Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy

Lint Barrage*

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Abstract

How should carbon be taxed as a part of fiscal policy? The literature on optimal carbon taxes often abstracts from other taxes. However, when governments raise revenues with distortionary taxes, carbon levies have fiscal impacts. While they raise revenues directly, they may shrink the bases of other taxes (e.g., by decreasing employment). This paper theoretically characterizes and then quantifies optimal carbon tax schedules in a climate-economy model with distortionary fiscal policy. The macroeconomic setup is a dynamic general equilibrium model with linear taxation. The environmental setup uses the state-of-the-art representation of the carbon cycle and climate-economy feedbacks based on the DICE framework. First, this paper establishes a novel theoretical relationship between the optimal taxation of carbon and of capital income. This link arises because carbon emissions destroy natural capital: They accumulate in the atmosphere and decrease future output. Consequently, this paper shows how the standard logic against capital income taxes extends to environmental capital. Quantitatively, the welfare costs of distorting investment by taxing capital income or by *not* taxing carbon are both large ($30 and $40 trillion, respectively, $2005 lump-sum consumption equivalent). Second, this study demonstrates that optimal carbon taxes must internalize climate change production impacts (e.g., on agriculture) and direct utility impacts (e.g., on biodiversity existence value) differently. Third, this paper compares the setting with distortionary taxes to the setting with lump-sum taxes considered in the literature. The central quantitative finding is that optimal carbon tax schedules are $8\% - 30\%$ lower when there are distortionary taxes. This adjustment produces a global welfare gain of $190 billion to $2.8 trillion, depending on the structure of income taxes.

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1 Introduction

Raising revenues and addressing climate change are two fundamental challenges facing governments. This paper considers these tasks jointly. Specifically, I study the optimal design of carbon taxes both as an instrument to control climate change and as a part of fiscal policy.

The Intergovernmental Panel on Climate Change (IPCC) recently reiterated that "warming of the climate system is unequivocal," based on detailed reviews of the scientific literature (IPCC AR5 WG I, 2013). Moreover, "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC AR5 WG I, 2013). Climate change is expected to affect human welfare through numerous channels. These include changes in agricultural productivity, sea-level rise, ocean acidification, species extinctions, increased extreme weather events, disease vector changes, and others (IPCC AR4 WG II, 2007). The prices of carbon-based fuels do not currently reflect these external costs in all but a few countries.[1]

Both academic[2] and policy[3] studies of optimal carbon pricing often focus on this market failure as the only distortion in the economy. In such a setting, the optimal carbon tax is *Pigouvian*. This levy internalizes the environmental damage costs of carbon emissions.[4] However, theses studies do not consider potential interactions between carbon levies and other taxes.

Carbon levies, if implemented, will interact with existing tax policy (e.g., taxes on labor, capital income, and consumption). On the one hand, carbon taxes raise revenues directly. On the other hand, they may decrease revenues indirectly by shrinking the bases of other taxes. For example, if climate policy decreases employment, this will reduce the revenue benefits and exacerbate the welfare costs of labor taxes. Several studies using detailed computable general equilibrium models have found that the welfare costs of these fiscal interactions likely exceed the (non-environmental) revenue benefits of carbon taxes (Goulder, 1995; Bovenberg and Goulder, 1996; Jorgenson and Wilcoxen, 1996; Babiker, Metcalf, and Reilley, 2003; etc.). Bovenberg and Goulder (1996) consequently advocate taxing carbon below Pigouvian rates. However, these papers abstract from the environmental benefits of climate policy. That is, they do not consider feedback effects between the climate and the economy.

This paper theoretically characterizes and then quantifies optimal carbon tax schedules in an integrated assessment climate-economy model (IAM) with distortionary fiscal policy. I combine a dynamic general equilibrium model of the world economy that includes linear taxes with the seminal representation of the carbon cycle and climate-economy feedbacks based on the DICE

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[1] Countries with carbon taxes include Sweden, Finland, and Denmark (see Sumner, Bird, and Smith, 2009).

[2] Nordhaus (2008), Golosov, Hassler, Krusell, and Tsyvinski (2014), Acemoglu, Aghion, Bursztyn, and Hemous (2011), Hope (2011), Manne and Richels (2005), Anthoff and Tol (2013), etc.

[3] E.g., U.S. Interagency Working Group (2010).

[4] Specifically, the Pigouvian tax equals the social cost of carbon - the value of marginal damages from another ton of carbon emissions - evaluated at the optimal allocation.

framework (Nordhaus, e.g., 2008). Indeed, the DICE model is widely applied in the literature, and is one of the three IAMs used by the United States government to value the impacts of carbon dioxide emissions.[5] The three main findings of this paper are as follows.

First, I establish a novel theoretical relationship between the optimal taxation of carbon and of capital income. Intuitively, the climate is an asset used in production (e.g., of agriculture). Carbon emissions accumulate in the atmosphere and change the climate, with adverse effects on output. Giving up consumption to reduce emissions thus yields a future return of avoided production damages. In other words, the climate is an *environmental capital* good.[6] I show that setting carbon taxes below Pigouvian rates distorts incentives to invest in climate capital. This is analogous to capital income taxes, which create an intertemporal wedge for investments in physical capital. The first main result is as follows: If it is optimal to set capital income taxes to zero, then the optimal carbon tax fully internalizes production damages at the Pigouvian rate, even if labor markets are distorted. This is because both policies reflect the government's desire to leave intertemporal decisions undistorted. The literature on optimal dynamic Ramsey taxation has demonstrated the desirability of undistorted savings decisions in a wide range of models (Chamley, 1986; Judd, 1985; Atkeson, Chari, and Kehoe, 1999, Acemoglu, Golosov, Tsyvinski, 2011, etc.). My result shows that the logic against capital income taxes extends to environmental capital.

Second, I find that optimal carbon taxes must value climate damages that affect production differently from those that affect utility directly. Utility impacts reflect the value of the climate as a final consumption good (e.g., biodiversity existence value). Internalizing these damages yields no production gain and creates efficiency costs due to tax interactions. Consequently, I show that the optimal carbon tax does not fully internalize utility damages, taxing them below the Pigouvian rate. This result formally extends Bovenberg and Goulder's (1996) classic formulation to a dynamic setting with capital and carbon accumulation. Their formulation and much of the literature[7] on pollution control in the presence of distortionary taxes applies to environmental degradation that affects only utility. However, I find that the benchmark formulation does not extend to output damages.[8] This finding arises because of the climate's role as an input to production. A central result of optimal commodity taxation theory states that intermediate input usage should not be distorted, because such distortions reduce production efficiency (Diamond and Mirrlees, 1971). In line with this theorem, I find that output losses from climate change are

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[5] U.S. Interagency Working Group, 2010.

[6] The notion of the climate as environmental capital is standard in the literature (see, e.g., Nordhaus, 2010).

[7] E.g., Parry, Williams, and Goulder, 1999; Bovenberg and Goulder, 1996; Goulder, 1995; Bovenberg and de Mooij, 1994; Sandmo, 1975, etc.

[8] As discussed below, in a static setting, this result was previously demonstrated by Williams (2002) and Bovenberg and van der Ploeg (1994).

fully internalized through a Pigouvian tax in the benchmark setting.[9] Quantitatively, I argue that production impacts account for 75% of climate damages at $2.5°C$ warming. Consequently, I find that attributing all climate change impacts to direct utility losses leads to an underestimate of the optimal carbon tax by $9 - 14\%$, and to an overestimate of optimal peak temperature change by $0.2 - 0.25°C$.

Third, I use my model to compare optimal climate policy in the setting with distortionary taxes to the setting with lump-sum taxes considered in the literature. I find that the optimal carbon tax schedule is $8 - 30\%$ lower when there are distortionary taxes. Two effects of distortionary taxes explain this result. One, they decrease the size of the economy and hence the value of climate damages. Two, they alter the optimal carbon tax formulation to charge less than the full value of marginal damages. Optimal carbon prices start at $\$45 - 60$ per metric ton of carbon ($\$2005/mtC$) in 2015 and rise to $\$430 - 585/mtC$ by 2105. The upper end of this range reflects a full tax reform scenario, in which the government simultaneously optimizes over capital, labor, and carbon taxes. The lower end reflects a green tax reform scenario, in which capital and labor income taxes continue at suboptimal business-as-usual levels, but optimized carbon levies are added to the tax code.

These three results further relate to the literature in the following ways.

First, the carbon-capital tax link is a novel result, to the best of my knowledge. On the theory side, a rich literature has explored pollution taxes in a setting with distortionary taxes (reviewed by Bovenberg and Goulder, 2002).[10] However, this literature has predominantly focused on static models. As a result, few studies in this area have considered intertemporal distortions and their effects on dynamic processes, such as carbon or capital accumulation.[11] Schmitt (2013) studies optimal carbon levies in the presence of other taxes in a dynamic model; however he focuses on different aspects of the problem, such as the implications of limited committment. Several studies have also modeled pollution levies in endogenous growth settings with distortionary taxes

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[9] Intuitively, without a Pigouvian tax, the tradeoff between carbon-energy and climate inputs to production would be distorted. In other words, the Pigouvian tax precisely balances the reductions in the returns to investment and labor due to decreased energy inputs against the gains in productivity due to avoided climate change. For this reason, the internalization of production damages does not cause the same kind of tax interaction effect as the internalization of utility damages.

[10] This literature includes, inter alia: Sandmo (1975); Bovenberg and de Mooij (1994, 1997, 1998); Bovenberg and van der Ploeg (1994); Ligthart and van der Ploeg (1994); Goulder (1995; 1996; 1998); Bovenberg and Goulder (1996); Jorgenson and Wilcoxen (1996); Parry, Williams, and Goulder (1999); Goulder, Parry, Williams, and Burtraw (1999); Schwarz and Repetto (2000); Cremer, Gahvari, and Ladoux (2001; 2010); Williams (2002); Babiker, Metcalf, and Reilley (2003); Bernard and Vielle (2003); Bento and Jacobsen (2007); West and Williams (2007); Carbone and Smith (2008); Fullerton and Kim (2008); Parry and Williams (2010); d'Autume, Schubert, and Withagen (2011); Kaplow (2012); Carbone, Morgenstern, Williams and Burtraw (2013); Schmitt (2013); Goulder, Hafstead, and Williams (2014); etc.

[11] Chiroleu-Assouline and Fodhab (2006) formally link the welfare effects of general pollution taxes to capital accumulation in an overlapping generations model with distortionary taxes. However, their focus differs from the current study; they do not consider capital income taxation and do not solve for optimal policies.

(Fullerton and Kim, 2008; Bovenberg and de Mooij, 1997; Hettich, 1998; Ligthart and van der Ploeg, 1994). However, these papers again focus on somewhat different questions than this study,[12] and follow a correspondingly different approach. For example, these studies focus on outcomes along a balanced growth path, where environmental quality is constant. In the climate change setting, this would correspond to stabilized greenhouse gas concentrations. In contrast, I study carbon taxes and fiscal policy in the short- and medium-term during the transition to balanced growth. This approach builds on a wide literature that has studied environmental policy and optimal carbon taxation in dynamic general equilibrium growth models with capital accumulation (e.g., van der Ploeg and Withagen, 1991; 2012; Bovenberg and Smulders, 1996; Leach, 2009; Golosov, Hassler, Krusell, and Tsyvinski, 2014; Gerlagh and Liski, 2012; etc.). The central difference in this study is that I consider taxation of carbon jointly with taxation of capital and labor from the perspective of a government that needs to both raise revenues and address climate change at the same time.

On the quantitative side, the dynamic Ramsey tax literature has attributed large welfare costs to capital income taxes (e.g., Lucas, 1990). I estimate that the welfare costs of *failing* to tax carbon emissions and of taxing capital income are of a similar order of magnitude (up to \$30 trillion, and \$40 trillion, respectively, in \$2005 lump-sum consumption equivalent; or 1.1% and 1.4% permanent consumption increase, resectively).

Second, the distinction between production and utility damages relates to two sets of studies. On the theory side, Williams (2002) and Bovenberg and van der Ploeg (1994) previously established the need for this differentiation in a static setting.[13] These studies' results imply that production damages from pollution should generally be internalized with a Pigouvian tax. I provide conditions under which this result does and does not generalize to the dynamic setting. On the one hand, I show that this finding continues to hold for flow pollutants (i.e., pollutants which dissipate rapidly from the environment, such as sulfur dioxide). On the other hand, for accumulative pollutants such as carbon, this result does not hold if capital income is taxed. I consider two cases where the government taxes capital income, and show that Pigouvian levies on production damages are not optimal in those settings. My analysis thus theoretically extends and empirically quantifies the importance of these papers' findings for the optimal dynamic taxation of carbon emissions.

On the quantitative side, several climate-economy models aggregate all damages into pure output losses (e.g., the DICE model, Nordhaus, 2008; Golosov, Hassler, Krusell, and Tsyvinski, 2014; Leach, 2009; Cai, Judd, and Lontzek, 2012), pure utility losses (Acemoglu, Aghion,

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[12] For example, they study the very long run effects of pollution taxes on growth rates. I take the rate of technological progress as given.

[13] In a dynamic optimal fiscal policy model, Judd (1999) provides an analogous insight for optimal levels of public spending that enter utility and production, respectively.

Bursztyn, and Hemous, 2011), or into market and non-market impacts (e.g., MERGE, Manne and Richels, 2005; PAGE, Hope, 2011, 2006; Tol, 1997). The latter is close but not identical to a separation of utility and production effects. In a setting without distortionary taxes, these separations make no difference for optimal climate policy under certain conditions (Gars, 2012). However, for an analysis of carbon taxes as a part of fiscal policy, the separation of output and utility damages is essential. To this end, I disaggregate the regional-sectoral damage estimates from the DICE model (Nordhaus, 2008) accordingly. I further add a new damage function component to capture long-term labor productivity effects of malaria exposure. The results suggest that approximately 75% of climate change impacts from 2.5° warming affect production; 25% affect utility directly.

Third, the quantitative results build on two branches of the literature. On the one hand, several studies have employed highly detailed multi-sector dynamic computable general equilibrium models to assess the welfare impacts of carbon levies in economies with distortionary taxes (e.g., Goulder, 1995; Bovenberg and Goulder, 1996; Jorgenson and Wilcoxen, 1996; Babiker, Metcalf, and Reilley, 2003; Bernard and Vielle, 2003; Carbone, Morgenstern, and Williams, 2012). Several of these studies provide welfare comparisons across different carbon tax revenue recycling regimes (e.g., reducing labor income taxes versus capital income taxes). However, these studies abstract from the environmental benefits of climate policy. On the other hand, existing estimates of optimal carbon prices from integrated assessment climate-economy models do not consider interactions with distortionary taxes.

More broadly speaking, this paper also relates to (i) studies on environmental regulation alongside pre-existing distortions that arise not from taxes but from market power (e.g., Ryan, 2012), (ii) the literature emphasizing the importance of climate-related factors for macroeconomic outcomes (e.g., Dell, Jones, and Olken, 2012), and (iii) applied studies which integrate environment-economy feedbacks from pollution into general equilibrium models with distortionary taxes (Carbone and Smith, 2008; Ballard and Medema, 1993).

How important is it to consider other taxes in climate policy design? I contrast the welfare gains from imposing optimized carbon levies with those of climate policy that ignores distortionary tax interactions.[14] Adjusting carbon taxes to account for their fiscal impacts yields an estimated welfare gain of $190 billion to $2.8 trillion ($2005 lump-sum consumption equivalent).

There are, of course, many caveats that apply to the presented analysis. In particular, the model is based on a highly simplified representation of the global economy and fiscal policy. However, optimizing integrated assessment climate-economy models necessarily represent the world in simplified terms. Though imperfect, they are the best available tool to value the welfare impacts of carbon dioxide emissions. Indeed, the United States government uses the DICE

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[14] Specifically, this policy imposes carbon taxes that would be optimal if there were no distortionary taxes.

model for this purpose (U.S. Interagency Group, 2010), and this is the framework upon which I build. While my model certainly does not match the sectoral and fiscal detail of country-specific CGE models used in previous work on carbon tax interactions with fiscal policy (e.g., Goulder, 1995), it instead provides the first formal integration of distortionary taxes in an integrated assessment climate-economy model. This framework enables me to consider climate-economy feedback effects, as well as to solve for optimal temperature, emissions, and tax paths.

I structure the remainder of this paper as follows. Section 2 describes the core model. Section 3 provides the benchmark setting theory results. The calibration and further additions to the quantitative model are outlined in Section 4. Section 5 discusses the quantitative results. Section 6 considers extensions to settings with capital income taxation and non-renewable energy resources. Finally, Section 7 concludes.

2 Model

This section describes the setup of the core version of the model. It is kept as simple as possible to maximize analytic transparency. Both subsequent theoretical extensions and the quantitative model expand upon this basic structure. A brief summary of the theoretical framework is as follows. The model essentially combines the climate-economy structure of Golosov, Hassler, Krusell, and Tsyvinski (GHKT) (2014) with an optimal dynamic taxation model in the Ramsey tradition (see, e.g., Chari and Kehoe, 1999). Following GHKT, I assume an infinitely-lived, representative household. An important difference to GHKT is that agents have preferences not only over consumption, but over leisure and climate change as well. There are two production sectors. The aggregate final consumption-investment good is produced using capital, labor, and energy inputs. Climate change affects productivity in this sector. A carbon-based energy input is produced from capital and labor. Energy use causes greenhouse gas emissions, which accumulate and lead to climate change. Importantly, I incorporate an exogenous government revenue requirement, following the standard Ramsey approach.[15] In contrast, the government in GHKT does not need to raise revenues to finance public expenditures. Later on, I consider exogenous social transfer spending obligations as well. The key assumption of this literature is that the government must resort to distortionary taxes because lump-sum (non-distortionary) taxes are not available for reasons outside of the model.[16] The revenues raised from Pigouvian carbon taxes are assumed to be insufficient to meet government revenue needs. Otherwise, there

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[15] In contrast, Cremer, Gahvari, and Ladoux (2001; 2010) study optimal environmental taxes in a (static) Mirrleesian optimal taxation setting.

[16] One can point to several examples in recent history where governments' attempts to impose lump-sum taxes were met with intense political resistance. For example, an estimated 50% of Irish homeowners refused to pay the $133 flat-rate property tax imposed by the Irish government in January 2012 (Dalby, 2012).

would be no need for distortionary taxes, and the analysis would revert to the first-best setting considered by GHKT.

Households

An infinitely-lived, representative household has preferences over consumption C_t, labor supply L_t, and a climate change variable T_t. Integrated assessment models vary in the set of climate indicators they consider (see review by Tol and Frankenhauser, 1997). I follow the common approach of using *mean global surface temperature change* over pre-industrial levels, T_t, as a sufficient statistic for climate change. Households and firms take temperature change as given. That is, climate change is an externality. Households maximize lifetime utility U_0 :

$$U_0 \equiv \sum_{t=0}^{\infty} \beta^t U(C_t, L_t, T_t) \tag{1}$$

I generally assume that environmental quality enters preferences additively separably from consumption and leisure:

$$U(C_t, L_t, T_t) = h(C_t, L_t) + v(T_t) \tag{2}$$

The literature on pollution tax interactions with distortionary taxes commonly assumes weak separability. In the Online Appendix, I show that relaxing assumption (2) does not change the main theoretical insights of this paper, which pertain to the differential and optimal dynamic taxation of output and utility climate change impacts. However, assuming separability could bias the optimal *total* carbon tax estimate upwards or downwards. This bias depends on whether temperature change is a relative complement or substitute to leisure (see, e.g., Schwartz and Repetto, 2000). Intuitively, this result goes back to the Corlett and Hague (1953) rule that goods which are relative complements to leisure should be taxed relatively more. The potential quantitative importance of non-separability for enviornmental policy design has been demonstrated, for example, by Carbone and Smith (2008) in the context of particulate matter pollution in the United States. Unfortunately, the literature provides very little empirical evidence on the likely magnitudes and signs of the relative complementarity between climate change and leisure and consumption.[17] For this reason, and since the main theoretical results are robust to this issue, I abstract from non-separabilities.

