

Suboptimal climate policy

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1 Introduction

There is scientific consensus that humans cause global warming and that the warming can turn out to be substantial. There is less agreement, and much uncertainty, regarding how much warming there will be and how this warming affects human welfare around the globe. Given the uncertainty, the “optimal” path for carbon emissions cannot be easily agreed on, or pinned down with great confidence.¹ However, what seems to have emerged as a rather broad consensus is that we should limit emissions in significant ways. The central point in this paper is that we need to analyze the How question: what to do, especially in light of the large uncertainty.

The How question fundamentally needs to be answered based on an understanding of how our societies work: how our economies work. The reason, of course, is that the vast majority of the world’s citizens live in market economies, so it really is markets that we have to influence away from excessive carbon emissions. For obvious reasons, this cannot simply be accomplished by decree. Thus, the relevant area here is one where we, as economists, are the main experts: though our science is young and there is much in our economies that we have a limited understanding of, if anyone is to have a chance at providing insightful and quantitative answers to the How question, it is economists. In our view, for this reason, stepping up to the task of guiding policy choice in this area is our collective duty. It is, of course, not one all research economists should engage in, but we actually think it is one where we should, researcher by researcher, think about whether we might have insights to offer, given our specific knowledge and skills. We also happen to think that there is a beneficial side effect from working on economics

¹The point here is not that made in Weitzman (2011), i.e., it is not about fat-tailed risk (which could come about because of tipping points), but merely that different scientists disagree significantly about numbers.

and climate change: it is an area where there is an opportunity to showcase the power of economic analysis.

In the research project from which we present results in this paper, we are using the knowledge and skills that we, as quantitative macroeconomist modelers, think can be helpful in the climate-economy area. We have found the joint study of economics and climate change to also offer its own intellectual challenges and the purpose here is to discuss an example of such a challenge. Before laying out the example, let us mention that it is a part of a broader project: to compare different climate policies with a focus not on what is ideal but rather on how different suboptimal policies compare, both qualitatively and quantitatively. The aim is thus not to calculate the optimal, first best policy; it is rather well understood, among economists, that a Pigou tax (an idea dating back more than 100 years—to Pigou, 1920) is fully optimal: a tax on carbon that cancels the negative externalities from the emissions that carbon use causes. However, world leaders are unfortunately far from following up on this kind of insight and advice. Our idea, then, is the much more applied one of looking at, and comparing, different policies that have been discussed in policy spheres and therefore, at least, have the hope of being implemented. Hopefully our analysis can then offer insights to guide policymakers: we will be able to point to the “amount of money they leave on the table” by choosing specific suboptimal policies. We have, *ex ante*, no hunch as to *how much worse* the policies that policymakers adopt are, compared to available alternatives: that is an altogether open and quantitative question, where we believe the answer will vary from case to case. To us, it is intellectually challenging not only because it is usually not asked, but also because seeking an answer will force us to explain the mechanisms, qualitative and quantitative, by which a given suboptimal policy is either “as good as optimal” or “leaving fortunes on the table” (or anything in between).²

The example we study in this paper is very simple but, we believe, quite important. The question is: suppose policymakers use the *right kind* of policy but *at the wrong level*; how bad is it, then, to fail by different amounts in different directions? Thus, we will assume that the policy instrument is a global tax on carbon, just like the one that would follow from applying Pigou’s insights, but that policymakers are either too optimistic—in that they expect climate change to be limited, or the effects of it to be minor, when in fact both of these suppositions are wrong—or too pessimistic (when the reverse applies). Computing the size of

²We are also not deriving “second-best” results, i.e., optimal policy subject to well-defined constraints, as it is not clear to us exactly what the constraints are.

these errors is the key goal of the paper. Are they large or small; are they of equal size?

As a first goal, we assume that we are in a *laissez-faire* world, which we believe is a decent approximation to the global world we live in, and ask about the costs and benefits of implementing a modest tax on carbon—at the level implied by the prices of emission trading rights in the EU ETS system—when climate change is significant and the damages from warming are large. We find the costs, i.e., the distortionary impacts of imposing a tax, to be very minor, but the benefits to be large. Here, the main intuition is that the costs are minor because although a small tax would significantly affect carbon use, the effects of carbon on overall welfare is close to nil, taking its benefits and production costs into account: at zero taxes, welfare is maximized, and the net benefit from a marginal tax change is literally zero.

Our second goal is to compare two large errors: that from over-optimism and that from over-pessimism. We find the costs from these errors to be quite different: the cost of setting a high tax on carbon, i.e., one that is based on too pessimistic a view on climate change, is not very large at all, but the cost of not taxing when climate change is a major problem is actually quite large. We define the size of the mis-perceptions in each case based on the ranges for warming and for climate damages: we take the respective end-points of the intervals offered in the IPCC reports and in the economics literature on global damages.

The key intuition behind our results is, first, that a tax on carbon based on over-pessimism will not hurt the economy so much: carbon use will fall significantly, but most of the distortions will occur for modest taxes, and these distortions are not, as discussed above, so detrimental. A key reason for this is that the bulk of fossil fuel is coal, and the coal industry is quite sensitive to costs: unlike for oil, it does generate large profits because there are decent substitutes, and the marginal cost of producing coal is rather high. Thus, small taxes make coal use fall significantly and yet have a minor aggregate effect on welfare. As for the other kind of error, the intuition is not the same: applying a near-zero tax, because of over-optimism that climate change will not occur or not be problematic, will be very costly if this belief is wrong: too low a tax will simply leave a large amount of welfare on the table, since coal use could have been made to fall—for a major benefit to humans, at a small cost.

In Hassler, Krusell, and Olovsson (2018), we touch on the results herein, but no analysis as to mechanisms, either quantitative or qualitative, is offered. A paper with a similar aim is van der Ploeg and Rezai (2019), who consider a DICE model

with model uncertainty and shows that the optimal robust climate policy involves taxing carbon even if there is a probability that the “climate deniers” turn out to be correct.³ In Section 2 of this paper, we thus begin by analyzing the forces at work using a stylized static model that we believe captures all the key ideas. It allows us to explain the mechanisms by which different errors have different implications and interpretations. In that section, we also offer some quantitative analysis. Section 3 then describes and solves a fully dynamic model. The dynamic model is an example of those developed in the literature on IAMs (Integrated Assessment Models of economics and climate change), that is, it is a neoclassical growth model with optimal saving and input use. It is different from the static model in that the latter assumes additive damages, i.e., there is no interaction between damages and economic activity. This simplifies the analytical work we offer but also turns out to offer a good approximation to the dynamic IAM we also study. Section 4 concludes.

2 A static one-region model

We first describe the setting and then analyze it, first qualitatively and then quantitatively.

2.1 General assumptions

The static economy we consider here is the simplest possible version of that studied in Section 3. Thus, we only have one region and one representative consumer in this region, whose welfare is determined by consumption. The production Y of the consumption good is given by

$$Y = F(K, L, E) \tag{1}$$

where F is a twice differentiable constant-returns-to-scale function to be considered gross output. The two basic inputs are capital and labor— K and L , respectively—with an energy composite, E , serving as an intermediate input. We will specialize this production function to be of the Cobb-Douglas variety, as we argue that this formulation offers a decent account of the long-run data, but let us keep the more general specification for now. Neither K nor L are endogenous

³Robust-control analysis is also offered in the very recent paper by Barnett, Brock, and Hansen (2021).

in the static model so let us therefore use f to describe the (strictly concave) production function: $Y = f(E) \equiv F(1, 1, E)$.

The energy composite, in turn, is produced from two factors: a fossil-based input e_1 and another, non-fossil, or “green”, input e_2 . We thus use

$$E = G(e_1, e_2) \tag{2}$$

where G is a standard (also twice differentiable), constant-returns-to-scale index, which we will momentarily specialize to be CES. We think of e_1 as “coal” and e_2 as “green energy”. These terms are adopted because we assume a production structure for both these inputs that has constant marginal costs, p_1 and p_2 , respectively, in terms of output. This certainly appears to be a reasonable assumption for coal, though the level of the marginal cost varies by region, and is arguably not far off for green energy either.

In our analysis below, we use the standard formulation adopted in the literature—damages from climate change lowers total-factor productivity in aggregate production—but here, for simplicity, we think of damages as simply additively destroying consumption goods. We view damages as a convex, twice differentiable function D of e_1 . Thus, D encapsulates how the use of e_1 causes emissions, which affect the carbon concentration in the atmosphere, leading to harmful global warming.

Thus, our economy’s resource constraint reads

$$C + p_1 e_1 + p_2 e_2 = f(E) - D(e_1), \tag{3}$$

where C , p_1 and p_2 are the respective marginal costs for the two energy inputs, and D is our damage function.

Hence, a social planner in our economy would simply maximize

$$f(G(e_1, e_2)) - D(e_1) - p_1 e_1 - p_2 e_2 \tag{4}$$

by choice of (e_1, e_2) . The climate-economy literature often proceeds by finding the solution to the planner’s problem, defining a market equilibrium, where climate damages are not internalized by agents, and finally finding a policy choice—such as that of a tax on carbon—that implements the planner’s optimal (e_1, e_2) choice. Here, in contrast, we will focus on suboptimal policy in a market equilibrium. Let us first define a perfectly competitive *laissez-faire* (no-policy) equilibrium.

We assume that there are representative firms operating at three levels of the productive chain, all on perfectly competitive markets. There is a firm produc-

ing final goods from capital, labor and the energy composite. A second kind of firm produces the energy composite from coal and green energy, thus selling it to the final-good firm. Coal and green energy, finally, are produced at constant marginal cost (in terms of the final output good) by a third kind of firm and sold at production cost to the second.

The final-goods firm solves

$$\max_E f(E) - PE \equiv \pi,$$

where P is the market price of the energy composite. Firms providing the energy composite solve

$$\max_{E, e_1, e_2} PE - p_1 e_1 - p_2 e_2,$$

subject to (2) and where P is the price of energy services; here, since G is CRS, profits will be zero in equilibrium.

Consumers own firms and act passively. Their utility is increasing in their level of consumption, which in equilibrium is given by

$$C = \pi - D(e_1). \tag{5}$$

An equilibrium is thus defined by the quantities (C, E, e_1, e_2) , the price P , and profits π such that the quantities (E, e_1, e_2) solve their respective maximization problems and satisfy (3) and π is defined in (2.1).

Policy in this simple economy is defined by specifying instruments available to the government. In this paper, we will focus on a proportional tax on carbon, mostly because it is a well-understood instrument; a key focus in this literature is indeed what the value—in the economic environment at hand—of the optimal carbon tax should be. Though we will comment on this shortly, the focus in the present paper is rather on taxes that are set suboptimally. Note, of course, that other instruments are possible. The most commonly discussed in our context would be a regulatory system where only a certain amount of carbon emissions is allowed, with well-defined property rights to emit that can be traded. In the context we focus on, such a “cap-and-trade” system would be equivalent to a carbon-tax system: for any carbon tax there is a maximum emissions level yielding the same equilibrium allocation, and vice versa.

