff
Felix Kubler
Andrey Polbin
Simon Scheidegger

ABSTRACT

Climate change will impact current and future generations in different regions very differently. This paper develops a large-scale, annually calibrated, multi-region, overlapping generations model of climate change to study its heterogeneous effects across space and time. We model the relationship between carbon emissions and the global average temperature based on the latest climate science. Predicated average global temperature is used to determine, via pattern-scaling, region-specific temperatures and damages. Our main focus is determining the carbon policy that delivers present and future mankind the highest uniform percentage welfare gains – arguably the policy with the highest chance of global adoption. Damages from climate change are positive for all regions apart from Russia and Canada, with India and South Asia Pacific suffering the most. The optimal policy is implemented via a time-varying global carbon tax plus region- and generation-specific net transfers. Uniform welfare improving carbon policy can materially limit global emissions, dramatically shorten the use of fossil fuels, and raise the welfare of all current and future agents by over four percent. Unfortunately, the pursuit of carbon policy by individual regions, even large ones, makes only a limited difference. However, coalitions of regions, particularly ones including China, can materially limit carbon emissions.

Laurence J. Kotlikoff
Department of Economics
Boston University
270 Bay State Road
Boston, MA 02215
and NBER
kotlikoff@gmail.com

Felix Kubler
University of Zurich
Plattenstrasse 32
CH-8032 Zurich
Switzerland
and Swiss Financial Institute
fkubler@gmail.com

Andrey Polbin
The Russian Presidential Academy
   of National Economy
   and Public Administration
82 Vernadskogo prosp 117517
Moscow Russian Federation
and The Gaidar Institute for Economic Policy
apolbin@gmail.com

Simon Scheidegger
University of Lausanne
Department of Economics
Internef 509
CH-1015 Lausanne
Switzerland
simon.scheidegger@gmail.com

1 Introduction

Our problems are man-made; therefore, they can be solved by man. These inspiring words of President Kennedy apply in full measure to anthropogenic climate change with its massive projected damages. This paper determines the carbon policy that delivers present and future humankind the highest uniform percentage welfare gain. This policy is implemented via a time-varying global carbon tax plus region- and generation-specific net transfers. Uniformity of climate-stakeholder treatment may be essential to achieve global carbon-policy adoption.

Our model features 18 regions inhabited by 80 overlapping generations. Output is produced with capital, labor, and a time-varying combination of dirty and clean energy. Dirty energy comprises oil, gas, and coal, each of whose extraction is subject to increasing costs. Clean energy is produced with capital, labor, and a fixed factor land, which ensures some use of clean energy in early years when its technology is in a nascent stage.

Our Pareto-improving policy, which combines time-varying carbon taxation with generation- and region-specific compensation, treats the carbon externality as a problem of economic efficiency not social welfare insufficiency, however defined by the researcher. Our positive approach is standard in public finance. It differs markedly from Nordhaus (1979)'s normative treatment of the problem, which invokes a social planner. Nordhaus' study is seminal. Nevertheless, it offers neither a value-free prescription for global carbon taxation nor an incentive for generations within a given country, let alone in different countries, to cooperate.

The climate externality – burning fossil fuels, which emit carbon, heat the atmosphere, and damages the planet – arises naturally in our life-cycle model as agents have no qualms in harming their future progeny, let alone unrelated future foreigners.

Our optimal uniform welfare improving (UWI) policy is measured as an equal percentage compensating consumption variation across all generations in all regions. As such, it seems most likely to attract international and intergenerational support. Implementing such policy requires jointly solving for the optimal time path of global carbon taxation and the time paths of generation- and region-specific redistribution. Region- and generation-specific net tax payments are needed since global warming inflicts time-varying damages on different regions. Indeed, our model's damage function, which marries Nordhaus (2018)'s asymmetric DICE[1] damage function with Krusell and Smith Jr (2018)'s symmetric damage function, admits climate-change winners as well as losers.

The analysis in this work addresses five key climate-policy questions. First, how high is the initial optimal UWI tax? Second, how does the optimal UWI tax change through time? Third, by how much does each region optimally reduce its CO2 emissions through time? Fourth, how is the production of coal, gas, and oil differentially affected by the optimal policy? And fifth, how large are region-specific net transfers required, through time, to affect the UWI policy.

1.1 Background

As with other externalities, climate change reflects market failure whose correction can generate a Pareto improvement, benefiting some without harming others. Climate change presents two such failures – missing carbon-abatement markets across generations and regions. However, as

---

[1]DICE was originally termed by Nordhaus (1979) and abbreviates "Dynamic Integrated Model of Climate and the Economy".

indicated, the early work on climate change featured a social planner with no necessary interest in achieving a Pareto improvement. Much of the more recent optimal carbon-tax literature (see, e.g., Golosov et al. (2014)) emulates the social-planner framework by positing models of infinitely lived dynasties. Each dynasty comprises altruistically linked agents with typically one such agent alive at a point in time, hence, the nickname *single-agent model*. The social planner framework begs the question of which social planner with which degree of intergenerational altruism, as captured by the time preference rate, to invoke. The single-agent framework begs the same question when it comes to positing the single-agent's time preference rate, which controls her relative regard for current versus future dynasty members. The difficulty in answering this question is acute given the strong evidence, at least in the US, against such altruism – evidence that includes Abel and Kotlikoff (1994), Altonji et al. (1992), Hayashi et al. (1996), Gokhale et al. (1996), and Altonji et al. (1997). In addition, the single-agent model has a major theoretical drawback. Intermarriage across any two dynasties links the two dynasties altruistically, and, given even a very small rate of intermarriage, it links the planet altruistically. This absurd proposition was first pointed out by Kotlikoff (1983) and then studied in detail by Bernheim and Bagwell (1988). Moreover, were the economy comprised of altruistic dynasties, they would surely agree to tax carbon. Although the social planner and single-agent approaches are analytically tractable and computationally convenient, both seem limited for studying climate change.

1.2 Model Overview

The model we study in this paper features three goods: i) output, which can be consumed or invested (used as capital), ii) clean energy, and iii) dirty energy. Output is produced with capital, labor, and energy, be it clean or dirty. Clean energy is produced with capital, labor, and land. The land is in fixed supply in each region and proxies for region-specific physical limits on generating clean energy. As for dirty energy, its production is, as indicated, based on the increasingly costly extraction of fossil fuels. Dirty energy companies are owned globally.

Under "business-as-usual" (BAU, i.e., no policy), our assumed technological advances in clean energy bring an end to dirty energy use at dates that depend on the region. Regions with limited initial clean energy use have, per our calibration, low initial clean energy productivity meaning it takes them longer to wean themselves from the use of fossil fuels. Thus, Sub-Saharan Africa uses dirty energy through the end of the next century whereas the US stops using fossil fuels before this Century ends. However, the regions' collective carbon end dates are sufficiently distant to permit dirty energy to wreck long-lasting, major damage on most of the world's regions – regions that house the vast majority of the world's current and future populations.

The multi-region overlapping generations (OLG) model's UWI carbon policy has two components. First, it taxes, at time-varying rates, emissions from the use of dirty energy.[2] Second, it lump-sum redistributes on a generation- and region-specific basis to ensure the maximum uniform welfare gain. As for carbon-tax revenues, they are lump-sum rebated to dirty energy producers on a period-by-period basis.[3]

---

[2]Note that taxing fossil fuel extraction would generate identical results.

[3]Since our model's net transfers achieve a UWI gain, this choice – rebating carbon revenues to dirty energy suppliers does not alter outcomes. Were we, for example, to rebate carbon revenues on a global per capita basis, the UWI region- and generation-specific net transfers would adjust to maintain the original equilibrium.

Who pays positive net transfers? The answer is future generations living in regions that gain from a cooler planet. However, their negative net transfer payments (net taxes) are worth the price, leaving them better off to the same degree as all other generations in each region. How can the policy's redistribution be implemented in practice? An international authority, such as the International Monetary Fund could issue bonds to initially make net transfers and subsequently service the debt.

Our study makes five significant methodological contributions. First, it provides what may be the first large-scale, multi-regional OLG model of global climate change – one that incorporates all regions of the world. Second, region-specific temperatures (thus, allowing for region-specific damages) are calculated via a technique from climate science called "pattern scaling" where the temperature at each 1-degree latitude by 1-degree longitude grid location can be derived on the concomitant global average temperature.[4] Third, our solution takes full account of the feedback loop in which the path of global temperature impacts the paths of region-specific temperature, the paths of region-specific temperatures impact paths of region-specific output and emissions, and the sum of paths of region-specific emissions impacts the global temperature path. Fourth, we incorporate region-specific damages. However, unlike social planner models with multiple regions[5], we calibrate the damage function proposed by Krusell and Smith (2018) to permit negative damages while delivering approximately the same aggregate damages as the DICE-2016 model (Nordhaus, 2017).[6] Furthermore, fifth, we use a recent study by Folini et al. (2021) that employs state-of-the-art climate science.

1.3   Preview of Findings

In our baseline, high damage scenario, our model predicts region-specific climatic disasters absent policy intervention. With no policy, that is, BAU, the rise in the global mean surface temperature for the year 2200 relative to pre-industrial levels is approximately 3.6 degrees Celsius. This is good news for Russia and Canada, whose GDP levels in the year 2200 are 3.9 percent and 2.6 percent higher, respectively. However, the other 16 regions in our global model suffer, with India, South Asia Pacific, Sub-Saharan African, and the Middle East. Their GDP levels in the year 2200 are reduced by 43.9, 38.3, 37.9, and 36.0 percent, respectively, relative to their BAU values. As for the global GDP, it's 2200 value is lowered by 16.5 percent.

In the BAU scenario, dirty energy lasts for 200 years. Optimal UWI policy cuts dirty energy's usage to 85 years and reduces cumulative oil, gas, and coal consumption by 88 percent, 89 percent, and 99 percent, respectively. These are significant changes. They limit the rise in the global mean surface temperature to 2.1 degrees Celsius. Moreover, the peak GDP loss declines from 16.7 percent to 9.1 percent. Peak regional damages now range from 0.5 percent to 27.3 percent of GDP. The striking messages here are both encouraging – global carbon taxation can significantly mitigate losses from climate change – and discouraging – Atmospheric carbon concentration is already so high that the optimal UWI carbon tax policy can only limit peak global damage by 45.5 percent.

Achieving this highest UWI policy requires substantial inter-generational and inter-regional

---

[4]For more details on pattern scaling, see, e.g., Lynch et al. (2017), Kravitz et al. (2017), and references therein.

[5]See our discussion of the RICE (i.e., the so-called "Regional Integrated model of Climate and the Economy") model (Nordhaus and Yang, 1996a) below.

[6]Below, we use DICE and DICE-2016 interchangeably.

net transfers. The largest net transfers, around 15 percent of annual and, thus, lifetime consumption, must be made to current and near-term generations in three regions – Russia, Former Soviet Central Asia, and Eastern Europe. These regions experience particular large increases in energy costs, not due to their ownership or production of fossil fuels (recall, fossil fuels are a global asset), but due to their heavy use of fossil fuels in production. Indian generations born after the year 2200 face the largest net tax (negative net transfer) – roughly 30 percent. This reflects the huge benefit future Indians incur from carbon taxation. Generations born in the long run in the Middle East, Latin America excluding Mexico and Brazil, Sub Saharan Africa, Brazil, and South Asian Pacific face roughly 20 percent taxes. As for those born in the long run in the US, Japan/South Korea/Hong Kong, China, South Africa, Australia, and New Zealand, the net tax is roughly 10 percent.

One of our model's key advantages is the ability to assess climate reforms conducted by subsets of regions. We find that no region can materially improve climate change if it operates solely on its own. Coalitions of regions can make a difference for themselves. For example, if all regions apart from China adopt a UWI carbon policy, their uniform welfare gain would be about 60 percent of the value were China also to participate. Through this century, the emissions reduction achievable by a coalition absent China is far less than half of the reduction including China. In short, China's participation in carbon policy is a sine qua non for real progress against climate change. However, the efficacy of UWI policy, even when universally adopted, is greatly reduced if the policy's implementation is delayed.

The remainder of this article is organized as follows: Section 2 proceeds with a brief summary of the related literature. Section 3 outlines our multi-regional climate-OLG model. In Section 4, we present the calibration strategy; section 5 discusses our results and findings. Finally, section 6 concludes.

2 Literature Review

There is a vast and growing body of literature on exhaustible resources and climate change emanating from seminal contributions by Hotelling (1931), Solow (1974b,a), and Nordhaus (1979). Our paper builds on early, small-scale OLG models of resource extraction and global warming (see, e.g., Howarth and Norgaard (1990), Howarth (1991b), Howarth (1991a), Burton (1993), Pecchenino and John (1994), John et al. (1995), Marini and Scaramozzino (1995), and Burton (1993)). Howarth (1991b) is of particular relevance since he considered, in general terms, how to analyze economic efficiency in OLG models in the context of technological shocks. Howarth and Norgaard (1992) introduced damages to the production function from environmental degradation and studied the problem of sustainable development.[7] Rasmussen (2003) and Wendner (2001) examine the impact of the Kyoto Protocol on the future course of the energy sector. Wendner (2001) also considers the extent to which carbon taxes can shore up Austria's state pension system. These two latter studies feature large-scale, perfect-foresight, single-country models. However, they omit climate damage.

---

[7]An alternative approach to incorporating a negative environmental externality is to include environmental quality directly in the utility function. Pecchenino and John (1994) and John et al. (1995) make this assumption in a discrete-time OLG model. Marini and Scaramozzino (1995) does the same but in a continuous-time OLG framework. The problem of generational equity and sustainable development is also discussed by Mourmouras (1991, 1993), Batina and Krautkraemer (1999) in a model where energy is renewable.

Howarth and Norgaard (1990), using a pure exchange OLG model, and Howarth (1991a), using a standard OLG model, demonstrate that policymakers can choose among an infinite number of Pareto paths in correcting externalities. Clearly, social judgments will matter in deciding which, if any, of such paths to adopt.[8] The multiplicity of the Pareto-paths message holds for our analysis. However, only the UWI policy path treats everyone equally, at least percentage-wise. Moreover, equal percentage gains seem most likely to gain universal support.

The fact that OLG models do not admit unique solutions when it comes to allocating efficiency gains across agents, including agents born at different dates, has led some economists to introduce social welfare weights. Papers in this genre include Burton (1993), Calvo and Obstfeld (1988), Endress et al. (2014), Howarth (1998), Ansuategi and Escapa (2002), Marini and Scaramozzino (1995), Schneider et al. (2012), and Lugovoy and Polbin (2016). In these studies, the social planner's time preference plays a critical role in influencing policy choice.[9]

Apart from Kotlikoff et al. (2021), our paper's closest antecedents are Bovenberg and Heijdra (1998, 2002), Heijdra et al. (2006), Karp and Rezai (2014). Their studies consider the use of debt policy to achieve Pareto improvements in the context of adverse climate change.[10] But this model differs from ours in two important ways. First, they confine environmental damage to the utility function. Second, they do not model clean and dirty energy, with dirty energy exhausting in the future based on the speed of technological change in the clean energy sector, not to mention climate-change policy.

Nordhaus' seminal climate change paper (Nordhaus, 1979) – the Dynamic Integrated Model of Climate and the Economy (DICE) – spawned a massive literature, including Nordhaus' development of the RICE (the Regional Integrated model of Climate and the Economy) model (Nordhaus and Yang, 1996b, Nordhaus, 2010, 2015), which examines how region-specific production of and damages from global warming underlies the global problem. Hassler et al. (2020) presents a quantitative integrated assessment model (IAM) designed as a dynamic, multi-region general-equilibrium model coupled with climate and carbon-cycle modules. Their IAM setup is aimed toward policy evaluation, focusing on policies that: (i) are not necessarily optimal and (ii) potentially differ quantitatively and qualitatively across regions. Their model features a single infinitely lived agent in each region and region-specific production of clean and dirty energy. Unlike RICE, they model resource extraction explicitly.

Hillebrand and Hillebrand (2020) also posit a dynamic climate model with multiple regions to evaluate how implementing an optimal climate tax affects production, emissions, and welfare in each region. Their model distinguishes six major world regions and incorporates a wide array of regional heterogeneities, including a detailed description of the energy production process in

---

[8]Gerlagh and Keyzer (2001), Gerlagh and van der Zwaan (2001) consider the choice among Pareto paths and the potential use of trust-fund policies to provide future generations a share of the income derived from the exploitation of natural resources. Gerlagh and van der Zwaan (2001) also point out that demographics can impact the set of efficient policy paths through their impact on the economy's general equilibrium.

[9]Yet if the framework respects individual preferences, it is not clear how aggregating them according to a researcher's implicit preferences as conveyed by the envisioned social planner does more than confound normative and positive analysis. Once one has a model that generates individual outcomes for different policies, displaying those outcomes for a range of policy choices appears to be the economist's role – not, in effect, lobbying with readers for the researcher's preferred intergenerational welfare weighting. Our focus on UWI policy is due to its likely political attractiveness, not its ethical superiority.