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[17] Existing work on the amenity value of the climate by Nordhaus (1998), and research by Neidell and Zivin (2010) on labor time changes due to weather shocks both suggest small overall impacts.

Each period, the representative household faces the following flow budget constraint:

$$C_t + \rho_t B_{t+1} + K_{t+1} \leq w_t(1-\tau_{lt})L_t + \{1 + (r_t - \delta)(1-\tau_{kt})\} K_t + B_t + \Pi_t \tag{3}$$

where B_{t+1} denotes one-period government bond purchases, ρ_t the price of one-period bonds, K_{t+1} the household's capital holdings in period $t+1$, w_t the gross wage, τ_{lt} linear taxes on labor income, τ_{kt} linear taxes on capital income, r_t the return on capital, δ the depreciation rate, and Π_t profits from energy production. I place several restrictions on these variables. First, capital holdings cannot be negative. The consumer's debt is bounded by some finite constant M via $B_{t+1} \geq -M$. Similarly, purchases of government debt are bounded above and below by finite constants. Finally, initial asset holdings B_0 are given.

The household's first order conditions imply that savings and labor supply decisions are governed by the standard rules, respectively:

$$\frac{U_{ct}}{U_{ct+1}} = \beta \{1 + (r_{t+1} - \delta)(1-\tau_{kt+1})\} \tag{4}$$

$$\frac{-U_{lt}}{U_{ct}} = w_t(1-\tau_{lt}) \tag{5}$$

where U_{it} denotes the partial derivative of utility with respect to argument i at time t. In words, the Euler equation (4) states that households equate their marginal rate of substitution between consumption in periods t and $t+1$ to the after-tax return on saving between periods t and $t+1$. Similarly, the implicit labor supply equation (5) states that agents equate their marginal rate of substitution between consumption and leisure to the after-tax return on working.

Final Goods Production

There are two production sectors: a final consumption-investment good (with input variables indexed by "1") and energy (with input variables indexed by "2"). The consumption-investment good is produced by a technology $\widetilde{F_{1t}}$ which features constant returns to scale in energy E_t, labor L_{1t}, and capital K_{1t} inputs, and satisfies the standard Inada conditions. Output Y_t further depends on temperature change T_t and an exogenous technology parameter A_t :

$$\begin{aligned} Y_t &= (1-D(T_t)) \cdot A_{1t}\widetilde{F_{1t}}(L_{1t}, K_{1t}, E_t) \qquad (6) \\ &= F_{1t}(T_t, L_{1t}, K_{1t}, E_t) \qquad (7) \end{aligned}$$

The formulation of climate damages as fraction of output lost in (6) was pioneered by Nordhaus

(1991) and is extensively used in the literature.[18,19] A common approach is to monetize all types of damages, including ones that do not literally affect production of consumption goods (e.g., biodiversity existence value), and to subtract those costs from output as in (6). However, in a setting with distortionary taxes, differentiation between climate damages that affect physical production possibilities and those that do not is important. In the current study, formulation (6) thus represents only literal production effects of climate change. These impacts are expected to occur because the final consumption good represents an aggregate of many goods that rely on the climate as productive input, such as agriculture, energy, fisheries, forestry products, skiing services, etc. Section 4.3 discusses this distinction in more detail.

Final goods producers choose factor inputs in competitive markets so as to equate their marginal products with their prices:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{8}$$

where F_{1it} denotes the partial derivative of the final goods production function (7) with respect to input i at time t.

Energy Production

The baseline model assumes that carbon-based energy can be produced from capital K_{2t} and labor L_{2t} inputs through a constant returns to scale technology:

$$E_t = A_{2t}F_{2t}(K_{2t}, L_{2t}) \tag{9}$$

Hotelling rents (pure profits) from energy production are then given by:

$$\Pi_t = (p_{Et} - \tau_{Et})E_t - w_tL_{2t} - r_tK_{2t} \tag{10}$$

The constant returns to scale formulation (9) assumes that carbon energy is in unlimited supply and therefore has zero Hotelling rents. As argued by GHKT (2014), this is a reasonable assumption for coal. Section 6.2 extends the theoretica model to consider non-renewable carbon energy. If preferences are of a certain commonly used constant elasticity forms, the key theoretical re-

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[18] Climate impacts can, of course, be positive for certain regions and ranges of temperature change. Indeed, the calibration of $D(T_t)$ used below follows Nordhaus and Boyer (2000) in assuming positive overall impacts from 2.5° warming for Russia. See also Tol (2002).

[19] Rezai, van der Ploeg, and Withagen (2012) study the implications of *additive* production damages.

sults of the paper are unaltered by this extension. However, an important difference is that an additional term may be added into the optimal carbon tax formulation if the government cannot impose full Hotelling profits taxes. This carbon tax premium is used to indirectly tax Hotelling rents from non-renewable energy production.

The quantitative version of the model also incorporates the possibility of clean energy production (emissions abatement technologies).

I assume that both labor and capital are mobile across sectors, implying market clearing conditions:

$$\begin{aligned} L_t &= L_{1t} + L_{2t} \\ K_t &= K_{1t} + K_{2t} \end{aligned} \tag{11}$$

This assumption is in line with GHKT (2014). Due to the 10 year time step used in the empirical model, formulation (11) is also more realistic than in an annual formulation. An important implication of (11) is that factor prices will be equated across sectors in equilibrium. Competitive energy producers thus equate marginal factor products and prices:

$$\begin{aligned} (p_{Et} - \tau_{Et}) F_{2lt} &= w_t \\ (p_{Et} - \tau_{Et}) F_{2kt} &= r_t \end{aligned} \tag{12}$$

Government

As is standard in the Ramsey approach to optimal taxation, I assume that the government needs to finance an exogenously given sequence of positive revenue requirements $\{G_t > 0\}_{t=0}^{\infty}$, and to pay off inherited debt B_0^G. The government can issue new, one-period bonds B_{t+1}^G and levy linear taxes on labor and capital income. In addition, the government can impose excise taxes τ_{Et} on carbon emissions E_t.[20] The consumption good serves as the untaxed numeraire. The government's flow budget constraint each period is given by:

$$G_t + B_t^G = \tau_{lt} w_t L_t + \tau_{Et} E_t + \tau_{kt}(r_t - \delta) K_t + \rho_t B_{t+1}^G \tag{13}$$

Market clearing requires that consumer demand and government supply for bonds be equated:

$$B_{t+1}^G = B_{t+1} \tag{14}$$

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[20] Energy is denoted in units of carbon content. One unit of energy thus emits one ton of carbon.

Carbon Cycle

The only assumption placed on the carbon cycle at this stage is that temperature change T_t at time t is some function of initial carbon concentrations S_0 and all past carbon emissions:

$$T_t = \digamma_t \left(S_0, E_0, E_1, ..., E_t\right) \tag{15}$$

where:

$$\frac{\partial T_{t+j}}{\partial E_t} \geq 0 \ \forall j, t \geq 0$$

Competitive Equilibrium

Competitive equilibrium ("CE") in this economy can now be formally defined as follows:

Definition 1 *A competitive equilibrium consists of an allocation* $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, T_t\}$*, a set of prices* $\{r_t, w_t, p_{Et}, \rho_t\}$ *and a set of policies* $\{\tau_{kt}, \tau_{lt}, \tau_{Et}, B^G_{t+1}\}$ *such that*

(i) the allocations solve the consumer's and the firm's problems given prices and policies,
(ii) the government budget constraint is satisfied in every period,
(iii) temperature change satisfies the carbon cycle constraint in every period, and
(iii) markets clear.

The most important difference to the standard definition is the addition of the carbon cycle constraint. All variables pertaining to energy production and temperature change are also different from the standard setup in Chari and Kehoe (1999).

The Ramsey tax framework assumes that the government seeks to maximize the representative agent's lifetime utility (1) subject to the constraints of (i) feasibility and (ii) the optimizing behavior of households and firms. Note that I assume throughout that the government can commit to a sequence of tax rates at time zero. Given the potential for time inconsistency problems with regards to capital taxation in a closed economy, this is not an innocuous assumption. However, with regards to optimal carbon taxes in the presence of other taxes, Schmitt (2013) finds that the quantitative differences between committment and Markov-perfect equilibrium without committment are small, due to counterveiling differences across the scenarios.

In the current framework, the optimal allocation - the Ramsey equilibrium - can now be formally defined for a given initial level of debt B_0, an initial level of capital K_0, an initial capital tax $\overline{\tau_{k0}}$, and initial carbon concentration S_0 :

Definition 2 *A Ramsey equilibrium is the CE with the highest household lifetime utility for a given initial bond holdings* B_0*, initial capital* K_0*, initial capital tax* $\overline{\tau_{k0}}$*, and initial carbon concentrations* S_0*.*

I characterize the optimal allocations using the primal approach. By solving for optimal *allocations*, rather than for optimal tax rates, this method avoids normalization issues (see, e.g., Williams, 2001). Intuitively, optimal tax rates depend on the choice of numeraire, whereas optimal allocations do not. The validity of the primal approach setup in this context requires the following proposition:

Proposition 1 *The allocations* $\{C_t, L_{1t}, L_{2t}, K_{1t+1}, K_{2t+1}, E_t, T_t\}$, *along with initial bond holdings* B_0, *initial capital* K_0, *initial capital tax* $\overline{\tau_{k0}}$, *and initial carbon concentrations* S_0 *in a competitive equilibrium satisfy:*

$$Y_t + (1-\delta)K_t \leq C_t + G_t + K_{t+1} \tag{RC}$$

$$T_t \geq \digamma_t(S_0, E_0, E_1, ...E_t)] \tag{CCC}$$

$$E_t \leq F_{2t}(A_{Et}, K_{2t}, L_{2t}) \tag{ERC}$$

$$L_{1t} + L_{2t} \leq L_{2t} \tag{LC}$$

$$K_{1t} + K_{2t} \leq K_t \tag{KC}$$

and

$$\sum_{t=0}^{\infty} \beta^t \left[U_{ct}C_t + U_{lt}L_t\right] = U_{c0}\left[K_0\left\{1 + (F_{k0} - \delta)(1 - \tau_{k_0})\right\} + B_0\right] \tag{IMP}$$

In addition, given an allocation that satisfies (RC)-(IMP), one can construct prices, debt holdings, and policies such that those allocations constitute a competitive equilibrium.

Proof: Online Appendix. This proposition and its proof differ from the standard setup in Chari and Kehoe (1999) mainly through the addition of the energy production sector and the carbon cycle constraint. In words, Proposition 1 ensures that any allocation satisfying the six conditions (RC)-(IMP) can be decentralized as a competitive equilibrium. I assume that the solution to the Ramsey problem is interior and that the planner's first order conditions are both necessary and sufficient. Formally, the government's problem is thus to maximize household lifetime utility (1) subject to the constraints (RC)-(IMP) required to ensure that the chosen allocation is both technologically feasible and consistent with competitive equilibrium:

$$\begin{aligned}
&\max_{k}\sum_{t=0}^{\infty}\beta^{t}[\underbrace{U(C_t, L_t, T_t) + \phi\left[U_{ct}C_t + U_{lt}L_t\right]}_{\equiv W_t}] \\
&-\phi\left\{U_{c0}\left[K_0\left\{1 + (F_{k0} - \delta)(1 - \tau_{k_0})\right\}\right]\right\} \\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{1t}\left[\left\{A_t(T_t)\widetilde{F_{1t}}(L_{1t}, E_t, K_{1t})\right\} + (1-\delta)K_t - C_t - G_t - K_{t+1}\right] \\
&+\sum_{t=0}^{\infty}\beta^{t}\xi_t[T_t - \digamma_t(S_0, E_0, E_1, ...E_t)] \\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{lt}\left[L_t - L_{1t} - L_{2t}\right] \\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{kt}\left[K_t - K_{1t} - K_{2t}\right] \\
&+\sum_{t=0}^{\infty}\beta^{t}\omega_t\left[F_{2t}(A_{Et}, K_{2t}, L_{2t}) - E_t\right]
\end{aligned} \tag{16}$$

Note that (16) follows the common approach of splitting the implementability constraint into its time-zero and lifetime summation components, and including the latter in the maximand. Before describing the results, define the following two concepts.

The Marginal Cost of Public Funds The marginal cost of public funds (MCF) measures the welfare cost of raising an additional dollar of government revenue. Lump-sum taxes are pure transfers: households give up \$1 to increase government revenue by \$1. Consequently, the MCF in a setting with lump-sum taxes is equal to one. In contrast, raising \$1 in revenue from distortionary taxes costs households \$1 *plus* the excess burden (or the marginal deadweight loss) created by the distortionary tax increase. The Online Appendix summarizes empirical estimates from the literature. The GDP-weighted global average across countries and tax instruments from these studies is 1.48, implying that \$0.48 cents of welfare are lost for every \$1 of government revenue raised on average.[21] I follow the standard approach in the literature on pollution tax interactions with other taxes of defining the MCF as follows:

Definition 3 *Let the Marginal Cost of Public Funds ("MCF") be defined as the ratio of the*

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[21] A caveat to pooling these estimates is that the precise definitions of the MCF, the marginal excess burden, and the marginal deadweight loss can vary across studies (see discussions by Dahlby, 2008; Fullerton, 1991; Triest, 1990; Snow and Warren, 1996).

public marginal utility of consumption to the private marginal utility of consumption:

$$MCF \equiv \frac{\lambda_{1t}}{U_{ct}} \tag{17}$$

The MCF thus measures the welfare cost of transferring a unit of the consumption good from households to the government.[22]

Pigouvian Carbon Taxes

Definition 4 *Let the Pigouvian carbon tax be defined as the present value of marginal damages evaluated at the optimal allocation, and valued at the agent's marginal utility of consumption. More formally, the Pigouvian tax to internalize climate damages to production and utility, respectively, is given by:*

$$\text{Production damages: } \tau_{Et}^{Pigou,Y} \equiv (-1)\sum_{j=0}^{\infty}\beta^j \frac{U_{ct+j}}{U_{ct}}\left[\frac{\partial Y_{t+j}}{\partial T_{t+j}}\frac{\partial T_{t+j}}{\partial E_t}\right] \tag{18}$$

$$\text{Utility damages: } \tau_{Et}^{Pigou,U} = (-1)\sum_{j=0}^{\infty}\beta^j \frac{U_{Tt+j}}{U_{ct}}\left[\frac{\partial T_{t+j}}{\partial E_t}\right] \tag{19}$$

where $\frac{\partial Y_{t+j}}{\partial T_{t+j}}$ is the marginal production loss from temperature change at time $t+j$, U_{Tt+j} denotes the marginal utility loss from temperature change at time $t+j$, and $\frac{dT_{t+j}}{dE_t}$ is the change in temperature at time $t+j$ caused by a marginal increase in today's carbon emissions dE_t. The key differentiating feature between production and utility damages is that production damages alter the economy's production possibility frontier (PPF). Conversely, utility damages affect welfare but leave production possibilities unchanged.

The Pigouvian tax is thus defined in the standard way as the present value of marginal environmental damages, evaluated at the optimal allocation. Focusing on production impacts, GHKT (2014) show that (18) defines the optimal carbon tax in their setting without distortionary taxes. The Pigouvian tax also equals the social cost of carbon (SCC) if the SCC is evaluated at the optimal level of emissions.[23]

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[22] The Online Appendix derives a general expression for the MCF at time t, and one for the MCF along a balanced growth path for the functional forms used in the quantitative version of the model. However, even in the latter case one cannot express the long-run MCF in closed form. This is because the long-run MCF depends on endogenous fiscal variables such as the optimal long-run labor income tax rate, which depends on the history of tax rates and government revenues collected. For studies that link expressions of the MCF to various income and price elasticities, see, e.g., Atkinson and Stiglitz (1980), Bovenberg and Goulder (1996), Williams (2002), and Parry and Bento (2000).

[23] Studies on the SCC differ on whether they consider the marginal impact of carbon emissions at optimal or current emissions levels (see, e.g., Pearce, 2003).

3 Theory Results

Taken together, the planner's first order conditions for consumption C_t, aggregate capital savings, K_{t+1}, and final goods production capital K_{1t} imply that, for $t > 0$,

$$\frac{W_{ct}}{W_{ct+1}} = \frac{\lambda_{1t}}{\lambda_{1t+1}} = \beta \left[F_{kt+1} + (1 - \delta) \right] \tag{20}$$

Comparison of (20) with the representative agent's Euler equation (4) demonstrates the well-known result (e.g., Atkeson, Chari, and Kehoe, 1999) that it is optimal to set effective tax capital income taxes at $t + 1$ to zero whenever:

$$\frac{\lambda_{1t}}{\lambda_{1t+1}} = \frac{U_{ct}}{U_{ct+1}} \tag{21}$$

I discuss optimal carbon tax schedules in three separate cases: If climate change affects welfare (1) only through production impacts, (2) only through direct utility losses, and (3) through both types of damages.

Case 1: Climate Change Affects Only Production

Consider first the setting where climate change affects only production. Combining the planner's first order conditions from problem (16) for emissions E_t, temperature change T_t, and the labor allocation to energy production L_{2t} implies that, for $t > 0$,

$$F_{Et} + \sum_{j=0}^{\infty} \beta^j \left[\frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}} \right] \frac{dT_{t+j}}{dE_t} = \frac{F_{1lt}}{F_{2lt}} \tag{22}$$

Expression (22) equates the social marginal costs and benefits of carbon energy input usage. The benefits consist of the marginal product of energy in final goods production, F_{Et}, minus the sum of future production losses $\left(\frac{\partial Y_{t+j}}{\partial T_{t+j}} \right)$ due to the additional climate change resulting from time t carbon emissions $\left(\frac{dT_{t+j}}{dE_t} \right)$. Note that the planner values future production losses at the public value of output in each time period, λ_{1t+j}. The private marginal cost of carbon energy is simply the production cost expressed in units of the final consumption good $\left(\frac{F_{1lt}}{F_{2lt}} \right)$.

What carbon tax τ_{Et} can decentralize (22)? Substituting for equilibrium prices in (22) based on the producers' first order conditions (8) and (12), and rearranging immediately yields the following result. The carbon price in period $t > 0$ that decentralizes the optimal allocation, provided that all other prices and taxes are set appropriately, is implicitly defined by:

$$\tau^*_{Et} = (-1) \sum_{j=0}^{\infty} \beta^j \left[\frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}} \right] \frac{dT_{t+j}}{dE_t} \tag{23}$$

Expression (23) captures the social cost of carbon energy usage. Intuitively, this value embodies the difference between the social and private marginal cost of carbon energy, and thus represents the optimal carbon tax. The first result follows immediately.