A completely different kind of policy would be one where the government, or some private individuals, try to change the objective functions of economic agents in order to take the climate externality into account in their decisions. We are

unsure how to formulate such a policy problem in a nontrivial manner but it would be interesting to consider it; we leave it for future research.⁴

Our economy with a carbon tax is a very slight variation of the formulation above. We simply alter the energy provider's problem to read

$$\max_{E, e_1, e_2} PE - (p_1 + \tau) e_1 - p_2 e_2,$$

still subject to (2), a problem that again will imply zero profits. The revenues from taxes will simply be handed to consumers, so that consumption is now

$$C = \pi - D(e_1) + \tau e_1. \quad (6)$$

2.2 Analysis

Let us first look at the laissez-faire economy. The composite-energy provider's problem allows us to specify a cost function $\mathcal{C}(p_1, p_2)$ that we know is homogeneous of degree 1, and its maximization problem will deliver $P = \mathcal{C}(p_1, p_2)$. Its optimal choices of inputs are, from Shephard's lemma, given by the demand functions $e_1 = \mathcal{C}_1(p_1, p_2)E$ and $e_2 = \mathcal{C}_2(p_1, p_2)E$, again because of the unitary homogeneity of the composite. I.e., \mathcal{C}_1 and \mathcal{C}_2 are the cost-minimizing input levels delivering one unit of the composite output.

The final-goods producer hence maximizes $f(E) - \mathcal{C}(p_1, p_2)E$ with respect to E . This straightforwardly delivers

$$f'(E) = \mathcal{C}(p_1, p_2).$$

This equation uniquely defines E , along with e_1 and e_2 .

Moving to the planner's problem, it is straightforward to see that it delivers

$$D'(e_1) + p_1 = f'(E)G_1(e_1, e_2) \quad \text{and} \quad p_2 = f'(E)G_2(e_1, e_2).$$

In the case without an externality, $D'(e_1)$ is zero and these conditions are identical to the equilibrium conditions. To see this, note from the E -producing firm's problem that $\mathcal{C}_i(p_1, p_2) = p_i/G_i(e_1, e_2)$ for its cost-minimizing choices, for $i = 1, 2$.

⁴If, for example, the government could use an information campaign, at no cost, that in effect makes all key agents internalize a carbon tax—at a specific value they are asked to use in their calculations—then such an allocation would seem to be equivalent to Pigou taxation (Pigou, 1920). However, if such a key agent is a firm and the firm returns losses as a result, these losses need to be addressed.

Hence, the equilibrium is not optimal.

Pigou's recipe In the economy with taxes, the analysis is also very simple: the price index P now simply equals $\mathcal{C}(p_1 + \tau, p_2)$ and the two demand functions are thus $e_1 = \mathcal{C}_1(p_1 + \tau, p_2)E$ and $e_2 = \mathcal{C}_2(p_1 + \tau, p_2)E$; the equilibrium level of E is given by $f'(E) = \mathcal{C}(p_1 + \tau, p_2)$. Now Pigou's theorem emerges: since firms' cost minimization are the same as before, except that τ appears in $\mathcal{C}_i(p_1 + \tau, p_2) = (p_i + \tau)/G_i(e_1, e_2)$, we see that $\tau = D'(e_1)$, where e_1 is the value delivered by the optimum, reproduces the planner's choice.⁵

Suboptimal policy, I: the Ramsey program The next question is: what is the welfare loss from not setting the τ according to the Pigou formula? As a basic for our analysis, we will look at a planner that chooses a policy optimally given a certain belief about damages, though these beliefs may be wrong. It will be of particular importance to evaluate the different errors that can arise.

To proceed with this aim, note that the choice of a tax rate can be analyzed in Ramsey style: choose a rate subject to the allocation being a competitive equilibrium with a tax. Hence, the Ramsey program would be

$$\max_{\tau, E, e_1, e_2} f(E) - p_1 e_1 - p_2 e_2 - \tilde{D}(e_1)$$

subject to

$$f'(E) = \mathcal{C}(p_1 + \tau, p_2), \quad e_1 = \mathcal{C}_1(p_1 + \tau, p_2)E, \quad \text{and} \quad e_2 = \mathcal{C}_2(p_1 + \tau, p_2)E.$$

Note that the tax payments that the firm makes are rebated to the consumer and therefore these payments cancel. We denote the damage function \tilde{D} , thus indicating the possibility that $\tilde{D} \neq D$, where D would have been the correct perception. Thus, formally, we look for a solution to the program above, $\tilde{\tau}$, and then evaluate the objective at $\tilde{\tau}$, with \tilde{D} replaced by D . At the end, the loss in the objective function can then be translated into percentage consumption terms for easier interpretation.

Let us also make a distinction between the different terms in the Ramsey planner's objective function: we think of the first two jointly as the payoff to the "private economy", thus without taking damages into account. The last term is then the damage term, which of course is important but in this particular

⁵See Pigou (1920).

formulation does not interact with the private-economy payoff. In the typical integrated assessment model of the climate and the economy, damages enter the productivity level of firms, and hence damages are not additive. We abstract from the interaction here for illustration, but add it in our dynamic, quantitative models below.

In our first step, we thus take derivatives with respect to τ . We obtain, with the arguments of functions repressed, a marginal benefit of taxation equal to

$$\frac{\mathcal{C}_1}{f''} (f' - p_1\mathcal{C}_1 - p_2\mathcal{C}_2) - (p_1\mathcal{C}_{11} + p_2\mathcal{C}_{12}) E - \tilde{D}' \left(\mathcal{C}_{11}E + \frac{\mathcal{C}_1^2}{f''} \right).$$

We can simplify this expression considerably. The first term can be rewritten, since the first constraint reads $f' = \mathcal{C}$ and $\mathcal{C} = (p_1 + \tau)\mathcal{C}_1 + p_2\mathcal{C}_2$ from Euler's theorem, as simply $\frac{\mathcal{C}_1^2}{f''}$. Moreover, $(p_1 + \tau)\mathcal{C}_{11} + p_2\mathcal{C}_{12}$ is also zero: since \mathcal{C} is $H(1)$, its partial derivatives are $H(0)$. Hence, the second term can be replaced by $\tau\mathcal{C}_{11}E$, and we can write the first-order effect of taxation for the Ramsey planner as

$$\tau \left(\frac{\mathcal{C}_1^2}{f''} + \mathcal{C}_{11}E \right) - \tilde{D}' \left(\mathcal{C}_{11}E + \frac{\mathcal{C}_1^2}{f''} \right) = \left(\frac{\mathcal{C}_1^2}{f''} + \mathcal{C}_{11}E \right) (\tau - \tilde{D}'). \quad (7)$$

The Ramsey planner's choice is clearly a τ that equals \tilde{D}' .⁶ But let us also consider the shape of the expression around this value. The parenthesis $\frac{\mathcal{C}_1^2}{f''} + \mathcal{C}_{11}E$ really represents the private-economy equilibrium response $de_1/d\tau$, and it is globally negative, since its terms are both negative: $f'' < 0$, $\mathcal{C}_{11} < 0$, and $E > 0$. This expression multiplied by τ is the marginal impact on the private sector of a higher tax and it is negative for a carbon tax (and positive for a carbon subsidy), reflecting a mountain-shaped objective for the private economy.

As for damages, we see of course from the expression in (7) that the marginal effect of an increased tax is always positive, but as e_1 falls, the effect is smaller and smaller in magnitude. Hence, the damage function will, generally speaking, have a concave shape and flatten out as e_1 goes to its lower bound of 0.

Suboptimal policy, II: should the global tax be raised above zero? As a rough approximation of where the current carbon policy is world-wide, let us use zero.⁷ Thus, an important question what possible gains or losses can be made if the tax is raised above zero—even by a small amount. The analysis is rather

⁶We assume throughout that the solution is unique. For our particular functional forms, this assumption is satisfied.

⁷Some estimate that the average tax is at the “right” level, given the average damage estimates available in the literature, though with the wrong sign.

trivial but, given the significant uncertainty about \tilde{D} , rather important.

Let us first consider the possibility that the economy's true D is globally equal to zero as well. The correct optimal tax is of course zero then, but by the same argument, the marginal effect of a tax increase (as also evident from the expression in (7)) is also zero. The import of this observation is that although a higher tax rate will impose costs on the private economy it will have to depart substantially from zero for costs to be appreciable. Mathematically: the costs of taxation for the private economy are small around a zero tax because utility is maximized there, and the indirect (Ramsey) utility function is smoothly mountain-shaped, and concave, around a zero tax. The quantitative question, which we will address next, is how just how concave the objective is if one adopts quantitatively reasonable functional forms.

The second experiment here is to assess the consequences of raising the tax above zero when in fact the climate damages are significant. Given that, in our economy, \tilde{D} does not interact with market transactions, the first term in the expression in (7) is still zero. Of course, now \tilde{D}' is strictly positive, and the factor it multiplies—how much e_1 rises by raising the tax—is strictly negative. Hence, the whole last term is strictly positive at $\tau = 0$. The benefit of a small tax change above zero is not negligible. Of course, with a mountain-shaped overall Ramsey payoff function, one would expect further tax increases to have less and less positive impact, to eventually become zero at the Pigou tax given \tilde{D} .

The above observations can be expressed jointly as follows: *the costs on the private economy of modestly raising the global carbon tax above zero now are negligible, and the benefits may be large or may be small.* To us, given the large uncertainty about damages, this asymmetry of payoffs is a strong argument in favor of raising the tax above zero. How large the tax has to be to impose significant damages on the economy then depends on the concavity of the Ramsey objective. We will discuss this in the next sections to come.

Suboptimal policy, IIIa: excessive pessimism We will now define two errors and compare them. One arises if we set taxes based on being unduly pessimistic about climate change and one if set them out of undue optimism.

More precisely, we will first find the tax \tilde{D} setting the expression in (7) above equal to zero for a “large” damage function \tilde{D} , i.e., using “pessimistic” beliefs, both about climate change and about humans’ ability to cope with it, documented in the IPCC and in the economics literature on damages. The size of that tax, together with the degree of concavity of the Ramsey objective, will then determine

the size of this kind of error: we will compare the Ramsey objective for a zero tax and the tax $\tilde{\tau}$ under a hypothetical true damage function that is zero. The former value will be higher by construction, but how much depends on the concavity to the right (in the tax dimension) of the Ramsey maximum. That is, just how bad is it to use a large tax?

