Walras-Bowley Lecture: Climate Policy in the Wide World*

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Abstract

We construct a dynamic integrated assessment model of climate and the economy with very high geographic resolution. Migration is free within, but not allowed across, countries. The model parameterization uses a wealth of data, including the distribution of output, population, energy sources and use, and estimates of the local damages from climate change. It implies very large geographic dispersion in damages from warming. We conduct three kinds of policy experiments. In one, we note that a modest, uniform carbon tax limits global warming and damages around the world substantially. In a second experiment we let the poorest countries not tax carbon, while the rest compensate by setting higher taxes; the efficiency losses are large. In a final experiment we find that fast green technology growth alone is a poor substitute for carbon taxes, whether globally available or not.

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1 Introduction

Despite much uncertainty, efforts by climate scientists around the world have now allowed the most recent report of the IPCC (Intergovernmental Panel on Climate Change) to finally make a clear summary statement: human greenhouse gas emissions lead to global warming.[1] IPCC's summary moreover states that global warming is very long-lasting—for practical purposes permanent—and continues as long as human greenhouse gas emissions continue. In fact, best-practice climate science summarizes the effects of emissions as follows: each added unit of carbon emission will irreversibly increase warming by x degrees, where x is independent of past emissions. This linearity is still not to be taken for granted, and the slope—the value x—of the relationship contains significant remaining uncertainty, but the linear structure remains the best summary of what is known.

The point estimate of x is large: it is 0.45 degrees Celsius (°C) of warming per TtCO_2. At the current rate of emissions, this would mean around 0.2 degrees additional warming per decade. With further growth, together with the fact that the remaining amounts of fossil fuels yet in the ground are very large, warming would rise several degrees further. We regard these large numbers, along with the large uncertainty around x and a remaining worry that the effects may in fact be convex in cumulative emissions, as a great cause of concern. How a changed climate affects humans around the world is also associated with much uncertainty. It has, however, at least been established that in those parts of the world where average temperatures are already high, there will be large dents into human welfare. In our view, these facts together call for us to curb emissions sharply, if nothing else as a precautionary measure. The present paper belongs to a rapidly growing literature that explores the role of economics in these efforts. It develops a framework, an integrated assessment model (IAM), that can be viewed as a direct continuation of William Nordhaus's efforts and agenda. It is aimed at providing a tool for analyzing how different economic policies around the world impact global warming and our economies.

The core model is one with neoclassical growth, due to technology and population change, capital accumulation, and perfect foresight. The model has carbon-cycle and climate blocks taken from the seminal work by Nordhaus in the early 1990s. While

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[1] The previous reports did not draw a definite conclusion; see Allan, Hawkins, Bellouin, & Collins (2021).

keeping the original five-equation structural form, the parameters of the model have been updated by Nordhaus and others in several steps to address concerns about its ability to account for the relation between emissions and climate change (see Barrage and Nordhaus, 2023, and Dietz et al. (2021)). We use a recent re-parameterization that has been shown to imply that the model replicates the predictions of the most advanced comprehensive global climate models quite accurately (Folini et al., 2025).

We include very rich spatial heterogeneity, allowing correspondingly rich experiments to be run. Despite this complexity, our model is also highly accessible to others. The main reason for this is that our equilibria can be solved for very handily, without the need for sophisticated numerical toolboxes. We offer the model, along with instructions for how to characterize and solve it, in a "plug-and-play" form.[2] The scope for introducing heterogeneity in our model, while still maintaining tractability, is significant. We explore some of these avenues in the present paper.

We put the model to use by analyzing different policy options that have been discussed or already implemented. We begin by studying a relatively modest carbon tax, applied uniformly around the world. We show that such a tax would be hugely beneficial by limiting warming substantially, without significantly damaging output levels around the world.

Second, we explore deviations from policy uniformity, with particular attention paid to policy proposals suggesting that poor countries would not need to use carbon taxes. Here we find that although such policies might (depending on their scope) work in the sense of limiting emissions, they would be very costly. Who would bear these costs depends on possible compensating transfer schemes, but our fear is that the size of these transfers would prevent the policies from being undertaken in the first place.

Finally, we study a particularly prominent policy proposal: that of refraining entirely from carbon taxation, instead focusing on promoting green energy. This policy is reminiscent of the IRA (the Inflation Reduction Act). We implement this policy option by assuming that, at no cost, we can raise the rate of technological change in the production of green energy significantly, including a tilting of energy provision toward electrifica-

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[2] In this sense, our efforts are closely related to Nordhaus's dissemination of the DICE package. DICE is Nordhaus's first complete Dynamic Integrated assessment model of Climate and the Economy and it was offered in a package based on numerical solution using GAMS.

tion. This de facto boils down to a rapidly and persistently falling relative price of green relative to fossil energy. We look at two versions of the model. In one, the fast green technology growth becomes available globally; in the other, it becomes available only in the United States and the European Union. We find that although this experiment raises energy use substantially where it occurs, it does not solve the global warming problem because green energy is not sufficiently potent in reducing the use of fossil fuel. This conclusion resonates with one in Cruz & Rossi-Hansberg (2022), but is derived using a much richer energy sector.[3]

Our model also makes contact with several literatures that emerged since Nordhaus's work. First, several frameworks with the same aim as DICE were developed and used, e.g., in efforts to identify the social cost of carbon.[4] Models building on explicit microeconomic structures include the MERGE model (Manne, Mendelsohn, & Richels (1995)) and the WITCH model (featuring regional heterogeneity; see Bosetti (2007)); these models develop DICE in different directions with regard to the climate system, production, population, the energy system, policy interactions, and so on. Our parameterizations and calibration are informed by these papers but our setting builds most directly on Golosov, Hassler, Krusell, & Tsyvinski (2014), who develop a dynamic, stochastic general equilibrium model that, despite considerable richness, is very easy to solve and analyze. Compared to that framework, which is a global model without sub-regions, we add not only spatial heterogeneity but also a much richer and more realistic model of energy supply, a different damage function (both qualitatively and quantitatively), and an updated climate system. Developments on that path toward the current paper includes Hassler & Krusell (2012), which show how several regions can be incorporated, and Hassler, Krusell, & Olovsson (2021), which explores suboptimal policy.

Nordhaus also developed a regional model—RICE (in Nordhaus & Yand (1996)), with 10 broad regions—but models with higher spatial resolution have also been developed based on methods from trade and economic geography. As do we, the majority of these papers use 1° × 1° cells on the map as a unit of analysis.[5] The economic geography

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[3] We distinguish between many different green and fossil energy sources.

[4] E.g., the U.S. government's Interagency Working Group on the Social Cost of Carbon in 2009 used DICE alongside two other models.

[5] The implied area of a unit thus varies across the globe but is roughly 100km by 100km. Only cells including land are included, producing a little under 20,000 regions.

approach to spatial heterogeneity includes Desmet & Rossi-Hansberg (2015) and a number of subsequent studies; a review article appears in Desmet & Rossi-Hansberg (2024). On the one hand, these frameworks are not neoclassical growth models, but on the other hand they focus precisely on the mobility of people.[6] They also feature local amenities, local crowding, but also (positive) local agglomeration effects on productivity. In the present paper, in contrast, TFPs are exogenous, save for effects from to climate damages. We do model local crowding, but through different means: we assume decreasing returns to final production. Moving is costless within countries, but not allowed between countries. The economic geography literature also has examples with multiple sectors and trade; these features are important in that especially developing countries have a heavy reliance on agricultural goods and natural resources and a good deal of their exports focus on these goods.[7] We see the economic geography as complementary to the approach here, which is a more direct continuation of Nordhaus's research.

The literature on climate change and economics has also expanded significantly in ways that do not focus on regional heterogeneity. One active area has been to discuss directed technology, e.g., the empirical work in Popp (2004) and the theory in Acemoglu, Aghion, Bursztyn, & Hemous (2012); here, we study the effects, but not the roots, of rapid technological change in the green sector. The focus on the roots is clearly highly relevant but we believe that it is not central to the main points in this paper.

Another literature in climate economics has considered the roles of uncertainty, risk, and significant non-linearities (including tipping points). We do not include risk or uncertainty explicitly but it is analytically and computationally straightforward to incorporate them into the model; calibration, however, is much more challenging. The large uncertainty surrounding climate change and damages makes the search for "optimal" policy very challenging, however. Section 4 below discusses extensions and how to approach actual policy choice.

The paper is organized as follows: Section 2 describes the model in great detail, including how to solve and calibrate it. Section 3 describes the policy experiments and the results and Section 4 how uncertainty and non-linearities can be studied. Section 5

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[6] An exception is the recent paper Bilal & Rossi-Hansberg (2023), a study of U.S. interstate migration that also features capital accumulation.

[7] In ongoing work, we are developing multisectoral versions of the present setting with trade. Nath (2020) is an interesting recent example of research in this direction.

concludes.

2 The global economy-climate model

2.1 Overview

The model's central feature is the same feedback loop that lies at the heart of all economy-climate models: economic activity emits carbon into the atmosphere, raising the Earth's temperature and influencing economic activity in turn. One of the main purposes of the model is to study this feedback at a high degree of geographic resolution. The global land mass is divided into approximately 19,000 regions, each of which belongs to one out of J countries; countries are identified by their national boundaries.[8]

Within each country, people and production inputs are assumed to be able to move freely. On the other hand, neither people nor production inputs can move across countries. The one exception is oil: we consider it to be a globally traded good. In each region, there is a production function of the economy's aggregate output good, a good that is also identical across countries. The inputs we consider are labor, capital—which is accumulated in a standard neoclassical manner—and a composite of energy services. In addition to oil, the energy service composite contains a number of different (home-produced) inputs—coal, natural gas, and a number of "green" energy sources, including hydro, nuclear, solar, and wind—and distinguishes energy in the form of electricity and other, where electricity is also distinguished by whether it is plannable or not. All these energy sources are combined in heterogenous country specific production functions. Moreover, the total-factor productivity levels differ across regions in a country (and across countries), both in terms of an exogenous component and in the extent to which climate change causes damages. Within each country, the assumption of free factor mobility allows us to derive a country-level aggregate production function whose total-factor productivity is a non-linear weighted average of the productivity levels in the country's different regions.

The regions also interact through the global climate system. The aggregate carbon emissions of the different regions cause the globe to warm which, in turn, alters the productivity levels across the globe. The model, which can accommodate taxes on carbon

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[8] We consider any region that is part of more than one country to belong to the country that the largest share of its land mass is in.

emissions that vary across space and time, generates equilibrium time paths not only for global output and the global temperature but also for output and the temperature in every region.

Next, we describe the different parts of our model in detail and, thereby, make clear how we define our global equilibrium. We then show how key parts of the model solution are obtained.

2.2 Time and space

The globe is divided into a large number of regions containing land, each of which corresponds to a 1° × 1° cell defined by the lines of latitude and longitude at one-degree intervals. Time is discrete, lasts forever, and begins in period 0. There is no uncertainty.

2.3 Consumers

Each country j contains a large number, N_{jt}, of identical, price-taking consumers at time t. Consumers in different countries have identical preferences: they value streams of per-capita consumption, $\{c_{jt}\}_{t=0}^{\infty}$, according to:

$$\sum_{t=0}^{\infty} N_{jt}\beta^t \log(c_{jt}), \tag{1}$$

where we assume N_{jt} to be an exogenously given path. We denote the growth rate of population from t to $t+1$ by x_{t+1}: $x_{j,t+1} = N_{j,t+1}/N_{j,t}$. The discount factor, β, is between zero and one and consumers do not value leisure.

We assume that most regions cannot produce oil; those that can only produce oil and export all the oil in exchange for consumption goods. We describe the decision problems of oil-producing regions, which are very few, after first describing consumers in oil-importing regions.[9] Thus, consumers in country j are endowed with k_{j0} units of physical capital per capita in period 0 and one unit of time in each period. We use

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[9] To map the setting to data (see our detailed discussion later in the paper), we consider most countries not to have oil production at all, even when their production is not literally zero (but small). For countries where oil production is a significant part of GDP, we assume there to be two "synthetic countries" within the actual country: one which produces oil only and one which produces no oil. In the description of the model, the notion of a country (indexed by j) is the broader one, i.e., we have in mind also the synthetic countries.

lower-case letters to denote per-capita quantities. In most of the derivations below, we will use per-capita notation; the exceptions are where we sum (emissions and oil use) across countries, where we re-introduce N_{jt} as the "weight" of country j at time t.

Because labor is mobile within each country, the consumer's choice problem will not involve region-specific variables: "the" wages and rental rates are common to all consumers in the country and, in the background, workers as well as capital spread across regions so as to make these prices the same everywhere. Consumers can save by investing in physical capital in their own country. Letting the period-t consumption good serve as the numéraire, consumers in country j thus earn a wage w_{jt} in period t per effective unit of labor and the rental rate of capital in period t is r_{jt}. Capital depreciates fully from period to period (and thus one needs to think of a period as being relatively long).

