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

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1 Theory Details

1.1 Proof of Proposition 1

This section proves the validity of the primal approach setup as laid out in Proposition 1. The proof follows closely the method outlined in Chari and Kehoe (1999), with appropriate extensions and revisions to accommodate the multi-sector climate-economy setting of this paper. Consider first the representative household's problem and associated first order conditions (FOCs). Note that I assume throughout that the solution to the household's problem is interior. The consumer maximizes household utility U_0 while taking climate change T_t as given:

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

Every period, he faces the following flow budget constraint:

$$C_t + \rho_t B_{t+1} + K_{t+1} \leq w_t(1-\tau_{lt})L_t + \{1 + (r_t - \delta)(1 - \tau_{kt})\} K_t + B_t + \Pi_t + G_t^T \tag{2}$$

Letting γ_t be the Lagrange multiplier on (2) in period t, his FOCs are given by:

$[C_t]$:

$$\gamma_t = \beta^t U_{ct} \tag{3}$$

$[L_t]$:

$$\frac{-U_{lt}}{U_{ct}} = w_t(1-\tau_{lt}) \tag{4}$$

$[K_{t+1}]$:

$$\gamma_t = \beta \gamma_{t+1} \{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\} \tag{5}$$

$[B_{t+1}]$:

$$U_{ct}\rho_t = \beta U_{ct+1} \tag{6}$$

Next, consider the final goods producer's problem, which is to choose L_{1t}, K_{1t}, and E_t to solve:

$$\max F_1(A_{1t}, T_t, L_{1t}, K_{1t}, E_t) - w_t L_t - p_{Et} E_t - r_t K_t$$

Letting F_{1jt} denote the first derivative of the production function with respect to factor j, the associated first order conditions are:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \tag{7}$$

The energy producer solves:

$$\begin{aligned} &\max \Pi_t = (p_{Et} - \tau_{It})E_t - [(1-\mu_t)E_t]\tau_{E_t} - w_t L_{2t} - r_t K_{2t} - \Theta_t(\mu_t E_t) \\ \text{s.t.:} \quad & E_t = A_{2t} F_2(, K_{2t}, L_{2t}) \end{aligned}$$

The associated FOCs are:

$$\begin{aligned} [p_{Et} - \tau_{It} - \tau_{Et}]F_{2lt} &= w_t \\ [p_{Et} - \tau_{It} - \tau_{Et}]F_{2kt} &= r_t \\ \tau_{Et} &= \Theta_t' \end{aligned} \tag{8}$$

Direction: If the allocations and initial conditions constitute a competitive equilibrium, then constraints (RC)-(IMP) are satisfied. If we are in a competitive equilibrium, the consumer's FOCs (3)-(6) will be satisfied. Note that we can multiply both sides on the FOC for capital savings (5) by K_t to find that:

$$\left[\gamma_t - \gamma_{t+1}\left\{1 + (r_{t+1} - \delta)(1 - \tau_{kt+1})\right\}\right] K_{t+1} = 0 \tag{9}$$

Similarly, for bonds we have that:

$$\left[\gamma_t \rho_t - \gamma_{t+1}\right] B_{t+1} = 0 \tag{10}$$

The consumer's transversality conditions necessarily hold in a competitive equilibrium:

$$\begin{aligned} \lim_{t\to\infty} \gamma_t B_{t+1} &= 0 \\ \lim_{t\to\infty} \gamma_t K_{t+1} &= 0 \end{aligned} \tag{11}$$

In a competitive equilibrium, the consumer's flow budget constraint (2) also needs to be satisfied. Multiplying both sides of the flow budget constraint in each period by γ_t yields:

$$\gamma_t \left[C_t + \rho_t B_{t+1} + K_{t+1}\right] = \gamma_t \left[w_t(1-\tau_{lt})L_t + \left\{1 + (r_t - \delta)(1-\tau_{kt})\right\} K_t + B_t + \Pi_t + G_t^T\right] \tag{12}$$

Note that energy sector profits in competitive equilibrium will be equal to zero, given the assumptions of constant returns to scale and perfect competition in energy production. Taking note of this fact and summing equation (12) over all t leads to:

$$\sum_{t=0}^{\infty}\gamma_t\left[C_t+\rho_t B_{t+1}+K_{t+1}-w_t(1-\tau_{lt})L_t-\{1+(r_t-\delta)(1-\tau_{kt})\}K_t-B_t-G_t^T\right]=0 \quad (13)$$

Except for the time zero bonds and capital return, all of the other terms relating to capital and bonds cancel out of equation (13) out as per equations (9), (10) and the transversality conditions (11). We thus end up with:

$$\sum_{t=0}^{\infty}\gamma_t\left[C_t-w_t(1-\tau_{lt})L_t-G_t^T\right]=\gamma_0\left[K_0\{1+(r_0-\delta)(1-\tau_{k_0})\}+B_0\right] \quad (14)$$

Next, based on the consumer's and firm's FOCs, one can substitute out for γ_t, $w_t(1-\tau_{lt})$, and r_0 in (14) to obtain the implementability constraint (15):

$$\sum_{t=0}^{\infty}\beta^t\left[U_{ct}C_t+U_{lt}L_t-U_{ct}G_t^T\right]=U_{c0}\left[K_0\{1+(F_{k0}-\delta)(1-\tau_{k_0})\}+B_0\right] \quad (15)$$

We have thus shown that competitive equilibrium implies that the implementability constraint is satisfied. Next, to show that the final goods resource constraint holds in competitive equilibrium, (i) add up the consumer and government flow budget constraints, (ii) substitute in the bond market clearing condition, (iii) invoke the definition of energy sector profits, (iv) substitute in capital and labor market clearing conditions, (v) substitute in for factor prices based on the final good producer's FOCs, and (vi) invoke Euler's theorem based on the assumption of constant returns to scale in final goods production. Finally, the carbon cycle constraint and the energy producer's resource constraint hold by definition in competitive equilibrium.

Direction: If constraints (RC)-(IMP) are satisfied, one can construct competitive equilibrium. We proceed by construction. First, let factor prices be given by:

$$\begin{aligned} F_{1lt} &= w_t \\ F_{1Et} &= p_{Et} \\ F_{1kt} &= r_t \end{aligned} \quad (16)$$

These factor prices are obviously consistent with profit maximization in the final goods sector, as required in a competitive equilibrium. Next, let the return on bonds be given by:

$$\rho_t = \beta U_{ct+1}/U_{ct}$$

Again, this price is clearly consistent with utility maximization as per the agent's FOC (6). Let the labor tax rate be determined by:

$$\begin{aligned} -U_{lt}/U_{ct} &= (1-\tau_{lt})F_{1lt} \\ 1+\frac{U_{lt}/U_{ct}}{F_{1lt}} &= \tau_{lt} \end{aligned}$$

Similarly, let the tax rate on capital income for each time $t > 0$ be defined via:

$$\begin{aligned} U_{ct} &= \beta U_{ct+1}\left\{1+(F_{1kt+1}-\delta)(1-\tau_{kt+1})\right\} \\ \tau_{kt+1} &= 1-\frac{U_{ct}/\beta U_{ct+1}-1}{(F_{1kt+1}-\delta)} \end{aligned}$$

As per the consumer's and final goods producer's FOCs , these tax rates will clearly be consistent with utility and profit maximization. Next, let the tax rates on carbon emissions and energy, respectively, be given by:

$$\tau_{Et} = \Theta_t'(\mu_t E_t) \tag{17}$$

$$\tau_{It} = \left[p_{Et}-\frac{F_{1lt}}{F_{2lt}}\right]-\tau_{Et} \tag{18}$$

Again, this tax is clearly consistent with profit maximization in the energy and final goods production sectors as per FOCs (8) and (7).

To construct bond holdings in period t, first multiply the consumer budget constraint (2) by its Lagrange multiplier γ_t and sum over all periods *from period t onwards*:

$$\sum_{s=t}^{\infty}\gamma_s\left[C_s+\rho_s B_{s+1}+K_{t+1}-w_s(1-\tau_{ls})L_s-\{1+(r_s-\delta)(1-\tau_{ks})\}-B_s-\Pi_s-G_t^T\right]=0$$

In a competitive equilibrium, the consumer's FOCs and transversality conditions (11) must hold, implying that all future terms relating to capital and bonds cancel out, yielding:

$$\sum_{s=t}^{\infty}\gamma_s\left[C_s-w_s(1-\tau_{ls})L_s-\Pi_s-G_t^T\right]+\gamma_t\left\{1+(r_t-\delta)(1-\tau_{kt})\right\}K_t=\gamma_t B_t \tag{19}$$

Again using the agent's and the firms' FOCs to substitute out prices in equation (19) yields:

$$\sum_{s=t}^{\infty}\frac{\beta^{s-t}U_{cs}}{U_{ct}}\left[C_s+\frac{U_{ls}}{U_{cs}}L_s-G_s^T\right]+\frac{U_{ct-1}}{\beta U_{ct}}K_t=B_t$$

This equation defines the unique bond holdings that are consistent with a competitive equilibrium, given allocations. Being based on agents' and firms' first order conditions and constraints, the prices and policies defined above are clearly consistent with utility and profit maximization. It remains to be shown that all the necessary constraints for competitive equilibrium are satisfied.

The final goods resource constraint, the carbon cycle constraint, the energy production resource constraints, and the factor market clearing conditions all hold by assumption. By Walras' law, demonstrating that the consumer budget constraint is satisfied is sufficient to imply that the government budget constraint must be satisfied also.

Note that only the consumer's competitive equilibrium-budget constraint is relevant to our proof, as we seek to demonstrate that our constructed prices, bond holdings, and policies are constitute a competitive equilibrium. In a competitive equilibrium, the household's intertemporal budget constraint must hold, along with the consumer's FOCs, implying (9) and (10), and the consumer's transversality conditions. The key point, then, is that, at the prices selected above, the consumer's competitive equilibrium-budget constraint then becomes identical to the implementability constraint, which holds by assumption. Thus, the competitive equilibrium budget constraint at the chosen prices is satisfied ■.