The answer here is an entirely economic one and depends on the distortionary effects of taxes on carbon: the answer will depend on the substitutability between carbon and green energy, as given by G , on the importance of energy in production, as given by f , as well as on the relative values of p_1 and p_2 , not just locally around a zero tax but for large positive values too. As we shall see below, in a quantitative evaluation, e_1 drops rather rapidly as the tax is increased above zero: intuitively, coal is not that competitive, so even small changes in the tax rate above zero will have large effects on its use. However, the net first-order effect of this rapid drop is very small since we are at an optimum when $\tau = 0$. As the tax rate is increased further, the net effect is larger, but e_1 eventually asymptotes, and hence $de_1/d\tau$, the factor multiplying τ in the expression (7) for the marginal effect of taxation, becomes zero. The existence of green energy here as a decent substitute limits the total loss from carbon taxation. Thus, *a priori, the error made by overestimating the damage from climate change is likely not very large.* We will of course also evaluate the quantitative effects below.

Suboptimal policy, IIIb: excessive optimism The other kind of error arises when the tax is set at zero, i.e., when it is based on optimism, when actually damages are large. The private-economy part of the Ramsey objective, as reflected by the first term in (7), is still the same. Thus, the first term is zero at $\tau = 0$ (and negative for positive tax rates). Now, however, the overall maximum of the objective involves the second, damage, term, which is positive at $\tau = 0$. How large the error is from setting $\tau = 0$ then depends primarily on the concavity of the damage function, in particular to the left of its optimum, viewed as a function of the tax rate. Thus, it is a combination of (i) the convexity of the damage function, $\tilde{D}(e_1)$, and (ii) how much e_1 responds to the tax, which is given by the term multiplying \tilde{D}' in (7).

We know that e_1 will be more sensitive to the tax at low values of τ than at high values, and that as the tax is increased toward infinity, it will asymptote to zero. Thus, a lowering of the tax from the value it should take, if the true damage is large, of course initially gives small gains: at the “correct” optimum, the first-order effect of changing the tax rate on welfare is zero. However, as the tax is

further lowered, the damage increases, since now e_1 is rising, and for very low taxes it rises significantly. We already made this point above: the benefit from increasing the tax above zero is large, especially of course if the true damages are large. Hence, *a priori, the error made by significantly underestimating the damage from climate change is likely quite large.*

The above comparison suggests that the two errors are different in magnitude: the error of underestimating climate change is likely to be significantly larger than the error of overestimating it. The quantitative comparison between the two kinds of errors obviously depends on functional forms and on how their parameter values are calibrated. We now introduce explicit functional forms.

2.3 Parametric forms

We assume that final output is given by

$$Y = AK^\alpha L^{1-\alpha-\nu} E^\nu, \quad (8)$$

where A is total factor productivity, K is the capital stock, L is labor, and E energy services. This assumption is based on our earlier work—Hassler, Krusell, and Olovsson (2021)—where we examine production functions in these three variable against U.S. data. We use annual data and find that a specification which is near Leontief in a Cobb-Douglas aggregate in capital and labor, on the one hand, and fossil energy, on the other, provides a good account of the data over a long time period; the key aspects of the data that drive this conclusion is that the capital vs. labor share is remarkably stable over a long time period whereas the energy share moves in lockstep with the relative price of energy.⁸ Whereas short-run movements in prices and shares suggest a very low elasticity of substitution between energy and other inputs, the longer-run movements suggest a near-one elasticity: the fossil energy price varies significantly across decades while the share is remarkably stable.⁹ Hence, a unitary elasticity appears as a reasonable formulation for a model where a time period is long. This is definitely the interpretation of our static model, but also in our dynamic model below, a time period is a decade.

⁸Another paper, Bornstein, Krusell, and Rebelo (2021), uses global data and a world model and finds a similarly good performance for a similar production function (the main difference is that the focus there is on oil, and hence more narrow than a broader energy measure).

⁹This is also consistent with the results in Hassler, Krusell, and Olovsson’s formulation, where there is directed technical change into different forms of input saving. The coefficients in the CES aggregator are then chosen endogenously over time, thus saving on an input when it is expensive. The reduced form turns out to be close to Cobb-Douglas in the medium to long run.

In conclusion, our assessment is that a production function that is Cobb-Douglas in capital, labor, and fossil energy is reasonable. Of course, here we need an aggregate— E in our model—of fossil-based and other (green) energy, suggesting suggests that further specification search is needed. Given the lack of longer time series on green energy prices and shares, our choice has been to simply introduce a CES nesting of fossil and green and examine different elasticities in that nesting. In sum, our production function amounts to a choice of $f(E) = AE^\nu$.

As already mentioned, for let energy services be a CES in fossil and green inputs:

$$G(e_1, e_2) = (\lambda e_1^\rho + (1 - \lambda) e_2^\rho)^{\frac{1}{\rho}}.$$

As already mentioned in the previous sections, the production of both fossil and green energy inputs are assumed to have constant marginal costs in units of output. This assumption is often used for coal as well as green. First, they are argued to be highly competitive industries. For oil, it would be more appropriate to assume that there are rents, i.e., that there is a finite resource and that its owners can sell it above marginal cost; however, most of the remaining fossil energy supplies consist of coal, or coal-like substitutes. Second, the assumption of constant marginal costs in terms output is equivalent to assuming that the production function for e_i is a multiple of $F(k_i, l_i, E_i)$, with the multiple equaling $1/p_i$; i.e., the total amounts of k and l are allocated efficiently across the three technologies for c , e_1 , and e_2 . Here, our assumption thus reflects a somewhat agnostic view: assuming a similar technology across final output, coal, and green seems a reasonable starting point. It would be very valuable to gather data to evaluate this assumption for long time series and, as a result, possibly refine it.

Finally, we assume a damage function that is quadratic:

$$D(e_1) = \gamma e_1^2.$$

Convexity is a standard assumption here, and although different functional forms could be used (e.g., one could use higher powers) we have found the convexity of the quadratic formulation to be sufficiently powerful. What is less standard, as we emphasized above, is that our damage function is measured directly in consumption units and additive in our economy's resource constraints. In practice, damages appear in numerous ways, and our formulation here simply allowed cleaner theoretical results in the above sections. In our dynamic model below we use the standard formulation (total factor productivity decreases with higher carbon dioxide concentrations in the atmosphere).

With these functional forms, we obtain, in line with the analysis in the previous section, the following solutions for equilibrium quantities and prices:

$$P = \left(\lambda^{\frac{1}{1-\rho}} (p_1 + \tau)^{\frac{\rho}{\rho-1}} + (1 - \lambda)^{\frac{1}{1-\rho}} p_2^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \quad (9)$$

$$E = \left(\frac{\nu A}{P} \right)^{\frac{1}{1-\nu}} \quad (10)$$

$$e_1 = E \left(\frac{P\lambda}{p_1 + \tau} \right)^{\frac{1}{1-\rho}} \quad (11)$$

$$e_2 = E \left(\frac{P(1 - \lambda)}{p_2} \right)^{\frac{1}{1-\rho}}. \quad (12)$$

The expressions for output and consumption (which equals welfare here) then follow immediately.

2.4 Calibration

There are, in total, seven parameters to calibrate: ν , λ , p_1 , p_2 , ρ , A , and γ . We set the weight on coal in (2), λ , to 0.64, which corresponds to the weights on coal and oil ($\lambda_1 + \lambda_2$) used in the dynamic model outlined below (these are calibrated to data on prices and shares). Along the same lines, we set $\nu = 0.031$, $p_1 = 1$ and $p_2 = 5.87$ similar to in the dynamic model.

The parameter governing the elasticity of substitution between coal and green energy, ρ , is set to -0.058 in the benchmark calibration. This value implies an elasticity of substitution of 0.95 and it matches the unweighted mean of the oil-coal, oil-electricity and coal-electricity elasticities that is found in the meta-study by Stern (2012).¹⁰ To evaluate how the results vary with respect to substitutability we also consider the values $\rho = 0.5$ and $\rho = -1$, which respectively correspond to elasticities of substitution of 2 and 0.5. Clearly, as green technologies evolve and become adapted to a more fossil-fuel free world, one could imagine that the elasticity also becomes higher. However, we regard it as another potential, and hazardous, case of excessive optimism to simply assume high substitutability: it is a form of wishful thinking. Therefore, we keep with available studies here until further evidence may call for a re-assessment.

The parameter A is calibrated so that the level of consumption is normalized to 100 without any taxes and climate damages. This implies $A = 103.72$, 102.17 and 104.69 for $\rho = -0.058, 0.5$, and -1 .

¹⁰More specifically, Stern (2012) is based on 47 studies of interfuel substitution.

Turning to damages, we consider two levels. Under “high damages”, damages are 20, i.e., 20% of gross output in *laissez faire*. This is large but it is a value that follows from being pessimistic about climate change and about humans ability to adapt and it is a value that is at the end of the intervals usually given—but not more extreme than that. With the calibration just described, coal use can be directly computed from inserting (9) and (10) into (11). This delivers $e_1 = 1.9511$. Inserting this number into (??) and setting damages equal to 20, we obtain that $\gamma = 5.2538$ in the pessimistic scenario.

Without much loss of generality we set the climate costs in the favorable case to zero, i.e., $\gamma = 0$, since the other end of the intervals considered are not far from zero (only minor warming and great abilities to adapt to a modest temperature increase). In sum, in our two benchmark scenarios, $\gamma \in \{0, 5.2538\}$.

2.5 Quantitative results

In Figure 1 we plot all the key variables of interest for assessing our static model from a quantitative perspective.

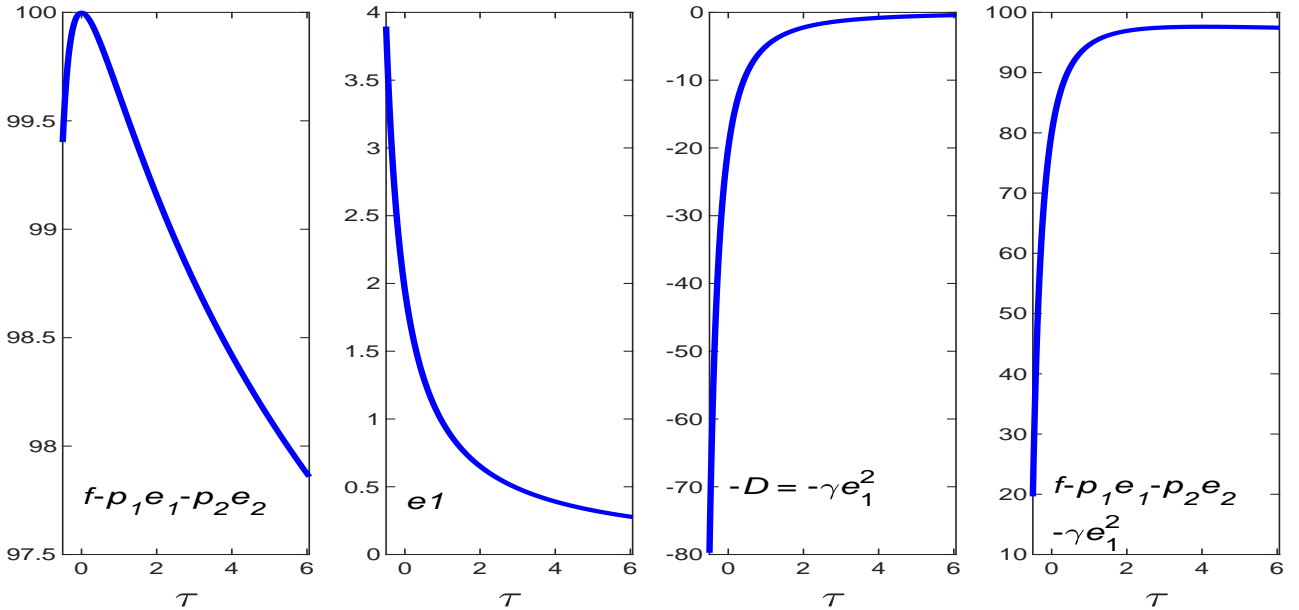


Figure 1: Output, fossil use, damages, and welfare as functions of the carbon tax

The figure allows us to read off all the key conclusions. First, the left-most curve is the output of the private economy as a function of the tax rate. As discussed above, this graph does not involve the damage specification, since damages are additive. We see that output is maximized at a zero tax, and we see that the curve is locally concave around zero but, ultimately, bell-shaped: as the tax

rises further the slope falls. However, the key observation in this part of the figure is the magnitude of the losses to the private economy as taxes are raised. The range for taxes includes the tax rate that would be the choice under a pessimistic belief, i.e., under the perception that damages are large. Thus, the tax rate of 6 is actually above the optimal value under pessimism, and it only involves an output loss of a little over 2 percent of global GDP.

