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ABSTRACT

Carbon taxation is a widely proposed and in some countries already adopted means to limit anthropogenic climate change. This paper studies carbon taxation using an 18-region, 80- period overlapping generations model. We focus on carbon policy that delivers present and future mankind the highest uniform percentage welfare gain. The policy combines global carbon taxation and region- and generation-specific net transfers. In our main calibration, uniform welfare-improving carbon tax policy can make those agents already here and those yet to come, no matter their location, 4.35 percent better off. Achieving (such) equal proportionate gains, which may be needed for universal support, requires major interregional as well as intergenerational transfers. Universal support, though, is not essential. For example, even absent participation by China, whose projected carbon emissions are massive, the rest of the world can still materially limit the carbon externality. However, absent China, their optimal carbon tax is roughly half as large, and the uniform welfare-improving gain is less than three-fifths as large.

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1 Introduction

Our problems are man-made; therefore, they can be solved by man. Do these inspiring words of President Kennedy apply to anthropogenic climate change with its myriad and massive projected damages? Climate activists certainly believe so. Many support a global carbon tax, which has already been adopted by a handful of countries. This paper studies whether optimal carbon-tax policy can make a difference and how it might garner global support.

But how should one judge optimality? One approach is simply to assume a social planner with "correct" intergenerational preferences and the power to enforce their desires. This normative route, taken by Nordhaus (1979), launched climate-change economics – a singular accomplishment. Nevertheless, it provides 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.

In contrast, our paper offers a positive approach grounded in the standard economics of externalities. We calibrate and solve for the optimal uniform welfare improving (UWI) compensated carbon policy. Carbon policy references a global, time-varying carbon tax coupled with generation- and region-specific net transfers that produce the highest uniform percentage welfare increase. We calculate the optimal carbon policy in an 80-period, 18-region overlapping generations (OLG) model of global climate change. Our model features oil, gas, and coal, whose extraction is subject to increasing costs, as well as clean energy. The climate externality is apparent. Burning the three fossil fuels emits carbon, which heats the atmosphere, which in turn damages the planet. This externality arises naturally in our life-cycle model as agents have no qualms in harming their future progeny, let alone unrelated future foreigners.

Our optimal UWI policy is measured as an equal percentage compensating consumption equivalent across all generations in all regions. As such, it seems most likely to attract international and intergenerational support. Implementing such a 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, features status-quo gains for two of our model's 18 regions.

Deriving the optimal UWI carbon tax addresses eight key climate-policy questions that we answer below. 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? Fifth, which regions need to pay on net and which regions need to receive on net to achieve the requisite uniform payoff? Sixth, how large are the net transfers paid to each region initially and over time? Seventh, how quickly does the optimal UWI policy definitively end fossil-fuel combustion? Eighth, which regions stop using fossil fuels early and which ones late?

We also consider optimal UWI policy within a subset of regions assuming the other regions do not participate in the optimal global carbon policy. Our main finding here is striking.

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

Absent China's participation, the available UWI gain to all other regions from implementing UWI carbon policy is only 57.5 percent as large. Moreover, peak global climate damage is reduced by only 20.7 percent rather than by 45.2 percent. Other results in this arena are equally discouraging. For example, were Western Europe, including the UK, to adopt optimal carbon policy solely on its own, its optimal carbon tax would be zero; that is, the gains from reducing emissions would be too small to justify the costs.

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 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 (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. 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, Hayashi, and Kotlikoff (1992), Gokhale, Kotlikoff, and Sabelhaus (1996), Hayashi, Altonji, and Kotlikoff (1996), and Altonji, Hayashi, and Kotlikoff (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 ill-suited to 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 based on the increasingly costly extraction of fossil fuels. Dirty energy companies are owned globally. Hence, as we do, taxing dirty energy production in proportion to its carbon emissions does not differentially harm particular regions. This assumption substantially improves the model's tractability and eases its computation. Furthermore, as clarified below, our model's carbon levy taxes emissions arising from the use of dirty energy, not its production per se.

Our assumed technological advances in clean energy eventually bring an end to dirty energy. However, the model's carbon end date is 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. Under the UWI policy, inhabitants in regions that would benefit from climate change are compensated for their losses, as are early generations, who pay a higher energy price but are born too soon to suffer greatly from global warming. As for carbon-tax revenues, they are lump-sum rebated to dirty energy producers on a period-by-period basis.[2]

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 exact same degree as all other generations. However, how, in practice, is the policy implemented? The answer is first, levying a time-varying, global carbon tax, and second, making net lump-sum transfers to each generation in each region. The net transfers zero out in present value. We characterize our net transfer policy as a deficit policy under which an international authority, such as the International Monetary Fund (IMF), issues bonds to make net transfers in the early years of the policy and receives net taxes in subsequent years, which are used to service the debt. In what follows, we use IMF as a moniker for this global authority.

Since our model features no uncertainty, we take a certainty equivalent approach and focus on a high damage scenario. Absent climate policy, our business as usual global economy suffers a 16.7 percent decline in global GDP in 2200. The worst-hurt region, India, suffers a 43.9 percent GDP loss in 2200. With this damage function, optimal UWI policy delivers a 4.35 percent welfare gain. The initial optimal tax is $97.0 per ton with an optimal real growth rate of 1.5 percent. The tax significantly reduces and shortens the use of fossil fuels. Absent policy, dirty energy is used for 200 years. With the policy, it ends 85 years earlier. More importantly, the maximum global damage drops from 16.7 percent to 9.1 percent. Furthermore, the maximum regional damage drops from 43.9 percent to 27.3 percent.

Our study makes five significant methodological contributions. First, it provides what may be the first large-scale, regional, overlapping generations (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 "pattern scaling", where the temperature at each 1-degree latitude by 1-degree longitude grid location is based on the concomitant global average temperature.[3] 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[4], 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). Furthermore, fifth, we use a recent study by Folini et al. (2021) to align the relationships between output and carbon emissions, emissions and carbon concentration in the atmosphere, and carbon concentration's impact on temperature with CMIP5.[5]

[2]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.

[3]See, e.g, Kravitz et al. (2017), Lynch et al. (2017), and references therein for more details.

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

[5]CMIP5 is a consortium of 40 plus climate-modeling groups from around the world. Each group runs its

1.3 Preview of Findings

As with most climate change studies, our model predicts region-specific climatic disasters absent policy intervention. With no policy, that is, business-as-usual (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, Sub-Saharan African and South Asia Pacific, the Middle East, and North Africa being hit worst. Their GDP levels in the year 2200 are reduced by 43.4, 37.4, 37.8, and 35.4 percent, respectively. 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 big changes. They limit the rise in the global mean-surface temperature to 2.1 degrees Celsius. And 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 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), that is, 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 rate is 10 percent.

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 main results. 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 (1974a,b), 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 (1991a), Howarth (1991b), Bur-

model on a common set of global RCPs – representative greenhouse gas concentration pathways, after which their results are pooled to produce a CMIP5 temperature projection for each scenario.

ton (1993), Pecchenino and John (1994), John et al. (1995), Marini and Scaramozzino (1995), and Burton (1993)). Howarth (1991a) 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.[6] 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. Their papers feature large-scale, perfect-foresight, single-country models. However, they omit climate damage.

Howarth and Norgaard (1990), using a pure exchange OLG model, and Howarth (1991b), 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.[7] The multiplicity of 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), Ansuategi and Escapa (2002), Howarth (1998), Marini and Scaramozzino (1995), Schneider, Traeger, and Winkler (2012), and Lugovoy and Polbin (2016). In these papers, the social planner's time preference plays a critical role in influencing policy choice.[8]

Apart from Kotlikoff et al. (2021), our paper's closest antecedents are Bovenberg and Heijdra (2002, 1998), Heijdra, Kooiman, and Ligthart (2006), Karp and Rezai (2014). Their studies consider the use of debt policy to achieve Pareto improvements in the context of adverse climate change.[9] 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

[6]An alternative approach to incorporating a negative environmental externality is including 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 Batina and Krautkraemer (1999), Mourmouras (1991, 1993) in a model where energy is renewable.

[7]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.

[8]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.

[9]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.

of Climate and the Economy (DICE) – spawned a massive literature, including Nordhaus' development (Nordhaus and Yang (1996b), Nordhaus (2010), and Nordhaus (2015)) of the RICE (the Regional Integrated model of Climate and the Economy) model, 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 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. The model features several mechanisms by which individuals can adapt to global warming, including costly migration. In addition, they estimate local welfare losses through global warming that are in line with our estimates.