Proposition 2 *If the government optimally sets capital income taxes to zero from period* $t+1$ *onwards, then the optimal carbon tax to internalize production damages at time* $t > 0$ *is the Pigouvian tax.*

Proof. First, for all $j \geq 1$, multiply the $t + j^{th}$ term in the sum of (23) by:

$$\left(\prod_{m=1}^{j-1} \frac{\lambda_{1t+m}}{\lambda_{1t+m}} \right) = 1$$

Each term $\frac{\lambda_{1t+j}}{\lambda_{1t}}$ can then be rearranged to equal $\left(\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}} \frac{\lambda_{1t+j-1}}{\lambda_{1t-2}} ... \frac{\lambda_{1t+1}}{\lambda_{1t}} \right)$.

Second, note that the optimality of zero capital income taxes from period $t+1$ onwards implies that condition (21) must be satisfied for all $t+j$, $j \geq 1$. That is, for all $j \geq 1$,

$$\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}} = \frac{U_{ct+j}}{U_{ct+j-1}} \tag{24}$$

Third, repeatedly use (24) to substitute out for all $\frac{\lambda_{1t+j}}{\lambda_{1t+j-1}}$ terms in the sum on the right-hand side of (23), which then becomes:

$$\tau^*_{Et} = (-1) \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{ct+j}}{U_{ct}} \frac{\partial Y_{t+j}}{\partial T_{t+j}} \right] \frac{dT_{t+j}}{dE_t} = \tau^{Pigou,Y}_{Et} \tag{25}$$

Finally, comparison with the definition of the Pigouvian tax (18) demonstrates the desired result. Note that no manipulation of the $j = 0$ term in the summation is necessary because $(\lambda_{1t}/\lambda_{1t} = U_{ct}/U_{ct} = 1)$ regardless of whether condition (21) is satisfied. ■

The intuition for this result is twofold, and can be summarized as follows. First, the climate is an asset used in production (e.g., of agriculture), analogous to physical capital. Second, pricing carbon emissions at less-than-Pigouvian rates is conceptually equivalent to taxing climate capital investments. Consequently, the economic factors that make it desirable for the government to leave households' physical capital investments undistorted likewise make it desirable to leave investments in environmental capital undistorted. This requires precisely a Pigouvian tax.[24]

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[24] The necessary conditions required for intertemporal wedges to be optimally set to zero, (24), also impiles

To make these points more concrete, briefly consider a simplified two period version of the model. The marginal rate of transformation (MRT) between consumption in the two periods based on investment in physical capital is given by:

$$MRT^{K}_{0,1} = \frac{\text{Give up 1 unit of } C_0 \text{ to invest in capital}}{\text{Get } (F_{k1}{+}(1-\delta)) \text{ units of } C_1 \text{ tomorrow:}} = \frac{-1}{F_{k1}+1-\delta}$$

An *undistorted intertemporal margin* requires that this $MRT^{K}_{0,1}$ be equated with the household's marginal rate of substitution (MRS) between consumption in the two periods:

$$MRS_{0,1} = MRT^{K}_{0,1} \tag{26}$$

$$\frac{\beta U_{c1}}{U_{c0}} = \frac{1}{F_{k1}+1-\delta} \tag{27}$$

Implementing the allocation (27) requires a zero effective capital income tax. However, the key issue in this economy is that there is an additional technology for converting C_0 into C_1: investments in climate capital.[25] Specifically, assume initial period carbon emissions E_0 are reduced by one unit. In terms of the initial period consumption good, this will create a loss of F_{E0}, the marginal product of energy. However, it will also save marginal energy production costs MC. The net loss of C_0 associated with the emissions reduction is thus $F_{E0} - MC$.[26] The return on this investment is avoided output losses from climate change in the next period. Specifically, the gain in terms of C_1 is the additional output from marginally lower temperature change $(\partial Y_1/\partial T_1)$, multiplied by the actual decrease in temperature change achieved by the reduction in E_0 $(\partial T_1/\partial E_0)$. In sum, the MRT based on investments in climate capital is given by:

$$MRT^{\text{Climate}}_{0,1} = \frac{\text{Reduce } E_0 \text{ by 1 unit} \rightarrow \text{Give up } F_{E0}-MC \text{ units of } C_0}{\text{Get } (\partial Y_1/\partial T_1)(\partial T_1/\partial E_0) \text{ units of } C_1} = \frac{F_{E0}-MC}{(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)}$$

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that the MCF is constant across time. An alternative way of stating this result is thus that the optimal carbon tax to internalize production damages from climate change in period $t > 0$ is the Pigouvian tax if the MCF is optimally constant across time from period $t+1$ onwards. Intuitively, a constant MCF again corresponds to no intertemporal distortions. I thank Francois Salanié for pointing this out.

[25] The general idea that investment in natural capital should be considered as part of a portfolio problem along with physical capital has been formalized in many previous studies (e.g., Bovenberg and Smulders, 1996; Fullerton and Kim, 2008; see also Nordhaus, 2010, discussing the climate as natural capital stock).

[26] This illustration assumes no contemporaneous climate change impacts.

Equating the household's MRS with this second MRT yields:

$$MRS_{0,1} \quad = \quad MRT_{0,1}^{\text{Climate}} \tag{28}$$

$$\frac{\beta U_{c1}}{U_{c0}} \quad = \quad \frac{F_{E0} - MC}{(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)} \tag{29}$$

What carbon tax decentralizes (29)? Multiplying both sides by $(\partial Y_1/\partial T_1)(\partial T_1/\partial E_0)$ immediately demonstrates that *an undistorted intertemporal margin for climate capital investments requires precisely a Pigouvian tax on carbon:*

$$\frac{\beta U_{c1}}{U_{c0}} \left(\frac{\partial Y_1}{\partial T_1} \frac{\partial T_1}{\partial E_0} \right) = F_{E0} - MC = \tau_{E0}^{Pigou}$$

Here, the second equality follows because (i) competitive factor pricing implies that $F_{E0} = p_{E0}$ in equilibrium (see (8)), and (ii) the energy sector produces carbon up until the point where $(p_{Et} - \tau_{Et}) = MC$ (see (12)).

The literature on optimal dynamic Ramsey taxation has found that capital income taxes are undesirable in wide range of models and settings (see, e.g., Chamley, 1985; Judd, 1986; Atkeson, Chari, and Kehoe, 1999; Acemoglu, Golosov, and Tsyvinski, 2011). A number of studies have explored the implications of this result for human capital taxation (Judd, 1999; Jones, Manuelli, and Rossi, 1993, 1997). Proposition 3 demonstrates that the logic against capital income taxes further extends to environmental capital. Indeed, in the current setting, the well-known example of constant elasticity preferences discussed below gives rise to both zero optimal capital income taxes after the first period (see, e.g., Chari and Kehoe, 1999) and to the optimality of Pigouvian carbon taxes to internalize production damages:

Corollary 5 *If preferences are of either commonly used constant elasticity form,*

$$U(C_t, L_t) \quad = \quad \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) \tag{30}$$

$$U(C_t, L_t) \quad = \quad \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} \tag{31}$$

then:

(i) the optimal capital income tax in period $t > 0$ is zero, and:

(ii) the optimal carbon tax to internalize production damages in period $t > 0$ is Pigouvian:

$$\tau_{Et}^{*} = \tau_{Et}^{Pigou,Y}$$

Both results follow from the fact that preferences of forms (30) or (31) imply that $\frac{\lambda_{1t+1}}{\lambda_t} = \frac{U_{ct+1}}{U_{ct}}$ for all $t > 0$. As discussed above, comparison of the planner's intertemporal optimality conditions (20) with the representative agent's Euler equation (4) demonstrate that the optimal allocation is implemented by zero capital income taxes in period $t > 0$. Similarly, the optimality of the Pigouvian carbon tax to internalize production damages whenever $\frac{\lambda_{1t+j}}{\lambda_t} = \frac{U_{ct+j}}{U_{ct}} \forall j \geq 0$ was established in the proof of Proposition 2. To summarize, Corollary 5 provides concrete conditions under which capital income taxes are optimally zero and carbon taxes are optimally Pigouvian.

In reality, most countries do impose capital income taxes (Piketty and Saez, 2012; Mankiw, Weinzierl, and Yagan, 2009.). A natural follow-up question to Proposition 2 is thus: What is the optimal structure of carbon taxes in an economy where capital taxes are not zero? Perhaps surprisingly, the answer can depend on the underlying reason *why* capital taxes are positive. In Section 6.1, I analyze two extensions of the core model that involve positive capital income taxes and affect carbon tax schedules differently.

First, with an upper bound on capital income tax rates, the government sets capital income taxes at this upper bound for a finite number of periods and eventually decreases them to zero. In this setting, carbon taxes to internalize output damages are lower than Pigouvian rates for as long as capital income taxes remain positive.

Second, with an exogenous constraint that capital income tax rates be fixed at some positive level, carbon taxes to internalize output damages may be adjusted upwards or downwards relative to Pigouvian rates. The adjustment depends in part on the impact of output damages on the tightness and direction with which the capital income tax constraint binds.

There are other modifications of the basic Ramsey setup and fundamentally different models of taxation that imply the desirability of capital income taxes (see, e.g., Golosov, Kocherlakota, and Tsyvinski, 2003; Erosa and Gervais, 2002, etc.). Integrating climate capital into these models and exploring optimal carbon taxes in those frameworks is beyond the scope of this study but an interesting area for future research.[27] In summary, the results of this section suggest that the reasons against capital income taxation brought forth by the benchmark Ramsey model extend to environmental capital, and imply the optimality of Pigouvian taxes to internalize production losses from climate change.

Case 2: Climate Change Affects Only Utility

Consider now climate change impacts that affect utility but do not alter production possibilities. For example, biodiversity existence value losses from species extinctions or health impacts on

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[27] For example, Cremer, Gahvari, and Ladoux (2001) study optimal pollution taxation in a Mirrleesian taxation model, where distortions arise due to informational frictions. Their study focuses on a static setting. It would thus be interesting to extend their work to the dynamic setting.

non-working populations affect human welfare but not productivity.

Proposition 3 *The optimal carbon tax to internalize utility damages in period* $t > 0$ *is implicitly defined by:*

$$\tau^*_{Et} = \frac{\tau^{Pigou,U}_{Et}}{MCF_t} \tag{32}$$

where MCF_t *is the contemporaneous marginal cost of public funds as defined in (17).*

Proof. Proceeding analogously to Case 1, first combine the planner's first order conditions for emissions E_t, temperature change T_t, and the labor allocation to energy production L_{2t}. For periods $t > 0$, this yields:

$$F_{Et} + \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{Tt+j}}{\lambda_{1t}}\right] \frac{dT_{t+j}}{dE_t} = \frac{F_{1lt}}{F_{2lt}} \tag{33}$$

Next, invoke competitive equilibrium prices based on (8) and (12) to find the implicitly defined optimal tax:

$$\tau^*_{Et} = \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{Tt+j}}{\lambda_{1t}}\right] \frac{dT_{t+j}}{dE_t} \tag{34}$$

Finally, multiply the right hand side of (34) by $\frac{U_{ct}}{U_{ct}}$. Applying the definition of the marginal cost of public funds (17) completes the proof. ■

While formulation (32) only defines optimal carbon taxes implicitly, it demonstrate that the optimal provision of the climate consumption good is distorted if the marginal cost of public funds exceeds one. Specifically, it is easy to show that (34) implies a wedge between the household's MRS between the climate and the consumption good, and the MRT between these goods. That is, the optimal carbon tax does not internalize utility losses from climate change fully. In contrast, as discussed in Case 1, the optimal tax internalizes *output losses* fully in a wide range of model structures. I will discuss the intuition for this difference from two perspectives: first, the difference in tax interactions, and second, optimal commodity taxation theory.

When climate change affects only utility, imposing a carbon tax to reduce global warming does not yield any production benefits. To the contrary, carbon taxes decrease the returns to labor. This is because carbon taxes increase the cost of energy inputs and thus the cost of producing the consumption-investment good. As a result, carbon taxes can increase the costs of consumption relative to leisure, and hence decrease the returns to labor. Importantly, carbon taxes can thus exacerbate the effects of labor income taxes, which alter labor supply decisions by lowering the after-tax return to labor.[28] The MCF_t measures the marginal welfare cost of taxation. The optimal climate policy thus discounts utility damages by the MCF_t to account

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[28] This is the tax interaction effect that has been most extensively studied in the literature (see review by Bovenberg and Goulder, 2002).

for carbon tax interactions with other taxes. Intuitively, these interactions increase the cost of providing the public consumption good of environmental quality.

In contrast, when climate change affects production possibilities, carbon taxes are levied specifically to increase production efficiency. That is, the environmental benefits of carbon taxes can offset the increases in production costs resulting from higher energy prices. As a result, the labor tax interaction effect does not arise with output damages, as long as carbon levies are set appropriately. Climate policy must weigh output losses due to reduced energy usage in the present against output gains due to avoided climate change in the future. As discussed above, the Pigouvian tax (18) precisely balances these costs and benefits if there are no intertemporal distortions (e.g., no capital income taxes).

One can also explain the difference between Case 1 and Case 2 by appealing to optimal commodity taxation theory. Utility damages reflect the value of the climate as a final consumption good (e.g., existence value for biodiversity). Conversely, output damages reflect the value of the climate as an input to production (e.g., in agriculture). The intermediate goods taxation theorem states that it is preferable to distort consumption of final goods rather than usage of intermediate inputs. This is because taxing the latter leads to violations of aggregate production efficiency (Diamond and Mirrlees, 1971). With utility damages, setting $\tau_{Et} < \tau_{Et}^{Pigou}$ distorts consumption of the climate good. With output damages, setting $\tau_{Et} < \tau_{Et}^{Pigou}$ distorts usage of the climate input. As a result, setting $\tau_{Et} < \tau_{Et}^{Pigou}$ to account for tax interactions is desirable in the case of utility damages, but commonly undesirable in the case of output damages.

The static version of (32), ($\tau_E^* = \tau_E^{Pigou}/MCF$), is a classic formulation in the literature on pollution taxes and distortionary taxes (e.g., Bovenberg and van der Ploeg, 1994; Bovenberg and Goulder, 1996, etc.) Proposition 3 thus provides a generalization of this formulation to carbon taxation in a dynamic setting with capital.

Case 3: Climate Change Affects Both Production and Utility

In the realistic case that climate change affects both production and utility, the optimal carbon tax for $t > 0$ is implicitly defined by:

$$\tau_{Et}^* = \left[\frac{\tau_{Et}^{Pigou,U}}{MCF_t}\right] - \sum_{j=0}^{\infty}\beta^j \left[\frac{\lambda_{1t+j}}{\lambda_{1t}}\frac{\partial Y_{t+j}}{\partial T_{t+j}}\right]\frac{dT_{t+j}}{dE_t} \tag{35}$$

The derivation of (35) is analogous to the procedure outlined for Case 1 and Case 2 above.

Remark 6 *If preferences are of either commonly used constant elasticity form,*

$$U(C_t, L_t, T_t) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + v(T_t) \tag{36}$$

$$U(C_t, L_t, T_t) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + v(T_t) \tag{37}$$

then the optimal carbon tax for period $t > 0$ is implicitly defined by:

$$\tau^*_{Et} = \tau^{Pigou,Y}_{Et} + \frac{\tau^{Pigou,U}_{Et}}{MCF_t} \tag{38}$$

This result follows from (35) and the observation that preferences of the form (36) or (37) imply that $\frac{\lambda_{1t+1}}{\lambda_t} = \frac{U_{ct+1}}{U_{ct}}$ for all t.

Expressions (35) and (38) demonstrate that it is critical to distinguish between climate change impacts on production and on utility. In the literature on pollution tax interactions with other taxes, many studies assume that environmental quality affects only utility (see review in Bovenberg and Goulder, 2002). However, a few studies have previously emphasized the need for this damage type distinction (Williams, 2002; Bovenberg and van der Ploeg, 1994) in a static setting, and have derived analogous formulations to (38). Expressions (35) and (38) thus extend these studies' finding to the dynamic taxation of carbon.

The dynamic setting in particular yields the insight that utility damages should be discounted at the after-tax return on capital, whereas production damages should be discounted at the pre-tax return on capital. Intuitively, the pre-tax interest rate equals the marginal rate of transformation, and thus captures the tradeoff between present and future output. In contrast, the after-tax interest rate equals the household's marginal rate of substitution, and thus captures the tradeoff between present and future utils.

Many climate-economy models aggregate all damages into pure output losses (e.g., the DICE/RICE models, Nordhaus, 2008, 2010; Golosov, Hassler, Krusell, and Tsyvinski, 2014; Leach, 2009), pure utility losses (Acemoglu, Aghion, Bursztyn, and Hemous, 2011), or into market and non-market impacts (e.g., MERGE, Manne and Richels, 2005; PAGE, Hope, 2006, 2011; Tol, 1995). The latter is similar but not the same as a disaggregation into utility and production damages. On the basis of these theoretical results, I propose an alternative representation of climate change impacts that accounts separately for production and utility damages, as discussed below.

4 Calibration of the COMET Model

4.1 Model Overview

The **C**limate **O**ptimization **M**odel of the **E**conomy and **T**axation (COMET) outlined above could be combined with a range of integrated assessment climate-economy models. Given its status as benchmark in the literature, I choose the DICE (Dynamic Integrated Climate Economy) model (Nordhaus, 2008) as a baseline. Table 1 provides an overview of the quantitative model components, delineating which features have been (i) adopted directly from DICE, (ii) adapted for the purposes of the COMET, or (iii) newly created for COMET:

Adopted from DICE	Adapted for COMET	New for COMET
Carbon cycle	Damage function	Energy production
Abatement costs	Preferences	Government expenditures
Productivity growth	Final goods production	Tax policy
Population growth		

Table 1: Overlap of DICE and COMET Model Features

The COMET model assumes a global planner who is looking for a unique carbon tax to maximize global welfare. In reality, taxation is a national policy matter, thus raising the question of whether a global model and tax prescription provide a useful benchmark. d'Autume, Schubert and Withagen (2011) explore this issue in a general theoretical setting. They find that even when countries have heterogeneous distortionary tax systems, the optimal carbon tax is globally uniform as long as lump-sum transfers between countries are possible. The optimal global carbon price is then defined by a weighted sum of damages across countries, with the weights depending in part on countries' marginal cost of public funds.[29]

As shown in the Online Appendix, the literature's estimates of the marginal excess burden of taxation vary considerably across countries. Correspondingly, Babiker, Metcalf, and Reilley (2003) find heterogeneous non-environmental welfare impacts of carbon taxes and revenue recycling schemes across countries; see also Bernard and Veille (2003). While the COMET model does not consider these heterogeneous costs explicitly, it does use GDP-weighted global average measures of different countries' government revenue needs, transfers, and effective tax rates to derive representative global aggregate distortions.[30] The benefit of this approach is that it provides comparatively transparent insights to the main question of how optimal carbon price estimates are affected by distortionary tax interactions in a well-known integrated assessment model, and to the underlying mechanisms at play. The central quantitative finding is that optimal carbon tax rates are $8 - 30\%$ lower in a setting with distortionary taxes, compared to the setting with lump-sum taxes generally considered in the IAM literature.

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[29] If intercountry transfers are not possible, the authors show that the optimal carbon tax differs across regions, and is lower in countries with a higher cost of public funds, ceteris paribus.