Each country contains a government that taxes carbon emissions into the atmosphere and rebates all the proceeds to consumers in the country at a rate $\hat{\tau}_{jt}$ that is proportional to all income.[10] Consumers in country j, then, maximize the utility function above subject to the following sequence of budget constraints for $t \geq 0$, written in per-capita terms:

$$c_{jt} + k_{j,t+1} x_{j,t+1} = (r_{jt} k_{jt} + w_{jt} + \pi_{jt})(1 + \hat{\tau}_{jt}), \tag{2}$$

where k_{jt} is a typical consumer's holdings of capital in region j in period t and where π_{jt} is a return to land ownership (or, equivalently, firm profits). As indicated above, the budget constraint is written in per-capita terms, which explains the occurrence of x in multiplying tomorrow's per-capita capital stock.[11]

Consumers in oil-producing regions have a somewhat simpler maximization problem, since their only income is from oil. Oil, moreover, is extracted from a finite reserve at zero cost, an assumption we adopt from Golosov et al. (2014). The motivation behind this assumption is that the global price of (conventional) oil is much above the marginal cost of producing it; assuming a positive, small extraction cost would not change the results but lead to more burdensome computations. Thus, a region (i, j) producing oil

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[10] This form of transfer makes saving rates independent of the capital stock as well as independent of other variables (such as energy prices and tax rates). Under lump-sum taxation, the saving rate is also independent of the capital stock but depends on energy prices and tax rates. The quantitative difference between these transferring schemes is negligible, so we choose the one that leads to simpler analysis.

[11] There is also a no-Ponzi game constraint that holds for each country's all consumers, but we omit it for brevity.

would have a budget constraint

$$c_{ijt} + p_{t,o} x_{j,t+1} R_{ij,t+1} = p_{t,o} R_{ijt}, \tag{3}$$

i.e., consumption is the market value of the current extraction of the resource, $R_{ijt} - x_{j,t+1} R_{ij,t+1}$. The key restriction implicit in this equation, one that is binding, is that oil producers cannot invest the proceeds from oil sales abroad, or otherwise store the proceeds from sold oil. These assumptions are clearly not consistent with the data but greatly simplify the analysis; oil extraction becomes determined regardless of demand. Allowing for price-sensitive oil supply would be valuable but mainly influence the price formation for oil in the model, as energy services are chiefly determined by the remaining energy sources.

2.4 Firms and their technologies

Each region (within each country) not producing oil has a large number of price-taking firms operating in different sectors. One of the sectors is that producing the final good; the other sectors are the energy input producers.

We assume that the gross production-function of the final good—a function of capital, labor, and the energy composite—is given by $\hat{A}_{ijt} \left(K_{ijt}^{\alpha} N_{ijt}^{1-\alpha-\nu_j} E_{ijt}^{\nu_j} \right)^{\varphi_j}$, where K, N, and E are totals. Defining k, n, and e as their capitalized counterparts divided by N_{jt} and factorizing by the region's population size, we obtain $\hat{A}_{ijt} N_{jt}^{\varphi_j} \left(k_{ijt}^{\alpha} n_{ijt}^{1-\alpha-\nu_j} e_{ijt}^{\nu_j} \right)^{\varphi_j}$. Thus the per-capita gross production function reads

$$A_{ijt} \left(k_{ijt}^{\alpha} n_{ijt}^{1-\alpha-\nu_j} e_{ijt}^{\nu_j} \right)^{\varphi_j},$$

where $A_{ijt} \equiv \hat{A}_{ijt} N_{jt}^{\varphi_j - 1}$. Thus k_{ijt} refers to the capital stock used in region i (of country j at time t) measured per capita in the country: $\sum_i k_{ijt} = k_{jt}$. Similarly, $\sum_i e_{ijt} = e_{jt}$ and $\sum_i n_{ijt} = 1$, where e_{ijt} and n_{ijt} are the uses of energy services and labor, respectively, in region i of country j at t. Implicit in this function is a fixed factor that we can think of as land, which is in a fixed supply normalized to 1. Firms are price-takers: they solve

$$\pi_{ijt} \equiv \max_{k,n,e} A_{ijt} \left(k_{ijt}^{\alpha} n_{ijt}^{1-\alpha-\nu_j} e_{ijt}^{\nu_j} \right)^{\varphi_j} - r_{jt} k - w_{jt} n - p_{jt} e. \tag{4}$$

Turning to the production of energy services, we use a multi-layer CES structure. In the top layer, electricity services are combined with a fossil composite, consisting of oil, gas and coal, to produce general energy services that enter the final good production. Electricity services are produced by combining plannable and non-plannable electricity generation. Plannable electricity is produced with coal, gas, hydro and nuclear power. Non-plannable electricity is produced from wind and photovoltaic (solar) power. The share parameters in the aggregation of the different energy sources are country specific, accounting for the fact that the fuel mix varies tremendously across countries.

Countries that currently have hydro and nuclear power are assumed to have these energy sources in fixed supply at a zero marginal cost. The other energy sources, except conventional oil, are produced domestically at a country specific exogenous cost $p_{jt,m}$ in terms of the final good. The energy sources are traded at competitive domestic markets with different prices across countries. Oil is instead traded at a world market and its price will therefore be the same in all countries: $p_{t,o}$.[12]

It follows that the resources available for consumption and saving in country j at time t is

$$\sum_i A_{ijt}\left(k_{ijt}^{\alpha} n_{ijt}^{1-\alpha-\nu_j} e_{ijt}^{\nu_j}\right)^{\varphi_j} - \sum_m p_{jt,m} e_{jt,m}.$$

It remains to describe the details behind how, using the $e_{jt,m}$ inputs, the downstream energy service $e_{jt} = \sum_i e_{ijt}$ is produced.

The basic energy sources $m \in \{o, o^s, c, g, s, w, h, q\}$, where o refers to conventional oil, o^s to shale oil (a form of "non-conventional" oil available in the U.S.), c to coal, g to natural gas, s to solar power, w to wind power, h to hydroelectricity, and q to nuclear. Here, the first three are fossil sources, giving rise to carbon dioxide emissions that we detail in Section 2.7 below.

We now formally specify how the different energy sources are combined in a nested CES function. An overview of the energy sector is displayed in Figure 1.

Starting with the energy-service input used in the production of final goods, it is a nested CES function of fossil fuels ($\bar{f}_{jt}$)—mainly transportation and heating—and an electricity service composite (v_{jt}):

$$e_{jt} = \left(\lambda_j^{\frac{1}{\rho}} \bar{f}_{jt}^{\frac{\rho-1}{\rho}} + (1-\lambda_j)^{\frac{1}{\rho}} \bar{v}_{jt}^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}. \tag{5}$$

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[12] The assumption that an energy input is produced using output at fixed marginal cost is equivalent to assuming that it is produced using capital, labor, and energy, with the same production function as that of final output, save for a relative TFP factor.

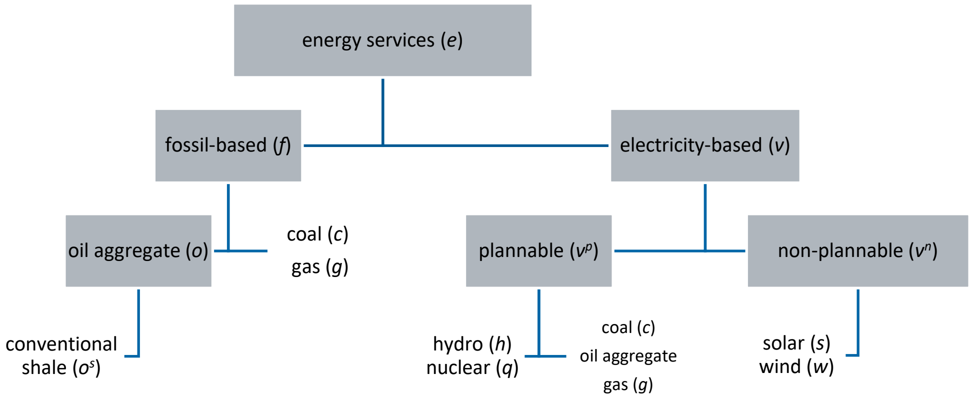

Figure 1: Overview of the energy sector. The boxes denote aggregates that are produced with CES functions.

The fossil-fuel component in (5) is then a CES composite of three different types of fuels: an oil composite used here ($\bar{o}^f$), coal used here (c^f), and natural gas (g^f) used here, i.e.,

$$\bar{f}_{jt} = \left(\lambda_{jf,1}^{\frac{1}{\rho_f}} \left(\bar{o}_{jt}^{f}\right)^{\frac{\rho_f-1}{\rho_f}} + \lambda_{jf,2}^{\frac{1}{\rho_f}} (c_{jt}^{f})^{\frac{\rho_f-1}{\rho_f}} + (1-\lambda_{jf,1}-\lambda_{jf,2})^{\frac{1}{\rho_f}} \left(g_{jt}^{f}\right)^{\frac{\rho_f-1}{\rho_f}} \right)^{\frac{\rho_f}{\rho_f-1}} . \tag{6}$$

The oil composite is an aggregate of conventional oil (o_{jt}) and fracking/shale oil (o_{jt}^s):

$$\bar{o}_{jt} = \left(\lambda_{jo}^{\frac{1}{\rho_o}} \left(o_{jt}\right)^{\frac{\rho_o-1}{\rho_o}} + (1-\lambda_{jo})^{\frac{1}{\rho_o}} \left(o_{jt}^{s}\right)^{\frac{\rho_o-1}{\rho_o}} \right)^{\frac{\rho_o}{\rho_o-1}} . \tag{7}$$

The second argument in (5) is electricity services, which is a CES aggregate of plannable ($\bar{v}_{jt}^p$) and non-plannable energy sources ($\bar{v}_{jt}^n$); formally, we have

$$\bar{v}_{jt} = \left(\lambda_{jv}^{\frac{1}{\rho_v}} (\bar{v}_{jt}^{p})^{\frac{\rho_v-1}{\rho_v}} + (1-\lambda_{jv})^{\frac{1}{\rho_v}} \left(\bar{v}_{jt}^{n}\right)^{\frac{\rho_v-1}{\rho_v}} \right)^{\frac{\rho_v}{\rho_v-1}} . \tag{8}$$

Plannable sources are hydropower (h), nuclear power (q), and the fossil sources of coal, oil and natural gas. We assume that hydro and nuclear both exist in fixed supply with the fixed quantities given by $\widehat{h}_{jt}$ and $\widehat{q}_{jt}$, respectively, but are traded competitively. We also assume that that these two inputs are perfectly substitutable; their prices are market determined in perfect competition and the firms supplying them hence make "Hotelling rents", $\pi_{jt}^h = p_{jt,h}\widehat{h}_{jt}$ and $\pi_{jt}^q = p_{jt,q}\widehat{q}_{jt}$, respectively. Plannable energy is then given by

$$\begin{aligned} v_{jt}^p = \Bigg(& \lambda_{jp,1}^{\frac{1}{\rho_p}} \left(h_{jt}+q_{jt}\right)^{\frac{\rho_p-1}{\rho_p}} + \lambda_{jp,2}^{\frac{1}{\rho_p}} (c_{jt}^{v})^{\frac{\rho_p-1}{\rho_p}} + \lambda_{jp,3}^{\frac{1}{\rho_p}} (\bar{o}_{jt}^{v})^{\frac{\rho_p-1}{\rho_p}} \\ & + (1-\lambda_{jp,1}-\lambda_{jp,2}-\lambda_{jp,3}) \left(g_{jt}^{v}\right)^{\frac{\rho_p-1}{\rho_p}} \Bigg)^{\frac{\rho_p}{\rho_p-1}} . \end{aligned} \tag{9}$$

Non-plannable electricity, finally, is a composite of photovoltaic (s) and wind power (w):

$$v_{jt}^{n}=\left(\lambda_{jn}^{\frac{1}{\rho_n}}s_{jt}^{\frac{\rho_n-1}{\rho_n}}+\left(1-\lambda_{jn}^{\frac{1}{\rho_n}}\right)^{\frac{1}{\rho_n}}w_{jt}^{\frac{\rho_n-1}{\rho_n}}\right)^{\frac{\rho_n}{\rho_n-1}}. \tag{10}$$

Total oil composite, coal, and natural gas use are thus given by

$$\bar{o}_{jt}=\bar{o}_{jt}^{f}+\bar{o}_{jt}^{v},\quad c_{jt}=c_{jt}^{f}+c_{jt}^{v},\quad \text{and}\quad g_{jt}=g_{jt}^{f}+g_{jt}^{v}, \tag{11}$$

respectively. The above nested structure allows us to incorporate different degrees of substitutability between different energy inputs. For instance, oil and fracking are a priori much closer substitutes in the production of liquid fuel than are, for example, fossil fuel and electricity in the production of energy services. Thus, our structure has four elasticity parameters, ρ, ρ_o, ρ_u, and ρ_v, and a set of country-specific share parameters; all these need to be calibrated to the data.

