Optimal Climate Policy: Making do with the taxes we have

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Abstract

This paper studies the optimal climate policy in an economy that faces constraints on the availability of policy instruments. In a standard macro-climate growth model that includes a carbon emissions externality, the optimal policy is the introduction of a global carbon tax. After years of climate negotiations and no success in the introduction of a carbon price, this paper suggests an alternative approach which is to look for the best policies that the global economy can seek constrained by the fact that a global carbon tax is not an available tool. We show that standard fiscal instruments - not often included in the climate negotiations table - are capable of achieving the optimal outcome. We theoretically characterize and quantitatively estimate the optimal tax rates, and we find that they are well within existing tax rates. These results suggest that there is value in broadening the discussion on climate policies by exploring the role that standard taxes, such as income and consumption taxes, can play in tackling the climate problem. Politicians might be keener on recalibrating the tax rate on existing taxes than on introducing new taxes.

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1 Introduction

Despite decades of climate negotiations, global emissions of greenhouse gases are rising, and the global climate externality remains uncorrected. The solution to the climate problem is simple from an economic point of view: put a price on carbon. Carbon should be priced equal to the discounted value of the marginal damages associated with an extra ton of carbon added to the atmosphere. However, political constraints make the introduction of the first-best instrument infeasible.

Countries willing to pursue a climate policy have sought alternative strategies to curb emissions such as the encouragement of carbon capture and sequestration technologies and the subsidization of renewable energies. There is a vast literature that studies these options from an optimal policy design perspective, such as Acemoglu et al. (2012), van der Ploeg and Withagen (2014), and many others. In this paper, we take a different approach and explore how existing taxes can be harnessed to achieve optimal climate policy. Governments around the world use consumption and income taxes for all kind of goals such as raising revenue, fixing market distortions, and pursuing an optimal level of income redistribution. The question we pose is whether these taxes could also be used to achieve the goal of stabilizing the climate. Our underlying presumption is that given political institution modifying existing tax rates is easier than introducing new taxes to the tax code.

We use a standard growth model with a single consumption good and capital, labor, and oil as inputs to production. Oil use entails carbon emissions, which negatively impact the climate and consequently production. Since emitters are not facing this cost, emissions are a negative externality. After establishing the well-known result that this externality can be corrected efficiently using a global price on carbon equal to the discounted sum of marginal production damages, we study what role consumption and income taxes can play in climate policy when carbon taxes are politically infeasible. We find that a combination of consumption and capital income taxes does as well as the first-best instrument and can implement the optimal allocation. We theoretically characterize the optimal tax rates, and we show that the optimal consumption tax is decreasing and that the capital income tax is positive. In a numerical example calibrated to Golosov et al. (2014), we also show that a consumption tax of 10.4% coupled with a capital income tax of 4.1% fully compensate for the missing price on carbon. This fiscal policy is equivalent to a carbon tax of \$57 per ton of coal. Also, these rates are well within the range of existing taxes on consumption and capital income.

The intuition behind this result is simple. A decreasing consumption tax shifts consumption into the future, inducing less consumption today and more consumption tomorrow. This reduction in consumption today implies a decrease in oil use and carbon emissions. In this sense, a consumption tax can achieve the same goal that a carbon tax would. Moreover, it is easy to show that a decreasing consumption tax translates into a capital income subsidy on the capital investment margin. Thus, a capital income tax is required to keep the capital investment decision undistorted and push the return on capital income back to the optimal level.

It is worth mentioning that the implementation we are proposing (using consumption and capital income taxes) has the advantage of utilizing taxes already in use in about every country. The drawback, however, is that a consumption tax might prove to be, in practice, too close to a carbon tax in the sense that it directly enters the oil extraction decision. Formally, this means that the tax affects the firms' Hotelling rents fully, making its use susceptible to the same kind of conflicting interests at play at climate negotiations.

Related literature. Sinn (2008) is among the first to argue for a capital income tax in the absence of a carbon tax. He argues that a capital income tax makes it less attractive for oil companies to extract oil and invest the proceedings in interest-bearing assets. van der Ploeg (2016) extends this result to a multi-country setting with elastic oil supply. We share with this paper the rationale for incorporating a capital income tax. The rationale comes from an equilibrium non-arbitrage condition on the return of capital and oil as alternative assets. Unlike van der Ploeg (2016), we explicitly incorporate the constraint on the lack of carbon taxes into the policy design problem, and we theoretically characterize how the optimal capital income tax formula depends on this constraint.

The paper is also related to the literature that studies optimal capital income taxes in the context of a neoclassical growth model extended to include climate change. Barrage (2018b), Barrage (2018a) and Schmitt (2014) are the first to study how carbon taxes can be added optimally to the fiscal policy toolbox. That is, in these papers the optimal policy consists of a combination of positive taxes on carbon, income, and consumption. This article differs from these papers in that we study the optimal fiscal policy when a carbon tax is restricted to be zero. Also, this article differs in that we characterize the Pigouvian and Ramsey component of the optimal tax rates separately. In this respect, this paper is related to Sandmo (1975)'s additivity result. That is, we find that the optimal tax rate is equal to the Pigouvian rate plus the Ramsey tax rate. We also do not contemplate redistributive policy goals through social discounting like in Barrage (2018a). As it is well-known, the Ramsey taxation problem is time-inconsistent in the spirit of Kydland and Prescott (1977), and we work under the assumption that a commitment device is available. We differ from Schmitt (2014) in that dimension.

The paper is organized as follows. Section 2 sets up the basic model. Section 3 solves the social planning problem. Section 4 proposes a market economy with taxes. Section 5 characterizes the optimal tax rates and contains the main theory results of the paper. Section 6 presents a quantitative exercise that contains the optimal tax rates estimation. Section 7 provides some concluding remarks. Finally, the mathematical proofs and technical details are in the appendix.