[10]Karp and Rezai (2014) also considers a life-cycle model but explores the degree to which policy-induced general equilibrium changes in factor and asset prices could effect a Pareto improvement with no direct redistribution across generations.

each region. As in Hassler et al. (2020), there is a single infinitely lived agent in each region. However, in contrast to Hassler et al. (2020), they allow for additional international trade via an international capital market.

The ongoing work by Krusell and Smith Jr (2018) considers a model with 19,000 regions and studies distributional effects of climate change and climate policy. As detailed below, we use their calibration strategy to obtain region-specific damages. The main upshot of their work is that since some regions gain and some regions lose through climate change, a Pareto-improving carbon tax requires transfers to northern regions.

Cruz and Rossi-Hansberg (2021) develop a dynamic economic assessment model of the world economy with high spatial resolution. Their model features several endogenous climate-adaptation mechanisms absent in our paper. These include costly migration, changes in fertility, alterations in patterns of trade, and impacts on technological change. This aside, our models' structures are very different. In particular, our model includes finite-lived agents, capital, and quite different clean and dirty energy technologies. In addition, we focus on Pareto efficiency rather than social welfare. These differences not withstanding, Cruz and Rossi-Hansberg (2021) estimate local climate damages generally in line with our estimates.

Somewhat connected to our study below, a series of papers in a recent special issue of the Journal of Economic Geography (Peri and Robert-Nicoud, 2021) discussed how climate change yields heterogeneous effects across space, and also points out geographic mobility as one key element of human adaptation (Conte et al., 2021, Castells-Quintana et al., 2020, Indaco et al., 2020, Bosetti et al., 2020, Grimm, 2019). We reserve these important factors for future research.

To summarize, our paper appears to be the first large-scale multi-regional OLG model to explicitly solve the carbon-externality problem as a Pareto improvement. It builds, with major changes, on Kotlikoff et al. (2021), and adds climate change to the Global Gaidar Model (Benzell et al., 2017).

3 Model

We first describe in section 3.1 our model's region-specific representative firm and then, in section 3.2, its households. Section 3.3 considers our climate model. For the detailed calibration of the model presented in this section, we refer to section 4.

3.1 Firms

Firms in each region, z, in each period, t, produce final output, $Y_{z,t}$, with capital, $K_{z,y,t}$, labor, $L_{z,y,t}$, and energy, $E_{z,t}$, according to

$$Y_{z,t} = A_{z,t} K_{z,y,t}^{\alpha_z} L_{z,y,t}^{\beta_z} E_{z,t}^{1-\alpha_z-\beta_z}, \tag{1}$$

where subscript y denotes the use of capital and labor in the final output, α_z and β_z are region specific capital and labor shares in production function. $A_{z,t}$ abbreviates region-specific total factor productivity (TFP).

Profit maximization implies that the following holds:

$$\alpha_z A_{z,t} K_{z,y,t}^{\alpha_z-1} L_{z,y,t}^{\beta_z} E_{z,t}^{1-\alpha_z-\beta_z} = r_t + \delta, \tag{2}$$

$$\beta_z A_{z,t} K_{z,y,t}^{\alpha_z} L_{z,y,t}^{\beta_z-1} E_{z,t}^{1-\alpha_z-\beta_z} = w_{z,t}, \tag{3}$$

and

$$(1 - \alpha_z - \beta_z) A_{z,t} K_{z,y,t}^{\alpha_z} L_{z,y,t}^{\beta_z} E_{z,t}^{-\alpha_z-\beta_z} = p_{z,t}, \tag{4}$$

where r_t is the world interest rate, reflecting our assumption of perfect capital mobility. δ is capital's depreciation rate. $w_{z,t}$ is the region-specific wage at time t, and $p_{z,t}$ is the region-specific price of energy at t. Note that the wage and price of energy are region-specific.

Clean-energy production, $S_{z,t}$, obeys

$$S_{z,t} = B_{z,t} K_{z,s,t}^{\theta} L_{z,s,t}^{\varphi} H_{z,t}^{1-\theta-\varphi}, \tag{5}$$

where $B_{z,t}$, $K_{z,s,t}$, $L_{z,s,t}$, $H_{z,t}$ reference, respectively, the clean energy sector's region- and time-specific productivity level and its demands for capital, labor, and land. The parameters θ and φ are the clean-energy production parameters, subscript s means the use of capital and labor in the clean-energy production.

Profit maximization in the clean-energy sector implies that

$$p_{z,t}^S \theta B_{z,t} K_{z,s,t}^{\theta-1} L_{z,s,t}^{\varphi} H_{z,t}^{1-\theta-\varphi} = r_t + \delta, \tag{6}$$

$$p_{z,t}^S \varphi B_{z,t} K_{z,s,t}^{\theta} L_{z,s,t}^{\varphi-1} H_{z,t}^{1-\theta-\varphi} = w_{z,t}, \tag{7}$$

and

$$p_{z,t}^S (1 - \theta - \varphi) B_{z,t} K_{z,s,t}^{\theta} L_{z,s,t}^{\varphi} H_{z,t}^{-\theta-\varphi} = n_{z,t}, \tag{8}$$

holds, where $n_{z,t}$ is the rental price for land and $p_{z,t}^S$ is the price of clean energy.

Total regional energy consumption satisfies

$$E_{z,t} = S_{z,t} + E_{z,t}^D, \tag{9}$$

where $E_{z,t}^D$ is a dirty energy composite produced via a CES production function, namely

$$E_{z,t}^D = \left(\kappa_{z,o}^{\frac{1}{u}} O_{z,t}^{\frac{u-1}{u}} + \kappa_{z,g}^{\frac{1}{u}} G_{z,t}^{\frac{u-1}{u}} + \kappa_{z,\mathcal{C}}^{\frac{1}{u}} \mathcal{C}_{z,t}^{\frac{u-1}{u}} \right)^{\frac{u}{u-1}}, \tag{10}$$

where $O_{z,t}$, $G_{z,t}$, and $\mathcal{C}_{z,t}$ reference oil, gas and coal consumption, respectively, measured in British thermal units (Btu). The constants κ_O, κ_G, and $\kappa_\mathcal{C}$ represent the shares. The parameter u represents the elasticity of substitution between different dirty energy sources.[11]

Oil, gas, and coal are freely traded on the world market at prices p_t^O, p_t^G and $p_t^\mathcal{C}$. Cost minimization in producing a unit of dirty energy implies the following demands for alternative dirty energies, that is,

$$O_{z,t} = \kappa_{z,O} E_{z,t}^D \left(\frac{p_t^O}{p_{z,t}^D} \right)^{-u}, \tag{11}$$

---

[11]One can question, per Hassler et al. (2012), at least the short-run realism of perfectly clean and dirty energy substitutability. Boeing 747 jets, for instance, cannot yet fly on batteries, although lighter planes can (see, e.g., https://aroundtheworld.solarimpulse.com). However, assuming less than perfectly clean and dirty energy substitutability would mean indefinite use of fossil fuels, which we view as unrealistic. It would also preclude long-run balanced growth, which would undermine our solution method. We plan to incorporate a transition from imperfect to perfect substitutability in future work.

$$G_{z,t} = \kappa_{z,G} E_{z,t}^D \left(\frac{p_t^G}{p_{z,t}^D} \right)^{-u}, \tag{12}$$

$$\mathcal{C}_{z,t} = \kappa_{R,\mathcal{C}} E_{z,t}^D \left(\frac{p_t^{\mathcal{C}}}{p_{z,t}^D} \right)^{-u}, \tag{13}$$

where the price of the dirty energy composite is given by:

$$p_{z,t}^D = \left(\kappa_{z,O} \left(p_t^O \right)^{1-u} + \kappa_{z,G} \left(p_t^G \right)^{1-u} + \kappa_{z,\mathcal{C}} \left(p_t^{\mathcal{C}} \right)^{1-u} \right)^{\frac{1}{1-s}}. \tag{14}$$

Decreasing returns to scale in the clean-energy production sector ensures nonzero production of clean energy regardless of the price of energy. Thus, $S_{z,t} > 0$ holds in equilibrium as well as $p_{z,t} = p_{z,t}^S$. On the other hand, the price of the dirty energy composite, $p_{z,t}^D$, can exceed the price at which energy demand is fully met by clean energy. This eliminates the demand for the dirty energy composite. The following equations capture this outcome and follow from cost minimization and the constraint that dirty-energy consumption is non-negative:

$$p_{z,t} = p_{z,t}^D - \chi_{z,t}, \tag{15}$$

$$\chi_{z,t} E_{z,t}^D = 0, \tag{16}$$

$$E_{z,t}^D \geq 0, \tag{17}$$

and

$$\chi_{z,t} \geq 0. \tag{18}$$

Note that when dirty energy production is zero, its Lagrangian, $\chi_{z,t}$, is positive, indicating, from equation (15), that the cost of producing a unit of dirty energy exceeds the price of producing a unit of clean energy.

Dirty energy producers, indexed by their energy-type, $M \in \{O, G, \mathcal{C}\}$, have finite energy reserves, R_t^M. The costs of extracting these reserves are increasing in the cumulative amounts extracted. We posit the following functional form for the extraction cost of dirty energy of type M per unit of dirty energy extracted:

$$c_t^M(R_t^M) = \left(\xi_1^M + \xi_2^M \left(R_0^M - R_t^M \right) + \left(\frac{1}{R_t^M} \right) \right). \tag{19}$$

Note that the last term in equation (19) ensures that all three extraction costs approach infinity as reserves approach zero.

Dirty energy firms maximize market value, V_t^M, given by

$$V_t^M = \sum_{j=0}^{\infty} \left[\left(p_{t+j}^M - c_{t+j}^M(R_{t+j}^M) - \varrho^M \tau_{t+j} \right) M_{t+j} + \mathcal{T}_t^M \right] \left(\prod_{i=0}^{j} \frac{1}{1 + r_{t+i}} \right), \tag{20}$$

subject to

$$R_t^M = R_{t-1}^M - M_t, \tag{21}$$

9

$$-R_t^M \leq 0, \tag{22}$$

and

$$-M_t \leq 0, \tag{23}$$

where p_t^M is the price of a unit of dirty energy, M_t, at time t, ϱ^M is the amount of CO2 emitted per unit of energy of type M (measured in Btu), τ_t is the absolute tax per unit of CO2 emitted at time t, and $\mathcal{T}_t^M$ is the lump-sum rebate of time-t carbon taxes to type M dirty energy producers.

The dirty-energy Kuhn–Tucker conditions are given by

$$p_t^M - c_t^M(R_t^M) - \varrho^M \tau_t - \ell_t^M + \mu_t^M = 0, \tag{24}$$

and

$$\frac{\partial c_t^M(R_t^M)}{\partial R_t^M} M_t + \ell_t^M - \frac{\ell_{t+1}^M}{1+r_{t+1}} - \psi_t^M = 0, \tag{25}$$

where ℓ_t, ψ_t and μ_t are non-negative Lagrange multipliers for the restrictions in equations (21), (22), and (23), respectively.

The complementary slackness conditions are given by

$$M_t \mu_t^M = 0, \tag{26}$$

and

$$R_t^M \psi_t^M = 0. \tag{27}$$

The value of land, $Q_{z,t}$, equals the present value of future land rents, that is,

$$Q_{z,t} = \sum_{j=0}^{\infty} n_{z,t+j} H_{z,t+j} \left(\prod_{i=0}^{j} \frac{1}{1+r_{t+i}} \right). \tag{28}$$

3.2 Households

Agents enter the labor force at the age of 20 and face annual idiosyncratic mortality risk through age 100, that is, their maximum age of life. Mortality risk, which we take to be region- and year-specific, is assumed to be fully hedged via an actuarially fair annuities market.[12] Region- and year-specific mortality probabilities are inferred from United Nations demographic projections (see United Nations (2019a) and United Nations (2019b)).

Agents born in region z in year t maximize

$$U_{z,t} = \sum_{j=1}^{80} P_{z,t+j-1,j} \frac{1}{(1+\rho)^j} \frac{C_{z,t+j-1,j}^{1-\sigma} - 1}{1-\sigma}, \tag{29}$$

subject to

$$a_{z,t+1,j+1} = (1+r_t)a_{z,t,j} + w_{z,t}l_{z,t,j}P_{z,t,j} + \mathbb{T}_{z,t,j} - P_{z,t,j}C_{z,t,j}, \tag{30}$$

---

[12]This precludes needing to model bequests and inheritances.

where $C_{z,t,j}$, $l_{z,t,j}$, $P_{z,t,j}$, and $a_{z,t,j}$ reference, respectively, consumption, labor supply, population size, and asset level of those born in region z at time t who are currently age j. The term $\mathbb{T}_{z,t,j}$ references net transfers received at age j by the generation born at t in region z. Finally, ρ is the time preference rate and σ is the coefficient of relative risk aversion.

Total household assets comprise physical capital, the value of dirty energy firms, the value of land, and carbon-policy debt, that is,

$$\sum_{z=1}^{18}\sum_{j=1}^{80} a_{z,t,j} = K_t + V_t^O + V_t^G + V_t^C + \sum_{z=1}^{18} Q_{t,j} + \mathcal{D}_t, \tag{31}$$

where $\mathcal{D}_t$ is debt. The debt evolves according to

$$\mathcal{D}_{t+1} = (1 + r_t)\mathcal{D}_t + \sum_{z=1}^{18}\sum_{j=1}^{80} \mathbb{T}_{z,t,j}. \tag{32}$$

The world supplies of capital equal the sum of sectoral and regional demands, that is,

$$K_t = \sum_{z=1}^{18} K_{z,y,t} + \sum_{z=1}^{18} K_{z,s,t}. \tag{33}$$

Finally, regional supplies of labor equal the sum of their sectoral demands:

$$L_{z,t} \equiv \sum_{j=1}^{80} P_{z,t,j} l_{z,t,j} = L_{z,y,t} + L_{z,s,t}. \tag{34}$$

3.3 Modeling Climate Change's Negative Externality

To describe the evolution of the climate in our multi-region OLG model, we follow the functional form of DICE-2016 (Nordhaus, 2017), but use a parameterization proposed by Folini et al. (2021).[13] DICE-2016 models the carbon cycle via three carbon reservoirs – the atmosphere (A), the upper ocean (U), and the lower ocean (L). The DICE-2016 process by which output increases carbon concentration in the atmosphere is given by the following expression:

$$\begin{pmatrix} J_t^A \\ J_t^U \\ J_t^L \end{pmatrix} = \Phi^J \begin{pmatrix} J_{t-1}^A \\ J_{t-1}^U \\ J_{t-1}^L \end{pmatrix} + \begin{pmatrix} \varrho^O O_t + \varrho^G G_t + \varrho^C C_t + E_t^{Land} \\ 0 \\ 0 \end{pmatrix}, \tag{35}$$

where J_t^A, J_t^U, J_t^L are the CO_2 concentrations in the atmosphere (A), the upper ocean (U), and the lower ocean (L). Φ^J is a 3 by 3 matrix of parameters that describes the mass transfer across the three reservoirs, and that has units "mass fraction per time step". E_t^{Land} is the land-based carbon emission, which obeys the following relationship:

$$E_t^{Land} = E_0^{Land} e^{-\delta^{Land} t}, \tag{36}$$

---

[13]The parameters governing carbon concentration are provided in section 4.

where δ^{Land} is our assumed declination rate of land-based emissions decline. CO_2 in the atmosphere impacts radiative forcing, F_t, according to

$$F_t = \eta_1 \frac{\log \frac{J_t^A}{J^0}}{\log(2)} + F_t^{EX}, \tag{37}$$

where J^0 is the pre-industrial concentration of carbon in the atmosphere. F_t^{EX} references time-t radiative forcing, which evolves as

$$F_t^{EX} = F_0^{EX} + \frac{1}{T'}(F_1^{EX} - F_0^{EX}) \min(t, T'), \tag{38}$$

where F_0^{EX} and F_1^{EX} are the exogenous radiative forcing in the initial period and in the year 2100, respectively. T' references years between the initial period and 2100.

In DICE-2016, the evolution of the temperature is formally given by a two-layer energy balance model, that is,

$$\begin{pmatrix} T_t^A \\ T_t^L \end{pmatrix} = \Phi^T \begin{pmatrix} T_{t-1}^A \\ T_{t-1}^L \end{pmatrix} + \begin{pmatrix} \eta_2 F_t \\ 0 \end{pmatrix}, \tag{39}$$

which formally corresponds to the evolution described in Geoffroy et al. (2013). In equation (39), T_t^A and T_t^L denote the global mean temperature change with respect to pre-industrial times of the upper layer (atmosphere and upper ocean) as well as the lower layer (deep ocean), respectively, at time step t. From a physics perspective, the free parameters in equation (39), including the matrix Φ^T, may be interpreted as a heat exchange coefficient between the upper and lower layer, the effective heat capacities of the upper and lower layer, and the ratio of the forcing from a doubling of CO2 to the associated temperature change.