Our structure allows an energy services price index p_{jt} to be constructed as an explicit function of the underlying prices of energy inputs. We will entertain taxes on the fossil energy inputs used by the producer of energy services. The firm producing energy services is a price-taker and, given constant returns to scale, supplies input at a constant unit cost:

$$p_{jt}\equiv\min_{\{m_{jt}\}\forall m}\sum_{m\in\{o,o^s,c,g,s,w,h,q\}}\hat{p}_{jt,m}m_{jt}\quad \text{s.t. (5)-(11)} \tag{12}$$

for all j and t and where we use the notation $\hat{p}_{jt,m}\equiv p_{jt,m}+\tau_{jt}, m\in\{o,o^s,c,g\}$ and $\hat{p}_{jt,m}\equiv p_{jt,m}$ otherwise.[13] The nested CES structure leads to closed-form price indices and the input demands all have simple representations that are linear in final demand e_{jt}.

Firm profits aggregated across regions within a country is then simply $\pi_{jt}\equiv\sum_i\pi_{ijt}+\pi_{jt}^{h}+\pi_{jt}^{q}$, which is the profit, or land income, plus the Hotelling rents from hydroelectric and nuclear power, distributed to the representative consumer of country j.

2.5 Governments

Each oil-consuming country implements a (per-unit) carbon tax, τ_{jt}, and recycle all the revenues back to the household within the period in the form of a negative income tax rate, $\hat{\tau}_{jt}>0$, times total household income:

$$\hat{\tau}_{jt}\left(w_{jt}+r_{jt}k_{jt}+\pi_{jt}\right)=\tau_{jt}\left(\bar{o}_{jt,m}+c_{jt,f}+g_{jt,c}\right). \tag{13}$$

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[13] Recall that $p_{jt,o}$ does not depend on j, as oil is a world price.

2.6 TFPs

As indicated, "A" is total-factor productivity, TFP. It has several components. One is exogenous, region-specific, and constant over time; another one is global, exogenous, and time-dependent; and a third component, due to damages from climate change, is endogenous and time- and region-dependent. We now describe these in detail.

Our region- and time-specific TFPs are

$$A_{ijt} = \exp(z_{ijt}) D_{ij,t}.$$

Beginning with the first factor, we assume that, in the long run, all zs are given as

$$z_{ijt} = z_{ij} + \sum_{s=0}^{t} g_{js}.$$

The time-dependent component thus differs across countries, so as to accommodate a period of continued growth in some regions of the world (such as China and India) above the world average rate, which we denote as g and which will apply in all countries for high enough t.

Turning to TFP damages, we employ a formulation where damages depend on regional temperature. As we will show below, our estimated regional productivities for 2005 have a hump-shaped relation with the temperature, with a maximum around 15 degrees Celsius. We assume that this relation remains in the future, which implies that regions colder than the optimal gain from becoming warmer while the hotter ones lose. We thus posit a map from regional temperature into productivity as follows:

$$D(T_{ij,t}) = \bar{D}_{\max} \cdot \begin{cases} (1-d^-) \exp\left(-\kappa^- \left(T_{ijt} - T^*\right)^2\right) + d^- \text{ for } T_i < T^* \\ (1-d^+) \exp\left(-\kappa^+ \left(T_{ijt} - T^*\right)^2\right) + d^+ \text{ for } T_i \geq T^*. \end{cases}$$

Here, T_{ijt} is local temperature in region i of country j at time t, $\bar{D}_{max}$ is the productivity at the optimal temperature and the parameters d^-, d^+ are, respectively, the asymptotic productivities relative to $\bar{D}_{max}$ as the temperature becomes very low or very high. Finally, κ^+ and κ^- determine the curvature of the mapping.

2.7 Temperature

The mapping from emissions via the atmospheric CO_2-concentration to the global atmospheric temperature is determined through climate and carbon cycle blocks. We use

Nordhaus's seminal specification with three carbon sinks: the atmosphere, the surface oceans and biosphere, and the deep oceans. For the climate block, we also follow Nordhaus and incorporate two temperatures: the global mean atmospheric ground level temperature and the mean temperature in the oceans.

Starting with the carbon cycle, the total amount of CO_2 emissions in period t is given by

$$M_t = \sum_j N_{jt} \left(\bar{o}_{jt,o} + c_{jt} + g_{jt} \right); \tag{14}$$

all energy sources are measured by their carbon content and hence they are added here, without weights.

All emissions enter the carbon cycle through the atmosphere. Denoting the stock of CO_2 in the atmosphere, the surface oceans and biosphere, and the deep oceans S, S^U, and S^L, respectively, the carbon cycle block is formulated as follows.

$$\begin{aligned} S_t - S_{t-1} &= -\phi_{12} S_{t-1} + \phi_{21} S^U_{t-1} + M_{t-1} && (15) \\ S^U_t - S^U_{t-1} &= \phi_{12} S_{t-1} - \left(\phi_{21} + \phi_{23} \right) S^U_{t-1} + \phi_{32} S^L_{t-1} && (16) \\ S^L_t - S^L_{t-1} &= \phi_{23} S^U_{t-1} - \phi_{32} S^L_{t-1}. && (17) \end{aligned}$$

The climate block features two temperatures: the global mean ground level temperature in the atmosphere denoted by T_t, and the mean temperature in the deep ocean denoted by T^L_t. The representation of the climate obeys the following system of equations.

$$\begin{aligned} T_t &= T_{t-1} + \sigma_1 \left(F_{t-1} - \kappa T_{t-1} - \sigma_2 \left(T_{t-1} - T^L_{t-1} \right) \right) && (18) \\ T^L_t &= T^L_{t-1} + \sigma_3 \left(T_{t-1} - T^L_{t-1} \right), && (19) \end{aligned}$$

where F is forcing:

$$F_t = \chi \frac{\eta}{\ln 2} \ln \left(\frac{S_t}{S_0} \right), \tag{20}$$

Note the factor χ that appears multiplicatively in (20). This factor, which exceeds 1, is added to capture non-CO_2 forcing such as from atmospheric methane.

Folini et al. (2025) show that the above specification of the carbon cycle and the climate system can well replicate the mean behavior of the most advanced comprehensive global climate models if the parameters are chosen appropriately.[14] Finally, note that our

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[14] This is carried out by comparing the output from the model with the data from the archive CMIP5 (Coupled Model Intercomparison Project, Phase 5) that collects output from a number of advanced earth system climate models.

system implies an inertia that makes T_t predetermined: it is affected by past, not current emissions.

Local temperatures in different regions of the world are interdependent in a highly complex way. However, it is possible to use "statistical downscaling", an approach developed in the climate sciences.[15] The idea used in this approach is that historical data or results from model simulations can be used to establish a pattern that relates changes in the global temperature and the temperature in each region. When such a pattern is established the changes in the global temperature can be used as a sufficient statistic for all regional temperatures. It is well established that a linear relation between the global and the regional temperature sufficies quite well for the purpose provided region specific coefficients are allowed. Thus, given a change in the global mean temperature $\Delta T_t \equiv T_t - T_0$:

$$T_{ijt} = \bar{T}_{ij} + \gamma_{ij} \Delta T_t \tag{21}$$

where T_{ijt} is the temperature in (i, j) at $t, \bar{T}_{ij}$ is the time-zero temperature in (i, j) The region-specific coefficients γ_{ij} thus measure the sensitivity of the local to the global temperature.

2.8 Equilibrium

This section defines a perfect-foresight equilibrium. It consists of a set of sequences of prices and quantities, along with climate-related variables, at different levels of aggregation, satisfying a number of conditions. More precisely,

1. given the emissions paths, the global climate variables $\left\{M_t, S_t, S_t^U, S_t^L, F_t, T_t, T_t^L\right\}_{t=0}^{\infty}$ satisfy equations (14)–(20);
2. given the global temperature path, local temperatures $\{T_{ijt}\}_{t=0}^{\infty}$ satisfy (21) for all (i, j);
3. for all oil-consuming countries j and given a sequence $\{r_{jt}, w_{jt}, \hat{\tau}_{jt}, x_{j,t+1}, \pi_{jt}\}_{t=0}^{\infty}$, consumers choose a sequence $\{c_{jt}, k_{j,t+1}\}_{t=0}^{\infty}$ that maximizes (1) subject to the sequence of budget constraints (2);
4. for all oil producers (i, j), given oil prices $\{p_{t,o}\}_{t=0}^{\infty}$, the oil supply sequence $\{R_{ijt}\}_{t=1}^{\infty}$ maximizes (1) subject to the sequence of budget constraints (3);

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[15] See, e.g., Tebaldi and Arblaster (2014).

5. for all (i, j, t), given the TFPs implied by the temperature levels T_{ijt} and given prices (r_{jt}, w_{jt}, p_{jt}), $(k_{ijt}, n_{ijt}, e_{ijt})$ solves the final-good firms profit maximization problems (4), delivering profits π_{ijt};
6. for all (j, t), p_{jt} satisfies (12) given prices $(\hat{p}_{jt,o}, \hat{p}_{jt,f}, \hat{p}_{jt,c}, \hat{p}_{jt,g}, p_{jt,s}, p_{jt,w}, p_{jt,h}, p_{jt,q})$, and given the same prices and total energy demand e_{jt}, the implied demands for hydroelectricity and nuclear power satisfy $h_{jt} = \widehat{h}_{jt}$ and $q_{jt} = \widehat{q}_{jt}$;
7. for each j and t, total input demands equal input supplies: $\sum_i k_{ijt} = k_{jt}$, $\sum_i n_{ijt} = 1$, and $\sum_i e_{ijt} = e_{jt}$;
8. for each j and t, final-goods markets clear: $c_{jt}+k_{j,t+1}x_{j,t+1} = \sum_i A_{ijt} \left(k_{ijt}^{\alpha} n_{ijt}^{1-\alpha-\nu_j} e_{ijt}^{\nu_j}\right)^{\varphi_j} - \sum_m p_{jt,m} e_{jt,m}$;
9. for all j and all t, $(\tau_{jt}, \hat{\tau}_{jt})$ is such that the government budget constraint (13) is met; and
10. world demand for oil equals world supply: for all t, $\sum_j e_{jt,o} N_{jt} = \sum_{i,j} (R_{ijt} - x_{ij,t+1} R_{ij,t+1}) N_{ijt}$.

Before proceeding to the solution of the model, it is useful to check the resource constraint in each country (condition 8 above) is implied by the other conditions as follows. To do this, sum across firms' profits (including the Hotelling rents), substitute into the expression $(r_{jt}k_{jt} + w_{jt} + \pi_{jt})(1 + \hat{\tau}_{jt})$ on the right-hand side of the consumer's budget constraint, and use the energy suppliers' zero-profit conditions and the government budget constraint to obtain the quantity on the right-hand side of condition 8.

2.9 Solving for the equilibrium

For given policy sequences $\{\tau_{jt}\}_{t=0}^{\infty}$ across the world, the model can be solved forward; this amounts to a major saving on computational time. The key reason for this result is simple: the only forward-looking decisions involve the consumers' maximization problems and, as we shall demonstrate, these problems deliver solutions for saving rates (for capital accumulation, in the case of oil-consuming countries, and for oil resource management, in the case of oil producers) that only depend on exogenous parameters. The saving rates themselves are time-dependent and forward-looking, but satisfy a simple recursion.

Given a capital stock and a population in each country, one can compute country output with relative ease, assuming a value for the world price of conventional oil. Although the different regions' TFP levels are endogenous, they are predetermined at this point in time because the temperature is predetermined. We will begin by going through this calculation, which involves the allocation of the inputs across regions within the country, step by step. Along with output, one obtains the country's demand for oil. It is then possible to use a simple fixed-point algorithm for finding the oil price that clears the world markets period by period. This algorithm also involves finding the country-specific prices for the energy services that come from hydroelectricity and nuclear power. We finally show how to obtain the saving rates, which allow us to map the state variables at time t into states at $t+1$.

