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Second-best Carbon Taxation in the Global Economy: The Green Paradox and Carbon Leakage Revisited

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SECOND-BEST CARBON TAXATION IN THE GLOBAL ECONOMY

The Green Paradox and Carbon Leakage Revisited

Frederick van der Ploeg, University of Oxford[ℜ]

ABSTRACT

Unilateral second-best carbon taxes are analysed in a two-period, two-country model with international trade in final goods, oil and bonds. Acceleration of global warming resulting from a future carbon tax is large if the price elasticities of oil demand are large and that of oil supply is small. The fall in the world interest rate weakens this weak Green Paradox effect, especially if intertemporal substitution is weak. Still, green welfare rises if the fall in oil supply and cumulative emissions is strong enough. If the current carbon tax is too low, the second-best future carbon tax is set below the first best to mitigate adverse Green Paradox effects. Unilateral second-best optimal carbon taxes exceed the first-best taxes due to an import tariff component. The intertemporal terms of trade effects of the future carbon tax increase current and future tariffs and those of the current tax lower the current tariff. Finally, carbon leakage and globally altruistic and unilateral second-best optimal carbon taxes if non-Kyoto oil importers do not price carbon or price it too low are analysed in a three-country model of the global economy.

Keywords: unilateral carbon taxes, intertemporal terms of trade, tax incidence, Green Paradox, asset tax, carbon leakage, second best, global altruism, unburnt fossil fuel

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1. Introduction

Prominent in the debate on how to fight global warming is the notion that badly designed climate policy is counter-productive. An example of this is the Green Paradox, which states that politicians that put off carbon taxation bring oil consumption forward and thus accelerate global warming (Sinn, 2008). However, if fossil fuel extraction costs rise as reserves diminish, a future carbon tax might also cut the total amount of fossil fuel that is burnt and thus cut cumulative fossil fuel emissions (e.g., van der Ploeg and Withagen, 2012). Physicists have also recognized the importance of locking up enough fossil fuel in the crust of the earth (e.g., Allen et al., 2009). Indeed, as much as third of oil, half of gas and over four fifths of coal reserves may need to be left unburnt for global warming to not exceed 2 degrees Celsius (McGlade and Ekins, 2015). Much of this debate is cast in terms of a partial equilibrium framework. Our objective is to adopt a global general equilibrium perspective taking full account of the repercussions in global markets for final goods, bonds and fossil fuel. To get a grip on the vexing issue of the cumulative amount of fossil fuel to be burnt, we model exploration investment (Gaudet and Laserre, 1988; Cairns, 1990), so cumulative fossil fuel use and carbon emissions depend on carbon taxation.

Our aim is to deepen the understanding of unilateral, second-best carbon taxes in general equilibrium where we distinguish oil-importing and oil-exporting countries with homothetic, symmetric preferences. With second best we mean that, on the one hand, politicians wish to postpone carbon taxation, and, on the other hand, carbon taxation has to be conducted knowing that other countries including fossil fuel producers are not willing to price carbon at the appropriate level. We are also interested in the welfare impacts of such second-best and unilateral policies and how such policies should be optimally set. Our contributions are as follows.

First, we show that a future carbon tax leads to a bigger increase in current oil demand and carbon emissions if the price elasticities of current and future oil demand are large and the price elasticity of oil exploration and oil supply is small. We also show that this *weak* Green Paradox effect is attenuated by the fall in the world interest rate, especially if intertemporal substitution is weak (cf., van der Meijden et al., 2015). The adverse effect on green welfare is further mitigated by locking more carbon in the earth as a result of curbing oil exploration. The net effect on green welfare is negative if the ecological discount rate is large enough while the price elasticity of oil demand is high and that of oil supply is small. Even if such a *strong* Green Paradox occurs (Gerlagh, 2011), welfare of oil-importing countries can improve due to the import tariff and intertemporal terms of trade benefits of a higher anticipated carbon tax.

Second, we show that with a strong Green Paradox an asset holding tax on oil producers can be a viable policy alternative. But, if oil supply reacts strongly to oil prices and oil demand does not, postponed carbon taxation is productive and an asset holding tax is not.

Third, we show that weak Green Paradox effects arise if renewable energy is subsidized provided that it is a good enough substitute for oil. Also, if there is an abundant and cheap alternative fossil fuel (i.e., coal), we give the conditions under which the weak Green Paradox effect is reversed (cf., Michielsen, 2014) and the oil barons benefit from climate policy at the expense of coal producers (cf., Coulomb and Henriet, 2015).