The second sub-figure makes clear what we pointed to above: fossil-fuel use declines sharply as the tax rate is raised. For the tax rate that is given by the pessimistic belief, fossil-fuel use has gone from 8 to below 0.5, i.e., it has fallen by over 90%. However, the bulk of this decline occurs very quickly. Still, as we just saw, output does not respond so much, first because the optimum private output is flat around a tax of zero, and then because the losses never become so big anyway.

The third sub-figure looks at (minus) the damages. This curve thus takes the output of the second subfigure, squares it, and multiplies by γ , and γ here is given by the pessimistic belief. As a consequence, there are extremely sharp improvements from raising the tax rate initially, because damages are large but even more so because taxes are so detrimental to fossil use. Clearly, quite a modest tax will go a long way here in terms of improving welfare—if the pessimistic damage scenario is correct, which is the maintained hypothesis underlying this graph.

Finally, in the right-most panel we see overall welfare, i.e., consumption, which equals the output of the private economy minus the damages (given, again, a pessimistic damage belief). We see that the optimal tax rate is around 4 and that the welfare curve is quite flat for a significant range around the optimum but drops very sharply for low enough tax rates.

In terms of our two kinds of errors discussed above, we are ready to be quantitative, given these graphs. The first kind of loss—that of excessive pessimism—is equal to about 2, i.e., 2% of global GDP: here, the left-most graph is used, and we evaluate at the pessimistically set tax rate of 4. The second kind of loss—that of excessive optimism—must be gauged from the right-most graph, by reading off the consumption value at a zero tax rate. This value is around 80, i.e., the loss is 20% of global GDP.

We can also provide some insight about the relevance of the elasticity of substitution between fossil and green energy for our analysis. Figure 2 thus shows the results when the elasticity of substitution is assumed to be 2 (instead of slightly below 1). The graphs in the figure are based on the same parameters as assumed

before, with the exception of ρ .¹¹

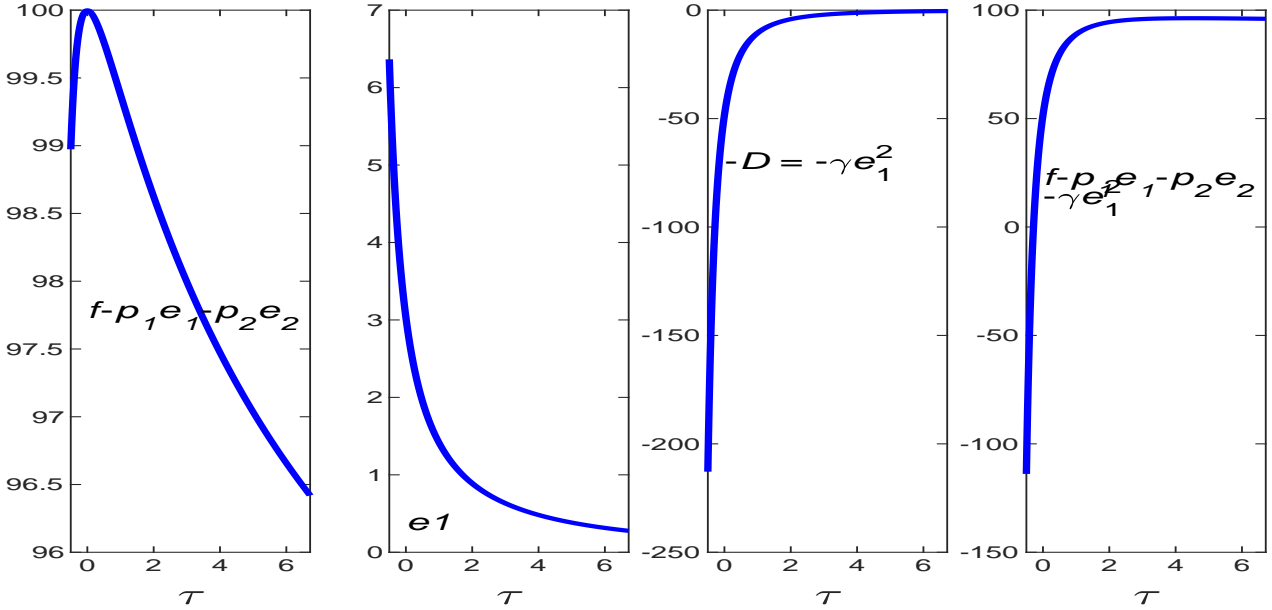


Figure 2: Output, fossil use, damages, and welfare: higher energy substitutability

We see that the qualitative and quantitative results are similar to those we noted for our benchmark economy. When fossil and green are closer substitutes, a raised tax rate lowers fossil use more. Hence, the error from being overly optimistic becomes larger: the gain from lowering fossil use, by means of taxation, is larger. At the same time, we see larger welfare loss from over-pessimism as well, again because fossil fuel is affected more by the tax; however, this effect is not huge.

Finally, Figure 3 shows the results from using a lower substitutability between fossil and green energy: a value of 0.5. We now see that fossil energy is affected less by the tax, and that the private-economy losses are somewhat smaller. The gain from taxation when the damages are large are also smaller, since the effects on fossil energy are more limited.

All in all, the results are quite robust to using different fossil-green elasticity parameters. We conclude that *the error made by setting policy based on being excessively pessimistic about climate change is about ten times smaller than that made by being excessively optimistic*. In our assessment, this speaks very clearly in favor of taking a highly precautionary approach to this policy question.

¹¹With a different ρ , a proper calibration would require adjustments in other parameter values to meet our calibration targets. Thus, the exercise here is focusing only on illustrating the relevance of ρ for the workings of the model.

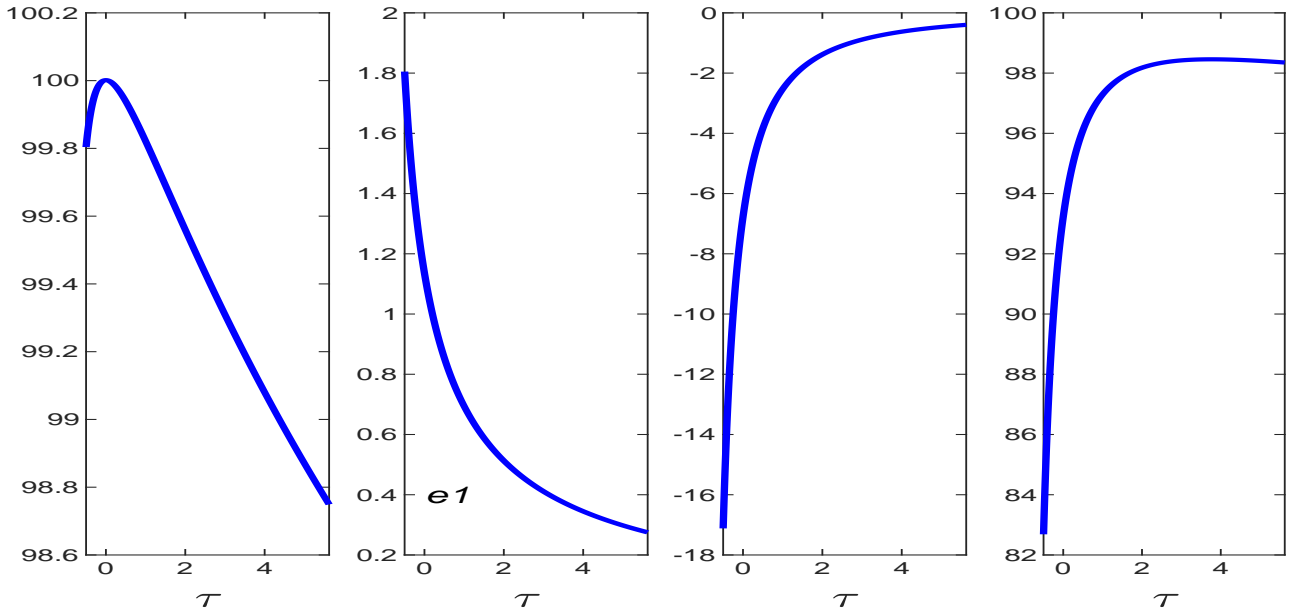


Figure 3: Output, fossil use, damages, and welfare: lower energy substitutability

3 A dynamic model

We now consider a fully dynamic model of the world to make a quantitative assessment of the costs associated with the two policy mistakes. There are r regions in the model. Region 1 features a representative oil producer that is endowed with a finite amount of conventional oil that it extracts and sells to the rest of the world in a competitive manner. This region will be referred to as the *oil producer*. The remaining $r - 1$ regions have no endowments of conventional oil. Instead, they import oil from the oil producer and pay for this import with a common final good that is identical in all countries. These regions share a number of features but are allowed to differ with respect to size, productivity, and initial capital stocks. We will refer to them as *oil consumers*. We will consider two versions of the model: one with several oil consumers, referred to as the multi-regional model, and one with just one representative oil consumer, referred to as the one-region model. Relative to the static model, we also add both conventional and unconventional oil as energy inputs.

There are no international capital markets in the multi-regional model. The absence of capital markets is a simplification but likely not a major one: if the model is calibrated such that marginal products of capital are similar at time 0—as it will be here—and preferences are the same—which we assume they are—then the long-run marginal products of capital will also be the same. Hence, neither at time zero nor as time goes to infinity will there be a need for capital

to move across regions. During a transition path, the marginal products will in general differ across regions, but these differences turn out not to be major.¹² The model is now described formally.