2.9.1 The pricing and production of energy

Because the production technology is a nested CES with CRS, it is straightforward to derive the implied price of a unit of energy services as

$$p_{jt} = \left[\lambda_j p_{jt,\bar{f}}^{1-\rho} + (1-\lambda_j)\, p_{jt,\bar{v}}^{1-\rho}\right]^{\frac{1}{1-\rho}}, \tag{22}$$

where

$$\begin{gathered}
p_{jt,\bar{f}} = \left[\lambda_{jf,1} p_{jt,\bar{o}}^{1-\rho_f} + \lambda_{jf,2}\left(p_{jt,c}+\tau_{jt}\right)^{1-\rho_f} + \left(1-\lambda_{jf,1}-\lambda_{jf,2}\right)\left(p_{jt,g}+\tau_{jt}\right)^{1-\rho_f}\right]^{\frac{1}{1-\rho_f}} \\
p_{jt,\bar{v}} = \left[\lambda_{jv} p_{jt,p}^{1-\rho_v} + (1-\lambda_{jv})\, p_{jt,n}^{1-\rho_v}\right]^{\frac{1}{1-\rho_v}} \\
p_{jt,\bar{o}} = \left[\lambda_{jo}\left(p_{t,o}+\tau_{jt}\right)^{1-\rho_o} + (1-\lambda_{jo})\left(p_{jt,o^s}+\tau_{jt}\right)^{1-\rho_o}\right]^{\frac{1}{1-\rho_o}} \\
p_{jt,p} = \left[\lambda_{jp,1} p_{jt,h}^{1-\rho_p} + \lambda_{jp,2}\left(p_{jt,c}+\tau_{jt}\right)^{1-\rho_p} + \lambda_{jp,3} p_{t,o}^{1-\rho_p} + \right. \\
\left.\left(1-\lambda_{jp,1}-\lambda_{jp,2}-\lambda_{jp,3}\right)\left(p_{jt,g}+\tau_{jt}\right)^{1-\rho_p}\right]^{\frac{1}{1-\rho_p}} \\
p_{jt,n} = \left[\lambda_{jn} {p_{jt,s}}^{1-\rho_n} + (1-\lambda_{jn})\, {p_{jt,w}}^{1-\rho_n}\right]^{\frac{1}{1-\rho_n}}
\end{gathered}$$

and where, for convenience given the recursive structure, we have also defined prices for the sub-composite nests.[16]

We finally need to compute the demand for all energy inputs. These all take the form of the ratio of its price to the price of the composite in which the good is an input, taken to a power one minus the elasticity in the composite, times its λ times the composite quantity. I.e., the amounts are all linear in the composite quantity and a power function of the price.[17] For the energy inputs in fixed supply, which are perfect substitutes, one

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[16] The derivations are laid out in the Appendix.

[17] For brevity, we omit the formulas here; they are all displayed in our online appendix.

similarly solves for their price as a power function of the sum of their quantities relative to the composite total.

Recall, finally, that all the underlying prices for the energy inputs are exogenously given except the world market price for conventional oil ($p_{t,o}$) and the local prices for hydroelectricity and nuclear power ($p_{jt,h} = p_{jt,q}$). Hence, there are two prices that will require a numerical solution.

2.9.2 Aggregation across regions within each country

As was made clear above, within each country, i.e., between regions in a country, capital, labor, and energy can be freely allocated within each time period. In a region i, belonging to a country j, production of gross output takes three inputs: capital, k, labor, n, and energy services e. In a first stage, we derive an expression for production net of energy costs in each region i as a function of capital and labor, thus maximizing over the intermediate energy input, and then derive the resulting aggregate.[18] First, thus,

$$y_{ijt}(k,n) = \max_{e} A_{ijt} \left(k^{\alpha} n^{1-\alpha-\nu_j} e^{\nu_j}\right)^{\varphi_j} - p_{jt} e,$$

where k and n are yet to be determined and p_{jt} is the price index for energy services e derived in the previous section; it is given. The TFP term A_{ijt} embodies climate damages that depend on the local temperature given in the previous period; it is hence predetermined. Note that the parameter $\varphi_j \in (0,1)$ captures a degree of decreasing returns, or crowding, in any given region; its interpretation is also consistent with an omitted input factor, such as land. The overall idea here is that decreasing returns will prevent areas from emptying out completely (unless TFP there is literally zero). The maximization problem over e delivers $p_{jt} e_{ijt} = \nu_j \varphi_j A_{ijt} \left(k^{\alpha} n^{1-\alpha-\nu_j} e_{ijt}^{\nu_j}\right)^{\varphi_j}$, resulting in a function

$$y_{ijt}(k,n) = (1-\nu_j\varphi_j) \left(\frac{\nu_j \varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{ijt}^{\frac{1}{1-\nu_j\varphi_j}} \left(k^{\alpha} n^{1-\alpha-\nu_j}\right)^{\frac{\varphi_j}{1-\nu_j\varphi_j}} = B_{ijt} k^{\alpha_{kj}} n^{\alpha_{jn}},$$

where we have defined $\alpha_{jk} \equiv \frac{\alpha\varphi_j}{1-\nu_j\varphi_j}$ and $\alpha_{jn} \equiv \frac{(1-\alpha-\nu_j)\varphi}{1-\nu_j\varphi_j}$; we note that this production function has overall decreasing returns to scale. For convenience, we have also defined $B_{ijt} = (1-\nu_j\varphi_j) \left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{ijt}^{\frac{1}{1-\nu_j\varphi_j}}$.

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[18] Production net of energy costs would equal value added if taxes were zero.

An efficient allocation of capital and labor across regions i (within a country j) then implies

$$\alpha_{jk} B_{ijt} k_{ijt}^{\alpha_{jk}-1} n_{ijt}^{\alpha_{jn}} \equiv r_{jt}$$

$$\alpha_{jn} B_{ijt} k_{ijt}^{\alpha_{jk}} n_{ijt}^{\alpha_{jn}-1} \equiv w_{jt}$$

and, dividing these two equations for each i, we obtain $k_{ijt} = \frac{\alpha_{jk}}{\alpha_{jn}} \frac{w_{jt}}{r_{ijt}} n_{ijt}$. Summing over i, we obtain

$$\frac{k_{ijt}}{n_{ijt}} = \frac{k_{jt}}{n_{jt}} = k_{jt} = \frac{\alpha_{jk}}{\alpha_{jn}} \frac{w_{jt}}{r_{jt}} \quad \forall i.$$

Using this in the efficiency condition for capital above we see that

$$\alpha_{jk} B_{ijt} \left(n_{ijt} k_{jt}\right)^{\alpha_{jk}-1} n_{ijt}^{\alpha_{jn}} = r_{jt}$$

and we can express n_{ijt} as

$$n_{ijt} = \left(\frac{\alpha_{jk} B_{ijt}}{r_{jt}}\right)^{\frac{1}{1-\alpha_{jk}-\alpha_{jn}}} k_{jt}^{\frac{\alpha_{jk}-1}{1-\alpha_{jk}-\alpha_{jn}}}. \tag{23}$$

We can now sum over i to find the value for r in terms of k. The first step yields

$$1 = n_{jt} = \left(\frac{\alpha_{jk}}{r_{jt}}\right)^{\frac{1}{1-\alpha_{jk}-\alpha_{jn}}} k_{jt}^{\frac{\alpha_{jk}-1}{1-\alpha_{jk}-\alpha_{jn}}} \left(\sum_{i=1} B_{ijt}^{\frac{1}{1-\alpha_{jk}-\alpha_{jn}}}\right)$$

and then, solving for r_{jt}, we arrive at

$$r_{jt} = \alpha_{jk} \left(\sum_{i=1} B_{ijt}^{\frac{1}{1-\alpha_{jk}-\alpha_{jn}}}\right)^{1-\alpha_{jk}-\alpha_{jn}} k_{jt}^{\alpha_k - 1}.$$

Now note that $1 - \alpha_{jk} - \alpha_{jn} = (1-\varphi_j)/(1-\nu_j\varphi_j)$. The definitions of α_{jk} and B_{ijt} above then deliver

$$r_{jt} = \alpha\varphi_j \left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}-1}, \tag{24}$$

where

$$A_{jt} \equiv \left(\sum_{i=1} A_{ijt}^{\frac{1}{1-\varphi_j}}\right)^{1-\varphi_j}, \tag{25}$$

i.e., the TFP factor A_{jt} is a CES average of the individual TFPs A_{ijt}. The functional form implies “convex weighting” given $\varphi_j < 1$: higher values for A_{ijt} count more. The two limits are, first, for $\varphi_j = 0$, an unweighted arithmetic average (reflecting equal use of inputs in all regions) and, for $\varphi_j = 1$, $\max_i A_{ijt}$ (reflecting that all factors move to the region with the highest TFP). Also, note that the weighting depends on j: it differs (potentially) across countries.

We similarly obtain

$$w_{jt} = (1-\alpha-\nu_j)\varphi_j \left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}}. \tag{26}$$

We can now also derive total value added in any country j. The Cobb-Douglas structure for value added at the regional level gave us the first-order condition for capital as $r_{jt}k_{ijt} = \alpha_{jk}y_{ijt}(k_{ijt}, n_{ijt})$, so summing over i we obtain

$$r_{jt}k_{jt} = \alpha_{jk}y_{jt},$$

where $y_{jt} = \sum_i y_{ijt}(k_{ijt}, n_{ijt})$. Hence, using (24), we now obtain country js value added as

$$y_{jt} = \frac{r_{jt}k_{jt}}{\alpha_{jk}} = (1-\nu_j\varphi_j)\left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}}. \tag{27}$$

Here, only p_{jt} is endogenous; it is given by (22), where all variables are exogenous except $p_{t,o}$ and $p_{jt,h}$. The former value is determined in the global equilibrium, to which we turn next. Note, as a summary, that country GDPs are given as Cobb-Douglas functions of capital and labor, with a TFP term given as a nonlinear average of the regional TFPs. The share parameters for capital and labor are $\frac{\alpha_j\varphi_j}{1-\nu_j\varphi_j}$ and $\frac{(1-\alpha-\nu_j)\varphi_j}{1-\nu_j\varphi_j}$, respectively, and country js TFP is given by a constant and the non-linear average of regional TFPs, all to the power of $1/(1-\nu_j\varphi_j)$, where $\nu_j\varphi_j$ is energy's share.

2.9.3 Oil demand, oil supply, and the clearing of the world oil market

Firm demand for energy services and capital in any region must satisfy $p_{jt}e_{ijt}/(\nu_j\varphi_j) = r_{jt}k_{ijt}/(\alpha\varphi_j)$ from the first-order conditions. Summing across regions we see that country j's demand for energy services is given by

$$e_{jt} = \frac{\nu_j}{\alpha}\frac{r_{jt}}{p_{jt}}k_{jt}. \tag{28}$$

Here, k_{jt} is predetermined, r_{jt} is given by (24), and p_{jt} is an increasing function of $p_{t,o}$ from the price index formulas above.

World demand for oil equals $\sum_j N_{jt}o_{jt}$. In a given country, oil per capita is used in the composite oil production of an amount $o_{jt} = \lambda_{jo}\left(\frac{p_{t,o}+\tau_{jt}}{p_{jt,\bar{o}}}\right)^{-\rho_o}\bar{o}_{jt}$. Hence, world oil demand becomes

$$\sum_j N_{jt}\lambda_{jo}\left(\frac{p_{t,o}+\tau_{jt}}{p_{jt,\bar{o}}}\right)^{-\rho_o}\bar{o}_{jt}. \tag{29}$$

In turn, $\bar{o}_{jt} = \bar{o}^f_{jt} + \bar{o}^v_{jt}$, each of which is linear in e_{jt}. Hence, this sum becomes:

$$\left[\lambda_{jf,1}\left(\frac{p_{jt,\bar{o}}}{p_{jt,\bar{f}}}\right)^{-\rho_f}\lambda_j\left(\frac{p_{jt,\bar{f}}}{p_{jt}}\right)^{-\rho}+\lambda_{jp,3}\left(\frac{p_{jt,\bar{o}}}{p_{jt,p}}\right)^{-\rho_p}\lambda_{j,v}\left(\frac{p_{jt,p}}{p_{jt,\bar{v}}}\right)^{-\rho_v}(1-\lambda_j)\left(\frac{p_{jt,\bar{v}}}{p_{jt}}\right)^{-\rho}\right]e_{jt} \tag{30}$$

Inserting $\bar{o}_{jt}$, as given by (30), and e_{jt}, as given by (28), into (29) gives us world oil demand as a function all domestic prices and the world price of oil.