1.1.1 Formulation with Population Growth

The numerical implementation of the COMET considers the model in per-capita terms and allows the population to change over time. In this setup, the dynastic household maximizes:

$$\max\sum_{t=0}^{\infty}\beta^t N_t U(c_t,l_t,T_t)$$

where N_t denotes the world's population at time t (exogenously given), $c_t\equiv C_t/N_t$, and $l_t\equiv L_t/N_t$. The associated budget constraint is:

$$N_tc_t+\rho_tb_{t+1}N_{t+1}+k_{t+1}N_{t+1}\leq w_t(1-\tau_{lt})l_tN_t+\{1+(r_t-\delta)(1-\tau_{kt})\}k_tN_t+b_tN_t+\pi_tN_t+g_t^TN_t$$

where all lower case variables are again in per-capita terms (e.g., $b_{t+1}\equiv B_{t+1}/N_{t+1}$, etc.). The household's optimality conditions cancel out to be the same as above (3)-(6). Following the same steps as outlined above, it is then straightforward to show that the implementability constraint

(IMP) in this setup is given by the simple per-capita version of (15):

$$\sum_{t=0}^{\infty} N_t \beta^t \left[U_{ct}c_t + U_{lt}l_t - U_{ct}g_t^T\right] = N_0 U_{ct}\left[k_0\left\{1+(r_0-\delta)(1-\tau_{k_0})\right\}+b_0\right]$$

1.2 Third-Best Climate Policy

1.2.1 Corollary 1: Capital Income Tax Constraints

Proof: Assume the government is constrained to maintain capital income taxes at some level $\tau_{kt+1} = \overline{\tau_k} \in (0,1)\ \forall t > 0$. In the primal approach, this constraint implies the planner must maintain a wedge of size $\overline{\tau_k}$ between the household's intertemporal marginal rate of substitution, and the marginal rate of transformation:

$$1 + (1-\overline{\tau_k})(F_{1kt+1} - \delta) = \frac{U_{ct}}{\beta U_{ct+1}} \tag{20}$$

Adding (20) to the planner's problem with Lagrange multipliers Ψ_t, and taking the first-order conditions with respect to abatement μ_t and temperature change T_t yields:

$[\mu_t]$, $t > 0$:

$$\Theta_t' = \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t^M} \tag{21}$$

$[T_t]$, $t > 0$:

$$U_{Tt} + \lambda_{1t}\frac{\partial Y_t}{\partial T_t} + \frac{\Psi_{t-1}}{\beta}\frac{\partial F_{1kt}}{\partial T_t}(1-\overline{\tau_k}) = -\xi_t \tag{22}$$

Combining (21) and (22) yields an implicit expression for the marginal abatement cost at the optimal allocation:

$$\Theta_t' = (-1)\sum_{j=0}^{\infty}\beta^j \left[\frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}}\frac{\partial Y_{t+j}}{\partial T_{t+j}} + \frac{\Psi_{t-1+j}/\beta}{\lambda_{1t}}\frac{\partial F_{1kt+j}}{\partial T_{t+j}}(1-\overline{\tau_k})\right]\frac{\partial T_{t+j}}{\partial E_t^M} = \tau_{Et}^* \tag{23}$$

Invoking the definition of the MCF_t, multiplying the utility damages term in (23) by $\frac{U_{ct}}{U_{ct}}$, and noting that the marginal abatement cost defines the optimal carbon tax τ_{Et}^* as per (17) completes the derivation of the optimal carbon tax expression in Corollary 1.

Next, in order to derive the government's discount factor, take and combine the first-order conditions with respect to K_{t+1} and K_{1t}, respectively, for $t > 0$ to obtain:

$$\frac{\lambda_{1t}}{\beta\lambda_{1t+1}} = F_{1kt+1} + (1-\delta) + \frac{\Psi_t/\beta}{\lambda_{1t+1}}\frac{\partial F_{1kt+1}}{\partial K_{1t+1}}(1-\overline{\tau_k}) \tag{24}$$

Finally, inverting (24) yields the desired result. ■.

Intermediate Good Taxes: The unconstrained optimal Ramsey allocation was shown to feature no energy taxes beyond levies on carbon emissions, in line with the standard Intermediate Goods Taxation result (Diamond and Mirrlees, 1971). In this third-best setting, however, this result no longer applies. To see this formally, taking the FOCs with respect to total energy E_t, and labor in each sector L_{1t}, L_{2t} for $t > 0$ yields:

$[E_t]$, $t > 0$:

$$\lambda_{1t} F_{1Et} - \lambda_{1t}\Theta'_t \mu_t - \sum_{j=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t^M}(1-\mu_t) + \frac{\Psi_{t-1}}{\beta}\frac{\partial F_{1k,t}}{\partial E_t}(1-\overline{\tau_k}) = \lambda_{2t} \tag{25}$$

$[L_{2t}]$, $t > 0$:

$$\lambda_{2t} = \frac{\lambda_{lt}}{F_{2lt}} \tag{26}$$

$[L_{1t}]$, $t > 0$:

$$\lambda_{1t} F_{1lt} + \frac{\Psi_{t-1}}{\beta}\frac{\partial F_{1k,t}}{\partial L_{1t}}(1-\overline{\tau_k}) = \lambda_{lt} \tag{27}$$

Substituting in from (21) and (26)-(27) into (25) yields an implicit expression for the wedge between the marginal product of energy and its marginal production cost at the optimal allocation, net of the carbon tax:

$$\left[F_{1Et} - \frac{F_{1lt}}{F_{2lt}}\right] - \underbrace{\left[\frac{1}{\lambda_{1t}}\sum_{j=0}^{\infty}\beta^j \xi_{t+j}\frac{\partial T_{t+j}}{\partial E_t^M}\right]}_{=\tau^*_{Et}} = \frac{\Psi_{t-1}/\beta}{\lambda_{1t}}\left[\frac{-\partial F_{1kt}}{\partial E_t} + \frac{1}{F_{2lt}}\frac{\partial F_{1kt}}{\partial L_{1t}}\right](1-\overline{\tau_k}) = \tau^*_{It} \tag{28}$$

As per the benchmark decentralization (18), this equation defines the optimal intermediate good tax in the third-best setting with capital income tax constraint (20). This tax is thus non-zero only if the capital income tax constraint is binding ($\Psi_{t-1} \neq 0$). In this case, the planner needs to take into account interactions between energy usage and the efficiency costs of constraint (20). For example, assume that the planner would like to set capital taxes below $\overline{\tau_k}$, so that $\Psi_t > 0$. If higher energy use increases the marginal product of capital $\left(\frac{\partial F_{1kt}}{\partial E_t} > 0\right)$, it can counteract the capital income tax constraint (by increasing the returns to capital closer towards optimal levels). All else equal, this additional value of energy usage in the third-best would be reflected in an energy subsidy ($\frac{\Psi_{t-1}/\beta}{\lambda_{1t}}\frac{-\partial F_{1kt}}{\partial E_t}(1-\overline{\tau_k})$). At the same time, however, higher energy production requires additional labor input, resulting in less labor available for final goods production. To the extent that pulling labor out of the final goods sector decreases the marginal product of capital there ($\frac{\partial F_{1kt}}{\partial L_{1t}} > 0$), this represents an additional cost of energy production in the constrained setting, reflected in an energy tax ($\frac{\Psi_{t-1}/\beta}{\lambda_{1t}}\frac{1}{F_{2lt}}\frac{\partial F_{1kt}}{\partial L_{1t}}(1-\overline{\tau_k})$). The sign of the intermediate good tax is thus theoretically ambiguous. Importantly, these considerations pertain to a general energy tax applied to both clean- and fossil-based energy; the optimal carbon emissions tax (which is the focus of the analysis) remains characterized by (23).

1.2.2 Corollary 2: Labor Income Tax Constraints

Proof: Assume the government is constrained to maintain labor income taxes at some level $\tau_l = \overline{\tau_l} \in (0,1)$ $\forall t > 0$. In the primal approach, this constraint implies the planner must maintain a wedge of size $\overline{\tau_l}$ in the household's consumption-leisure decision margin:

$$F_{1lt}(1-\overline{\tau_l}) = \frac{-U_{lt}}{U_{ct}} \tag{29}$$

Adding (29) to the planner's problem with Lagrange multiplier Λ_t, and taking the first-order conditions with respect to abatement μ_t and temperature change T_t yields:

$[\mu_t]$, $t > 0$:

$$\Theta_t' = \frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t^M} \tag{30}$$

$[T_t]$, $t > 0$:

$$U_{Tt} + \lambda_{1t} \frac{\partial Y_t}{\partial T_t} + \Lambda_t \frac{\partial F_{1lt}}{\partial T_t}(1-\overline{\tau_l}) = -\xi_t \tag{31}$$

Combining these conditions yields an implicit expression for the marginal abatement cost at the optimal allocation:

$$\Theta_t' = (-1) \sum_{j=0}^{\infty} \beta^j \left[\frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}} \frac{\partial Y_{t+j}}{\partial T_{t+j}} + \frac{\Lambda_{t+j}}{\lambda_{1t}} \frac{\partial F_{1lt+j}}{\partial T_{t+j}}(1-\overline{\tau_l}) \right] \frac{\partial T_{t+j}}{\partial E_t^M} = \tau_{Et}^* \tag{32}$$

Invoking the definition of the MCF_t, multiplying the utility damages term by $\frac{U_{ct}}{U_{ct}}$, and noting that the marginal abatement cost defines the optimal carbon tax τ_{Et}^* in the decentralization as per (17) completes the derivation of the optimal carbon tax expression in Corollary 2.