2 Model

Consider the following economy. Time is discrete and infinite, $t \in \{0, ..., \infty\}$. The economy is populated by a unit mass continuum of identical individuals. There is a single consumption good that is produced using capital, labor, and energy. The production function is given by

$$\tilde{F}(A_t, L_t, K_t, E_t) \tag{1}$$

where E_t is the energy sector that can be thought of as oil. The function $\tilde{F}$ displays constant returns to scale, and it is increasing, concave and continuously differentiable in all its inputs. Oil is an exhaustible resource, and the economy starts with oil reserves given by R_0. Therefore, at each point in time, oil use equals total oil extraction

$$E_t = R_t - R_{t+1} \tag{2}$$

Furthermore, oil use increases carbon in the atmosphere, S_t, so that

$$S_{t+1} = (1 - \gamma)S_t + E_t \tag{3}$$

where γ is the natural rate of carbon reabsorption. The stock of carbon in the atmosphere generates a climate externality that takes the form of an output loss. Thus, total output with the climate externality is given by

$$Y_t = F(A_t, S_t, L_t, K_t, E_t) = [1 - x(S_t)]A_t\tilde{F}(L_t, K_t, E_t) \tag{4}$$

The damage function x is increasing, concave and twice differentiable with $\lim_{S \to \bar{S}} x'(S) = 0$, where $\bar{S}$ represents a lower bound on the atmospheric CO2 concentration. The amount of labor is exogenously given and can vary over time.

Individuals derive utility from consumption, disutility from working, and discount the future with the discount factor $\beta \in (0,1)$. Over time, individuals care about the value

$$\sum_{t=0}^{\infty} \beta^t [u(C_t) - v(L_t)] \tag{5}$$

The utility function u is increasing, concave and twice differentiable with $lim_{c \to 0} u'(c) = \infty$. The function v is increasing, convex and twice differentiable with $lim_{L \to 0} v'(L) = 0$. Individuals consume, work, and invest in capital. Capital depreciates fully within one period, and the economy starts with a given stock, K_0. The feasibility constraint in this economy is given by

$$C_t + K_{t+1} + G_t = Y_t \tag{6}$$

for every period t, where G_t is some exogenously given stream of government spending.

3 Optimal Allocation

The *socially optimal allocation* is the path of consumption, labor, energy, capital, and carbon, $\{C_t, L_t, E_t, K_t, S_t\}_{t=0}^{\infty}$, that maximizes the welfare function (5) subject to the resource constraint (6), the carbon cycle (3) and the initial conditions K_0, R_0, and S_0.

At an interior solution, two intertemporal conditions characterize the optimal allocation: the investment in physical capital and the oil depletion rate. In particular, the first order condition for oil extraction is given by

$$\beta \lambda_{t+1} [F'_{e,t+1} - \mu_{t+1}] = \lambda_t [F'_{e,t} - \mu_t] \tag{7}$$

where λ_t, the Lagrange multiplier on the feasibility constraint, is the social value of final output and μ_t is the social cost of carbon. The social cost of carbon comes from iterating forward on the optimality condition for the carbon stock, and it is equal to

$$\mu_t = \sum_{j=0}^{\infty} [\beta(1-\gamma)]^j \frac{\lambda_{t+j}}{\lambda_t} x'(S_{t+j}) A_{t+j} F_{t+j} \tag{8}$$

The social cost of carbon measures the cost of the climate externality, which equals the output losses associated with burning an extra unit of oil in present value terms.

Equation (7) is a version of the Hotelling rule in this economy. The marginal benefit from extracting the exhaustible resource must be the same at every point in time. This benefit is the output growth from a marginal increase in oil extraction, net of the associated climate damages. Because output tomorrow (and consumption) can grow either by postponing extraction or by accumulating capital, a similar Euler equation holds for the capital investment decision:

$$\beta\lambda_{t+1}(C_{t+1})F'_{k,t+1} = \lambda_t \tag{9}$$

The social cost of carbon does not show up in the capital stock Euler equation because it is the energy use, and not production, what causes the increase in the carbon stock.

Also, notice that oil reserves and the capital stock are the assets that allow the economy to transfer resources over time. It follows that the return on both assets must be the same so that there are no arbitrage opportunities. In particular, the combination of the equations (7) and (9) implies that the following non-arbitrage condition holds at the optimum

$$\frac{F'_{e,t+1} - \mu_{t+1}}{F'_{e,t} - \mu_t} = F'_{k,t+1} \tag{10}$$

At the intratemporal margin, the usual tradeoff between leisure and consumption holds. That is, the marginal rate of substitution between consumption and labor equals the marginal rate of transformation

$$\frac{v'(L_t)}{u'(C_t)} = F'_L(t) \tag{11}$$

The following section presents a decentralized environment that implements this optimal allocation with taxes.

4 Market Economy

In this section, we propose a decentralized economy with taxes. The set of tax instruments is said to be "complete" if it allows the government to affect the relevant economic decisions and also includes lump-sum taxes. Although it is easy to see that a Pigouvian carbon tax on carbon emissions alone would be enough to solve the climate externality, we allow for a complete set of tax instruments that includes carbon taxes, capital and labor income taxes, consumption taxes, and lump-sum taxes. Thus, all goods in the economy are subject to taxation. The goal is to explore the role that these different policy instruments can play to shape the climate policy when we later introduce restrictions on the tools available to the government.

In the market economy, there are two production units or "sectors" indexed by $j = \{0, 1\}$. Sector $j = 0$ corresponds to the final consumption good production, and $j = 1$ represents the oil companies. A representative firm operates the technology (1) that produces the final consumption good. The firm hires labor at wage w_t, rents capital from households at rate r_t and buys energy from the oil sector at relative prices p_t. The problem of the firm is to choose the path of capital, energy, and labor $\{K_t, E_t, L_t\}_{t=0}^{\infty}$ to maximize discounted profits given by

$$\Pi_0 = \sum_{t=0}^{\infty} q_t^0 [F(A_t, S_t, L_t, K_t, E_t) - r_t K_t - p_t E_t - w_t L_t] \tag{12}$$

where q_t^0 is the Arrow-Debreu price of one unit of consumption in period t in terms of consumption in period zero.

A representative firm in the oil sector owns the stock of oil and faces a per-unit carbon tax τ_t^e on oil extraction. The problem of the firm is to choose the path of oil extraction that maximizes the discounted profits given by

$$\Pi_1 = \sum_{t=0}^{\infty} q_t^0 [(p_t - \tau_t^e)(R_t - R_{t+1})] \tag{13}$$

where p_t is the price of oil in units of the consumption good, and R_0 is the initial stock of oil reserves.