Our model requires knowledge of regional climate damages and, thus, the regional temperatures. We compute the regional temperatures from the global temperature by adopting a popular technique from climate sciences called "pattern scaling" (see, e.g., Tebaldi and Arblaster (2014), Lynch et al. (2017), Kravitz et al. (2017), and references therein). Pattern scaling, first introduced by Santer et al. (1990), is a statistical method that, based on large-scale Earth system models, relates, for instance, the global average temperature, T_t^A, in a computationally efficient fashion to local temperatures at resolutions as fine as about 1° longitude ×1° latitude.

Our computations use the publicly available pattern scaling repository by Lynch et al. (2017).[14] Specifically, we use the CCSM4 model that follows the RCP8.5 for all our computations. This choice minimizes our model's interpolation error in ascribing the temperature to

---

[14]The respective data sets and codes can be found under the following URL: `https://github.com/JGCRI/CMIP5_patterns`. The function that relates the global average temperature to a local one is determined by using (sometimes pooled) calculations of dozens of large-scale climate models developed by climate scientists across the world. Their calculations are organized by CMIP5 (Taylor et al., 2012) – the Coupled Model Intercomparison Project Phase 5, which collects climate-model calculations for specific greenhouse gas scenarios called representative concentration pathways (RCP). The four primary RCP scenarios are denoted as RCP2.6, RCP4.5, RCP6, and RCP8.5. Each RCP scenario generates particular paths of greenhouse gases, aerosols, and other climatically relevant forcing agents over the 21st century. The RCP8.5 scenario, for instance, reflects a "no policy" narrative, in which total anthropogenic forcing reaches approximately $8.5W/m^2$ in the year 2100. Conversely, the RCP2.6 scenario involves aggressive decarbonization, causing radiative forcing to peak at approximately $3W/m^2$ around 2050 and to decline to approximately $2.6W/m^2$ at the end of the 21st century. For the exact specifications of the RCP scenarios and the related data, see Meinshausen et al. (2011), and `http://www.pik-potsdam.de/~mmalte/rcps/`.

the 1° longitude ×1° the latitude grid we are using to map the global to a local temperature. Our results appear robust to the choice of RCP scenarios in connecting the global average temperature to grid-specific and, thus, region-specific temperature (Link et al., 2019).

In forming regional average surface temperatures $T_{z,t}$ in our multi-regional OLG models below, we apply pattern scaling as follows. First, we compute T_t^A. Second, we derive local temperatures on a 1° by 1° grid, each of which belongs to a certain region of our model. Third, we use cell-specific GDP values to weigh cell-specific temperature values to produce our regional GDP-weighted average temperatures.[15]

We model the regional TFP, $A_{z,t}$, as the product of an exogenous trend, $\tilde{A}_{z,t}$, and a regional function, $Z_{z,t}$. $\tilde{A}_{z,t}$ grows at a time-varying, region-specific growth rate $g_{z,t}$, that is,

$$\frac{\tilde{A}_{z,t}}{\tilde{A}_{z,t-1}} = 1 + g_{z,t}. \tag{40}$$

Following Krusell and Smith Jr (2018), we assume that the component $Z_{z,t}$ obeys

$$Z_{z,t} = \begin{cases} 0.02 + 0.98e^{(-\upsilon^+(T_{z,t}-T^*)^2)} & \text{if } T_{z,t} > T^*, \\ 0.02 + 0.98e^{(-\upsilon^-(T_{z,t}-T^*)^2)} & \text{if } T_{z,t} \leq T^*. \end{cases} \tag{41}$$

Next, we define the regional climate damages as:

$$D_{z,t} = 1 - Z_{z,t}/Z_{z,1900}. \tag{42}$$

Equation (41) models the regional TFP as peaking at T^* (cf. Krusell and Smith Jr (2018)). Thus, cold regions with temperatures below T^* will benefit from global warming as their temperature approaches T^*. Similarly, hot regions will be harmed as their temperature moves farther away from T^*. Larger values of υ^+ and υ^- raise the cost of a given deviation from the optimal temperature. In our calibration below (cf. section 4), we choose υ^+ to relate regional damage functions to global damage functions used in the literature.[16]

4 Calibration

Our 18 region OLG model builds on the 17-region Global Gaidar Model (GGM; cf. Benzell et al. (2017)) but adds climate change and an extra region.[17] Table 1 provides a list of the regions and their acronyms, whereas figure 1 displays them on a map of the globe.

Throughout our computations, we will use the year 2017 as the baseline for our calibration. The World Bank's Development Indicators (WDI) is a main data source, providing, in

---

[15]Note that we leverage Nordhaus' G-Econ database to construct the GDP-weighted regional temperature patterns (see `https://gecon.yale.edu`, GEcon 4.0 of the year 2005). This weighting step ensures that the location of human activity dominates the average temperature within a region. In a model region such as Canada (cf. Table 1 below), the GDP-weighted average temperature is concentrated in regions close to the border of the US, whereas the naive average would be driven by cells closer to the North pole.

[16]The notion that some regions might gain from climate change is controversial given the potential for tipping points causing catastrophic global climate events. However, our certainty-equivalent approach requires incorporating climate change gains as well as losses.

[17]In particular, the GGM's single region consisting of Canada, Australia and New Zealand is divided here into two – Canada by itself, and Australia plus New Zealand.

Table 1: Regions in the model and their acronyms.

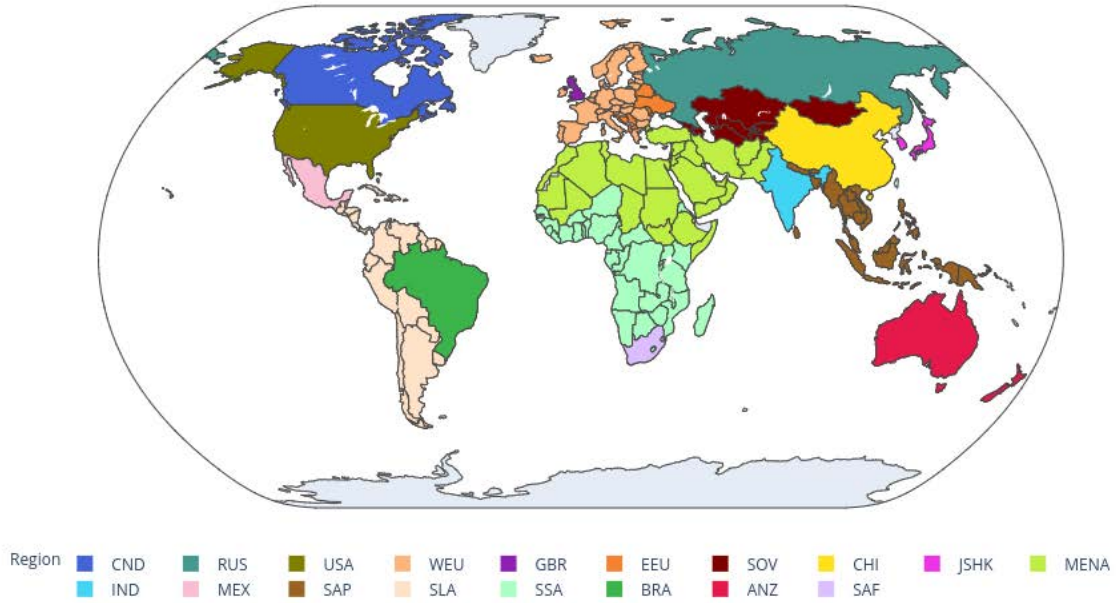| Acronym	Region (Excludes Countries Modeled Independently)
ANZ	Australia and New Zealand
BRA	Brazil
CND	Canada
CHI	China
EEU	Eastern Europe
GBR	The U.K.
IND	India
JSHK	Japan, South Korea, and Hong Kong
MENA	Middle East and North Africa
MEX	Mexico
RUS	Russian Federation
SAF	South Africa
SAP	South Asia Pacific
SLA	Latin America excluding Mexico and Brazil
SOV	Former Soviet Central Asia
SSA	Sub-Saharan Africa
US	USA
WEU	Western Europe

Figure 1: The 18 Regions of our model on a world map.

particular, 2017 GDP values. These are used to calibrate 2017 levels of regional TFP. Energy consumption/usage data come from the US Energy Information Administration (EIA). These EIA data are available in four categories: 1) coal, 2) natural gas, 3) petroleum and other

Table 2: 2017 GDP (in trillions of 2017 USD) and energy consumption (in quad Btus).

	GDP (Y)	Coal ($\mathcal{C}$)	Natural gas (G)	Petroleum and other liquids (O)	Nuclear, renewables, and other (S)
ANZ	1.53	1.77	1.82	2.74	0.67
BRA	2.06	0.67	1.28	6.05	4.58
CND	1.65	0.69	4.61	4.91	4.85
CHI	12.14	88.42	8.81	24.91	17.30
EEU	0.26	1.57	1.92	1.06	1.21
GBR	2.67	0.38	2.97	3.26	1.61
IND	2.65	16.62	2.09	8.96	2.81
JSHK	7.07	8.65	7.27	17.32	3.66
MENA	4.22	2.27	26.08	24.45	1.99
MEX	1.16	0.48	2.86	3.97	0.60
RUS	1.58	4.93	16.94	7.29	3.67
SAF	0.35	3.98	0.19	1.27	0.24
SAP	2.50	4.23	5.92	8.92	1.27
SLA	2.09	0.63	4.55	6.96	3.29
SOV	0.36	2.67	4.13	1.47	0.59
SSA	1.00	0.17	1.13	2.70	0.83
US	19.49	13.84	28.06	37.57	18.28
WEU	15.94	9.14	14.64	25.48	17.19

liquids, 4) nuclear, renewables, and others. All data is measured in Btus. We treat these energy categories as coal, gas, oil, and clean energy. Table 2 presents region-specific GDP and energy-consumption data.

The EIA data allows us to calibrate the region-specific CES production functions specified in equation (10). As in Hillebrand and Hillebrand (2020), we assume an elasticity of substitution between oil, coal, and gas of $u = 2$. This value lies between Acemoglu et al. (2012)'s (higher) and Golosov et al. (2014)'s (lower) assumed values. We measure the shares parameters κ_O, κ_G, and $\kappa_{\mathcal{C}}$ using data on 2017 world energy prices. Taking the 2017 $50.8 price per barrel of the West Texas Intermediate crude, and assuming that the one barrel of oil contains $5.7 \cdot 10^6$ Btus, our 2018 price of oil equals $8.9 \cdot 10^{-6}$ per Btu. Analogous calculations produce a 2017 price of gas of $5.7 \cdot 10^{-6}$ per Btu and a price of coal of $4.5 \cdot 10^{-6}$ per Btu. Normalizing the sum of κ_O, κ_G, and $\kappa_{\mathcal{C}}$ to 1, and using equations (11)-(13) provides our region-specific, dirty-energy share parameters. These coefficients are then used to construct the price of the dirty energy composite per equation (14). This determines the 2017 price of clean energy as well as the levels of the 2017 dirty energy consumption by region.

The ratio of each region's total energy consumption as a share of its GDP provides our measure of $1 - \alpha_z - \beta_z$. To pin down the different values for α_z and β_z, we assume that one-third of this remaining output share is paid to capital, with the rest paid to labor.

Table 3 contains the regional dependence of production on energy, in general, and on particular energy sources. The table shows remarkable differences across regions in energy reliance – from 2.25 percent of GDP in Great Britain to 14.67 percent in SOV – former Soviet states in Asia. Table 2 also contains our calculated 2017 region-specific GDP and consumption levels of the three dirty energies. The major users of fossil fuels are China, at 122.14 quad Btus, the US at 80.01 quad Btus, and Western Europe at 49.26. Even though China's 2017 GDP is less than two-thirds that of the US and only three-fourths that of the WEU, its carbon emissions

Table 3: Energy consumption as a share of GDP.

	Coal ($\mathcal{C}$)	Natural gas (G)	Petroleum and other liquids (O)	Nuclear, renewables, and other (S)	Total
ANZ	0.52%	0.68%	1.59%	0.32%	3.12%
BRA	0.15%	0.36%	2.61%	1.85%	4.97%
CND	0.19%	1.61%	2.65%	2.23%	6.68%
CHI	3.28%	0.42%	1.83%	0.86%	6.39%
EEU	2.76%	4.31%	3.67%	3.08%	13.81%
GBR	0.06%	0.64%	1.09%	0.46%	2.25%
IND	2.83%	0.45%	3.01%	0.71%	6.99%
JSHK	0.55%	0.59%	2.18%	0.39%	3.72%
MENA	0.24%	3.55%	5.16%	0.35%	9.31%
MEX	0.19%	1.42%	3.05%	0.40%	5.06%
RUS	1.41%	6.16%	4.11%	1.56%	13.24%
SAF	5.13%	0.31%	3.23%	0.43%	9.10%
SAP	0.76%	1.36%	3.17%	0.39%	5.67%
SLA	0.14%	1.25%	2.96%	1.23%	5.58%
SOV	3.36%	6.61%	3.66%	1.04%	14.67%
SSA	0.08%	0.65%	2.41%	0.68%	3.81%
US	0.32%	0.83%	1.72%	0.70%	3.57%
WEU	0.26%	0.53%	1.42%	0.82%	3.03%

are twice that of the US and three times that of the WEU. This reflects its overwhelming dependence on coal, which arises from its higher calibrated value of $\kappa_{\mathcal{C}}$. Indeed, the Chinese value of $\kappa_{\mathcal{C}}$ is almost seven times that of the US. However, the US is a better green citizen than China but pales in comparison with the WEU. The US GDP is one-fifth larger than the one of WEU. However, its emissions are three-fifths larger. Table 4 shows GDP, energy consumption, and CO2 emissions relative to the USA (note that the US values are normalized to 100).

We adopt θ and φ, the clean-energy production parameters specified in equation (5), from Kotlikoff et al. (2021). In particular, we assume that 60 percent of clean energy output is paid to land, and the rest is distributed between labor and capital in the same proportion as in the final goods sector. In calibrating TFP levels in the final goods and clean energy production sectors, we assume a 10 percent annual capital depreciation rate and a 4 percent base-year global interest rate. This implies a 14 percent rental rate on capital. With this rental price, data on regional labor endowments, calculated values of output, and the levels of clean and dirty energy consumption, we compute regional capital demands and TFP values in both sectors using equations (1)-(7). This delivers a 2017 value of world capital equal to $178 trillion.[18]

To calibrate region-specific productivity growth in final goods production, we rely on univariate, country-specific regressions graciously estimated by Müller et al. (2019). First, we aggregated the country estimates to generate regional productivity growth rates. These rates, through 2100, measured relative to the US productivity growth rate, are shown in the table 5. After 2100, we assume productivity growth in all regions equals the assumed fixed 1.56 percent US growth rate. As for productivity growth in clean energy, we set it to generate a 0.5 percent per year decline in the energy price.

---

[18]This amount is based on the world GDP estimated by the World Bank, region-specific capital shares governing the production of the final output, the assumed initial global rental price of capital, and the region-specific production of clean energy.

Table 4: 2017 Index of GDP, energy consumption, and CO2 emissions relative to US.

	GDP index	Energy consumption index	CO2 emission index
ANZ	7.85	7.16	8.41
BRA	10.57	12.87	10.28
CND	8.47	15.41	12.01
CHI	62.29	142.65	195.75
EEU	1.33	5.89	5.96
GBR	13.70	8.41	7.75
IND	13.60	31.18	42.79
JSHK	36.28	37.75	44.67
MENA	21.65	56.05	60.74
MEX	5.95	8.09	8.75
RUS	8.11	33.59	34.30
SAF	1.80	5.81	8.81
SAP	12.83	20.81	24.69
SLA	10.72	15.79	14.52
SOV	1.85	9.06	10.53
SSA	5.13	4.94	4.90
US	100.00	100.00	100.00
WEU	81.79	67.98	63.20

Table 5: Convergence of non-US regions' productivity relative to US productivity.