Each region $i \in \{1, 2, \dots, r\}$ features a representative consumer with preferences given by

$$\sum_{t=0}^{\infty} \beta^t \log(C_{i,t}). \quad (13)$$

3.1 Oil consumers

In the oil-consuming regions, energy services are produced by local competitive firms that combine different energy sources as inputs. One energy input is the oil that is imported from the oil-producing region, whereas the other energy sources are all produced locally. Including conventional oil, these regions have access to $n + 1$ different imperfectly substitutable energy inputs. These include other conventional fossil fuels such as coal, but also hydraulic fracturing (or fracking), which in recent years has made it possible to produce “unconventional” oil and gas in substantial quantities in the United States, and potentially in other regions. We thus include this unconventional fossil as one that is highly substitutable with conventional oil. The specific functional-form assumptions will now be discussed.

In regions that engage in fracking, the supply of oil is a composite of the imported conventional oil and the locally produced unconventional substitute, i.e., the output from fracking. Denoting conventional oil used by region i by e_1 and unconventional oil by e_4 , we assume, for country i at time t , an oil composite of

$$O_{i,t} = 2 \left(\lambda_1^{oil} e_{1,i,t}^{\rho_h} + (1 - \lambda_1^{oil}) e_{4,i,t}^{\rho_h} \right)^{\frac{1}{\rho_h}}, \quad (14)$$

where ρ_h determines the elasticity of substitution between the two inputs.¹³ In regions that do not engage in fracking, $O_{i,t}$ is just given by $e_{1,i,t}$.

The total amount of energy services in region i in period t is then an aggregate of oil and the $n - 1$ remaining energy inputs

$$E_{i,t} \equiv \mathcal{E}(O_{i,t}, e_{2,i,t}, \dots, e_{n,i,t}) = \left(\lambda_1 O_{i,t}^\rho + \sum_{\kappa=2}^n \lambda_\kappa e_{\kappa,i,t}^\rho \right)^{\frac{1}{\rho}}, \quad (15)$$

¹²In Krusell and Smith (2020) a similar setting is examined under both intertemporal trade across regions and autarky and very small differences are found there.

¹³The multiplication of 2 ensures that the oil price index can be normalized to 1.

where ρ determines the elasticity of substitution, and $\sum_{k=1}^n \lambda_k = 1$.

Except for conventional oil, all energy sources are locally produced with a production technology that is linear in the final good. Specifically, $p_{k,i,t}$ units of the final good are required to produce $e_{k,i,t}$ units of the energy source $\in \{2, \dots, n+1\}$ in region i and period t .¹⁴

Final goods that are not used for energy production are consumed or invested, and capital is assumed to fully depreciate between periods. In business-cycle models, where a time period is a quarter or a year, this is a wholly inappropriate assumption, but in models where a period is ten years or even longer, this assumption is much less problematic. The resource constraint for the final good is then given by

$$C_{i,t} + K_{i,t+1} = A_{i,t} L_{i,t}^{1-\alpha-\nu} K_{i,t}^\alpha E_{i,t}^\nu - p_{1,t} e_{1,i,t} - \sum_{k=2}^{n+1} p_{k,i,t} e_{k,i,t}, \quad (16)$$

where $p_{1,t}$ denotes the world market price for conventional oil. The assumption of an identical final good allows us to express this price in terms of the global final good.

3.2 Oil producers

Region 1 extracts oil without any resource cost, and the total stock of oil in the ground at time t has size R_t . With extraction in period t given by $\sum_{i=2}^r e_{1,i,t}$, the law of motion for the stock of oil is given by

$$R_{t+1} = R_t - \sum_{i=2}^r e_{1,i,t}, \text{ s.t. } R_t \geq 0, \forall t. \quad (17)$$

Since the oil producer derives all its income from oil, its budget/resource constraint is given by

$$C_{1,t} = p_{1,t} (R_t - R_{t+1}). \quad (18)$$

A key assumption that was mentioned above and that is implicit in this equation is that the oil producer cannot invest the proceeds from oil sales abroad; it also cannot store oil. These assumptions are clearly not consistent with the data but greatly simplify the analysis, as we shall see shortly. Relaxing them would be

¹⁴These assumptions are equivalent to another assumption: there are explicit energy-source production sectors, side by side with the production of final output, between all of which all production factors can be moved freely within the period, and the corresponding production functions are all identical up to their TFP levels; the TFP for sector k in country i at time t is simply $1/p_{k,i,t}$ times TFP in the final-goods sector.

valuable but would, we suspect, mainly influence the price formation for oil in the model.

3.3 Carbon circulation

Usage of fossil energy sources generates CO₂ emissions. The parameter g_j measures how dirty energy source j is. Because we will measure fossil energy sources by their carbon content, the fossil energy sources all have $g_j = 1$. Purely green energy sources, in contrast, have $g_j = 0$.¹⁵ Total emissions from region i in period t are then given by

$$M_{i,t} = \sum_{j=1}^{n+l} g_j e_{j,i,t}.$$

Following Golosov et al. (2014), the law of motion for the atmospheric excess stock of carbon S_t is assumed to be given by $S_t = \sum_{s=0}^{\infty} (1 - d_s) \sum_{i=2}^r M_{i,t-s}$, where $1 - d_s = \varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s$ measures carbon depreciation from the atmosphere. Specifically, the share of emissions that remains in the atmosphere forever is φ_L , the share that leaves the atmosphere within a period is $1 - \varphi_0$, and the remainder $(1 - \varphi_L) \varphi_0$ depreciates geometrically at rate φ . The formulation provides a good approximation to much more elaborate circulation models.

3.4 Climate and damages

The climate is affected by the concentration of CO₂ in the atmosphere via the greenhouse effect. Golosov et al. (2014) gives arguments to the effect that the effect of the CO₂ concentration on productivity is well captured by a log-linear specification. We therefore assume that

$$A_{i,t} = \exp(z_{i,t} - \gamma_i S_{t-1}), \quad (19)$$

where $z_{i,t}$ is a potentially stochastic productivity trend and γ_i is a region-specific parameter that determines how climate-related damages depend on the level of the atmospheric CO₂ concentration. Note that this specification implies that the marginal damage per unit of excess carbon in the atmosphere is a constant share of net-of-damage output given by the parameter γ_i . The value γ_i is positively affected by (i) the sensitivity of the global mean temperature to changes in the CO₂ concentration, (ii) the sensitivity of the regional climate to global mean temperature,

¹⁵Allowing intermediate cases, i.e., emissions from non-fossil energy sources is straightforward.

and (iii) the sensitivity of the regional economy to climate change.¹⁶

The climate system follows the energy budget model in DICE/RICE:

$$\begin{aligned} T_t &= T_{t-1} + \sigma_1 \left(\frac{\eta}{\ln 2} \ln \left(\frac{S_{t-1}}{S_0} \right) - \kappa T_{t-1} - \sigma_2 (T_{t-1} - T_{t-1}^L) \right) \\ T_t^L &= T_{t-1}^L + \sigma_3 (T_{t-1} - T_{t-1}^L) \end{aligned}$$

where T_t is the global mean temperature in the atmosphere (and upper layers of the oceans) and T_t^L is the mean temperature in the deep oceans. Both these temperatures are measured as deviations from their pre-industrial levels. Note that temperature does not appear in the model equations anywhere but here. Hence, the temperatures are solved for residually.

3.5 Governments

Each oil-consuming region sets a carbon tax, $\tau_{i,t}$. As in the static model, we consider per-unit taxes. The cost for the energy-service provider of using energy source j in region i is then $\tau_{i,t}g_j + p_{\kappa,i,t}$. For simplicity, tax revenues are recycled back to the household within the period in the form of a negative income tax rate, $\Gamma_{i,t}$, times total household income $w_{i,t}L_{i,t} + r_{i,t}K_{i,t}$.¹⁷ The government budget constraint is then given by

$$\Gamma_{i,t} (w_{i,t}L_{i,t} + r_{i,t}K_{i,t}) = \tau_{i,t} \sum_{\kappa=1}^{n+l} g_{\kappa} e_{\kappa,i,t}.$$

3.6 Markets and equilibrium

All agents are price takers and markets within regions are assumed to be perfect and complete. Price-taking behaviour of the final-good producing firms implies

¹⁶The specification in (19) implies that climate damages materialize with a lag of one period. Given that climate change is a slow-moving process and the evolution of the atmospheric CO₂-concentration is sluggish, this is immaterial for the dynamics of climate damages. The introduction of this lag substantially simplifies the computation of the equilibrium allocation.

¹⁷This subsidy, thus, is not lump-sum. If taxes were paid back as lump-sum transfers, the model would be somewhat more difficult to solve. Given that the potential revenues are very small and, hence, the implied tax rate is small, this assumption will not be of quantitative importance.

that the wage and the interest rate, respectively, are given by

$$w_{i,t} \equiv \frac{\partial Y_{i,t}}{\partial L_{i,t}} = (1 - \alpha - \nu) \frac{Y_{i,t}}{L_{i,t}} \quad (20)$$

$$r_{i,t} \equiv \frac{\partial Y_{i,t}}{\partial K_{i,t}} = \alpha \frac{Y_{i,t}}{K_{i,t}}. \quad (21)$$

$$P_{i,t} = \nu \frac{Y_{i,t}}{E_{i,t}}. \quad (22)$$

The assumption of constant returns to scale implies that profits are zero in equilibrium, and that output net of energy expenses is given by $(1 - \nu) Y_{i,t} \equiv \hat{Y}_{i,t}$. The shares of spending on different energy sources will not necessarily be constant, unless $\rho = 0$, i.e., if the overall production function is Cobb-Douglas in all inputs.

Turning to the representative oil producer, the problem is to choose how much oil to keep in the ground for next period, R_{t+1} , while taking the world market price of oil as given. Substituting (18) into (13) and taking the first-order condition with respect to R_{t+1} delivers the solution $R_{t+1} = \beta R_t$. Hence, the depletion rate is constant, and the path of oil use is entirely supply-determined.¹⁸ This is convenient for solving the model, but it also implies that the oil price does not need to satisfy a typical Hotelling equation where the price of oil rise at the rate of interest. Instead, the oil price is entirely demand driven: given the supply of oil, a higher or lower demand for oil is directly reflected in the oil price without any change in oil use.¹⁹

Households in the oil-consuming regions supply labor inelastically and maximize (13) subject to the budget constraint

$$C_{i,t} + K_{i,t+1} = (1 + \Gamma_{i,t}) (w_{i,t} L_{i,t} + r_{i,t} K_{i,t}) = (1 + \Gamma_{i,t}) \hat{Y}_{i,t}, \quad (23)$$

which delivers the Euler equation

$$\frac{C_{i,t+1}}{C_{i,t}} = \beta (1 + \Gamma_{i,t+1}) r_{i,t+1}. \quad (24)$$

It is straightforward to verify that (24) in combination with (21) implies that the saving rate is constant and given by $s_{i,t} = \alpha\beta / (1 - \nu) \equiv s, \forall t$.