Next, in order to derive the government's discount factor, take and combine the first-order conditions with respect to K_{t+1} and K_{1t}, respectively, for $t > 0$ to obtain:

$$\frac{\lambda_{1t}}{\beta \lambda_{1t+1}} = F_{1kt+1} + (1-\delta) + \frac{\Lambda_{t+1}}{\lambda_{1t+1}} \frac{\partial F_{1lt+1}}{\partial K_{1t+1}}(1-\overline{\tau_l}) \tag{33}$$

Finally, inverting (33) yields the desired result. ■.

Intermediate Good Taxes: In order to characterize general energy taxes in this setting, we again take the FOCs with respect to total energy E_t, and labor in each sector L_{1t}, L_{2t} for $t > 0$, yielding:

$[E_t]$, $t > 0$:

$$\lambda_{1t} F_{1Et} - \Theta'_t \mu_t - \sum_{t=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t} (1 - \mu_t) + \Lambda_t \frac{\partial F_{1lt}}{\partial E_t} (1 - \overline{\tau_l}) = \lambda_{2t} \tag{34}$$

$[L_{2t}]$, $t > 0$:

$$\lambda_{2t} = \frac{\lambda_{lt}}{F_{2lt}} \tag{35}$$

$[L_{1t}]$, $t > 0$:

$$\lambda_{1t} F_{1lt} + \Lambda_t \frac{\partial F_{1lt}}{\partial L_{1t}} (1 - \overline{\tau_l}) = \lambda_{lt} \tag{36}$$

Substituting in from (21) and (35)-(36) into (34) again yields an implicit expression for the wedge between the marginal product of energy and its marginal production cost at the optimal allocation, net of the carbon tax:

$$\left[F_{1Et} - \frac{F_{1lt}}{F_{2lt}} \right] - \underbrace{\left[\frac{1}{\lambda_{1t}} \sum_{j=0}^{\infty} \beta^j \xi_{t+j} \frac{\partial T_{t+j}}{\partial E_t^M} \right]}_{= \tau^*_{Et}} = \frac{\Lambda_t}{\lambda_{1t}} \left[\frac{-\partial F_{1lt}}{\partial E_t} + \frac{1}{F_{2lt}} \frac{\partial F_{1lt}}{\partial L_{1t}} \right] (1 - \overline{\tau_l}) = \tau^*_{It}$$

In contrast to the case with a capital income tax constraint (28), the sign of the optimal energy tax in this setting follows directly from the sign of Λ_t. In the empirically relevant setting where the government would like to set a higher labor income tax, $\Lambda_t < 0$, so that the optimal general energy tax will be positive (as final goods production is assumed to satisfy the usual Inada conditions). The optimal carbon tax τ^*_{Et}, however, again remains characterized by (32).

1.3 Non-Separable Preferences over Climate Change

The COMET model assumes that household preferences are (additively) separable between climate change and consumption/leisure. A key implication is that climate change does not affect the set of allocations decentralizable as a competitive equilibrium other than through its effects on output. If, however, climate change were a relative complement or substitute for leisure, this would no longer be the case, and the optimal carbon tax formulation would have to be modified. In particular, relaxing this assumption does not change the planner's problem relative to the benchmark except that U_{ct} and U_{lt} are now functions of temperature change T_t. As a result, it is easy to show that the marginal damage of temperature change in period $t > 0$ (in utils) is then given by:

$$\underbrace{U_{Tt}}_{\text{Utility damage}} + \underbrace{\lambda_{1t}\frac{\partial Y_t}{\partial T_t}}_{\text{Output damage}} + \underbrace{\phi[U_{cTt}C_t + U_{lTt}L_t]}_{\text{Offer curve impact}} = \underbrace{-\xi_t}_{\text{Marginal damage from } T_t} \tag{37}$$

where ϕ is the Lagrange multiplier on the implementability constraint, and $U_{jTt} \equiv \frac{\partial^2 U(.)}{\partial j \partial T_t}$. In addition to utility losses and output damages, climate change can thus impact welfare in a third way in this setting. If temperature affects households' offer curves, it changes the set of allocations that can be decentralized as a competitive equilibrium. For example, if climate change is complementary with leisure, households will be less willing to supply labor at a given wage as the climate warms.

Combining the planner's first order conditions for energy inputs E_t, total labor supply L_t, and energy sector labor L_{2t} with (37), and comparing with the energy producer's optimality conditions leads to the following expression implicitly defining the optimal tax in this setting:

$$\begin{aligned} \tau^*_{Et} &= \sum_{j=0}^{\infty}\beta^j \left\{ \frac{U_{Tt+j}}{\lambda_{1t}} + \frac{\lambda_{1t+j}}{\lambda_{1t}}\frac{\partial Y_{t+j}}{\partial T_{t+j}} + \frac{\phi}{\lambda_{1t}}[U_{cTt+j}C_{t+j} + U_{lTt+j}L_{t+j}] \right\} \frac{dT_{t+j}}{dE^M_t} \\ &= \underbrace{\frac{\tau^{Pigou,U}_{Et}}{MCF_t}}_{\text{Utility damages}} + \sum_{j=0}^{\infty}\beta^j \left\{ \underbrace{\frac{\lambda_{1t+j}}{\lambda_{1t}}\frac{\partial Y_{t+j}}{\partial T_{t+j}}}_{\text{Output damages}} + \frac{(MCF_t - 1)}{MCF_t} \underbrace{\left[\frac{U_{cTt+j}C_{t+j} + U_{lTt+j}L_{t+j}}{U_{cct}C_t + U_{ct} + U_{lct}L_t}\right]}_{\text{Offer curve impacts}} \right\} \frac{dT_{t+j}}{dE^M_t} \end{aligned} \tag{38}$$

where the second equation follows from substituting in for ϕ from the planner's first order condition for C_t, multiplication by U_{ct}/U_{ct}, and invoking the definition of the MCF_t.

Expression (38) leads to two main insights. On the one hand, non-separability in preferences does not change the key theoretical findings of this paper. That is, it is still the case that (i) utility damages are internalized differently from production damages, and (ii) the optimal tax component for output damages is Pigouvian if the planner optimally sets capital income taxes to zero from time t onwards (implying that $\frac{\lambda_{1t+j}}{\lambda_{1t}} = \frac{U_{ct+j}}{U_{ct}}$ for all $j \geq 0$).

On the other hand, the optimal total carbon tax can now be larger or smaller than the Pigouvian tax, depending on the sign and size of the size and sign of the impacts of temperature change on the agents' offer curves. In particular, the offer curve impact will increase the level of the optimal carbon tax if climate change utility impacts are *complementary with leisure* and *a substitute for consumption.* 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. Relatedly, Schwartz and Repetto (2000) demonstrate that the welfare costs of the interaction between labor income taxes and pollution taxes are reduced to the extent that improved environmental quality can increase labor supply. Carbone and Smith (2008) provide a quantitative analysis of the implications of non-separability in a model of particulate matter pollution in the U.S. economy.

Unfortunately, the literature provides very little empirical evidence on the likely magnitudes and signs of the complementarity between climate change and leisure and consumption, respectively. The climate amenity value estimates underlying the DICE damage function include modest increases in the value of time use for cold regions and negative impacts for warm regions, based on estimates for the United States by Nordhaus (1998). Neidell and Zivin (2010) find that overall labor supply in the United States does not appear responsive to changes in weather-induced temperature variation. However, labor supply in climate-sensitive industries (agriculture, construction, utilities, etc.) does decrease significantly and sizably during hot weather. A well-known concern in extrapolating from weather variation impacts to climate change is that they do not account for long-term adaptation (e.g., Mendelsohn, Nordhaus, and Shaw 1994). Indeed, Neidell and Zivin do find that the impacts of warm temperatures are weaker in warmer regions. Future research in this area would thus be highly valuable for more accurate calibration of environmental tax interaction studies.

1.4 Extension: Multi-Country Setting

1.4.1 Case 1: Transfers Across Countries Are Possible

Assume there are N countries with the economic structure as in the benchmark model. The representative consumer in country i has preferences over his consumption C_{it}, labor supply, L_{it}, and global temperature change T_t (separably). Letting γ_t^i denote the weight that the global planner attaches to country $i's$ utility at time t, he seeks to maximize:

$$\max \sum_{i=1}^{N} \sum_{t=0}^{\infty} \beta^t \gamma_t^i U(C_{it}, L_{it}, T_t)$$

Letting Υ_{it} denote country $i's$ *net* foreign transfers in period t (which can be positive or negative), its economy-wide budget constraint is then given by:

$$F_{1i}(A_{1it}, T_t, L_{1it}, K_{1it}, E_{it}) + (1-\delta)K_{it} \geq C_{it} + G_{it}^C + \Upsilon_{it} + K_{it+1} - \Theta_{it}(\mu_{it}E_{it}) \tag{39}$$

If the global planner can assign international transfers Υ_{it}, he effectively faces a single international resource constraint for the final consumption-investment good:[1]

$$\sum_{i=1}^{N} \left\{ F_{1i}(A_{1it}, T_t, L_{1it}, K_{1it}, E_{it}) + (1-\delta)K_{it} - C_{it} - G_{it}^{C} - K_{it+1} - \Theta_{it}(\mu_{it}E_{it}) \right\} \geq 0 \tag{40}$$

Note that (40) holds regardless of whether we allow countries to trade the energy and consumption good. Assume that country i can export energy E_{it}^{X} and import energy E_{it}^{Im}. Maintaining the notation of E_{it} as the total energy input consumed by country i in final goods production in period t, its energy resource constraint becomes:

$$E_{it} \leq A_{2it}F_{2i}(K_{2it}, L_{2it}) - E_{it}^{X} + E_{it}^{\text{Im}} \tag{41}$$

Letting p_{Et} denote the (now internationally harmonized) price of the energy good, country $i's$ economy-wide budget constraint becomes:

$$F_{1i}(A_{1it}, T_t, L_{1it}, K_{1it}, E_{it}) + (1-\delta)K_{it} + p_{Et}(E_{it}^{X} - E_{it}^{\text{Im}}) \geq C_{it} + G_{it}^{C} + \Upsilon_{it} + K_{it+1} - \Theta_{it}(\mu_{it}E_{it}) \tag{42}$$

However, summing (42) across countries again leads to (40) as the sum of net energy exports must equal zero. While tradability of energy does change energy resource constraints from N country-specific ones to a single-global one, this does not alter the optimal carbon tax formula.