Fourth, we use our general equilibrium framework to establish that introducing a carbon tax that grows at a rate equal to the rate of interest is neutral if oil reserves are given. Carbon taxes that rise faster than the rate of interest induce Green Paradox effects and are detrimental to green welfare whilst carbon taxes that rise slower than that improve green welfare. But if oil supply is elastic, a carbon tax that rises at a rate equal to the interest rate curbs oil extraction as well as exploration investment, cumulative oil extraction and cumulative carbon emissions, and thus boosts green welfare.

Fifth, we show that, if for political reasons the current carbon tax is set below the Pigouvian tax, the second-best optimal future carbon taxes are set below the first-best globally optimal carbon taxes to mitigate Green Paradox effects, and more so if the price elasticity of oil demand is relatively large compared with that of oil supply (possibly turning the future tax into a subsidy). The first-best global carbon taxes equal the Pigouvian taxes (the present value of marginal global warming damages), which rise slower than the rate of interest and thus induce no Green Paradox effects.

Sixth, we show that if carbon taxes are set unilaterally by the oil-importing countries, they exceed the first-best taxes as they contain an import tariff component. We also establish that the intertemporal terms of trade effects of a future carbon tax increase both the current and future import tariff components and that of the current carbon tax depresses the current import tariff component. We also discuss the time inconsistency of these unilateral second-best optimal carbon taxes that result from the pure rents inherent in future reserves and show that reneging implies that carbon taxes are set even higher, at an even greater welfare cost to oil-exporting countries.

Finally, carbon leakage (e.g., Elliott et al., 2010; Elliot et al., 2012; Fischer and Salant, 2013; Elliott and Fullerton, 2014; Eichner and Pethig, 2011, 2013; Richter and Schopf, 2014; Sen, 2015) strengthens the Green Paradox as non-participating countries that do not price carbon raise their current (and also future) carbon emissions in response to a future unilateral carbon tax. We show that green welfare improves if oil supply responds more to prices than current oil demand, but welfare of countries that do price carbon rises by more. We also derive the globally altruistic and the unilateral second-best optimal carbon taxes.

Our contribution owes a lot to the analysis of Eicher and Pethig (2011), who offer a general equilibrium analysis of the Green Paradox and carbon leakage within the context of a 2-period, 3-country world with zero extraction costs and fixed oil reserves. Ritter and Schopf (2014) extend this general equilibrium analysis to allow for stock-dependent extraction costs. Van der Meijden et al. (2015) focus on two countries and extend the analysis to allow for endogenous oil reserves, investment in physical capital and asymmetric preferences between oil importers and oil exporters. They give examples with CES production functions for which the Green Paradox can be attenuated or reinforced rather than attenuated in general equilibrium. With identical preferences and no investment in physical capital, a future carbon tax unambiguously reduces the interest rate and attenuates the Green Paradox. Our innovation over these three studies is to use duality theory and offer, to the best of our knowledge for the first time, a comprehensive clear-cut welfare analysis of the Green Paradox and carbon leakage and easy-to-interpret formulae for the global first-best and global and unilateral second-best carbon taxes in a general equilibrium setting with an endogenous amount of cumulative extraction. To keep matters tractable, we suppose identical preferences (i.e., identical rates of time preference and coefficients of intergenerational inequality aversion)[1].

Our contribution is thus to offer a general equilibrium public finance perspective on the Green Paradox and carbon leakage. It therefore focuses at the role of the price elasticities of demand and supply and the ecological discount rate to assess the welfare effects and second-best and unilateral carbon taxes and how these are impacted by the Green Paradox and carbon leakage. For example, starting with a two-country framework, we show that a

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[1] This can be relaxed, but would make the expressions more cumbersome without giving more insights.

future carbon tax worsens welfare if the supply of fossil fuel is relatively inelastic compared with the fossil fuel demand and the ecological discount rate is large enough. More generally, duality allows us to quickly and conveniently establish the general equilibrium welfare effects of first-best, second-best optimal and unilateral carbon taxes.