There is a continuum of mass one individuals, or a representative household, who derives utility from consumption. The representative household makes the capital investment decision and owns the firms. Consumers face a tax on consumption, labor income, and capital income. Therefore, households consume, work, and save subject to the following present value budget constraint

$$\sum_{t=0}^{\infty} q_t^0 [(1 + \tau_t^c) C_t + K_{t+1}] \leq \sum_{t=0}^{\infty} q_t^0 [(1 - \tau_t^k) r_t K_t + w_t (1 - \tau_t^\ell) L_t + T_t] + \Pi \tag{14}$$

where $\Pi = \sum_{j=0}^{1} \Pi_j$ are dividends from the firms, T_t is a lump sum tax or rebate, and K_0 is the initial capital stock. The problem of the households is to choose a sequence $\{C_t, L_t, K_t\}_{t=0}^{\infty}$ to maximize (5) subject to (14), taking prices and taxes as given.

The government collects the tax revenue and rebates any surplus to households in a lump-sum fashion. Also, the government must finance an exogenous stream of spending. Thus, the government budget constraint is given by

$$\sum_{t=0}^{\infty} q_t^0[\tau_t^e E_t + \tau_t^\ell w_t L_t + \tau_t^k r_t K_t + \tau_t^c C_t] = \sum_{t=0}^{\infty} q_t^0[T_t + G_t] \tag{15}$$

A *competitive equilibrium with a fiscal policy* $\{\tau_t^e, \tau_t^c, \tau_t^\ell, \tau_t^k, T_t, G_t\}_{t=0}^{\infty}$ is a sequence of prices $\{q_t^0, p_t, r_t, w_t\}_{t=0}^{\infty}$ and an allocation $\{C_t, E_t, K_t, L_t, S_t\}_{t=0}^{\infty}$ such that: (*i*) given the fiscal policy and prices, the allocation solves the consumer's problem, maximizing (5) subject to (14), and the firms' problem, maximizing Π_j for j={0,1}; (*ii*) the government budget constraint (15) is satisfied; (*iii*) the carbon stock follows the carbon cycle (3); and (*iv*) prices clear the markets.

At an interior solution, profit maximization of the final good's producer implies that prices must satisfy

$$F'_{\ell,t} = w_t \tag{16}$$

$$F'_{k,t} = r_t \tag{17}$$

$$F'_{e,t} = p_t \tag{18}$$

Further, following the Hotelling (1931) rule, profit maximization requires the return on oil extraction to be the same across time so that

$$q_{t+1}^0(p_{t+1} - \tau_{t+1}^e) = q_t^0(p_t - \tau_t^e) \tag{19}$$

Further, the Arrow-prices satisfy

$$q_t^0 = \beta \frac{u'(C_t)}{u'(C_0)} \frac{(1+\tau_0^c)}{(1+\tau_t^c)} \tag{20}$$

where q_0^0 is normalized to 1.

Finally, on the consumer's side, the first order conditions for consumption and the capital stock imply that a standard Euler equation must hold

$$\beta \frac{u'(C_{t+1})}{1+\tau_{t+1}^c}[(1-\tau_{t+1}^k)r_{t+1}] = \frac{u'(C_t)}{1+\tau_t^c} \tag{21}$$

Besides, the intratemporal tradeoff between leisure and consumption implies that the marginal rate of substitution equals the marginal rate of transformation so that

$$\frac{u'(C_t)}{v'(L_t)} = \frac{1+\tau_t^c}{(1-\tau_t^\ell)w_t} \tag{22}$$

To summarize, after plugging prices in, the competitive equilibrium is fully characterized by the following system of equations

$$\frac{u'(C_t)}{v'(L_t)} = \frac{1+\tau_t^c}{(1-\tau_t^\ell)F'_{\ell,t}} \tag{23}$$

$$\beta\frac{u'(C_{t+1})}{1+\tau_{t+1}^c}[F'_{e,t+1}-\tau_{t+1}^e] = \frac{u'(C_t)}{1+\tau_t^c}[F'_{e,t}-\tau_t^e] \tag{24}$$

$$\beta\frac{u'(C_{t+1})}{1+\tau_{t+1}^c}[(1-\tau_{t+1}^k)F'_{k,t+1}] = \frac{u'(C_t)}{1+\tau_t^c} \tag{25}$$

together with the feasibility constraint (6) and the transversality condition for the capital stock. Also, a no-arbitrage condition for the two assets arises from combining the equations (24) and (25) and establishes that the return on oil and capital must be the same in equilibrium. Thus,

$$(1-\tau_{t+1}^k)F'_{k,t+1} = \frac{F'_{e,t}-\tau_t^e}{F'_{e,t+1}-\tau_{t+1}^e} \tag{26}$$

5 Optimal Policy

When lump-sum taxes are available, it is easy to show that implementing the optimal allocation requires the introduction of a carbon tax equal to the social cost of carbon. The lump-sum tax is such that the government budget constraint is satisfied. The consumption and capital income taxes are both redundant and can be set to zero. To see this, notice that such a carbon tax would guarantee that the optimal allocation satisfies the equilibrium condition (19), and equation (21) and (23) are also satisfied if the tax rates on consumption and capital income are zero. It is straightforward to verify that the remaining conditions for an equilibrium are also satisfied. We thus have (proof omitted):

Proposition 1 (Optimal carbon taxes) *Suppose that $\{R_t^*, K_t^*, L_t^*, S_t^*\}_{t=0}^\infty$ is the socially optimal allocation. Then there exists a sequence of prices such that $\{R_t^*, K_t^*, L_t^*, S_t^*\}_{t=0}^\infty$ together with the prices constitute a competitive equilibrium with taxes equal to*

$$\tau_t^e = \mu_t \ ; \ \tau_t^c = \tau_t^\ell = \tau_t^k = 0 \tag{27}$$

for every period t, and any surplus is rebated lump-sum through T_t.

The next result characterizes an alternative decentralization. The proposition shows that even without a carbon tax, a combination of taxes on consumption and capital income can implement the optimal allocation. This result is interesting because it suggests that governments could rely on existing taxes to pursue climate goals. Also, this alternative implementation has the advantage that it might be easier for the governments to modify existing tax rates than to introduce a new tax to the tax code. The proof is in the appendix.