¹⁸Note that even if $p_{1,t}$ were to be stochastic, this would have no effect on the oil supply, since income and substitution effects exactly cancel under logarithmic preferences.

¹⁹A model where oil use is determined jointly by supply and demand would be preferable, as would a setting where oil producers could conduct some amount of intertemporal arbitrage, based on the evolution of the world interest rate, using storage. In reality, however, the costs associated with storage may be non-trivial, as stored amounts are not very large.

In regions that engage in fracking, the problem for the energy-service provider can be solved in two steps. First, the regional relative demands of conventional and unconventional oil can be determined by minimizing the costs of buying/producing the different types of oil subject to a desired supply of oil. As a second step, the demand functions for all fuels are determined by minimizing the costs of all fuels subject to a desired level of energy services; these cost minimization problems are laid out in the Appendix.

The key properties of the market allocation can now be summarized in the following proposition.²⁰

Proposition 1 *In each period, the equilibrium allocation is determined by state variables $K_{i,t}$, R_t and S_{t-1} such that*

1. the capital saving rate is constant at $s = \frac{\alpha\beta}{1-\nu}$
2. the supply of conventional oil is given by $(1 - \beta)R_t$
3. the price of the oil composite is $P_{i,t}^O = \left((\lambda_1^{oil})^{\frac{1}{1-\rho_h}} \hat{p}_{1,i,t}^{\frac{\rho_h}{\rho_h-1}} + (\lambda_2^{oil})^{\frac{1}{1-\rho_h}} \hat{p}_{n+1,i,t}^{\frac{\rho_h}{\rho_h-1}} \right)^{\frac{\rho_h-1}{\rho_h}}$
4. the price of energy services is $P_{i,t} = \left(\lambda_1^{\frac{1}{1-\rho}} (P_{i,t}^O)^{\frac{\rho}{\rho-1}} + \sum_{j=2}^n \lambda_j^{\frac{1}{1-\rho}} \hat{p}_{j,i,t}^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}}$
5. energy-service demand is $E_{i,t} = \left(\nu \frac{e^{(z_{i,t} - \gamma_{i,t} S_{t-1})} L_{i,t}^{1-\alpha-\nu} K_{i,t}^\alpha}{P_{t,i}} \right)^{\frac{1}{1-\nu}}$
6. regional demand for composite oil is given by $O_{i,t} = \left(\lambda_1 \frac{P_{i,t}}{P_{i,t}^O} \right)^{\frac{1}{1-\rho}} E_{i,t}$
7. regional demands for conventional and unconventional oil is $e_{j,i,t} = \frac{O_{i,t}}{\tilde{l}} \left(\tilde{l} \lambda_j^{oil} \frac{P_{i,t}^O}{\hat{p}_{j,i,t}} \right)^{\frac{1}{1-\rho_h}}$,
 $j \in \{1, n+1, \dots, n+l\}$
8. regional demands for the remaining $n-1$ fuels are $e_{j,i,t} = \left(\lambda_j \frac{P_{t,i}}{\hat{p}_{j,i,t}} \right)^{\frac{1}{1-\rho}} E_{i,t}$,
 $j \in \{2, \dots, n\}$
9. net output is $\hat{Y}_{i,t} = (1 - \nu) A_{i,t} L_{i,t}^{1-\alpha-\nu} K_{i,t}^\alpha E_{i,t}^\nu$.

The price of oil is determined from market clearing in the world oil market, $\sum_{i=2}^r e_{1,i,t} = (1 - \beta) R_t$, and the state variables evolve according to $K_{i,t} = \frac{\alpha\beta}{1-\nu} (1 + \Gamma_{i,t}) \hat{Y}_{i,t}$, $R_{t+1} = \beta R_t$ and $S_t = \sum_{v=0}^t (1 - d_{t-v}) \sum_i M_{i,t}$.

²⁰We leave out the formal equilibrium definition—it is straightforward given the discussion above.

Two things should be noted. First, the allocation is determined sequentially without any forward-looking terms; this is due to the combination of logarithmic utility, Cobb-Douglas production, full depreciation, and the way that tax revenues are rebated. Second, given a world market price of oil ($p_{1,t}$), all equilibrium conditions have closed-form solutions. Hence, in each period, finding the equilibrium is only a matter of finding the equilibrium oil price where supply is predetermined at $(1 - \beta) R_t$. As a result, the model typically solves in under a second.

3.7 Calibration

We now turn to the calibration of the model. Most of the calibration is the same for the one-region and the multi-regional models, but the details that are specific for the multi-region model are laid out in Section 3.9.

3.7.1 Energy sources and their properties

The number of different fuel inputs into energy production that are available in all regions is set to $n = 3$. The first fuel represents the oil aggregate, whereas fuel of types two and three are given by coal and green (renewable) energy, respectively. Given that the amount of non-conventional reserves of fossil fuel that are extractable by fracking and other existing or future technologies is hard to assess, we only allow for fracking in the United States in the multi-regional model. Hence, we let the fourth fuel represent the output from fracking in the United States. Measuring oil and coal in carbon units implies that $g_{j,i,t} = 1$ for $j \in 1, 2, 4$, and 0 for $j = 3$.

As in the static model, the elasticity of substitution between the $n = 3$ energy sources is set to 0.95, which implies setting ρ to -0.058 . As a robustness check we also consider a higher elasticity. The elasticity of substitution between the output from fracking and conventional fossil fuels is imposed to be higher and set to 10, implying $\rho_h = 0.9$.²¹

To calibrate the λ 's, prices and quantities of the three types of fuel are needed. Abstracting from fracking and combining the demand equations (31) and (32) that are found in the Appendix, we derive the following relationships

$$\frac{\lambda_1}{\lambda_k} = \left(\frac{e_{1,t}}{e_{k,t}} \right)^{1-\rho} \frac{p_{1,t}}{p_{j,t}}, \quad j = 2, 3.$$

²¹For related studies on the U.S. shale oil boom, see Çakir Melek, Plante, and Yücel (2017) and Bornstein et al. (2017).

Using world market prices from Golosov et al. (2014), the coal price is set to (USD) \$74/ton. The oil price is endogenous and will therefore vary slightly between the different experiments considered. The (pre-financial crises) oil price in the multi-regional model is calibrated to be about \$70/barrel, corresponding to \$70·7.33 per ton.²² These prices are assumed to apply in all regions. The price of coal is calibrated to include the cost of production and transportation. The relative price between oil and coal in units of carbon is then 5.87; i.e., markets value oil much higher than coal. Using the same source for the ratio of global oil to coal use in carbon units we find that $\lambda_1/\lambda_2 = 5.348$. For green energy, we use data for the sum of nuclear, hydro, wind, waste, and other renewables from Golosov et al. (2014) and adopt their (somewhat arbitrary) assumption of a unitary relative price between oil and renewables. This gives $\lambda_1/\lambda_3 = 1.527$. Together with the normalization $1 = \lambda_1 + \lambda_2 + \lambda_3$, the λ s are then given by $\lambda_1 = 0.543$, $\lambda_2 = 0.102$, and $\lambda_3 = 0.356$. Fracking costs in the U.S. are roughly \$40 per barrel, corresponding to \$347 per ton of carbon.

3.7.2 Fossil-fuel reserves

Turning now to existing stocks of fossil fuels, BP (2010) reports that global proved reserves of oil are 181.7 gigatons. However, this number only includes the aggregate reserves that are economically profitable to extract at current economic and technical conditions. In particular, it does not take technical progress into account, or factor in potential discoveries of new, profitable oil reserves. An alternative study is Rogner (1997), which does take technical progress into account. This study estimates global fossil reserves to be larger than 5,000 gigatons of oil equivalents (Gtoe).²³ About 16% of these reserves constitute oil, i.e., 800 Gtoe. Against this background, we set the existing stock of oil to be about 330 Gtoe, i.e., somewhere well within the range of these two estimates. The carbon content of oil and coal in weight is 84.6% and 71%, respectively. As has been clear from the description of production, coal stands in a sharp contrast to oil, which is costless to produce in our model: coal is a zero-profit industry and there is no upper limit in the model on how much can be produced. The marginal costs of oil are estimated to be a small fraction of the price and hence oil earns “Hotelling rents”. Coal, in the data, appears to be making only minor profits and to be highly vulnerable to competition. Our assumption of no bound on how much coal can be produced is,

²²Taxes and subsidies of fossil fuel and other energy sources are disregarded.

²³By expressing quantities in oil equivalents, the difference in energy content between natural gas, oil, and various grades of coal is accounted for.

in a literal sense, not reasonable, of course; the motivation for it is rather that we take for granted that technical improvements in green energy and/or carbon taxes will make the upper bound on coal non-binding.

3.7.3 Climate damages and the carbon cycle

The initial stock of atmospheric carbon, S_0 , is set to 586 gigatons of carbon (GtC) and our calibration implies that it is feasible to emit several multiples more of what has already been emitted. What are the potential damages of these emissions? The core questions we are dealing with in this paper concern, precisely, the fact that any climate policy today has to be implemented under fundamentally imperfect knowledge about both the climate system and the resulting economic damages.

To answer our questions we focus on imperfect knowledge about two sets of crucial parameters: those regulating climate sensitivity and the parameters that determine the regional damages as functions of the global temperature. The climate sensitivity quantifies how much the temperature increases from a doubling of the concentration of CO_2 in the atmosphere, and here the IPCC (2013) reports a wide range of values. Regarding the economic damages, we rely on the recent meta-study by Nordhaus and Moffat (2017). Rather than focusing on the risk, and possible movements over time, in these parameters, we focus on the extremes as given by as upper and lower bounds of intervals given in these documents.

The damages are calibrated using the latest estimates from RICE (Nordhaus, 2010). Specifically, this study provides linear-quadratic regional damage functions that are stating the share of GDP lost due to changes in the global mean temperature. Using the Arrhenius equation, we can then, for each set of damage parameters, express the damage elasticity as a function of the global mean temperature:

$$\gamma_i = -\frac{\ln(1 - (\phi_{1,i}T + \phi_{2,i}T^2))}{S_0 \left(e^{\frac{T \ln(2)}{\xi}} - 1 \right)}, \quad (25)$$

where ξ denotes the climate sensitivity that measures how many degrees Celsius that the temperature increases as a result of a doubling of atmospheric CO_2 concentration.