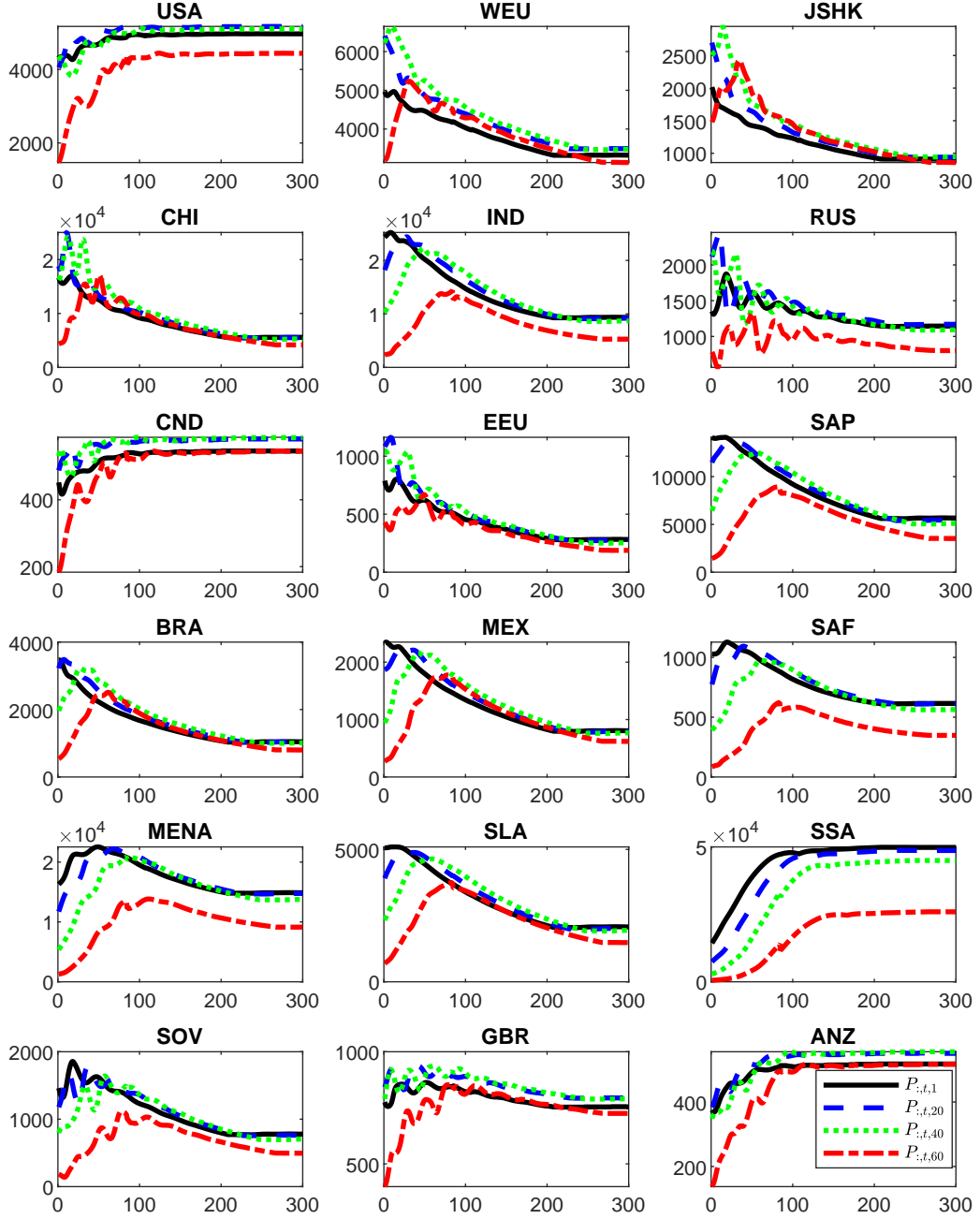| ANZ	BRA	CND	CHI	EEU	GBR	IND	JSHK	MENA
-0.11%	0.27%	-0.08%	2.54%	0.09%	0.04%	1.99%	1.92%	0.05%
MEX	RUS	SAF	SAP	SLA	SOV	SSA	WEU	
-0.64%	-0.06%	-0.20%	1.09%	-0.67%	0.87%	-0.73%	0.76%	

Figure 2: Projected population counts (in millions) of specified age-groups as a function of years (starting in the year 2017).

We use United Nations population projections (United Nations (2019b)) to calibrate population dynamics. These data account for fertility, mortality, and migration. Figure 2 charts projected population counts of specified age groups. As indicated, in some regions, there are pronounced demographic waves, in particular for Russia. The initial distribution of assets between generations and regions is taken from Benzell et al. (2017). The time preference rate, ρ, is calibrated to 1.45 percent per year. Furthermore, the coefficient of relative risk aversion, σ, is calibrated to 1.45.

Based on McGlade and Ekins (2015), we calibrate the globally available oil reserves to 600 GtC, global available gas reserves to 400 GtC, and global available coal reserves to 2700 GtC. We assume CO2 emissions of 97.5 kg per million Btu of coal, 72.6 kg per million Btu of oil, and 53.1 kg per million Btu of natural gas, which helps to calibrate ϱ^M.[19] In calibrating our extraction cost parameters, we assume that the extraction costs double when the available reserves decline by half. This assumption links ξ_2^M with ξ_1^M in equation (19). Then, we solve for the values of ξ_1^M that reproduce the 2017 energy prices under BAU.

The parameters for the climate block of the DICE model are adopted from Folini et al. (2021).[20] We therefore assume that 2017 land emissions, E_t^{Land}, equal 0.709 GtC, and that annual rate of reduction in land emissions, δ^{Land}, equals 0.023. Radiative forcing in 2017 and 2100, F_0^{EX} and F_1^{EX}, are set to 0.5 and 1, respectively. The radiative-forcing sensitivity parameter, η_1, is set to 3.45. The parameter determining how global mean surface temperature responds to radiative forcing, η_2, is set at 0.137. Initial values for climate variables are calibrated as $J_0^A = 3116$ GtCO2, $J_0^U = 2804$ GtCO2, $J_0^L = 6596$ GtCO2, $T_t^A = 1.278$ Celsius change since 1900, and $T_t^L = 0.313$ Celsius change since 1900. The equilibrium concentration in the atmosphere, J^0, is set to 607 GtC.

Following Folini et al. (2021), the parameter matrices Φ^J and Φ^T are chosen as:

$$\Phi^J = \begin{pmatrix} 0.947 & 0.0536 & 0 \\ 0.053 & 0.9422 & 0.0014 \\ 0 & 0.0042 & 0.9986 \end{pmatrix}, \Phi^T = \begin{pmatrix} 0.7546 & 0.1 \\ 0.0069 & 0.9931 \end{pmatrix}. \tag{43}$$

As for regional damages, we follow Krusell and Smith Jr (2018) in setting $T^* = 11.6$ in equation (41). In our most optimistic calibration we set $\upsilon^+ = \upsilon^- = 0.001$. Recall, these are damages sensitivity parameters arising from the regional temperature in equation (41). With this calibration, global damages in DICE-2016 correspond closely, as shown in figure 3, to those generated based on our variant of the "Krusell-Smith" damage function (Krusell and Smith Jr, 2018). However, this scenario seems overly optimistic along two dimensions. First, our climate calibration uses the multi-model mean from CMIP5 as a target. However, CMIP5 produces a large range of predictions, and the more pessimistic ones entail much higher temperatures (see Folini et al. (2021)). Moreover, the Krusell-Smith calibration for global damages takes DICE-16 as a benchmark. As Nordhaus (2008) points out, *"the economic impact of climate change ... is the thorniest issue in climate-change economics"*. This is a major and very important theme of Pindyck (2013). Howard and Sterner (2017) conducts a meta-analysis of different global

---

[19]See `https://www.eia.gov/tools/faqs/faq.php?id=73&t=11` for more details.

[20]Dietz et al. (2021), among others, criticize the climate emulators commonly used in economics, including Nordhaus' widely used DICE-2016 model (Nordhaus, 2017). A key functionality that any climate emulator needs to possess is to translate anthropogenic emissions, as computed by the economic model, into a global mean temperature change. The said emulators typically consist of two parts: The first is a "carbon cycle" that describes how anthropogenic emissions in the wake of human economic activity translate into changes in the CO2 concentration in the atmosphere. The second is a temperature model that determines how the CO2 concentration in the atmosphere translates into an average temperature. The latter, in turn, feeds back again into the economic model. The climate emulator of DICE-2016 (cf. section 3.3) in its original formulation, however, is not capable of doing this translation according to state-of-the-art physics, i.e., the CMIP5 benchmark data. Folini et al. (2021) propose a suite of test cases that allow for a thorough re-calibration of the free DICE-2016 parameters to bring it in line with the latest climate science. Compared to the original DICE-2016 model, this leads to less long-term warming because of changes in the carbon cycle.
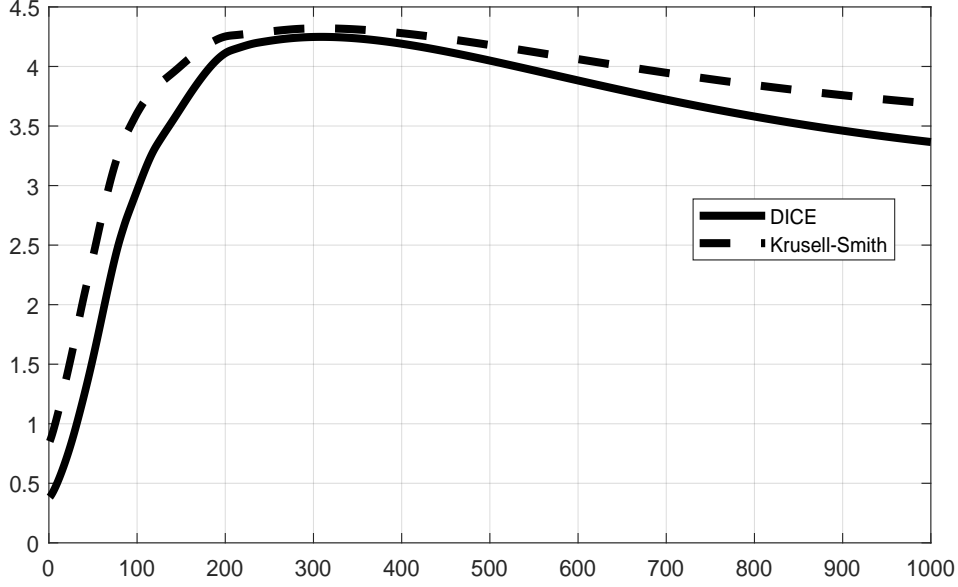
Figure 3: Comparing the "DICE-2016" and "Krusell-Smith"(cf. equation (42)) global damages as share of global GDP (measured in %) by year (starting 2017).

damage functions and argue that damages might be much larger than in DICE-2016. Since in our model damages depend only on the product of the parameter υ and $T_z - T^*$, the regional temperatures in excess of T^*, we vary the parameter κ to jointly capture different damage functions and degrees of climate sensitivity.

We consider cases with $\upsilon^+ = 2\upsilon^*$, $\upsilon^+ = 4\upsilon^*$, $\upsilon^+ = 6\upsilon^*$, where $\upsilon^* = 0.001$ corresponds to the value in the most optimistic calibration. We label these as our 2x, 4x, and 6x cases/scenarios, and call them sometimes also "low", "medium", and "high" damage scenarios. In all cases, υ^- remains fixed at υ^*. Figure 4 depicts the "Krusell-Smith" productivity function (see equation (41)). Note that only the right side of the productivity function shifts. In short, we allow for higher damages in regions that incur losses from global warming. At the same time, we assume only moderate gains for regions that incur gains from global warming.

5 Results

Next, we present in section 5.1 our baseline results for both BAU and under optimal UWI carbon policy, assuming all regions fully cooperate in effecting the policy. Section 5.2 examines whether carbon-tax policy matters for the evolution of global economic power. Finally, sections 5.3 and 5.4 discuss how outcomes differ if global participation does not materialize, leaving single regions or subsets of regions to implement their own UWI carbon policies.

5.1 Baseline Results – Global Participation in UWI Carbon Policy

Figure 5 compares the global CO2 emissions for our 6x BAU scenario over the next 200 years with the emissions leading to the four RCPs adopted by the Intergovernmental Panel on Climate
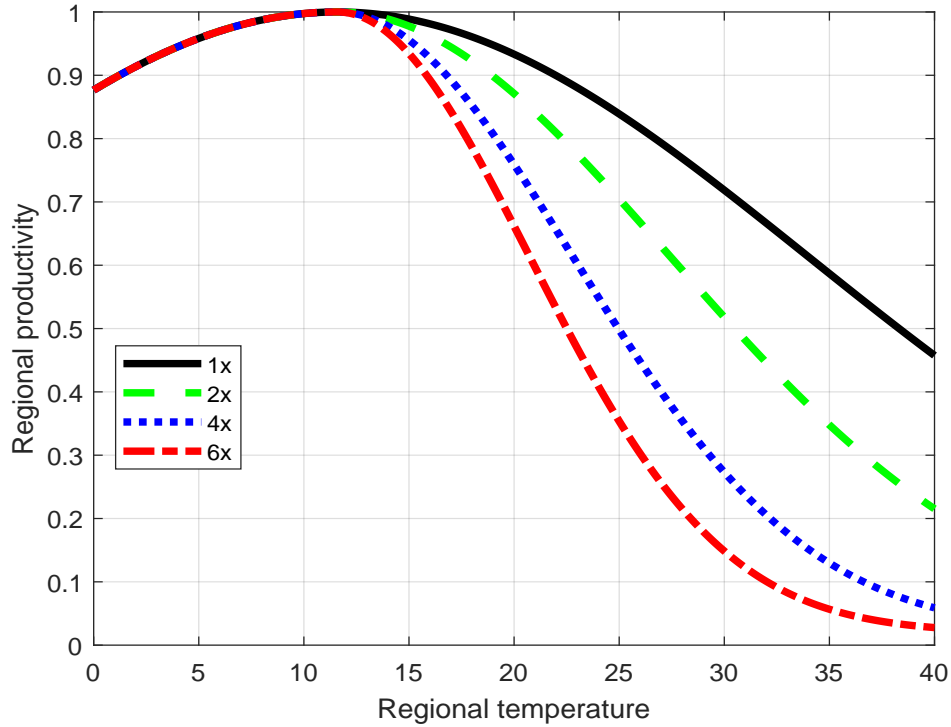
Figure 4: Alternative calibrations of the "Krusell-Smith" -type productivity functions as a function of temperature, measured in °C.

Change (IPCC)[21] and the emissions in DICE-2016. As figure 5 shows, our BAU emissions are significantly lower than in DICE-2016 or in RCP8.5, respectively. The emissions scenario used to generate RCP8.5 was constructed to be a "worst-case" scenario and has recently come under criticism by a number of researchers for its prediction of a dramatic expansion of coal use. Hausfather and Peters (2020) for instance argue that "*RCP8.5 was intended to explore an unlikely high-risk future*". In this light, the RCP6 scenario seems more relevant for forecasting emissions in a world without policy. Our baseline BAU emissions path lies between the RCP6 and RCP4.5 scenarios. Ours is, thus, a relatively optimistic path of emissions. On the other hand, our baseline damages are quite high, particularly for severely impacted regions.

Table 6 displays key BAU and optimal UWI carbon-policy results for our alternative damage functions. The table conveys six important messages. First, under BAU, the global average temperature rises from roughly 3.5 to 4.5 degrees Celsius regardless of which damage scenario is considered. Second, global damages can be very high. In the 6x scenario, on which we focus on certainty-equivalent grounds, damages peak at 17 percent of global GDP. Third, particular regions can suffer extreme damage. In the 6x BAU transition, India's peak loss is 43.82 percent of GDP. Forth, higher BAU damages can, paradoxically, limit global warming by reducing output and, thereby, reducing emissions. Indeed, peak BAU temperature falls as we consider worse damage functions. Fifth, the extent of global damages is highly sensitive to the shape of the upper tail of the damage function. In the 6x case, peak global and regional damages are almost four times larger than with the 1x parameterization. The close to 20 percent global peak GDP

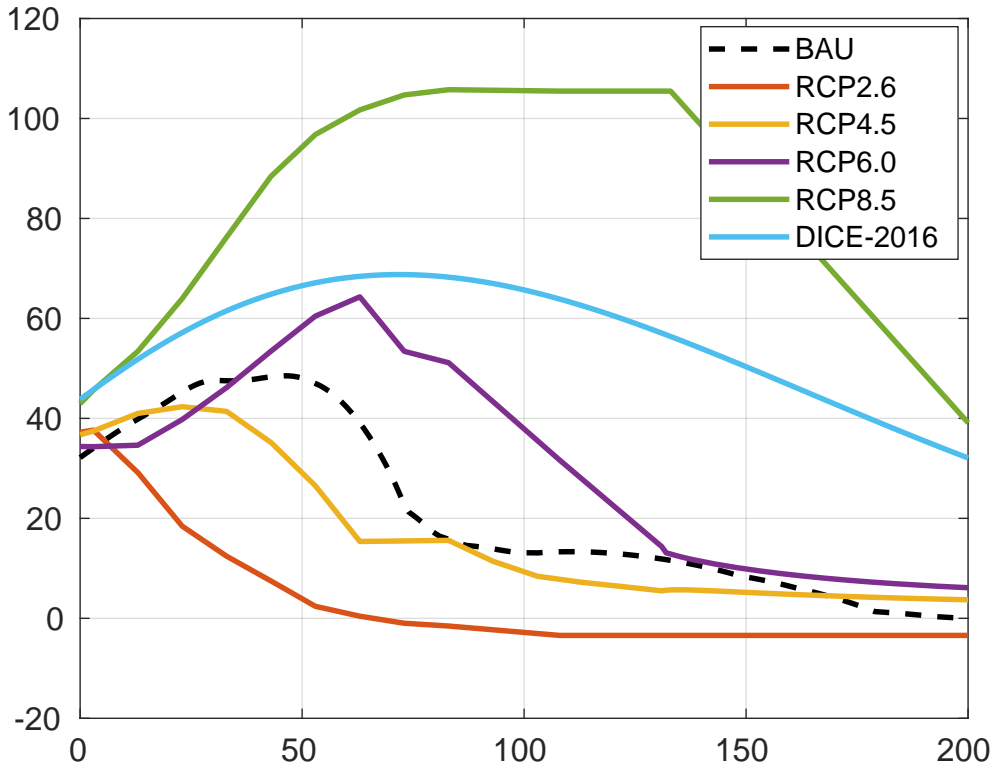[21]For more details on the IPCC, see `ipcc.ch`.