Proposition 2 (Optimal taxes without a carbon tax) *Assume $\tau_t^e = 0$ for all t. Suppose that $\{R_t^*, K_t^*, L_t^*, S_t^*\}_{t=0}^{\infty}$ is the socially optimal allocation. Then there exists a sequence of prices such that $\{R_t^*, K_t^*, L_t^*, S_t^*\}_{t=0}^{\infty}$ together with the prices constitute a competitive equilibrium with taxes equal to*

$$\tau_t^c = \frac{\mu_t}{F'_{e,t} - \mu_t} \tag{28}$$

$$\tau_{t+1}^k = \frac{\mu_t - \mu_{t+1}/F'_{k,t+1}}{F'_{e,t}} \tag{29}$$

$$\tau_t^\ell = \frac{\mu_t}{\mu_t - F'_{e,t}} \tag{30}$$

for every period t, and any surplus is rebated lump-sum through T_t.

Without a carbon tax, oil consumption is inefficiently high. Proposition 2 suggests that governments can rely on consumption taxes for delaying consumption, inducing less consumption today and more consumption tomorrow. This achieves the environmental goal of lowering future climate damages through a reduction in consumption today. Intuitively, it is a consumption tax that decreases over time what is needed to induce individuals to postpone consumption - and we show this formally in Corollary 1. However, it is easy to demonstrate that a decreasing consumption tax acts as a capital income subsidy on the capital investment decision. This is an undesired result because the capital investment decision should remain undistorted as shown by (9). Thus, the proposition also states that a capital income tax is required to push the return on capital income back to the optimal level.

Similarly, the consumption tax makes leisure relatively cheaper. Hence, a labor income subsidy is optimal to counteract this effect and keep employment at the optimal level.

Notice that the optimal tax rates characterized in Proposition 2 imply that the capital income tax is positive (negative) if the consumption tax is decreasing (increasing). We show in the appendix that both tax rates are positive and, therefore, the optimal consumption tax is decreasing over time. Also, the optimal labor income subsidy decreases over time as the consumption tax does it too.

Corollary 1 (Decreasing consumption taxes) *Let* $\{\tau_t^c\}_{t=0}^{\infty}$ *be the optimal tax sequence implied by proposition 2. Then*

$$\tau_t^c > \tau_{t+1}^c > 0$$

for every period t.

Intuitively, the optimal tax rate on consumption is positive because it is the ratio of the social cost of carbon over the shadow price of oil, both of which are positive at an interior solution. Also, we show in the appendix that the optimal tax rate on capital income is equal to the flow environmental damage (the difference between the current social cost of carbon and the discounted social cost of carbon in the next period) over the marginal product of oil. This, it is a positive tax rate.

It is worth mentioning that Proposition 2 depends on the assumption that the tax system is complete as the government can affect every economic decision. In this model, this means that the government can still induce optimal oil depletion by resource firms, even in the absence of a global carbon tax. In this sense, the consumption tax is very similar to a carbon tax and, in practice, it might be susceptible to the same kind of conflicting interests and coordination problems as a carbon tax. An alternative exercise that would address this issue is to consider an incomplete tax code. In particular, a sensible assumption would be to think of a scenario where both the carbon emissions tax and the consumption tax are constrained to be zero. In this case, the government lacks an instrument to affect (19), and the oil extraction decision margin must remain (sub-optimally) undistorted. Exploring this sort of tax code incompleteness is an exciting avenue for future research.

5.1 Distortionary Ramsey taxes

We have shown that governments can use standard fiscal instruments to pursue climate policies. The optimal Pigouvian taxes assume that the government uses the consumption, labor income, and capital income taxes only to correct the climate externality. However, these taxes already exist in almost every country and are a vital source of government revenue. Therefore, it is important to explore the interactions between the existing tax rates and the changes that pursuing climate policy with them would imply. The overall optimal tax, in this case, will display a combination of Pigouvian and Ramsey elements. The “Pigouvian” part captures the climate externality; the “Ramsey” part captures the government financing needs.

Given an exogenous stream of government spending, the Ramsey problem is to maximize social welfare subject to two types of constraints. The first constraint is that taxes must finance the government spending and lump-sum taxes are not available; the second constraint is that taxes must induce an allocation that is a competitive equilibrium. Following the Ramsey tradition, the competitive equilibrium conditions can be summarized in a so-called "Implementability constraint". The implementability constraint is the consumer's budget constraint after substituting in the equilibrium behavior of consumers and firms given the tax policy. The implementability constraint, together with the feasibility constraint, guarantees that the present value budget constraint of the government holds. We show in the appendix that the implementability constraint for this economy takes the following form:

Proposition 3 (Implementability constraint) *Given the initial condition* (K_0, R_0, S_0)*, the allocation* $\{R_t, K_t, L_t, S_t\}_{t=0}^{\infty}$ *in a competitive equilibrium is fully characterized by (3), (6) and the following implementability constraint*

$$\sum_{t=0}^{\infty} \beta^t [u'(C_t)C_t - v'(L_t)L_t] = \frac{u'(C_0)}{1+\tau_0^c}[(F'_{k,0}(1-\tau_0^k)K_0 + (F'_{E,0} - \tau_0^e)R_0] \tag{31}$$

As it is standard, we assume that taxation of the initial capital stock and initial oil reserves is bounded above because these are a form of lump-sum taxation. Initial taxes are given.

The *Ramsey allocation* is the solution to the Ramsey problem, which is to choose an allocation $\{R_t, K_t, L_t, S_t\}_{t=0}^{\infty}$ to maximize the welfare function (5) subject to the carbon cycle (3), the resource constraint (6), the implementability constraint (31), and the initial conditions $\{K_0, R_0, S_0, \tau_0^c, \tau_0^k, \tau_0^e\}$.

Because it will be useful to characterize the main results of this section, we first study a business-as-usual economy as a benchmark case. This business-as-usual economy corresponds to a Ramsey government that raises revenue using taxes, but does not seek any climate goal nor does it take into account the climate externality. The carbon tax is, thus, equal to zero by definition.

Let α be the Lagrange multiplier on the implementability constraint. Following the literature, especially Chari and Kehoe (1999), we define: $H_{ct} \equiv \frac{-u''(C_t)C_t}{u'(C_t)}$ and $H_{\ell t} \equiv \frac{-v''(L_t)L_t}{v'(L_t)}$. The following lemma characterizes the optimal Ramsey tax rates in a business-as-usual scenario.

