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ABSTRACT

Climate change will impact current and future generations in different regions very differently. This paper develops the first large-scale, annually calibrated, multi-region, overlapping generations model of climate change and carbon policy. It features region-specific temperature and damage functions with the phased impact of emissions on global and regional temperature calibrated to the latest scientific evidence. Absent policy, climate change may, over time, dramatically reduce GDP in most regions, with India, Brazil, and the South Asian Pacific suffering catastrophic damages. Carbon taxation, coupled with region- and generation-specific transfers, can both correct the carbon externality and raise the welfare of all current and future agents across all regions by 4.3 percent. The impact on the use and duration of fossil fuels is dramatic as is the reduction in the path of global emissions. However, achieving completely uniform welfare gains leaves future generations in particular regions facing exceptionally high compensatory payments. Fortunately, a carbon tax-cum redistribution policy that limits this burden for any generation in any region to less than 10 percent, measured on a consumption-equivalent basis, can deliver a 4.0 percent or higher welfare gain for all peoplekind – present and future. However, carbon taxes set through time, at carbon's marginal social cost, do far too little to mitigate climate change unless all major emitters, particularly China, adopt them and do so immediately.

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1 Introduction

Our problems are man-made; therefore, they can be solved by man. These inspiring words by President Kennedy apply in full measure to anthropogenic climate change with its massive projected damages – arguably humankind's worst externality. This paper develops a large-scale, multi-region, overlapping generations (OLG) model to study climate change's cumulative damage to global and regional output as well as carbon taxation's mitigation potential. Our model features 18 regions inhabited by 80 overlapping, selfish generations. Each region's demographic conditions and projections are closely calibrated to UN data. 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 that proxies for regional limits on green-energy production. Our equations connect carbon emissions to atmospheric carbon concentration and, thereby, mean global temperature accord with the latest climate science and projections.

Our focal carbon policy is not just Pareto improving. It is uniform welfare improving (UWI), indeed, the policy that delivers the highest uniform welfare gain to all cohorts no matter their year or place of birth. For our preferred calibration, an initial $100 carbon tax rising annually at a 1.5 percent coupled with appropriate cohort- and region-specific transfers limits global damages in 2100 (2150) by 38 (42) percent. Hence, rather than experiencing a 14.6 percent drop in global output by 2100, compared to its level absent climate change, global output is only 9.1 smaller. For India, the hardest hit region, our optimal UWI carbon tax limits the percentage decline in end-of-century output from 38.5 percent to 26.2 percent. For the U.S., the reduction in 2100 GDP is 13.9 percent without the UWI policy and 8.0 percent with it. China's respective values are 13.7 percent without policy and 7.8 percent with policy. For Canada, which benefits from climate change, climate change will raise GDP in 2100 by 2.5 percent. The UWI policy reduces Canada's 2100 GDP by 0.6 percent relative to its no climate-change level. In short, absent policy, climate change will, in general, materially undermine economic growth, but do so differentially by region. Yet, carbon taxation, coupled with the appropriate interregional and intergenerational redistribution, can substantially limit the damage while making everyone, across space and time, equally better off.

Background. As with other externalities, climate change reflects market failure, i.e., no cross-region, let alone cross-generation markets for agents to buy or sell abatement. That is the downside. The upside is that correcting the externality permits a continuum of Pareto improvements - efficiency gains that can be allocated to all or some segment of humankind. Identifying the Pareto frontier is a standard operating procedure in analyzing externality problems. It dates to Pigou (1920)'s path-breaking work. However, starting with Nordhaus (1979), climate-change modelers have posited a social planner with no concern with the status-quo (i.e., "business as usual" (BAU)) welfare distribution and, consequently, no inherent interest in Pareto improvements. This framework begs the question of which social planner with which degree of intergenerational altruism, as captured by the planner's time preference rate, to invoke.

Much of the more recent optimal carbon-tax literature (see, e.g., Golosov et al. (2014)) emulates the social-planner framework by positing 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 single-agent framework begs the question of *the* single-agent's time preference rate, which controls the intergenerationally altruistic economy's regard for current versus future dynasty members. As in the planner setup, the single-agent approach considers a single-time preference rate. Doing otherwise would endow the most altruistic dynasty with the highest saving rate and eventuate in its holding all of the economy's wealth. The single-agent model has another major theoretical drawback. Intermarriage across any two dynasties links the two dynasties altruistically and, given even a very small rate of intermarriage, links the entire planet altruistically. This issue was first pointed out by Kotlikoff (1983) and then studied in detail by Bernheim and Bagwell (1988). However, the most important reason for questioning the single-agent approach is the abundant evidence, at least in the US, rejecting operative intergenerational 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).

Modelling Choice. Kotlikoff et al. (2021) introduced the concept of a UWI carbon tax in an OLG model, albeit with a single region. Developing, as we do here, a regional model raises major modeling, methodological, computational, and calibration challenges. However, doing so makes it possible to consider ten critical climate-change realities.

The first is that some regions benefit from climate change. The second is that given nonlinearities in climate damages, one needs to disaggregate regionally region to accurately calculate the optimal UWI global carbon tax and the generation- and region-specific net transfers needed to implement Pareto improvements. Third, the magnitude and duration of fossil-fuel usage differs according to region. Fifth, changes in the course of GDP due to carbon policy will differ by region, which, in turn, will impact global emissions, which, in turn, will impact region-specific GDP paths. Consequently, disaggregation presents a more multifaceted simultaneity challenge for calculating optimal carbon policy. Sixth, region-specific generations that are slated to suffer the most from climate change will, under UWI policy, need to pay the highest taxes to compensate for their out-sized climate gains. Collecting such taxes raises questions of compliance and whether limiting compensatory taxation by some will come at a major loss of Pareto gains to others. Seventh, certain regions, such as China, may not agree to tax carbon. Consequently, a regional model is needed to understand what welfare gains subsets of regions can achieve on their own. Eighth, disaggregating by region raises the question of how to maintain carbon cooperation across regions through time. The ninth is the need to develop an algorithm to compute global, intertemporal Pareto policies. And the tenth is to understand how policy delay limits welfare gains in a realistic multi-region setting.

Our model 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. Each region's land is in fixed supply, which proxies for region-specific physical limits on generating clean energy. This input fixity ensures that clean energy is always produced, including in the early stages of the transition when its technology is limited. As for dirty energy, its production is, as indicated, based on the increasingly costly extraction of fossil fuels. Since our model is deterministic and agents are indifferent between holding particular assets, we treat dirty energy companies as globally owned.

Under BAU, that is, no policy, our assumed technological advances in clean energy bring an end to dirty energy's use at region-specific dates. Regions with limited initial clean-energy use have, per our calibration, low initial clean-energy productivity. Consequently, they take longer to wean themselves off fossil fuels. Thus, under BAU, Sub-Saharan Africa will use dirty energy through the end of the next century, whereas the US will stop much sooner. Unfortunately, even though clean energy's productivity growth brings an end under BAU to carbon emissions, the regional carbon end dates are sufficiently distant to permit dirty energy to wreak long-lasting, major damages. Moreover, the worst damage arises in regions that house the vast majority of the world's current and future populations.

As indicated, our model's UWI policy has two components. First, it taxes carbon emissions at time-varying rates equal to year t's social cost of carbon (SCC) – the present value of the future global cost of an extra current ton of emissions produced in t.[1], the equilibrium is unchanged. Second, it lump-sum redistributes (compensates) on a generation- and region-specific basis to ensure that all cohorts in all regions experience an identical welfare gain. Given that we are pricing the externality correctly at each point in time, our algorithm delivers the maximum efficiency gains available. In addition to studying UWI carbon tax policy, which shares all efficiency gains uniformly with all generations across all regions, we entertain UWIF and UWIL policies. The former allocates all efficiency gains solely to future generations. The latter allocates all gains to existing generations. As for carbon-tax revenues, they are lump-sum rebated to dirty energy producers on a period-by-period basis.[2] As pointed out by Goulder (1995), carbon revenues could be used to reduce other distortions, delivering a "double dividend" and, thus, a higher UWI gain than that computed here.

Who pays (measured as a share of lifetime consumption) the most in compensatory net taxes? Clearly, it is future generations in regions that gain the most from a cooler planet. However, their tax payments are worth the price, leaving them better off to the same percentage degree as all current and future generations in all other regions. How can the policy's redistribution be implemented in practice? An international authority, such as the International Monetary Fund, could issue green bonds to initially make net transfers and subsequently collect taxes to service the debt.

Our study builds what we believe is the first large-scale OLG integrated assessment model (IAM) with region-specific emissions and damages. As in Krusell and Smith Jr (2022) and several other recent studies, our model determines region-specific temperatures – required to derive region-specific damages – based on a climate-science technique called "pattern scaling". The latter method can be used to compute the local temperature at grid resolutions as fine as 1-degree latitude by 1-degree longitude, given the global average temperature.[3] Our study also handles key feedbacks, specifically the impact of global temperature on region-specific temperature, the impact of region-specific temperatures on region-specific damages, the impact of region-specific damages on region-specific production, the associated region-specific dirty energy on regional emissions, and the sum of regional emissions determining global emissions and, thus, global temperature. In determining region-specific damages, we rely on Krusell and Smith Jr (2022)'s damage function (albeit based on our calibration), which admits negative damages while delivering approximately the same aggregate damages as the DICE-2016 (henceforth, simply DICE) model (Nordhaus, 2017). Finally, we use Folini et al. (2021)'s recent study that employs state-of-the-art climate modeling to re-calibrate Nordhaus' DICE functions governing the relationships between global emissions, carbon concentration, and global mean temperature.

[1]Taxing fossil fuel extraction rather than fossil fuel usage, i.e., operating on the other side of the market, would generate identical results.

[2]Rebating carbon revenues to dirty energy suppliers does not alter outcomes. For example, were we 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., Lynch et al. (2017), Kravitz et al. (2017), and references therein.

Preview of Findings. In our baseline, high-damage scenario, the increase in the planet's mean surface temperature through 2200, absent policy, is approximately 3.7 degrees Celsius. This is moderately good news for Canada and Russia, whose GDP levels in 2200 are 2.6 percent and 3.9 percent higher, respectively, compared with no climate change. However, the remaining 16 regions suffer, with India, the South Asian Pacific, Sub-Saharan Africa, and the Middle East being hit the worst. Relative to a world with no carbon-based damage, climate change lowers their 2200 GDP levels by 43.9, 38.3, 37.9, and 36.0 percent, respectively. As for global GDP, its 2200 value is reduced by 16.7 percent. In our BAU scenario, dirty energy lasts through 2217 years. In contrast, optimal UWI policy endogenously ends all dirty energy usage in 2103 and dramatically reduces cumulative oil, gas, and coal consumption by 84.4 percent, 86.2 percent, and 98.1 percent, respectively. These major impacts limit the rise in the global mean surface temperature to 2.1 degrees Celsius. Moreover, the peak global GDP loss declines from 16.7 percent to 9.1 percent. Peak regional damages now range from 0.5 percent to 27.8 percent of GDP compared with the range from 2.1 percent to 43.9 under BAU. 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 damages by 44.3 percent.

How large is the optimal UWI gain? It is 4.3 percent measured as a consumption compensating variation. Thus, implementing UWI policy is equivalent to increasing the annual consumption of each cohort, whether already born or yet to be born, by 4.3 percent under BAU. Implementing UWI policy requires substantial inter-generational and inter-regional net transfers. The largest transfers, around 15 percent of annual and, thus, lifetime consumption, are made to current and near-term generations in three regions, namely, Russia, Former Soviet Central Asia, and Eastern Europe. These regions experience particularly 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.

In contrast, Indian generations born after the year 2200 face the largest taxes – roughly 40 percent of lifetime consumption. This reflects the huge benefit future Indians accrue from carbon taxation. Generations born in the long run in the Middle East, Latin America excluding Mexico and Brazil, Sub-Saharan Africa, Brazil, and the South Asian Pacific face net taxes equal to roughly 30 percent of their lifetime consumption. 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 equivalent to almost 15 percent of lifetime consumption.

The time consistency problem raised by the UWI solution is apparent. Once the danger of climate change has been reduced, policy beneficiaries may choose not to service outstanding green bonds or refuse to do so beyond a limit. One response is to consider UWIF policy, which limits the UWI gain to future generations, leaving, as mentioned, current generations at their BAU levels of remaining lifetime utility. The 7.7 percent UWIF gain is, as expected, significantly higher than the 4.3 UWI gain. Moreover, UWIF policy does reduce the very high taxes facing many future cohorts. However, it still leaves future generations in otherwise badly hurt regions facing very high net taxes. In India's case, the net tax peaks at 38.2 percent with the UWIF policy rather than 39.9 percent with the UWI policy.

As an alternative, we consider the aforementioned UWIL policy, where the L refers to limiting any generation's net tax to 10 percent of their lifetime consumption. Under UWIL, all generations in all regions whose tax is not limited experience a 4.0 percent welfare gain. All tax-limited, region-specific generations experience a larger welfare gain. For example, India's peak gain is 35.6 percent for the generation born in 2285.

Another sensitivity question concerns short- and medium-term substitutability between clean and dirty energy in production. Clearly, jetliners can't yet fly on battery power. But very small planes already can – something unthinkable 30 years back. In this analysis, we posit gradual increases, over nine decades, in the elasticity of substitution in production between clean and dirty energy. The differences in results are predictable – significantly more use of dirty energy, particularly coal, in the short run and roughly 15 percent higher damages. Nonetheless, our basic conclusion is little affected by this assumption. Specifically, the optimal UWI path of carbon taxation is barely affected. The same holds for the size of the UWI welfare gain.

One of our model's key advantages is the ability to assess carbon taxation enacted by only a subset 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.[4] This said, the emissions reduction achievable in this century by any coalition that excludes China is far less than half of the reduction were China to be included. In short, China's participation in carbon policy is a sine qua non for real progress against climate change.

Another finding involves Sinn (2009)'s *Green Paradox* – the proposition that delays in implementing carbon taxation can, due to dirty-energy producers' adoption of a *use it or lose it* strategy, dramatically undermines the value of carbon taxation. Indeed, it could render carbon taxation counterproductive. *Use it or lose it* is of most concern when fossil fuels can be extracted at zero marginal cost. Since our model features costly extraction, delay in policy initiation is less of a concern. Unfortunately, the size of the UWI gain is still reduced by 35 percent – to 2.8 percentage points – if the policy's implementation is delayed for 20 years.

Our model also provides insight into a key issue that is largely independent of climate change and climate policy, namely, the future of economic power (i.e., the regional distribution of GDP). Thanks to catch-up productivity growth, China will become the world's dominant economy by the century's end, accounting for almost one-third of world GDP compared with roughly 16 percent today. This is true despite its projected roughly 400 million population decline through 2100. In contrast, the US global GDP share will decline from a quarter now to 16 percent in 2100. In short, China and the US will switch economic places in the coming decades.

The climate-relevant question is whether a carbon-tax policy will impact growth rates enough to materially change shares of world GDP in, for example, 2100. Our model's unequivocal answer is no. With or without carbon taxation, the distribution of long-term global GDP shares is little affected. Yes, India and other regions hurt most by climate change do lose some ground. But the Chinese and U.S. 2100 shares of output are essentially unchanged whether or not there is major carbon damage, let alone carbon policy that ameliorates that damage. The simple explanation is found in the standard specification, emulated here, of climate damage. It total factor productivities proportionately based on global temperature. Yes, our model entertains different damage functions and, thus, different global temperature-determined percentage

[4] This would entail all regions but China taxing carbon at the global SCC value and the IMF or a similar agency redistributing welfare gains among generations in all regions apart from China to achieve a UWI gain.

reductions in TFP, depending on the initial prevailing temperature. But the U.S. and China have similar initial climates and, thus, experience, through time, very similar proportionate GDP declines due to the rise in global temperature. Thus, labor-productivity catch-up growth, which happens on a faster scale than climate damage, is the dominant growth driver with or without climate damage and with or without carbon policy, given climate damage – even major climate damage.

The remaining article is organized as follows. In section 2, we proceed with a brief review of the related literature. Section 3 presents our model. Section 4 describes the model's calibration. Section 5 presents our 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 presence of natural resources. Howarth and Norgaard (1992) introduced damages to the production function from environmental degradation and studied the problem of sustainable development.[5] 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 latter two studies 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 (1991a), using a standard OLG model, emphasize 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.[6] The continuum of available Pareto improvements holds in our setting as it does in general. However, only the UWI policy path treats everyone equally, at least percentage-wise. Moreover, a carbon-tax cum net transfer policy delivering equal percentage gains to all current and future generations, no matter their region, seems likely to gain universal support. The same is true of UWIL policy since everyone would have a vested interest in ensuring the carbon-tax policy is sustainable.