[30] See also Schmitt (2013), who considers optimal fiscal and climate policy design in a multi-region climate-economy model. In particular, he provides a direct comparison of the relative effects on the optimal carbon tax due to distortionary taxes and countries' ignoring the global externality from climate change.

4.2 Carbon Cycle and Climate Model

The carbon cycle is taken directly from the 2010 DICE model (Nordhaus, 2010). It is represented by three carbon reservoirs: the atmosphere (S_t), the upper oceans and biosphere (S_t^{Up}), and the deep oceans (S_t^{Lo}). Endogenous industrial carbon emissions E_t and exogenous land-based emissions E_t^{Land} first enter the atmosphere, and subsequently begin to be absorbed by the upper oceans and biosphere. There is two-way mixing between adjacent carbon reservoirs, and the corresponding evolution of concentrations can be represented as:

$$\begin{pmatrix} S_t^{At} \\ S_t^{Up} \\ S_t^{Lo} \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} S_{t-1}^{At} \\ S_{t-1}^{Up} \\ S_{t-1}^{Lo} \end{pmatrix} + \begin{pmatrix} E_t + E_t^{Land} \\ 0 \\ 0 \end{pmatrix}$$

Changes in atmospheric carbon concentrations lead to increases in radiative forcings $\mathcal{F}_t$. Loosely speaking, radiative forcings measure the net change in the earth's radiation energy balance measured in watts/m^2. Along with other, exogenous forcings F_t^X, this effect is captured by:[31]

$$\mathcal{F}_t = \eta\{\ln\left(\frac{S_t}{S_{1750}}\right)/\ln(2)\} + \mathcal{F}_t^X$$

Finally, increased forcing leads to atmospheric temperature change. The DICE carbon cycle keeps track of both atmospheric and lower ocean temperature change, which evolve according to:

$$\begin{pmatrix} T_t^{At} \\ T_t^{Lo} \end{pmatrix} = \begin{pmatrix} (1-\xi_1\xi_2-\xi_1\xi_3) & \xi_1\xi_3 \\ (1-\xi_4) & \xi_4 \end{pmatrix} \begin{pmatrix} T_{t-1}^{At} \\ T_{t-1}^{Lo} \end{pmatrix} + \begin{pmatrix} \xi_1\mathcal{F}_t \\ 0 \end{pmatrix}$$

The parameters are set such that the equilibrium temperature change associated with a doubling of carbon dioxide concentrations - the climate sensitivity - is $3.2°C$.

4.3 Damages

The theoretical results demonstrate that it is essential to account separately for production and utility damages from climate change in an environment with distortionary taxes. In this section, I first briefly survey different approaches to modeling climate damages that have been taken in the literature, and then describe my approach.

Many integrated assessment models aggregate all climate damages into pure production losses (e.g., Nordhaus, 2008; Golosov, Hassler, Krusell, and Tsyvinski, 2014). Some models aggregate all climate damages into utility losses (e.g., Acemoglu, Aghion, Bursztyn, and Hemous, 2011).

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[31] Examples of sources of exogenous forcings include aerosols, ozone, and chloroflourocarbons (Nordhaus, 2008).

Other studies classify damages into market and non-market impacts, as discussed below. In a setting without distortionary taxes, these separations make no difference for climate policy under certain conditions (Gars, 2012).

A number of authors have differentiated climate damages into categories of economic and non-economic (*Page*, Hope, 2006, 2011), tangible and intangible (*FUND*,[32] Tol, 1995, 1997), or market and non-market (*Merge*, Manne and Richels, 2005). These categorizations essentially distinguish damages with direct market impacts from those "for which there are no market values" or that "are difficult to monetize" (Tol, 1994; Manne and Richels, 2004; Plambeck, Hope, and Anderson, 1997). This distinction is almost identical to production and utility damages. However, there are several differences between the categorizations of market/non-market damages and production/utility damages.

First, some climate damages may be difficult to monetize *ex-ante*, but their *ex-post* impacts entail significant shifts of the production possibility frontier. For example, Manne and Richels (2006) mention a shutdown of the North Atlantic thermohaline circulation as an example of non-market damages. However, such an event would assuredly affect productivity (Link and Tol, 2004), and should not be categorized as pure utility impact.

Second, while human health is classified as non-market good in the studies cited above, health impacts can alter production possibilities by affecting the global labor force time endowment, labor productivity, and health expenditures. I discuss this issue in further detail below.

Third, utility damages could affect equilibrium prices if climate change did not enter preferences separably. That is, by moving agents' offer curves, utility damages can change equilibrium prices without altering the production possibility frontier. The COMET model currently abstracts from these price impacts by assuming separable preferences of the form (43). However, this issue is discussed in the Online Appendix.

Table 2 showcases estimates of market and non-market impacts from the literature:

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[32] Current versions of the FUND model do not focus on this distinction and provide disaggregated output for damages across sectors such as agriculture, sea-level rise, and health (see, e.g., Anthoff and Tol, 2013; Tol, 2013).

		Scenario	Damages (% of GDP)		
Model	Region	ΔT (C°)	Market	Non-Market	%Market
PAGE2009	European Union (mean)	3°	0.5%	0.53%	(49%)$^{\triangledown}$
PAGE2002	European Union (mean)	2.5°	0.5%	0.73%	41%
MERGE2004	Wealthy nations	2.5°	0.25%	2%	11%
	Per capita income of $25,00		0.5%	1%	33%
	Per capita income of $5,000		0.5%	$\sim$ 0%	$\sim$ 100%
FUND (1995)	Global aggregate	$[2 \times CO_2]$	0.31%†	1.59%	16%
ICAM 2.5	Developed	$[2 \times CO_2]$	0.5%‡	2%	20%
	Developing		2.5%	0.5%	83%
Nordhaus (1994)	Expert Survey (mean)	3°			62.4%

$^{\triangledown}$The PAGE09 model also accounts for sea-level rise and catastrophic impacts separately.

†Computed using Tol's (1995) description of the fraction of damages in each sector considered "tangible" along with the damage estimates from Appendix Table A1.

‡Figures taken from Tol and Frankenhauser (1997)

Table 2: Differentiated Damage Estimates

In order to maintain close comparability with the DICE model, I mainly derive estimates of production and utility damages by splitting and re-aggregating the regional-sectoral[33] damage estimates underlying the DICE/RICE models into these two categories (Nordhaus, 2007; Nordhaus and Boyer, 2000). Table 3 shows the proposed classification scheme:

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[33] The distinct regions represented are: the United States, Western Europe, Russia, Eastern Europe/former Soviet Union, Japan, China, India, Middle East, Sub-Saharan Africa, Latin America, other Asian countries, and other high income countries.

Impact Category	Classification
Agriculture	Production
Other vulnerable markets (energy services, forestry production, etc.)	Production
Sea-level rise coastal impacts	Production
Amenity value	Utility
Ecosystems	Utility
Human (re)settlement	Utility
Catastrophic damages	Mixed
Health	Mixed

Table 3: Climate Damage Categorization

Seal-level rise coastal impacts are expected to destroy capital assets. Extending the core theoretical model to incorporate these damages explicitly through a climate-dependent capital depreciation rate ($\delta(T_t)$), one can easily show that capital depreciation losses are internalized identically to production damages. This is because, with a single investment-consumption good and capital malleability, both increased depreciation $\delta(T_t)$ and output losses $D(T_t)Y_t$ have the same effect of reducing the amount of the investment-consumption good left over at the end of period t. For parsimony, I thus classify these coastal impacts as production damages.

For catastrophic damages, the figures underlying the DICE model are based on expected damages from catastrophic outcomes. These outcomes are defined as equivalent to a permanent income loss of 30% of global GDP. However, this loss represents both literal output losses and accounts for disutility of non-production damages. Climate "tipping point" impacts, such as a shutdown of the North Atlantic thermohaline circulation, or changes in the Indian summer monsoon would likely affect ecosystems, human health, and human settlements in addition to causing production impacts (see, e.g., Lenton et al., 2008; IPCC Working Group II, 2007). For each region, I thus split catastrophic damages into production and utility components according to the region's share of non-catastrophic impacts affecting production and utility, respectively. There are two noteworthy technical points. First, I use the absolute value of total non-catastrophic impacts for each region in this calculation. This is to avoid miscalculating the relative importance of production or utility damages in regions where positive and negative impacts of 2.5° warming cancel out to a certain extent.[34] Second, I exclude climate amenity values from the calculation of

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[34] For example, in Russia, total production impacts of 2.5° warming are projected to be positive (negative damages), whereas health, ecosystem, and human settlement impacts are expected to be negative (positive damages). *Total non-catastrophic damages* for Russia are thus less than utility damages, implying a share of catastrophic utility impacts greater than 100%. Consideration of the absolute value share of climate change impacts in each category thus arguably represents the relative importance of either category more accurately.

production and utility shares of catastrophic damages, as amenity value changes do not appear to be an important component of damages associated with catastrophic climate change.

Health Impacts

The health impacts of climate change affect welfare in at least four key ways: mortality, morbidity, labor productivity, and health expenditures. The integrated assessment climate-economy models cited above focus on mortality and morbidity impacts of climate-sensitive diseases. A common approach is to value lost life years in accordance with the value of statistical life (VSL) literature (e.g., DICE, Nordhaus, 2008; FUND 3.7, Anthoff and Tol, 2013). For the models that separate market and non-market damages, these losses are then typically classified as non-market impacts (Page2002, Hope, 2006; FUND, Tol, 1995, 1997; MERGE, Manne and Richels, 2005).

The consideration of general equilibrium effects from distortionary taxes and labor supply in this study complicates the appropriate modeling of health impacts considerably. In particular, treating statistical losses of life as a consumption good of the representative agent misses the labor market impacts of changes in the workers' time endowments. However, such changes have both leisure and labor impacts, depending on the relevant elasticities. Williams (2002) provides a detailed theoretical treatment of these issues. Capturing all the details accurately in the climate change setting would likely require a dynamic heterogenous agent model with endogenous probabilities of death and disease as well as general equilibrium wage effects at the regional level. Such a detailed treatment is beyond the scope of this study. I nonetheless seek to capture and differentiate labor and leisure effects in a simplified framework, as discussed below. In addition, I compute a new damage function component to incorporate long-term labor productivity impacts from malaria exposure. Labor productivity impacts have not generally been included in standard integrated assessment models (Tol, 2011). While this paper considers only one channel through which climate change can affect labor productivity, I view this as an important area to explore. The remainder of this subsection discusses the three categories of health impacts included in COMET.

First, the framework for assigning years of life lost (YLL) to *labor-production losses* is as follows. Individual households chose to supply fraction l_t of their productive time endowment in decade t, ω_t. Following Jones, Manuelli, and Rossi (1993), 60.4% of time is assumed to be available for productive purposes (14.5 hours per day). The basic normalization of the model sets $\omega_t = 1$. The aggregate productive time endowment per decade is thus $\Omega_t = N_t\omega_t$, and aggregate labor supply is $L_t = l_t\Omega_t$. The final goods production technology is Cobb-Douglas (see below in (46)) and can thus be written as:

$$Y_t = (1 - \widehat{D}(T_t))A_t \cdot K_t^{\alpha} E_t^{v} [l_t \cdot \Omega_t]^{1-\alpha-v} \tag{39}$$

where $\widehat{D}(.)$ represents production climate damages gross of labor health impacts. Let $\xi(T_t)$ denote the fraction of the aggregate productive time endowment lost due to climate change-induced YLLs from T_t degrees of warming. Output net of health-labor losses Y_t' is thus:

$$\begin{aligned} Y_t' &= (1-\widehat{D}(T_t))A_t \cdot K_t^{\alpha} E_t^{v} [l_t \cdot \Omega_t (1-\xi(T_t))]^{1-\alpha-v} \\ &= (1-\xi(T_t))^{1-\alpha-v} \cdot Y_t \end{aligned} \tag{40}$$

I use the regional YLLs implied by the DICE model (Nordhaus, 2007) to calculate production damages from health-related labor time losses according to (40).[35] Equilibrium global labor supply remains fully endogenous. However, to maintain a given level of output Y_t, labor supply l_t has to be increased to compensate for the loss in the time endowment $\xi(T_t)$. Intuitively, if a household member falls sick to malaria, the other household members have to increase labor supply to maintain a given level of income. Note that I do not adjust the population level N_t to account for deaths, since doing so would *decrease* the welfare weight given to the generation alive at time t.

Second, the *non-labor component of YLLs* is valued as a consumption good (utility loss). The specific measure is two times per capita income per YLL, following Nordhaus and Boyer (2002).[36] To avoid double-counting, I discount YLLs by the baseline share of time spent on leisure.

Third, *labor productivity* impact estimates included in COMET seek to account for long-term effects of malaria exposure. Malaria is one of the most climate-sensitive diseases (WHO, 2009). There is growing empirical evidence on the long-term effects of malaria exposure on labor productivity (Bleakley, 2003, 2010; see also discussion in Gollin and Zimmermann, 2007). A

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[35] I also considered estimates from a report from the World Health Organization (WHO) on climate change and health (McMichael et al. 2004). Unfortunately, the report only provides direct estimates of disease-adjusted life years lost (DALYs) for the year 2000, based on a backwards-extrapolation of their model output. First, I thus extrapolate the temperature change implied by their climate scenarios for 2000. Second, I calibrate a quadratic temperature-based damage function given their estimates, and project it forward to 2.5° warming. The 2010-DICE values yield a GDP-weighted global loss for *utility* health impacts of 0.09% of GDP for $2.5°C$. In contrast, the value calculated based on the WHO estimates is significantly larger at 0.47% of GDP. Using this estimate would affect my quantitative results, and would increase the share of utility damages to around 50%. The WHO estimates are likely on the high side, however. For example, they assume zero adaptation to increased malaria risk, even with rising incomes.

[36] Alternatively, one could value the utility/non-labor component of YLLs at the price of leisure. Jorgenson, Goettle, Hurd, Smith, and Mills (2004) essentially follow this approach. They integrate the health impacts from thermal stress and tropospheric ozone due to climate change into a dynamic general equilibrium model of the U.S. economy. More specifically, the authors decrease agents' time endowments in accordance with the health impacts, and evaluate the welfare costs of the associated changes in leisure and consumption. Their resulting estimate of the value of a statistical life is at the low end of the VSL literature, and considerably below the U.S. Environmental Protection Agency's standard value. As such, the authors note that there is likely a willingness-to-pay premium to avoid statistical loss of life above and beyond the direct value of consumption and leisure losses. The authors further point to the possibility of adding a VSL premium to market-based damage estimates.

central underlying mechanism is anemia, which has been shown to significantly impair labor productivity, including in large-scale field-experiments (Duncan et al., 2004). Lucas (2010) finds evidence of significant increases in educational attainment due to malaria eradication. I use Bleakley's (2003) estimate that a malarious childhood decreases adult wages by 15%,[37] along with Tol's (2008) estimates of climate change-induced increases in malaria morbidity, and World Bank data on baseline malaria prevalence[38] to calculate GDP-weighted labor productivity losses from 2.5° warming. At the global level, these impacts are small: I find an estimated decrease in total factor productivity of 0.0105%. However, in Sub-Saharan Africa, malaria-induced total factor productivity losses from 2.5° warming alone are predicted to be around 0.33%. These impacts are added to the production damages as outlined in Table 3.

Production vs. Utility Damages: Results

The base year GDP-weighted estimates for production and utility damages are as follows:

$$\begin{aligned} \text{Total damages from } 2.5^\circ \text{ warming} &= 1.44\% \text{ of output} \\ \text{Total } \textbf{production damages} &: 1.06\% \text{ of output} \\ \text{Total } \textbf{direct utility damages} &: 0.37\% \text{ of output} \\ \text{Share of output damages} &: 74\% \end{aligned} \tag{41}$$

The 2010-DICE model assumes climate damages equivalent to 1.74% of output at the calibration point. The difference to (41) arises due to alternative aggregation across sectors and countries. In order to maintain maximum comparability with DICE, I thus adopt the share of output damages from (41), but assume total damages as in the original DICE framework. This implies production damages of $(.74 * 1.74) = 1.29\%$ of GDP, and utility damages of $(.26 * 1.74) = 0.46\%$ of GDP at 2.5° warming. The COMET also adopts the functional form of the output damage function from DICE. However, the damage coefficient θ_1 is calibrated based on (41) such that output losses from 2.5° temperature change equal 1.29% of output:

$$\begin{aligned} (1 - D_t(T_t)) &= \frac{1}{1+\theta_1 T_t^2} \\ 1 - 0.0129 &= \frac{1}{1+\theta_1 (2.5)^2} \\ \theta_1 &= 0.0021 \end{aligned} \tag{42}$$

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[37] Gollin and Zimmermann (2007) use a slightly lower value of 10%. However, in more recent work, Bleakley (2010) finds evidence for impacts considerably larger than 15%.

[38] World Bank *World Development Indicators*, "Notified cases of malaria (per 100,000 people)," for all available countries, year 2008.

4.4 Preferences

In the DICE model, the representative agent has preferences over consumption. The current setup adds preferences over leisure and temperature change. The essential traits of a utility function for the current setting is that it be: (1) consistent with a balanced growth path, (2) able to match the intertemporal elasticity of substitution (IES) from the DICE model, and (3) possible to calibrate to a desired range of Frisch elasticity of labor supply values, given benchmark labor supply estimates. In addition, climate change preferences should be formulated such that the temperature risk aversion coefficient (defined by Weitzman, 2010 and described in the Appendix) is the same for utility damages and equivalent consumption losses. The function chosen to satisfy these criteria is:

$$U(c_t, l_t, T_t) = \frac{\left[c_t \cdot (1 - \phi l_t)^{\gamma}\right]^{1-\sigma}}{1-\sigma} + \frac{\left(1 + \alpha_0 T_t^2\right)^{-(1-\sigma)}}{1-\sigma} \tag{43}$$

where c_t and l_t are individual-level consumption and labor supply ($c_t = C_t/N_t$, where N_t is the population at time t). Specification (43) is based on King-Plosser-Rebelo (KRB) preferences (King, Plosser, and Rebelo, 2001), with two modifications. The first is the addition of preferences over temperature change. The second is a technical modification to simultaneously match both desired labor supply and IES values.[39] Baseline labor supply is estimated from OECD data to be $l_{2005} = 0.227$ (see Appendix for details).

I calibrate to base year values to maintain consistency in preference parameters across model runs. That is, different fiscal scenarios may lead to different long-term labor taxes and labor supply rates. In contrast, base year labor supply and tax values are given in the data. The only exception is the first-best calibration without distortionary taxes, where I calibrate preferences to match the observed l_{2005} with $\tau_{l2005} = 0$ instead of $\tau_{l2005} = 35.19\%$. The details of the calibration are outlined in the Appendix. The benchmark calibration uses a Frisch elasticitiy of $\eta^F = 0.78$ based on a survey by Chetty, Guren, Manoli, and Weber (2011).