Lemma 1 (Ramsey taxes - Business as usual) *The Ramsey taxes in a business-as-usual economy are equal to*

$$\tau_t^{c,Ramsey} = \frac{\alpha(1-H_{ct})}{1-\alpha+\alpha H_{ct}} \tag{32}$$

$$\tau_t^{\ell,Ramsey} = \frac{\alpha(H_{\ell t} - 1)}{1 - \alpha + \alpha H_{\ell t}} \tag{33}$$

and $\tau_t^e = \tau_t^k = 0$ *for every period* $t \geq 1$*.*

This result reflects some well-known principles in Ramsey taxation. In particular, the taxation of capital income is specially distortionary because it affects the intertemporal investment decision which has long-lasting effects on economic growth. A Ramsey government typically prefers to raise revenue with labor income taxes as opposed to capital income taxes. The well-established Chamley-Judd result is that capital income taxation should be zero in the long run. This result holds in this economy, both for the capital stock and for the oil reserves as the consumption taxes distort the capital investment decision in much the same way as the oil depletion choice. Importantly, the after-tax non-arbitrage condition between the two assets remains unchanged, which minimizes the distortions to the intertemporal trade-offs.

Some special cases are worth being discussed. The Ramsey tax rates are equal to zero if the government financing needs are not binding and $\alpha = 0$ - for example, because there exist lump-sum taxes. Also, the Ramsey consumption tax is constant when the utility function is separable and takes a standard CRRA form over consumption with parameter σ. Moreover, the Ramsey consumption tax is equal to zero when $\sigma = 1$. In this case, the government must rely on labor income taxes and initial taxes, $\tau_{k,0}$ and $\tau_{e,0}$, to meet its financing requirements.

When the need to finance government spending combines with the need to correct a climate externality, the tax rates naturally reflect both tasks. This combination of Pigouvian and Ramsey problems was first studied in Sandmo (1975), who finds that an additivity result holds. That is, the optimal tax rate is equal to the Pigouvian tax rate plus the Ramsey tax rate. The following proposition shows that a version of Sandmo (1975) additivity result holds in this economy. We denote these taxes as "distortionary taxes" to reflect the fact that these taxes introduce inefficient distortions in the economy to raise revenue. However, notice that the distortions here not only come from collecting revenues but also from correcting the climate externality.

Proposition 4 (Distortionary taxes) *Assume* $\tau_t^e = 0$ *for all* t*. Suppose that the Ramsey allocation is* $\{C_t^*, K_t^*, E_t^*, S_t^*\}_{t=0}^{\infty}$*. Then there exists a sequence of prices that, together with* $\{C_t^*, K_t^*, E_t^*, S_t^*\}_{t=0}^{\infty}$*, constitute a competitive equilibrium with taxes equal to*

$$\tau_t^c = \frac{\mu_t}{F'_{e,t} - \mu_t} \frac{1}{1 - \alpha + \alpha H_{ct}} + \tau_t^{c,Ramsey} \tag{34}$$

$$\tau^k_{t+1} = \frac{\mu_t - \mu_{t+1}/F'_{k,t+1}}{F'_{e,t}} \tag{35}$$

$$\tau^\ell_t = \frac{\mu_t}{\mu_t - F'_{e,t}} \frac{1}{1-\alpha+\alpha H_{\ell,t}} + \tau_t^{\ell,Ramsey} \tag{36}$$

for every period t.

The optimal consumption and labor incometaxes are now composed of two elements. The first element is the Pigouvian tax rate and corresponds to the one characterized in Proposition 2. The second element is the Ramsey tax rate, which coincides with that in Lemma 1. Also, notice that the capital income tax is the Pigouvian rate because the Ramsey component is zero as shown in Lemma 1. Thus, Sandmo (1975)'s additivity result holds.

These optimal tax rates are essentially the same as those in Barrage (2018b). The main difference with that article is that this paper presents a decomposition of the tax rates into the Ramsey and the Pigouvian components and, importantly, that we show the equivalence of these taxes to a unique carbon tax[1].

In the next section, we provide a quantitative estimate of these optimal taxes.

6 A quantitative exercise

The government can fully compensate for the absence of carbon pricing if it has access to a complete set of tax instruments. Here we establish that for a calibrated version of our model these tax rates necessary to achieve the first-best allocation are well within existing tax rates. To do so follow further the assumptions about functional forms and parameters used in Golosov et al. (2014). We assume no disutility from labor. Notice that we already adopted the additional assumptions of full depreciation of capital and geometric dissipation of carbon stocks in the previous sections.

Assumption 1 *Suppose that utility is logarithmic and separable,* $U(C_t, L_t) = \log(C_t)$ *with no disutility from labor, damage is multiplicative and exponential,* $1-x(S_t) = \exp(-\bar{\gamma}(S_t-\bar{S})$*, and final output production is unit-elastic with* $F(K_t, E_t, L_t) = A_t K_t^\alpha E_t^\nu L_t^{1-\alpha-\nu}$*, the carbon cycle is given by* $S_t = \bar{S} + \sum_{s=0}^{\infty}(1-d_s)E_{t-s}$ *with* $1-d_s = \varphi_L + (1-\varphi_L)\varphi_0\varphi^S$*.*

[1]The underlying economy differs to that in Barrage (2018b) in that oil is the only energy source and that we do not include distutility costs from climate change.

Under assumption 1, first best consumption and the social cost of carbon are proportional to output $Y_t = (1 - x(S_t))F(K_t, E_t, L_t)$:

$$C_t^* = (1 - \alpha\beta)Y_t \tag{37}$$

$$\mu_t^* = \theta\ Y_t = \frac{\bar{\gamma}}{1-\beta}\left(\frac{\varphi_0\,(1-\varphi_L)}{1-\beta\varepsilon} + \frac{\varphi_L}{1-\beta}\right)Y_t \tag{38}$$

See Golosov et al. (2014) for a derivation of these results.

The assumption of oil as sole energy input allows us to express equation (10) as

$$\frac{\nu}{E_t(1-\alpha\beta)} - \theta = \beta\left(\frac{\nu}{E_{t+1}(1-\alpha\beta)} - \theta\right) \tag{39}$$

It follows that the optimal fossil fuel depletion is independent of the dynamics of capital.