As indicated, our paper appears to be the first large-scale regional OLG model of climate change. It builds, with major changes, on Kotlikoff et al. (2021), which, in turn, adds climate change to the Global Gaidar Model (Benzell, Kotlikoff, and LaGarda, 2017). Our model's 18 regions encompass essentially all countries of the world, representing over 99 percent of the world's population and 98 percent of the world's GDP.

3 Model

This section details our multi-region OLG model. We describe the the firms in section 3.1, and the households in section 3.2. Section 3.3 considers the climate externality, including our use of pattern scaling to derive regional paths of temperature and damage from the global temperature path. For the detailed calibration of the model presented in this section, we refer to section 4.

3.1 Firms

Firms in each region, $z \in \mathbb{N}$, in each period, t,[10] produce final output, $Y_{z,t}$, with capital, $K_{z,y,t}$, labor, $L_{z,y,t}$, and energy, $E_{z,t}$, according to

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

Profit maximization implies

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

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

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. Furthermore, $A_{z,t}$ abbreviates region-specific total factor productivity (TFP).

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

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

where $O_{z,t}$, $G_{z,t}$, and $\mathcal{C}_{z,t}$ reference oil, gas and coal consumption, respectively. The parameter s represents the elasticity of substitution between different dirty energy sources.

[10] In our model, time is discrete; increments in time correspond to a one year interval.

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.

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

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

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

where the price of the dirty energy composite is defined as:

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

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. They 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

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

subject to

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

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

and

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

where p_t^M is the price of a unit of dirty energy, M, at time t, τ_t is the absolute tax per unit of carbon 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

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

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 markets. Region- and year-specific mortality probabilities are inferred from United Nations demographic projections (see United Nations (2019a) and United Nations (2019b)).

Agents born in regions 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

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

where $C_{z,t,j}$, $l_{z,t,j}$, $P_{z,t,j}$, and $a_{z,t,j}$ reference, respectively, the number of agents, 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 IMF debt. Thus,

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

where $\mathcal{D}_t$ is IMF debt. IMF 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).[11] 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 (Nordhaus, 2017) is given by the following expression:

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

where J_t^A, J_t^U, J_t^L are concentrations of CO_2 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 has units "mass fraction per time step". E_t^{Land} is land-based carbon emission, which obeys the following relationship:

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

[11] The modified 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 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.[12]

Our model requires knowledge of regional climate damages and, thus, regional temperature. We compute the regional temperatures from the global temperature by adopting a popular technique from climate sciences called "pattern scaling" (see, e.g., Kravitz et al. (2017), Lynch et al. (2017), Tebaldi and Arblaster (2014), 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 $\times 1°$ latitude.

The functions relating temperature at a grid location to global average temperature are determined by pooling calculations of dozens of large-scale climate models developed by climate scientists across the world. Their calculations are organized by CMIP5 – 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, with the higher numbers reflecting higher concentration due to assumed higher forcing coefficients.[13]

[12]As will be described in section 4, we calibrate this equation by using Folini et al. (2021)'s parameter values.

[13]Each RCP scenario generates particular paths of greenhouse gases, aerosols, and other climatically relevant forcing agents over the 21st century. The RCP85 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 RCP26 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.

Our computations use the publicly available pattern scaling repository by Lynch et al. (2017).[14] Specifically, we use the CCSM4 model that follows RCP85 for all our computations. This choice minimizes our model's interpolation error is ascribing temperature to our 1-degree by 1-degree grids. Our results appear robust to the choice of RCP scenarios in connecting grid-specific and, thus, region-specific temperature to global average temperature.[15]

In forming regional average surface temperatures, the $T_{z,t}$s, 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.[16]

We model the regional TFP, $A_{z,t}$, as the product of an exogenous trend, $\tilde{A}_{z,t}$, and a regional temperature 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

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

Regional climate damages are defined as:

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

Equation (41) models regional TFP as peaking at T^*. 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 κ^+ and κ^- raise the cost of a given deviation from the optimal temperature.

In our calibration below, we choose κ^+ to relate regional damage functions to global damage functions used in the literature. We take κ^- from Krusell and Smith Jr (2018).[17]

4 Calibration

Our 18 region OLG model builds on the 17-region Global Gaidar Model (GGM) (Benzell, Kotlikoff, and LaGarda, 2017) but adds climate change and an extra region.[18] Table 1 provides

[14] The respective data sets and codes can be found under the following URL: https://github.com/JGCRI/CMIP5_patterns.

[15] See Link et al. (2019).

[16] 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 USA, whereas the naive average would be driven by cells closer to the North pole.

[17] 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.

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

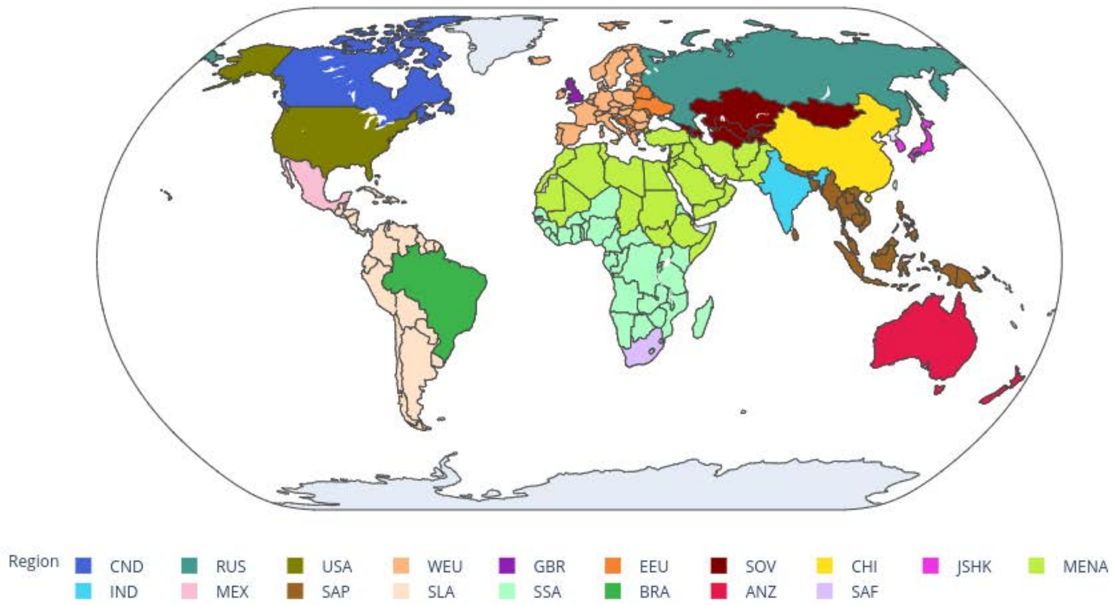

Figure 1: The 18 Regions of our model on a world map.

a list of the regions and their acronyms, whereas figure 1 displays them on a map of the globe.

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
USA	U.S.
WEU	Western Europe

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 particular, 2017 GDP values. These are used to calibrate 2017 levels of regional TFP. Energy consumption/usage data come from the U.S. Energy Information Administration (EIA). These EIA data are available in four categories: 1) coal, 2) natural gas, 3) petroleum and other liquids, 4) nuclear, renewables, and others. All data are measured in Btus. We treat these energy categories as coal, gas, oil, and clean energy. Table 3 presents region-specific GDP and energy-consumption data.

The EIA data help calibrate the region-specific CES production functions specified in (10). As in (Hillebrand and Hillebrand, 2020), we assume an elasticity of substitution between oil, coal, and gas of 2. This value lies between Acemoglu et al. (2012)'s high and Golosov et al. (2014)'s low assumed values. We measure the shares parameters $\kappa_O, \kappa_G, \kappa_C$ using data on 2017 world energy prices. Taking the 2017 \$50.8 price per barrel of West Texas Intermediate crude and assuming that the one barrel of oil contains $5.7e^6$ Btus, our 2018 price of oil equals $8.9e^{-6}$ per Btu. Analogous calculations produce a 2017 price of gas of $5.7e^{-6}$ per Btu and a price of coal of $4.5e^{-6}$ per Btu. Normalizing the sum of κ_O, κ_G, and κ_C to 1 and using (11)-(13) provides our 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 and the levels of 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 different values for α_z and β_z, we assume that one-third of this remaining output share is paid to the capital, with the rest paid to labor.

Table 2 presents the regional dependence of production on energy. 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 3 shows 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 U.S. 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 U.S. and only three-fourths that of the WEU, its carbon emissions are twice that of the U.S. and three times that of the WEU. This reflects its overwhelming dependence on coal. The U.S. is a better green citizen than China but pales in comparison with the WEU. U.S.GDP is one-fifth larger than the WEU's. However, its emissions are three-fifths larger.