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

[5]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) do 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.

[6]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.

debt policy to achieve Pareto improvements in the context of adverse climate change.[7] However, these models differ from ours in two important ways. First, they confine environmental damages 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.

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, 1996, 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 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 assume international capital mobility. Interestingly, their model's optimal tax policy is independent of transfers across regions since, with identical homothetic utility across all agents, neither the interest rate nor emissions are affected by the wealth distribution. This is quite different from our results, where transfers across generations can have large effects on the world interest rate.

Krusell and Smith Jr (2022) consider a model with $19,000$ regions and studies the 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 extremely cold regions gain and other regions lose via climate change, a Pareto-improving carbon tax requires transfers to the extremely cold regions. Below, we use the same functional form for specifying regional damages as proposed by Krusell and Smith Jr (2022), but apply our calibration.

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 model's structure is very different. In particular, our model includes finite-lived, selfish agents, dirty energy and capital mobility, and region-specific technologies for producing output. In addition, we focus on Pareto efficiency rather than social welfare. The difference in objective functions non-withstanding, Cruz and Rossi-Hansberg (2021) estimate local climate damages generally in line with our estimates.

A series of papers on the economic geography of climate change (Peri and Robert-Nicoud,

[7] 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.

2021) are also of relevance. They discuss how climate change yields heterogeneous effects across space, and they stress that geographic mobility as a key form of climate adaptation (Conte et al., 2021, Castells-Quintana et al., 2020, Indaco et al., 2020, Bosetti et al., 2020, Grimm, 2019), an issue earmarked for our own future research. Finally, there is literature on optimal carbon pricing together with cross-regional transfer schemes designed to maximize participation (see Klis and McGinty (2022)). We discuss a simple institutional setup that can facilitate, but not guarantee, compliance in our setup.

3 The Model

We first describe in section 3.1 our model's region-specific representative firm and then, in section 3.2, households. Then, in section 3.3, we define a competitive equilibrium. Finally, section 3.4 describes the climate emulator used in our computations, and section 3.5 the computational method to solve the model. For the detailed calibration of the model presented in this section, we refer to section 4 and appendix A.1, whereas appendix A.3 provides additional details on the solution procedure.

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

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. The term δ denotes the capital's depreciation rate, assumed identical across regions. The terms $w_{z,t}$ and $p_{z,t}$ reference, respectively, region-specific wages and energy prices at time t.

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, where s references clean energy. The parameters θ and φ are clean-energy production parameters.

Profit maximization in producing clean energy requires

$$p^S_{z,t}\theta B_{z,t}K^{\theta-1}_{z,s,t}L^{\varphi}_{z,s,t}H^{1-\theta-\varphi}_{z,t} = r_t + \delta, \tag{6}$$

$$p^S_{z,t}\varphi B_{z,t}K^{\theta}_{z,s,t}L^{\varphi-1}_{z,s,t}H^{1-\theta-\varphi}_{z,t} = w_{z,t}, \tag{7}$$

and

$$p^S_{z,t}(1-\theta-\varphi)B_{z,t}K^{\theta}_{z,s,t}L^{\varphi}_{z,s,t}H^{-\theta-\varphi}_{z,t} = n_{z,t}, \tag{8}$$

where $n_{z,t}$ is the region-z, time-t rental price of land and $p^S_{z,t}$ is region z's price of clean energy.

Total regional energy consumption satisfies

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

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

$$E^D_{z,t} = \left(\kappa^{\frac{1}{u}}_{z,O}O^{\frac{u-1}{u}}_{z,t} + \kappa^{\frac{1}{u}}_{z,G}G^{\frac{u-1}{u}}_{z,t} + \kappa^{\frac{1}{u}}_{z,\mathcal{C}}\mathcal{C}^{\frac{u-1}{u}}_{z,t}\right)^{\frac{u}{u-1}}, \tag{10}$$

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 terms κ_O, κ_G, and $\kappa_{\mathcal{C}}$ are CES share coefficients. The parameter u represents the elasticity of substitution between different dirty energy sources.

One can question, per Hassler et al. (2012), at least the short-run realism of perfectly clean and dirty energy substitutability. One way to handle this issue is to assume a gradual increase in the degree of clean and dirty energy substitutability, with the two forms of energy ultimately becoming perfect substitutes. We reformulate our model in this manner in Section 5.3 below. Although the short- and medium-term use of dirty energy, particularly coal, is greater, the optimal path of carbon taxation and the UWI welfare gain is barely changed.

Oil, gas, and coal trade freely on the world market at prices p^O_t, p^G_t, and $p^{\mathcal{C}}_t$. Clean energy is non-tradeable. Cost minimization in producing a unit of dirty energy implies the following demands for alternative dirty energies:

$$O_{z,t} = \kappa_{z,O}E^D_{z,t}\left(\frac{p^O_t}{p^D_{z,t}}\right)^{-u}, \tag{11}$$

$$G_{z,t} = \kappa_{z,G}E^D_{z,t}\left(\frac{p^G_t}{p^D_{z,t}}\right)^{-u}, \tag{12}$$

$$\mathcal{C}_{z,t} = \kappa_{z,\mathcal{C}}E^D_{z,t}\left(\frac{p^{\mathcal{C}}_t}{p^D_{z,t}}\right)^{-u}, \tag{13}$$

where the price of the dirty energy composite is given by

$$p^D_{z,t} = \left(\kappa_{z,O}\left(p^O_t\right)^{1-u} + \kappa_{z,G}\left(p^G_t\right)^{1-u} + \kappa_{z,\mathcal{C}}\left(p^{\mathcal{C}}_t\right)^{1-u}\right)^{\frac{1}{1-u}}. \tag{14}$$

Decreasing returns to scale in the clean-energy production sector ensures nonzero production of clean energy in each region regardless of the price of energy. Thus, $S_{z,t} > 0$ holds in equilibrium as well as $p_{z,t} = p^S_{z,t}$. On the other hand, the price of the dirty energy composite, $p^D_{z,t}$, can exceed the price at which energy demand is fully met by clean energy. When this occurs in a given region, there is no demand for the dirty energy composite, and the use of fossil fuels ends. The following equations encompass this outcome. They reflect cost minimization and the constraint that dirty-energy consumption is non-negative.

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

$$\chi_{z,t} E^D_{z,t} = 0, \tag{16}$$

$$E^D_{z,t} \geq 0, \tag{17}$$

and

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

Note that when dirty energy production is zero, its Lagrange multiplier, $\chi_{z,t}$, is positive, indicating, from equation (15), that producing a unit of dirty energy costs more than 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^M_t. 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:

$$c^M_t(R^M_t) = \left(\xi^M_1 + \xi^M_2 \left(R^M_0 - R^M_t\right) + \left(\frac{1}{R^M_t}\right)\right). \tag{19}$$

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^M_t, given by

$$V^M_t = \sum_{j=0}^{\infty} \left[\left(p^M_{t+j} - c^M_{t+j}(R^M_{t+j}) - \varrho^M \tau_{t+j}\right) M_{t+j} + \mathcal{T}^M_{t+j}\right] \left(\prod_{i=0}^{j} \frac{1}{1 + r_{t+i}}\right), \tag{20}$$

subject to

$$R^M_t = R^M_{t-1} - M_t, \tag{21}$$

$$-R^M_t \leq 0, \tag{22}$$

and

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

where p^M_t is the global price of a unit of dirty energy, M_t, at 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 t, and $\mathcal{T}^M_t$ 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

$$p^M_t - c^M_t(R^M_t) - \varrho^M \tau_t - \ell^M_t + \mu^M_t = 0, \tag{24}$$

and

$$\frac{\partial c^M_t(R^M_t)}{\partial R^M_t} M_t + \ell^M_t - \frac{\ell^M_{t+1}}{1 + r_{t+1}} - \psi^M_t = 0, \tag{25}$$

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 workforce at age 20 and face an annual idiosyncratic mortality risk through age 100, that is, their maximum age of life. Age-specific mortality risk, which is region- and year-specific, is fully hedged via an actuarially fair annuities market.[8] Region- and year-specific fertility and mortality probabilities by age are calibrated based on UN 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

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

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 assets of age-j agents born in the region z at time t. The term $\mathbb{T}_{z,t,j}$ references net transfers received at age j by the generation born at t in the region z. Finally, ρ is the time preference rate, and σ is the coefficient of relative risk aversion.

3.3 Equilibrium and Debt-Policy

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

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

where $\mathcal{D}_t$ is debt issued to finance carbon policy and where

$$K_t = \sum_{z=1}^{18} K_{z,y,t} + \sum_{z=1}^{18} K_{z,s,t}. \tag{32}$$

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

Debt evolves according to

$$\mathcal{D}_{t+1} = (1 + r_t)\mathcal{D}_t + \sum_{z=1}^{18} \sum_{j=1}^{80} \mathbb{T}_{z,t,j}. \tag{33}$$

The world supplies of oil, gas, and coal equal the sum of regional demands

$$O_t = \sum_{z=1}^{18} O_{z,t}, \; G_t = \sum_{z=1}^{18} G_{z,t}, \; \mathcal{C}_t = \sum_{z=1}^{18} \mathcal{C}_{z,t}. \tag{34}$$

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

$$L_{z,t} \equiv \sum_{j=1}^{80} P_{z,t,j} l_{z,t,j} = L_{z,y,t} + L_{z,s,t}. \tag{35}$$

IMF refers to the model's redistributive institution.[9] The IMF needs to assess a net tax of $\mathbb{T}_{z,j,t}$ on generation j in region z in each year t. Budget balance implies that

$$\sum_{t=0}^{\infty} \left(\prod_{\tau=0}^{t} \frac{1}{1 + r_\tau} \right) \sum_{z=1}^{18} \sum_{j=1}^{80} \mathbb{T}_{z,t,j} = 0, \tag{36}$$

or in other words, where debt policy satisfies

$$\lim_{t \to \infty} \mathcal{D}_{t+1} \left(\prod_{\tau=0}^{t} \frac{1}{1 + r_\tau} \right) = 0.$$

3.4 Modeling the Climate

To describe the evolution of the climate in our multi-region OLG model, we adopt the functional form of DICE (Nordhaus, 2017), which relates output to emissions, emissions to carbon concentration, and carbon concentration to global temperature, but use a parameterization proposed by Folini et al. (2021) and which is based on the latest findings from climate science.[10]

DICE mimics the carbon cycle via three carbon reservoirs: the atmosphere (A), the upper ocean (U), and the lower ocean (L). The process by which output increases atmospheric carbon concentration is given by

$$\begin{pmatrix} J_t^A \\ J_t^U \\ J_t^L \end{pmatrix} = \Phi^J \begin{pmatrix} J_{t-1}^A \\ J_{t-1}^U \\ J_{t-1}^L \end{pmatrix} + \begin{pmatrix} \varrho^O O_t + \varrho^G G_t + \varrho^{\mathcal{C}} \mathcal{C}_t + E_t^{Land} \\ 0 \\ 0 \end{pmatrix}, \tag{37}$$

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

$$E_t^{Land} = E_0^{Land} e^{-\delta^{Land} t}, \tag{38}$$

[9]This is the Lump Sum Redistribution Authority (LSRA) of Auerbach and Kotlikoff (1987).

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

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

$$F_t = \eta_1 \frac{\log \frac{J_t^A}{J^0}}{\log(2)} + F_t^{EX}, \tag{39}$$

where J^0 is the pre-industrial concentration of atmospheric carbon. F_t^{EX} references time-t radiative forcing, which is assumed to evolve as

$$F_t^{EX} = F_0^{EX} + \frac{1}{T'}(F_1^{EX} - F_0^{EX}) \min(t, T'), \tag{40}$$

where F_0^{EX} and F_1^{EX} are the exogenous values of radiative forcing in the initial period, 2017 and 2100, respectively. T' references years between 2017 and 2100.

In DICE, the temperature evolves according to a two-layer energy balance model, that is,

$$\begin{pmatrix} T_t^A \\ T_t^L \end{pmatrix} = \Phi^T \begin{pmatrix} T_{t-1}^A \\ T_{t-1}^L \end{pmatrix} + \begin{pmatrix} \eta_2 F_t \\ 0 \end{pmatrix}, \tag{41}$$

which formally corresponds to the evolution described in Geoffroy et al. (2013). In equation (41), T_t^A and T_t^L denote the global mean temperature change, relative to pre-industrial levels, of the upper layer (atmosphere and upper ocean) as well as the lower layer (deep ocean), respectively, at the time step t. From a physics perspective, the free parameters in equation (41), including the matrix Φ^T, may be interpreted as a heat exchange coefficient between the upper and lower layers, the effective heat capacities of the upper and lower layer, and the ratio of forcing arising from a doubling of CO2 to the associated temperature change.

Our IAM requires knowledge of regional climate damages and, thus, regional temperatures. We infer regional from global temperature using 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 $\times 1°$ latitude.

Our computations use the publicly available pattern-scaling repository by Lynch et al. (2017).[11] 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 temperature to the $1°$

[11] The respective data sets and codes can be found at URL: `https://github.com/JGCRI/CMIP5_patterns`. Each function relating the local average to the global average temperature is determined by using calculations from 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 "BAU" 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 related data, see Meinshausen et al. (2011), and `http://www.pik-potsdam.de/~mmalte/rcps/`.

longitude $\times 1^\circ$ latitude grids we use to map global to local temperature. Our results are robust to the choice of RCP scenarios in connecting global average temperature to grid-specific and, thus, region-specific temperature (Link et al., 2019).

In computing the regional average surface temperatures, $T_{z,t}$, we apply pattern scaling as follows. First, we compute T_t^A (cf. equation (41)). 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.[12]

The "handshake" of the climate emulator and the economics block of the model is done at the level of temperature-dependent damages to TFP. We model regional TFP, $A_{z,t}$, as the product of a region-specific exogenous trend, $\tilde{A}_{z,t}$, and a regional function, $Z_{z,t}$, which incorporates productivity differences due to differences in temperature. $\tilde{A}_{z,t}$ grows at a time-varying, region-specific growth rate $g_{z,t}$, that is,

$$\frac{\tilde{A}_{z,t}}{\tilde{A}_{z,t-1}} = 1 + g_{z,t}. \tag{42}$$

Following Krusell and Smith Jr (2022), we assume that the component $Z_{z,t}$ obeys

$$Z_{z,t} = \begin{cases} 0.02 + 0.98 e^{(-\upsilon^+ (T_{z,t} - T^*)^2)} & \text{if } T_{z,t} > T^*, \\ 0.02 + 0.98 e^{(-\upsilon^- (T_{z,t} - T^*)^2)} & \text{if } T_{z,t} \leq T^*. \end{cases} \tag{43}$$

Regional climate damages are given by

$$D_{z,t} = 1 - Z_{z,t}/Z_{z,1900}. \tag{44}$$

Equation (43) models regional climate-specific TFP as peaking at T^* (cf. Krusell and Smith Jr (2022)). 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 and figure 13 in the Appendix), we choose υ^+ to relate regional damage functions to the global damage functions used in the literature.[13]

3.4.1 The Social Cost of Carbon

We define the SCC at t to be the present discounted value of all future damages resulting from an additional unit of CO2 emitted at t. In much of the existing literature (see, e.g., Nordhaus (1979) or Golosov et al. (2014)), this cost is equal to a marginal rate of substitution of a social planner's value function. As explained in the introduction, our model features no social planner.

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

[13] 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.

Consequently, we need to determine the SCC by solving for the evolution of temperature and damages for two different emissions paths. We define the SCC at some time τ as the sum of all damages at times $\tau, \tau+1, ..., \infty$ that arise when one extra unit of CO2 is added exogenously to emissions given by equation (37), discounted at the path of the equilibrium world interest rate, minus the discounted sum of all damages that arise without this extra unit. Pareto efficiency requires setting the carbon tax each period to that period's SCC.

3.5 Computational Method

Our solution method uses a variant of the Gauss-Seidel iteration technique developed in Auerbach and Kotlikoff (1987). Specifically, it begins with guesses of the level of the UWI welfare gain and the time paths of the aggregate capital stock, oil, coal, gas reserves, global emissions, region-specific total factor productivities, and the carbon tax. It then uses a recursion to solve the model backward from its steady state, which the economy is assumed to reach in 3017. A millennium is clearly a very long time for the economy to stabilize. But it provides the climate's atmospheric carbon concentration sufficient time to stabilize. The recursion determines, on a year-by-year basis, all region-specific and global prices, including the world interest rate, and all region-specific quantities, including all inputs, outputs, and consumption amounts of all cohorts. It also calculates the region- and cohort-specific lump-sum net transfers needed to achieve the guessed UWI gain. These recursively calculated values are used to update the time paths of our guessed global aggregates, regional temperatures, regional damages, regional productivities, and the carbon tax. In addition, we raise (lower) the targeted UWI gain if the present value of net transfers across all regions and generations is negative (positive). Our algorithm is highly precise. Its annual variables converge, relative to their prior guessed values, to less than one-hundredth of one percent. Supplementary details on the algorithm are provided in appendix A.3.