The global planner's problem in this setting with transfers and energy trade is given by:

[1] To see this, note that the sum of international transfers cannot be negative $\left(\sum_{i=1}^{n} \Upsilon_{it} \geq 0\right)$, and substitute in from each country's resource constraint (39).

$$
\begin{aligned}
&\max \sum_{i}^{N}\sum_{t=0}^{\infty}\beta^t \left\{\gamma_t^i U(C_{it}, L_{it}, T_t) + \phi_i \left(U_{cit}C_{it} + U_{lit}L_{it} - U_{cit}G_{it}^T\right)\right\} \\
&+\sum_{t=0}^{\infty}\beta^t \lambda_{1t}\sum_{i}\left[F_{1i}(A_{1it}, T_t, L_{1it}, K_{1it}, E_{it}) + (1-\delta)K_{it} - C_{it} - G_{it} - K_{it+1} - \Theta_{it}(\mu_{it}E_{it})\right] \\
&+\sum_{t=0}^{\infty}\beta^t \xi_t[T_t - F(\mathbf{S}_0, \sum_{i}(1-\mu_{i0})E_{i0}, \sum_{i}(1-\mu_{i1})E_{i1}, ...\sum_{i}(1-\mu_{it})E_{it}, \boldsymbol{\eta}_0, ...\boldsymbol{\eta}_t)] \\
&+\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^t \lambda_{lit}\left[L_{it} - L_{i1t} - L_{i2t}\right] \\
&+\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^t \lambda_{kit}\left[K_{it} - K_{i1t} - K_{i1t}\right] \\
&+\sum_{t=0}^{\infty}\beta^t \lambda_{2t}\left[\sum_{i=1}^{N}A_{2it}F_{2i}(K_{2it}, L_{2it}) - \sum_{i=1}^{N}E_{it}\right] \\
&-\sum_{i}^{N}\phi_i\left\{U_{ci0}\left[K_{i0}\left\{1 + (F_{ki0} - \delta)(1 - \overline{\tau_{ki0}})\right\} + B_{i0}\right]\right\}
\end{aligned}
$$

Combining the planner's FOCs with respect to country $i's$ abatement, energy usage, and sectoral labor supplies leads to the following optimality conditions:

$$
\Theta'_{it} = F_{1iEt} - \frac{F_{1ilt}}{F_{2ilt}} = \frac{1}{\lambda_{1t}}\sum_{j=0}^{\infty}\beta^j \xi_{t+j}\frac{\partial T_t}{\partial E_{it}^M} \tag{43}
$$

In words, (43) says that both the marginal abatement cost (Θ'_{it}) and the wedge between country $i's$ marginal product of energy F_{1iEt} and the private production costs of energy $\frac{F_{1ilt}}{F_{2lit}}$ should be equal to the present discounted value of the shadow cost of additional carbon ξ_{t+j} in the atmosphere, valued by the uniform global public marginal utility of resources λ_{1t}. As is clear from (43), this optimal wedge is uniform across countries as the right-hand side of (43) does not depend on i (as the warming impacts of emissions in any country are the same, i.e., $\frac{\partial T_t}{\partial E_{it}^M} = \frac{\partial T_t}{\partial E_{jt}^M}$ $\forall j, i$). More precisely, substituting in the decentralized equilibrium conditions (e.g., $F_{1iEt} = p_{Eit}$) and comparing (43) with the energy producers' profit-maximization conditions demonstrates that the optimal allocation can be decentralized by a uniform global carbon price τ_{Et}^* implicitly defined by:

$$\begin{aligned}\tau_{Eit}^{*} &= \sum_{j=0}^{\infty}\sum_{n=0}^{N}\beta^{j}\left(\gamma_{t}^{n}\frac{(-U_{Tnt+j})}{\lambda_{1t}}+\frac{\lambda_{1t+j}}{\lambda_{1t}}\left(\frac{-\partial Y_{t+j}^{n}}{\partial T_{t+j}}\right)\right)\frac{\partial T_{t+j}}{\partial E_{it}^{M}} \\ &= \tau_{Et}^{*}\end{aligned} \tag{44}$$

Finally, multiplying the utility damage term in (44) by $\frac{U_{cmt}}{U_{cmt}}$ and invoking the definition of the MCF_{t}^{i} yields the desired result of Corollary 3. ■.

1.4.2 Case 2: Resource Transfers Across Countries Are Not Possible

Assume now that the planner cannot re-allocate resources across countries directly. The critical difference in this setup is that the planner now faces N national resource constraints rather than a single global resource constraint. In particular, the planner's problem becomes:

$$\begin{aligned}&\max\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^{t}\left\{\gamma_{t}^{i}U(C_{it},L_{it},T_{t})+\phi_{i}\underbrace{(U_{cit}C_{it}+U_{lit}L_{it}-U_{cit}G_{it}^{T})}_{\equiv H_{t}^{i}}\right\} \\ &+\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^{t}\lambda_{1it}\left[F_{1i}(A_{1it},T_{t},L_{1it},K_{1it},E_{it})+(1-\delta)K_{it}-C_{it}-G_{it}^{C}-K_{it+1}-\Theta_{it}(\mu_{it}E_{it})\right] \\ &+\sum_{t=0}^{\infty}\beta^{t}\xi_{t}[T_{t}-F(\mathbf{S}_{0},\sum_{i}(1-\mu_{i0})E_{i0},\sum_{i}(1-\mu_{i1})E_{i1},...\sum_{i}(1-\mu_{it})E_{it},\boldsymbol{\eta}_{0},....\boldsymbol{\eta}_{t})] \\ &+\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^{t}\lambda_{lit}\left[L_{it}-L_{i1t}-L_{i2t}\right] \\ &+\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^{t}\lambda_{kit}\left[K_{it}-K_{i1t}-K_{i1t}\right] \\ &+\sum_{i}^{N}\sum_{t=0}^{\infty}\beta^{t}\lambda_{2it}\left[A_{2it}F_{2i}(K_{2it},L_{2it})-E_{it}\right] \\ &-\sum_{i}^{N}\phi_{i}\left\{U_{ci0}\left[K_{i0}\left\{1+(F_{ki0}-\delta)(1-\overline{\tau_{ki0}})\right\}+B_{i0}\right]\right\}\end{aligned}$$

Combining again the planner's FOCs for country $i's$ abatement, energy usage, and sectoral labor supplies now yields:

$$\Theta_{it}'=F_{1iEt}-\frac{F_{1ilt}}{F_{2lit}}=\frac{1}{\lambda_{1it}}\sum_{j=0}^{\infty}\beta^{j}\xi_{t+j}\frac{\partial T_{t+j}}{\partial E_{it}^{M}} \tag{45}$$

As in Case 1, (45) shows that each country's marginal abatement cost (Θ_{it}') as well as the wedge between its marginal product of energy F_{1iEt} and its private production cost $\frac{F_{1ilt}}{F_{2lit}}$ are equal to the present discounted value of the shadow cost of additional atmospheric carbon. However, in contrast to (43), these damages are translated into national carbon taxes at different rates based on each country's marginal value of public resources λ_{1it}. Whether the optimal carbon tax remains uniform in this setting thus depends on whether the planner's welfare weights on each country offset the differences in marginal utilities of public income. In particular, by substituting in the planner's FOCs for temperature change, comparing to decentralized behavior of firms, and through some algebraic manipulations, one can show that the optimal carbon tax in country i for $t > 0$ is implicitly defined by:

$$\tau_{Mit} = \frac{1}{\lambda_{1it}} \sum_{j=0}^{\infty} \sum_{n=0}^{N} \beta^j (\lambda_{1nt}) \left\{ \gamma_{t+j}^n \frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n} + \frac{\lambda_{1nt+j}}{\lambda_{1nt}} (\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}}) \right\} \frac{\partial T_{t+j}}{\partial E_{it}^M} \tag{46}$$

The planner's FOC with respect to C_{it} for $t > 0$ yields the following optimality condition:

$$\lambda_{1it} = \gamma_t^i U_{cit} + \phi_i H_{ct}^i \tag{47}$$

In words, (47) indicates that the scarcity value of public resources in country i at time t is given by the welfare-weighted marginal utility of consumption $\gamma_t^i U_{cit}$ plus a term that captures the effect of a change in consumption on the planner's ability to decentralize the optimal allocation with distortionary taxes in country i ($\phi_i H_{ct}^i$). Plugging into (46) yields:

$$\tau_{Mit} = \sum_{j=0}^{\infty} \sum_{n=0}^{N} \beta^j \left(\frac{\gamma_t^n U_{cnt} + \phi_n H_{ct}^n}{\gamma_t^i U_{cit} + \phi_i H_{ct}^i} \right) \left\{ \gamma_{t+j}^n \frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n} + \frac{\lambda_{1nt+j}}{\lambda_{1nt}} (\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}}) \right\} \frac{\partial T_{t+j}}{\partial E_{it}^M} \tag{48}$$

Assume that the planner puts the following (Negishi) weights on utility in country i at time t :

$$\gamma_t^i = \frac{\overline{U_{ct}} + \overline{\phi H}_{ct} - \phi_i H_{ct}^i}{U_{cit}} \tag{49}$$

Plugging (49) into (48) and rearranging shows that the optimal carbon tax in this setting is once again uniform across countries, completing the proof of Corollary 4:

$$\tau_{Eit}^* = \sum_{j=0}^{\infty} \sum_{n=0}^{n} \beta^j \left\{ \gamma_{t+j}^n \frac{(-U_{Tnt+j}/U_{cnt})}{MCF_t^n} + \frac{\lambda_{1nt+j}}{\lambda_{1nt}} (\frac{-\partial Y_{t+j}^n}{\partial T_{t+j}}) \right\} \frac{\partial T_{t+j}}{\partial E_{it}^M}$$

Finally, in order to derive the general expression for the optimal country-specific carbon tax, multiply the weight term in (46) by $\frac{(U_{cnt}/U_{cnt})}{(U_{cit}/U_{cit})}$ and substitute in the definition of the MCF_t^n.