Table 4 shows GDP, energy consumption, and CO2 emissions relative to the US (US values are normalized to 100). The above observations are nicely summarized in this table. Figure 10 reports total emissions by region over time in both the BAU scenario as well as under the optimal policy.

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.[19]

[19]This amount is based on 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

Table 2: Energy consumption as a share of GDP.

	$\mathcal{C}$	G	O	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%
USA	0.32%	0.83%	1.72%	0.70%	3.57%
WEU	0.26%	0.53%	1.42%	0.82%	3.03%

Table 3: 2017 GDP (in trillions of 2017 USD) and energy consumption (in quad Btus).

	Y	$\mathcal{C}$	G	O	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
USA	19.49	13.84	28.06	37.57	18.28
WEU	15.94	9.14	14.64	25.48	17.19

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

	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
USA	100.00	100.00	100.00
WEU	81.79	67.98	63.20

To calibrate region-specific productivity growth in final goods production, we rely on univariate, country-specific regressions graciously estimated by Müller, Stock, and Watson (2019). First, we aggregated the country estimates to generate regional productivity growth rates. These rates, through 2100, measured relative to the U.S. 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 U.S. growth rate. As for productivity growth in clean energy, we set it to generate a 0.5 percent per year decline in backstop energy price.

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, Kotlikoff, and LaGarda (2017). The time preference rate, ρ, is calibrated at 1.45 percent per year. Furthermore, the coefficient of relative risk aversion, σ, is calibrated at 1.45.

Based on McGlade and Ekins (2015), we calibrate global available oil reserves at 600 GtC, global available gas reserves at 400 GtC, and global available coal reserves at 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.[20] In calibrating our extraction cost parameters, we assume that extraction costs double when 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 2017 energy prices under BAU.

The resulting CO2 emissions in the BAU scenario are significantly lower than those in DICE-2016 in the Hotelling (no policy) scenario. For example, DICE BAU emissions peak in

production of clean energy.

[20]see https://www.eia.gov/tools/faqs/faq.php?id=73t=11

100 years at 70 GtCO2, whereas our model's BAU emissions peak in 50 years at 50 GtCO2. There are several reasons for the difference, widening through time starting at essentially zero in emissions paths. First, the DICE model assumes zero extraction fossil-fuel extraction costs. Under this premise, all hydrocarbon reserves are consumed. In DICE, this assumption results in a near-zero initial price for dirty energy under BAU. In contrast, our model, run with no policy, closely matches the current uses of all energy resources and their current prices. Our model, to recapitulate, includes extraction costs, which rise through time as fossil fuel reserves are depleted and suffice to strand portions of the three stocks of reserves. Second, unlike DICE's assumption that output is produced via a time-varying Leontief function of energy and a Cobb–Douglas production function of capital and labor. Our model's final goods production function is Cobb-Douglas in all three inputs. This permits fairly high substitutability between energy and other factors. Hence, with rising energy prices, the demand for energy, in general, and fossil fuels, particularly, declines. Finally, the two models differ with respect to the substitutability, explicit in our model, implicit in DICE, between clean and dirty energy. Figure 12 depicts BAU emissions over time. Our BAU emissions lie between the RCP6 and RCP4.5 scenarios. This is a relatively optimistic path of emissions relative to those projections. However, this does not imply low BAU damages in our model due to other factors, particularly our updated impact of carbon concentration on global temperature.

The parameters for the climate block of the DICE model are adopted from Folini et al. (2021)[21] 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 $J_0^A = 850.09$ GtC, $J_0^U = 764.95$ GtC, $J_0^L = 1799.12$ GtC, $T_t^A = 1.278$ 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 (Folini et al., 2021).

As in Folini et al. (2021), parameter matrices Φ^J and Φ^T are calibrated 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 $\kappa^+ = \kappa^- = 0.001$. Recall, these are

[21] Dietz et al. (2021) among others criticize 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.

Table 5: Convergence of non-U.S. regions' productivity relative to U.S. 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%	

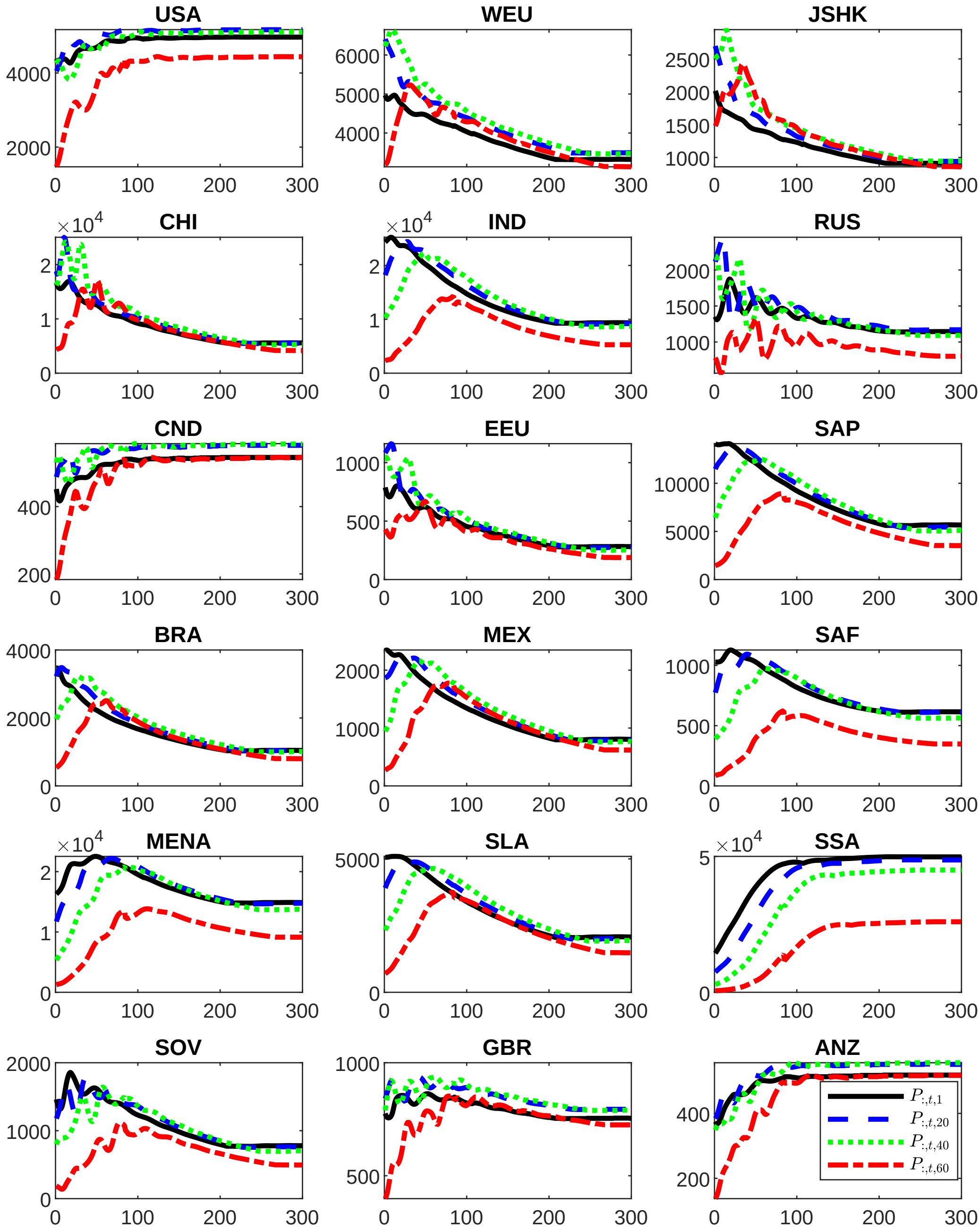

Figure 2: Projected population counts (in millions) of specified age-groups as a function of years (starting in the year 2017).