Finally, α_0 is chosen such that the aggregate global consumption loss equivalent of disutility from climate change at $2.5°C$ equals 0.49% of output as per the split in (41) (see Appendix for details). The monetization of damages usually considers the world at $2.5°C$ warming in the business-as-usual (BAU) scenario, and reflects predicted global income and consumption levels at that point in time. The corresponding values are taken from a slightly modified BAU run of

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[39] Specifically, I add a preference parameter for leisure, ϕ. Other studies using KRB preferences usually have both the IES and the leisure preference parameter γ available as degrees of freedom to match desired moments (e.g., Jones, Manuelli, and Rossi, 1993). However, in the current study, I want to maintain consistency with the DICE model by setting $\sigma = 1.5$, thus losing one degree of freedom, which is compensated for by introducing ϕ. In the Online Appendix, I show that specification (43) retains consistency with a balanced growth path for the relevant ranges of the parameters. This property is important, for example, to ensure that long run growth in wages does not cause labor supply to converge toward zero.

the 2010 DICE model (Nordhaus, 2010).[40] Consumption is further adjusted downward by the base year share of output devoted to government consumption in the COMET (as described in Section 4.7). Labor supply at that time is set at the baseline COMET value, since the BAU scenario represents the idea of no tax reform.

4.5 Energy Production and Emissions Abatement

There are two types of energy: carbon-based E_t^C and zero-carbon (no emissions) E_t^Z. Both fuels are perfectly substitutable in final goods production, but zero emissions energy production entails an additional cost over carbon-based energy. The assumption of perfect substitutability is appropriate given the calibration of the incremental cost of clean energy as based on the cost of emissions reductions for a given level of energy use and output from the DICE model.

The production of both types of energy requires capital and labor inputs with a Cobb-Douglas production technology:

$$E_t = A_{Et} \cdot (K_{Et}^{1-\alpha_E} L_{Et}^{\alpha_E}) \tag{44}$$

Paired with the assumption of perfect competition in the energy production sector, formulation (44) permits extracting the output elasticity α_E from observed expenditure shares. I use data from the U.S. Bureau of Economic Analysis on *components of value added by industry* to calculate labor shares. The details are provided in the Appendix. The GDP-contribution-weighted average share of $\alpha_E = 0.403$ is used in the model.

The calibration of the costs of emissions reductions at a given energy input level (conceptually analogous to zero emissions energy production) is based directly on the DICE model (Nordhaus, 2008). However, the costs are integrated in the model in a slightly different fashion. In the DICE framework, a fraction of emissions *relative to the BAU scenario* (without carbon taxes) can be eliminated at a total cost that is convex and proportional to output. In the COMET, this approach cannot be directly adopted as *both* carbon-based and clean energy use are endogenous. I thus employ an alternative specification which approximates the DICE abatement cost estimates on a per-ton basis.[41] Specifically, I compute a grid of total abatement costs in DICE for different amounts of clean energy produced in each decade through the year 2265.[42] I then approximate

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[40] Specifically, I deactive the sea level rise module and use the slightly older damage function parameters whose calibration includes sea level rise. In addition, I modify the carbon cycle in the first period so as to reflect changes in base year emissions.

[41] This approach implies, for example, that the cost of producing an additional unit of wind energy in a given year is independent of the number of coal power plants concurrently in operation. The per-ton cost representation is in line with how the IPCC reports cost estimates for electricity mitigation options (IPCC Working Group III, 2007).

[42] Ranging from 0 to 250 billion metric tons of carbon-equivalent energy in increments of 10 tons. The calcu-

these costs through a logistic function:

$$\Omega_t(E_t^{clean}) = \frac{\gamma P_{ct}}{1 + a_t \exp(b_{0t} - b_{1t}(E_t^{clean}))^{b_2}} \cdot E_t^{clean} \tag{45}$$

where P_{ct} denotes the backstop technology price in year t, taken directly from DICE.[43] The remaining parameters in (45) are solved for numerically by minimizing the sum of squared errors between the present discounted total costs implied by (45) and those computed based on the DICE model.[44]

4.6 Final Consumption Good Production

Following GHKT (2014), production of the final consumption-investment good is assumed to be:

$$\widetilde{F_{1t}}(K_{1t}, L_t, E_t) = K_t^{\alpha} L_{1t}^{1-\alpha-v} E_t^{v} \tag{46}$$

with expenditure shares $\alpha = 0.3$ and $v = 0.03$. Cobb-Douglas technology has been shown to be a poor representation of energy input use in the short-and medium run (e.g., Hassler, Krusell, and Olovsson, 2012). However, Hassler, Krusell, and Olovsson (2012) also note that the energy expenditure share in production does not appear to exhibit a clear trend. Furthermore, "the possibility that the unitary-elasticity is a good approximation for the very long run cannot be excluded" (Hassler, Krusell, and Olovsson, 2012). Given the 10-year time step of the model, I follow GHKT (2014) and other studies (e.g., Leach, 2009) in working with (46) as benchmark.

4.7 Government

Spending

The COMET disaggregates government spending G_t into government consumption G_t^C and social transfers Ω_t (unemployment insurance, disability insurance, etc.). This distinction is in line with other calibrated Ramsey tax studies such as Jones, Manuelli, and Rossi (1997; 1993) or Lucas (1990). The consumer and government budget constraints as well as the implementability constraint need to be adjusted to incorporate transfers Ω_t. It is assumed that households take Ω_t as given. Note that transfers cannot be negative, since negative transfers (lump-sum taxes)

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lations assume a constant marginal abatement cost for clean energy production in excess of the number of tons that would correspond to 100% emissions reduction in DICE, equal to the backstop technology price.

[43] Here, the time-dependent coefficients α_t, b_{0t}, and b_{1t} are modeled as $\alpha_t = \alpha_1 + \alpha_2 \log(t)$ and $b_{it} = b_{i1} + b_{i2} \log(t)$ for $i = 0, 1$. These functional forms were chosen after solving non-parametrically for the optimal sequence of t different values for α_t, b_{0t}, and b_{1t}, which followed a time-logarithmic trend extremely closely.

[44] The results are that $\gamma = 0.9245$; $\alpha_1 = 49.9096; \alpha_2 = 1.0995$; $b_{01} = 15.5724$; $b_{02} = 3.4648$; $b_{11} = 13.0210$; $b_{22} = 1.5725$; and $b_2 = 0.0921$.

would imply a first-best fiscal setting. As shown formally in the Appendix, the implementability constraint with social transfers is given by:

$$\sum_{t=0}^{\infty}\beta^t\left[U_{ct}C_t + U_{lt}L_t - U_{ct}\Omega_t\right] = U_{c0}\left[K_0\left\{1+(F_{k0}-\delta)(1-\tau_{k_0})\right\}+B_0\right] \tag{IMP2}$$

The key government spending parameters that need to be calibrated are thus the sequence of government consumption $\{G_t^C\}_{t=0}^{\infty}$ and government transfers $\{\Omega_t\}_{t=0}^{\infty}$. To this end, I obtain IMF Government Finance Statistics data for all available countries in the model base year (2005).[45] The PPP-adjusted GDP-weighted average share of government expenditure is 33.75% of GDP in the base year.[46] Table 4 displays the breakdown of weighted average spending by category:

	% of GDP	% of Government Expenditure
Compensation of Employees	9.32	27.61
Use of Goods and Services	5.08	15.04
Grants	1.31	3.87
Subsidies	1.06	3.13
Other Expense	1.00	2.95
Social Benefits	13.32	39.45
Total	33.75	

Data sources: IMF Government Finance Statistics, IMF International Finance Statistics. Calculations exclude consumption of fixed capital for countries with noncash (accrual) basis of recording; shares recalculated given revised total expenditure estimates.

Table 4: Government Expenditure Shares (2005)

Of the expenditure items in Table 4, *Social Benefits* represents a variety of government transfers that go back to households, such as unemployment insurance, disability insurance, and most types of social security. One delicate issue is deciding the extent to which these transfers should be considered independent of agents' work and consumption choices. In particular, social security benefits should be considered forced savings rather than tax-and-transfer programs to the extent that benefits depend on agents' contributions. In the literature, different authors deal with this challenge differently.[47] This choice matters because it affects the estimated distortionary cost of

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[45] The countries covered by the IMF data account for roughly 71% of world GDP (in 2005 PPP-adjusted dollars) in 2005.

[46] One complication in combining data across countries that use cash and noncash bases of recording, respectively, is that government consumption of fixed assets is recorded in one system but not the other. Since government consumption of fixed assets (i) is typically a small share of GDP (1.86% on average among countries that record it), (ii) is computed using a variety of methodologies in different countries, and since (iii) I am not modeling government capital, I remove consumption of fixed assets from the data and recompute expenditure shares accordingly.

[47] On one side of the spectrum, Prescott (2004) considers all social security payments as true tax payments,

taxation. It should be noted that the IMF data do not include defined contribution retirement schemes or other compulsory savings schemes that "maintain the integrity of the participants' contributions" as social protection schemes (IMF, 2001). In addition, the baseline estimates of effective capital and labor income tax rates used in the calibration (discussed below) stem from studies that designate all social security tax payments as true tax payments. I thus follow Prescott's (2004) approach, and model social benefits as lump-sum transfers.

Base year government consumption and transfers are thus computed as 17.75% and 13.32% of base year GDP, respectively. Interest payments are subtracted from total government expenditure because they are accounted for separately in the model. The shares of government consumption and transfers of total government expenditure are thus 57% and 43%, respectively. The *level* of total government expenditure G_t is assumed to grow at the rates of labor productivity and population growth.[48] Government consumption in period t is then equal to $[G_t^C = G_t\,(.57)]$, and similarly government transfers are calculated as $[\Omega_t = G_t\,(.43)]$.

Lastly, the model requires estimates of baseline tax rates. Carey and Rabesona (2002) provide updated estimates of average effective tax rates across countries following the Mendoza, Razin, and Tesar (1994) methodology.[49] This procedure uses data on government revenues collected from different tax instruments to compute effective tax rates as revenues divided by the estimated size of the tax base. I calculate the base year PPP-adjusted GDP-weighted average effective tax rates for 1995-2000 based on the countries in Carey and Rabesona:[50]

$$\begin{aligned} \text{Labor \& Consumption:} &\quad 35.19\% \\ \text{Capital:} &\quad 43.27\% \end{aligned} \tag{47}$$

The benchmark calibration uses (47) as initial tax rates, and, depending on the model run, as continued "business as usual" (no tax reform) rates.[51]

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arguing that the marginal savings effect is minimal. Jones, Manuelli, and Rossi (1993) take a middle-of-the-road approach and designate 50% of social security payments as true transfers, and 50% as forced savings. On the other side of the spectrum, in the IGEM model, all social security payments are considered as forced savings (Goettle, Ho, Jorgenson, Slesnick, Wilcoxen, 2007).

[48] Goulder (1995) similarly models government expenditure as growing from an initial level at technology growth rate of the model, as do Jones, Manuelli, and Rossi (1993).

[49] Carey and Rabesona (2002) propose several modifications to relax assumptions made by the the Mendoza methodology. I use Carey and Rabesona's (2002) revised effective tax rate estimates, although the authors also provide updated figures using the precise Mendoza methodology through the year 2000.

[50] For capital taxes, I use Carey and Rabesona's estimates based on *net operating surplus* since those are consistent with the model's assumption that depreciation is not part of the capital tax base.

[51] The Mendoza, Razin, and Tesar methodology estimates *average* rather than marginal effective tax rates. Estimates of the latter across countries are rare. Prescott (2004) uses an adjustment factor of 1.6 to transform average non-social security labor income tax rates to marginal rates for G-7 countries. However, it is unclear to which extent this adjustment factor would apply to the rest of the world, or to capital income taxes. One would nonetheless expect this discrepancy to be a source of downward bias on estimates . Conversely, a source

5 Quantitative Results

Computation

In order to numerically solve this infinite horizon problem, I follow a similar though slightly different approach as Jones, Manuelli, and Rossi (1993). I first optimize over all allocations for T periods as well as over the continuation gross savings rate for period T. In the benchmark calibration, $T = 25$, representing 250 years. In contrast to studies such as Jones, Manuelli, and Rossi (1993), however, one cannot impose a balanced growth path after some terminal period T in the current setting. The reason is that full effects of carbon emissions in late periods would not be accounted for due to lags in the climate system between emissions and warming. In addition, a balanced growth path requires that the climate be in steady state, that is, that carbon concentrations have stabilized. Given the assumption that clean energy backstop technologies will become fully cost competitive by the year 2255 (Nordhaus, 2010), industrial carbon emissions will stop at the latest thereafter, allowing the climate to gradually reach a new steady state.

After the last direct optimization period $T > 2255$, I thus use the continuation gross savings rate as well as the period T labor supply and period T factor distribution across sectors (i.e., the share of capital allocated to energy and final goods production) to simulate the economy and climate for another 100 years. Finally, after this additional 100 years (generally in the year 2365), I assume that the economy has reached a balanced growth path and calculate the consumption continuation value based on the theoretically calculated balanced growth path savings rate, and thus compute the present value of all future utility. The optimization is performed in Matlab.

Results

Table 5 summarizes the key quantitative results for the following COMET runs:

1. An "All Taxes BAU" scenario where there are no carbon taxes throughout the twenty-first century.[52] Variant (1a) holds labor income taxes fixed at 36.58%[53] and varies capital

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of upward bias is that the figures underlying (47) come exclusively from OECD member countries. However, a study by PricewaterhouseCoopers found that effective average tax rates faced by large firms incorporated in non-OECD countries (16.5%) are considerably below the non-U.S. OECD average rate (22.6%) (PWC, 2011). Applying OECD-based figures to the rest of the world may thus bias the estimates in (47) upwards. I find that using (47) as baseline values yields MCF estimates that are on the high end for capital income taxes and on the low end for labor income taxes, but within the range of the literature.

[52] I permit carbon taxes after the year 2105 in all scenarios in order to avoid estimating welfare effects of climate change well in excess of $4°C$, as would occurr without carbon taxes. This is done because the smooth damage function employed does not reflect discontinuities that may occur at high temperature change. In addition, without assurance of stabilization of carbon concentration, the existence of a non-zero balanced growth path cannot be ensured.

[53] Here, BAU labor taxes are set at 36.58% rather than the base year estimate of 35.19% in order to maintain

income taxes to meet the government budget constraint. Variant (1b) holds capital income taxes fixed at 43.27% and varies labor income taxes to meet the public budget constraint.

2. An "Income Tax Reform" scenario where income taxes are optimized but there are no carbon taxes in the twenty-first century This scenario measures the welfare gains from conventional tax reform as considered by the literature on optimal capital income taxes (e.g., Lucas, 1990).

3. A "Green Tax Reform, Optimal Carbon Taxes" scenario where carbon taxes are set optimally. Variant (3a) holds labor income taxes fixed at 36.58% and thus uses carbon and energy tax revenues to reduce capital income taxes ('revenue recycling'). Variant (3b) holds capital income taxes fixed at 43.27% and recycles carbon tax revenue to reduce labor income taxes. These scenarios measure the welfare gains from environmental tax reform. Note that taxation (but not subsidization) of clean energy/abatement is permitted.

4. A "Green Tax Reform, 'Wrong' Carbon Taxes" scenario which is identical to (3) except that carbon taxes are set at first-best levels that would be optimal if there were no distortionary taxes. These levels correspond to the Pigouvian tax or the social cost of carbon in a setting without distortionary fiscal policy. The differences in welfare between (4) and (3) reflect the additional value of adjusting carbon taxes to the fiscal setting.

5. A "Fully Optimized" scenario that optimizes over both income taxes and carbon taxes.

6. An "Income Tax Reform, 'Wrong' Carbon Taxes" scenario where income taxes are optimized but carbon taxes are set at first-best levels as in (4). The difference between (5) and (6) once again reflects the additional value of adjusting carbon taxes for the fiscal setting.

7. A "First-Best" scenario where the government is allowed to raise revenues by imposing non-distortionary lump-sum taxes, and optimally levies first-best carbon taxes. This scenario represents the common implicit assumption in the integrated assessment model literature.

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comparability between the scenarios holding labor and capital income taxes fixed, respectively. That is, fixing capital income taxes at benchmark levels of 43.27% requires labor income taxes of 36.58% to meet the government budget constraint in the BAU model run.

Table 5 summarizes the central quantitative results:

	Fiscal Scenario		Capital Tax	Labor Tax	Carbon Tax			MCF	T_t	ΔWelfare[1]	
			Avg.	Avg.	$\$/mtC$			Avg.	C°	\$2005 bil.	$\%\Delta C_t$
	Income Taxes:	Carbon Tax:	2025-2255	2025-2255	2015	2025	2035	2025-2255	Max	ΔC_{2015}	$\forall t$
(1a)	BAU (τ_l fixed)	None (until 2115)	43.27	36.58	0	0	0	1.04[6]	4.29	-	-
(1b)	BAU (τ_k fixed)	None (until 2115)	42.41	36.58	0	0	0	1.78[5]	4.28	(−\$141)	(−0.05%)
(2)	Optimized	None (until 2115)	2.58[3]	41.48	0	0	0	1.07	4.28	\$40,591	1.42%
(3a)	BAU+ RR(τ_k)[2]	Optimized	38.59	36.58	45[4]	69	98	1.62[5]	3.04	\$30,711	1.09%
(3b)	BAU+ RR(τ_l)[2]	Optimized	43.27	36.17	53	88	124	1.04[6]	3.01	\$20,221	0.73%
(4a)	BAU+ RR(τ_k)[2]	'Wrong' (first-best)	39.82	36.58	70	102	142	1.67[5]	2.73	\$27,915	1.00%
(4b)	BAU+ RR(τ_l)[2]	'Wrong' (first-best)	43.27	36.22	70	102	142	1.03	2.78	\$19,158	0.69%
(5)	Optimized	Optimized	2.57[3]	41.38	59	90	129	1.06	3.0	\$64,908	2.22%
(6)	Optimized	'Wrong' (first-best)	2.02[3]	41.35	70	102	142	1.06	2.87	\$64,715	2.22%
(7)	First-Best	Optimized	0	0	70	102	142	1.0	2.96	[121,830][7]	[3.93%]

[1] Relative to All Tax BAU scenario (1a). EV change in aggregate initial consumption ΔC_{2015} or permanent change in consumption $\%\Delta C_t$.

[2] Carbon tax revenue recycled to reduce only capital income tax rates RR(τ_k) or labor income tax rates RR(τ_l).

[3] Consists of high initial tax followed by $\sim 0\%$ tax (except for the last direct optimization period $T = 2265$; see Section 5.)

[4] Carbon tax here is defined as the difference between total taxes on carbon energy (\$87/t in 2015, \$126 in 2025, etc.) and on clean energy/ abatement (\$42/t in 2015, \$57 in 2025, etc.). Here, all types of energy are taxed because they increases the marginal product of labor and tighten the labor income tax constraint of 36.58%.

[5] Measures the MCF of raising revenues from capital income taxes only.

[6] Measures the MCF of raising revenues from labor income taxes only.

[7] Calculation uses utility function parameters from second-best model to evaluate and compare both first- and second-best allocations. In reality, leisure preferences are calibrated differently in the first-best setting because ($\tau_{l0} = 0$), whereas (τ_{l0}= 35%) in all other model runs. Leisure preferences needed to rationalize labor supply thus differ across the scenarios, making welfare calculations not exactly comparable.

Table 5: Main Results

Several findings emerge from the results in Table 5.