2 Calibration Details

2.1 Full Parameter Summary

Table A1: Calibration Parameters		
Parameter	**Value**	**Sources and Notes**
Preferences: $U(c_t, l_t, T_t) = \frac{[c_t\cdot(1-\varsigma l_t)^\gamma]^{1-\sigma}}{1-\sigma} + \frac{\left(1+\alpha_0 T_t^2\right)^{-(1-\sigma)}}{1-\sigma}$		
σ	1.5	Nordhaus (2008)
β	$(.985)^{10}$	Nordhaus (2008)
ς	2.2381 if distortionary; 2.0785 if first-best	Jointly match Frisch elasticity (0.78) and rationalize base labor supply ($l_{2005} = .2272$) at base year marginal product of labor w_{2005} with $\tau_{l,2005}= 0.37$ or $\tau_{l,2005}= 0.0$, resp.
γ	0.7178 if distortionary; 1.2985 if first-best	
α_0	.00023808 if distortionary; .00027942 if first-best	Match disutility from $2.5°C$ warming equiv. to to 0.46% output loss given the relevant ς, γ
Production Damages: $(1 - D_t(T_t)) = \frac{1}{1+\theta_1 T_t^2}$		
θ_1	0.0021	Match 1.29% output loss from $2.5°C$ warming
Final Goods Production: $F_1(A_{1t}, T_t, L_{1t}, K_{1t}, E_t) = (1 - D_t(T_t))A_{1t}(K_{1t}^\alpha L_{1t}^{1-\alpha-v} E_t^v)$		
α	0.3	GHKT (2014)
v	0.03	GHKT (2014)
K_{2005}	1.1068e+05	$= \frac{\alpha\cdot GDP_{2005}^{World}}{(r+\delta^{Yr})} = \frac{\alpha\cdot GDP_{2005}^{World}}{(.05+.10)}$ (\$2005 billions)
$\pi_{1,2005}^l$	.9823	Base year share of labor in final goods sector
		$=\frac{1-\alpha-v}{\alpha_E v+1-\alpha-v}$ (equates $MPL_{1,2005}$=$MPL_{E,2005}$)
$\pi_{1,2005}^k$	0.9437	Base year share of capital in final goods sector
		$=\frac{\alpha}{(1-\alpha_E)v+\alpha}$ (equates $MPK_{1,2005}$=$MPK_{E,2005}$)
E_{2005}	7.990	Nordhaus (2010) (GtC/year)
l_{2005}	.2272	OECD (2005) (fraction of time supplied as labor)
$A_{1,2005}$	1.1931e+04	$= \frac{(10\cdot GDP_{2005}^{World})}{(1-D(T_{2005}))K_{1,05}^\alpha(l_{2005}\cdot\pi_{1,2005}^l\cdot N_{2005})^{1-\alpha-v}(10\cdot E_{05})^v}$
$A_{1,t}$	$= A_{1,t-1}\cdot\frac{1}{1-gA_{1,t-1}}$	for $t \geq 2015$
δ	0.6513	Match annual $\delta^{Yr} = 10\%$ (in % per decade)
K_{2015}	1.7447e+05	$= K_{2005}(1-\delta) + (.24554)(GDP_{2005}^{World}\cdot 10)$
Energy Good Production: $E_t = A_{2t}(K_{2t}^{1-\alpha_E} L_{2t}^{\alpha_E})$		
α_E	0.403	U.S. Bureau of Economic Analysis Data (2000-10)
$K_{2,2005}$	6.2353e+03	$= (1-\pi_{1,2005}^k)K_{2005}$ (\$2005 billions)
- Continued on next page -		

Table A1: Calibration Parameters,		
Parameter	**Value**	**Sources and Notes**
$A_{2,2005}$	1.8924	$= \frac{E_{2005}\cdot 10}{(K_{E,2005})^{(1-\alpha_E)}(l_{2005}(1-\pi^l_{1,2005})N_{2005})^{\alpha_E}}$
$A_{2,t}$	$=A_{2,t-1}\cdot(1+gZ_{t-1})^{\alpha_E}$	Note: gZ_{t-1} is *labor* productivity growth (see below)
Government:		
$\tau_{l,2005}$	$\begin{cases} 3609\% & \text{if distortionary} \\ 0\% & \text{if first-best} \end{cases}$	GDP-weighted global avg. effective rate
$\tau_{k,2015}$	$\begin{cases} 33.4\% & \text{if distortionary} \\ 0\% & \text{if first-best} \end{cases}$	GDP-weighted global avg. effective rate
G^C_{2005}	98.395 $trillion	$= (.331)(.57)(GDP^{World}_{2005}\cdot 10)$ ($2005), IMF data
G^T_{2005}	73.713 $trillion	$= (.331)(.43)(GDP^{World}_{2005}\cdot 10)$ ($2005), IMF data
G^{total}_t	$= G^{total}_{t-1}\cdot e^{gN_t+gZ_t}$	
G^C_t	$= (.57)G^{total}_t$	
G^T_t	$= (.43)G^{total}_t$	
B_0	34.659 $trillion	$= (.6263)GDP^{World}_{2005}$ ($2005), World Bank WDI
Abatement Costs: $\Theta_t(\mu_t E_t) = \frac{\overline{a}P^{backstop}_t}{1+a_t\exp(b_{0t}-b_{1t}(\mu_t E_t))^{b_2}}\cdot(\mu_t E_t)$		
$\overline{a}$	0.9245	Minimize difference to DICE abatement costs
a_t	$= 49.9096 + 1.0995\log(t)$	
b_{0t}	$= 15.5724 + 3.4648\log(t)$	
b_{1t}	$= 13.0210 + 1.5725\log(t)$	
$P^{backstop}_t$	$= 0.63(1+\exp(-0.05\cdot t))$	Nordhaus (2010) ($1000/mtC, $2005)
	$= 0$ after 2250	
Growth Parameters:		
$gA_{1,2005}$	0.160023196685654	Nordhaus (2010)
γ_0	0.00942588385340332	Nordhaus (2010)
γ_1	0.00192375245926376	Nordhaus (2010)
$gA_{1,t}$	$= gA_{1,0}\exp(-\gamma_0\cdot t\cdot 10\cdot\exp(-\gamma_1\cdot t\cdot 10))$	
	$= gA_{1,2255}$ after 2255	
gZ_t	$= [(1+gA_{1,t})^{\frac{1}{1-\alpha-v}}]-1$	Labor productivity
$gA_{2,t}$	$= (1+gZ_t)^{\alpha_E}$	Energy sector productivity
Population Growth: $N_t = \left(\frac{N_{Max}}{N_t}\right)^{\gamma_N}$		
N_{2005}	6.411	Nordhaus (2010) (billions)
N_{Max}	8.7	Nordhaus (2010)
γ_N	0.485	Nordhaus (2010)
gN_t	$= \left(\frac{N_t}{N_{t-1}}-1\right)$	Nordhaus (2010), Population growth rate
- Continued on next page -		

Table A1: Calibration Parameters,		
Parameter	**Value**	**Sources and Notes**
Carbon Stocks: $\begin{pmatrix} S_t^{At} \\ S_t^{Up} \\ S_t^{Lo} \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} S_{t-1}^{At} \\ S_{t-1}^{Up} \\ S_{t-1}^{Lo} \end{pmatrix} + \begin{pmatrix} E_t^M + E_t^{Land} \\ 0 \\ 0 \end{pmatrix}$		
S_0^{At}	787	Nordhaus (2010) (GtC)
S_0^{Up}	1600	Nordhaus (2010) (GtC)
S_0^{Lo}	10010.493	Nordhaus (2010) (GtC)
E_0^{Land}	16	Nordhaus (2010) (GtC/decade)
E_t^{Land}	$=E_0^{Land}(0.8)^t$	Nordhaus (2010) (GtC/decade)
ϕ_{11}	0.88	Nordhaus (2010)
ϕ_{21}	0.047	Nordhaus (2010)
ϕ_{12}	0.12	Nordhaus (2010)
ϕ_{22}	0.94796	Nordhaus (2010)
ϕ_{32}	0.00075	Nordhaus (2010)
ϕ_{23}	0.005	Nordhaus (2010)
ϕ_{33}	0.99925	Nordhaus (2010)
E_0^{Land}	16	Nordhaus (2010) (GtC/decade)
E_t^{Land}	$=E_0^{Land}(0.8)^t$	Nordhaus (2010) (GtC/decade)
Radiative Forcings: $\chi_t = \kappa\{\ln\left(\frac{S_t^{At}}{S_{1750}^{At}}\right)/\ln(2)\} + \chi_t^{Ex}$		
κ	3.8	Nordhaus (2010)
S_{1750}	596.4	Nordhaus (2010) (GtC)
χ_{2000}^{Ex}	0.83	Nordhaus (2010) (Watts/m^2)
χ_{2100}^{Ex}	0.30	Nordhaus (2010) (Watts/m^2)
χ_t^{Ex}	$= \chi_{2000}^{Ex} + (0.1)(\chi_{2100}^{Ex} - \chi_{2000}^{Ex}) \cdot t$	
Temperature: $\begin{pmatrix} T_t \\ T_t^{Lo} \end{pmatrix} = \begin{pmatrix} (1-\zeta_1\zeta_2-\zeta_1\zeta_3) & \zeta_1\zeta_3 \\ (1-\zeta_4) & \zeta_4 \end{pmatrix} \begin{pmatrix} T_{t-1} \\ T_{t-1}^{Lo} \end{pmatrix} + \begin{pmatrix} \zeta_1\chi_t \\ 0 \end{pmatrix}$		
T_0	0.83	Nordhaus (2010) ($^\circ C$)
T_0^{Lo}	0.00680	Nordhaus (2010) ($^\circ C$)
ζ_1	0.208	Nordhaus (2010)
ζ_2	1.1875	Nordhaus (2010)
ζ_3	0.31	Nordhaus (2010)
ζ_4	0.05	Nordhaus (2010)