4 Calibration

This section summarizes the key components of our calibration strategy, whereas appendix A.1 provides additional details. Our 18-region OLG model builds on the so-called Global Gaidar Model (GGM; cf. Benzell et al. (2017)), but is substantially extended by coupling it to a climate emulator (cf. section 3.4) and by adding an extra region.[14] Table 1 lists the model's 18 regions and their acronyms, and figure 1 displays them on a map of the globe. The World Bank's Development Indicators (WDI) is a primary data source, providing, in particular, 2017 GDP values. These are used to calibrate the 2017 levels of regional TFP. Energy consumption/usage data come from the US Energy Information Administration (EIA). These data, measured in Btus, comprise four categories: i) coal, ii) natural gas, iii) petroleum and other liquids, iv) nuclear, renewables, and others. We aggregate energy sources into four composites: coal, gas, oil, and clean energy. Table 2 presents region-specific GDP and energy-consumption data.

The EIA data let us calibrate the region-specific CES production functions specified in equation (46). 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)

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

Table 1: Regions 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	The South Asian Pacific
SLA	Latin America excluding Mexico and Brazil
SOV	Former Soviet Central Asia
SSA	Sub-Saharan Africa
US	USA
WEU	Western Europe

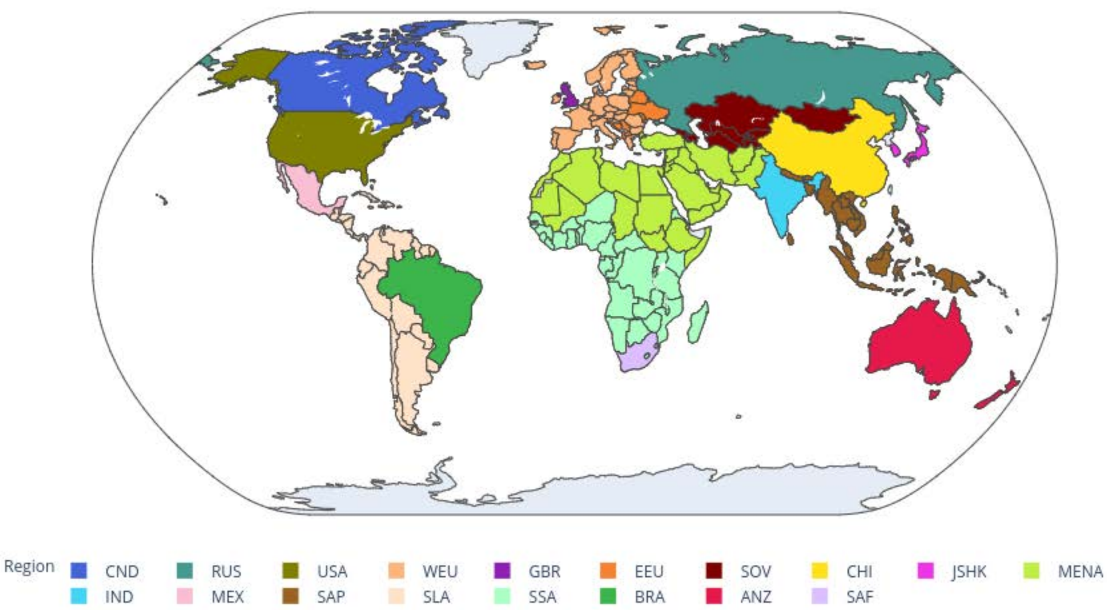

Figure 1: Our global model's 18 regions.

and Golosov et al. (2014)'s (lower) assumed values. We measure the share parameters, κ_O, κ_G, and κ_C, using data on 2017 world energy prices. Taking the 2017 \$50.8 price per barrel of West Texas Intermediate crude and assuming that one barrel of oil contains $5.7 \cdot 10^6$ Btus,

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

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 also pins down the 2017 price of clean energy as well as 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 determine 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 reports region-specific contributions of energy to output as well as contributions of 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 reports our calculated 2017 region-specific GDP and dirty-energy usage levels. The major consumers 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 are twice that of the US and three times that of the WEU. This reflects its overwhelming dependence on coal, which arises from its very high 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 hardly a model green citizen. US GDP is one-fifth larger than that of WEU. However, its emissions are three-fifths larger. For further comparisons, table 8 in the Appendix shows region-specific GDP, energy consumption, and CO2 emissions relative to the USA.

We adopt $\theta = 0.13$ and $\varphi = 0.27$, 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, with the rest distributed between labor and capital in the same

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%

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 real 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 the year 2017 value of world capital equal to \$178 trillion.[15]

To calibrate region-specific productivity growth in final goods production, we rely on univariate, country-specific regressions graciously provided by Müller et al. (2019). We aggregated the country estimates to generate regional productivity growth rates. Table 4 presents these productivity rates relative to the US productivity growth rate. The depicted productivity growth rate differentials are applied through 2100. After 2100, we assume that 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 steady-state energy price.

We use United Nations population projections (United Nations, 2019b) to calibrate population dynamics. These data account for fertility, mortality, and migration. Figure 12 in the Appendix provides a graphical summary of these data. As indicated, there are pronounced demographic waves in some regions, particularly in Russia. The initial distribution of assets between generations and regions is taken from Benzell et al. (2017). The time preference rate, ρ, is calibrated at 1.5 percent per year. The coefficient of relative risk aversion, σ, is set to 1.45.

Based on McGlade and Ekins (2015), we calibrate the globally available oil reserves to 600

[15]This amount is based on world GDP as 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 region-specific production of clean energy.

Table 4: 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%	

GtC, globally available gas reserves to 400 GtC, and globally 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 us calibrate ϱ^M.[16] 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 (cf. 3.4) are adopted from Folini et al. (2021).[17] The 2017 land emissions, E_t^{Land}, are calibrated at 0.709 GtC, and that annual rate of reduction in land emissions, δ^{Land}, at 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 at 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 at 607 GtC.

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

$$\Phi^J = \begin{pmatrix} 0.947 & 0.0536 & 0 \\ 0.053 & 0.9422 & 0.0014 \\ 0 & 0.0042 & 0.9986 \end{pmatrix}, \Phi^T = \begin{pmatrix} 0.7546 & 0.1 \\ 0.0069 & 0.9931 \end{pmatrix}. \tag{45}$$

As for regional damages, we follow Krusell and Smith Jr (2022) in setting $T^* = 11.6$ in equation (43). In our most optimistic calibration, $\upsilon^+ = \upsilon^- = 0.001$. Recall, these are damage-sensitivity parameters arising from the regional temperature in equation (43).

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

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

[17]Dietz et al. (2021), among others, criticize the climate emulators commonly used in economics, including Nordhaus' widely used DICE model (Nordhaus, 2017). A key functionality that any climate emulator has to provide is to translate anthropogenic emissions, as computed by the economic model, into a global mean temperature change. 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 (cf. section 3.4) in its original formulation, however, does not accord with the latest physical data. Fortunately, the CMIP5 benchmark data. Folini et al. (2021) provide a suite of test cases that permit a full re-calibration of DICE parameters. Compared to the original DICE model, this leads to less long-term warming because of changes in the carbon cycle.

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) conduct a meta-analysis of different global damage functions and argue that the damages might be far larger than assumed in DICE. In our model, damages depend only on the product of the parameter υ and $T_z - T^*$, the regional temperatures in excess of T^*. Hence, 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 reference them as our low-, medium-, and high-damage scenarios. In all cases, υ^- remains fixed at υ^*. Figure 2 depicts the "Krusell-Smith" productivity function (see equation (43)). Note

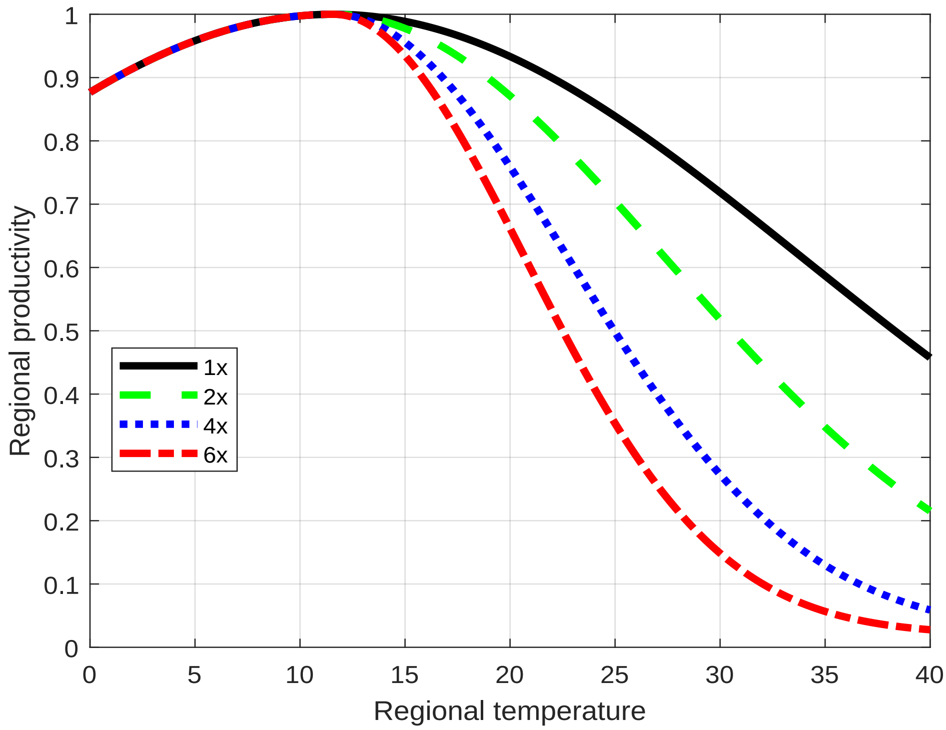

Figure 2: Alternative calibrations of "Krusell-Smith"-type productivity functions as a function of temperature, measured in °C.

that only the right side of the productivity function shifts. In short, we consider 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

This section first presents BAU results for our different damage-function specifications. Next, we consider alternative carbon policies assuming all regions levy annual carbon taxes equal to each year's global SCC. Our "No Transfers" policy taxes carbon but provides no compensation to those suffering welfare losses. Our UWI policy, as indicated, uniformly allocates efficiency gains

Table 5: Peak BAU Losses and Gains (Negative Sign) as Percentage of GDP and Maximal Temperature Increases.

	1x	2x	4x	6x
US	4.0	7.4	12.8	17.1
WEU	1.6	2.9	4.9	6.5
JSHK	3.9	7.1	12.4	16.7
CHI	4.0	7.4	12.7	17.0
IND	11.8	21.1	34.6	43.9
RUS	-4.1	-4.4	-4.0	-3.9
CND	-2.7	-2.7	-2.6	-2.6
EEU	1.8	3.2	5.3	6.9
SAP	9.9	17.9	29.9	38.3
BRA	8.6	15.7	26.6	34.7
MEX	6.1	11.2	19.2	25.5
SAF	5.7	10.4	17.8	23.7
MENA	9.1	16.4	27.6	36.0
SLA	7.4	13.5	23.2	30.6
SSA	9.7	17.5	29.3	37.9
SOV	2.0	3.6	5.9	7.6
GBR	0.5	1.0	1.6	2.1
ANZ	4.6	8.6	14.9	19.9
GLOBAL	4.4	7.9	13.0	16.7
Max. Global Temperature	4.4	4.2	3.9	3.7

to all current and future cohorts in all regions. Our UWIF policy reprises our UWI policy but restricts the uniform welfare gains to only future generations; all current generations receive their BAU utility levels. Our fourth policy is UWIL, which, to repeat, runs UWI under the restriction that the lifetime net tax payment of any generation in any region is limited (hence, the L in UWIL) to 10 percent of that region-specific generation's lifetime consumption. We also consider carbon policies that are not Pareto-efficient, but that might, nonetheless, arise in the political process.

5.1 Simulating BAU

Table 5 reports the maximal BAU increases in global mean temperature (relative to pre-industrial levels) as well as peak BAU losses and gains by region for our four damage-function specifications detailed in equation (44). According to our model, absent carbon policy, the planet's average temperature will rise by 3.7 to 4.4 degrees Celsius over the next 200 years. Paradoxically, global mean BAU temperature increases are significantly higher in the (1x and 2x) low damage cases because lower damages mean higher GDP and, thus, higher emissions. Despite the higher rise in global temperature, global and regional damages are lower in these cases thanks to their more benign damage functions. Planetary warming under BAU is beneficial to Russia and Canada, whose temperatures rise from between 2.8 and 3.8 degrees and 2.7 and 3.6 degrees, respectively. This reflects their initial (2017) very low average temperatures – temperatures far too low to achieve peak productivity.

As indicated, damages under BAU can be extraordinarily large for the world as a whole, but particularly for specific regions. For example, in the 6x scenario, global damages peak at almost 17 percent of world output. However, India's damages reach over 40 percent of GDP by 2200, with this percentage output loss persisting for more than a century. For the US, China, and Japan, the year 2200 damages exceed 16 percent of output with no improvement and, in some cases, a worsening over the following 100 years. GBR experiences the smallest damages, peaking at just 2.1 percent of GDP. Russia and Canada's climate gains peak above 3.9 percent and 2.6 percent of GDP, respectively. ANZ, SSA, SLA, SAF, MEX, BRA, MENA, and SAP also experience significant damages.

The magnitude of global damages is highly sensitive to the shape of the upper tail of the damage function. In the 6x case, peak global as well as regional damages are almost four times larger compared to the 1x parameterization (cf. table 5). Despite the fact that emissions and temperature increases are significantly lower than in the 1x case (again, because of the paradox that higher damages limit output and, thus, emissions), extreme damages in some regions are far larger.

The close-to-20 percent global peak GDP loss in the 6x case lies well within recent projections of climate damages. Hänsel et al. (2020), for instance, strongly criticizes the DICE damage function, advocating more realistic specifications that lead to much more substantial damages for a 3-degree Celsius or larger increase in temperature. Cruz and Rossi-Hansberg (2021) provide region-specific damage estimates that are roughly in line with our 6x case.

The damage function is just one of many factors that impact the cost of climate change. As indicated, we calibrate our climate emulator according to the multi-model mean of CMIP5 simulations. Calibrating to more pessimistic scenarios would entail both higher temperatures and higher damages, holding the damage function fixed. In addition, the data to which we calibrate may be understating true fossil-fuel reserves, overstating fossil-fuel extraction costs, and suggest faster clean-energy productivity growth that will arise.

Figure 3 compares global CO2 emissions for our 6x BAU scenario over the next 200 years with the emissions projections used in the four RCP scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC)[18] and the emissions in DICE.[19] As the figure shows, our BAU emissions are significantly lower than in DICE or in RCP8.5. As Hausfather and Peters (2020) point out, RCP8.5 was intended to explore an unlikely high-risk future, that entails unrealistically high coal usage. In this light, the RCP6.0 scenario seems more relevant for forecasting emissions absent policy. Our baseline BAU emissions path, which falls between the RCP6.0 and RCP4.5 scenarios, represents a relatively optimistic path.

Under BAU, oil, gas, and coal production definitively ends worldwide in 200 years.[20] However, dirty energy usage terminates far sooner in some regions. Brazil is the first region to end the use of all fossil fuels in 2045. The US end date of dirty energy usage is 2105. For China, it is 2092.

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

[19]For tractability, the figure omits results based on our more benign damage function. Their emissions are, as indicated, slightly higher.

[20]See figures 14, 15, and 16 in the appendix, in which the projected oil, gas, and coal use both under BAU and under the 6x UWI optimal policy is shown.