The optimal tax rates in the absence of carbon pricing, equations (28) and (29), reduce to the following expressions:

$$\tau_t^C = \frac{\theta}{\nu/E_t - \theta}$$

$$\tau_t^k = \frac{(1-\beta)\theta}{\nu/E_t}$$

Notice that the optimal tax rates in proposition 1 and 2 are also independent of the capital stock, and we only need to solve for the optimal rate of fossil fuel depletion in order to calculate the optimal tax rates for consumption and capital income. We follow the calibration in Golosov et al. (2014), and we solve equations (39) and (3) numerically to obtain the optimal path of fossil fuel extraction[2]. Table 1 summarizes the parameter values and the Appendix 9 discusses the solution algorithm.

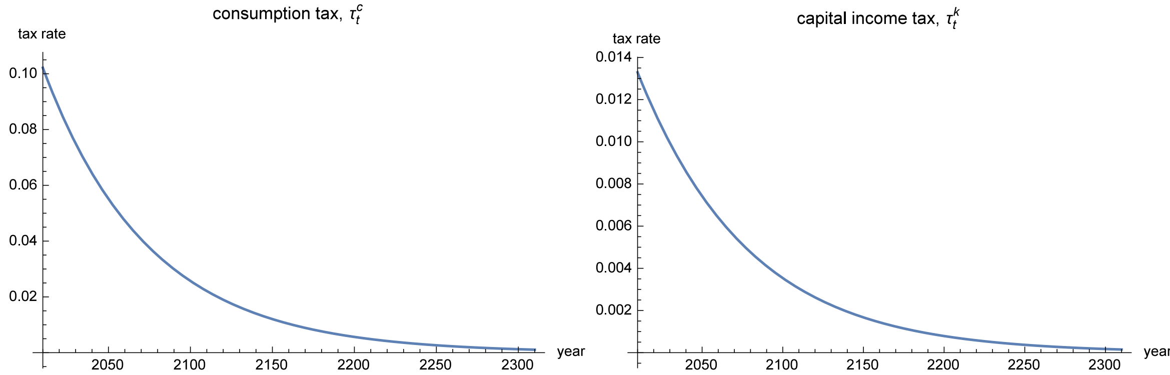
Figure 1 presents the optimal fiscal policy that is equivalent to a carbon tax but relies on consumption and income taxes to implement the optimal allocation. Notice that, given the log-utility functional form assumption, these optimal taxes correspond to the Pigouvian tax rates as the Ramsey component cancels out. The consumption tax starts at 10.4% and falls to 2.6% by the end of the century. The tax on capital income is significantly lower, starting

[2]Our model differs from Golosov et al. (2014) in that we do not include alternative sources of energy such as coal and renewable energy, and oil is the only source of carbon emissions in the model. Given the initial oil stock in the benchmark calibration, we obtain that the initial oil extraction is too low when compared to current carbon emissions levels. To get current emissions equal to 100 GtC per decade (~10GtC/yr), R_0 should increase to 800 GtC. This would increase the initial tax on consumption to 38% and on capital income to 4%.

Table 1: **Calibration.**

φ	φ_L	φ_0	α	ν	β
0.0228	0.2	0.393	0.3	0.04	0.985^{10}
R_0	$\overline{S}$	S^P	S^T	$\bar{\gamma}$	
253.8	581	684	118	$2.379\ 10^{-5}$	

Figure 1: **Optimal tax rates on consumption and capital income**



at 4.1% and falling to 1.2% by 2100. These rates are well within the range of existing taxes on consumption and capital income.

7 Concluding Remarks

Political institutions impose important constraints on the feasibility of climate policy. While from an economic theory perspective a global price on carbon would be the first-best instrument to correct the climate externality, this instrument has proved elusive. Except for some taxes on fossil fuel, most governments are not taxing carbon emissions. The world economy remains on a business-as-usual path to 4C warming by the end of the century.

Previous studies have focused on estimating the optimal carbon price in addition to the more conventional motives for public finance (raising revenue, fixing other market distortions, or redistributing income). We turn this question around, asking how the existing toolbox available to ministers of finance can be harnessed to limit climate change if the price on carbon is constrained to zero. In our neoclassical growth model with a single capital stock, exhaustible fossil fuel, and climate change, we find that here a combination of falling consumption and capital income taxes is sufficient to implement the first best.

The intuition for result is straight-forward and starts with the simple observation that the price of oil needs to rise if its use is to fall. A positive price on carbon achieves this directly. Alternatively, the price of using oil can be raised by making the resource more valuable (by increasing its rent). In equilibrium, fossil fuel owners choose to deplete their reserves such that leaving the resource untouched and extracting and investing the proceeds on the capital market provides the same return. Raising interest rates, makes investing more attractive, raises the price of oil, and weakens the climate problem. However, higher interest rates also increase the return of capital and incentivize the accumulation of capital which increases the attractiveness of using oil by increasing its marginal product. Therefore, optimal tax policy increases equilibrium interest rates while curbing investment to its socially optimal level. We show that combination of consumption and capital income taxes achieves this and the tax rates required to implement the efficient allocation are within reasonable levels.

Our proposed tax scheme is time-consistent. This is due to the fact that we are allowing for lump-sum taxation and are excluding a public borrowing requirement, the usual sources of time-inconsistency. Clearly, a more general model would have to take into account the standard reasons for distortionary taxation and study second-best taxation in such a setting. While we draw confidence from the fact that our tax rates are within the range of conventional numbers, implying that our argument can survive in a more complex setting, we leave the formal for future research.