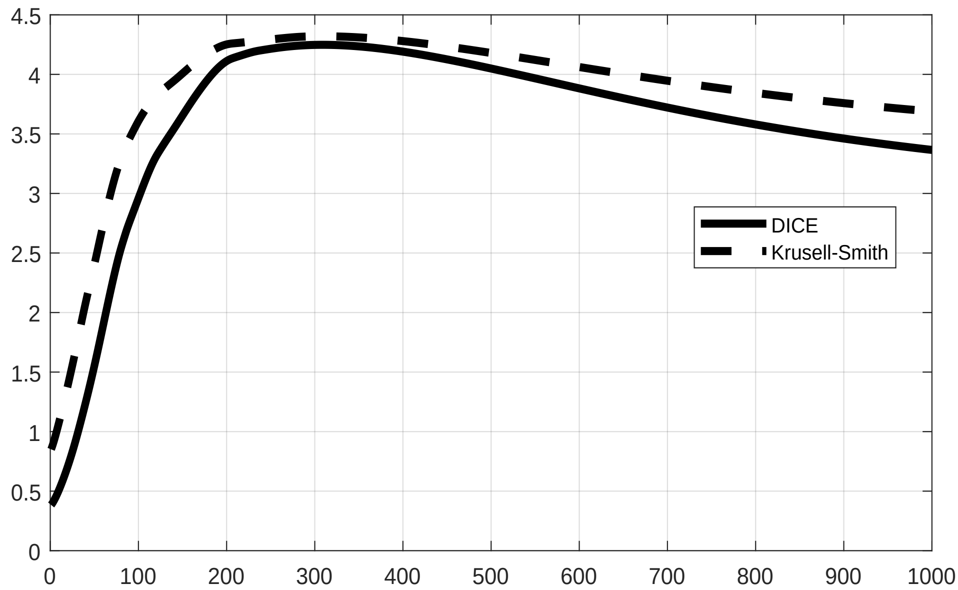

Figure 3: Comparing the DICE and Krusell-Smith (Krusell and Smith Jr, 2018) global damages as share of global GDP (measured in %) by year (starting in our calibration in 2017).

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 KS damage function. 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 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 κ 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 $\kappa^+ = 2\kappa^*$, $\kappa^+ = 4\kappa^*$, $\kappa^+ = 6\kappa^*$, where $\kappa^* = 0.0015$ corresponds to the value in the most optimistic calibration. We label these as our 2x, 4x, and 6x cases. In all cases, κ^- remains fixed at κ^*. Figure 4 plots the KS productivity function (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

In this section, we discuss the key findings from our simulations. In section 5.1, we will present the results from our baseline model, whereas in section 5.2, we discuss how do our baseline

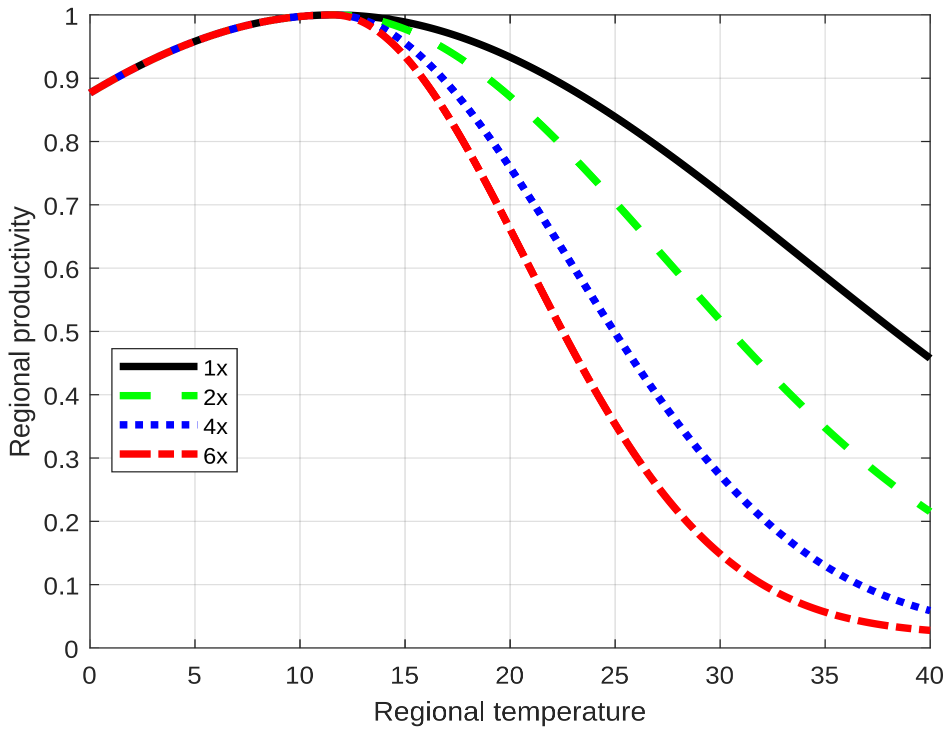

Figure 4: Alternative calibrations of the KS-type productivity functions as a function of temperature, measured in °C.

results change if we assume that only some of the regions introduce a carbon tax.

5.1 Baseline Results

This section presents findings beginning with table 6, which displays key simulation results for each specification of the damage function. The 6x function is, in our view, of most relevance from a certainty equivalent perspective. Unfortunately, our convergence method, which works precisely for 1x through 6x damages, fails for 8x and higher multiples of k^+. This said, we can infer from our 1x through 6x simulations that damages would continue to substantially increase with higher damage factors. The first four rows of table 6 yield six important messages about the global economy absent policy (i.e., with BAU). Message one is that global average temperature rises from roughly 3.5 to 4.5 degrees Celsius regardless of which damage function is considered. Message two contained in the table is that the global damages can be very high. Along the 6x transition path, they peak at 17 percent of global GDP. Message three is that regional damages can dramatically exceed global damages. In the 6x case, the maximum regional damage in the region hit hardest – India – under the BAU transition is 43.82 percent of regional GDP. Message four contained in the table is that paradoxically, higher BAU damages can limit global warming not by altering the physics of climate change but by reducing output and, thereby, reducing emissions. Indeed, the maximum BAU temperature rise with 6x damages is 0.76 degrees, which is lower than with 1x damages. Message five is that the extent of global damages is highly sensitive to the shape of the upper tail of the damage function. With the 6x parameterization, peak global and regional damages are almost four times larger than with the

Table 6: Key simulation results.

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

1x parameterization. Almost one-fifth of global peak GDP losses are, in this 6x case, well within the recent projections of economic damages from climate change. For example, Hänsel et al. (2020) strongly criticizes the DICE damage function, advocating more realistic specifications that lead to much larger damages for a 3 degree or larger increase in temperature. In fact, using DICE-2016 emissions and the climate calibration used in this paper, Folini et al. (2021) obtain global damages of more than 20 percent of GDP. Finally, message six is that 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, in this case, six key findings. First, the optimal initial carbon tax is highly sensitive to the damage function, ranging from 21 per ton to 97 per ton for the 1x through 6x functions. Second, the optimal carbon-tax growth rate is 1.5 percent for all but the 2x function. 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. That is, the function is fairly flat at the optimum. Hence, 1.5 percent real growth appears to be the best or close to the best growth rate for our range of damage functions. In our global (single-region) model (cf. Kotlikoff et al. (2021)), a 1.5 percent real growth rate proved to be 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 UWI is equivalent to not taxing carbon but, 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 functions would, of course, spell even higher UWI gains. Fourth, optimal UWI taxation keeps the increase in global temperature from exceeding 1.5 degrees Celsius for all sized damage functions. Fifth, 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 reports peak BAU losses and gains by region. It also shows regional net losses for the four damage functions as well as maximal global losses and extreme global temperature for each case. The list comprises the present value of consumption, regional damages, regional temperature, and oil, gas, and coal usage. As the table clarifies, increasing the damages sensitivity parameter 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 due to general equilibrium effects. When damages are higher, demand for dirty energy is lower. The initial optimal tax increases from $21 per ton of CO2 to $97 per ton of CO2. The growth rate of the optimal tax is stable and equal to 1.5 percent per year except in the 1x case, where the growth rate equals 2 percent per year. Welfare gains range from 0.58 to 4.35 percent. It is noteworthy that the higher the damage, the more the long-term interest rates increase in the optimal policy scenario.

Figures 5-11 show paths of 6 key simulation outcomes assuming 6x damages.

We start by discussing Figure 5. The latter shows how regional temperatures evolve in the 6x-damage case under BAU (in black) and 6x-optimal UWI policy (in red). Two things are worth mentioning. First, climate change will raise temperatures across the globe. Second, there will be very large temperature increases everywhere. RUS, CND, and SOV, for example, see their temperatures rise by 2.8, 2.7, and 2.4 degrees, respectively.

Figure 6 shows the extremely heterogeneous nature of climate damages. Of all 18 regions, 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 U.S., 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 U.K., peaking at just 2 percent of GDP. Russia and Canada incur climate gains, peaking above 2.5 percent of GDP and reaching almost 4 percent of GDP, respectively. Other regions with extremely high damage are ANZ, SSA, SLA, SAF, MEX, BRA, MENA, and SAP. 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 7-9 show that under BAU, the different regions stop using dirty energy at very different points of time. For example, coal usage in the WEU comes to an end in the year 2070. It ends in SAF in the year 2210. The regions that end coal usage earliest are WEU, EEU, SLA, and BRA, with the latest being SLA in 2075. The regions that end coal usage latest include SAF, SSA, and MENA.[22] The last user of coal is SSA, which stops coal burning in 2215. China ends coal usage in 2090. The U.S. burns its last ton of coal in 2105.