First, optimal carbon levies are consistently lower when there are distortionary taxes. Figure 1 displays optimal carbon tax schedules for the twenty-first century from the key model runs, as well as optimal carbon taxes from a slightly modified 2010 DICE model comparison run:

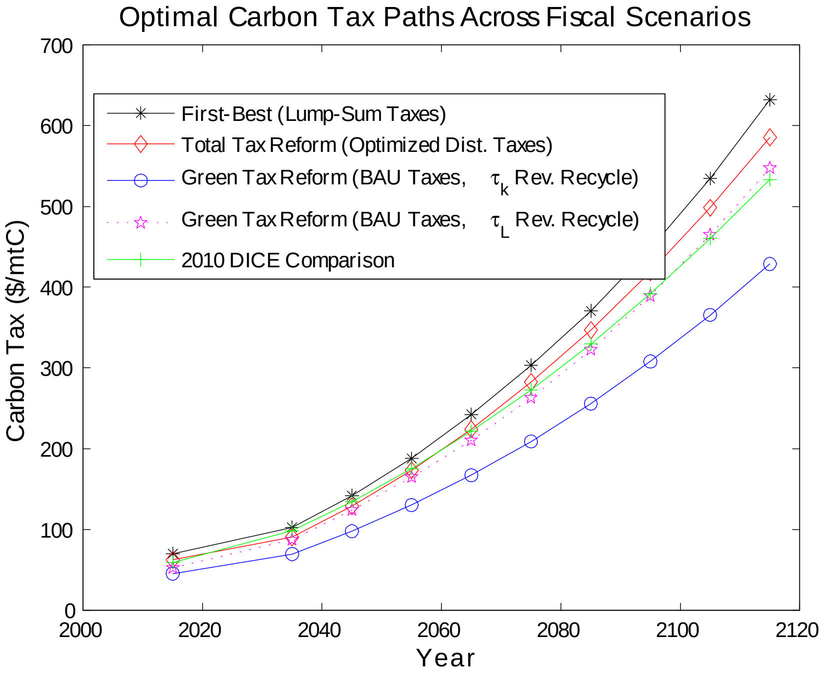

Figure 1: Optimal Carbon Tax Schedules

Throughout the century, optimal carbon taxes are on average 8% to 30% lower when levied alongside distortionary taxes. They start at \$45 to \$62/mtC in 2015, rising to \$428 to \$585/mtC by 2105, depending on the income tax reform scenario. The change in optimal carbon taxes in a setting with distortionary fiscal policy is driven by three factors. First, the size of the economy is smaller. As a result, the dollar value of marginal damages from carbon emissions is lower. In a smaller economy, the level of carbon taxes needed to achieve a given temperature change target is also lower. On average over the time horizon 2015 to 2265, compared to the first-best setting with lump-sum taxes, output is 4% to 12% lower when there are distortionary taxes. Second, in a setting with distortionary taxes where the marginal cost of public funds exceeds one, optimal carbon taxes do not fully internalize the value of marginal damages, as discussed above. Third, when income tax rates are constrained to remain at BAU levels, the planner also considers the impact of climate change on the tightness with which these constraints bind, as shown in the Appendix for the case of fixed capital income tax rates, and as discussed below.

Next, Figure 2 shows the optimal carbon tax-GDP ratio across fiscal scenarios:

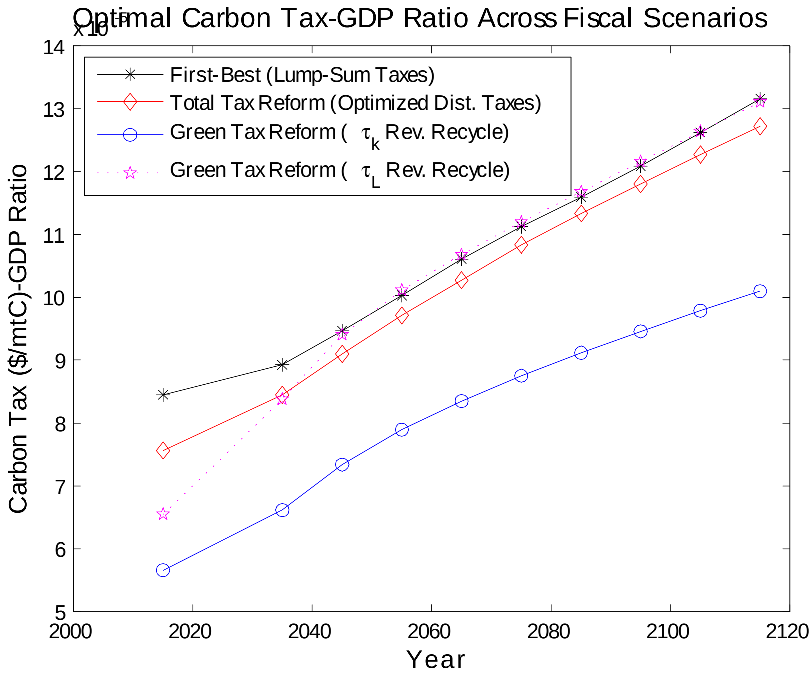

Figure 2: Optimal Carbon Tax-GDP Ratios

Again, the results reveal that carbon taxes are typically lower when there are other, distortionary taxes, even when accounting for GDP differences across scenarios.

The second main result is that using carbon tax revenue to reduce capital income taxes produces a much larger efficiency gain than using them to reduce labor income tax rates. The efficiency gain from capital income tax revenue recycling is estimated to be \$10 trillion, or a 0.36% permanent increase in consumption. This finding is fully in line with previous studies such as Goulder (1995), who finds that the non-environmental welfare costs of carbon taxes in the U.S. economy are lower for capital income tax revenue recycling than for personal labor income tax revenue recycling. Perhaps surprisingly, the results here also suggest that optimal carbon taxes conditional on capital income tax recycling are *lower* than for labor income tax recycling. The reason for this result is that the constrained optimal carbon tax takes into account the impacts of future climate change on the tightness with which the BAU income tax constraints bind. The Appendix formally derives and describes the relevant expression for the case of fixed capital income taxes and labor tax revenue recycling. In scenario ($3a$), the constraint that labor income taxes remain at BAU levels is downwardly binding: the optimal labor income tax is *higher* than 36.58%, and the optimal net marginal product of labor is thus lower than the constraint allows. Future climate change decreases the marginal product of labor, thus slightly loosening the BAU labor income tax constraint. All else equal, this effect decreases the optimal carbon tax rate. Conversely, in scenario ($3b$), the constraint that the capital income tax remain at BAU levels is upwardly binding: the optimal capital income tax is *lower* than the prescribed 43.27%, and the optimal net return on capital is higher than the constraint allows. By decreasing the marginal product of capital, climate change thus exacerbates the capital return constraint, giving the planner an additional incentive to mitigate carbon emissions. However, there are much larger welfare gains associated with capital income tax revenue recycling.

Next, Metcalf (2003) notes the importance of evaluating both how distortionary taxes affect optimal pollution prices and the associated changes in optimal quantities. In particular, he finds that environmental quality may be higher in a world with distortionary taxes and lower economic activity, despite lower pollution tax rates. Figure 3 illustrates optimal temperature change in the main model runs:

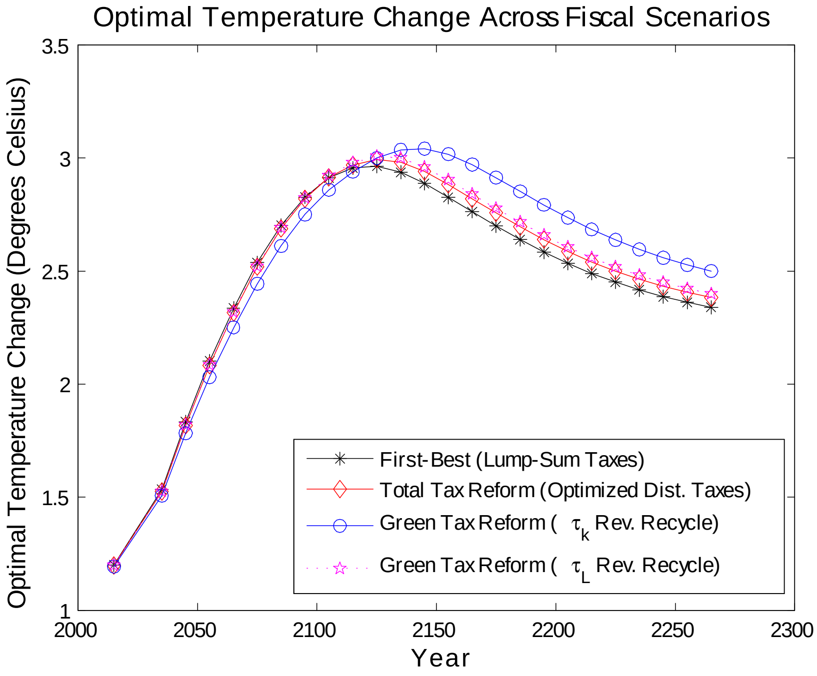

Figure 3: Optimal Temperature Change Across Fiscal Scenarios

Optimal peak temperature change is projected to be between $0.03C^\circ$ (1%) and $0.08C^\circ$ (3%) higher when there are distortionary taxes. The desirability of slightly higher temperature change is essentially a reflection of the increased social marginal emissions reduction costs in the setting with distortionary taxes. However, echoing Metcalf's (2003) results, the difference in temperature change across the scenarios is small relative to the variation in carbon taxes.

How important is it to consider distortionary taxes in climate policy design? I compare the welfare gains from imposing optimized carbon taxes (model runs 3a, 3b, and 5) to the welfare gains from imposing carbon taxes that were designed for a setting without distortionary taxes (model runs 4a, 4b, and 6). The *additional* welfare gain from setting adjusted carbon taxes ranges from \$190 billion to \$2.8 trillion (\$2005 lump-sum consumption equivalent), depending on the structure of income taxes. While this welfare gain is arguably large in absolute levels, it is modest as a percentage of the total welfare gain from carbon taxes, estimated to reach up to \$30 trillion (\$2005 lump-sum consumption equivalent, 1.1% permanent increase in consumption).

Finally, given the theoretical similarity between capital income taxes and the absence of carbon taxes, I compare the efficiency costs of these two policies. Relative to the "All Taxes BAU" scenario (1a), adding optimized carbon taxes yields a welfare gain of $\$20 - \$30$ trillion, depending on how revenues are recycled. In contrast, income tax reform that optimally phases out capital income taxes yields a welfare gain of \$40 trillion. These figures suggest that the global efficiency costs of *failure* to enact carbon taxes until 2115 are on a similar order of magnitude as the efficiency costs of continuing to tax capital income at current rates. Estimating the efficiency costs of capital income taxes in a global aggregate model with a single type of physical capital is, of course, a gross approximation. However, it should be noted that the estimated 1.4% welfare gain from the optimal capital income tax phase out compares favorably with Lucas' (1990) estimates for the U.S. economy (0.75% to 1.25%). Finally, the combined welfare gains from adding optimized carbon taxes and reforming income taxes are estimated to be very large at \$65 trillion, or a 2.22% permanent consumption increase equivalent.

To summarize, the benchmark model yields four main quantitative results. First, the optimal carbon tax schedule is $8 - 30\%$ lower when there are distortionary taxes. The associated optimal peak temperature change is $0.03 - 0.08°C$ higher. Second, the efficiency gains from using carbon tax revenues to reduce capital income taxes rather than labor income taxes are estimated to be large, in line with previous studies. Third, the welfare gains from adjusting carbon taxes to account for their fiscal impacts is between \$190 billion and \$2.8 trillion, depending on the tax reform scenario. Fourth, the welfare gains from income tax reform that optimally phases out capital income taxes is of a similar order of magnitude as the gains from an environmental tax reform which imposes optimal carbon levies and uses their revenues to reduce capital income tax rates.

5.1 Differentiation of Production and Utility Damages

One of the main contributions of this study is to incorporate a representation of distortionary fiscal policy into an integrated assessment climate-economy model. In contrast, previous studies on interactions between carbon taxes and other taxes have employed highly detailed multi-sector CGE models which feature much more realistic representations of tax policy, but abstract from climate-economy feedback effects. That is, welfare calculations in studies such as Goulder (1996), Jorgenson and Wilcoxen (1996), Babiker, Metcalf, and Reilley (2003), etc. implicitly assume that climate change affects only utility and not production possibilities. In order to assess the importance of climate-economy feedback effects for the optimal carbon tax in the presence of other taxes, I thus conduct the following additional COMET runs:

1. "First-Best, All Utility Damages": This scenario replicates case (7) discussed above, which assumes that governments can raise revenues through non-distortionary lump-sum taxation. However, the total value of damages (1.44% of GDP at $2.5°C$) is assumed to affect utility directly, and there are no production damages.
2. "First-Best, All Output Damages": Identical to scenario (1) but with the total value of damages affecting production, and no direct utility damages.
3. "Fully Optimized, All Utility Damages": This scenario replicates the "fully optimal" case where distortionary taxes are optimally set. However, the total value of damages is assumed to affect utility directly, with no production damages.
4. "Fully Optimized, All Ouptut Damages": Identical to scenario (3) but with the total value of damages affecting production, and no direct utility damages.
5. "Green Tax Reform, All Utility Damages ": Identical to the corresponding scenarios in the previous section, but with the total value of damages assumed to affect utility directly, with no production damages.
6. "Green Tax Reform, All Output Damages ": Identical to scenarios (5) but with the total value of damages affecting production, and no direct utility damages.

Figures 4 and 5 display optimal temperature change paths across fiscal scenarios in the settings with all utility and output damages, respectively.
In line with the theoretical results, I find that optimal temperature change is essentially unaffected by distortionary taxes when climate change only affects production possibilities. In contrast, when all damages enter utilitly directly, optimal peak temperature change ranges from $2.97°C$ without distortionary taxes to $3.24°C$ in the "Green Tax Reform, Capital Tax Revenue Recycling" scenario. Compared to the benchmarke estimate of 75% production impacts proposed by this study, I thus find that attributing all climate impacts to separable utility damages leads to an *overestimate* of optimal peak temperature change around $0.2 - 0.25°C$.

Next, Figures 6 and 7 compare optimal carbon tax schedules across fiscal scenarios for all utility and all production damages, respectively:

For both extreme cases of 100% production and 100% utility damages, the optimal carbon taxes are lower, the more distortionary the fiscal setting. However, the impact of distortioary

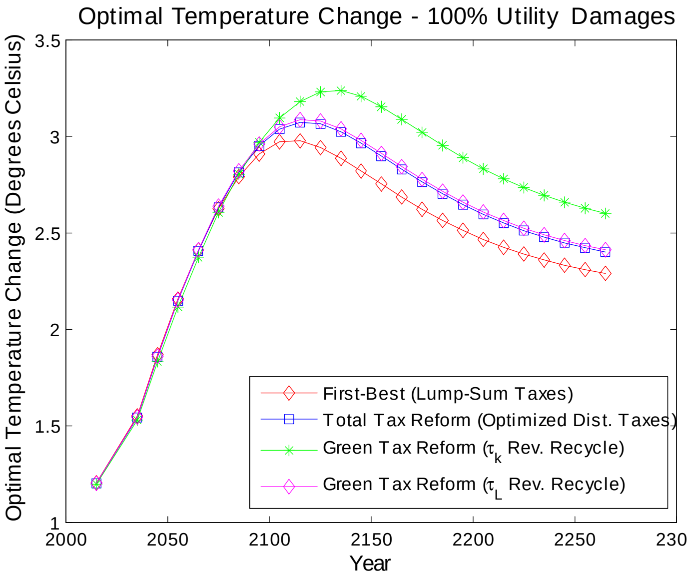

Figure 4: Optimal Temperature Change Across Fiscal Scenarios - All Utility Damages

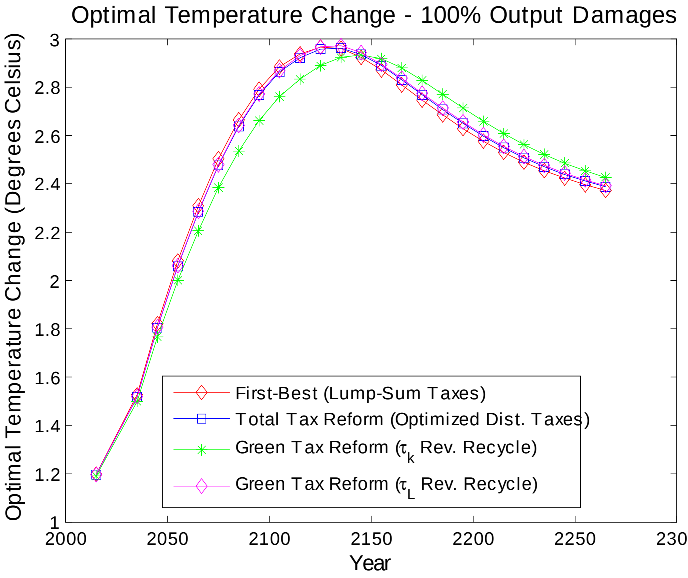

Figure 5: Optimal Temperature Change Across Fiscal Scenarios - All Output Damages

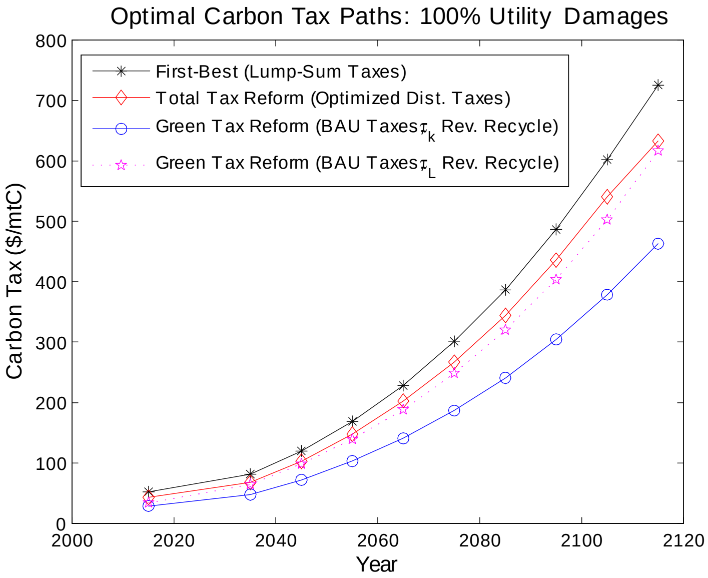

Figure 6: Optimal Carbon Tax Paths Across Fiscal Scenarios: All Utility Damages

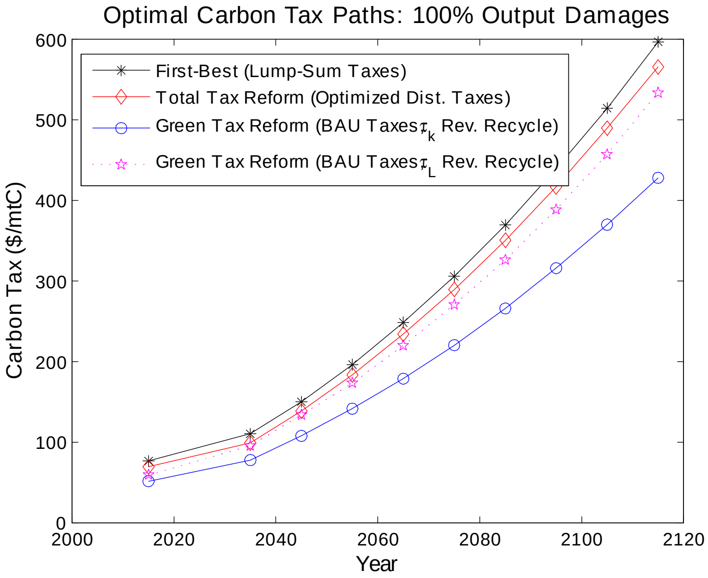

Figure 7: Optimal Carbon Tax Paths Across Fiscal Scenarios: All Output Damages

income taxes on the optimal carbon levy is bigger with 100% utility damages. Specifically, optimal carbon taxes over the 21st Century are on average between $7-30\%$ lower when climate change affects only output, but $13-40\%$ lower when there are only utility damages. Abstracting from the production impacts of climate change thus biases the optimal carbon tax downward. Relative to the COMET benchmark estimate of 75% production damages, I find that assuming 100% utility damages leads to an *underestimate* of the optimal carbon tax by $9-14\%$, depending on the fiscal scenario.