As for oil supply, let us turn to the oil producer's utility maximization problem and recall that its budget reads $c_{ijt} + p_{t,o}x_{j,t+1}R_{ij,t+1} = p_{t,o}R_{ijt}$. Suppressing country and regional indexes, the first-order conditions with respect to c_{jt}, $c_{j,t+1}$, and $R_{j,t+1}$ (all per-capita variables) become

$$\frac{N_{jt}\beta^t}{c_{jt}} = \lambda_{jt}, \quad \frac{N_{j,t+1}\beta^{t+1}}{c_{j,t+1}} = \lambda_{j,t+1}, \quad \text{and} \quad p_{t,o}x_{j,t+1}\lambda_{jt} = p_{t+1,o}\lambda_{j,t+1}.$$

This delivers the Euler equation $p_{t,o}/c_{jt} = \beta p_{t+1,o}/c_{j,t+1}$. Given the budget, we define a saving rate s_{jt} and write $c_{jt} = (1-s_{jt})p_{t,o}R_{jt}$. Substitution into the Euler equation delivers

$$R_{j,t+1} = \beta\frac{1-s_{jt}}{1-s_{j,t+1}}R_{jt}. \tag{31}$$

To solve for the saving rate sequence, we use $x_{j,t+1}R_{j,t+1} = s_{jt}R_{jt}$ from the budget to obtain

$$s_{jt} = \frac{\beta x_{j,t+1}}{1-s_{j,t+1}+\beta x_{j,t+1}}. \tag{32}$$

Given an exogenous sequence of population growth rates $\{x_{j,t+1}\}_{t=0}^{\infty}$, which we assume will equal and remain at 1 after a finite period of time, we can solve backwards for these saving rates. When $x_{j,t+1} = 1$ forever after, $s_j = \beta$ for all j. Hence, (31)–(32) give us the oil supply of the region: it is an exogenous fraction of the remaining supply R_t, a fraction that will eventually become $1-\beta$ but differs slightly from that earlier on due to population growth.

Total oil supply in period t of oil-producing country j is thus given by $N_{jt}(R_{jt} - x_{j,t+1}R_{j,t+1})$, so world supply equals

$$\sum_j N_{jt}\left(1-\beta x_{j,t+1}\frac{1-s_{jt}}{1-s_{jt+1}}\right)R_{jt}. \tag{33}$$

Hence, the propensities to extract oil are not the same for all oil producers, but depend on their respective population growth paths, since these influence their saving propensities. After population growth ends, however, their extraction rates become equal to β. Setting this amount equal to world oil demand allows us to solve for $p_{t,o}$, period by period, from period 0 and onward.[19]

2.9.4 Saving rates in oil-consuming countries

In a manner similar to that described in the previous section, we can derive an Euler equation for the representative oil-consuming resident of country j as

$$\frac{1}{c_{jt}} = \beta \frac{r_{j,t+1}(1+\hat{\tau}_{j,t+1})}{c_{j,t+1}}.$$

The budget constraint (2) allows us to write $c_{jt} = (1-s_{jt})(r_{jt}k_{jt} + w_{jt} + \pi_{jt})(1+\hat{\tau}_{jt})$. Now recall that $r_{jt}k_{jt} + w_{jt} + \pi_{jt} = (1-\nu_j\varphi_j)\left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}}$ and, from (24), that $r_{jt} = \alpha\varphi_j \left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}-1}$. We then obtain that

$$\frac{1}{(1-s_{jt})(1-\nu_j\varphi_j)\left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}}(1+\hat{\tau}_{jt})} =$$

$$\beta \frac{\alpha\varphi_j \left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{j,t+1}^{\frac{1}{1-\nu_j\varphi_j}} k_{j,t+1}^{\alpha_{jk}-1}(1+\hat{\tau}_{j,t+1})}{(1-s_{j,t+1})(1-\nu_j\varphi_j)\left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{j,t+1}^{\frac{1}{1-\nu_j\varphi_j}} k_{j,t+1}^{\alpha_{jk}}(1+\hat{\tau}_{j,t+1})},$$

yielding, after using the fact that $x_{j,t+1}k_{j,t+1} = s_{jt}(r_{jt}k_{jt} + w_{jt} + \pi_{jt})(1+\hat{\tau}_{jt}))$ and some simplifications,

$$\frac{s_{jt}}{1-s_{jt}} = \frac{\frac{\alpha\beta\varphi_j}{1-\nu_j\varphi_j} x_{j,t+1}}{1-s_{j,t+1}}, \tag{34}$$

which can be written

$$s_{jt} = \frac{\frac{\alpha\beta\varphi_j}{1-\nu_j\varphi_j} x_{j,t+1}}{1-s_{j,t+1} + \frac{\alpha\beta\varphi_j}{1-\nu_j\varphi_j} x_{j,t+1}}. \tag{35}$$

This is a forward-looking equation in saving rates that is very similar to that for oil-producing countries given in (32).

We conclude that the per-capita saving of country j follows

$$k_{j,t+1} = \frac{s_{jt}(1+\hat{\tau}_{jt})}{x_{j,t+1}}(1-\nu_j\varphi_j)\left(\frac{\nu_j\varphi_j}{p_{jt}}\right)^{\frac{\nu_j\varphi_j}{1-\nu_j\varphi_j}} A_{jt}^{\frac{1}{1-\nu_j\varphi_j}} k_{jt}^{\alpha_{jk}}.$$

The heterogeneity across economies appear in multiple places: saving rates differ due to population growth heterogeneity, taxes differ, the decreasing-returns parameter φ differs, and TFPs differ, in part due to TFP heterogeneity within countries and in part due to differences in the costs of producing energy services from different sources.

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[19] Here, note that if the temperatures, which enter the TFP terms and hence affect demand, were to depend on current (not past) emissions, one would simply iterate jointly on $(p_{t,o}, M_t)$ to clear the market.

2.9.5 Full model solution

The model solution works as follows, given paths for tax rates on fossil fuel around the world. First, one solves for the saving rates of all countries; this involves forward-looking equations but no other endogenous variables.

Second, one can compute the equilibrium forward, starting at time 0. To do this, note that at each point in time, there is a set of state variables: capital stocks, temperatures, and oil resources by country, in addition to the global state variables in the carbon cycle and climate system. All endogenous variables follow directly—in closed form, given the above equations—from knowing the values of these state variables *and* (i) the global oil price $p_{t,o}$ and (ii) the value of hydroelectricity services in each country, $p_{jt,h}$, all of which are endogenous and need to be solved for numerically. $p_{t,o}$ needs to clear the world oil market and, for each j, $p_{jt,h}$ needs to be set so that the implied demand equal the inelastic supplies $\widehat{h}_{jt} + \widehat{q}_{jt}$ country by country. The numerical algorithm at each point in time thus guesses on $p_{t,o}$ in an outer loop and then on the $p_{jt,h}$s in an inner loop.

2.10 Parameter selection

We now describe how we select our model parameters. For output and population, we have data at the level of our smallest model unit, the regions; for other variables, we only have country data. We begin describing the former.[20]

2.10.1 High-resolution data

We make use of the G-Econ database, version 4.0, which provides data on gross domestic product (GDP) and population for every 1°× 1° cell that contains land for the model's base year, 2005. The universe of cells cover the 360 degrees of longitude and the 180 degrees of latitude, which implies a total of $360 \times 180 = 64{,}000$ cells. The current data set covers approximately 27,500 terrestrial grid cells. G-Econ 4.0 then contains GDP and population data for 16,443 cells in 2005, and these are the cells that comprise the basic unit of analysis in the global economy-climate model.

In Figure 2 we plot the share of global GDP in 2005 against the local temperatures. As we see that most of the output is produced in regions with intermediate temperatures.

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[20] When USD measures are mentioned in the paper, they refer to 2015.

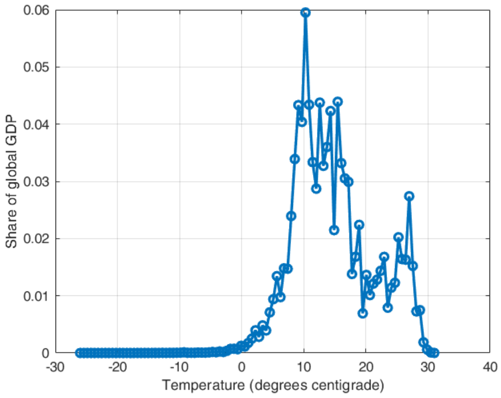

Figure 2: Share of world GDP produced in different locations, as ranked by temperature.

In Figure 3 we show that, while a large fraction of the population lives relatively close to the optimum temperature, a large fraction of the population actually lives in much warmer regions. These are the masses of people who will be hit hard by global warming.

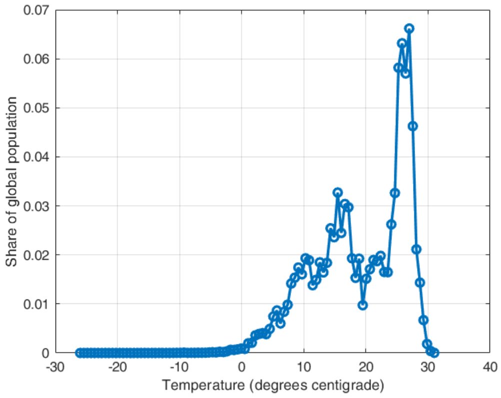

Figure 3: The share of regional population as a function of the regional temperature.

Oil-producing countries in our model are not given geographical location, and they do not produce final goods: they simply sell their resources over time. Since oil revenues do not account for 100 percent of the income of any country, we simply deduct the income shares that are coming from oil for OPEC and Russia. The remaining income in these countries then comes from final goods production.[21]

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[21] The exact oil shares for each country are provided in the online appendix.

2.10.2 The assumptions behind underlying the determination of saving rates

Each model time period is taken to cover ten years, and our preference discount factor is set to 0.985^{10}; we set the initial date to 2005.

As detailed above, our model solution is made significantly less burdensome by the combination of assumptions on preferences and technology: logarithmic curvature for consumption utility; Cobb-Douglas production in capital, labor, and energy services; and full depreciation of capital from one period to the next. The assumption of logarithmic curvature is standard in the macroeconomic growth literature; Cobb-Douglas production is a very good approximation for intermediate to long-run analysis; and although full capital depreciation is inappropriate for model periods of one year, it is arguably satisfactory for ten-year periods.[22]

2.10.3 Exogenous drivers: population and TFP growth rates

Estimated and projected population growth rates from 1990 to 2100 by country are given by the United Nations.[23] From 2100 to 2200 we assume a linear progression from the respective 2100 country population growth rates to 0.

The future paths for the TFP growth rates by country are estimated based on Penn World Table 10.01, where TFP data by country in terms of 2017 levels. TFP is assumed to follow a linear time trend from the actual TFP growth rate for the period 2010–2020, to an eventual growth rate of 1%.[24]

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[22] These assumptions are all motivated and discussed in Hassler, Krusell, and Olovsson (2021). In the very short run, a much lower substitution elasticity is called for between energy services and the other production inputs. Regarding capital depreciation, it is straightforward to solve the model with a time period covering, say, twenty years, for which the 100% depreciation assumption would be better. No major changes in the model dynamics are visible if the time period is doubled, however.

[23] We use the "median" scenario of the probabilistic approach; see 1990, United Nations, Department of Economic and Social Affairs, Population Division (2022). World Population Prospects: The 2022 Revision, custom data acquired via website. The projections (from 2023) are available on `https://population.un.org/wpp/Download/` and the associated documentation is available at `https://population.un.org/wpp/DefinitionOfProjectionScenarios/`.

[24] Source: `https://www.rug.nl/ggdc/productivity/pwt/?lang=en`. The TFP variable used is `rtfpna`.

2.10.4 Local production functions

Our Cobb-Douglas parameters are chosen to be $\alpha = 0.3$ and $\nu = 0.07$.[25] Given these choices, we proceed to find values for the extent of decreasing returns within country j (φ_j), initial country-regional TFP parameters (A_{ij0}), and initial country capital stocks as follows. We impose that the marginal products of capital, following Caselli & Feyrer (2007), are equal across countries initially, and we match total production and total population using the G-ECON database for 2005.[26] Thus, imposing that the marginal products of capital and labor are equated within countries due to the free movement of inputs allows us, using a minimization procedure, to pin down the φ levels, which are in the range 0.8 and above.[27]

The results from using this procedure yield local TFP data with properties that are displayed in Figure 4. The upper graph shows the 90/10 spread in productivities within a country as a function of the temperature levels within that country. There is plausible heterogeneity: it is not huge, and there does not seem to be a strong correlation with temperature. The bottom graph displays the estimated value for φ, also as a function of the temperature. The lower the φ, the lower will the de facto extent of population mobility within the country be. There is heterogeneity, but most values are quite close to 1, and there is no strong correlation with temperature either.