In the one-region model, the damage elasticity, γ_{World} , is approximated with the value of γ_i that results from evaluating (25) at 3.5°C , yielding $\gamma_{World} = 3.21 \cdot 10^{-5}$. Our focus is on the extreme outcomes for the climate-related costs and, as described in Hassler, Krusell, and Olovsson (2018), the upper and lower bounds of these costs are computed by, respectively, multiplying γ_{World} by the numbers

3.44 and 0.0894. Moreover, the corresponding (approximate) optimal taxes at these bounds are also computed by multiplying the tax that would be optimal at $3.5^\circ C$ with 3.44 and 0.0894, respectively. The calibration of the region-specific damage elasticities, γ_i , are described in Section 3.9 below. For the carbon-cycle parameters, we follow Golosov et al. (2014) by setting $\varphi_L = 0.2$, $\varphi_0 = 0.393$, and $\varphi = 0.0228$.

3.7.4 Production and growth

The discount factor is set to 0.985^{10} , with the understanding that a period is a decade. The production parameters α and ν determine the income shares for capital and energy, respectively. We set α to 0.3 and ν to 0.031 to match a capital share equal of 0.3 and an energy share of 0.031.²⁴ Initial global GDP is set to \$80 trillion, which matches the observed value for 2017. In the one-region model, the constant technological growth rate is set to be $\Delta z_{i,t} = 1.5\%$ per year. The multi-regional model allows the developing regions to grow faster for a period of time; the details on these processes are laid out in Section 3.9 below. The full calibration is summarized in Tables 2-1 in Appendix A.2. We now proceed to present the results.

3.8 Results, I: the one-region (global) special case

Using the static model in Section 2, we made two main policy points. The first point was to argue that it seems wise to apply at least a modest global tax on carbon. The argument was based on two observations. One was that raising the global carbon tax from the current level (of approximately zero) to a modest level brings virtually no damages to the private economy—given that a zero tax is optimal from the perspective of the private economy and welfare is rather flat, as a function of the tax, around zero. The second observation was that the benefit of a tax rise was either zero—under the optimistic perception on climate change—or quite large—if climate change instead is significant, and highly damaging. Then, given that these costs and benefits were additive, it followed that, at least in expected value, it was beneficial to raise the tax. In this section we use a model where the point cannot be made exactly this way, since we now use a quantitative dynamic model where the damages from climate change interact non-linearly with the economy. What would a modest tax, then, do in the model entertained in this

²⁴The model with one oil consumer features a slightly higher ν of 0.05 and a slightly lower stock of oil of 300 Gtoe; this is to prevent the model from predicting too low an oil price.

section?

Figure 4 below shows that the argument is quantitatively powerful in the richer model as well. The figure is based on the case where climate sensitivity is large, i.e., where the global temperature responds strongly to emissions—our pessimistic scenario. The laissez-faire (zero-tax) equilibrium then takes global mean temperature to a little under three degrees warming by 2100 and then warming accelerates, bringing the net temperature increase to 8 degrees by 2200. A modest tax, then—set at the level of the current prices of emission rights in the EU-ETS trading system—brings the temperature increase down by almost a full degree by 2100 and by a total of five degrees by 2200. Under this scenario, which also involves high damages from warming, the optimal tax—which is straightforwardly defined since the model is dynastic and has one region—would bring the temperature down by roughly one degree more by year 2200.²⁵ Hence the modest tax takes us most of the way to the global optimum.

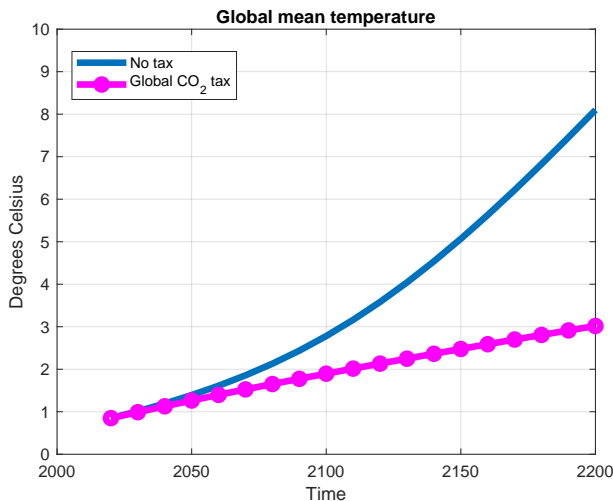


Figure 4: A modest global tax is potent

Next, the costs associated with the two kinds of policy errors—based on under- or overestimating climate change and its effects on the economy—are plotted in Figure 5 for two different elasticities of substitution.

The figure makes clear that the results from Section 2 hold also in the dynamic setting: the cost associated with underestimating climate change is substantially larger than the cost of overestimating it. In the dynamic setting here, we also see that this effect becomes increasingly important over time. Indeed, the cost of underestimating climate change and its effects is initially marginally lower than

²⁵The curve representing the optimal path, given high climate sensitivity and high damages, is not shown in the figure.

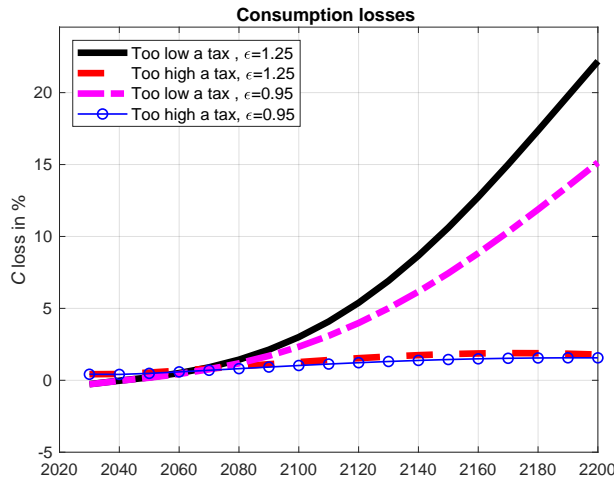


Figure 5: The two kinds of errors

that of overestimating it, even though this difference is small. This feature could, however, potentially make it harder to get support for a more precautionary policy in the near future.

The figure also confirms that the asymmetry between the costs for the two political mistakes is increasing in the elasticity of substitution between the energy inputs. The cost of being too pessimistic is essentially unaffected by the elasticity, but the cost of being too optimistic is always higher with the higher elasticity and the difference increases substantially over time.

3.9 Results, II: the multi-regional model

We now expand the model further and set $r = 8$ to include seven oil-consuming regions. Specifically, these regions represent Europe, the U.S., China, South America, India, Africa, and Oceania. The oil-producing region consists of OPEC and Russia. South America includes all countries in South America except the countries that are part of OPEC, and the same is true for Africa. The region referred to as India also includes Pakistan and Bangladesh. Our definition of Oceania, finally, is also wider and somewhat different from the geographical region: it includes Australia, Japan, Indonesia, Malaysia, Myanmar, New Zealand, Philippines, Thailand, and Vietnam.²⁶ Before we present the results, we need to assume values for a few regional parameters.

²⁶Together, the eight regions account for somewhat less than 90% of global emissions in 2016.

3.9.1 Regional calibration

The γ_i s approximated with values of γ_i that are evaluated at $3.5^\circ C$. Based on the estimates in Nordhaus and Moffat (2017), this implies $\gamma_{US} = 2.4 \cdot 10^{-5}$, $\gamma_{Eu} = 2.7 \cdot 10^{-5}$, $\gamma_{Ch} = 2.5 \cdot 10^{-5}$, $\gamma_{In} = 5.1 \cdot 10^{-5}$, $\gamma_{Af} = 5 \cdot 10^{-5}$, $\gamma_{SA} = 2.6 \cdot 10^{-5}$, and $\gamma_{OC} = 2.7 \cdot 10^{-5}$.

The TFP levels in the different regions are calibrated to match each region's share of global 2016 PPP-adjusted GDP as reported by the World Bank.²⁷ The distribution implies that roughly 60% of world GDP is produced in equal shares in the U.S., the EU, and China, whereas Oceania accounts for 13%, India 9%, South America 6%, the oil countries 12%, and Africa 6%. Based on Stefanski (2017), we acknowledge that China subsidizes coal production and we set the subsidy to match China's share of world CO₂ emissions.²⁸ Given the close connection between GDP and emissions, the model then matches emission shares in all regions quite well. GDP and emission shares in the model and data are plotted in Figure 6.²⁹

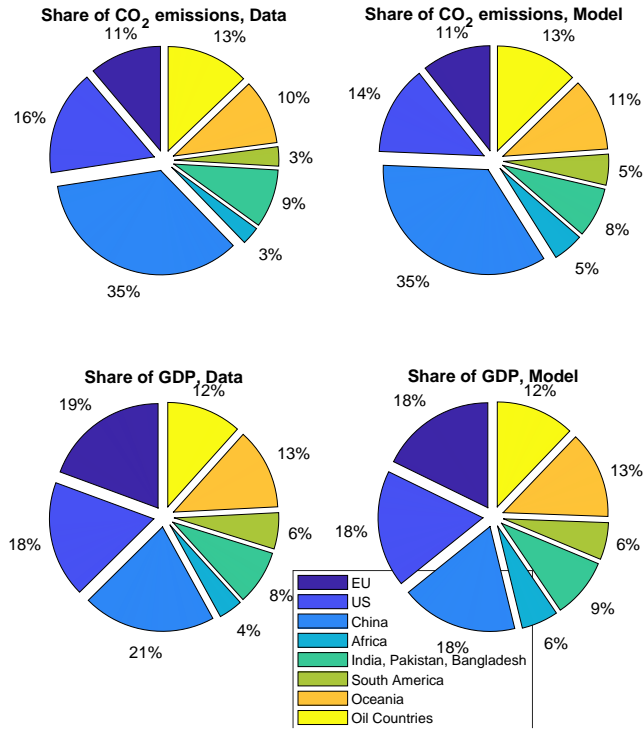


Figure 6: Shares of world GDP and CO₂ emissions: model and data

²⁷World Bank: World Development Indicators.

²⁸The implied subsidy is \$83 per ton of carbon. The share coming from the oil producer is also targeted directly by assuming that a fraction of their oil extraction gives rise to CO₂ emissions. This share is set at 0.32.

²⁹The figure plots PPP-adjusted GDP in constant 2011 international \$s and world CO₂ emissions in the model and in the data. The source for GDP is the World Bank and for emissions it is EDGAR: the Emissions Database for Global Atmospheric Research.

The U.S. and the EU are both assumed to start out on their respective balanced growth paths, where the constant technological growth rate is given by $\Delta z_{i,t} = 1.5\%$ per year, as in the one-region model. Based on the findings in Caselli and Feyrer (2007), the initial capital stock is set to equalize real interest rates across all regions. Together, these assumptions imply a GDP growth rate of 2.1% per year, and they pin down initial productivities and capital stocks in all regions.³⁰ Due to catching-up effects, China, India, Africa, South America, and Oceania are all assumed to initially grow faster than the EU and the United States.³¹ These assumptions are implemented by allowing TFP in those regions to converge to a growth path that is 60% higher than their current ones. The implication is that China converges to a balanced growth path with approximately twice the GDP of the EU and the U.S., whereas India and Africa both converge to a path with the same GDP as the EU and the U.S. Formally, we assume that, for these regions, $\log(\text{TFP})$ obeys

$$\begin{aligned} z_{i,t+1} &= z_{i,t} + 10 \log 1.015 + \frac{1}{4} (\hat{z}_{i,t} - z_{i,t}), \\ \hat{z}_{i,t+1} &= \hat{z}_{i,t} + 10 \log 1.015, \\ \hat{z}_{i,0} &= z_{i,0} + \log 1.6, \end{aligned} \tag{26}$$

where $e^{\hat{z}_{i,t}}$ is the TFP path that actual TFP converges to, and $t = 0$ is the initial period. As seen in equation (26), 1/4 of the productivity gap ($\hat{z}_{i,t} - z_{i,t}$) is removed each decade. The regional damage functions are summarized in Tables 2–1 in Appendix A.2. We are now ready to present the results.