8 Mathematical Appendix

Proof of Proposition 2. The proof consists of showing that all conditions for an equilibrium are satisfied by the optimal allocation when taxes are set optimally. A competitive equilibrium is fully characterized by the intratemporal condicion (23), the intertemporal equations (24) and (25) together with the feasibility constraint (6) and the transversality conditions for the capital stock and oil reserves. To see that equation (24) coincides with the optimal condition (7), plug the tax rates as defined in the proposition to get

$$\beta \frac{u'(C_{t+1})}{1+\frac{\mu_{t+1}}{F'_{e,t+1}-\mu_{t+1}}}[F'_{e,t+1}-0] = \frac{u'(C_t)}{1+\frac{\mu_t^*}{F'_{e,t}-\mu_t}}[F'_{e,t}-0]$$

After some simple algebra, we obtain

$$\beta u'(C_{t+1})[F'_{e,t+1}-\mu_{t+1}] = u'(C_t)[F'_{e,t}-\mu_t]$$

which coincides with (7). Moreover, plug the capital income tax rate into (25) in order to get

$$\beta\frac{u'(C_{t+1})}{1+\tau^c_{t+1}}[(1-\frac{\tau^c_t-\tau^c_{t+1}}{1+\tau^c_t})F'_{k,t+1}]=\frac{u'(C_t)}{1+\tau^c_t}$$

which coincides with (9) after canceling out the tax rates from both sides. Finally, plug in the consumption and labor income tax rates into (23) to get

$$\frac{u'(C_t)}{v'(L_t)}=\frac{1+\mu_t/(F'_{E_t}-\mu_t)}{[1-\mu_t/(\mu_t-F'_{E_t})]F'_{\ell t}}$$

which coincides with (11) after some simple algebra. The feasibility constraint and the transversality conditions are satisfied by definition of the competitive equilibrium. This completes the proof that all conditions for a competitive equilibrium with taxes are satisfied by the optimal allocation.

Proof of Corollary 1. After doing the relevant substitutions using the characterization of the social planner's solution, the optimal tax on consumption is equal to

$$\tau^c_t=\frac{\mu_t}{F'_{e,t}-\mu_t}=\frac{\mu_t}{\lambda_t}>0$$

where λ_t is the shadow price of oil. At an interior solution both, the social cost of carbon and the shadow price of oil, are positive. Therefore, the consumption tax is positive. Further, the capital income tax is equal to

$$\tau^k_{t+1}=\frac{\tau^c_t-\tau^c_{t+1}}{1+\tau^c_t}=\frac{\mu_t-\frac{\mu_{t+1}}{F'_{k,t+1}}}{F'_{e,t}}=\frac{x'(S_{t+1})A_{t+1}\tilde{F}_{t+1}}{F'_{e,t}}$$

where the second equality comes from using the asset's optimal arbitrage condition. Thus, the capital income tax rate is equal to the flow environmental damage (the difference between the current social cost of carbon and the discounted social cost of carbon in the next period) over the marginal product of oil. This implies a positive capital income tax and, therefore, a decreasing consumption tax rate.

Proof of Proposition 3. Let $\mathbf{x}\equiv\{q^0_t,p_t,r_t,w_t,C_t,E_t,K_t,L_t,S_t\}^\infty_{t=0}$ be a competitive equilibrium given a fiscal policy $\left\{\tau^e_t,\tau^c_t,\tau^k_t,T_t,G_t\right\}^\infty_{t=0}$. At an interior solution, $\mathbf{x}$ satisfies (16)-(21) together with the carbon cycle dynamics (3), the feasibility constraint (6), the government budget balance (15), and the transversality condition for the capital stock. By Walras law, if the consumer's budget constraint holds, then (15) holds as well. The proof consists on showing that (14) can be combined with (16)-(21) to get the implementability constraint. Rewrite (14) to get

$$\sum_{t=0}^{\infty} q_t^0[(1+\tau_t^c)C_t - w_t(1-\tau_t^\ell)L_t] = \sum_{t=0}^{\infty} q_t^0[(1-\tau_t^k)r_tK_t - K_{t+1}] + \Pi \tag{40}$$

Using (20) and (23), we have that

$$\sum_{t=0}^{\infty} \beta^t \frac{1+\tau_0^c}{u'(C_0)}[u'(C_t)C_t - v'(L_t)L_t] = \sum_{t=0}^{\infty} q_t^0[(1-\tau_t^k)r_tK_t - K_{t+1} + T_t] + \Pi \tag{41}$$

Notice that the right-hand side of (41) can be opened up to obtain

$$\sum_{t=0}^{\infty} \beta^t \frac{1+\tau_0^c}{u'(C_0)}[u'(C_t)C_t - v'(L_t)L_t] = q_0^0(1-\tau_0^k)r_0K_0 - q_0^0K_1 + q_1^0(1-\tau_1^k)r_1K_1 - q_1^0K_2 + .. + \sum_{t=0}^{\infty} q_t^0T_t + \Pi \tag{42}$$

where

$$\Pi = q_0^0[(p_0 - \tau_0^e)(R_0 - R_1)] + q_1^0[(p_1 - \tau_1^e)(R_1 - R_2)] + ...$$

and profits in sectors $j = 0$ and $j = 2$ are zero in equilibrium in every period t. That is,

$$\sum_{t=0}^{\infty} \beta^t \frac{1+\tau_0^c}{u'(C_0)}[u'(C_t)C_t - v'(L_t)L_t] = (1-\tau_0^k)r_0K_0 - K_1\{1 - q_1^0(1-\tau_1^k)r_1\} - q_1^0K_2 + .. + \sum_{t=0}^{\infty} q_t^0T_t + \Pi \tag{43}$$

with

$$\Pi = (p_0 - \tau_0^e)R_0 - R_1\{(p_0 - \tau_0^e) + q_1^0(p_1 - \tau_1^e)\} - (p_1 - \tau_1^e)R_2) + ...$$

where the terms in between curly brackets in the right-hand side of the equation are zero from (21) and (19). Proceeding forward with the rest of the summands, and using the first order conditions with respect to capital and oil in every t, we get

$$\sum_{t=0}^{\infty} \beta^t \frac{1+\tau_0^c}{u'(C_0)}[u'(C_t)C_t - v'(L_t)L_t] = (1-\tau_0^k)r_0K_0 + (p_0 - \tau_0^e)R_0 \tag{44}$$

where the value of the capital stock at $T \to \infty$ is zero by the Transversality condition. Further, use (17) and (18) to write down the implementability constraint only in terms of the allocation.

$$\sum_{t=0}^{\infty} \beta^t[u'(C_t)C_t - v'(L_t)L_t] = \frac{u'(C_0)}{1+\tau_0^c}[(1-\tau_0^k)F'_{k,0}K_0 + (F'_{E,0} - \tau_0^e)R_0] \tag{45}$$

which coincides with (31).