2.10.5 Local damages

Figure 2 suggests a hump-shaped relation between productivity and temperature. To recover this feature, we use the TFP factors A_{ij} that we estimated for the baseline year

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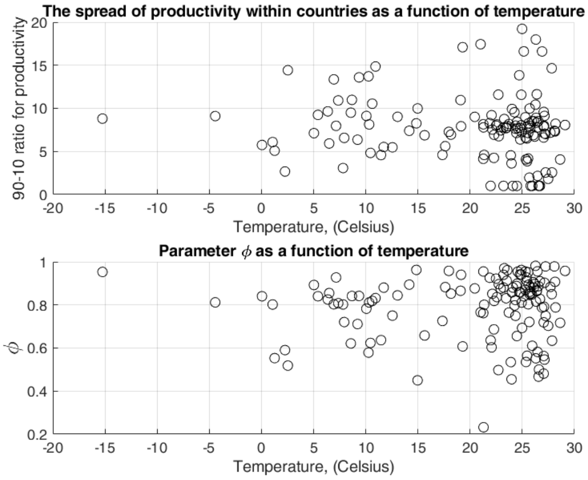
[25] This is a higher value than in Hassler et al. (2021) and is needed to match historical data given the more elaborate energy system used here.

[26] The assumption of equal marginal products of capital is warranted since capital markets are abstracted from in our setting. Moreover, Krusell & Smith (2022) show, in a very similar model to the one here, that if this assumption is imposed at time zero, autarky delivers an allocation that is quite close to that arrived at with international capital markets (subject to a borrowing constraint). Intuitively, given an assumption that all regions share the same discount rate and long-run growth rate, long-run autarky allocations will—from the Euler equation—all imply the same marginal product of capital. Starting from equalized marginal products and converging toward equalized marginal products leaves limited room for departures from equalized marginal products along the transition.

[27] This procedure involves a minimization procedure, as there are more restrictions than unknown parameters.


The spread of productivity within countries as a function of temperature

Parameter ϕ as a function of temperature

Figure 4: Local estimated TFP as a function of local temperature.

2005. First, we sort all regional productivities into temperature bins. The first bin contains regions with a temperature below minus 15 degrees Celsius. Thereafter follow one-degree bins, the first with regions with temperatures between minus 15 and minus 14 and the last containing the the warmest regions, with temperatures between 30 and 31 degrees Celsius. We then calculate the average productivity in each bin. This is shown as the somewhat jagged curve in Figure 5.

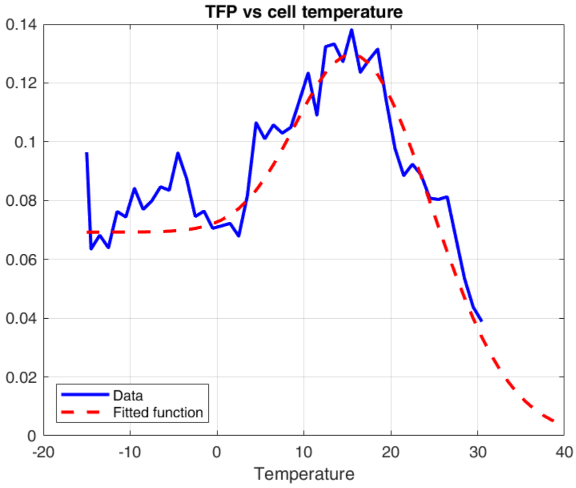

TFP vs cell temperature

Figure 5: Productivity bins by temperature and fitted productivity function.

The parameter $\bar{D}_{max}$ is set to the average of the three highest productivities, occurring for temperatures between 14 and 17 degrees Celsius. This average is 0.13. d^- is set to the average relative productivity of the six coldest bins (colder than minus 10 degrees Celsius), which is 0.57. d^+ is set to zero. Finally, we choose κ^+ and κ^- to minimize the sum of squared deviations between the bin averages and $\hat{D}(T_{ij,t})$. This yields $\kappa^+ = 0.0053$ and $\kappa^- = 0.0098$. The resulting mapping is shown as the smooth curve in the figure.

2.10.6 Energy services

The calibration of our energy system model is challenging, given the number of parameters involved and a lack of empirical estimates. We use a richer structure than those used in most simple integrated assessment models, in part to make calibration somewhat more straightforward: on a more abstract level, what is otherwise the elasticity of substitution between "clean" and "dirty" inputs? We begin by discussing our elasticities, which we assume to be the same across countries, and then turn to the share parameters, which will be heterogeneous.

Elasticities We base our calibration on the following principles. First, we assume that the elasticities, which are all static, change over time, so as to mimic the notion that the economy allows more long-run flexibility than in the short run. We thus assume that some elasticities are lower in the initial two periods (which are a decade long each) and higher thereafter. Second, we assume a high elasticity of substitution between energy sources that are used for similar purposes, such as conventional and fracked (shale) oil, and the energy sources for plannable and non-plannable electricity, respectively.

Given these principles, we calibrate the elasticity of substitution between conventional and fracked oil, ρ_o, to be 10 throughout time. The elasticity between the inputs for plannable energy, ρ_p, and the corresponding elastiticity in the production of non-plannable energy, ρ_p, are both set to 4.[28] Plannable and non-plannable sources of electricity generation are instead assumed to be less substitutable with a substitution elasticity of $\rho_v = 1.5$. This lower substitutability is consistent with the so-called *cannibalization effect*, where increases in the share of non-plannable energy tend to reduce its profitability by making the correlation between price and supply more negative.

This moderately low elasticity is also used for the aggregation of fossil fuels ($\rho_f = 1.5$), since this aggregation represents fairly different uses of fossil fuels: transportation, heating, and industrial use. Finally, we set the elasticity of substitution between the

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[28] This is a bit higher than the value of 3.08 for the elasticity between clean dirty inputs, as calculated for France by Jo (2024).

electricity and fossil-fuel composites, ρ, to be 0.66, which is taken from the WITCH integrated assessment model.[29]

To account for higher long-run elasticities, we raise the low elasticities from the third time period an on: we raise $\rho_v = \rho_f$ from 1.5 to 3 and ρ from 0.66 to 1.5.

Share parameters The calibration of the share parameters (the λs) is country-specific. Given the substantial variation in the fuel mix in energy use across countries, we believe this is important. The general procedure for calibration is to note that data on the relative prices and volumes of any two energy sources pins down the relative share parameters. To see this, note that for a CES production function that uses any two fuels x and y, the ratio of the (competitive) demands for them satisfy $x/y = (\lambda_x/\lambda_y)(p_x/p_y)^\rho$, where λ_x and λ_y are the two share parameters, p_x and p_y are the two prices, and ρ the elasticity of substitution. For a production function in n arguments, this provides $n-1$ equations. Together with the normalization that the λs sum to one, this provides sufficient information for pinning them all down.

Given a calibration of the lowest nest in the nested CES, we calculate the exact country-specific price indices and volumes for the aggregates that enter the higher nests. This provides the necessary data for calibrating the λs in the higher nests. Next, we briefly describe the data and how we use it.[30]

We use data for 2015 on the use of the different fuels in each country and their prices. The fuel mix is obviously country-specific and data on volumes of the different sources of energy exist for most countries. Prices have less variation across countries. Some energy sources, in particular conventional oil, is priced at the world market and we take this price to apply everywhere. [31] The energy sources used for electricity production involve large fixed costs and here we use estimates from IPCC of the total cost per produced MWh of electricity. Coal and gas is traded but it is less reasonable to assume a world market price for these energy sources. Natural gas, in particular, is substantially cheaper in the U.S. than in other countries due to the recent shale gas revolution. There is some, but not very large, variation across countries in the price of coal. For countries where we find coal prices we use these; for the remaining countries we instead use the price in

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[29] See https://doc.witchmodel.org/.

[30] Details on the data sources and the calibration is available in our on-line appendix.

[31] We do not take into account country-specific fuel taxation.

the nearest country for which we have data. Due to the small variation in the coal price across countries, we believe that this is a reasonable procedure.

2.10.7 The global climate

Turning to the carbon cycle and the climate model, we use the model developed by Nordhaus, but (as already noted) updated using key parameters from Folini et al. (2025).

With a ten-year period, our carbon cycle equations look as follows.[32]

$$\begin{bmatrix} S_t \\ S_t^U \\ S_t^L \end{bmatrix} = \begin{bmatrix} 0.6743 & 0.3864 & 6.742 \times 10^{-3} \\ 0.3115 & 0.5529 & 2.317 \times 10^{-2} \\ 1.4235 \times 10^{-2} & 6.0705 \times 10^{-2} & 0.9701 \end{bmatrix} \begin{bmatrix} S_{s-1} \\ S_{s-1}^U \\ S_{s-1}^L \end{bmatrix} + E \begin{bmatrix} 8.2054 \\ 1.753 \\ 4.251 \times 10^{-2} \end{bmatrix}. \tag{36}$$

The system implies that if annual emissions are E over a decade, then 81.8% of these emissions remain in the atmosphere (S) a decade later, 18% are in the upper ocean and biosphere $\left(S^U\right)$ and 2.2% are in the deep oceans $\left(S^L\right)$. Again following Folini, Kubler, Malova, & Scheidegger (2025), the climate system can be written as

$$\begin{bmatrix} T_s \\ T_s^L \end{bmatrix} = \begin{bmatrix} 6.8157 \times 10^{-2} & 0.36963 \\ 2.5465 \times 10^{-2} & 0.94982 \end{bmatrix} \begin{bmatrix} T_{s-1} \\ T_{s-1}^L \end{bmatrix} + F_{s-1} \begin{bmatrix} 0.5296 \\ 2.328 \times 10^{-2} \end{bmatrix}. \tag{37}$$

Relative to Nordhaus's original calibration, this updated system features a faster transition for both the carbon-dioxide dynamics and the atmospheric temperature. Further, we set χ to 1.26, following Mengis & Matthews (2020) who report that, between 1995 and 2015, non-CO_2 emissions (e.g., methane) have, on average, amounted to 26% of the CO_2 forcing. It is an open question whether this factor will remain. We assume that it will, thus strengthening forcing quite significantly relative to a pure CO_2-based model.

The model tracks the historic development of the atmospheric carbon content S_t and the global mean temperature quite well from to the present. This is described in Figure 6, where we fed the model with global emission data from 1850 and initial conditions for that year.

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[32] See the online appendix for details on how to adapt the Folini et al. (2025) calibration to decadal time steps.

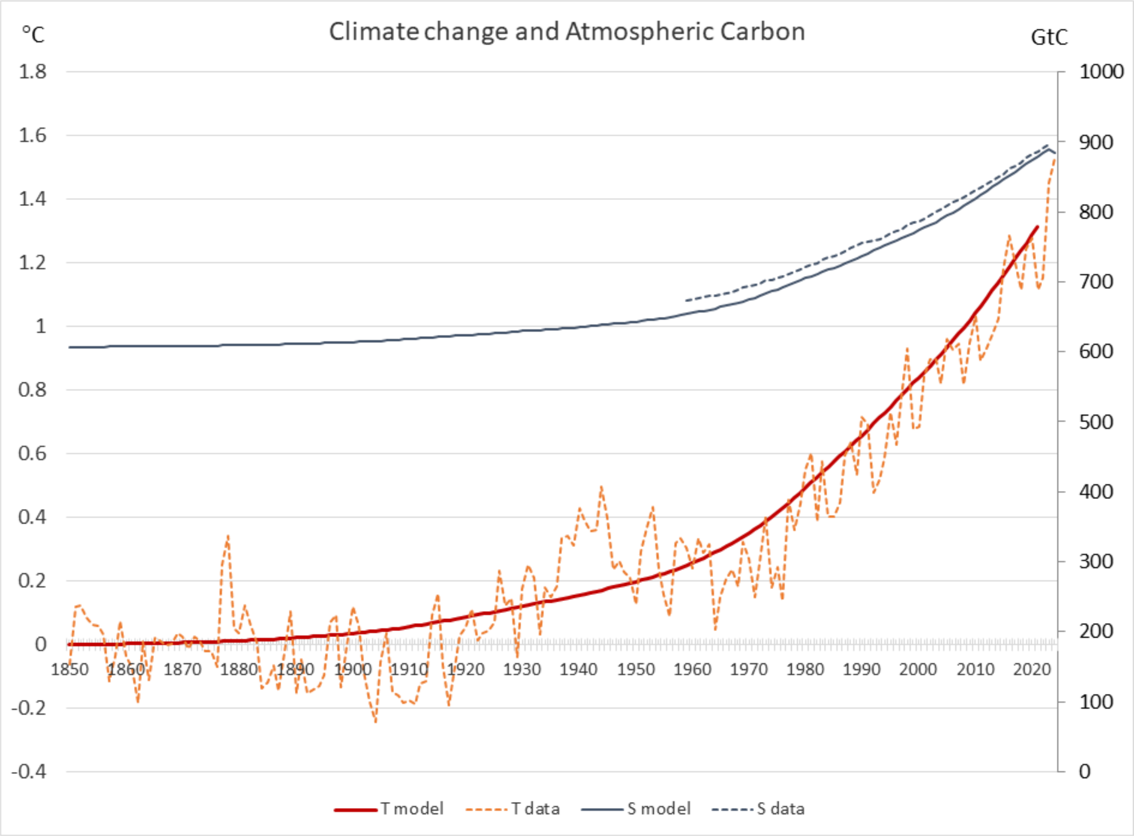

Figure 6: The distribution of CO_2 emissions and GDP in the data and in the model.