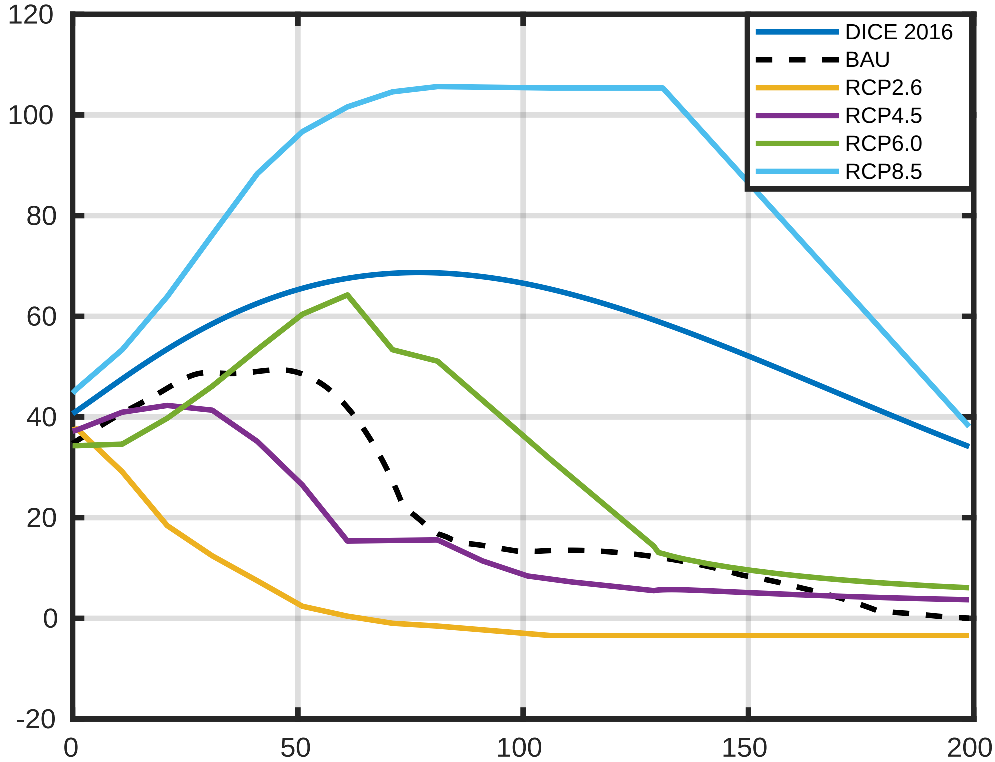

Figure 3: Global CO2 emissions (in GtCO2) in our BAU scenario, DICE 2016, and the different RCP scenarios (year 0 is 2017).

5.2 Carbon Policies

Table 6 summarizes our key findings. It indicates that optimal initial carbon taxes are extremely sensitive to the damage function. Absent transfers, they range from $22.8 per ton CO2 with the 1x damage specification up to $111.7 per ton with 6x calibration. The corresponding optimal UWI taxes range from $22.4 to $87.5 under UWI. For a given damage specification, the SCC is higher without net transfers for a simple reason. The net transfers associated with, say, the UWI policy entails significant crowding out of capital thanks to the compensatory transfers made to early generations from their future progeny. In the case of the 6x damage specification, this raises the global interest rate under UWI by some 100 basis points relative to taxing carbon but not compensating losers. Since the SCC is a discounted sum of marginal future global damages, the higher global interest rate under UWI policy than with no transfers implies, other things equal, a lower SCC and, thus, higher carbon taxes.[21]

As indicated, the UWI carbon policy can achieve a major win-win for all humanity. In the 6x UWI case, all generations, present and future, across all regions gain 4.3 percent. Even in the 4x case, arguably an optimistic damage scenario, the UWI gain is almost 3.0 percent. Without transfers, some generations incur large welfare losses (up to 18.0 percent) in the 6x case, while others experience huge gains (up to 47.6 percent).

Maximal global temperature and maximal regional damages are substantially reduced by carbon taxation. However, peak damages are slightly larger with a re-distributive policy than

[21] Tables 9 and 10 in the appendix provide supplementary results on the region-specific SCC for the 6x specification of the damage function.

Table 6: Key Simulation Results.

Damage case		1x	2x	4x	6x
Initial optimal tax, $ per ton of CO2	No Transfers	22.8	43.9	80.6	111.7
	UWI	22.4	39.3	66.4	87.5
	UWIF	22.6	42.2	75.2	101.9
	UWIL	22.4	39.7	68.3	91.4
Average growth rate of optimal tax over the next 50 years, percent per year	No Transfers	1.8	1.7	1.6	1.5
	UWI	1.8	1.6	1.5	1.4
	UWIF	1.8	1.6	1.5	1.4
	UWIL	1.8	1.6	1.5	1.5
Welfare gains, percent	No Transfers	-9.1–8.0	-12.1–16.9	-15.5–34.0	-18.0–47.6
	UWI	0.6	1.4	3.0	4.3
	UWIF	0–0.9	0–2.3	0–5.1	0–7.7
	UWIL	0.6	1.4–6.2	2.8–22.4	4.0–35.6
Max. global temperature, degree Celsius	BAU	4.4	4.2	3.9	3.7
	No Transfers	2.8	2.5	2.2	2.1
	UWI	2.8	2.5	2.3	2.1
	UWIF	2.8	2.5	2.2	2.1
	UWIL	2.8	2.5	2.2	2.1
Max. global damages, percent of global GDP	BAU	4.4	7.9	13.0	16.7
	No Transfers	2.5	4.1	6.7	8.9
	UWI	2.5	4.2	7.0	9.3
	UWIF	2.5	4.2	6.8	9.1
	UWIL	2.5	4.2	6.9	9.2
Max. regional damages, percent of regional GDP	BAU	11.8	21.1	34.6	43.9
	No Transfers	7.4	12.3	20.2	26.9
	UWI	7.4	12.6	21.0	27.8
	UWIF	7.4	12.4	20.5	27.2
	UWIL	7.4	12.6	20.8	27.5
Long-run interest rate, percent per year	BAU	2.9	2.9	2.9	2.9
	No Transfers	2.9	2.9	2.9	2.9
	UWI	3.4	3.7	4.0	4.2
	UWIF	3.3	3.5	3.8	3.8
	UWIL	3.4	3.7	3.9	4.0
Minimal regional transfers, percent of present value of consumption	UWI	-6.7	-14.6	-28.8	-39.9
	UWIF	-6.4	-14.1	-27.8	-38.2
	UWIL	-6.7	-10.0	-10.0	-10.0

without. Finally, the table shows that the UWI case entails extremely large transfers from future generations in regions hardest hit by climate change. In the 6x case, Indians born in 200 years

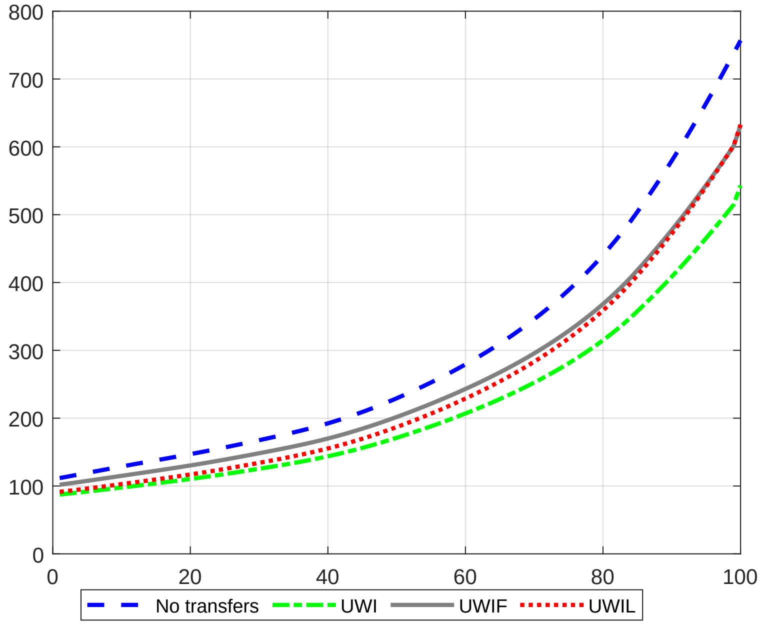

Figure 4: Global Carbon tax under different scenarios, in $ per ton of $CO2$, and the 6x damage specification as a function of years (starting in 2017).

would be required under UWI policy to surrender more than 45 percent of their consumption to help service outstanding carbon-policy debt. Even in the 2x and 4x cases, transfers under the UWI policy are exceptionally large. These findings prompted our consideration of UWIL policy, which, to repeat, caps net taxes on future generations, regardless of region, at 10 percent. Welfare gains are uniform for all region-specific generations not subject to the limit and higher for those subject to the limit. Maximal welfare gains for future generations are 35.6 percent in IND, 27.2 percent in SAP, 25.2 percent in BRA, 15.5 percent in MEX, 25.9 percent in MENA, 19.5 percent in SLA, and 25.9 percent in SSA. We next discuss our 6x results in more detail.

5.2.1 Alternative SCC-Determined Carbon-Tax Paths

Figure 4 shows the SCC-determined carbon taxes for the cases of no transfers, UWI, UWIF, and UWIL.

The initial carbon tax and its growth rate is the highest when there are no transfers. In fact, the carbon tax and, thus, the SCC in year 40 (counting from the year 2017) is almost one-third higher than, for example, under UWI policy. Hence, optimal carbon taxation cannot be determined without deciding whether and how to distribute the efficiency gains from taxing carbon.

In all four cases, SCC-based carbon taxes grow at time-varying rates, with the tax accelerating after 60 years. Optimal taxes 100 years from now are very high – above $700 in the no-transfer case. However, the welfare gains from setting a time-varying rather than a fixed growth rate are small, that is, a simple, time-invariant growth in the carbon tax suffices to produce the vast majority of any policy's welfare impacts.

As pointed out in table 6, the average annual carbon-tax real growth rate of the 6x specification ranges from 1.4 to 1.5 percent. This is in line with Kotlikoff et al. (2021), which featured a 1.5 percent optimal UWI carbon-tax growth rate, albeit in a global, that is, a single-region OLG model. For the 6x case with UWI policy, an initially $97 carbon tax growing at 1.5 percent per year, real, also yields a UWI gain of 4.3 percent up to 2 significant digits. One of the reasons for this is that, as we will see now, the high optimal tax for carbon leads to an immediate steep reduction of emissions in almost all regions, and a slight variation in taxes 50 years into the future has almost no effect on cumulative emissions.

Figure 5 shows the 6x welfare gains and losses for the different tax-transfer schemes.

Absent transfers, many early generations in CHI, IND, RUS, CND, EEU, SAF, MENA, SOV, and GBR, are harmed by SCC-based carbon taxation. Cross-region transfers across contemporaneous generations cannot Pareto improve since there are no welfare gains for generations born around t=0. Interestingly, older generations fare better under this policy. The explanation lies in the policy's implicit monopolization of the dirty-energy section, which raises the prices of dirty energy reserves and, for that matter, the value of land used in producing green energy.[22] However, as indicated in figure 5, there are large welfare gains for many region-specific future generations to be shared. The green line shows the uniform 4.3 percent UWI gain.

Figure 5's remarkable finding is the closeness of the green and red dotted lines for regions that never hit the limit. The dotted red line is slightly lower – 4.0 percent – under UWIL policy for generations in regions that do not exceed the limit. Other generations in other regions enjoy much larger welfare gains under UWIL. For example, the gain for future Indians peaks at close to 35.6 percent. For future members of SAP, BRA, SSA, and MENA, the peak gain exceeds 20 percent. Even future Americans enjoy far higher welfare gains, that is, roughly twice the UWI level.

The moral here is that by giving up a very small portion of their UWI gain, early generations can dramatically improve the welfare of future generations. Moreover, they can substantially enhance policy compliance as no generation in any region is asked to pay more than 10 percent of their lifetime consumption in net taxes. Paying this net tax will deliver net welfare gains in regions like India that are an order of magnitude larger than their required 10 percent net tax.

5.2.2 Reductions in Emissions, Temperature, and Damages

Next, we consider the effects of alternative carbon-tax policies on emissions and damages. We focus again on discussing the 6x damage specification. The results for the 4x damage case are similar. However, with even lower damages, optimal carbon taxes are low and, consequently, matter little. Figure 6 depicts the remarkable reduction of emissions in each region arising, in the 6x case, assuming SCC-based carbon taxes. The emissions reductions are very similar and decrease very quickly, regardless of the transfer schemes. As figures 14, 15, and 16 in the Appendix show, the different regions stop using dirty energy at very different points in time. China, for instance, stops using all fossil fuels in roughly 20 years compared to 75 years under BAU. Furthermore, Russia stops emitting carbon roughly 80 years earlier than in BAU due to the carbon policy. The quick substitution of clean energy, gas, and oil for coal may seem unrealistic. However, such a substitution is arguably already underway in China and other regions, which are rapidly building nuclear power plants while shutting down coal plants.[23]

[22]Recall, all carbon taxes are lump-sum rebated to the dirty-energy companies, i.e., to their owners, namely initial generations.

[23]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-

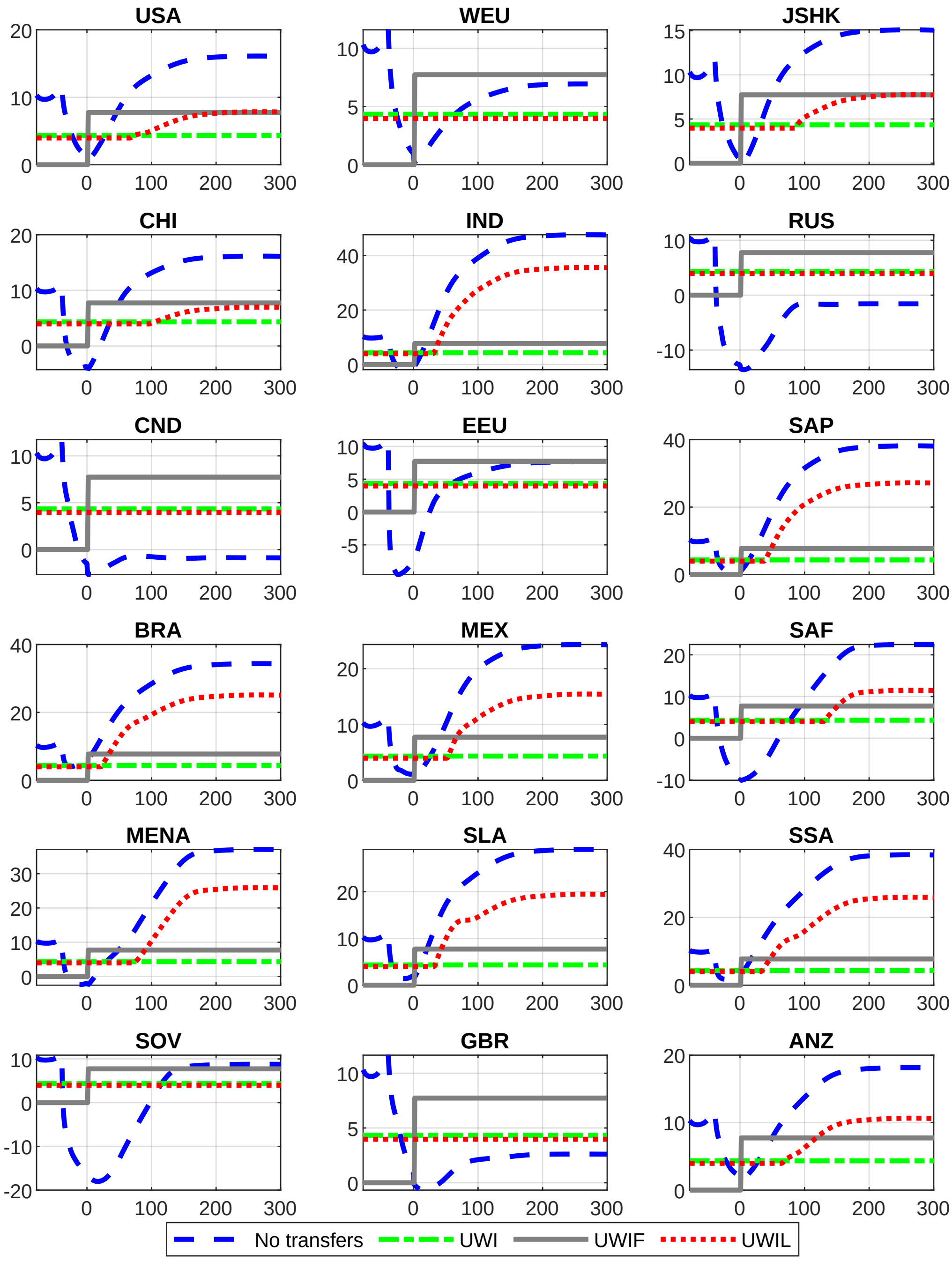

Figure 5: Welfare gains, measured as compensating consumption differentials in percentages (year 0 is 2017). The X-axis references the year of birth.

As table 6 shows, taxing carbon at its marginal social cost dramatically limits the increase in temperature. This is true whether or not compensation is provided. Indeed, the rise in global temperature stays within or near the 2.0-degree limit set in the Paris Agreement. Figure 7 shows,

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`other-energy-sources-sooner-than-you-think`, `https://world-nuclear-news.org/Articles/China-starts-construction-of-demonstration-SMR`, or `https://www.bbc.com/news/uk-england-somerset-58724732`.