In sum, there are three main results. First, distortionary taxes have a bigger impact on climate policy, the more important utility damages are, in line with the theoretical results. Second, abstracting from climate-economy feedback effects by assuming 100% utility damages leads to an overestimate of optimal peak temperature change of around $0.2-0.25°C$. Third, relative to the COMET's benchmark value of 75% production damages, I find that assuming 100% utility damages biases the estimated optimal carbon tax downward by $9-14\%$.

6 Extensions

This section considers three extensions of the core model. First, I explore a setting with endogenously positive capital income taxes. Second, I study the implications of an exogenous constraint that capital income taxes be positive. Third, I extend the theoretical model to incorporate non-renewable energy resource dynamics.

6.1 Positive Capital Income Taxes

Upper Bound on Capital Income Tax Rates

Following the treatment by Atkeson, Chari, and Kehoe (1999), consider adding an upper bound on the capital tax rate that the government can set. The rationale behind this assumption is as follows. If the government imposes capital taxes that are too high, consumers can always choose not to rent their capital out to firms and to earn a return of $(1-\delta)K_t$ instead. This return provides a lower bound on the equilibrium return to capital, which, in turn, defines the upper bound on capital taxes that can be supported in competitive equilibrium:

$$1-\delta \leq \{1+(r_{t+1}-\delta)(1-\tau_{kt+1})\} = \frac{U_{ct}}{\beta U_{ct+1}} \tag{48}$$

Revisiting the planner's problem with this additional constraint leads to the following proposition:

Proposition 4 *If consumer preferences are of the form:*

$$U(C_t, L_t) = \frac{C_t^{1-\sigma}}{1-\sigma} + \vartheta(L_t) + v(T_t) \tag{49}$$

or

$$U(C_t, L_t) = \frac{(C_t L_t^{-\gamma})^{1-\sigma}}{1-\sigma} + v(T_t) \tag{50}$$

(with $\gamma > 0$*), if capital is necessary in final goods production* ($F_{1t}(0, L_{1t}, E_t) = 0$)*, and if the capital tax rate is bounded above by the agent's ability to hold capital without renting it out to firms (48), then:*

(i) Optimal capital taxes are positive and at the upper bound for a finite number of periods, intermediate for one period, and then drop to zero forever.

(ii) Optimal carbon taxes on output damages are less than Pigouvian while carbon taxes are positive, and jump to Pigouvian levels two periods after the capital tax upper bound ceases to bind.

Proof: See Appendix. The intuition for this result is straightforward. As long as the government imposes maximal capital income taxes, it distorts households' savings decisions. That is, the planner creates a wedge between the marginal rates of substitution and transformation for present and future consumption. This wedge likewise implies the optimality of a less-than-Pigouvian carbon tax, as per the intuition discussed in Section 3.

Exogenously Given Capital Income Tax Rate

Suppose now that there is an exogenously given constraint that the capital income tax rate be equal to some level $\overline{\tau_k} \in (0, 1)$. Such an assumption may reflect unmodeled political constraints. From the consumer and final goods producer's first order conditions for capital, this constraint can be formalized as:

$$\frac{U_{ct}}{\beta U_{ct+1}} = 1 + (1 - \overline{\tau_k})(F_{kt+1} - \delta) \tag{51}$$

for all $t > 0$. In this setting, the impacts of changes in energy use, factor allocation to energy production, and temperature change on the tightness with which (51) binds all figure into the optimal carbon tax formulation. (See Appendix for the derivation and details.)

Importantly, *production damages* from climate change now enter the optimal carbon tax formulation in two ways. On the one hand, they decrease welfare directly by reducing available resources in future periods as shown in the benchmark expression (23). These future output losses are now discounted at a higher rate than households' intertemporal marginal rate of substitution due to the intertemporal wedge in (51). If this were the only difference to the benchmark model with production damages, the optimal carbon tax would thus be less-than-Pigouvian.

However, output losses also interact with the capital tax constraint. Consider the case where the optimal capital tax is below $\overline{\tau_k}$. The net-of-tax marginal rate of transformation faced by agents when making their savings decisions is thus lower than the planner would have wanted it to be. Climate change production losses decrease the marginal product of capital in future periods even further away from the unconstrained optimum. That is, climate change exacerbates the capital income tax constraint in (51). This interaction provides the planner with an additional incentive to avoid climate change. Ceteris paribus, this effect thus *increases* the optimal carbon tax to internalize output damages. In sum, the exogenous capital income tax can increase or decrease the optimal levy on production damages from climate change relative to the Pigouvian rate.

There are additional variables related to carbon taxes that interact with constraint (51) and alter the optimal total carbon tax formulation. For example, decreased energy use may decrease the marginal product of capital as well, depending on the complementarity between capital and energy in production. The optimal *total* carbon tax is thus also ex-ante ambiguously affected by the capital income tax constraint (51).

6.2 Nonrenewable Resources

A sizaeble literature has studied the optimal taxation of carbon emissions from non-renewable energy resources, including, for example, van der Ploeg and Withagen (1991; 2012), Ulph and Ulph (1994), Sinclair (1994), Hoel and Kvemdokk (1996), Farzin and Tahvonen (1996), Sinn (2008), Hassler and Krusell (2012), and Golosov, Hassler, Krusell, and Tsyvinski (2014). However, these studies have generally abstracted from government revenue requirements and other taxes. This sub-section builds on the insights of these studies and GHKT (2014) in particular by extending the benchmark COMET model to include non-renewable resource dynamics. Specifically, assume that carbon energy is in finite supply with initial stock R_0 in the ground. To focus on the central mechanisms, further assume that this carbon resource can be extracted costlessly, and that there is no alternative energy source. With a competitive fossil fuel production sector, the representative firm maximizes the present value of profits subject to its fuel resource constraint:

$$\begin{aligned} \max \sum_{t=0}^{\infty} q_t (1-\tau_{\pi t})\{(p_{Et}-\tau_{Et})E_t\} \\ + \sum_{t=0}^{\infty} q_t \widetilde{\mu}_t \left[R_t - E_t - R_{t+1}\right] \end{aligned}$$

Here, q_t denotes the relative price of consumption in period t (expressed in period 0 units). R_t and R_{t+1} represent the stock of the fossil fuel left in the ground at the beginning of periods t and $t+1$, respectively. Hotelling profits taxes at time t are denoted by $\tau_{\pi t}$. The firm's first order conditions with respect to extraction E_t and the remaining fossil fuel stock R_{t+1} are, respectively:

$$(1-\tau_{\pi t})(p_{Et}-\tau_{Et}) = \widetilde{\mu}_t \tag{52}$$

$$q_t\widetilde{\mu}_t = q_{t+1}\widetilde{\mu_{t+1}} \tag{53}$$

Combining equations (52) and (53) yields the standard Hotelling condition that the after-tax price of carbon energy rises at the rate of interest:

$$(1-\tau_{\pi t})(p_{Et}-\tau_{Et}) = \frac{q_{t+1}}{q_t}(1-\tau_{\pi t+1})\left(p_{Et+1}-\tau_{Et+1}\right) \tag{HOT}$$

Expression (HOT) demonstrates the well-known result that a constant Hotelling profit tax rate on non-renewable resource producers does not affect extraction behavior (see, e.g., Dasgupta and Heal, 1979). The relative returns to oil production across time periods determine optimal extraction schedules. As a result, decreasing fossil fuel profits in each period equiproportionally does not affect producers' incentives. In other words, constant Hotelling profit tax rates on oil production are non-distortionary. If possible, the government thus optimally sets these taxes equal to 100%.

On the other hand, if Hotelling profit taxes are not available, nonrenewable resource rents remain in the agent's budget constraint and hence in the implementability constraint. In order to employ the primal approach to characterizing optimal taxes, these profits must be expressed strictly in terms of allocations. In addition, one needs to prove that the optimal allocation can be decentralized by appropriately designed prices and policy instruments. In the Online Appendix, I formally show that this can be done *for a given initial carbon tax* $\overline{\tau_{E0}}$, and that the implementability constraint in this setting becomes:

$$\sum_{t=0}^{\infty}\beta^t\left[U_{ct}C_t+U_{lt}L_t\right] = U_{c0}\left[K_0\left\{1+(F_{k0}-\delta)(1-\overline{\tau_{k_0}})\right\}+B_0+\sum_{t=0}^{\infty}E_t\left(F_{E0}-\overline{\tau_{E0}}\right)\right] \tag{54}$$

Note that the initial emissions tax $\overline{\tau_{E0}}$ and the carbon resource endowment R_0 both need to be added as initial conditions to the definitions of competitive equilibrium and Ramsey equilibrium in this setting. If profits can be fully taxed, the implementability constraint is as in (IMP).

To facilitate analytic inference on the structure of optimal carbon taxes in this setting, I assume that preferences are of the commonly used forms (49) or (50).

Proposition 5 *Assume preferences are of the form (49) or (50).*

If profit taxes are not available, the optimal carbon tax at time $t > 0$ *is implicitly defined by:*

$$\tau^*_{Et} = \left(\frac{\tau^{Pigou,U}_{Et}}{MCF_t}\right) + \tau^{Pigou,Y}_{Et} + \kappa\left[1 - \frac{1}{MCF_t}\right](\widetilde{\mu_t}) \tag{55}$$

where κ *is a constant equal to* $(1-\sigma)^{-1}$ *for (49) and* $\kappa = ((1-\sigma)(1-\gamma))^{-1}$ *for (50).*
If 100% profits taxes are available, the optimal carbon tax at time $t > 0$ *is implicitly defined by:*

$$\tau^*_{Et} = \left(\frac{\tau^{Pigou,U}_{Et}}{MCF_t}\right) + \tau^{Pigou,Y}_{Et} \tag{56}$$

Proof: See Online Appendix. To summarize, Proposition 5 reveals that the optimal carbon tax in a setting with nonrenewable energy sources and distortionary taxes is structured similarly as in the core model setting with constant returns to scale in energy production. However, a difference arises if the government cannot fully tax away oil producers' Hotelling profits. In that case, optimal carbon taxes are increased as a means of indirectly capturing fossil fuel producers' rents. Previous studies which have noted that optimal pollution taxes may be higher when they can serve as proxy for taxes on rent/profits include, e.g., Bento and Jacobsen (2007), Fullerton and Kim (2008), and Williams (2002). However, these studies have considered more general models with (implicit) fixed factors giving rise to pure profits (and both Williams (2002) and Bento and Jacobsen (2007) do so in a static setting). While the intuition for the result is the same, the results derived here explicitly consider dynamic Hotelling rents arising from non-renewable energy resources in a fiscal climate-economy model.

In order to explore the quantitative significance of Proposition 5, I create a version of the COMET which adopts the energy production sector representation of GHKT (2011 paper version). This specification features a non-renewable energy resource with comparatively high energy content per ton of carbon emissions and zero extraction costs ("oil"), a carbon-based energy form producible from labor inputs ("coal"), and a backstop technology which becomes available in 2120. The optimal energy production trajectory thus typically begins with an oil-only regime, which lasts until economically viable petroleum reserves are exhausted. A coal regime then follows until alternative energy forms become available. Unfortunately, but not surprisingly, I find that the optimal carbon tax in this setting is extremely sensitive to the assumed initial carbon tax, $\overline{\tau_{E0}}$, and to the permissible oil rents profits tax.[54] Empirical estimates of effective tax rates levied on Hotelling profits from oil production vary greatly, from less than 30% in Ireland to over 90% in Iran (Johnston, 2008). A more detailed quantitative and empirically based assessment

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[54] These results are available upon request.

would thus be needed in order to provide serious estimates of the quantitative importance of Proposition 5. However, in sum, consideration of the fiscal setting could provide an impetus for much higher-than-Pigouvian taxes on carbon emissions if those could serve as a substitute for non-distortionary profit taxes on oil producers.

7 Conclusion

This paper considers the optimal taxation of carbon jointly with distortionary taxes enacted to raise government revenues. Specifically, I theoretically characterize and then quantify optimal dynamic carbon taxes as a part of fiscal policy in a climate-economy model based on the world economy. The three main results of the paper can be summarized as follows.

First, I demonstrate both a theoretical and quantitative link between capital and carbon taxes. On the theoretical side, I formally show that the optimal carbon tax to internalize production losses from climate change is the Pigouvian tax whenever capital income taxes are optimally set to zero. Intuitively, this is because setting carbon taxes below Pigouvian rates distorts incentives to invest in the environmental capital stock of the climate. This is analogous to capital income taxes, which distort incentives to invest in physical capital. On the quantitative side, I estimate that the welfare costs of continuing our current policy of *not* taxing carbon are of similar order of magnitude as the welfare costs of taxing capital income ($\$20-\$30$ trillion and \$40 trillion, respectively, \$2005 lump-sum consumption equivalent).

Second, I theoretically motivate and then quantify a distinction between production and direct utility impacts of climate change. On the theoretical side, the intuition for this result is that utility damages reflect the value of the climate as final consumption good. Conversely, production damages reflect the value of the climate as intermediate input to production. The optimal carbon tax internalizes these damages differently. Based on the seminal climate change impact estimates from the DICE model (Nordhaus, 2008), and a new damage function component to capture long-term labor productivity impacts from malaria exposure, I estimate that 75% of climate change impacts from 2.5° affect production; 25% affect utility directly. I further find that abstracting from these production impacts, as many studies do, leads to an *underestimate* of the optimal carbon tax by $9-14\%$.

Third, I quantify optimal carbon tax schedules across fiscal scenarios. Compared to the setting with lump-sum taxation considered by the literature, I find that optimal carbon levies are $8-30\%$ lower when there are other, distortionary taxes. I estimate that adjusting carbon taxes in this way increases the welfare gains from climate policy by \$190 billion to \$2.8 trillion. The total welfare gains from introducing globally optimized carbon taxes are estimated to range from $\$20-\$30$ trillion (0.7% to 1.1% permanent consumption increase).

I would like to conclude by discussing some potential extensions of this study. First, this paper focuses on a deterministic setting, as a natural benchmark. Climate-economy models have considered uncertainty in a variety of forms (parametric uncertainty, stochasticity, autonomous learning, endogenous learning, etc., see, e.g., Peterson, 2006). For example, Lemoine and Traeger (2012) find that consideration of uncertainty over tipping points or irreversibilities in the climate system can increase optimal carbon levies compared to a benchmark based on the DICE model. It is unclear how consideration of such tipping points would interact with distortionary taxes. Several recent models also consider both climate and economic uncertainty (e.g., Krusell and Smith, 2012; Cai, Judd, and Lontzek, 2012). Briggs (2012) incorporates uncertainty over abatement costs in a dynamic setting with (abatement) capital accumulation. Climate policy and business cycles have further been considered by studies such as Heutel (2012) and Fischer and Springborn (2011). A stochastic version of the COMET could consider uncertainty in yet another direction: fiscal fluctuations. Chari and Kehoe (1999) find that optimal labor, capital, and asset taxes vary differentially in response to fiscal shocks. It would correspondingly be interesting to study the optimal response of carbon taxes to fiscal shocks, particularly in light of this paper's finding that optimal capital and carbon taxes are closely linked.

Similarly, consideration of endogenous technical change in climate-economy models can alter optimal policy prescriptions (see, e.g., Popp, 2004; Acemoglu, Aghion, Bursztyn, and Hemous, 2012; Hemous, 2013). For example, Acemoglu, Aghion, Bursztyn, and Hemous (2012) propose a combination of carbon taxes and clean energy research subsidies. However, their analysis allows for lump-sum taxation to finance subsidies. In the context of an endogenous growth model with environmental degradation, Fullerton and Kim (2008) argue that pollution tax revenue may generally be insufficient to finance optimal levels of public abatement research spending. It would thus be interesting to reconsider the optimal policy mix between research subsidies and carbon taxes in a calibrated climate-economy model where subsidies have to be financed through distortionary taxation.

For many countries around the world, the current fiscal outlook is gloomy. This study has argued that carbon taxes have to be designed with care to account for their potentially adverse effects on other tax bases, such as employment. However, this study also found that the imposition of appropriately designed carbon taxes would yield very large and quantitatively significant benefits, both in terms of raising revenues and by significantly improving intertemporal production efficiency.

A Appendix A

A.1 Proof of Proposition 4

Proof Proof in four steps, closely following Atkeson, Chari, and Kehoe (1999).

Step 1: Prove that the upper bound on capital taxes (48) cannot be slack in period t, bind in some period after t, and then become slack again in some period $t+n$ ("Claim 1").

The proof of *Claim 1* proceeds by contradiction. First, note that, with utility of the assumed forms, for $t>0$, the planner's FOCs from (16) imply:

$$\frac{W_{ct}}{W_{ct+1}} = \frac{U_{ct}}{U_{ct+1}} \tag{A.1}$$

If the constraint (48) is binding for periods $t+1$ through $t+n$, then for $j \in \{0, ..., n-1\}$,

$$\frac{U_{ct+j}}{U_{ct+j+1}} = \beta(1-\delta) \tag{A.2}$$

Combining equations (A.1) and (A.2), and iterating forward yields:

$$\frac{W_{ct+1}}{W_{ct+n}} = \beta^{n-1}(1-\delta)^{n-1} \tag{A.3}$$

Let Ψ_t denote the Lagrange multiplier on constraint (48) in period t. The planner's FOC with respect to consumption for $t>0$ in the constrained problem is given by:

$$W_{ct} - \lambda_{1t} + \Psi_t U_{cct} - \Psi_{t-1} U_{cct}(1-\delta) = 0 \tag{A.4}$$

If $[\Psi_t = \Psi_{t+n} = 0]$ and $[\Psi_{t+1}, \Psi_{t+2,}..., \Psi_{t+n-1} > 0]$, then based on (A.4),

$$\lambda_{1t} = W_{ct} - (1-\delta)\Psi_{t-1} U_{cct} \tag{A.5}$$

$$\lambda_{1t+1} = W_{ct+1} + \Psi_{t+1} U_{cct+1} \tag{A.6}$$

and

$$\lambda_{1t+n} = W_{ct+n} - (1-\delta)\Psi_{t+n-1} U_{cct+n} \tag{A.7}$$

The planner's FOC for K_{t+1} is unchanged and implies that:

$$\lambda_{1t} = \beta\lambda_{1t+1}\left[F_{kt+1} + (1-\delta)\right] \tag{A.8}$$

From the planner's FOC for capital (A.8), we further can infer that:

$$\lambda_{1t} = \beta\lambda_{1t+1}[(1-\delta) + F_{kt+1}] \geq \beta\lambda_{1t+1}(1-\delta)$$

Plugging in from equations (A.5)-(A.7), and iterating forward yields:

$$W_{ct+1} + \Psi_{t+1} U_{cct+1} \geq \beta^{n-1}(1-\delta)^{n-1}[W_{ct+n} - (1-\delta)\Psi_{t+n-1}U_{cct+n}] \tag{A.9}$$

Finally, plugging in from equation (A.3) into condition (A.9) results in the contradiction required to prove *Claim 1*:

$$\begin{aligned} W_{ct+n}\beta^{n-1}(1-\delta)^{n-1} + \Psi_{t+1}U_{cct+1} &\geq \beta^{n-1}(1-\delta)^{n-1}[W_{ct+n} - (1-\delta)\Psi_{t+n-1}U_{cct+n}] \quad \text{(A.10)} \\ \Psi_{t+1}U_{cct+1} &\geq \beta^{n-1}(1-\delta)^{n-1}[-(1-\delta)\Psi_{t+n-1}U_{cct+n}] \end{aligned}$$

Since we have assumed that $\Psi_{t+1} > 0$ and $\Psi_{t+n-1} > 0$, condition (A.10) implies a contradiction since $U_{cc_t} < 0$.