Figure 5: Global CO2 emissions (in GtCO2) in DICE 2016, and our BAU scenario, as a function of years (starting in 2017).

Table 6: Key simulation results.

Damage case	1x	2x	4x	6x
Max. BAU global temperature, degree Celsius	4.41	4.22	3.89	3.65
Max. BAU global damages, percent of global GDP	4.42	7.91	12.99	16.66
Max. BAU regional damages, percent of regional GDP	11.82	21.12	34.64	43.92
BAU Long-run interest rate, percent per year	2.94	2.93	2.91	2.90
Initial UWI optimal tax, $ per ton of CO2	21	45	74	97
Growth rate of UWI optimal tax, percent per year	2	1.5	1.5	1.5
UWI Welfare gains, percent	0.58	1.40	2.98	4.35
Max. UWI global temperature, degree Celsius	2.86	2.53	2.22	2.10
Max. UWI global damages, percent of global GDP	2.54	4.26	6.88	9.12
Max. UWI regional damages, percent of regional GDP	7.47	12.64	20.67	27.31
UWI Long-run interest rate, percent per year	3.36	3.67	4.05	4.25

loss is, in this 6x case, well within recent projections of climate damages. For example, Hänsel et al. (2020) strongly criticizes the DICE-2016 damage function, advocating more realistic specifications that lead to much larger damages for a 3 degree Celsius or larger increase in temperature. Finally, climate change under BAU has little impact on the global economy's capital intensity and, thus, the global interest rate, regardless of the damage it causes.

The remaining rows of table 6 consider optimal UWI taxation, delivering seven key messages.

First, the optimal initial carbon tax is highly sensitive to the damage function, ranging from 21 per ton of CO_2 to 97 per ton of CO_2 for the low to the high damage specification. Second, the optimal carbon-tax growth rate is 1.5 percent for all but the 2x scenario. But for the 2x function, the UWI with a 2.0 percent growth-rate optimum differs little from the UWI with a 1.5 percent growth, meaning that the function is fairly flat at the optimum. Thus, a 1.5 percent real growth appears to be the best or close to the best growth rate for our range of damage specifications. In our global (single-region) OLG model (see Kotlikoff et al. (2021)), a 1.5 percent real growth rate also proved to be UWI optimal or essentially optimal. Third, as expected, the UWI gains are higher with larger damages. In the 6x case, the gains are 4.35 percent. Since the gains are consumption equivalents, a 4.35 percent UWI is equivalent to not taxing carbon rather, instead, providing every current and future member of the planet 4.35 percent more consumption in each year of their BAU lives. As efficiency gains go, this is remarkably large but not surprising given the size of the model's 6x carbon externality. Higher damage specifications would, of course, spell even higher UWI gains.Fourth, optimal UWI taxation limits the maximum increase in global temperature to 2.10 degrees Celsius rather than 3.65 degrees Celsius under BAU. Fifth, increasing damages sensitivity sharply alters equilibrium global temperature dynamics. For example, the maximum global temperature decreases from 4.41 degrees Celsius in the 1x case to 3.65 degrees Celsius in the 6x case. This reflects reduced production due to the higher damages, which, in turn, limits emissions and, thereby, the rise in temperature. Thus, climate change embeds a partially self-correcting mechanism. Sixth, the optimal UWI tax reduces peak global climate damages by almost one-half and peak regional damages by roughly 40 percent. Finally, compensating early generations crowds out capital, raising the world interest rate by, in the high damage cases, more than 100 basis points.

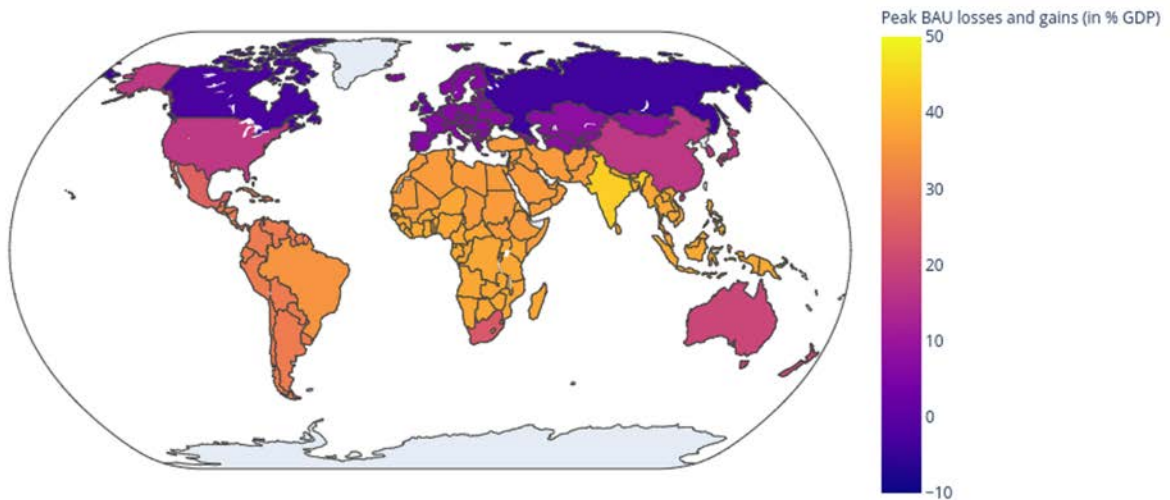Table 7 and figure 6 report peak BAU losses and gains by region.

Figure 6: Regional BAU losses and gains as percentage of GDP in the 6x case.

Table 7: Peak BAU losses (positive sign) and gains (negative sign) as percentage of GDP.

	1x	2x	4x	6x
US	4.02	7.39	12.77	17.09
WEU	1.61	2.92	4.93	6.49
JSHK	3.86	7.13	12.40	16.68
CHI	4.02	7.38	12.71	16.98
IND	11.82	21.12	34.64	43.92
RUS	-4.12	-4.08	-3.98	-3.88
CND	-2.66	-2.66	-2.65	-2.61
EEU	1.76	3.18	5.29	6.88
SAP	9.93	17.92	29.85	38.27
BRA	8.64	15.70	26.56	34.73
MEX	6.09	11.15	19.16	25.47
SAF	5.67	10.37	17.82	23.70
MENA	9.06	16.39	27.58	35.98
SLA	7.42	13.56	23.17	30.60
SSA	9.67	17.48	29.27	37.86
SOV	1.97	3.55	5.88	7.60
GBR	0.53	0.97	1.60	2.05
ANZ	4.64	8.56	14.86	19.94
GLOBAL	4.42	7.91	12.99	16.66

Figures 7-13 show the paths of 6 key outcomes under the 6x scenario. Figure 7 shows how regional temperatures evolve in the 6x case under BAU (in black) and 6x optimal UWI policy (in red). Climate change raises temperatures across the globe, including in RUS, CND, and SOV, which see their temperatures increase by 2.8, 2.7, and 2.4 degrees, respectively. Figure 8 shows the extremely heterogeneous nature of climate damages, from very large in India to negative in Russia and Canada. India suffers the most from climate change, with climate damages reaching close to half of GDP by 2200 and remaining there for more than a century. For the US, China, and Japan, damages in the year 2180 exceed 16 percent of output, also remaining at least that high for more than 100 years. The smallest positive damages arise in the UK, peaking at just 2 percent of GDP. Russia and Canada's climate gains peak above 2.5 percent of GDP and reach almost 4 percent of GDP, respectively. ANZ, SSA, SLA, SAF, MEX, BRA, MENA, and SAP also experience very high damages. The red, optimal 6x UWI carbon-tax damage curves lie below the black BAU curves for all regions but CND and RUS. The different heights of the two curves show that carbon taxation can dramatically reduce regional carbon damage.

Figures 9-11 show in particular that under BAU, the different regions stop using dirty energy at very different points of time. China, for instance, under optimal 6x policy, essentially ends its use of coal, eliminating its emissions within 20 years rather than within roughly 75 years in the BAU scenario. Russia, as another example, stops emitting carbon roughly 80 years earlier than in BAU due to carbon policy. The very quick substitution of clean energy, gas, and oil for coal may seem unrealistic. However, such substitution is arguably already underway in
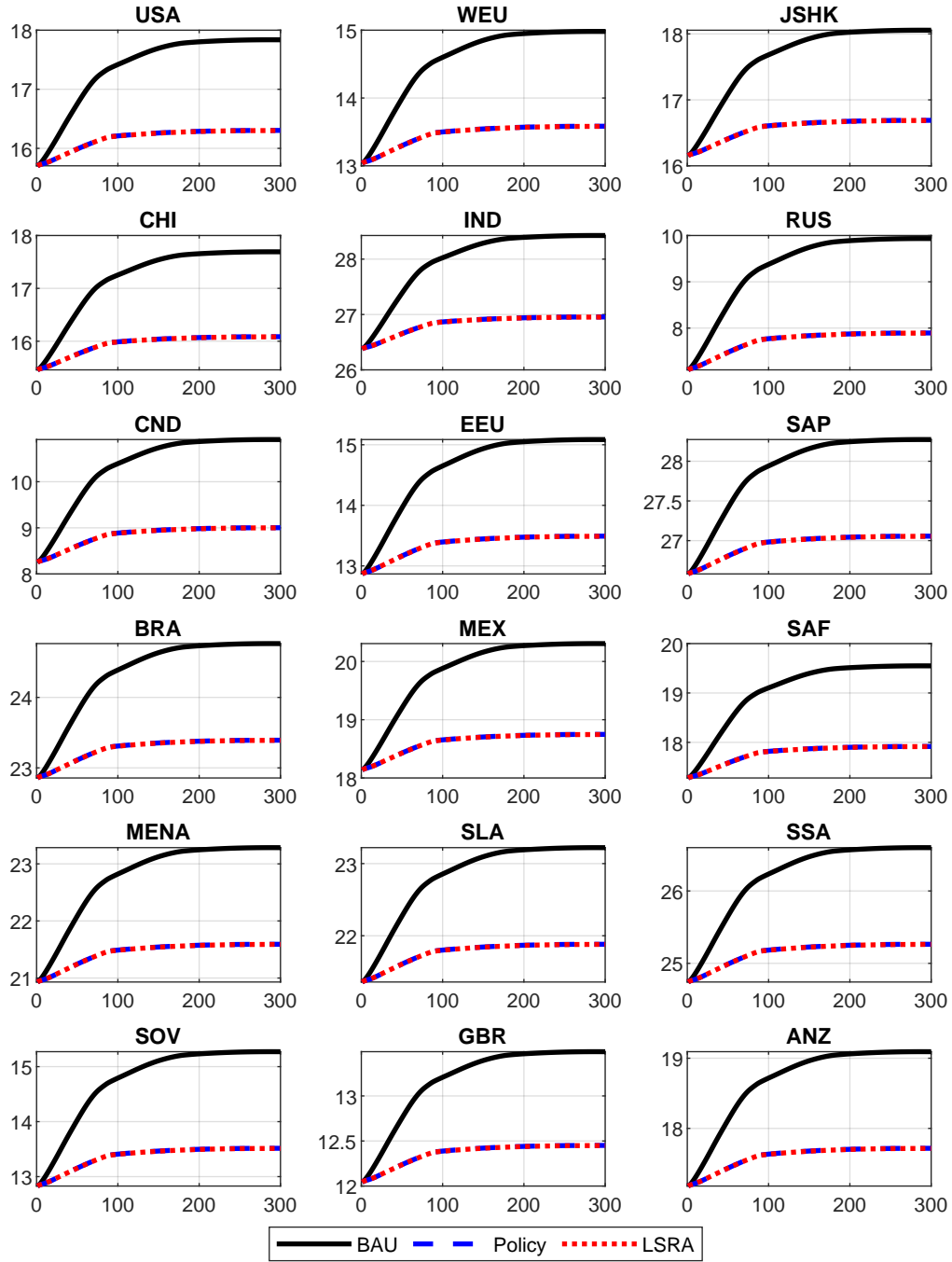
Figure 7: Regional temperature in the 6x case (measured in °C) as a function of years (starting in 2017).

China and other regions, which are rapidly building nuclear power plants while shutting down coal plants.[22] The regions that end coal usage earliest are WEU, EEU, SLA, and BRA, with

---

[22]See, e.g., https://cnpp.iaea.org/countryprofiles/China/China.htm, https://www.forbes.com/sites/jamesconca/2021/04/23/china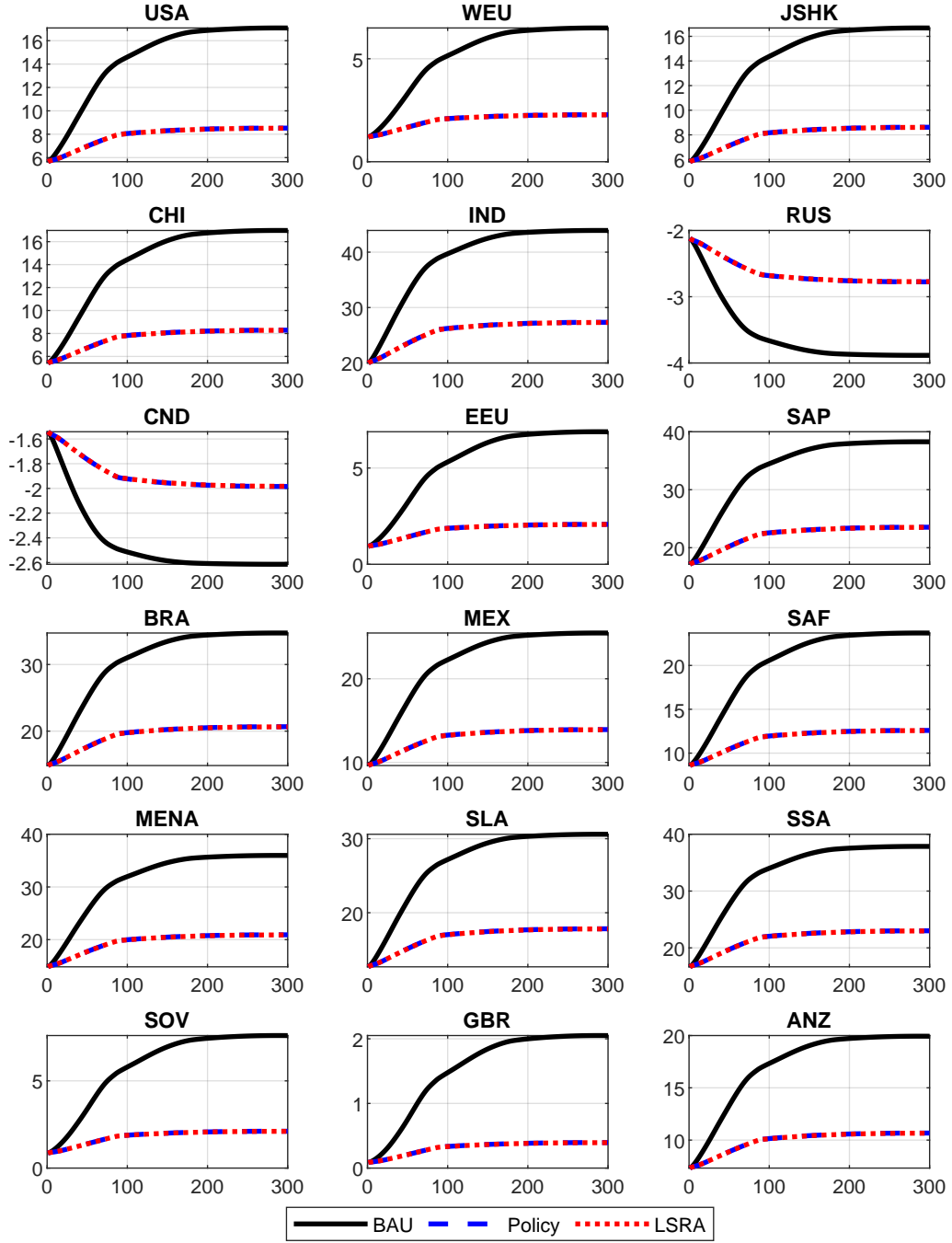-will-lead-the-world-in-nuclear-energy-along-with-all-other-energy-sources-sooner-than-you-think, https://world-nuclear-news.org/Articles/China-

Figure 8: Regional damages in the 6x case (measured in percentage of regional GDP) as a function of years (starting in 2017).