Figure 10 depicts the remarkable reduction in each region arising, in the 6x case, from the optimal UWI carbon tax. For example, under the optimal policy, China essentially ends its use of coal and essentially eliminates emissions within 20 years. The general emissions-reduction story is similar in other regions, although the magnitude of the emissions reductions is much smaller.

Figure 11 is also quite striking. It presents region-specific, 6x net transfers made to current and future generations as a share of the present values of their remaining or entire lifetime consumption. The horizontal axis indicates the cohort year of birth.[23] Note that net transfers are positive in all regions for the initial elderly and middle-aged. They are positive in almost all regions for the initial young. In RUS and CND (except for a few generations), net transfers

[22]Surprisingly, the data indicate the oil-rich Middle East uses some coal in producing energy.

[23]For example, negative 10 on the MENA chart's horizontal axis references the age-30 MENA generation in 2017.

Table 7: Peak BAU losses and gains as percentage of GDP.

	1x	2x	4x	6x
USA	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

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, namely global warming.

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 IMF debt. At first consideration, this sounds extremely onerous and unfair. After all, India is among the world's poorer regions. Why should it be effectively required to subsidize far richer regions, like the U.S. (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 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 11 deserve an explanation. To begin, 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.

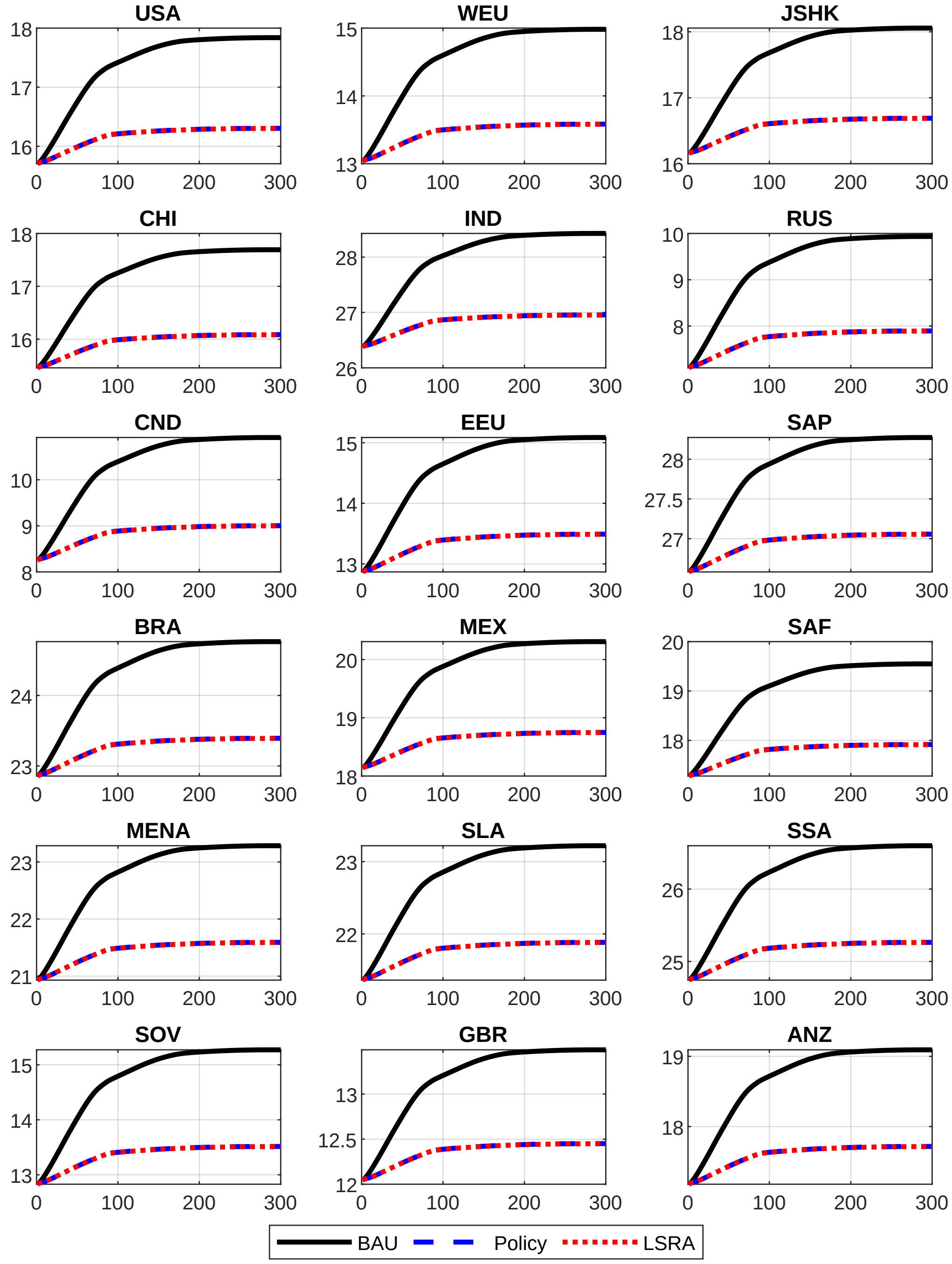

Figure 5: Regional temperature in the 6x-damage case (measured in °C) as a function of years (starting in 2017).

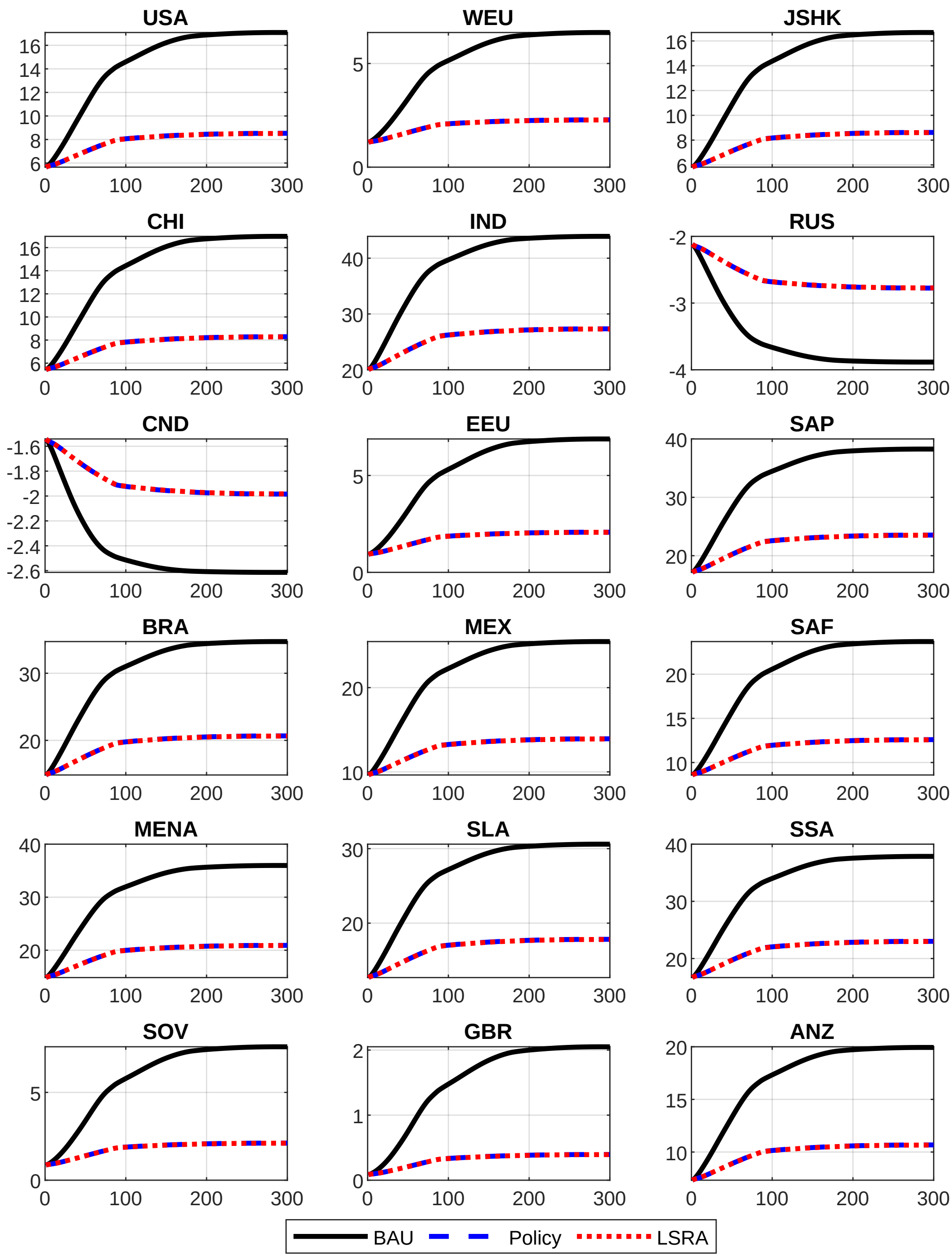

Figure 6: Regional damages in the 6x-damage case (measured in percentage of regional GDP) as a function of years (starting in 2017).