2.10.8 Regional temperatures

Finally, having determined the path for global atmospheric temperature, our model's downcaling coefficients—the γ_{ij}s, thus assigned on the very local level—are given values consistent with those in Cruz & Rossi-Hansberg (2023) and Krusell & Smith (2022). Specifically, we use the downscaling parameters that are estimated in Conte, Desmet, & Rossi-Hansberg (2022).[33] This delivers a heat map of these coefficients for the 16,859 cells in the economy climate model plotted in Figure 7. The coefficients range from -0.0117 from the Greenland coastline to 3.34 on the latitudes far north.

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[33] The location-specific downscaling parameters are based on the RCP 8.5 scenario from the IPCC AR5 Data Distribution Center (IPCC, 2020). The data can be downloaded from the replication package that is available at Bruno Conte's personal webpage.

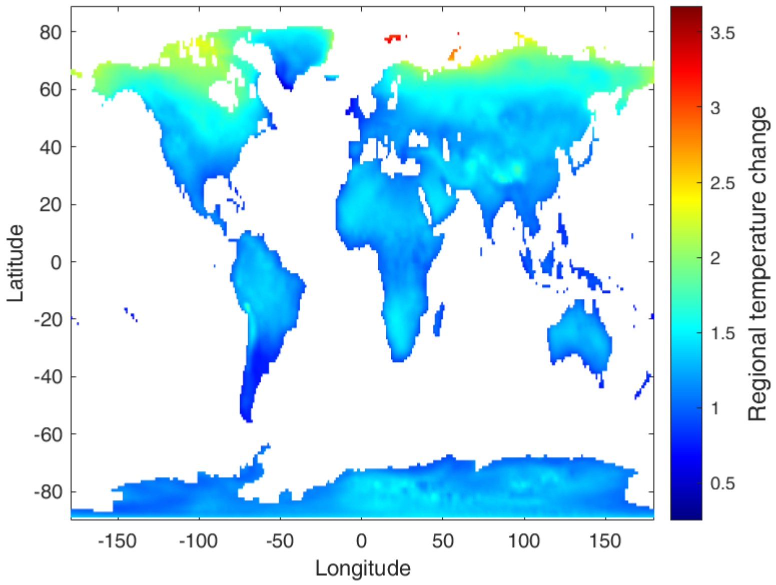

Figure 7: Regional warming as a result of global warming of 1 degree Celsius.

3 Policy experiments

Before reporting the results of our policy experiments, we show that the model matches the observed CO_2 emissions rather well, even though these were not directly targeted, as well as the GDP distribution. This is shown in Figure 8, where we have collected together countries from the same regions.

Our model can be used to run a host of both policy experiments and other counterfactuals. For illustration, we select three policy experiments involving different suboptimal policy packages implemented around the world.

3.1 A modest uniform low tax goes a long way

We start by evaluating the effects on the climate by implementing a modest global carbon tax of USD \$20/ton at the initial date, which is then taken to grow at the rate of world GDP. This value, which is approximately the prices of the emission trading rights in the EU (EU-ETS) around 2020, is well below the price that since the recent Fit-for-55 reforms of EU's climate policy has been around 70 euro/ton.

The results are presented in the left panel of Figure 9 along with the comparison with (i) the same tax only in the EU; (ii) the same tax applied only to coal; and (iii) no tax. We see that the modest tax is a potent policy for mitigating global warming. The

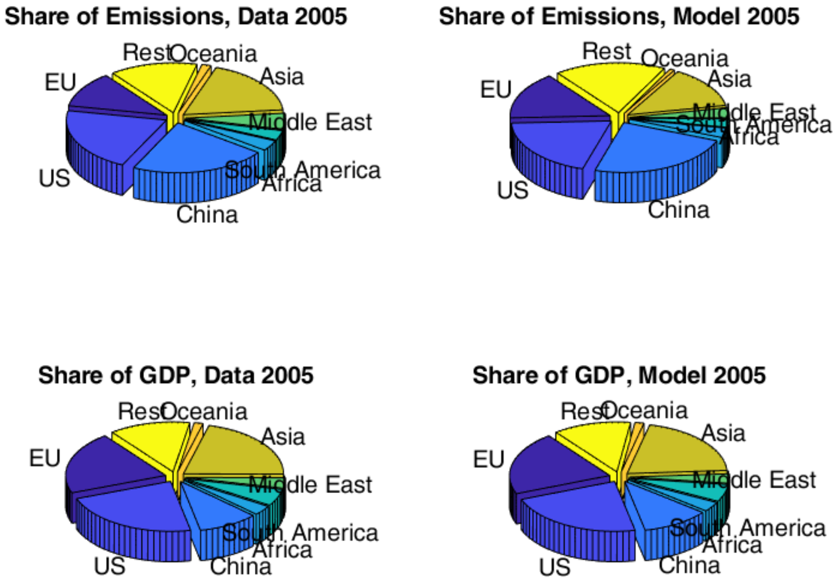

Figure 8: The distribution of CO_2 emissions and GDP in the data and in the model.

difference between no tax and the modest tax is, in fact, striking: it is more than 3°C by 2140! Even though a tax only applied to coal (and not to fracking, oil, or gas), is insufficient, this tax is still able to reduce global warming by about 1.5 degrees Celsius relative to laissez-faire. However, only applying the tax in the EU is as ineffective as having no tax at all: the EU is too small to make a difference.

The right panel in Figure 9 shows how the welfare gains from not implementing a carbon tax relative to a regime with a global modest tax are distributed across countries. Clearly, the effects of climate change vary drastically across countries, with many countries gaining while others lose. In particular, the negative effects are substantial for countries that are close to the Sahara desert, while the largest positive effects are found in the north where the initial temperature is very low. The local variations in output losses are thus much larger than the change in aggregate output that follows from climate change.

Additional distributional implications are displayed in Figure 10. Here we see that the no-tax policy effectively shifts a large share of the population to the right on the temperature axis. Specifically, the implied population distribution then features significantly more mass located at temperatures between 30°C and as high as 40°C. Because of the

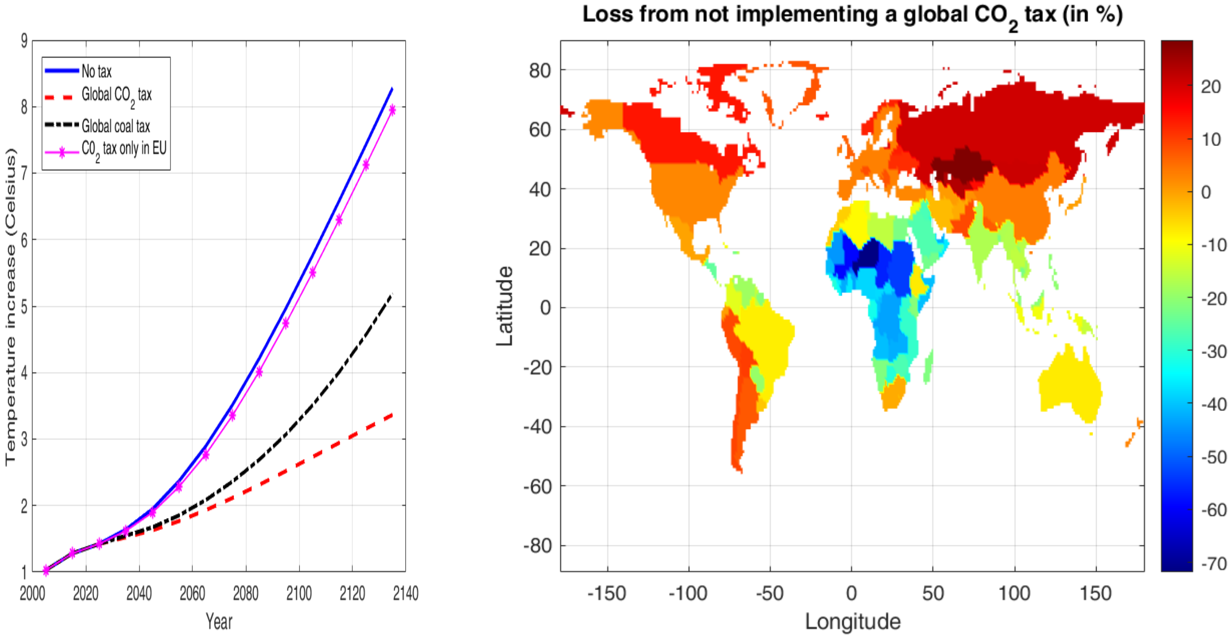

Figure 9: Left panel: the temperature increases that are associated with different carbon taxes. Right panel: distributional welfare effects, as a percentage permanent consumption flow, from implementing a carbon tax.

very low TFP levels that are associated with such high average temperatures, the associated welfare effects for a large share of the world's population are similar in magnitude to those incurred by several Great Depressions at once. Under a moderate carbon tax, while there is still a right-ward shift in the population, it is much smaller.

3.2 Non-uniform policy

A second policy of interest, often raised due to arguments of fairness, is that of implementing a non-uniform carbon tax. The Pigou principle states that the tax, where it is applied, should equal the negative externality caused. Since the negative externality is global—it is the effect of locally emitted carbon on the global temperature—the tax should be the same everywhere: it should be uniform. However, arguments are often raised in favor of tax breaks for some regions, especially poorer ones, for the sake of fairness.[34] Against this background, we are interested in quantifying how costly deviations from a uniform taxation policy are in dollar terms. High costs would suggest instead

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[34] A common motivation behind this argument is that these countries do not, and did not historically, contribute much to warming.

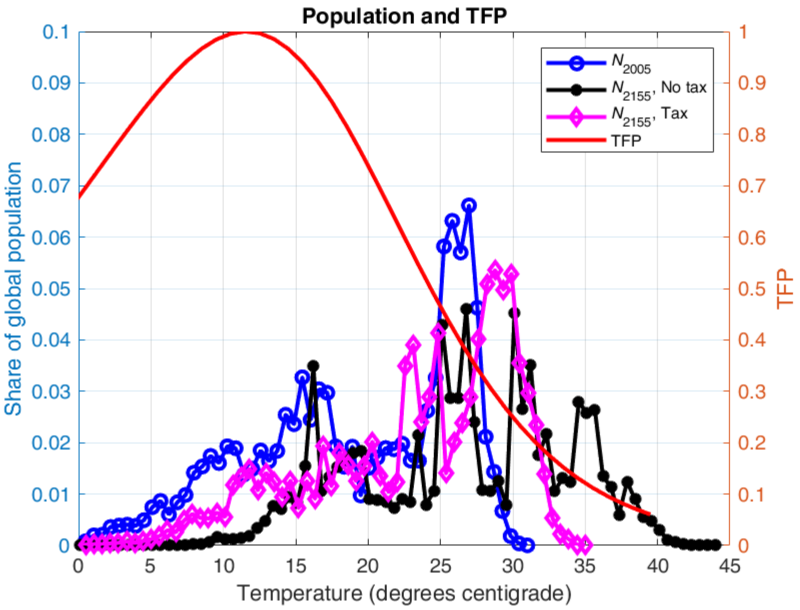

Figure 10: Global warming lowers productivity substantially in regions where a lot of people live.

maintaining a globally uniform tax, while compensating the poor countries in other ways, such as with direct transfers.

We first compute the implications for the temperature of uniform taxation, where we again use a moderate carbon tax of about USD \$20/ton. We then compare the results to a setting where the poorest countries have a zero or a very low tax; we define the poverty threshold here by a level of GDP per capita below 25% of the world average GDP per capita. The remaining countries (ROW) are assumed to use an identical tax, but now raised so that in year 2155, the temperature is the same as for a uniform tax (the increase at that time is 3.7^oC).

It turns out that it becomes impossible to match the temperature increase 150 years into the future if the tax-exempt developing region do not implement any carbon taxes: the emissions from the developing regions simply become too large. We therefore consider a scenario where (i) the ROW implements a carbon tax that is 20 times higher than the modest tax of US \$20; and (ii) the countries below the threshold implement a carbon tax that is about 14% of the modest tax. This allows us to match the targeted temperature increase.[35] The results are presented in Figure 11.