the latest being SLA in 2075. The regions that end coal usage latest include SAF, SSA, and

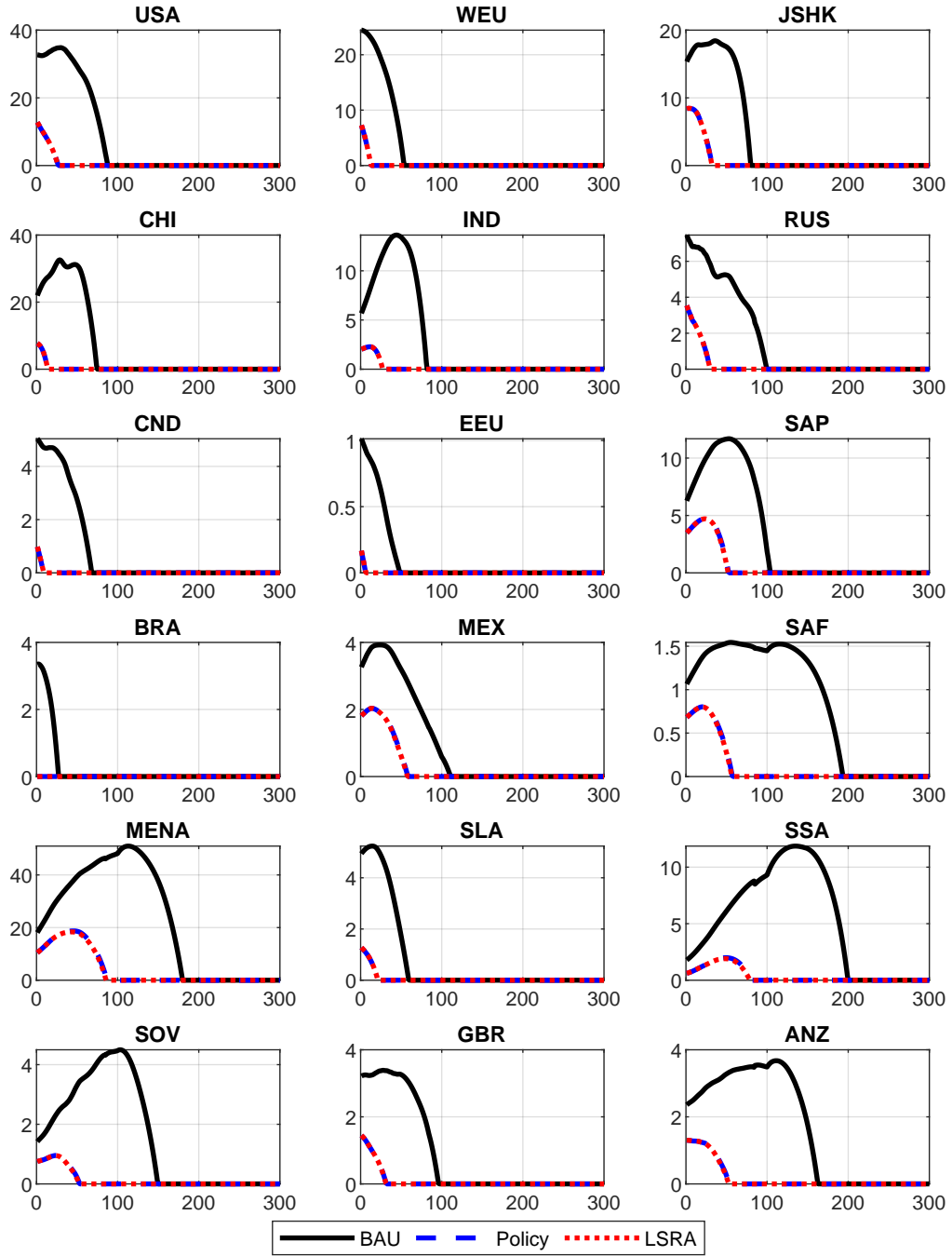starts-construction-of-demonstration-SMR, or https://www.bbc.com/news/uk-england-somerset-58724732.

Figure 9: Oil consumption in the 6x case (measured in quad Btu) as a function of years (starting in 2017).

MENA.[23] The last user of coal is SSA, which stops coal burning in 2215. China ends coal usage in 2090. The US burns its last ton of coal in 2105.

Figure 12 depicts the remarkable emissions reduction in each region arising, in the 6x case,

---

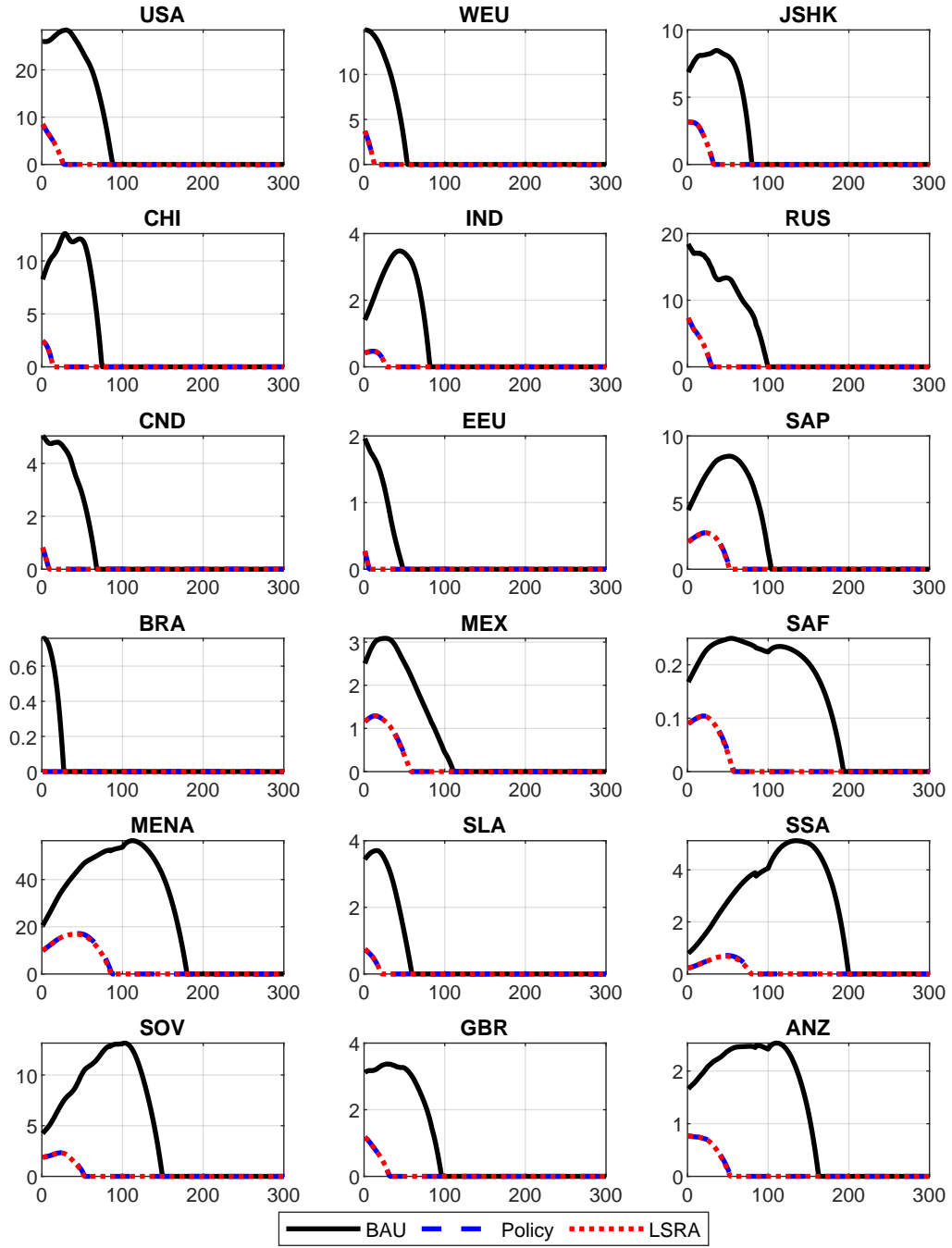[23]Surprisingly, the data indicate the oil-rich Middle East uses some coal.

Figure 10: Gas consumption in the 6x case (measured in quad Btu) as a function of years (starting in 2017).

from the optimal UWI carbon tax. Figure 13, which presents net transfers for the 6x case, is also quite striking. The horizontal axis specifies cohort year of birth.[24] Note that net transfers

---

[24]For example, negative 10 on the MENA chart's horizontal axis references the age-30 MENA generation in 2017.
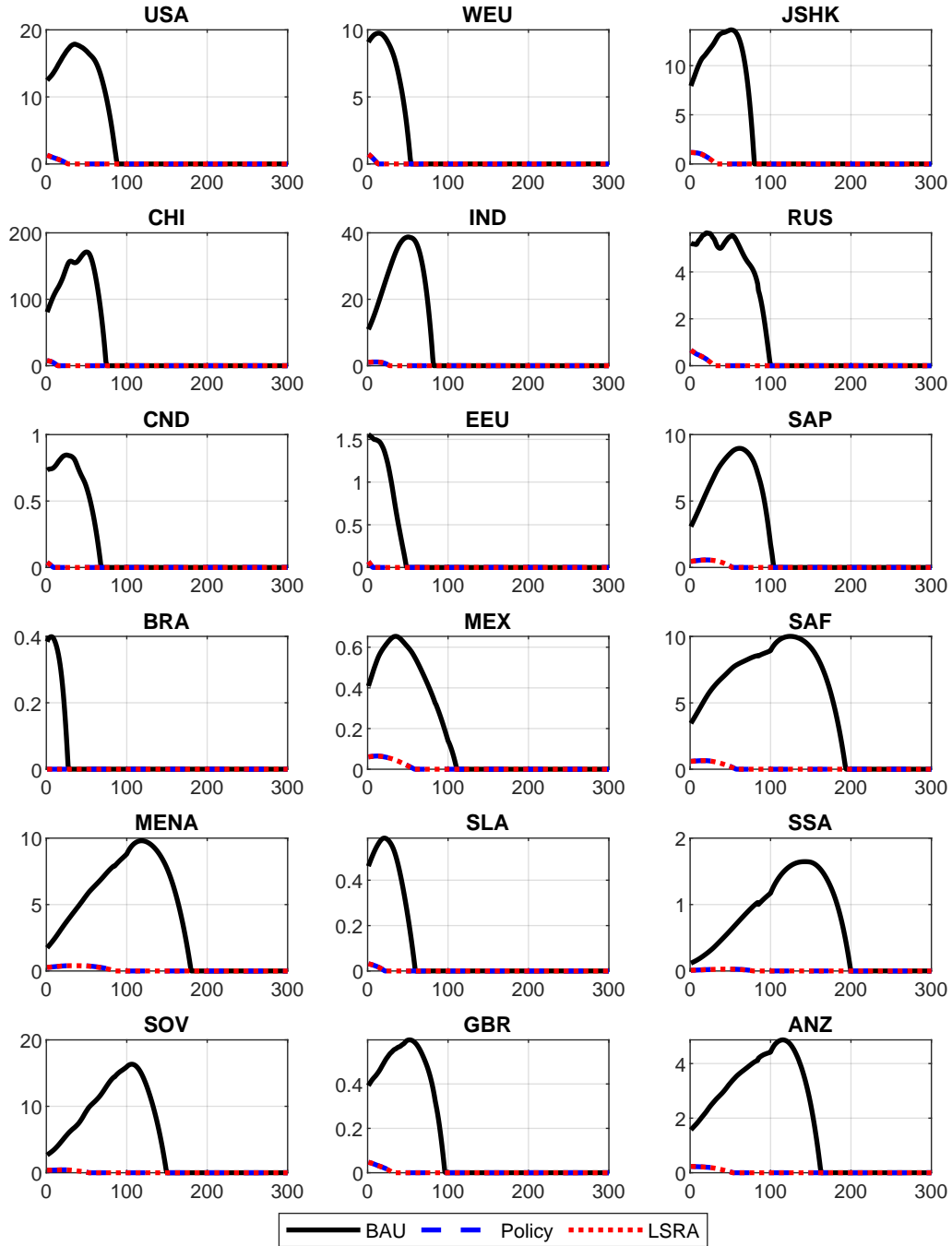
Figure 11: Coal consumption in the 6x case (measured in quad Btu) as a function of years (starting in 2017).

are positive in all regions for the initial elderly and middle-aged. They are positive in almost all regions for the initial young. In Russia and Canada (except for a few generations), net transfers are positive for all future generations. This, to repeat, reflects the need to compensate these regions for helping end something that would otherwise be beneficial to them, namely global warming.
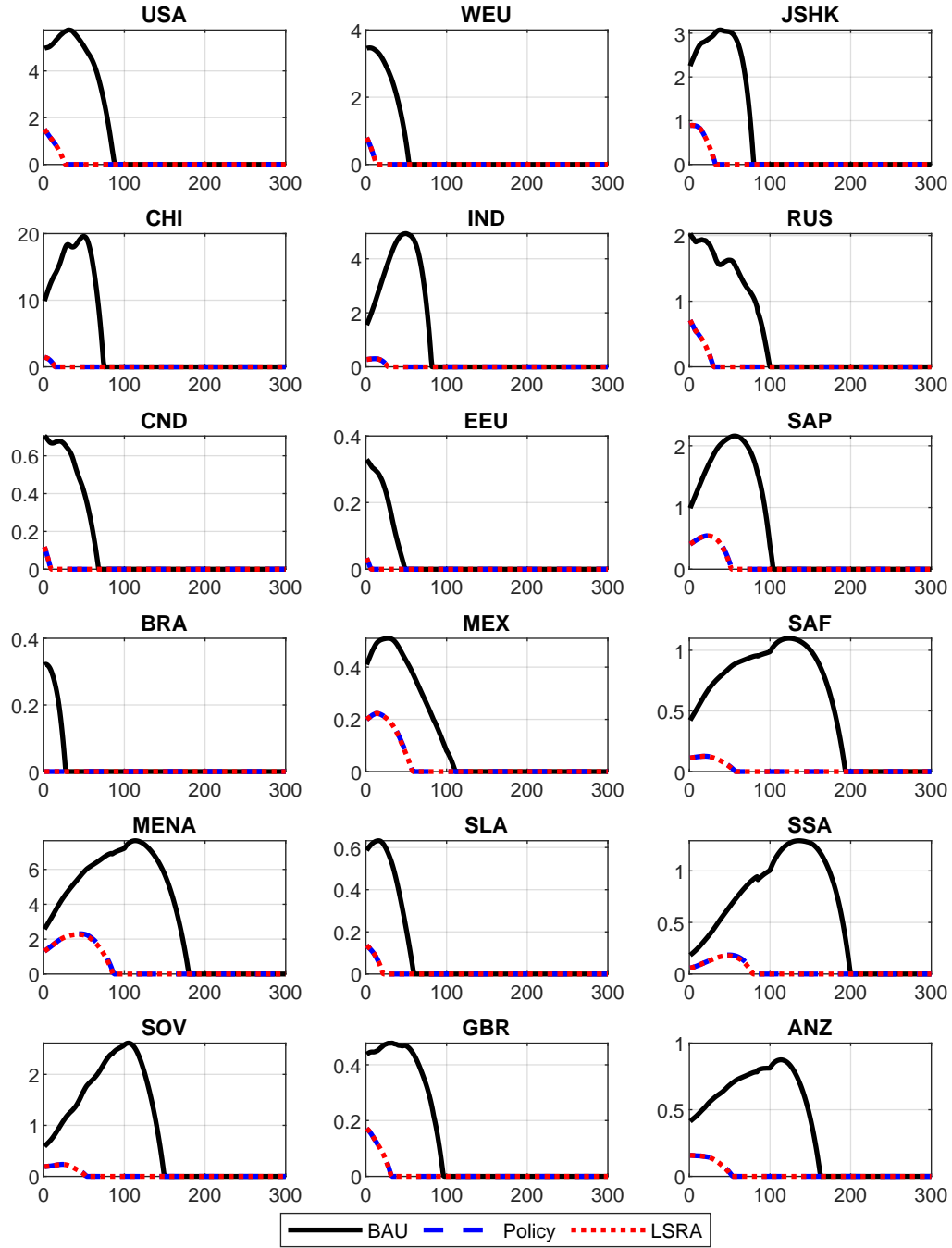
Figure 12: Total CO2 emissions in the 6x case (measured in GtCO2) as a function of years (starting in 2017).