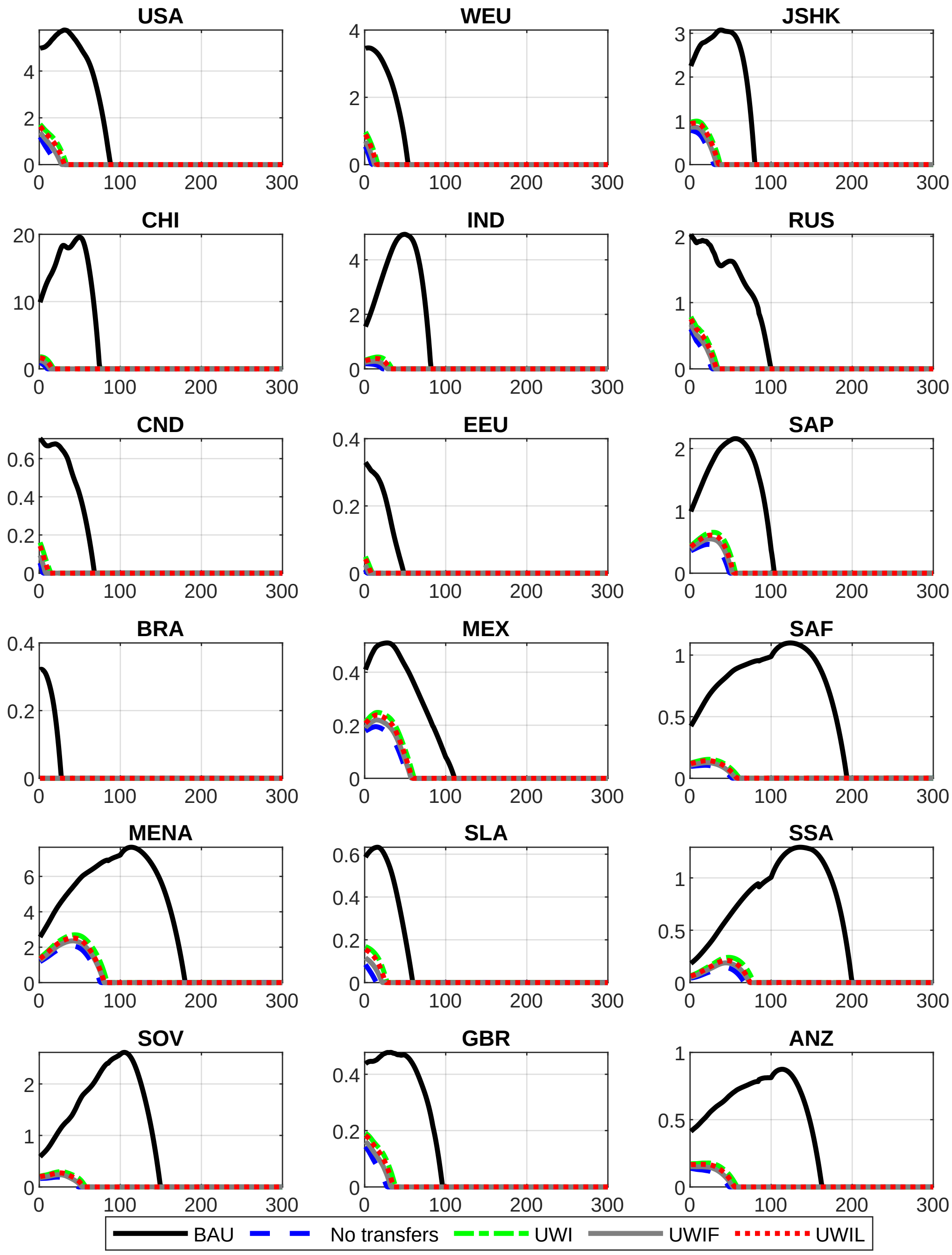

Figure 6: Total CO2 Emissions in the 6x Case (Measured in GtCO2, year 0 is 2017).

for 6x damages, that carbon taxation, again, no matter the compensation scheme, lowers all regions' temperature paths by roughly the same degree.

Figure 8 shows the extremely heterogeneous nature of climate damages across regions, ranging from very large ones in India to negative ones in Russia and Canada. In addition, the figure also displays the large reduction in economic damages caused by the optimal taxes: The green, 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 dramat-

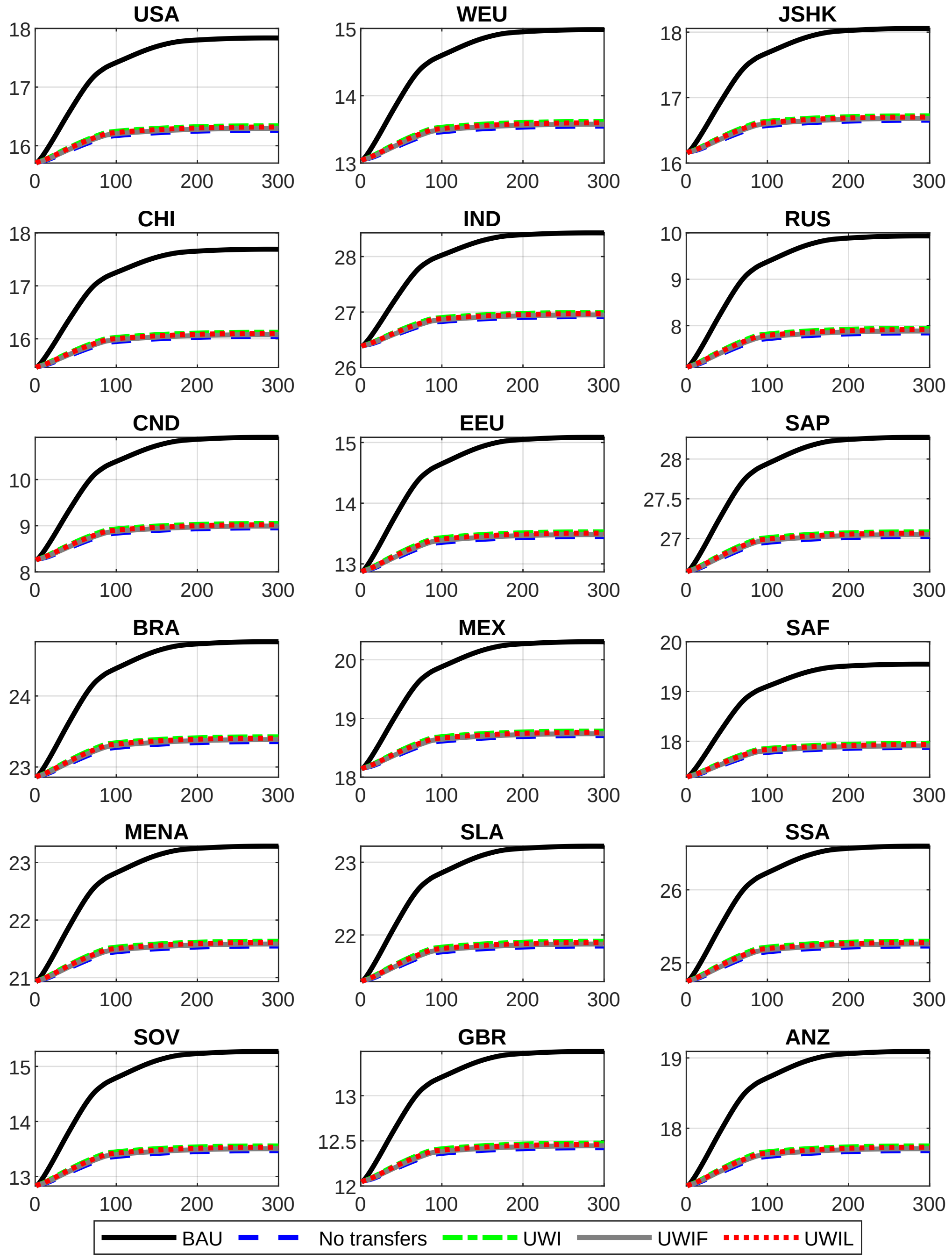

Figure 7: Regional temperature in the 6x case (measured in °C), year 0 is 2017.

ically reduce regional carbon damage. In some cases, the reduction is by almost 50 percent. For example, in ANZ, maximal damages drop from 20 percent to just above 10 percent, most notably in China, and the US damages drop from above 16 percent to around 8 percent of GDP.

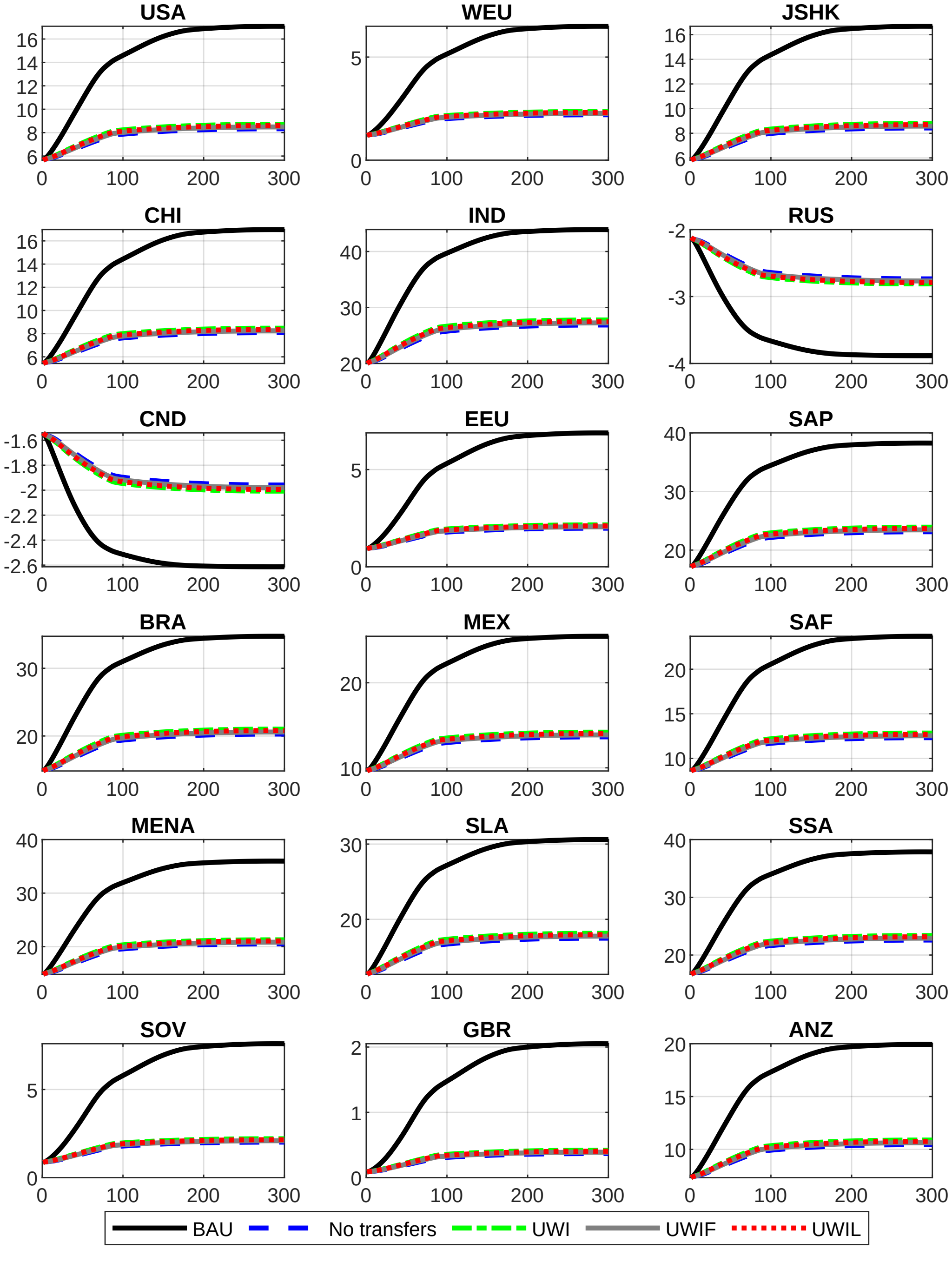

Figure 8: Regional damages in the 6x case (measured as a percent of regional GDP, year 0 is 2017).

5.2.3 Net Transfers

Optimal carbon taxes are, as indicated, both large and economically important (cf. figure 4). They dramatically reduce the use of dirty energy, which materially helps future generations. However, this can require compensating current generations to ensure that they do not incur welfare losses. Figure 9 compares paths of net transfers paid to successive cohorts by year of birth. The horizontal axis specifies the cohort year of birth.[24] The green dashed line references the UWI policy. The net UWI 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 more than 40 percent of their consumption to help service outstanding carbon-policy debt. Other regions with similarly large transfers include BRA, SAP, MENA, SLA, and SSA, whose future generations all need to transfer more than 20 percent of their consumption to other regions and generations.

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 US (whose long-run net tax is much smaller), which are causing a much larger share of the global externality? The answer is that adhering to this policy will benefit Indians, including all future Indians, to the same degree as it benefits those in the richest regions. 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. While *fairness* is not the issue, the UWI policy is unfortunately extremely unlikely to succeed. While future Indians today would agree on a contract that costs them 30 percent of lifetime consumption in exchange for optimal carbon taxes, come the year 2120, young Indians have absolutely no incentives to keep the contract. The vast literature on sovereign debt (e.g., Eaton and Fernandez (1995)) and the vast number of cases of sovereign default clearly shows that the enormous debt levels required by our UWI policy in the 6x case are not sustainable.

Therefore we consider our third efficient policy that caps tax rates at 10 percent for all regions and all future generations. The red dotted line shows transfer payments for this almost uniformly welfare-improving policy. This is arguably the policy with the largest chance of political support, both by current generations and future generations.

One needs to keep in mind that all carbon tax revenues are distributed among the currently alive; that is, these transfers are not included in figure 9, which explains why in the "Unborn" scenario, currently old agents need to make transfers to future generations. It also explains why there are large wiggles around time $t = 0$.[25]

Surprisingly, although maximal transfers for this policy are much smaller than for UWI, the welfare gains guaranteed for all generations and regions are almost as large. As depicted in figure 6, all generations in all regions gain at least 4.0 percent (as opposed to 4.3 percent in the full UWI case). Naturally, future generations in regions hit hardest by climate change gain much more, with future generations in India gaining almost 40 percent.

Since overall transfers are smaller than in the UWI case, the increase in the interest rate is also less pronounced, and hence optimal taxes are higher than in UWI. More details are shown in Figure 4.

[24] For example, a value of −10 on the MENA chart's horizontal axis references the age-30 MENA generation in 2017.

[25] In some regions, such as GBR, there are also wiggles at future dates. 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.

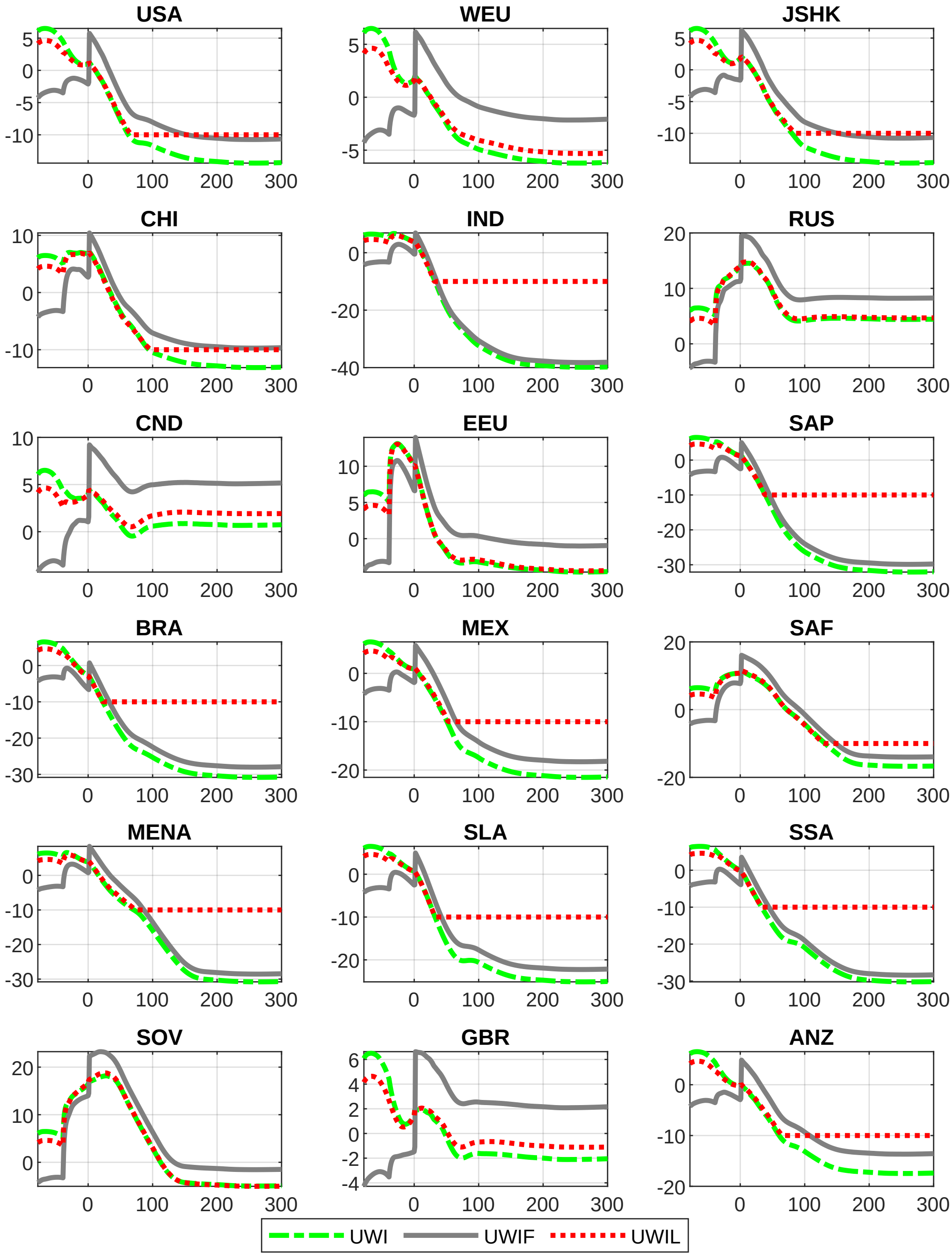

Figure 9: Net transfers as a share of the remaining or full lifetime consumption in the 6x case (year 0 is 2017). The X-axis references the year of birth.