2.2 Preferences

Given the assumed utility function,

$$U(c_t, l_t, T_t) = \frac{\left[c_t \cdot (1 - \varsigma l_t)^{\gamma}\right]^{1-\sigma}}{1-\sigma} + \frac{\left(1 + \alpha_0 T_t^2\right)^{-(1-\sigma)}}{1-\sigma} \tag{50}$$

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

$$\eta^F = \frac{U_{lt}}{l_t\left[U_{llt} - \frac{U_{clt}^2}{U_{cct}}\right]} \tag{51}$$

$$= \frac{(1-\varsigma l_t)}{\varsigma l_t}\frac{-1}{\left[[\gamma(1-\sigma)-1] - \frac{\gamma(1-\sigma)^2}{(-\sigma)}\right]} \tag{52}$$

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

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

$$\frac{c_t\gamma\varsigma}{(1-\varsigma n_t)} = w_t(1-\tau_{lt}) \tag{53}$$

I use the two equations (52) and (53) to solve for the two unknowns γ and ς 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. 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. In contrast, base-year values for consumption and labor supply are given from the data and constant across fiscal scenarios (except in the the first-best 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 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 Development Indicators data 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 $\left(w_t = \frac{(1-\alpha-v)Y_{2005}}{\pi^l_{1,2005} l_{2005} N_{2005}}\right)$. The base year average marginal labor tax rate τ_{l2005} is the GDP-weighted average labor-consumption effective tax based on estimates from the literature (see below). 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 $\gamma = 0.7178$ and $\varsigma = 2.2381$. In the first-best ($\tau_{l2005} = 0$), $\gamma = 1.2985$ and $\varsigma = 2.0785$.

Finally, given these parameters, Figure A1 depicts the optimal capital income tax sequence in the optimized model run (Scenario 5) in order to confirm that (50) yields similar prescriptions as the (simpler) utility functions used in Proposition 2:

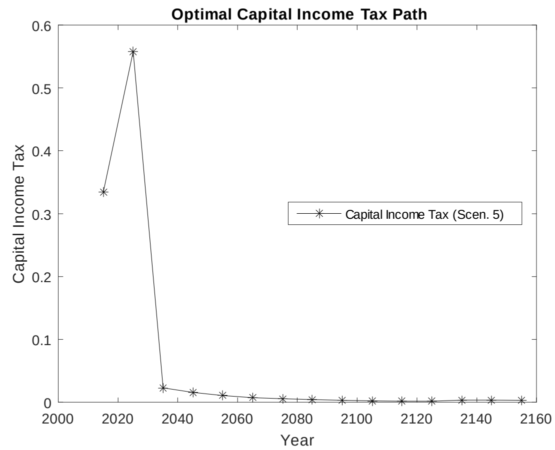

Figure A1

2.3 Energy Production Labor Share

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 Valentinyi 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.[2]

Table A3 summarizes the results from these factor elasticity calculations.

[2] 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."

Industry Title	2002 NAICS	2000-2010 Average: 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 A3: 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.

2.4 Clean Energy Production

The additional cost of zero emissions energy production $\mu_t E_t$ - conceptually analogous to emissions reductions at a given energy input level - is based on the DICE model (Nordhaus, 2008). However, as both carbon-based and clean energy use are endogenous in the COMET, the DICE abatement cost estimates - which are based on the fraction of emissions abated relative to the BAU scenario - need to be translated into a per-ton cost function. First, I thus compute a grid of total abatement costs in DICE for different amounts of clean energy produced in each decade through the year 2265.[3] Second, I approximate these costs through a logistic function:

$$\Theta_t(\mu_t E_t) = \frac{\overline{a} P_t^{backstop}}{1 + a_t \exp(b_{0t} - b_{1t}(\mu_t E_t))^{b_2}} \cdot (\mu_t E_t) \tag{54}$$

where $P_t^{backstop}$ denotes the backstop technology price in year t, taken directly from DICE.[4] 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 $i = 0, 1$.[5] The remaining parameters in (54) are solved for numerically by minimizing the sum of squared errors between the present discounted total costs implied by (54) and those computed based on the DICE model. The results are: $\overline{a} = 0.9245$; $\alpha_1 = 49.9096$; $\alpha_2 = 1.0995$; $b_{01} = 15.5724$; $b_{02} = 3.4648$; $b_{11} = 13.0210$; $b_{22} = 1.5725$; and $b_2 = 0.0921$.

2.5 Effective Tax Rate Estimates

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

[4] 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.

[5] 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.

	Avg. of Estimates			
Country	τ_l	τ_k	τ_c	Sources
Albania	33.4			World Bank (2007)
Argentina	37.3	43.5		IMF (2012), Chen and Mintz (2015)
Armenia	38.5			World Bank (2007)
Australia	24.1	45.5	10.6	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015)
Austria	40.9	28.9	15.8	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Azerbaijan	29.8			World Bank (2007)
Bangladesh		15.4		Chen and Mintz (2015)
Belarus	35.5			World Bank (2007)
Belgium	44.2	30.7	15.1	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Bolivia		21.0		Chen and Mintz (2015)
Bosnia	34.9			World Bank (2007)
Botswana		13.6		Chen and Mintz (2015)
Brazil	28.7	28.6	26.3	Azevedo and Fasolo (2015), Gandullia et al. (2012), IMF (2012), Chen and Mintz (2015)
Bulgaria	39	13.4		World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Canada	25.7	43.7	11.7	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Chad		39.1		Chen and Mintz (2015)
Chile	18.5	7.7		World Bank (2007), IMF (2012), Chen and Mintz (2015)
China	35.4	31.7		Gandullia et al. (2012), Chen and Mintz (2015)
Colombia	55.7	31.6		IMF (2012), Chen and Mintz (2015)
Costa Rica		27.9		Chen and Mintz (2015)
Croatia	40.3	10.8		World Bank (2007), Chen and Mintz (2015), Devereux et al. (2009)
Cyprus		17		Devereux et al. (2009)
Czech Republic	38.6	24	17.5	Carey & Rabesona (2002), World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Denmark	38	42.7	21.1	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Dominican Republic		23.4		Chen and Mintz (2015)
Ecuador		19.7		Chen and Mintz (2015)
Egypt	59.5	13.5		IMF (2012), Chen and Mintz (2015)

Table A4: Effective Tax Rate Estimates

	Avg. of Estimates			
Country	τ_l	τ_k	τ_c	Sources
Estonia	40.7	16.1		World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Ethiopia		15.8		Chen and Mintz (2015)
Fiji		18.3		Chen and Mintz (2015)
Finland	42.0	31.6	19.0	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
France	42.4	47.4	15.4	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Georgia	26.7	20.9		World Bank (2007), Chen and Mintz (2015)
Germany	38.5	35.7	13.5	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Ghana		14.6		Carey & Rabesona (2002)
Greece	36.8	23.6	15.4	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Guyana		36.9		Chen and Mintz (2015)
Hong Kong		35.5		Chen and Mintz (2015)
Hungary	44	25.8	21.5	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Iceland	23.6	16.1		IMF (2012), Chen and Mintz (2015)
India	0.8	26	15	IMF (2012), Chen and Mintz (2015), Ganduilla et al. (2012), Poirson (2006)
Indonesia	8.2	21.8		IMF (2012), Chen and Mintz (2015), Ganduilla et al. (2012)
Iran		13.3		Chen and Mintz (2015)
Ireland	22.9	24		Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009), World Bank (2007)
Israel	15.8	17.8		IMF (2012), Chen and Mintz (2015)
Italy	40.7	34.1	14.1	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Jamaica		17.0		Chen and Mintz (2015)
Japan	25.3	45.2	6.7	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Jordan	23.9	13.0		IMF (2012), Chen and Mintz (2015)
Kazakhstan	28.2	25.6		World Bank (2007), IMF (2012), Chen and Mintz (2015)
Kenya		15.1		IMF (2012), Chen and Mintz (2015)
Korea	15.6	29.1	14.2	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), World Bank (2007)
Kuwait		26.8		Chen and Mintz (2015)
Kyrgyz Republic	31.6			World Bank (2007)