Net transfers turn sharply negative for future generations in regions like India, where climate change, absent mitigation, would take the largest toll. For example, Indians born in 200 years would be required under the UWI policy to surrender roughly 30 percent of their consumption to help service outstanding carbon-policy debt. At first consideration, this sounds extremely onerous and unfair. After all, India is among the world's poorer regions. Why should it be
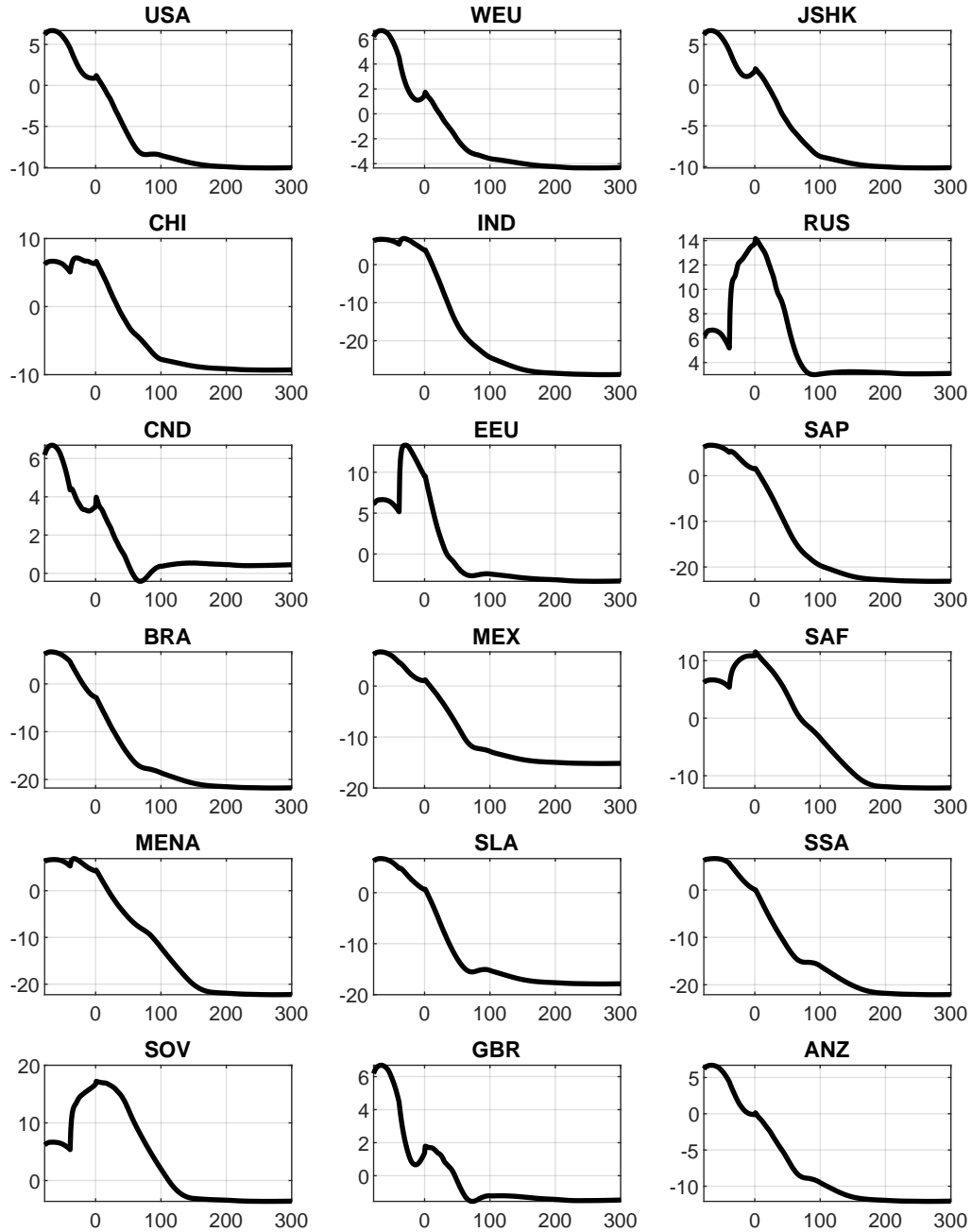
Figure 13: Net transfers as a share of the present value of remaining or full lifetime consumption in the 6x case (year 0 is 2017).

effectively required to subsidize far richer regions, like the US (whose long-run net tax is much smaller), who are causing a much larger share of the global externality? The answer is that fairness is not at issue. Self-interest is at issue. And, like all other regions and all generations in each region, adhering to this policy will benefit Indians, including all future Indians, to the same degree as it benefits those in the richest regions. Additionally, it is important to bear in

Table 8: Regional GDP as percentage share of world GDP in the 6x scenario.

	2017 year		2050 year		2100 year		2150 year	
	BAU	Optimal	BAU	Optimal	BAU	Optimal	BAU	Optimal
US	25.01	25.43	22.04	22.22	15.55	15.54	14.89	14.84
WEU	21.98	22.45	18.69	18.78	17.11	16.16	16.84	15.61
JSHK	9.05	9.20	9.37	9.36	12.34	12.30	13.63	13.48
CHI	15.59	14.92	20.56	20.03	32.61	32.69	35.54	35.47
IND	2.59	2.49	4.60	4.73	5.38	6.43	5.00	6.16
RUS	2.30	2.10	1.34	1.12	0.84	0.72	0.70	0.60
CND	2.37	2.33	2.02	1.94	1.49	1.34	1.44	1.25
EEU	0.35	0.31	0.19	0.18	0.10	0.10	0.08	0.08
SAP	2.60	2.60	3.28	3.43	2.73	3.03	2.26	2.63
BRA	2.24	2.27	1.84	2.02	0.93	1.04	0.70	0.79
MEX	1.39	1.40	1.12	1.14	0.39	0.40	0.25	0.26
SAF	0.42	0.39	0.42	0.38	0.23	0.20	0.16	0.15
MENA	4.53	4.41	5.51	5.58	3.83	3.74	2.85	3.05
SLA	2.36	2.36	1.83	1.90	0.70	0.76	0.46	0.50
SSA	1.05	1.07	1.62	1.73	1.51	1.64	1.37	1.55
SOV	0.50	0.44	0.63	0.52	0.60	0.47	0.46	0.42
GBR	3.74	3.86	3.20	3.15	2.41	2.20	2.24	2.00
ANZ	1.91	1.96	1.75	1.78	1.26	1.24	1.16	1.16

mind that, thanks to the global carbon tax, future Indians will be paying a high net tax rate on a far larger level of consumption than would otherwise be the case.

The wiggles in the curves in figure 13 deserve an explanation. To begin with, they are not spurious. They are fully consistent with each generation in each region experiencing a precisely identical UWI. They reflect discontinuous region-specific changes in demographics, changes through time in fossil fuel stock market values, and changes through time in carbon-tax revenue compensation to fossil fuel companies.

5.2 Carbon Policy and the Future of Economic Power

Table 8 examines, for the 6x scenario, whether carbon-tax policy matters for the evolution of global economic power.

The answer is mixed, that is, no and yes – first, the basic picture. With or without carbon policy, China is projected to eclipse the US economically. In 2100, the US accounts for only 15.5 percent of global output compared with 25.0 percent in 2017. In contrast, China's share of world output grows from 15.6 percent in 2017 to 32.6 percent in 2100. However, the end of the US economic hegemony and the path to that end is essentially invariant to carbon policy. This reflects the roughly equal proportionate 6x climate losses experienced, through time, by both the US and China reported in table 7. Interestingly, the US drops not from first to second place, but from first to third place, with WEU taking silver.

Absent carbon policy, the WEU's global GDP share, which is three percentage points less than the US share in 2017, surpasses the US share by almost 1.5 percentage points by the century's end. This gap drops in roughly half with carbon policy and reflects the relative importance of carbon policy to the US compared to the WEU indicated in table 7. India, which stands to lose the most from climate change, is another example of carbon policy's potential impact on the share of global GDP. In 2100, India's share of world output is 6.43 percent with UWI policy, but 5.38 percent without.

5.3 Partial International Participation

How do our results change if we assume that only some of the regions introduce a carbon tax? In considering UWI policy in a given subset of regions, we tax, as before, the use of dirty energy in all subset regions but now redistribute all carbon-tax revenues to households in participating regions in proportion to their populations. Figure 14 shows the effect of a regional 100 dollar carbon tax on global emissions. In addition to a global tax, we also consider a tax only in CHI, JSHK, GRB, WEU, and US, as well as taxes only in the US, only in CHI, only in JSHK, and only in WEU and GBR. As the figure shows, taxes levied in only a single region have limited effects, even if that region is China. A $100 Chinese-only carbon tax, with a 1.5 percent growth rate, lowers initial global emissions by roughly one-sixth. In contrast, a $100 carbon tax, growing at 1.5 percent annually but levied only in the US, only in Western Europe, or only in JSHK, have almost no effects on global emissions. The larger Chinese impact reflects China's coal-intensive technology for producing dirty energy.

Table 9 shows that the issue of partial participation is even more troubling. Take the case of China being the sole participant. It's optimal UWI carbon tax is just $9 per ton of CO2, which is nowhere near the $100 tax considered in figure 14. This implies far lower emission reductions through time than shown in the figure. The same story applies to other regions which prefer to act independently (of others). None will levy a carbon tax high enough to materially alter global warming. Table 9 also shows that if a coalition of the largest emitters opt for their own UWI policy, they impose a carbon tax that's less than only one-third of the global UWI optimal. Further, if all regions apart from China adopt that UWI carbon policy, the initial carbon tax

Table 9: Optimal taxes for different coalitions.

Coalition	Initial optimal tax	Growth rate optimal tax	UWI
US, WEU, GBR, JSHK, CHI	$ 36	1.5	1.08
CHI	$ 9	1.5	0.29
All regions apart from CHI	$ 52	1.5	2.50

is roughly half of the global UWI optimum.

The inability of subsets of regions to get close to the joint global optimum reflects, in large part, general equilibrium effects. When one region or a subset of regions impose carbon taxes, they drive down the price of dirty energy. This, in turn, leads non-participating regions to increase their use of fossil fuels. This Black Paradox is akin to the "Green Paradox" discussed below in section 5.4. The bottom line here is clear. Carbon taxation needs to be global to be effective.
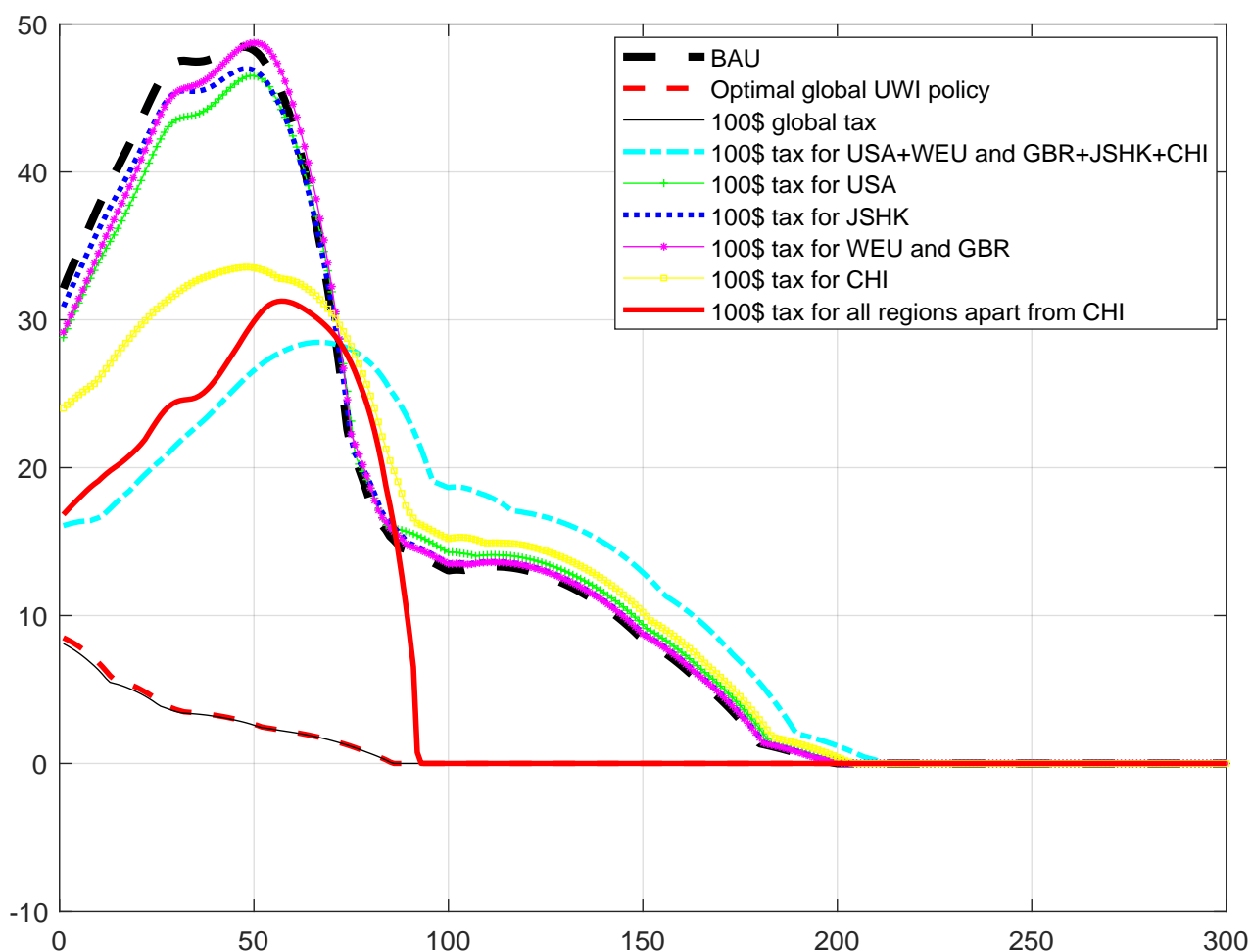
Figure 14: Global CO2 emissions (measured in GtCO2) in the 6x scenario under alternative coalitions as a function of years (starting in 2017).

5.4 Delaying Carbon Taxation and the Green Paradox

A major concern with carbon policy is its timing. As Sinn (1982) points out, announcing the implementation of a carbon tax in advance will alert dirty-energy producers to " use it or lose it. "Of course, speeding up the burning of fossil fuels will accelerate climate change relative to BAU – hence the term *Green Paradox*. The problem is lessened when, as in our model, there is costly dirty-energy extraction. However, delay in our model also comes at a cost. Indeed, postponing the implementation of the optimal UWI tax until 2040, taking into account its growth, reduces the 1x UWI gains from 0.58 to 0.46 percent. In the 2x case, they drop from 1.40 to 1.03 percent. In the 4x case, the decline is from 2.98 to 2.01 percent. Furthermore, in the 6x case, the reduction is from 4.35 to 2.73 percent. Re-optimization of the optimal carbon tax starting in 2040 does not materially change these findings. Delay reduces maximum UWI gains and increases emissions during the period of delay not only relative to immediate policy implementation, but relative to engaging in no policy. For example, 2030 carbon emissions are 13 percent higher than under BAU in the 6x case.

What if all regions but China immediately adopt a carbon tax, but China waits 20 years?[25] Our computations show that this lowers the UWI gain from 4.35 percent to 3.81 percent in the 6x case. In the 4x case, China's delayed participation reduces the UWI gain from 2.98 percent to 2.73 percent. In the 2x, the drop is from 1.40 to 1.38 percent. Moreover, in the 1x case, the UWI gains are virtually unaffected by a Chinese delay in joining all other regions in taxing carbon.

6 Conclusion

Climate policy is generally viewed as a zero-sum game pitting future against current generations and regions benefiting from climate change against regions that do not. This paper shows that carbon-tax policy can be a win-win. It can improve the welfare of current and future generations regardless of the region in which they live. Indeed, carbon taxation, coupled with region- and generation-specific positive or negative transfers, can achieve a uniform welfare gain – an identical percentage improvement in economic well-being no matter where one lives or when one is born. Such interregional and intertemporally equal treatment may be essential for obtaining global agreement on and enforcement of carbon taxation.

This paper calculates the optimal global carbon tax cum region- and generation-specific net transfer policy needed to achieve the highest feasible uniform welfare improvement for current and future humanity. In so doing, it reverts climate economics to its natural domain – identifying Pareto efficiency gains from correcting negative externalities, not calling winners and losers.

For our high-damage case, the optimal UWI carbon tax is roughly \$100 per ton of CO2, rising at a 1.5 percent real rate. Such a policy can dramatically reduce global and region-specific climate damage. It would also materially shorten the interval over which fossil fuels continue to be used and raise our planet's temperature. With the right inter-generational and inter-regional redistribution, carbon taxation can raise all of humanity's welfare by over 4 percent. This said, two factors are critical. The first is China's participation, given its massive current and projected future carbon emissions. China's failure to participate reduces the potential uniform welfare gain in our high calibration from 4.35 percent to 2.50 percent. The second is immediate policy implementation. Waiting until 2040 to tax carbon, even at the rate that would otherwise be implemented under an optimal policy, reduces the potential uniform gain from 4.35 percent to 2.73 percent.

---

[25]Chinese generations born after that receive transfers to ensure that they get the same uniform welfare gains as the rest of the world.

References

Andrew Abel and Laurence J Kotlikoff. Intergenerational altruism and the effectiveness of fiscal policy: New tests based on cohort data. *Savings and bequests*, pages 31–42, 1994.