5.2.4 Carbon Policy and the Future of Economic Power

This section considers whether carbon-tax policy matters for the evolution of global economic power. Table 7 examines this question for the 6x scenario. The answer is no and yes. First, with or without a 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

Table 7: Regional GDP as a 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

2100. However, the end of the US economic hegemony and the path to that end is essentially independent of carbon damage and carbon policy. This reflects the roughly equal proportionate 6x climate losses experienced, through time, by both the US and China (cf. table 5). By 2100, the U.S. is in third place with only 15.5 percent of world output, trailing WEU plus the UK's combined share of 19.5 percent.

Absent carbon policy, Western Europe's global GDP share, which is 3 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 to roughly half with carbon policy and reflects the relative importance of carbon policy to the US compared to Western Europe, indicated in table 5. India, which stands to lose the most from climate change, is another example of carbon policy's potentially significant, if hardly overwhelming, 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 Imperfect Short- and Medium-Term Substitutability Between Green and Dirty Energy

As mentioned above, our assumption that clean and dirty energy are perfect substitutes might seem problematic. Boeing 747 jets, for instance, cannot yet fly on batteries and will not in the next 20 years. However, in the very long run, hydrogen or other clean fuel may be ubiquitous.

How sensitive are our results to assuming clean energy substitutes perfectly for dirty energy?

To address this question, we posit a gradual transition from imperfect to perfect substitutability. In the short and medium runs, energy is produced according to equation (46)' CES function, rather than equation (9) that simply adds together clean and dirty energy. In equation (46)', $\tilde{u}_t$ is the time-dependent elasticity of substitution between clean energy and the dirty energy composite. We let $\tilde{u}_t$ rise linearly from 1 (the Cobb-Douglas case) to 10 in 0.1 increments over 91 years. After that, we assume perfect substitutability, that is, our energy output obeys equation 9).

$$E_{z,t} = \left(\kappa_{z,S}^{\frac{1}{\tilde{u}_t}} S_{z,t}^{\frac{\tilde{u}_t - 1}{\tilde{u}_t}} + (1 - \kappa_{z,S})^{\frac{1}{\tilde{u}_t}} (E_{z,t}^D)^{\frac{\tilde{u}_t - 1}{\tilde{u}_t}} \right)^{\frac{\tilde{u}_t}{\tilde{u}_t - 1}} . \tag{46}$$

Note that this technological advance could occur through a gradual rise in the elasticity of substitution were clean and dirty energy imperfect substitutes. Alternatively, with efficient technologies for carbon removal, dirty energy could become clean, leaving all energy clean (see, e.g., Fuss et al. (2020) for the role of carbon capture towards a net zero emissions scenario).

Figure 10 compares results for the 6x damage case. As expected, the lack of full green-for-dirty substitutability leads to significantly higher use of dirty energy in the short and medium terms. This is particularly true of coal. There is also roughly 15 percent greater damage by the end of this century, continuing for several thereafter. Remarkably, however, the end dates for the use of the three dirty energies are not greatly impacted by less ability to swap clean for dirty energy. Equally important, the optimal carbon-tax path turns out to be essentially unchanged. The initial optimal tax is equal to 87.3$ per ton of CO2 in 2-level CES specification, just 0.2$ lower than the baseline. And the average growth rate of optimal tax over the next 50 years is equal to 1.2 percent per year – 0.2 percentage points lower than the baseline. Moreover, the UWI gain equals 4.2 percent – just 0.1 percentage points lower than in the baseline.

5.4 Inefficient Policy

Pareto-optimal taxes require large inter-regional and intergenerational transfers and, absent transfers, significant welfare losses for current generations. It is all but clear how to enforce them globally. After all, climate change action is a classical free-rider problem. If one relatively small region does not participate and imposes no carbon tax, the overall reduction in CO2 emissions and future damages will be largely unaffected. Therefore, the region has no incentive to participate even if it expects significant future damages in the BAU scenario.

The subsequent sections 5.4.1 and 5.4.2 discuss how outcomes differ if global participation does not materialize, leaving single regions or subsets of regions to implement their own UWI carbon policies.

5.4.1 Partial International Participation

How do our results change if we assume that only some regions introduce a carbon tax? In considering carbon tax policy in a given subset of regions, we tax 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 11 shows the effect of a regional $100 carbon tax on global emissions. In addition to a global tax, we also consider a tax only in CHI, JSHK, GRB, WEU, and the US and 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,

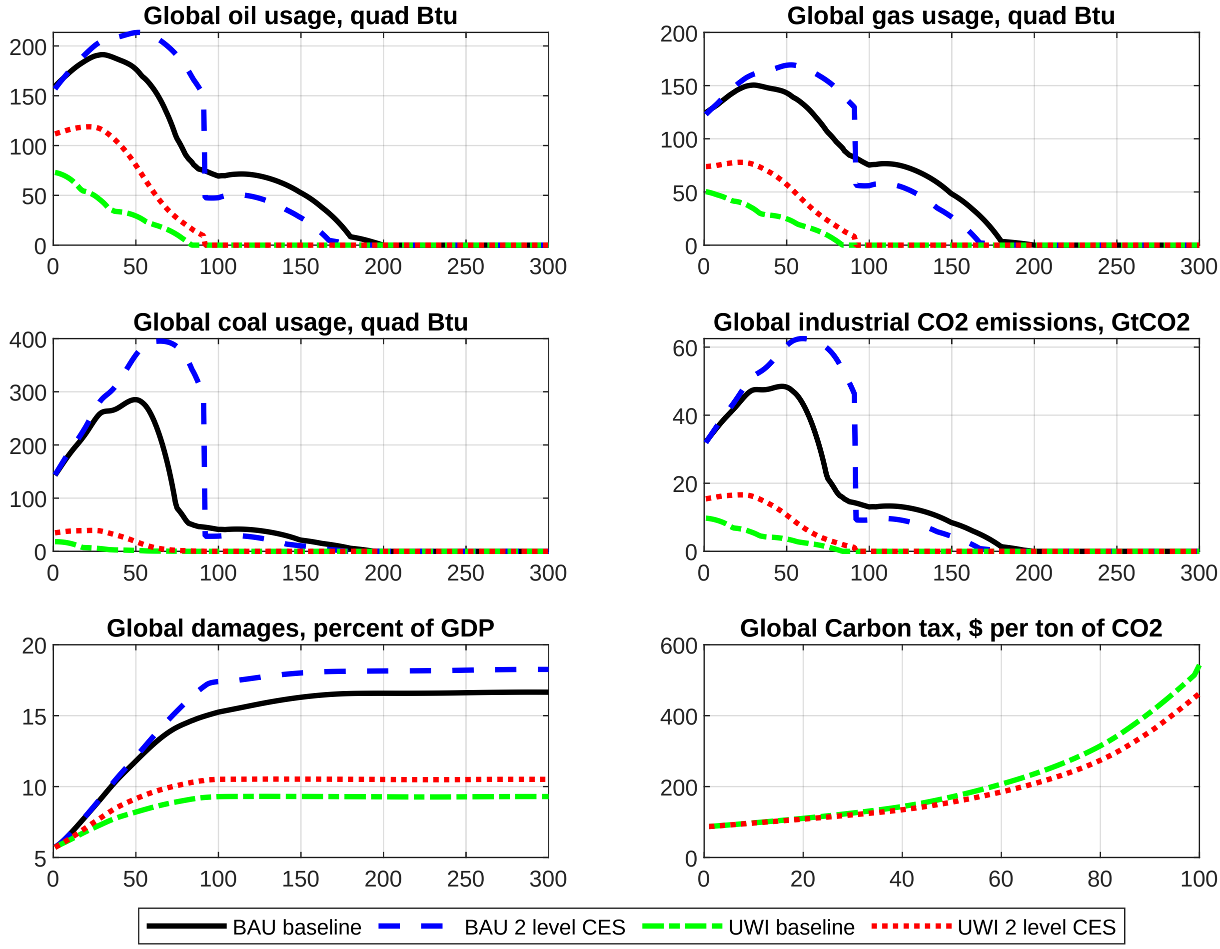

Figure 10: Key variables with 6x damages when dirty and clean energy are imperfect substitutes in the short and medium run.

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, has almost no effect on global emissions. The larger Chinese impact reflects China's coal-intensive technology for producing dirty energy.

Given the relatively small impact of a large regional tax on emissions and warming, the issue of partial participation is clearly problematic. If one hopes for regional welfare gains from optimal regional taxes and transfers, one is easily disappointed. Tables 9 and 10 in the Appendix illustrate the problem by reporting regional SCC for different regions and different years. For the 6x BAU case, this regional SCC is only significant in China and the US. Despite the fact that damages are projected to be very large in regions like India and Brazil, the 2017 SCC for India is only about $ 10.50, and for Brazil, only $ 3.12. The global SCC, in this case, is $ 111.69. As one would expect from these numbers, it turns out that only one partial coalition – all regions apart from China – appears capable of producing a positive welfare gain for its members. For example, a $100 carbon tax, approximately equal to the global SCC, levied by all regions apart from China and grown annually at 1.5 percent produces a 1.5 percent UWI

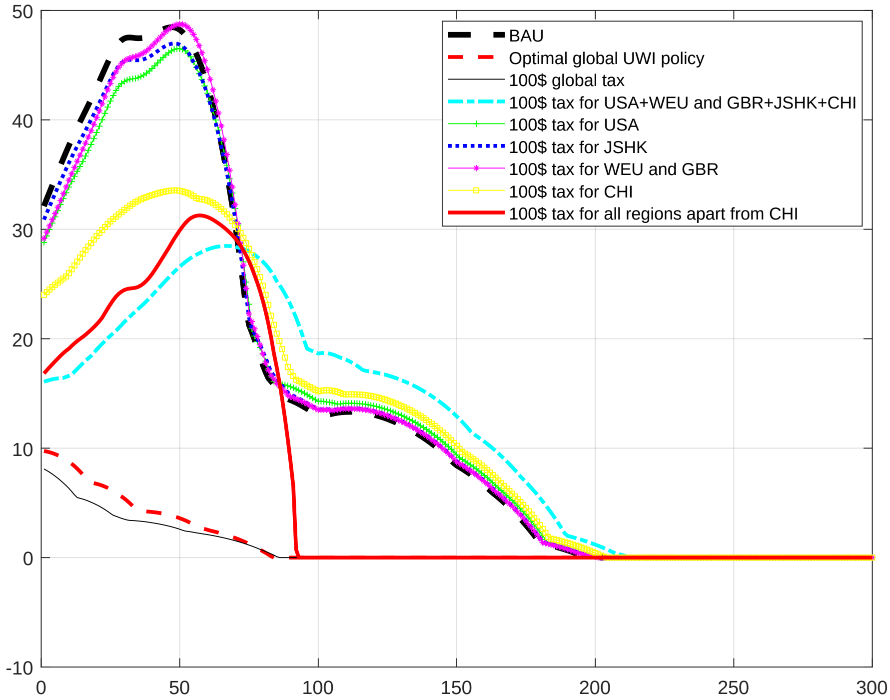

Figure 11: Global CO2 emissions (absent of land emissions, and measured in GtCO2) in the 6x scenario under alternative coalitions as a function of years (starting in 2017).

gain for coalition members.

We also considered coalitions that tax themselves not based on the global SCC but only on their collective local SCC. They redistribute among themselves to achieve a uniform welfare gain among all members. In this case, there are three coalitions with positive welfare gains: UWI gains equal to 1.6 percent for all regions apart from CHI. The equal 0.9 percent for a coalition consisting of the US, WEU, GBR, JSHK, and CHI. They equal only 0.3 percent for a coalition consisting solely of CHI.

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 imposes carbon taxes, they drive down the price of dirty energy. This, in turn, leads non-participating regions to increase their use of fossil fuels. For example, a $100 Chinese-only carbon tax, with a 1.5 percent growth rate, leads other regions to increase their collective cumulative, by the year 2250, carbon emissions by 17 percent. If all regions apart from China do the same, China will increase its cumulative emissions by 78 percent. If the USA, WEU, GBR, JSHK, and China impose a $100 carbon tax, with a 1.5 percent growth rate, other regions collectively increase their cumulative CO2 emissions by 43 percent. This Black Paradox is akin to the "Green Paradox" discussed below in section 5.4.2. The bottom line is clear. Carbon taxation needs to be global to be effective.

5.4.2 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". Indeed, Kotlikoff et al. (2016) suggest the Paris Accord may have worsened climate change via its Green Paradox repercussions. 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, a 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 0.6 to 0.5 percent. In the 2x case, they drop from 1.4 to 1.0 percent. In the 4x case, the decline is from 3.0 to 2.0 percent. Furthermore, in the 6x case, the reduction is from 4.3 to 2.8 percent. Note that delay reduces maximum UWI gains and increases emissions over the entire transition path, not starting when the policy begins.

What if all regions but China immediately adopt a carbon tax, but China waits 20 years?[26] This lowers the UWI gain from 4.3 percent to 3.8 percent in the 6x case. In the 4x case, China's delayed participation reduces the UWI gain from 3.0 percent to 2.7 percent. In contrast, in the 2x and 1x cases, 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 the future against current generations and regions that benefit from climate change against regions that do not. Our study suggests that, absent policy, potential losses to future generations are substantial. Indeed, absent policy, climate change produces peak GDP regional losses under our "high damage scenario", ranging from 17 to over 40 percent in 12 of our model's 18 regions. Peak losses for India reach 43.9 percent. They exceed 30 percent for SSA, SLA, MENA, BRA, SAP, and IND. For the US, losses peak at 17.1 percent. In contrast, for Russia and Canada, climate change is good news. Under BAU, Russia's and Canada's peak output gains are 3.9 percent and 2.6 percent, respectively.

These BAU reductions in output take decades, but not millennia. India's peak loss of over two-fifths of its output occurs in 2200. Since fossil fuels eventually because economically extinct, the BAU growth impact is "temporary" if our time frame is millennia and if long-run TFP growth remains positive. But this does not mean that it has small effects on welfare. India's current per capita GDP is just over $7,000. An immediate 40-plus percent reduction in India's GDP would spell massive starvation on that impoverished continent. The fact that, for India, primarily externally-generated climate change will extract its maximum penalty in 200 years is hardly comforting, neither for its inhabitants nor for the rest of the world.

Fortunately, there is a simple, mutually beneficial solution to this seemingly insurmountable problem. We show that a compensatory carbon-tax policy can achieve a win-win for all cohorts regardless of their place or time of birth. Indeed, carbon taxation coupled with region- and generation-specific positive or negative transfers can achieve a uniform welfare gain, that is, an identical percentage improvement in economic well-being for all. Our optimal UWI (uniform welfare improving) gain is 4.3 percent, measured as a consumption equivalent. This policy is effected by a) levying an annual global carbon tax equal to the contemporaneous social cost of carbon, b) making transfers to cohorts that would otherwise gain less than 4.3 percent, and

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

c) taxing cohorts that would otherwise gain more than 4.3 percent. Those receiving transfers include both Russians and Canadians, for whom climate change represents a positive externality, and early cohorts in most regions, that is, cohorts born too soon to benefit from climate change's mitigation, yet stuck paying higher energy prices. Those paying taxes are future generations in regions otherwise harmed, and potentially greatly so, by climate change.