Proof of Lemma 1. The proof consists of showing that all conditions for an equilibrium are satisfied by the business-as-usual Ramsey allocation when taxes are set according to the lemma. At an interior solution, the Ramsey allocation is characterized by the following system of equations for every period $t \geq 1$

$$\frac{u'(C_t)}{v'(L_t)} = \frac{1-\alpha+\alpha H_{\ell t}}{1-\alpha+\alpha H_{ct}} \frac{1}{F'_{\ell t}} \tag{46}$$

$$\beta u'(C_{t+1})(1-\alpha+\alpha H_{ct+1})F'_{e,t+1} = u'(C_t)(1-\alpha+\alpha H_{ct})F'_{e,t} \tag{47}$$

$$\beta u'(C_{t+1})(1-\alpha+\alpha H_{ct+1})F'_{k,t+1} = u'(C_t)(1-\alpha+\alpha H_{ct}) \tag{48}$$

together with (3), (6), (31), and the initial conditions $\{K_0, R_0, S_0, \tau_0^c, \tau_0^k, \tau_0^e\}$. Notice that the optimal consumption tax can be written as $1+\tau_t^c = \frac{1}{1-\alpha+\alpha H_{ct}}$. Plug this tax rate into (24) and (25) to get (55) and (48), respectively. Capital income and carbon taxes are both zero. Also, (31) guarantees that the Ramsey allocation satisfies (14), and (6) holds by definition of the Ramsey problem. It remains to show that the Ramsey allocation satisfies (23). To see this, plug in the tax rates to get

$$\frac{u'(C_t)}{v'(L_t)} = \frac{\frac{1}{1-\alpha+\alpha H_{ct}}}{\frac{1}{1-\alpha+\alpha H_{\ell t}} F'_{e,t}} \tag{49}$$

which holds since the Ramsey allocation satisfies (46). This completes the proofs that all conditions for a competitive equilibrium are satisfied by the Ramsey allocation.

Proof of Proposition 4. (Incomplete) The proof consists of showing that all conditions for an equilibrium are satisfied by the Ramsey allocation when taxes are set optimally. At an interior solution, the Ramsey allocation is characterized by the following system of equations for every period $t \geq 1$

$$\frac{u'(C_t)}{v'(L_t)} = \frac{1-\alpha+\alpha H_{\ell t}}{1-\alpha+\alpha H_{ct}} \frac{1}{F'_{\ell t}} \tag{50}$$

$$\beta u'(C_{t+1})(1-\alpha+\alpha H_{ct+1})(F'_{e,t+1}-\mu_{t+1}) = u'(C_t)(1-\alpha+\alpha H_{ct})(F'_{e,t}-\mu_t) \tag{51}$$

$$\beta u'(C_{t+1})(1-\alpha+\alpha H_{ct+1})F'_{k,t+1} = u'(C_t)(1-\alpha+\alpha H_{ct}) \tag{52}$$

together with (3), (6), (31), and the initial conditions $\{K_0, R_0, S_0, \tau_0^c, \tau_0^k, \tau_0^e\}$. Plug the expression for τ_t^c into (24) to get

$$\beta \frac{u'(C_{t+1})}{1 + \frac{\mu_t}{F'_{e,t}-\mu_t}\frac{1}{1-\alpha+\alpha H_{ct}} + \frac{\alpha(1-H_{ct})}{1-\alpha+\alpha H_{ct}}} F'_{e,t+1} = \frac{u'(C_t)}{1 + \frac{\mu_t}{F'_{e,t}-\mu_t}\frac{1}{1-\alpha+\alpha H_{ct}} + \frac{\alpha(1-H_{ct})}{1-\alpha+\alpha H_{ct}}} F'_{e,t} \tag{53}$$

With some algebra manipulation, this equation can be written as

$$\beta \frac{u'(C_{t+1})}{\frac{1}{1-\alpha+\alpha H_{c,t+1}} \frac{F'_{e,t+1}}{F'_{e,t+1}-\mu_{t+1}}} F'_{e,t+1} = \frac{u'(C_t)}{\frac{1}{1-\alpha+\alpha H_{c,t}} \frac{F'_{e,t}}{F'_{e,t}-\mu_t}} F'_{e,t} \tag{54}$$

That is,

$$\beta u'(C_{t+1})(1-\alpha+\alpha H_{ct+1})(F'_{e,t+1}-\mu_{t+1}) = u'(C_t)(1-\alpha+\alpha H_{ct})(F'_{e,t}-\mu_t) \tag{55}$$

which is satisfied by the Ramsey allocation. Similary, plug in the expressions for τ_t^c and τ_t^k into (25) to get

$$\beta \frac{u'(C_{t+1})}{1+\tau_{t+1}^c}[(1-\tau_{t+1}^k)F'_{k,t+1}] = \frac{u'(C_t)}{1+\tau_t^c} \tag{56}$$

Finally, (31) guarantees that the Ramsey allocation satisfies (14), and (6) holds by definition of the Ramsey problem.

9 Numerical appendix

The pair of simultaneous difference equations (3) and (39) reduces to

$$E_t = \frac{\nu}{\eta(1-\alpha\beta\gamma) + \left(\frac{1}{\beta\gamma}\right)^t (\beta\gamma C1\ \nu - \eta(1-\alpha\beta\gamma))} \tag{57}$$

$$\sum_{t=0}^{\infty} E_t = \frac{\nu}{\eta(1-\alpha\beta\gamma) 2\log\left(\frac{1}{\beta\gamma}\right)} \left(\log\left(\frac{1}{\beta\gamma}\right) + 2\log\left(\frac{1-\beta\gamma}{\beta\gamma}\right) + 2\log\left(\frac{\eta(1-\alpha\beta\gamma)}{\eta(1-\alpha\beta\gamma)-\nu\beta\gamma\ C1}\right) + 2\psi_{\frac{1}{\beta\gamma}}\left(-\frac{\log\left(\frac{\eta(1-\alpha\beta\gamma)}{\eta(1-\alpha\beta\gamma)-\nu\beta\gamma\ C1}\right)}{\log\left(\frac{1}{\beta\gamma}\right)}\right)\right) = R_0.$$

The second expression is a non-linear equation in the constant $C1$ which we solve numerically for parameters listed in assumption 1 using *Mathematica*'s FindRoot command (with $\widetilde{C1} = ((1-\beta)\beta R_0)^{-1}$ as initial guess which corresponds to the exact $C1$ for the case of laissez-faire). Given a solution for $C1$, we know efficient energy use (the first expression in 57) and, consequently, the optimal consumption and capital income tax rates in the absence of carbon pricing.

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