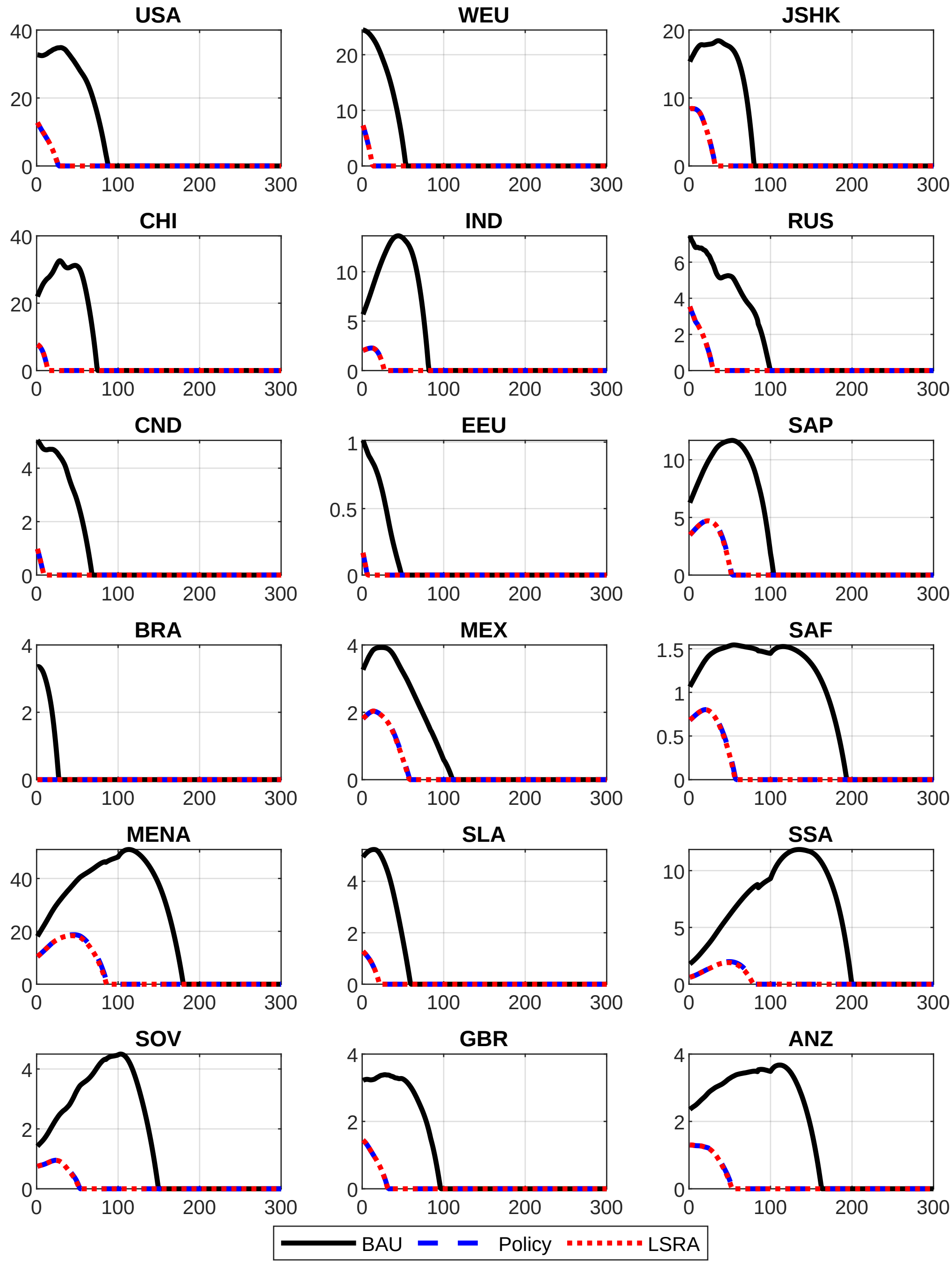

Figure 7: Oil consumption in the 6x-damage case (measured in quad Btu) as a function of years (starting in 2017).

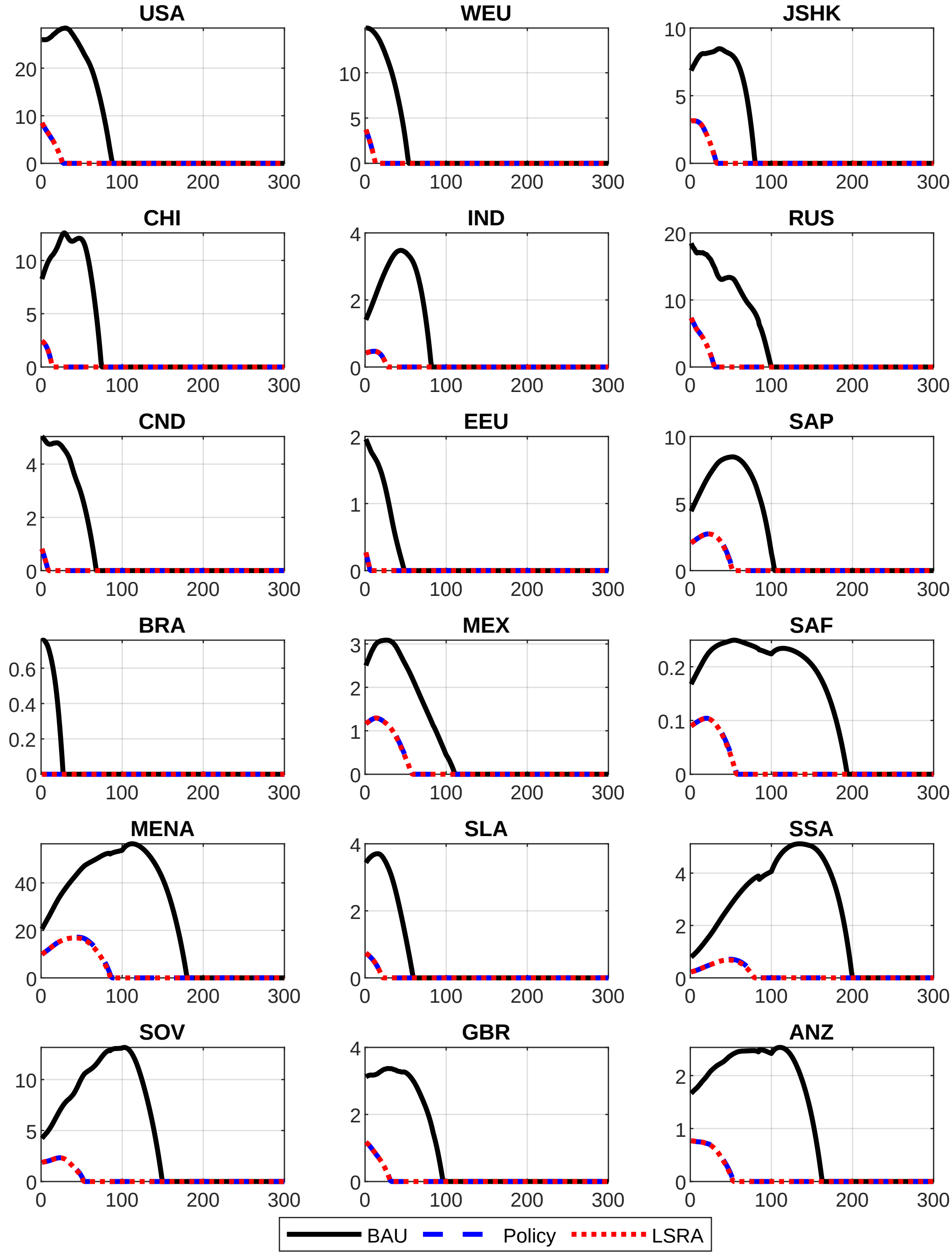

Figure 8: Gas consumption in the 6x-damage case (measured in quad Btu) as a function of years (starting in 2017).