Table A4: Effective Tax Rate Estimates

	Avg. of Estimates			
Country	τ_l	τ_k	τ_c	Sources
Latvia	42.5	11.0		IMF (2012), Chen and Mintz (2015), Devereux et al. (2009), World Bank (2007)
Lesotho		29.0		Chen and Mintz (2015)
Lithuania	43.7	12.7		IMF (2012), Devereux et al. (2009), World Bank (2007)
Luxembourg	22.1	25.3		IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Macedonia	41.4	14.0		Devereux et al. (2009)
Madagascar		16.6		Chen and Mintz (2015)
Malaysia		17.8		IMF (2012), Chen and Mintz (2015)
Mali	33.0			IMF (2015)
Malta		27.1		Devereux et al. (2009)
Mauritius		11.3		Chen and Mintz (2015)
Mexico	15.5	17.4		IMF (2012), Chen and Mintz (2015),
Moldova	32.4			World Bank (2007)
Morocco	35.7	14.5		IMF (2012), Chen and Mintz (2015)
Netherlands	33.8	30.6	15.6	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
New Zealand	16.6	28.1	16.0	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015)
Nigeria		12.0		Chen and Mintz (2015)
Norway	34.6	31.8	21.7	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Pakistan		25.8		Chen and Mintz (2015)
Panama		22.8		Chen and Mintz (2015)
Paraguay		16.2		Chen and Mintz (2015)
Peru	35.8	22.8		IMF (2012), Chen and Mintz (2015)
Philippines		26.4		IMF (2012), Chen and Mintz (2015)
Poland	39.3	23.0	17.1	Carey & Rabesona (2002), World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Portugal	28.2	25.0	15.9	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Qatar		12.0		Chen and Mintz (2015)
Romania	44.1	15.1		World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Russia	31.0	33.5		IMF (2012), Chen and Mintz (2015)

Table A4: Effective Tax Rate Estimates

	Avg. of Estimates			
Country	τ_l	τ_k	τ_c	Sources
Rwanda		18.5		Chen and Mintz (2015)
Saudi Arabia		20.0		IMF (2012), Chen and Mintz (2015)
Serbia	42.2	-2.4		World Bank (2007), Chen and Mintz (2015)
Sierra Leone		18.5		Chen and Mintz (2015)
Singapore		10.2		Chen and Mintz (2015)
Slovak Republic	36.5	16.4		IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Slovenia	38.0	20.6		IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
South Africa	13.7	14.9		Gandullia et al. (2012), Chen and Mintz (2015)
Spain	51.2	42.6	14.5	Carey & Rabesona (2002), World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Switzerland	23.4	30.8	8.5	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Taiwan		13.6		Chen and Mintz (2015)
Tajikistan	29.6			World Bank (2007)
Tanzania		18.0		Chen and Mintz (2015)
Thailand	14.3	12.8		World Bank (2007), IMF (2012), Chen and Mintz (2015)
Trinidad		15.1		Chen and Mintz (2015)
Tunisia		22.1		Chen and Mintz (2015)
Turkey	40.5	23.9		World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Uganda	13.6	13.4		World Bank (2007), IMF (2012), Chen and Mintz (2015)
Ukraine	39.2	11.1		World Bank (2007), IMF (2012), Chen and Mintz (2015)
United Kingdom	25.0	37.7	14.3	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
United States	24.0	41.1	5.6	Carey & Rabesona (2002), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)
Uruguay		35.1		Chen and Mintz (2015)
Uzbekistan	38.0	37.8		World Bank (2007), Chen and Mintz (2015)
Venezuela		30.2		Chen and Mintz (2015)
Vietnam	16.1	12.7		World Bank (2007), Chen and Mintz (2015)
Zambia		17.4		
				Carey & Rabesona (2002), World Bank (2007), IMF (2012), Chen and Mintz (2015), Devereux et al. (2009)

Table A4: Effective Tax Rate Estimates

3 Quantitative Results: Additional Sensitivity

Table A5 presents sensitivity analysis of the main results to two alternative fiscal scenarios. First, the benchmark third-best policy scenarios (4a) and (4b) assume that the planner can only choose one capital or labor income tax, respectively, and that this level must remain constant. Intuitively, this assumption is to ensure comparability of welfare with the 'business as usual' (BAU) scenario, which assumes no changes in tax rates. As is well-known, a considerable share of the welfare gains of Ramsey tax reform stems from the optimization of capital income taxes *over time* as being high initially and then dropping to a low rate thereafter, so that a carbon levy coupled with inter-temporal capital income tax optimization would change two fundamental constraints at once compared to the BAU case. Table A5 showcases the main results in variants of the third-best tax scenarios that allow such inter-temporal optimization (scenarios $4a^{\dagger}$ and $4b^{\dagger}$). As expected, the welfare gains are significantly higher when capital income taxes can vary flexibly over time (1.25% permanent consumption increase versus 0.95% increase in the benchmark). The optimal carbon tax adjustments are, however, similar to the benchmark, ranging from -10% to -20% on average. Next, the benchmark allows separate taxation of general energy (including clean energy) inputs versus carbon emissions, in order to consider a 'complete' tax system. Table A5 showcases what happens when energy input taxes are prohibited in the model in scenarios $4a^{\ddagger}$ and $4b^{\ddagger}$, respectively. As one might expect, carbon levies now assume some of the revenue-raising role of energy taxes in case ($4a^{\ddagger}$). Broadly, however, the optimal tax adjustments remain around -12%-13% over the century.

Table A5: Sensitivity of Fiscal Restrictions

	Fiscal Scenario				τ_l^*	τ_k^*	MCF	Carbon Tax τ_{Et}^* 2015	2025	%Adjust.	τ_I^*	T_t	ΔWelfare[1]	
	Labor	Capital	Carbon	Energy	avg. 2025-2255			\$/mtC		from (6)	2025	max	ΔC_{2015} (\$tril.)	$\%\Delta C_t\ \forall t$
4a	$\overline{\tau_l}$=38.3%	Variable, constant	Opt.	Opt.		31.12	1.35	49	77	-24%	35	3.03	\$26.25	0.95%
$4a^{\dagger}$	$\overline{\tau_l}$=38.3%	Flexible over time	Opt.	Opt.		22.8%	1.29	51	80	-20%	32	3.01	\$34.76	1.25%
$4a^{\ddagger}$	$\overline{\tau_l}$=37.8%	Variable, constant	Opt.	$\overline{\tau_I}$=0		31.6	1.36	60	97	-12%		3.03	\$25.96	0.94%
4b	Variable, constant	$\overline{\tau_k}$=34.6%	Opt.	Opt.	37.9%		1.06	58	91	-11%	-3	3.01	\$22.06	0.80%
$4b^{\dagger}$	Flexible over time	$\overline{\tau_k}$=34.6%	Opt.	Opt.	40.2%		1.03	58	91	-10%	0	3.01	\$24.74	0.90%
$4b^{\ddagger}$	Variable, constant	$\overline{\tau_k}$=34.6%	Opt.	$\overline{\tau_I}$=0	37.9%		1.01			-13%		3.01	\$22.05	0.80%

[1] Relative to BAU scenario (1a, see paper body). Equivalent variation change in aggregate initial consumption ΔC_{2015} or permanent change $\%\Delta C_t$.

Next, table A6 presents additional sensitivity analysis results for model runs that increase (decrease) the carbon abatement cost by 20%. While this change has a significant effect on, say, the optimal temperature change achieved, the optimal carbon tax adjustments to the fiscal setting remain robust to these parametric changes.

Table A6: Sensitivity of Abatement Costs								
All figures represent average of 2015-2115 values unless noted otherwise.								
	Fiscal Scenario	τ_l^*	τ_k^*	Carbon Tax τ_{Et}^*			MCF	T_t
		%	%	2015	2025	%Adjustment		
				\$/mtC	\$/mtC	from FB (6)		Max
Abatement costs +20%								
6.	First-Best	0	0	71	105	-	1	3.08
5.	Optimized Distortionary	41.9%	2.7%	59	92	-9%	1.06	3.11
4a.	BAU Labor tax $\overline{\tau_l}$=37.75%		34.6%	47	75	-27%	1.44	3.15
4b.	BAU Labor tax $\overline{\tau_k}$=34.57%	37.9%		58	91	-11%	1.06	3.12
Abatement costs -20%								
6.	First-Best	0	0	71	105	-	1	2.84
5.	Optimized Distortionary	42%	2.8%	58	91	-9%	1.06	2.87
4a.	BAU Labor tax $\overline{\tau_l}$=37.75%		34.5%	47	74	-27%	1.39	2.88
4b.	BAU Capital tax $\overline{\tau_k}$=34.57%	40%		57	90	-11%	1.06	2.88

Finally, Figures A2-A4 illustrate the importance of re-calibrating the utility parameters between the first-best and distortionary setting. Specifically, these figures illustrate equilibrium labor supply, output, and optimal carbon taxes in (i) the benchmark first-best (Scen. 6), (ii) the benchmark distortionary tax setting (Scen. 5), and (iii) a first-best model run without recalibration that uses the distortionary tax setting parameters while allowing lump-sum taxation. The figures show that, when using the same parameters for both settings, labor supply jumps, increasing output (by 16% on average over the Century), and thus also the optimal carbon tax. With re-calibration, the second-best carbon tax (Scen. 5) is only 8% lower than the first-best. Without re-calibration, this difference increases to -24% on average. Re-calibration of utility parameters thus mitigates the effect of distortionary taxes on optimal climate policy.