3.9.2 Findings

The results for the multi-regional model are presented in Figures 7-??.

Qualitatively, the results again confirm the findings in Section 2. Two aspects are, however, worth mentioning. First, for Africa and India, the costs of underestimating climate change are very large: a 40 percent reduction in consumption by the year 2200 relative to the optimal policy. Second, the results for the U.S. differ somewhat from those for the other regions. Specifically, the cost of overestimating climate change is higher than that of underestimating it, unless one takes a very long-run perspective. The reason is that higher taxes really hurt the fracking industry, which is calibrated to be important in that region.

³⁰See the appendix for details.

³¹For Oceania, which includes both developed and developing countries, this assumption is arguably exaggerating technology growth.

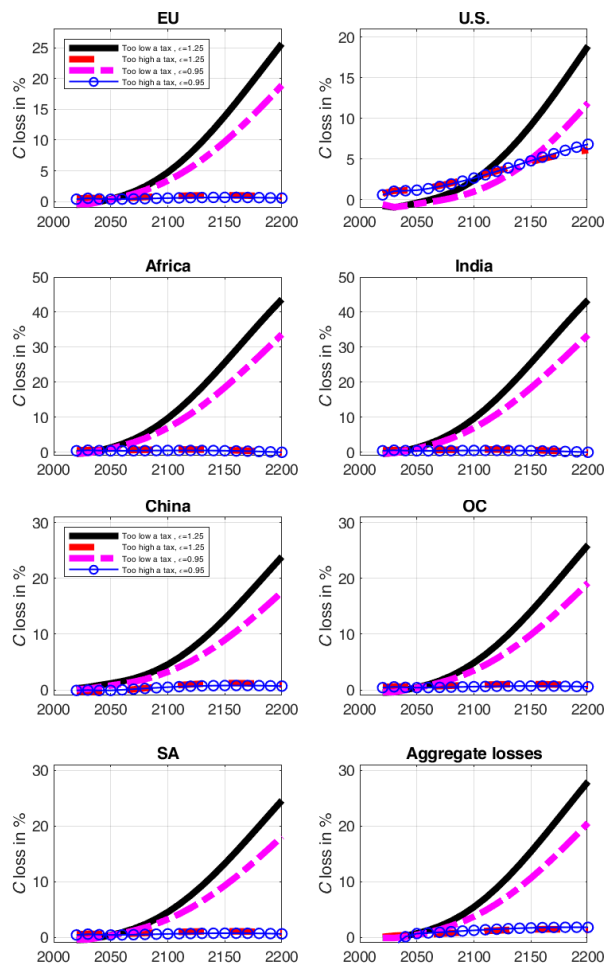


Figure 7: Consumption losses by region for the two policy errors

We also note, in line with the results in Sections 2 and 3.8, that the costs of underestimating climate change are higher with a higher elasticity of substitution between energy inputs. The cost of overestimating the effects of global warming are also higher with a higher elasticity, but this effect is just marginal. Our results thus reveals that a higher elasticity of substitution between energy goods creates a larger asymmetry: it increases the cost of underestimating climate change more than it increases the costs of overestimating climate change.

Of course, the limited costs of following a prudent (i.e., high-tax) policy crucially also depend on the design of the policy: it is a global (uniformly applied) carbon tax. If we considered a prudent stance under a less well-designed policy scheme, the costs could rise significantly. We explore these issues in Hassler, Krusell, Olovsson, and Reiter (2021).

4 Conclusions

The conclusions from our findings in this work are quite clear: based on looking at errors from setting the global tax on carbon incorrectly in different ways, the key takeaway is that it is wise to choose a tax in a precautionary manner. I.e., act as if climate change is rather severe and the damages from it are substantial. This way, the mistake made—the mistake that would occur if in fact climate change will be minor, or unproblematic to human welfare—is contained and quite small.

Of course, the focus here has been narrow and just a scratching on the surface; many more examples of suboptimal policy can be analyzed. One regards the global nature of policy: what are the losses from adopting different tax rates on carbon around the world, and perhaps especially by assuming zero taxes developing countries? What errors are made if the entire focus of policy is on green energy and carbon taxes are set to zero? Both these questions are studied in Hassler, Krusell, Olovsson, and Reiter (2020). Other interesting questions regard taxes that differ by sector of the economy—how much is lost, for example, by higher taxes on carbon in the transportation sector? What about different tax rates within regions (perhaps to alleviate inequality concerns), an issue that can also be studied from the perspective of a single country? We really see no end to the list of questions of this sort, and we have no strong hunch on how the quantitative answers will come out.

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World Bank, Databank, World Development Indicators.

World Bank: Databank, Online data for GDP.

A Appendix

A.1 First-order conditions

First, the regional relative demands of conventional and unconventional oil can be determined from the following cost-minimization problem:

$$\min_{e_{1,i,t}, e_{4,i,t}} \hat{p}_{1,i,t} e_{1,i,t} + \hat{p}_{4,i,t} e_{4,i,t} - P_{i,t}^O \left(2 (\lambda_1^{oil} e_{1,i,t}^{\rho_h} + (1 - \lambda_1^{oil}) e_{4,i,t}^{\rho_h})^{\frac{1}{\rho_h}} - O_{i,t} \right), \quad (27)$$

where $\hat{p}_{1,i,t}$ denotes the tax-inclusive price of conventional oil, with corresponding notation for the unconventional substitute.³² By construction, the Lagrange multiplier, $P_{i,t}^O$, defines the exact price index of the oil composite.

The first-order conditions for the problem defined in (27) yields

$$e_{j,i,t} = \frac{O_{i,t}}{2} \left(2 \lambda_j^{oil} \frac{P_{i,t}^O}{\hat{p}_{j,i,t}} \right)^{\frac{1}{1-\rho_h}}, \quad (28)$$

³²Note that assuming that all regions would have the same cost of producing unconventional oil products would be isomorphic to allowing global markets for “fracked” oil.

with $j \in \{1, 4\}$. Inserting (28) into the energy-service provider's expenditure function for oil goods, the exact price index for oil becomes

$$P_{i,t}^O = \frac{1}{2} \left((\lambda_1^{oil})^{\frac{1}{1-\rho_h}} \hat{p}_{1,i,t}^{\frac{\rho_h}{\rho_h-1}} + (1 - \lambda_1^{oil})^{\frac{1}{1-\rho_h}} \hat{p}_{4,i,t}^{\frac{\rho_h}{\rho_h-1}} \right)^{\frac{\rho_h-1}{\rho_h}}. \quad (29)$$

The second step is then to derive the demand functions for all fuels, which implies solving the following cost-minimization problem:

$$\min_{O_{i,t}, (e_{j,i,t})_{j=2}^n} P_{i,t}^O O_{i,t} + \sum_{j=2}^n \hat{p}_{j,i,t} e_{j,i,t} - \Lambda_{i,t} \left(\left(\lambda_1 O_{i,t}^\rho + \sum_{j=2}^n \lambda_j e_{j,i,t}^\rho \right)^{\frac{1}{\rho}} - E_{i,t} \right). \quad (30)$$

The first-order conditions deliver

$$O_{i,t} = \left(\lambda_1 \frac{P_{i,t}}{P_{i,t}^O} \right)^{\frac{1}{1-\rho}} E_{i,t}, \quad (31)$$

and

$$e_{j,i,t} = \left(\lambda_j \frac{P_{i,t}}{\hat{p}_{j,i,t}} \right)^{\frac{1}{1-\rho}} E_{i,t}, \quad j \in \{2, \dots, n\}. \quad (32)$$

The price index of energy services can then be shown to be given by

$$P_{i,t} = \left(\lambda_1^{\frac{1}{1-\rho}} (P_{i,t}^O)^{\frac{\rho}{\rho-1}} + \sum_{j=2}^n \lambda_j^{\frac{1}{1-\rho}} \hat{p}_{j,i,t}^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}}. \quad (33)$$

A.2 Calibration

The parameter values used in the main calibration of the model are given in Table 1.

Table 1: Calibration, common parameters

| Parameter | α | β | ν | ρ | ρ_h | λ_1^{oil} | R_0 |
|----------------------|-------------|---------------------|-------------|-------------|--------------|-------------------|----------|
| Value (multi region) | 0.30 | 0.985 ¹⁰ | 0.031 | -0.058 | 0.90 | 0.44 | 330 Gtoe |
| Value (one region) | 0.30 | 0.985 ¹⁰ | 0.031 | -0.058 | 0.90 | 0.44 | 300 Gtoe |
| Parameter | λ_1 | λ_2 | λ_3 | $p_{2,t}$ | $p_{3,t}$ | $p_{4,t}$ | |
| Value | 0.543 | 0.102 | 0.356 | US \$74/ton | US \$600/ton | US \$347/ton | |

We list the region-specific parameters in the regional model in Table 2; K_0 denotes the initial capital stock and the source for ϕ_1 and ϕ_2 is Nordhaus (2010).

Table 2: Calibration across regions

| | Initial TFP | K_0 | Linear ϕ_1 | Quadratic ϕ_2 | Regional γ |
|---------------|-------------|---------|--------------------|--------------------|-------------------|
| US | 52.7250 | 38.5336 | $0.000 * 10^{-2}$ | $0.1414 * 10^{-2}$ | $2.395 * 10^{-5}$ |
| EU | 52.7250 | 38.8080 | $0.000 * 10^{-2}$ | $0.1591 * 10^{-2}$ | $2.698 * 10^{-5}$ |
| China | 52.7250 | 39.2000 | $0.0785 * 10^{-2}$ | $0.1259 * 10^{-2}$ | $2.514 * 10^{-5}$ |
| Africa | 24.6050 | 12.3480 | $0.3410 * 10^{-2}$ | $0.1983 * 10^{-2}$ | $5.058 * 10^{-5}$ |
| India | 34.1050 | 20.0900 | $0.4385 * 10^{-2}$ | $0.1689 * 10^{-2}$ | $5.031 * 10^{-5}$ |
| South America | 24.6050 | 12.4460 | | | $2.57 * 10^{-5}$ |
| Oceania | 43.6050 | 29.2040 | | | $2.74 * 10^{-5}$ |