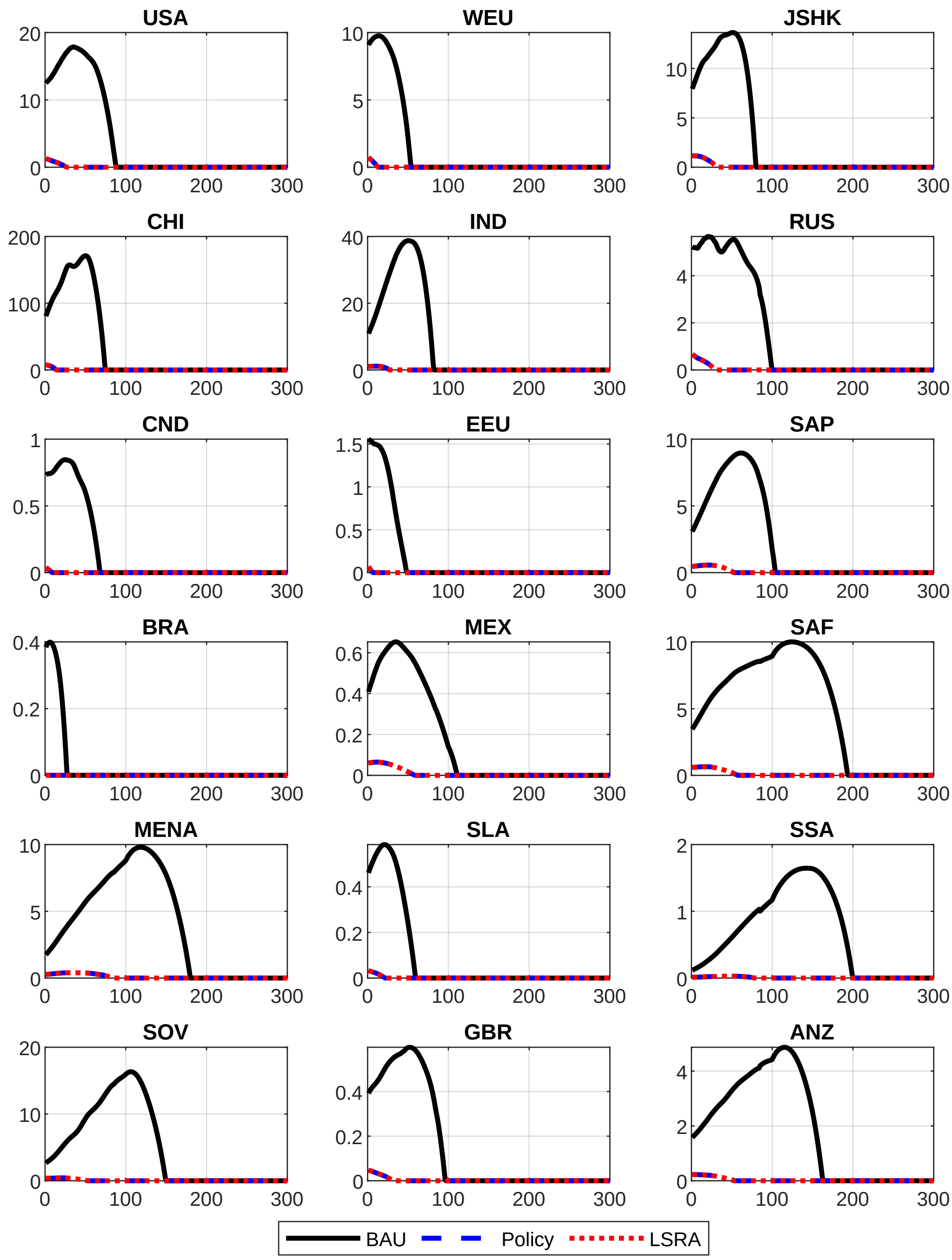

Figure 9: Coal consumption in the 6x-damage case (measured in quad Btu) as a function of years (starting in 2017).

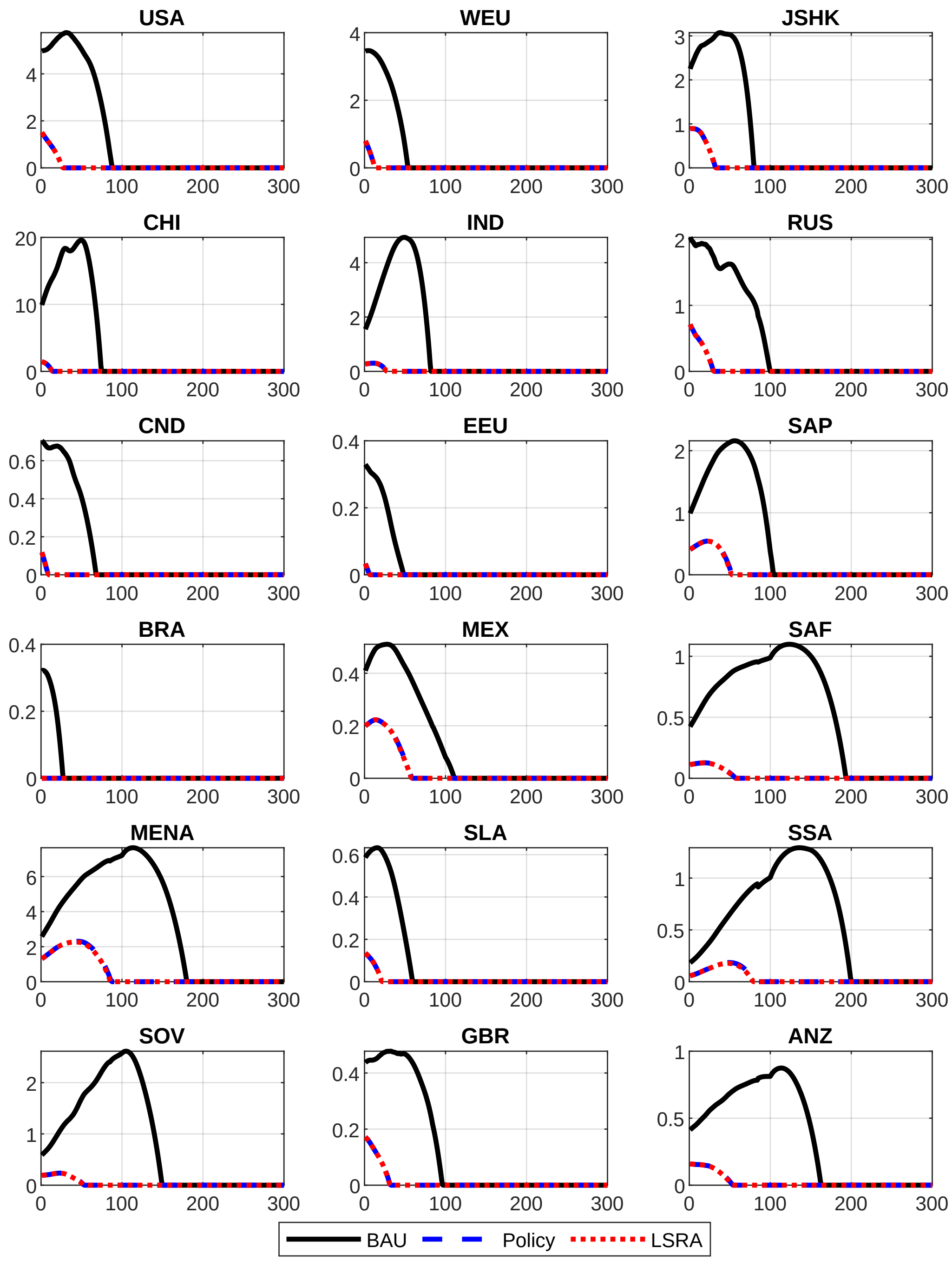

Figure 10: Total CO2 emissions in the 6x-damage case (measured in GtCO2) as a function of years (starting in 2017).