However, the redistributive aspect of UWI policy may be unenforceable due to the very high taxes required of future cohorts in many regions. To mitigate this time consistency problem, we explored UWIF policy, that is, UWI policy, but with the uniform welfare gain restricted to future generations. Current generations are left with their BAU levels of utility. UWIF policy provides all the next generations with a 7.7 percent welfare gain. Furthermore, it limits the taxes they face to service the now smaller issuance of green bonds. However, their projected tax bill remains extremely high, especially for Indians. Indians born in 2200, for example, pay the equivalent of 38.2 percent of lifetime consumption in taxes. This is only slightly lower than the 39.9 percent under UWI.

Our third policy – UWIL – significantly lessens the time-consistency problem. It provides a uniform welfare gain to all cohorts in all regions apart from cohorts who would otherwise pay taxes exceeding 10 percent of their lifetime consumption. Taxes on such cohorts are limited to this 10 percent level, meaning they enjoy a higher welfare gain than under UWI policy. Importantly, UWIL still delivers major welfare gains, namely 4.0 percent for all cohorts under the tax limit and far higher for cohorts at the tax limit. For example, Indians born in the long run experience a 35.6 percent welfare gain, which is dramatically higher than the gains under UWI or UWIF policy.

For our high-damage case, the UWIL carbon tax starts at $ 91.4 per ton of CO2, rising, in real terms, at roughly 1.5 percent per year. This policy dramatically reduces global and region-specific climate damage. It also materially shortens the duration of fossil-fuel usage by roughly 130 years. Rather than increasing by as much as 3.7 degrees Celsius under BAU, the peak temperature rise under UWIL policy is 2.1 degrees. Peak global damages under UWIL are 9.2 percent of the planet's GDP. For India, the worst-hit region under BAU, damages peak at 27.5 percent of GDP under UWIL versus 43.9 percent under BAU.

Our optimal path of carbon taxation as well as the associated UWI gain, is little affected by assuming less than perfect substitutability in the short- and medium-term of clean for dirty energy. Considering, as we do, a nine-decade transformation of technology to the point that clean and dirty energy are perfect substitutes does lead to significantly greater use of dirty energy, particularly coal. But the dirty-energy end dates, beyond which neither coal, oil, or gas are used, is little affected.

Appendix A Supplementary Materials

Appendix A.1 contains supplementary material for the calibration outlined in section 4, whereas appendix A.2 complements the results from section 5. Finally, appendix A.3 provides more details on the computation.

A.1 Calibration

Table 8 reports GDP, energy consumption, and CO2 emissions by region relative to the US. Figure 12 reports UN-projected demographics in the 18 regions. Projected population declines in almost all regions, with the only exceptions being the US, CND, SSA, and ANZ; it is projected to increase over the next 100 years and then remain constant. The wiggles in some of these graphs come directly from the UN data. Figure 13 compares aggregate BAU damages resulting from our 1x specification of the damage function to aggregate damages predicted by DICE (Nordhaus, 2017). It can be seen that predicted damages are similar in both specifications.

Table 8: 2017 GDP, Energy Consumption, and CO2 Emissions Relative to the 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

A.2 Additional Findings

Tables 9 and 10 depict the region-specific social costs of carbon for the 6x specification of the damage function. The optimal case refers to the UWI policy. Clearly, the SCC is high for regions with high total GDP, notably CHI and USA. Note that in the optimal cases, the tax on carbon equals the SCC.

Figures 14, 15, and 16 depict projected oil, gas, and coal use both under BAU and under the 6x UWI optimal policy. The dramatic effect of the taxes on coal use is notable.

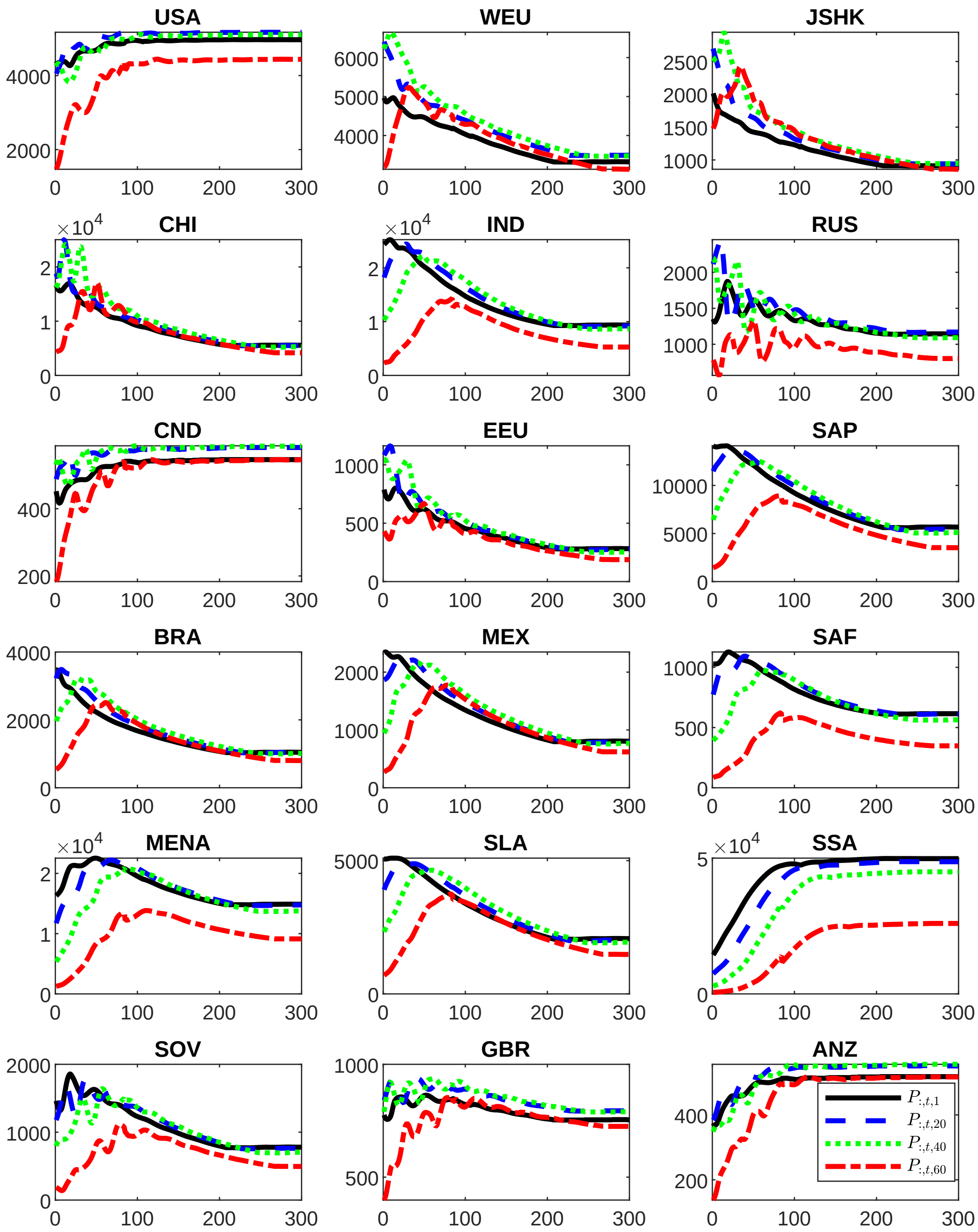

Figure 12: Projected Population (in millions) of Specified Age Groups

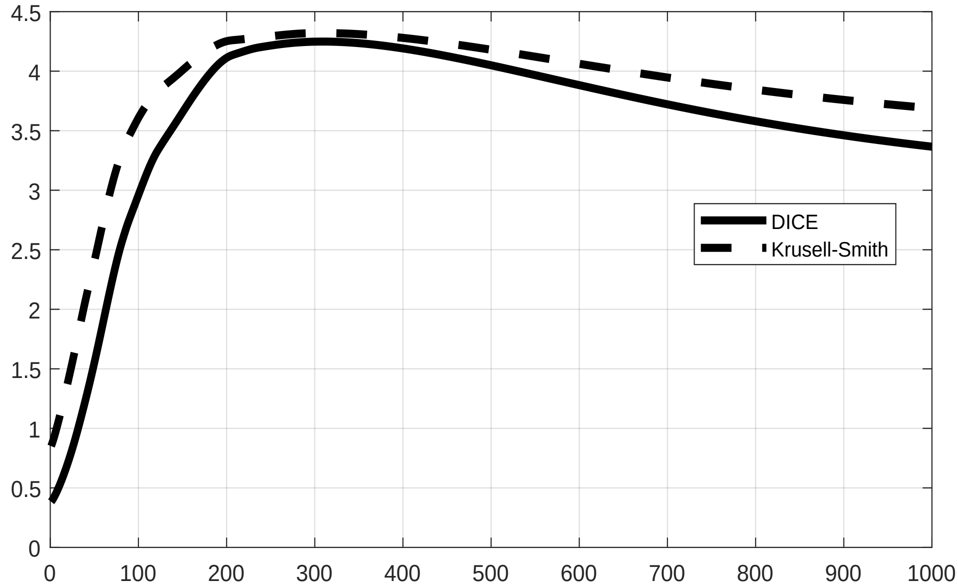

Figure 13: Comparing the "DICE" and "Krusell-Smith"(cf. equation (44)) global damages as a share of global GDP (measured in %) by year (starting 2017).

Table 9: Social Cost of Carbon, $ per Ton of CO2, Part 1.

	USA	WEU	JSHK	CHI	IND	RUS	CND	EEU	SAP
1x case, BAU									
2017	3.95	1.44	2.04	5.05	3.47	-0.22	-0.18	0.01	1.72
2025	4.53	1.70	2.42	6.17	4.23	-0.21	-0.18	0.02	2.00
2050	6.16	2.63	3.83	10.37	6.60	-0.16	-0.13	0.02	2.72
2100	16.56	8.26	12.98	36.72	18.66	-0.17	-0.06	0.05	6.35
1x case, optimal									
2017	3.84	1.27	1.98	4.71	3.61	-0.24	-0.23	0.01	1.80
2025	4.37	1.48	2.35	5.74	4.42	-0.24	-0.24	0.01	2.12
2050	5.95	2.23	3.74	9.76	7.17	-0.23	-0.26	0.02	3.01
2100	15.71	6.71	13.01	35.95	22.18	-0.44	-0.54	0.04	7.50
2x case, BAU									
2017	7.83	2.94	4.06	10.02	6.02	-0.23	-0.19	0.03	3.09
2025	8.91	3.46	4.79	12.17	7.25	-0.22	-0.19	0.03	3.56
2050	11.99	5.30	7.50	20.21	11.03	-0.17	-0.15	0.04	4.72
2100	31.79	16.45	25.03	70.37	30.17	-0.20	-0.12	0.09	10.72
2x case, optimal									
2017	6.97	2.25	3.50	8.12	5.86	-0.25	-0.23	0.02	3.09
2025	7.78	2.57	4.06	9.72	7.05	-0.25	-0.25	0.02	3.56
2050	10.07	3.67	6.21	15.99	11.09	-0.24	-0.27	0.03	4.86
2100	24.13	10.17	20.47	56.53	32.68	-0.43	-0.54	0.06	11.35
4x case, BAU									
2017	15.29	6.09	7.97	19.66	9.15	-0.24	-0.21	0.06	5.00
2025	17.17	7.10	9.29	23.54	10.78	-0.24	-0.21	0.06	5.64
2050	22.62	10.68	14.25	38.22	15.64	-0.19	-0.18	0.08	7.17
2100	58.56	32.39	46.41	129.31	40.88	-0.27	-0.22	0.18	15.63
4x case, optimal									
2017	12.62	4.08	6.17	14.01	8.73	-0.25	-0.24	0.04	4.90
2025	13.73	4.51	6.97	16.36	10.29	-0.25	-0.26	0.04	5.52
2050	17.07	6.17	10.32	26.29	15.81	-0.24	-0.29	0.05	7.32
2100	38.11	16.14	33.03	91.27	45.44	-0.42	-0.55	0.09	16.45
6x case, BAU									
2017	22.29	9.41	11.67	28.73	10.58	-0.26	-0.22	0.09	6.12
2025	24.71	10.84	13.42	33.96	12.24	-0.25	-0.22	0.10	6.77
2050	31.90	16.04	20.20	53.98	17.04	-0.22	-0.21	0.12	8.28
2100	80.96	47.67	64.47	178.62	43.24	-0.33	-0.31	0.26	17.54
6x case, optimal									
2017	17.63	5.81	8.48	19.06	10.19	-0.25	-0.25	0.06	5.99
2025	18.82	6.29	9.39	21.85	11.80	-0.24	-0.26	0.06	6.63
2050	22.93	8.38	13.64	34.58	17.97	-0.24	-0.29	0.07	8.62
2100	49.15	21.31	42.97	118.96	50.48	-0.42	-0.55	0.12	18.93

Table 10: Social Cost of carbon, $ per Ton of CO2, Part 2

	BRA	MEX	SAF	MENA	SLA	SSA	SOV	GBR	ANZ	Global
1x case, BAU										
2017	0.76	0.28	0.10	2.47	0.60	0.86	0.06	0.08	0.37	22.84
2025	0.83	0.29	0.11	2.86	0.63	1.03	0.07	0.09	0.42	27.03
2050	0.90	0.29	0.13	3.79	0.63	1.55	0.11	0.15	0.56	40.15
2100	1.67	0.41	0.25	8.02	0.91	4.03	0.30	0.46	1.43	116.84
1x case, optimal										
2017	0.80	0.28	0.09	2.50	0.62	0.90	0.04	0.06	0.37	22.41
2025	0.87	0.30	0.11	2.91	0.66	1.08	0.05	0.07	0.42	26.48
2050	1.00	0.31	0.13	3.97	0.69	1.67	0.08	0.11	0.56	39.90
2100	1.95	0.44	0.24	8.42	1.05	4.44	0.23	0.32	1.42	118.62
2x case, BAU										
2017	1.41	0.53	0.19	4.52	1.12	1.55	0.11	0.16	0.72	43.88
2025	1.52	0.56	0.21	5.20	1.18	1.84	0.14	0.19	0.82	51.43
2050	1.61	0.55	0.25	6.72	1.15	2.70	0.22	0.31	1.08	75.04
2100	2.92	0.75	0.46	13.82	1.64	6.85	0.60	0.93	2.72	215.00
2x case, optimal										
2017	1.43	0.52	0.17	4.34	1.13	1.52	0.08	0.11	0.67	39.28
2025	1.54	0.55	0.19	4.96	1.19	1.80	0.09	0.12	0.74	45.45
2050	1.69	0.54	0.22	6.48	1.19	2.68	0.13	0.18	0.96	65.49
2100	2.99	0.69	0.37	12.43	1.64	6.47	0.34	0.46	2.20	182.00
4x case, BAU										
2017	2.42	0.98	0.35	7.63	1.98	2.54	0.23	0.33	1.39	80.64
2025	2.55	1.02	0.39	8.59	2.05	2.96	0.28	0.40	1.55	92.94
2050	2.59	0.96	0.45	10.64	1.93	4.17	0.44	0.63	1.99	132.09
2100	4.53	1.28	0.80	20.89	2.66	10.12	1.18	1.86	4.91	371.09
4x case, optimal										
2017	2.44	0.94	0.30	7.08	1.96	2.42	0.13	0.18	1.20	66.70
2025	2.58	0.97	0.32	7.91	2.03	2.80	0.15	0.20	1.31	75.19
2050	2.73	0.92	0.36	9.98	1.99	4.04	0.21	0.28	1.61	104.63
2100	4.50	1.10	0.58	17.99	2.54	9.10	0.54	0.69	3.46	280.05
6x case, BAU										
2017	3.12	1.35	0.49	9.69	2.63	3.14	0.36	0.52	1.98	111.69
2025	3.22	1.39	0.54	10.70	2.68	3.59	0.43	0.62	2.18	126.89
2050	3.16	1.27	0.60	12.73	2.43	4.88	0.66	0.95	2.75	176.57
2100	5.34	1.66	1.05	24.13	3.28	11.45	1.72	2.77	6.65	490.15
6x case, optimal										
2017	3.18	1.28	0.40	8.91	2.60	2.97	0.18	0.25	1.66	88.16
2025	3.30	1.30	0.42	9.77	2.65	3.38	0.20	0.28	1.77	97.40
2050	3.41	1.21	0.47	12.06	2.57	4.79	0.28	0.37	2.14	132.95
2100	5.36	1.39	0.74	21.27	3.12	10.41	0.71	0.88	4.42	349.26