Daron Acemoglu, Philippe Aghion, Leonardo Bursztyn, and David Hemous. The environment and directed technical change. *American economic review*, 102(1):131–66, 2012.

Joseph G Altonji, Fumio Hayashi, and Laurence J Kotlikoff. Is the extended family altruistically linked? direct tests using micro data. *The American Economic Review*, pages 1177–1198, 1992.

Joseph G Altonji, Fumio Hayashi, and Laurence J Kotlikoff. Parental altruism and inter vivos transfers: Theory and evidence. *Journal of political economy*, 105(6):1121–1166, 1997.

Alberto Ansuategi and Marta Escapa. Economic growth and greenhouse gas emissions. *Ecological Economics*, 40(1):23–37, 2002. ISSN 09218009. doi: 10.1016/S0921-8009(01)00272-5.

Raymond G Batina and Jeffrey a Krautkraemer. On sustainability and intergenerational transfers with a renewable resource. *Land Economics*, 75(2):167–184, 1999.

Seth G Benzell, Laurence J Kotlikoff, and Guillermo LaGarda. Simulating business cash flow taxation: An illustration based on the 'better way' corporate tax reform. Technical report, National Bureau of Economic Research, 2017.

B Douglas Bernheim and Kyle Bagwell. Is everything neutral? *Journal of Political Economy*, 96(2):308–338, 1988.

Valentina Bosetti, Cristina Cattaneo, and Giovanni Peri. Should they stay or should they go? Climate migrants and local conflicts. *Journal of Economic Geography*, 21(4):619–651, 02 2020. ISSN 1468-2702. doi: 10.1093/jeg/lbaa002. URL https://doi.org/10.1093/jeg/lbaa002.

A. Lans Bovenberg and Ben J. Heijdra. Environmental abatement and intergenerational distribution. *Environmental and Resource Economics*, 23(1):45–84, 2002. ISSN 09246460. doi: 10.1023/A:1020236812676.

A.Lans Bovenberg and Ben J Heijdra. Environmental tax policy and intergenerational distribution. *Journal of Public Economics*, 67(1):1–24, 1998. ISSN 00472727. doi: 10.1016/S0047-2727(97)00064-9.

Peter S. Burton. Intertemporal preferences and intergenerational equity considerations in optimal resource harvesting. *Journal of Environmental Economics and Management*, 24(2):119–132, 1993. ISSN 0095-0696. doi: 10.1006/jeem.1993.1008. URL http://www.sciencedirect.com/science/article/B6WJ6-45P13FR-1D/2/3df3a733c83612ef9a6056ec25a0c47c.

Guillermo A. Calvo and Maurice Obstfeld. Optimal time-consistent fiscal policy with finite lifetimes. *Econometrica*, 56(2):411–432, 1988.

David Castells-Quintana, Melanie Krause, and Thomas K J McDermott. The urbanising force of global warming: the role of climate change in the spatial distribution of population. *Journal of Economic Geography*, 21(4):531–556, 11 2020. ISSN 1468-2702. doi: 10.1093/jeg/lbaa030. URL https://doi.org/10.1093/jeg/lbaa030.

Bruno Conte, Klaus Desmet, Dávid Krisztián Nagy, and Esteban Rossi-Hansberg. Local sectoral specialization in a warming world. *Journal of Economic Geography*, 21(4):493–530, 09 2021. ISSN 1468-2702. doi: 10.1093/jeg/lbab008. URL https://doi.org/10.1093/jeg/lbab008.

Jose-Luis Cruz and Esteban Rossi-Hansberg. The Economic Geography of Global Warming. 2021.

Simon Dietz, Frederick van der Ploeg, Armon Rezai, and Frank Venmans. Are economists getting climate dynamics right and does it matter? *Journal of the Association of Environmental and Resource Economists*, 8(5):895–921, 2021. doi: 10.1086/713977. URL https://doi.org/10.1086/713977.

Lee H. Endress, Sittidaj Pongkijvorasin, James Roumasset, and Christopher A. Wada. Intergenerational equity with individual impatience in a model of optimal and sustainable growth. *Resource and Energy Economics*, 36(2):620–635, 2014. ISSN 09287655. doi: 10.1016/j.reseneeco.2013.10.001. URL http://dx.doi.org/10.1016/j.reseneeco.2013.10.001.

Doris Folini, Felix Kubler, Aleksandra Malova, and Simon Scheidegger. The climate in climate economics. *Available at SSRN 3885021*, 2021.

Olivier Geoffroy, D. Saint-Martin, G. Bellon, A. Voldoire, D. J.L. Olivié, and S. Tytéca. Transient climate response in a two-layer energy-balance model. Part II: Representation of the efficacy of deep-ocean heat uptake and validation for CMIP5 AOGCMs. *Journal of Climate*, 26(6):1859–1876, 2013. ISSN 08948755. doi: 10.1175/JCLI-D-12-00196.1.

Reyer Gerlagh and Michiel A. Keyzer. Sustainability and the intergenerational distribution of natural resource entitlements. *Journal of Public Economics*, 79(2):315–341, 2001. ISSN 00472727. doi: 10.1016/S0047-2727(99)00122-X.

Reyer Gerlagh and B.C.C. van der Zwaan. The effects of ageing and an environmental trust fund in an overlapping generations model on carbon emission reductions. *Ecological Economics*, 36(2):311–326, 2001. ISSN 09218009. doi: 10.1016/S0921-8009(00)00232-9.

Jagadeesh Gokhale, Laurence J Kotlikoff, and John Sabelhaus. Understanding the postwar decline in us saving: A cohort analysis. brookings papers on economic activity. ed. w. brainard and g. perry. washington dc: Brookings institution. 1996.

Mikhail Golosov, John Hassler, Per Krusell, and Aleh Tsyvinski. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88, 2014.

Michael Grimm. Rainfall risk, fertility and development: evidence from farm settlements during the American demographic transition. *Journal of Economic Geography*, 21(4):593–618, 12 2019. ISSN 1468-2702. doi: 10.1093/jeg/lbz039. URL https://doi.org/10.1093/jeg/lbz039.

Martin C. Hänsel, Moritz A. Drupp, Daniel J.A. Johansson, Frikk Nesje, Christian Azar, Mark C. Freeman, Ben Groom, and Thomas Sterner. Climate economics support for the UN climate targets. *Nature Climate Change*, 10(8):781–789, 2020. ISSN 17586798. doi: 10.1038/s41558-020-0833-x. URL `http://dx.doi.org/10.1038/s41558-020-0833-x`.

John Hassler, Per Krusell, and Conny Olovsson. Energy-saving technical change. Technical report, National Bureau of Economic Research, 2012.

John Hassler, Per Krusell, Conny Olovsson, and Michael Reiter. On the effectiveness of climate policies. Technical report, 2020.

Zeke Hausfather and Glen P Peters. Emissions–the 'business as usual'story is misleading, 2020.

Fumio Hayashi, Joseph Altonji, and Laurence Kotlikoff. Risk-sharing between and within families. *Econometrica*, 64(2):261–294, 1996.

Ben J. Heijdra, Jan Peter Kooiman, and Jenny E. Ligthart. Environmental quality, the macroeconomy, and intergenerational distribution. *Resource and Energy Economics*, 28(1):74–104, 2006. ISSN 09287655. doi: 10.1016/j.reseneeco.2005.05.001.

Elmar Hillebrand and Marten Hillebrand. Who pays the bill? climate change, taxes, and transfers in a multi-region growth model. Technical report, 2020.

Harold Hotelling. The economics of exhaustible resources. *The journal of political economy*, pages 137–175, 1931.

Peter H. Howard and Thomas Sterner. Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environmental and Resource Economics*, 68(1):197–225, 2017. ISSN 15731502. doi: 10.1007/s10640-017-0166-z.

Richard B. Howarth. Intertemporal equilibria and exhaustible resources: an overlapping generations approach. *Ecological Economics*, 4(3):237–252, 1991a. ISSN 09218009. doi: 10.1016/0921-8009(91)90053-H.

Richard B. Howarth. Intergenerational competitive equilibria under technological uncertainty and an exhaustible resource constraint. *Journal of Environmental Economics and Management*, 21(3):225–243, 1991b. ISSN 10960449. doi: 10.1016/0095-0696(91)90028-H.

Richard B. Howarth. An overlapping generations model of climate-economy interactions. *The Scandinavian Journal of Economics*, 100(3):575–591, 1998.

Richard B. Howarth and Richard B. Norgaard. Intergenerational resource rights, efficiency, and social optimality. *Land Economics*, 66(1):1–11, 1990. ISSN 00987484. doi: 10.1186/1478-7547-10-9.

Richard B Howarth and Richard B Norgaard. Environmental valuation under sustainable development. *American Economic Review*, 82(2):473–477, 1992. ISSN 00028282. doi: 10.1002/sd.181.

Agustín Indaco, Francesc Ortega, Tapınar, and Süleyman. Hurricanes, flood risk and the economic adaptation of businesses. *Journal of Economic Geography*, 21(4):557–591, 11 2020. ISSN 1468-2702. doi: 10.1093/jeg/lbaa020. URL `https://doi.org/10.1093/jeg/lbaa020`.

A. John, R. Pecchenino, D. Schimmelpfennig, and S. Schreft. Short-lived agents and the long-lived environment. *Journal of Public Economics*, 58(1):127–141, 1995. ISSN 00472727. doi: 10.1016/0047-2727(94)01459-2.

Larry Karp and Armon Rezai. The political economy of environmental policy with overlapping generations. *International Economy Review*, 55(3):711–733, 2014.

Laurence Kotlikoff, Felix Kubler, Andrey Polbin, Jeffrey Sachs, and Simon Scheidegger. Making Carbon Taxation a Generational Win Win. *International Economic Review*, 62(1):3–46, 2021. ISSN 1468-2354. doi: 10.1111/iere.12483.

Laurence J Kotlikoff. Altruistic linkages within the extended family, a note. *Sloan Foundation Proposal*, 1983.

B. Kravitz, C. Lynch, C. Hartin, and B. Bond-Lamberty. Exploring precipitation pattern scaling methodologies and robustness among cmip5 models. *Geoscientific Model Development*, 10 (5):1889–1902, 2017. doi: 10.5194/gmd-10-1889-2017. URL `https://gmd.copernicus.org/articles/10/1889/2017/`.

Per Krusell and Tony Smith. Climate change around the world. Technical report, 2018.

Per Krusell and Anthony A Smith Jr. Climate change around the world. 2018. URL `http://www.econ.yale.edu/smith/munich2.pdf`.

R. Link, A. Snyder, C. Lynch, C. Hartin, B. Kravitz, and B. Bond-Lamberty. Fldgen v1.0: an emulator with internal variability and space–time correlation for earth system models. *Geoscientific Model Development*, 12(4):1477–1489, 2019. doi: 10.5194/gmd-12-1477-2019. URL `https://gmd.copernicus.org/articles/12/1477/2019/`.

Oleg Lugovoy and Andrey Polbin. On intergenerational equity of greenhouse gases emissions abatement. *The Journal of the New Economic Association*, 31(3), 2016.

C. Lynch, C. Hartin, B. Bond-Lamberty, and B. Kravitz. An open-access cmip5 pattern library for temperature and precipitation: description and methodology. *Earth System Science Data*, 9(1):281–292, 2017. doi: 10.5194/essd-9-281-2017. URL `https://essd.copernicus.org/articles/9/281/2017/`.

Giancarlo Marini and Pasquale Scaramozzino. Overlapping generations and environmental control. *Journal of Environmental Economics and Management*, 29(1):64–77, 1995. URL `http://www.sciencedirect.com/science/article/pii/S0095069685710315$\protect\delimiter"026E30F$npapers2://publication/uuid/E5065B74-2BDF-4783-81AE-6062A3C0D8CB`.

Christophe McGlade and Paul Ekins. The geographical distribution of fossil fuels unused when limiting global warming to 2 c. *Nature*, 517(7533):187, 2015.

M. Meinshausen, T. M. L. Wigley, and S. C. B. Raper. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. *Atmospheric Chemistry & Physics*, 11:1457–1471, February 2011. doi: 10.5194/acp-11-1457-2011.

Alex Mourmouras. Competitive equilibria and sustainable growth in a life-cycle model with natural resources. *The Scandinavian Journal of Economics*, 93(4):585–591, 1991. URL `http://links.jstor.org/sici?sici=0347-0520(199112)93:4{\T2A\textless}585:CEASGI{\T2A\textgreater}2.0.CO;2-L`.

Alex Mourmouras. Conservationist government policies and intergenerational equity in an overlapping generations model with renewable resources. *Journal of Public Economics*, 51 (2):249–268, 1993. ISSN 00472727. doi: 10.1016/0047-2727(93)90088-B.

Ulrich K Müller, James H Stock, and Mark W Watson. An econometric model of international long-run growth dynamics. Technical report, National Bureau of Economic Research, 2019.

William Nordhaus. Projections and uncertainties about climate change in an era of minimal climate policies. *American Economic Journal: Economic Policy*, 10(3):333–360, 2018. ISSN 1945774X. doi: 10.1257/pol.20170046.

William D. Nordhaus. *The efficient use of energy resources / William D. Nordhaus*. Monograph - Cowles Foundation for Research in Economics at Yale University ; 26. Yale University Press, New Haven, 1979.

William D Nordhaus. *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press, New Haven, CT, 2008.

William D Nordhaus. Economic aspects of global warming in a post-copenhagen environment. *Proceedings of the National Academy of Sciences*, 107(26):11721–11726, 2010.

William D Nordhaus. Climate clubs: overcoming free-riding in international climate policy. *The American Economic Review*, 105(4):1339–1370, 2015.

William D. Nordhaus. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, 114(7):1518–1523, 2017. ISSN 10916490. doi: 10.1073/pnas.1609244114.

William D. Nordhaus and Zili Yang. A regional dynamic general-equilibrium model of alternative climate-change strategies. *The American Economic Review*, 86(4):741–765, 1996a. ISSN 00028282. URL `http://www.jstor.org/stable/2118303`.

William D Nordhaus and Zili Yang. A regional dynamic general-equilibrium model of alternative climate-change strategies. *The American Economic Review*, pages 741–765, 1996b.

R Pecchenino and A. John. An overlapping generations model of growth and the environment. *The Economic Journal*, 104(427):1393–1410, 1994.

Giovanni Peri and Frédéric Robert-Nicoud. On the economic geography of climate change. *Journal of Economic Geography*, 21(4):487–491, 10 2021. ISSN 1468-2702. doi: 10.1093/jeg/lbab027. URL `https://doi.org/10.1093/jeg/lbab027`.

Robert S Pindyck. Climate change policy: what do the models tell us? *Journal of Economic Literature*, 51(3):860–72, 2013.

Tobias N. Rasmussen. Modeling the economics of greenhouse gas abatement: an overlapping generations perspective. *Review of Economic Dynamics*, 6(1):99–119, 2003. ISSN 10942025. doi: 10.1016/S1094-2025(02)00010-8.

B. D. Santer, T. M. L Wigley, M. E. Schlesinger, and J. F. B. Mitchell. Developing climate scenarios from equilibrium gcm results. Technical report, Tech. Rep., Max–Planck-Institut fuer Meteorologie, Hamburg, Germany, 1990.

Maik T. Schneider, Christian P. Traeger, and Ralph Winkler. Trading off generations: equity, discounting, and climate change. *European Economic Review*, 56(8):1621–1644, 2012. ISSN 00142921. doi: 10.1016/j.euroecorev.2012.08.006. URL http://dx.doi.org/10.1016/j.euroecorev.2012.08.006.

HW Sinn. Absatzsteuern, ölförderung und das allmendeproblem. *Reaktionen auf Energiepreissteigerungen, Frankfurt: Lang*, pages 83–103, 1982.

Robert M Solow. The economics of resources or the resources of economics. *The American Economic Review*, 64(2):1–14, 1974a.

Robert M Solow. Intergenerational equity and exhaustible resources. *The Review of Economic Studies*, 41:29–45, 1974b.

Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl. An Overview of CMIP5 and the Experiment Design. *Bull. Amer. Meteor. Soc.*, 93:485–498, 2012. doi: 10.1175/BAMS-D-11-00094.1.

Claudia Tebaldi and Julie Arblaster. Pattern scaling: Its strengths and limitations, and an update on the latest model simulations. *Climatic Change*, 122(3):459–471, February 2014. doi: 10.1007/s10584-013-1032-9. URL https://ideas.repec.org/a/spr/climat/v122y2014i3p459-471.html.

United Nations. World Fertility Prospects. *UN*, 2019a. URL https://esa.un.org/unpd/wpp.

United Nations. World Population Prospects 2019. *UN*, 2019b.

Ronald Wendner. An applied dynamic general equilibrium model of environmental tax reforms and pension policy. *Journal of Policy Modeling*, 23(1):25–50, 2001. ISSN 01618938. doi: 10.1016/S0161-8938(00)00025-9.