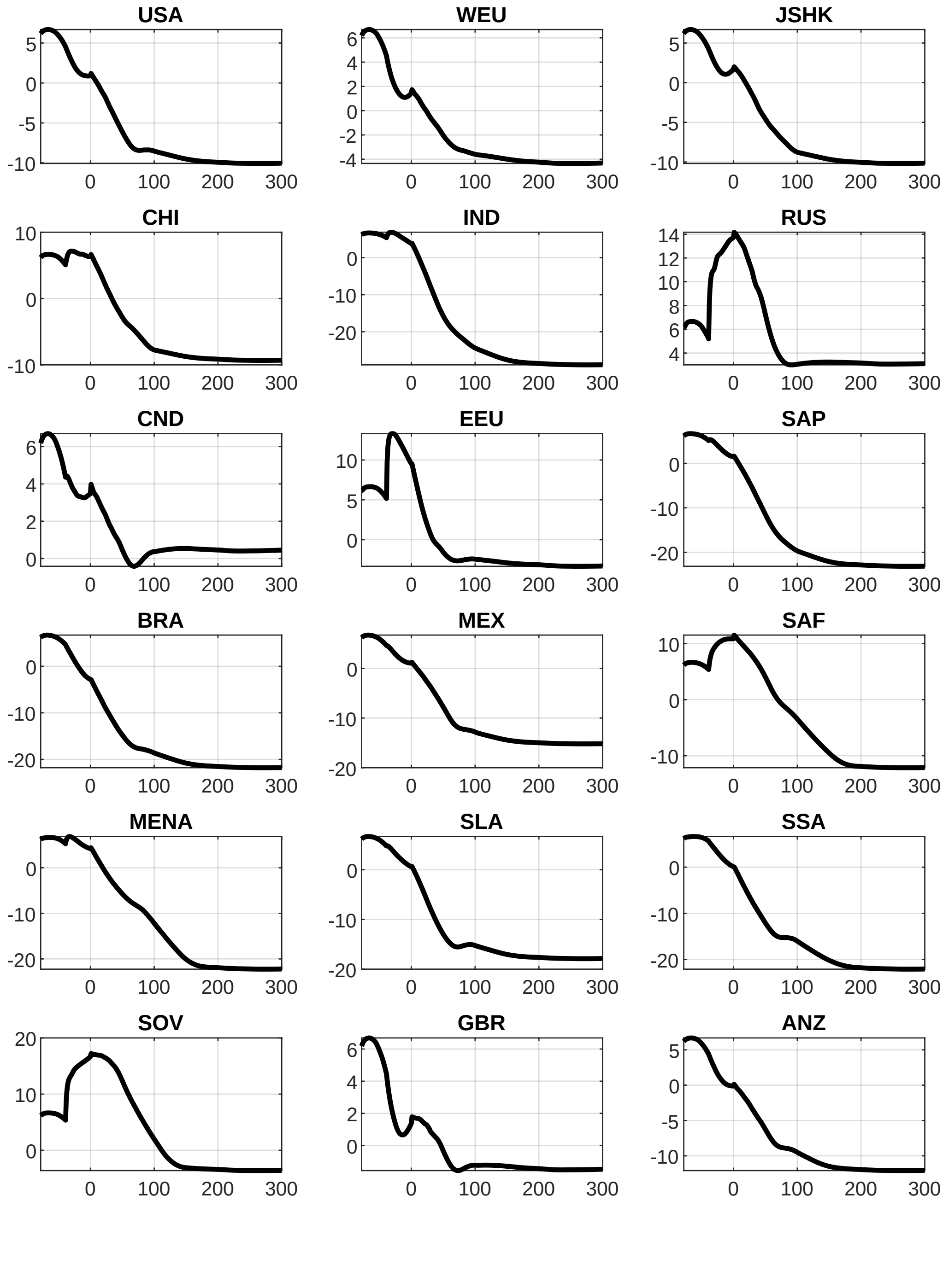

Figure 11: Net transfers as a share of the present value of remaining or full lifetime consumption in the 6x-damage case (year 0 is 2017).

5.2 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 12 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.

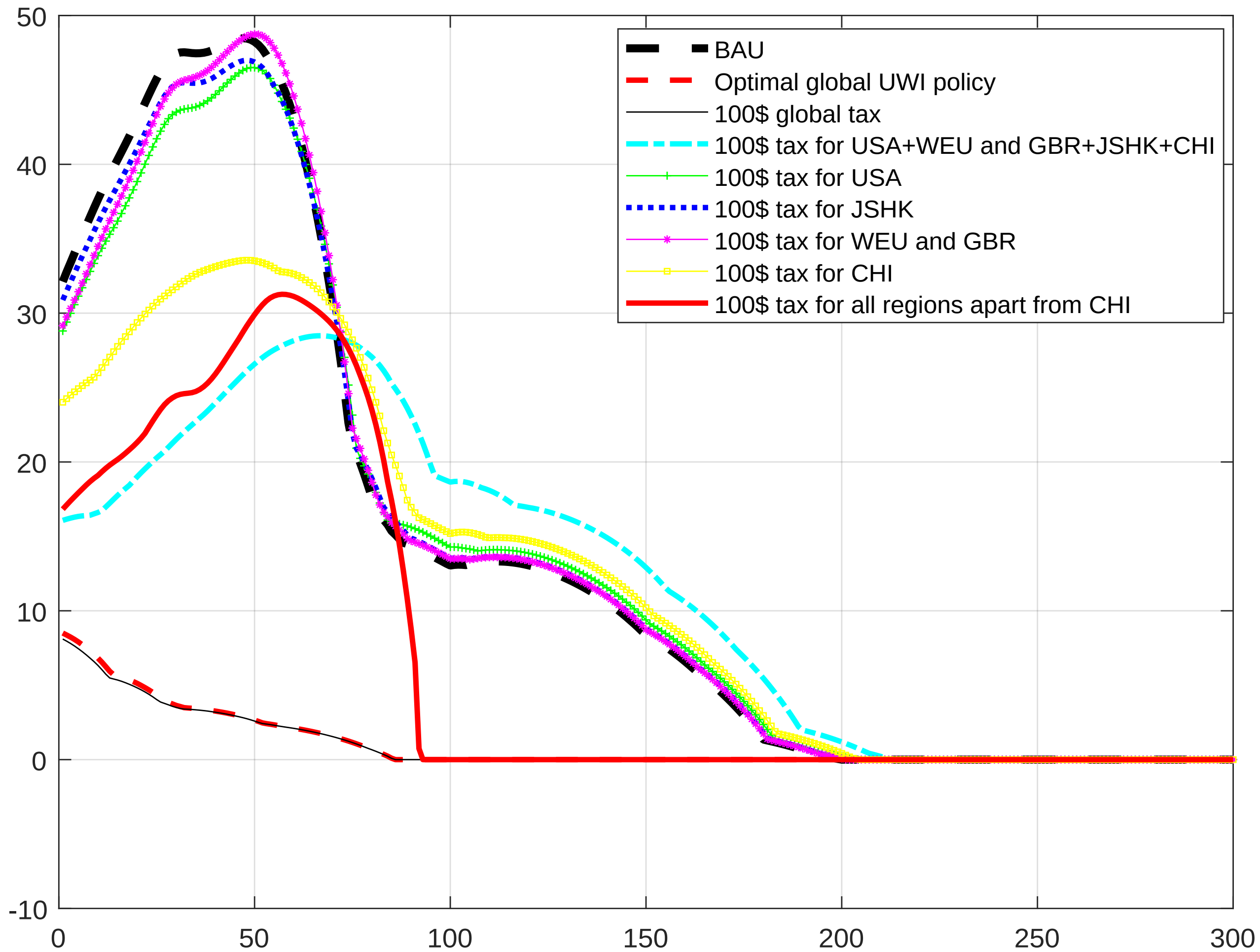

Figure 12: Global CO2 emissions (measured in GtCO2) in the 6x-damage case under alternative coalitions as a function of years (starting in 2017).

As the figure shows, taxes levied in only a single region only have sizable effects if that region is China. A $100 carbon tax, growing at 1.5 percent annually but levied only in Western Europe or only in JSHK, has almost no effect on global emissions. And were the US the region to adopt such a policy, it would have fairly small effects. This is reflected in the optimal taxes for these cases.

Table 8 shows that the issue of partial participation is even more troubling. Take the case of China being the sole participant. It's optimal carbon tax is just $9, which is nowhere near the

Table 8: 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

$100 tax considered in figure 12. 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.

5.2.1 Delaying Carbon Taxation and the Green Paradox

Postponing the implementation of the optimal tax until 2040, taking into account its growth, the UWI gains are reduced 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. 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. Delaying optimal carbon taxation accelerates the burning of fossil fuels, as the Green Paradox (see Sinn (1982)) teaches. For example, the production of fossil fuels in terms of CO2 emissions in 2030 is 13 percent higher than under BAU in the 6x case.

6 Conclusion

Climate policy is generally viewed as a zero-sum game pitting future against current generations and regions that benefit from climate change against regions that do not. This paper shows that carbon-tax policy can improve the welfare of current and future generations regardless of the region in which they live. Indeed, carbon taxation coupled with the 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. 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.

For our high-damage case, the optimal UWI carbon tax is roughly $100 per ton, 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 produced, burned, and used to harm our planet's future inhabitants. 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 very important. The first is China's participation. The second is the immediate carbon-tax implementation. China's failure to participate reduces the potential UWI gain in our baseline calibration from 4.35 percent to 2.50 percent. And waiting until 2040 to tax carbon, even at the rate that would otherwise be implemented under an optimal policy, reduces the potential UWI gain from 4.35 percent to 2.73 percent.

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