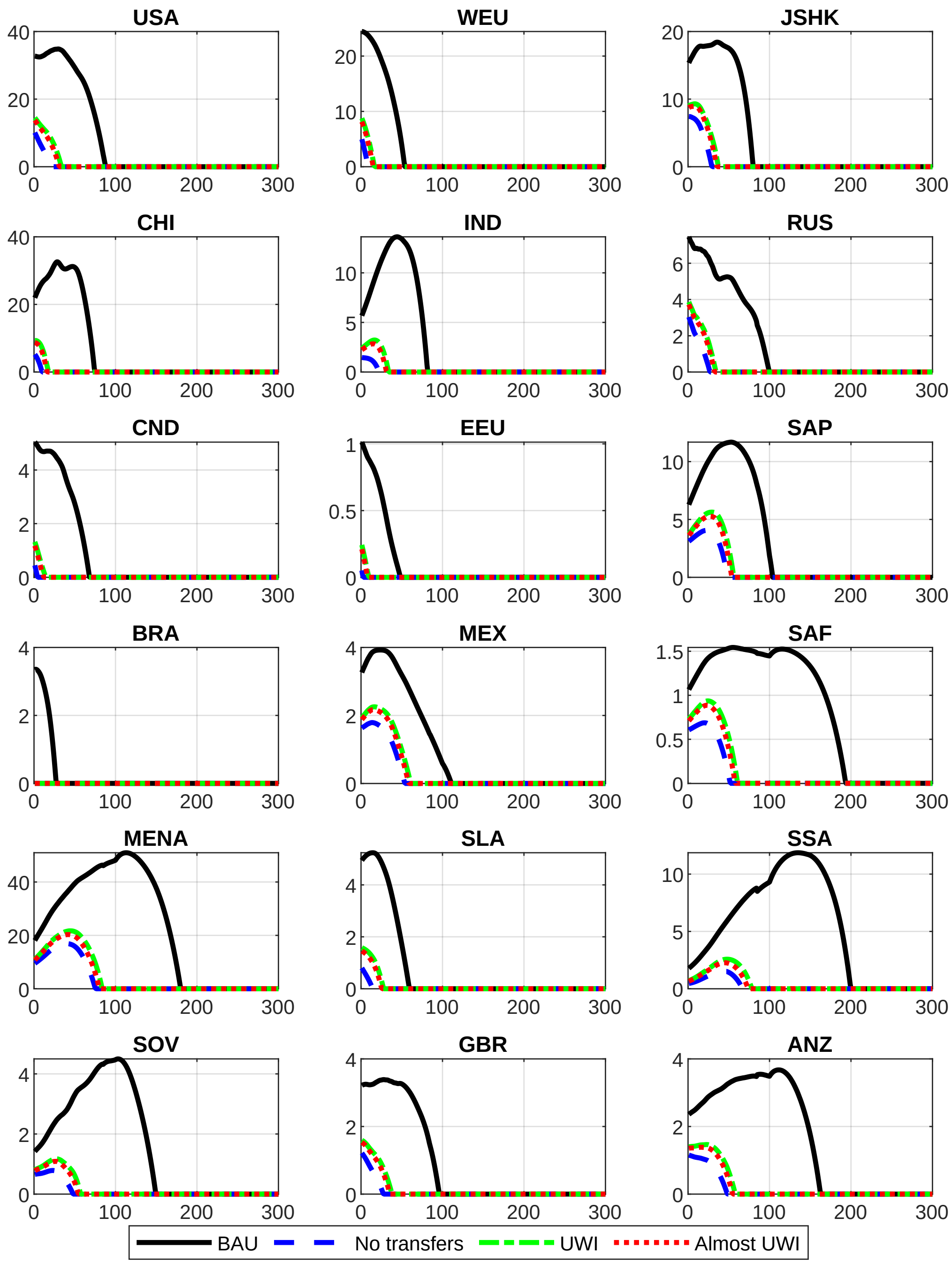

Figure 14: Oil consumption in the 6x case (measured in quad Btu)

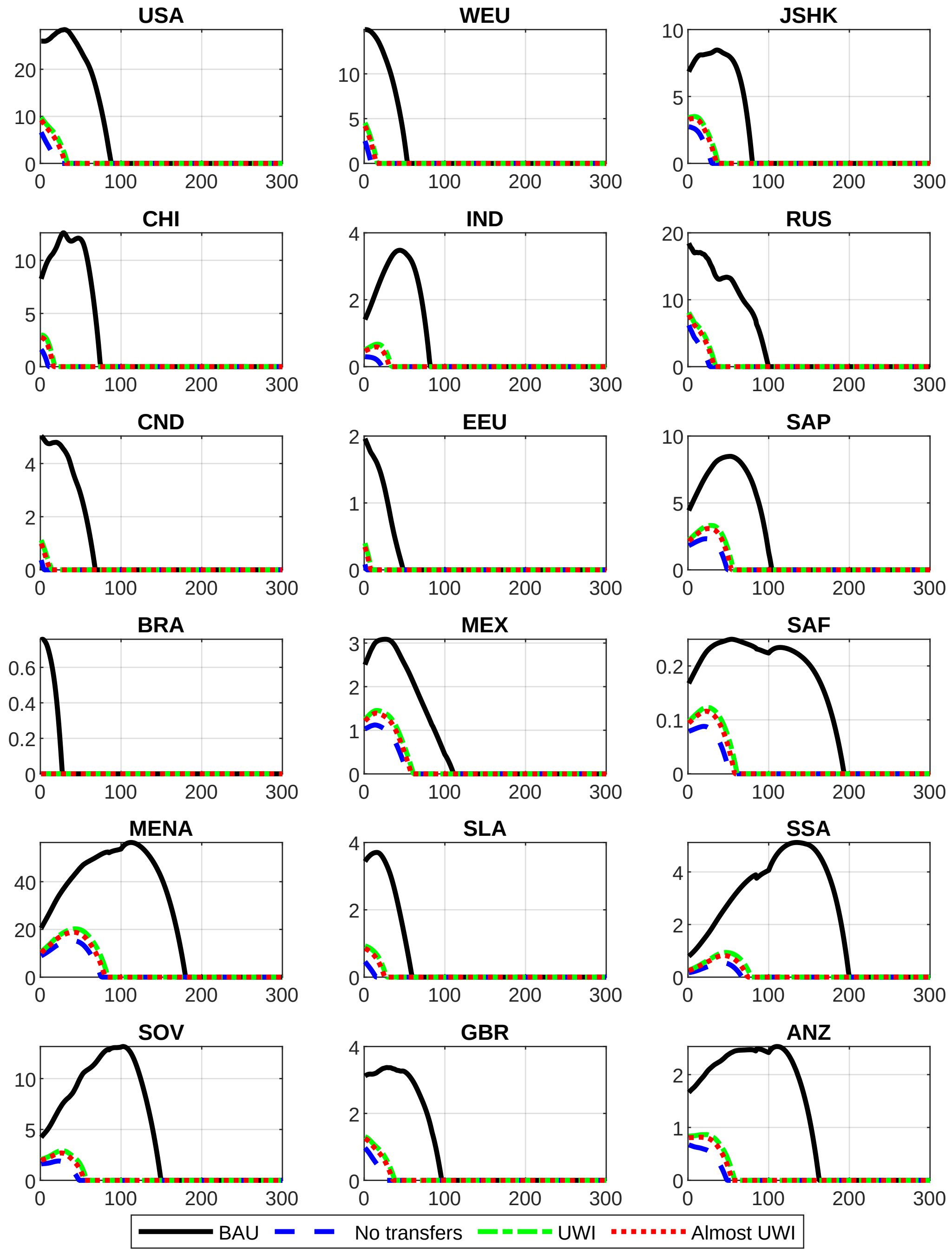

Figure 15: Gas consumption in the 6x case (measured in quad Btu)

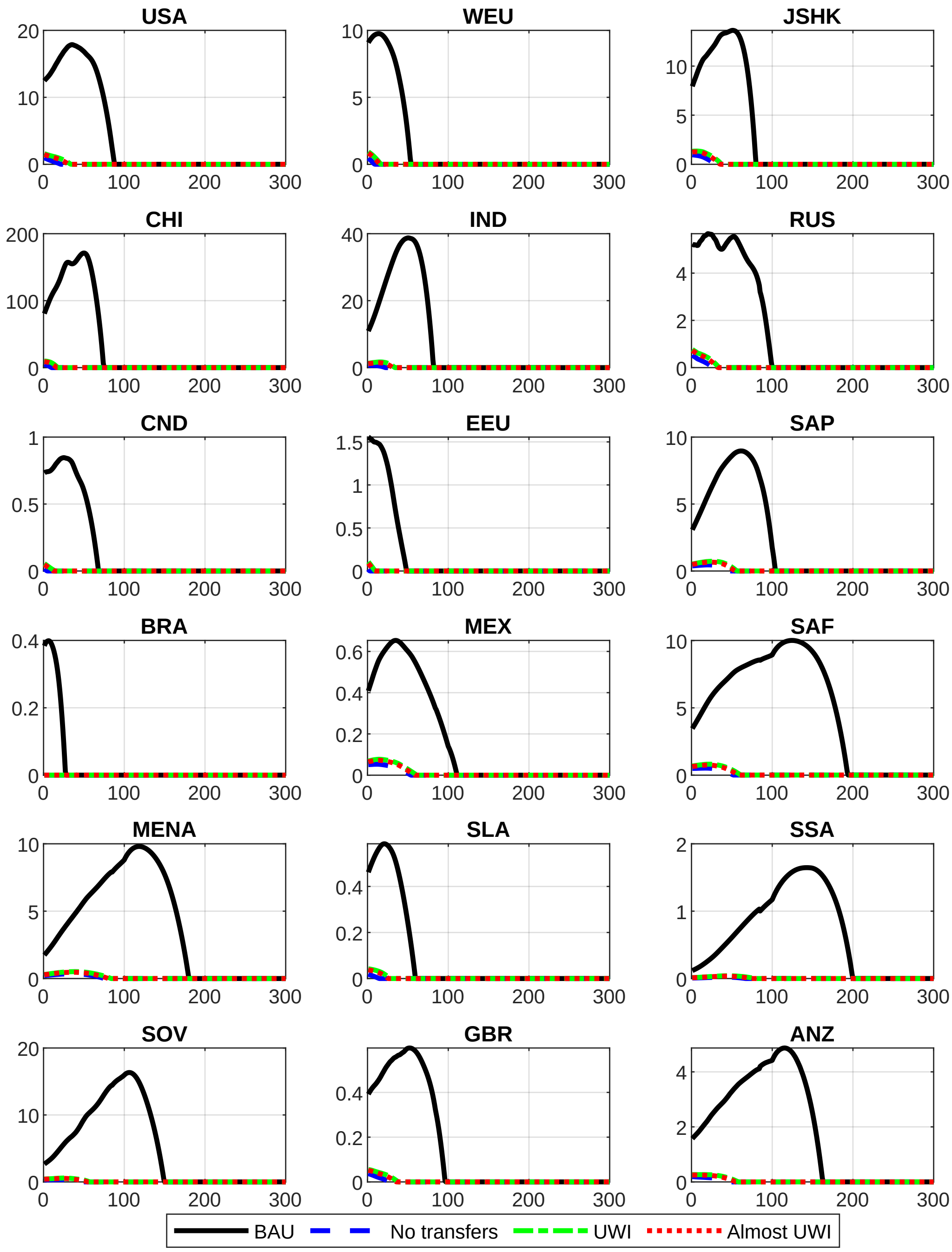

Figure 16: Coal consumption in the 6x case (measured in quad Btu)

A.3 Computational Details

This section details our solution algorithm, which recursively solves a series of simple one-period problems. This technique can be applied in more complex, multi-sector OLG trade models. We also use an iterative procedure to find the optimal carbon-tax path, updating each period's carbon tax to that period's SCC in each iteration.

We first describe our five-step algorithm conditional on a given tax path.

- Step 1.1: Set a high value of $\bar{t}$, in our case, 1000, to provide sufficient time for atmospheric CO2 to stabilize, permitting the economy to reach its steady state. Also, guess the time paths of the aggregate capital stock, oil, coal, and gas reserves, and region-specific total factor productivities.

- Step 1.2: Next, use backward induction for $t = \bar{t} - 1, .., 1$ to solve the nonlinear system of equations (1)-(9), (11)-(16), (24)-(26), and (32), (34), (35). Their solutions provide region-specific final output paths, $Y_{z,t}$, region-specific final-output factor demands for capital, $K_{z,y,t}$, labor, $L_{z,y,t}$, and energy, $E_{z,t}$, the world interest-rate path, r_t, region-specific paths of wages, $w_{z,t}$, region-specific paths of energy prices, $p_{z,t}$, region-specific clean-energy output paths, $S_{z,t}$, region-specific clean-energy factor-demand paths for capital, $K_{z,s,t}$, and labor, $L_{z,s,t}$, region-specific land rental price paths, $n_{z,t}$, region-specific usage paths of dirty energy, $E^D_{z,t}$, oil, $O_{z,t}$, gas, $G_{z,t}$, and coal, $\mathcal{C}_{z,t}$, region-specific dirty energy prices, $p^D_{z,t}$, regions-specific paths of the Lagrange multiplier governing dirty energy usage, $\chi_{z,t}$, paths of global extraction of oil, O_t, gas, G_t, and coal, $\mathcal{C}_t$, paths of global prices for oil, p^O_t, gas, p^G_t, and coal, $p^{\mathcal{C}}_t$, the path of Lagrange multipliers governing extraction of the dirty-energy reserves (21), ℓ^O_t, ℓ^G_t, $\ell^{\mathcal{C}}_t$, paths of Lagrange multipliers restricting dirty-energy extraction to be positive (23), μ^O_t, μ^G_t, $\mu^{\mathcal{C}}_t$ with given regional productivity in final output, $A_{z,t}$, and clean energy, $B_{z,t}$, production sectors, regional land supply, $H_{z,t}$, regional labor supply, $L_{z,t}$, world capital supply, K_t, reserves of oil, R^O_t, gas, R^G_t, and coal, $R^{\mathcal{C}}_t$, and next-period Lagrange multipliers for dirty energy reserves extraction dynamics (21), ℓ^O_{t+1}, ℓ^G_{t+1}, $\ell^{\mathcal{C}}_{t+1}$.

  The Lagrange multipliers, ψ^O_t, ψ^G_t and $\psi^{\mathcal{C}}_t$, ensuring the non-negativity of dirty-energy reserves (see (22)), are never binding and, thus, set to zero. Finally, the terminal values of the Lagrange multipliers for dirty-energy reserves dynamics are set equal to zero, $\ell^O_{\bar{t}}$, $\ell^G_{\bar{t}}$, $\ell^{\mathcal{C}}_{\bar{t}}$. Thus, for each point in time, t, we solve a system of 301 equations for 301 variables.

- Step 1.3) Use the above-referenced trial solution paths to determine the region-specific time paths of households' aggregate supplies of capital. From the paths of oil, gas, and coal extraction, we also determine the global time paths of dirty energy reserves, climate variables, damages, and region-specific productivity.

- Step 1.4) Update guessed time paths of the aggregate capital stock, oil, coal, and gas reserves, and region-specific productivity paths.

- Step 1.5) Iterate on steps 1.2-1.4 until convergence.

Next, consider solving the model for a given carbon-tax path (the zero-tax scenario is equivalent to the BAU scenario) combined with the use of the Auerbach and Kotlikoff (1987) Lump-Sum Redistribution Authority (LSRA), which can implement pre-specified Pareto-efficient outcomes. We first use the LSRA by Auerbach and Kotlikoff (1987) to derive the largest UWI carbon-tax policy, where welfare changes are measured as compensating consumption differentials, that is, λ.

- Step 2.1: Guess λ.
- Step 2.2: Given the guessed λ, iterate on steps 1.2-1.4, including updating transfers to ensure uniform welfare gains increase.
- Step 2.3: Calculate a present value of the transfers. If it is positive, decrease λ. If it is negative, increase λ.
- Step 2.4: Iterate on steps 2.2-2.3 until the present value of transfers approaches zero.

We determine the optimal global carbon-tax rate path numerically as follows:

- Step 3.1: Guess the time path of the optimal carbon tax based on the time path of the SCC (social costs of carbon) in the BAU scenario.
- Step 3.2: For a given tax path, find the LSRA solution (Steps 2.1-2.4).
- Step 3.3: Calculate the new equilibrium SCC path. Update the guessed path of the optimal carbon tax based on the new SCC path.
- Step 3.4: Iterate 3.2-3.3 until convergence.

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