Step 2: Show that Ψ_t cannot be positive in every period.

Proof by contradiction. As argued by Atkeson, Chari, and Kehoe (1999), suppose that Ψ_t was binding in every period, implying that the household would always be indifferent to just holding his capital stock and letting it depreciate (rather than investing it). In that case, the capital stock would go zero at rate $K_{t+1} = (1-\delta)K_t$. However, given the assumptions that $F_{1t}(0, L_{1t}, E_t) = 0$ and $\{G_t > 0 \ \forall t > 0\}$, this would violate the resource constraint. Hence, the constraint cannot bind in every period.

Step 3: Show that, if t is the last period in which (48) binds, the optimal capital tax may be at an intermediate value in period $t+1$, but is zero in all periods on or after $t+2$.

Consider the last period t in which the upper bound binds. We then know that $\Psi_{t+1} = 0$, and hence, given the planner's FOC for consumption (A.4), we know that, for $t+1$,

$$\lambda_{1t+1} = W_{ct+1} - (1-\delta)\Psi_t U_{cct+1} \tag{A.11}$$

and for $s \geq t+2$,

$$\lambda_{1s} = W_{cs} \tag{A.12}$$

Combining (A.12) with the optimality condition for capital (A.8), implies that:

$$W_{cs} = \beta W_{cs+1}[(1-\delta) + F_{ks+1}]$$

and since

$$W_{ct}/W_{ct+1} = U_{ct}/U_{ct+1}$$

this implies an optimal capital income tax of zero for $s \geq t+2$.

Step 4:

I now consider the implications of *Claims 1-3* for optimal carbon tax component to internalize output damages. Whether this tax is greater or less than Pigouvian depends on whether:

$$\sum_{j=0}^{\infty} \beta^j \frac{\lambda_{1t+j}}{\lambda_{1t}} \left[\frac{\partial Y_{t+j}}{\partial T_{t+j}} \frac{\partial T_{t+j}}{\partial E_t}\right] \lesseqgtr \sum_{j=0}^{\infty} \beta^j \frac{U_{ct+j}}{U_{ct}} \left[\frac{\partial Y_{t+j}}{\partial T_{t+j}} \frac{\partial T_{t+j}}{\partial E_t}\right]$$

Whenever Ψ_t is binding, we know that:

$$\frac{\beta U_{ct+1}}{U_{ct}} = (1-\delta)^{-1}$$

So the question is whether, at those times,

$$\frac{\beta\lambda_{1t+1}}{\lambda_{1t}} \lesseqgtr (1-\delta)^{-1} = \frac{\beta U_{ct+1}}{U_{ct}}$$

From the planner's FOC for capital (A.8), we know that:

$$\frac{\beta\lambda_{1t+1}}{\lambda_{1t}} = [(1-\delta)+F_{kt+1}]^{-1} < (1-\delta)^{-1}$$

where the inequality follows from the assumption that capital is an essential input to production. Hence:

$$\frac{\beta\lambda_{1t+1}}{\lambda_{1t}} < \frac{\beta U_{ct+1}}{U_{ct}}$$

We thus see that, if Ψ_t is binding for at least period t, the optimal carbon tax is less than Pigouvian. The intuition is that a less-than-Pigouvian tax is equivalent to a positive capital income tax for the climate-damage based intertemporal margin.

The issue left to be determined is what happens if period t is the intermediate period, when the upper bound was binding before and the optimal capital tax is zero from period $t+1$ onwards.

Combining the planner's FOCs for consumption (A.11) and (A.12) for period $s = 1+t$ yields:

$$\frac{\lambda_{1t+1}}{\lambda_{1t}} = \frac{W_{ct+1}}{W_{ct} - \beta^{-1}\Psi_{t-1}U_{cct}(1-\delta)} < \frac{W_{ct+1}}{W_{ct}} = \frac{U_{ct+1}}{U_{ct}}$$

where the inequality follows from the fact that $[U_{cct} < 0]$, and the second equality follows from the assumption on the structure of preferences (49)-(50). Hence, we also find a less-than-Pigouvian tax on output damages in period t when the last period in which the constraint was binding was $t-1$.

Overall, we thus shown that the optimal carbon tax to internalize output damages is less-than-Pigouvian for a finite number of periods, and jumps to the Pigouvian level as soon as capital income taxes are optimally set to zero.

A.2 Exogenously Fixed Capital Tax Rates

The planner's problem is now given by (16) with the addition of the capital tax constraint (51):

$$
\begin{aligned}
&\max_{k}\sum_{t=0}^{\infty}\beta^{t}\underbrace{[U(C_t,L_t,T_t)+\phi\left[U_{ct}C_t+U_{lt}L_t\right]]}_{\equiv W_t}\\
&-\phi\left\{U_{c0}\left[K_0\left\{1+(F_{k0}-\delta)(1-\tau_{k_0})\right\}\right]\right\}\\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{1t}\left[\left\{A_t(T_t)\widetilde{F_{1t}}(L_{1t},E_t,K_{1t})\right\}+(1-\delta)K_t-C_t-G_t-K_{t+1}\right]\\
&+\sum_{t=0}^{\infty}\beta^{t}\xi_t[T_t-F(S_0,E_0,E_1,...E_t)]\\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{lt}\left[L_t-L_{1t}-L_{2t}\right]\\
&+\sum_{t=0}^{\infty}\beta^{t}\lambda_{kt}\left[K_t-K_{1t}-K_{2t}\right]\\
&+\sum_{t=0}^{\infty}\beta^{t}\omega_t\left[F_{2t}(A_{Et},K_{2t},L_{2t})-E_t\right]\\
&-\sum_{t=0}^{\infty}\beta^{t}\Psi_t\left[\underbrace{\frac{U_{ct}}{\beta U_{ct+1}}-\left[1+(1-\overline{\tau_k})(F_{kt+1}-\delta)\right]}_{\equiv\chi_t}\right]
\end{aligned}
$$

The planner's first order condition with respect to temperature change T_t after $t>0$ implies the following marginal welfare cost of temperature change in period t, ξ_t :

$$-U_{Tt}-\lambda_{1t}F_{Tt}+\frac{1}{\beta}\Psi_t\chi_{Tt-1}=\xi_t$$

Here, Ψ_t denotes the Lagrange multiplier on the capital income tax constraint, and χ_{Tt-1} reflects the derivative of the capital tax constraint with respect to temperature change at time. The marginal welfare cost of temperature change thus consists of utility damages U_{Tt}, production damages F_{Tt} (valued at the *public* marginal utility of income λ_{1t}), plus an additional term reflecting the degree to which temperature change relaxes or tightens the capital tax constraint.

Note that:

$$\chi_{Tt}=(-1)\frac{\partial^2 F_{1t}}{\partial K_t\partial T_t}$$

If the government would ideally set capital taxes below $\overline{\tau_k}$, $\Psi_t>0$, and since we are assuming that T_t negatively affects all marginal products, $\chi_{Tt}>0$, and hence marginal welfare costs of temperature change are *higher* than without the capital tax constraint. Intuitively, this is because temperature change decreases the marginal product of capital, and thus exacerbates the capital income tax constraint.

Next, the FOC for energy use E_t for $t > 0$:

$$\lambda_{1t} F_{Et} - \sum_{t=0}^{\infty} \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t} - \frac{1}{\beta} \Psi_t \chi_{Et-1} = \omega_t \tag{A.13}$$

The planner thus seeks to equate the marginal cost of energy production ω_t with its marginal benefit in final goods production F_{Et}, adjusted for the present value of marginal costs with the associated temperature change $\sum_{t=0}^{\infty} \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t}$, and, in this setting, for the way in which energy use affects the capital income tax constraint, $\Psi_t \chi_{Et-1}$. Note that:

$$\chi_{Et} = (-1)(1 - \overline{\tau_k}) \frac{\partial^2 F_{1t}}{\partial K_t \partial E_t}$$

If capital and energy are complements in final goods production, $\chi_{Et} < 0$. If the planner would ideally want to set capital taxes below $\overline{\tau_k}$, $\Psi_t > 0$, and the marginal benefit of energy production is adjusted *upwards* due to its impacts on the capital tax constraint in (A.13). Intuitively, since higher energy uses increases the marginal product of capital, it helps counteract the exogenously given capital income tax. As a result, energy use is more valuable to the planner, ceteris paribus.

Finally, the marginal cost of energy production ω_t is now also adjusted to reflect the impact of changes in labor supply L_t and its allocation between the two production sectors (L_{1t}, L_{2t}) on the capital tax constraint. Combining the corresponding first order conditions yields:

$$\omega_t = \lambda_{1t} \underbrace{\frac{F_{l1t}}{F_{2lt}}}_{\substack{\text{Private MC of} \\ \text{energy production}}} - \underbrace{\frac{\Psi_{t-1} \chi_{l1t-1}}{\beta F_{2lt}}}_{\substack{\text{Capital tax} \\ \text{constraint inter-} \\ \text{action adjustment}}}$$

where:

$$\chi_{l1t} = (-1)(1 - \overline{\tau_k}) \frac{\partial^2 F_{1t}}{\partial K_{1t} \partial L_{1t}}$$

If capital and labor are complements in final goods production then $\chi_{l1t} < 0$. If the planner would want to set capital taxes below $\overline{\tau_k}$, $\Psi_t > 0$, and the marginal cost of energy production is thus adjusted *upwards* to reflect the decrease in the marginal product of capital (and thus the tightening of the capital income tax constraint) associated with allocating labor away from final goods production and towards energy production.

Combining the planner's first order conditions leads to the following implicit expression for optimal carbon taxes in this setting, conditional on all other taxes being set optimally (given the constraints):

$$\begin{aligned}\tau_{Et} \; = \; & \sum_{t=0}^{\infty}\left[\underbrace{\frac{U_{Tt+j}}{\lambda_{1t}}}_{\text{Utility damages}} + \underbrace{\frac{\lambda_{1t+j}}{\lambda_{1t}}F_{Tt+j}}_{\text{Output damages}} - \underbrace{\frac{1}{\beta}\frac{\Psi_{t+j}}{\lambda_{1t}}\chi_{Tt-1+j}}_{\substack{\text{Temperature change}\\ \text{impact on } \overline{\tau_k} \text{ constraint}}}\right]\frac{\partial T_{t+j}}{\partial E_t} \\ & - \underbrace{\frac{1}{\beta}\frac{\Psi_{t-1}}{\lambda_{1t}}\chi_{Et-1}}_{\substack{\text{Energy use}\\ \text{impact on } \overline{\tau_k} \text{ constraint}}} + \underbrace{\frac{1}{F_{2lt}}\frac{1}{\beta}\frac{\Psi_{t-1}}{\lambda_{1t}}\chi_{l1t-1}}_{\substack{\text{Energy production cost}\\ \text{impact on } \overline{\tau_k} \text{ constraint}}}\end{aligned}$$

There are thus several countervailing forces affecting the optimal carbon tax formulation in a setting with exogenously given, suboptimal capital income tax rates. Which effect dominates is ex ante ambiguous. Contrary to the endogenously arising capital income tax in Proposition 4, when the capital tax is imposed exogenously, the planner may thus adjust optimal carbon taxes upwards or downwards.

B Appendix B

B.1 Energy Production Function Labor Share Estimation

This section describes the estimation of the labor share in carbon-based energy production. Industry data from the U.S. Bureau of Economic Analysis ("BEA") on *components of value added by industry* were used for this calculation. Two technical points deserve special attention. First, well-known problems arise with regards to the treatment of mineral resources in industry and national accounts (BEA, 1994). Resource rents are not accounted for explicitly and are thus included as capital returns. Given this concern, and given that the baseline model and calibration focus on carbon energy in sufficiently large supply so as to not earn Hotelling rents (e.g., coal), I thus focus on data from the non-oil and gas energy industries as listed below. Second, in using the BEA data, it is necessary to distribute proprietors' income between capital or labor. In each of the industries considered, base year proprietors' income shares of value added are small, between 4.2% and 5.4%. I follow Valentyni and Herrendorf (2007) in calculating capital and labor shares without proprietors' income. This approach assumes that proprietor's income is split between capital and labor in the same way as other income.[55]

Table 6 summarizes the results from these factor elasticity calculations.

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[55] Very specifically, labor shares are calculated via:

$$\widehat{\alpha_E} = \frac{COM}{COM + \{GOS - BTP - PROP\}}$$

where COM is compensation of employees (including employer contributions to pensions, etc.), GOS is gross operating surplus, BTP is net business current transfer payments, and $PROP$ is proprietors' income, measured in the data as "Other gross operating surplus, noncorporate."

		2000-2010 Average:	
Industry Title	2002 NAICS	Labor Share	GDP Share
Mining, except oil and gas	212	0.606	0.0029
Support activities for mining	213	0.641	0.0024
Utilities	22	0.382	0.0175
Manufacturing of petroleum and coal products	324	0.181	0.0084
All Private Industries		0.719	
Weighted Average Share:		0.368	
Weighted Average Share w/o petroleum/coal manufacturing:		0.438	

Table 6: Labor Share of Value Added in Energy Production

A labor share value of $\alpha_E = 0.403$ is used a compromise between the estimates with and without petroleum and coal products manufacturing, respectively.

B.2 Appendix: Preferences and the Elasticity of Labor Supply

B.2.1 Calibration of Leisure Preferences

The Frisch elasticity of labor supply $\left(\eta^F = \frac{\partial l_t}{\partial w_t}\frac{w_t}{l_t}|_{\overline{\lambda_t}}\right)$ in the current setting is easily derived:

$$\eta^F = \frac{U_{lt}}{l_t\left[U_{llt} - \frac{U_{clt}^2}{U_{cct}}\right]} \tag{B.1}$$

$$= \frac{(1-\phi l_t)}{\phi l_t}\frac{-1}{\left[[\gamma(1-\sigma)-1] - \frac{\gamma(1-\sigma)^2}{(-\sigma)}\right]} \tag{B.2}$$

Similarly, the representative household's first oder condition for labor supply is given by:

$$\frac{-U_{lt}}{U_{ct}} = w_t(1-\tau_{lt})$$

$$\frac{c_t\gamma\phi}{(1-\phi n_t)} = w_t(1-\tau_{lt}) \tag{B.3}$$

I use the two equations (B.2) and (B.3) to solve for the two unknowns γ and ϕ as a function of η^F, l_t, $c_t, (1-\tau_{lt})w_t$, and σ. I calibrate to $t = 2005$ values from the data. The choice to calibrate to the base year is made to increase consistency across model runs with different fiscal scenarios. That is, steady-state labor supply depends on the steady-state labor income tax rate, which is an endogenous outcome of the model and can differ across the fiscal scenarios considered. Differences in steady-state labor supply would then require differences in preference parameters across model runs. These changes would obfuscate the interpretation of the results as being due to changes in tax policy and constraints across model scenarios. Observed base-year values for consumption and labor supply are given from the data and have the attractive trait of being constant across fiscal scenarios. An important exception is the calibration to the first-best (lump sum taxation) setting, which sets ($\tau_{l2005} = 0$).

Baseline labor supply l_{2005} is estimated using OECD data on "Average annual hours actually worked per worker" and on employment rates across all available countries in the model base year 2005. Given Jones, Manuelli, and Rossi's (1993) assumption that adults have 14.5 hours per day available for work, the GDP-weighted average time endowment share spent on labor is $l_{2005} = 0.2272$. Base year consumption per capita c_{2005} is calculated using World Bank data[56] on household final consumption expenditure as share of GDP across all available countries, which is 61% for 2005. The gross wage w_{2005} is calculated as the marginal product of labor in the base year $\left(w_t = \frac{(1-\alpha-v)Y_{2005}}{l_{2005}N_{2005}}\right)$. The base year average marginal labor tax rate τ_{l2005} is the GDP-weighted average labor-consumption effective tax based on estimates from Carey and Rabesona (2002) as discussed in section 4.7. Finally, the value $\sigma = 1.5$ is chosen to match the DICE model (Nordhaus, 2010). The resulting estimates in all distortionary tax model runs are $\gamma = 0.7303$ and $\phi = 2.2343$. In the first-best model run, $\tau_{l2005} = 0$ but all other parameters remain the same, yielding $\gamma = 1.2985$ and $\phi = 2.0785$.

B.2.2 Calibration of Preferences for Climate Change

The goal of the calibration is to find a parameter α_0 such that the disutility of 2.5° climate change is equivalent to the utility loss resulting from 0.49% output damages. Given the chosen preference specification (43), the total utility change from 2.5° warming from utility damages is given by:

$$\begin{aligned} \Delta U^U &= U(2.5^\circ) - U(0^\circ) \\ & \quad \left[\frac{(1+\alpha_0 T_t^2)^{-(1-\sigma)}}{1-\sigma} - \frac{1}{1-\sigma}\right] \end{aligned} \tag{B.4}$$

Analogously, the total utility change from a consumption loss of $D(2.5^\circ)$ can be approximated:[57]

$$\begin{aligned} \Delta U^Y &\approx U(2.5^\circ) - U(0^\circ) \\ &= \frac{(1-\phi l_t)^{\gamma(1-\sigma)}}{1-\sigma}\left[C_t^{\star(1-\sigma)}(1-D(2.5^\circ))^{1-\sigma} - C_t^{\star 1-\sigma}\right] \end{aligned} \tag{B.5}$$

Equating (B.4) and (B.5) allows one to solve for the parameter α_0 that creates utility losses from temperature change equivalent to the desired target value $D(2.5^\circ)$. The benchmark COMET specification (with distortionary taxes) has $\alpha_0 = .000237$. Finally, note that one can easily show that the temperature risk aversion coefficient (Weitzman, 2010) implied by utility function (43)

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[56] *World Development Indicators* data base, World Bank.

[57] Specification (B.5) is only an approximation because it ignores general equilibrium effects on labor supply and employment. However, this is intentional as utility damages are assumed to be separable and so the general equilibrium effects from a consumption change should not be included in the equivalent utility loss.

is given by:

$$\frac{TU_{TT}}{U_T} = \frac{1}{1 + \alpha_0 T_t^2}$$

for utility damages. Similarly, for consumption losses in (B.5) with $(1 - D(2.5°)) = \frac{1}{1+\theta T_t^2}$ as assumed for production damages in (42), we one can easily derive that:

$$\frac{TU_{TT}}{U_T} = \frac{1}{1 + \theta T_t^2}$$

Consequently, for a given amount of damages, the temperature risk aversion coefficient of utility damages matches that of an equivalent consumption loss (ignoring general equilibrium effects).

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