The world map (at the bottom of the Figure) shows that the countries that experience

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[35] Without this low tax, the global temperature is more than 1.5° C higher relative to the modest tax.

gains from this policy are constituted in Africa mainly, but also India and Bangladesh. These countries gain (gains are in green, yellow and red), whereas all others lose (light and dark blue).

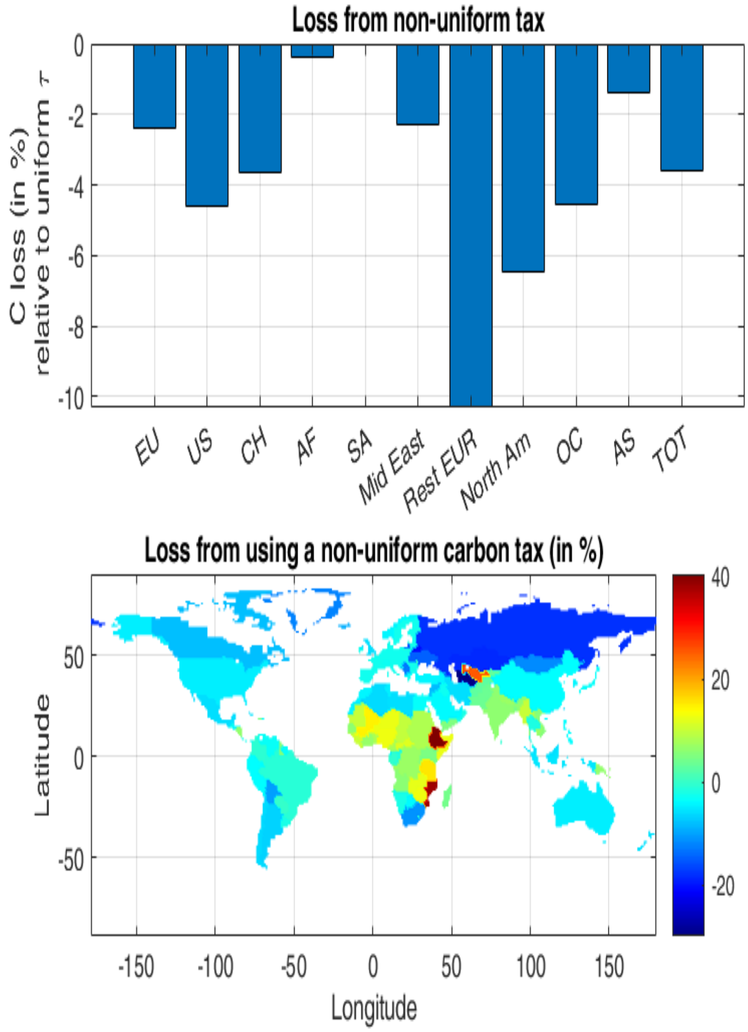

Figure 11: Gains and losses from non-uniform policy.

The welfare gains can be seen in the bar graph where we group countries from the same continents together.[36] The graph reveals that all continents are worse off, even Africa as a continent. The total loss (the rightmost bar) is 4.5% of world consumption. We conclude that this policy is actually very costly.[37]

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[36] Welfare gains are measured by permanent changes in consumption.

[37] Our framework allows for an evaluation of in-between cases, where taxes would be GDP-dependent (such dependence would distort capital accumulation), as well as for an evaluation of compensating transfers to poor countries, but we leave such experiments for future work.

3.3 Faster technical change in green energy vs. a carbon tax

In the U.S., the climate-change aspects of the Inflation Reduction Act (IRA) boil down to the hope that green technology, by being produced at lower cost, will compete out fossil fuel. To evaluate the promise of such proposals, we consider two very simple experiments, both contrasting a global carbon tax with the subsidization of green technology without taxing carbon. We capture the latter policy by an assumption that—at zero cost of implementation—the price of green energy falls by two percent per year in terms of the final good, whereas the relative price of fossil fuel production is unchanged over time. In the first experiment, we assume that the U.S.-like policy generates the fast green technology growth everywhere in the whole world, including in poor countries. In the second experiment, to capture notion that technological knowledge may not spread fully around the world, we assume that the sped-up green technology growth will occur only in the U.S. and in the EU. In both experiments, we also allow two parameters to change over time. One is λ, which we allow to decrease significantly. This implies a much higher degree of eventual electrification (and less dependence on fossil fuel) in the production of energy services. The other is λ_v, which we assume also falls and leads to a higher weight on the non-plannable energy inputs of photovoltaic and wind power in the production of electricity.[38] In particular, both these parameters fall by 5% in each country until they reach their respective lower bound. For λ this lower bound is set to 0.5 (which is among the lowest in the data sample we use) and for λ_v it is set to 0.84, which is the value in the EU today.[39]

The results of both these experiments are presented in Figure 12, where we also plot the effects of the modest tax as a comparison (recall Figure 9).

The results are quite shocking. In the absence of increased electrification, there is almost no effect of cheaper green energy inputs. Only if this cheap energy is combined with technological progress that implies a higher degree of electrification will it mitigate global warming. This mitigation effect is modest, however, and still far less attractive than even a modest, globally uniform carbon tax. The additional effect of a higher weight on non-plannable sources is also very small. Note from the bottom graph that the increase

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[38] We maintain the supplies of hydro and nuclear power at baseline, since we judge these to be mu ch harder or more expensive to alter.

[39] The respective means of λ and λ_v in 2005 are 0.64 and 0.96.

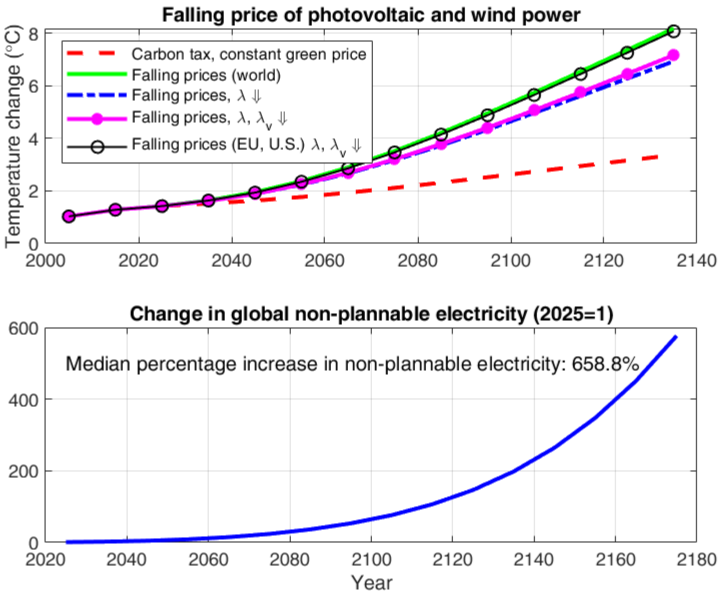

Figure 12: The temperature increases that are associated with different carbon taxes.

in non-plannable electricity is enormous: in the whole world the supply increases with a multiple of almost 400 and the median increase among countries is almost 700%. Still, this policy fails to make fossil fuel unprofitable, which is why it leads to too much global warming.

The second experiment, where only the U.S. and the EU are facing cheaper green energy, more electrification, and a higher weight on non-plannable electricity, is further limited in its ability to mitigate warming; this scenario is, in fact, very similar to the laissez-faire outcome presented in Figure 9. Thus, apparently, even with relatively high substitution elasticities (e.g., 3 between plannable and non-plannable electricity), green energy is highly impotent at competing out fossil fuel: it is a very poor substitute for a carbon tax. In conclusion, cheaper green energy thus leads to more energy use overall, but unfortunately with only modest decreases in fossil-fuel use.

4 Uncertainty and non-linearities

Our model does not feature risk or uncertainty. It is not linear either, but its non-linearities are relatively mild. Neither of these features are motivated by modeling difficulty, however. In the present section, we describe how our modeling is amenable to such applications.

First, we can straightforwardly incorporate randomness and risk considerations, while maintaining rational decision making (including rational expectations formation). Suppose, therefore, that our TFP parameters are random, whether on the country or region level or on the global level. Using the expected utility approach, this would introduce an expectations operator into the intertemporal (Euler-equation) conditions, but because of the assumption of full depreciation, the uncertainty in the future is all about TFP and therefore factors out, leaving an Euler equation that simply replaces future TFP by expected future TFP. Saving rates, in particular, are not affected.

Non-linearities, including tipping points, that appear in the mapping between emissions and TFP, whether in the mapping from emissions to (local or global) temperature or in the mapping from local temperature to damages, also do not lead to any modeling challenges at all.

Second, given the above, the model can be simulated with randomness and non-linearities. We do not pursue these extensions here, however; some well identified local tipping points could be included but a more ambitious aim would include all such occurrences globally, and when it comes to randomness, calibration is particularly challenging.[40]

An important point remains: that of deep uncertainty, which we also abstract from. This contrasts the very large uncertainty that exists regarding carbon-climate dynamics, climate damages and the potential for technological advancements. This element can also be incorporated into agents' decision making, for the same reason as we underline above. However, the explicit optimization over policy paths becomes much more difficult in this case. In particular, a policy that is optimal for a particular set of assumptions or probabilities can hardly provide a credible basis for normative conclusions; this is also why we abstain from calculating "optimal" policy in our model. Nevertheless, we do think that models like ours can be helpful in answering questions about what climate policy should be chosen. One such avenue involves the analysis of consequences of policy mistakes, such as having chosen a policy that turns out to be too lenient or too ambitious even given a deterministic model. The quantitative costs of such policy mistakes can be an input into formal models of choice under deep uncertainty with ambiguity aversion, such as that in Barnett, Brock, & Hansen (2021), but they can also be directly used in

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[40] The IPCC uses probability intervals rather than point estimates.

the search for robust policies that imply acceptable outcomes under a large set of possible assumptions with unknown likelihoods.

5 Conclusions and next steps

This paper offers a dynamic model of economics and climate change with very high regional resolution. It is, however, a conceptually straightforward extension of Nordhaus's seminal work in a multi-regional direction. The macroeconomics of the model rests on standard microeconomic foundations, thus allowing cost-benefit analysis and counterfactual policy analysis. As also found in the other work on regional integrated assessment models, after choosing model parameters that match a wealth of data from around the world, we document that the spatial dispersion of the welfare effects of global warming swamps the average effects. More importantly, however, we use our model to examine some country- or region-specific policy experiments. We find, in short, (i), that even a modest, globally uniform carbon tax would be extremely valuable, especially for the warmest countries, which experience worse and worse outcomes the more the globe heats. We then find, (ii), that a non-uniform tax on carbon is very inefficient: almost all continents suffer relatively large welfare costs when we excuse the poorest countries from taxing carbon, while maintaining the same temperature target by raising the carbon taxes in the rest of the world. Finally, (iii), we examine how good a substitute a "green deal" is for taxing carbon; we find that it is not a good deal, and it is even worse if the green-deal technology does not spread to the poor countries. Each of these policy experiments is worthy of its own in-depth study and our analysis here is very brief; we have, however, found all the key results remarkably robust.

We believe that the kinds of IAMs using dynamic (stochastic) general equilibrium frameworks (DSGE) developed here, as well as those based on trade and economic geography, contribute substantially, and in a number of ways, to "modular" approaches to climate change, which do not offer fully integrated assessment analysis. The three core policy experiments in the present analysis, such as that showing the power of an even very modest carbon tax, constitute one illustration of this point, as they offer—to us, at least—non-trivial and surprising insights, all of which rely on quantified general equilibrium feedbacks. Moreover, due in part to analytical insights and in part to new numerical tools and processing speed, the DSGE frameworks developed can accommodate extremely rich heterogeneity. We illustrate this here not only by spatial disaggregation but also with a very rich energy system. Thus, we enthusiastically foresee the DSGE approach to be highly complementary to recent advances in the empirical literature on spatial damage estimates, to the rich analyses of spatially disaggregated energy provision and energy policies, as well as to studies of climate policy and trade.

We would like to emphasize that the model developed here is designed to be extremely easy to solve, once downloaded: it is "plug-and-play". We therefore hope that users around the world can help in pushing our work forward, in particular focusing on their geographic area of expertise. It is set up for adding extensions, such as to more damage types, e.g., by separating out mortality and morbidity effects of warming and including endogenous technical change of different dimensions, and a host of other features. Some extensions are more challenging, such as shortening the time period and capturing the short-run pros and cons of policy, trade, and multi-sectoral production, but they are entirely feasible.[41] Lastly, we must point out that our research and learning using integrated assessment analysis involves a back-and-forth between complex models and extremely simple, sometimes even static, IAM frameworks: the complicated models often give surprising insights, and to understand them and be convinced that the results are both correct and rely on sensible mechanisms, the simpler models are invaluable.

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[41] One illustrated can be found in Krusell & Smith (2022).

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