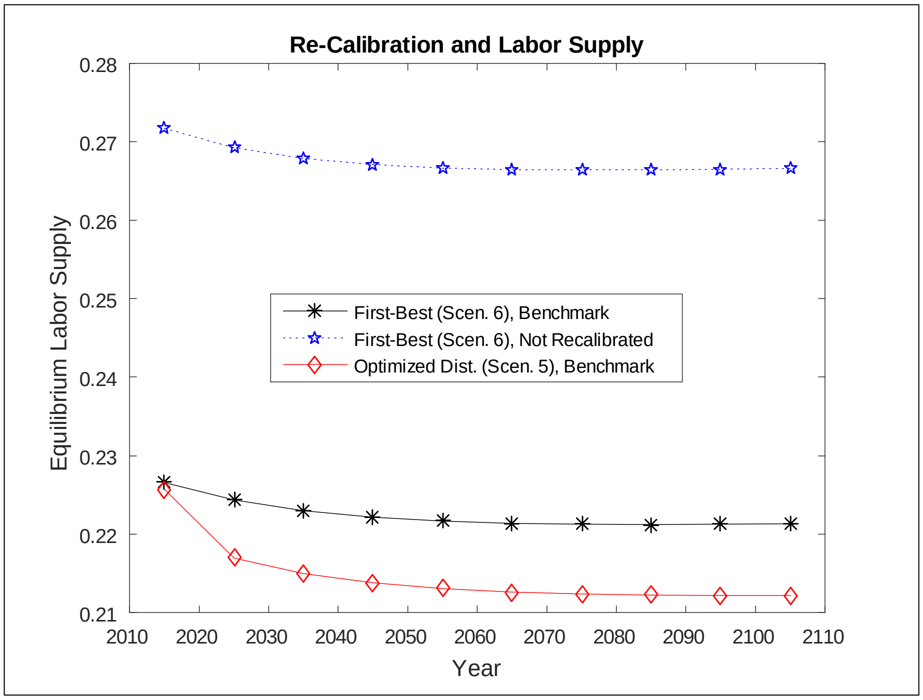

Figure A2

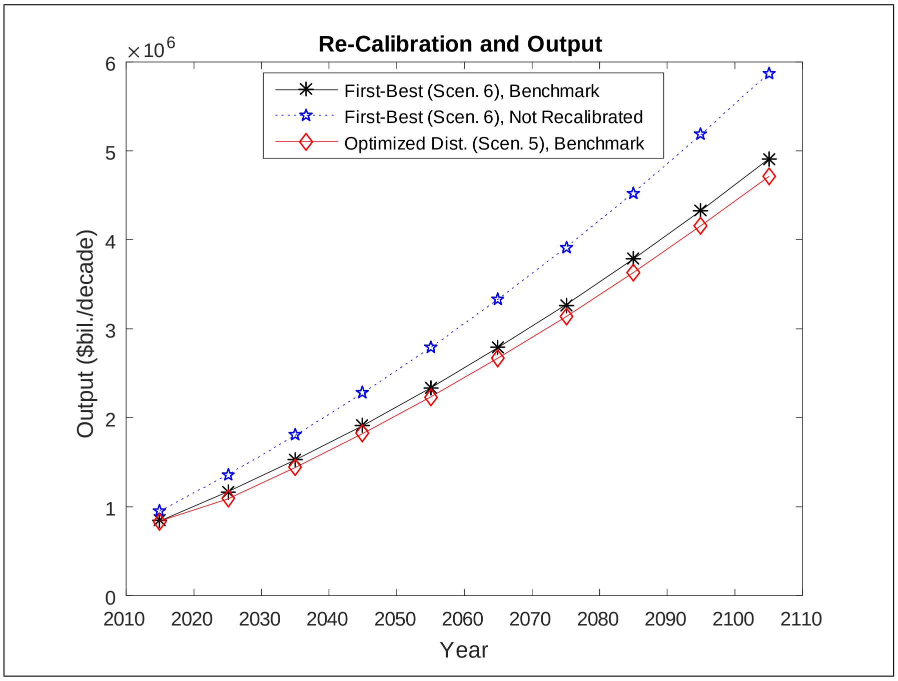

Figure A3

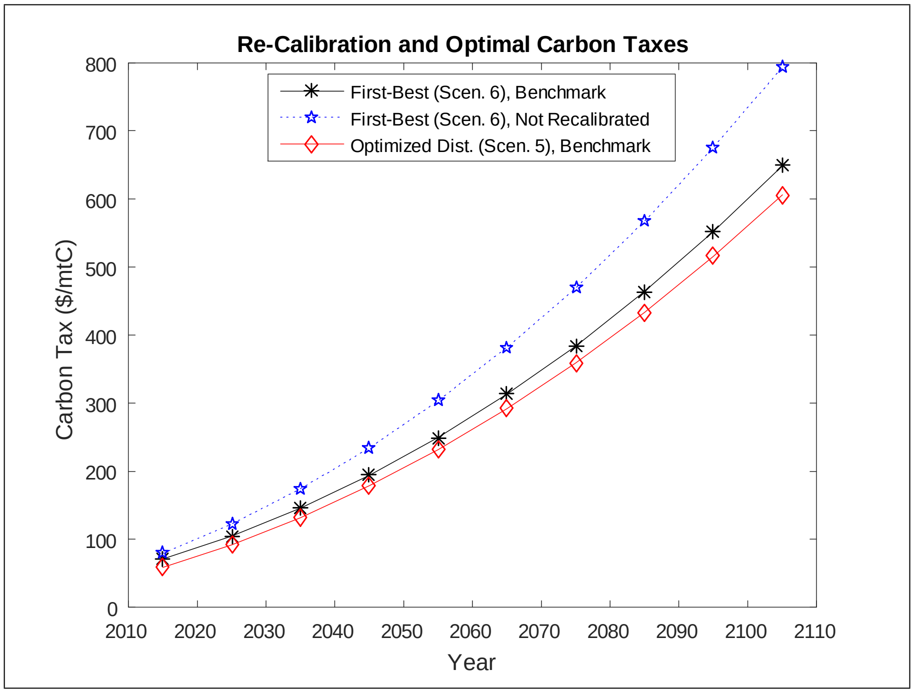

Figure A4

References

[1] Azevedo, Cyntia, and Angelo Fasolo (2015) Effective Tax Rates on Consumption and Factor Incomes: a quarterly frequency estimation for Brazil. No. 398.

[2] Bureau of Economic Analysis (1994) "Accounting for Mineral Resources: Issues and BEA's Initial Estimates" *Survey of Current Business*, 75(4): 50-72.

[3] Carbone, Jared C., and V. Kerry Smith (2008) "Evaluating policy interventions with general equilibrium externalities" *Journal of Public Economics*, 92: 1254-1274.

[4] Carey, David, and Josette Rabesona (2002) "Average Effective Tax Rates on Capital, Labour, and Consumption" Workshop on 'Measuring the Tax Burden on Capital and Labour,' Venice Summer Institute.

[5] Chari, V.V., and Patrick J. Kehoe (1999) "Optimal Fiscal and Monetary Policy" *Handbook of Macroeconomics*, 1: 1671-1745.

[6] Chen, Duanjieand Jack M. Mintz (2015) "The 2014 Global Tax Competitiveness Report: A Proposed Business Tax Reform Agenda" University of Calgary School of Public Policy Research Papers, Volume 8, Issue 4.

[7] Corlett, Wilfred J., and Douglas C. Hague (1953) "Complementarity and the excess burden of taxation" *The Review of Economic Studies* 21(1): 21-30.

[8] "Devereux et al.": Spengel, Christoph, Ch Elschner, D. Endres, A. Bartholmeß, Daniel Dreßler, L. Evers, M. T. Evers et al. (2009) "Effective tax levels using the Devereux/Griffith methodology." project for the EU Commission, TAXUD/2008/CC/099.

[9] Diamond, Peter A., and James A. Mirrlees (1971) "Optimal Taxation and Public Production I: Production Efficiency" *American Economic Review*, 61(1): 8-27.

[10] Findlay, Christopher C., and Robert L. Jones (1982) "The Marginal Cost of Australian Income Taxation" *Economic Record,* 58(3): 253-262.

[11] Gandullia, L., N. Iacobone and A. Thomas (2012) "Modelling the Tax Burden on Labour Income in Brazil, China, India, Indonesia and South Africa", OECD Taxation Working Papers, No. 14, OECD Publishing.

[12] IMF (2012) "Fiscal Policy and Employment in Advanced and Emerging Economies" *IMF Fiscal Affairs Department,* Washington, DC.

[13] IMF (2015) "Mali: Selected Issues*", IMF Country Report No. 15/340.*

[14] Jones, Larry E., Rodolfo E. Manuelli, and Peter E. Rossi (1993) "Optimal Taxation in Models of Endogenous Growth" *Journal of Political Economy*, 101(3): 485-517.

[15] Keen, Michael, and David Wildasin (2004) "Pareto-efficient international taxation" *American Economic Review,* 94(1): 259-275.

[16] King, Robert G., Charles I. Plosser, and Sergio T. Rebelo (2001) "Production, Growth, and Business Cycles: Technical Appendix."

[17] Mendelsohn, Robert, William D. Nordhaus, and Daigee Shaw (1994) "The impact of global warming on agriculture: a Ricardian analysis" *American Economic Review*: 753-771.

[18] Neidell, Matthew J., and Joshua Graff Zivin (2010) "Temperature and the Allocation of Time: Implications for Climate Change" *NBER Working Paper 15717.*

[19] Nordhaus, William D. (2010) "Economic aspects of global warming in a post-Copenhagen environment" *Proceedings of the National Academy of Sciences*, 107(26): 11721-11726.

[20] Nordhaus, William D. (2010) *DICE-2010 model*, available at http://nordhaus.econ.yale.edu/RICEmodels.htm

[21] Nordhaus, William D. (2008) *A Question of Balance*, Yale University Press.

[22] Nordhaus, William D. (1998) "Impact of Climate and Climate Change on Non-Market Time Use" Yale University, September 1998, as cited in: Nordhaus, William D., and Joseph Boyer (2000) *Warming the World - Economic Models of Global Warmings MIT Press*, Cambridge, Massachusetts, and London, England.

[23] Poirson, Hélène (2006) "The Tax System in India: Could Reform Spur Growth?" IMF Working Paper WP/06/93.

[24] Schwartz, Jesse, and Robert Repetto (2000) "Nonseparable Utility and the Double Dividend Debate: Reconsidering the Tax Interaction Effect" *Environmental and Resource Economics,* 15: 149-157.

[25] Valentinyi, Akos, and Berthold Herrendorf (2008) "Measuring Factor Income Shares at the Sectoral Level" *Review of Economic Dynamics*, 11(4): 820-835.

[26] World Bank (2007) *Fiscal Policy and Economic Growth: Lessons for Eastern Europe and Central Asia*. Washington, DC: World Bank.