Section 2 sets up the two-period, two-country model of global goods, capital and oil markets. Section 3 solves for the general equilibrium effects on oil prices and the world interest rate of present and future carbon taxes. Section 4 revisits the Green Paradox by discussing the general equilibrium effects of both a future carbon tax and a renewable energy subsidy on oil extraction, carbon emissions and welfare. Section 4 also discusses the merits of an asset holding subsidy and the Grey Paradox. Section 5 analyses the effects of introducing a balanced hike in carbon taxes on oil extraction, oil exploration and welfare. Section 6 discusses the effects of carbon taxes on the private and green components of welfare and then derives the first-best global and second-best unilateral carbon taxes. Section 7 shows that the optimal second-best, unilateral carbon taxes are excessive due an import tariff component to clobber the oil-producing countries and shows that the intertemporal terms of trade effect tends to tilt the import tariff component from the present to the future. It also shows that these second-best carbon taxes are time inconsistent. Section 8 extends the analysis to allow for three countries and carbon leakage and gives the globally altruistic and the unilateral second-best optimal carbon taxes when other countries that import fossil fuel do not price carbon. Section 9 concludes.

2. A Two-Period, Two-Country Model of Goods, Capital and Oil Markets[2]

We extend the two-period, two-country model of international trade in oil, final goods and bonds used in Dixit (1981), Marion and Svensson (1984) and van Wijnbergen (1985) to allow for endogenous exploration investment and carbon taxation. This model is as in van der Meijden et al. (2015), but uses duality to permit a convenient interpretation of the comparative statics and an analytical evaluation of welfare and optimal climate policy.

The model consists of two countries: an oil-exporting country, Oilrabia, and an oil-importing country, Industria. There is an international market for a homogenous final good which is only produced in Industria, an international bonds market, and an

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[2] From now on we refer to ‘oil’ as shorthand for gas, coal and other components of fossil fuel.

international market for oil. All markets operate under perfect competition. The stock of oil reserves and cumulative carbon emissions are endogenous, since initial reserves depend on initial investment in oil exploration. The only variable production factor in Industria is oil; other factors (e.g., land, labour or capital) are fixed. Preferences are homothetic and the same for Industria and Oilrabia. There are no bonds at the start and none left at the end. The market does not internalize climate externalities, but a carbon tax (or emissions market) can. There are no other market failures or distorting taxes.

2.1. Industria

Industria's preferences are defined by the concave unit expenditure function $e = e(\delta)$, where $\delta \equiv 1/(1+r)$ is the relative price of future final goods or the intertemporal terms of trade and *r* is the world rate of interest. This gives the minimum cost to finance one unit of real consumption or private welfare C, so $C_1 + \delta C_2 = e(\delta)C$ where C_1 denotes current and C_2 future consumption of final goods. The expenditure function corresponds to the homothetic and concave utility function $U(C_1, C_2)$, which satisfies the Inada conditions. Real consumption or private welfare *C* follows from $U(C,C) = U(C_1, C_2)$.

The production function in period *t* has diminishing returns, satisfies the Inada conditions and is given by $F(R_t)$, where R_t is oil use in period *t*. All other production factors are fixed, although in Section 4.2 and 4.3 we allow for endogenous demands for carbon-free renewable energy and abundant and carbon-intensive coal, respectively (and Appendix A discusses investment in physical capital). The price of oil includes a specific carbon tax τ_t and is thus $q_t \equiv p_t + \tau_t$, where p_t is the world producer price of oil in period *t*. Oil demands thus follow from the marginal productivity conditions $F'(R_t) = q_t$, namely $R_t = R(q_t), t = 1, 2.$ The price elasticities of oil demand are $\varepsilon_t^D \equiv -q_t R'(q_t)/R_t > 0, t = 1, 2.$ Let *Y* be the present value of income (wealth) and $T \equiv \tau_1 R_1 + \delta \tau_2 R_2$ that of rebated carbon tax revenue. The present-value budget constraint of Industria then is given by $e(\delta)C = Y \equiv F(R_1) - q_1 R_1 + \delta\left[F(R_2) - q_2 R_2\right] + T.$

The Hicksian demand function $C_2 = e'(\delta)C$ and $Y = eC$ give the present and future Marshallian demand functions for final goods, $C_1 = \left[1-\theta(\delta)\right]Y$ and $C_2 = \theta(\delta)Y/\delta,$ where $0 < \theta(\delta) \equiv \delta e'(\delta)/e < 1$ defines the share of future final goods in total expenditure.

2.2. Oilrabia

Oilrabia chooses initial oil exploration investment J to maximize the present value of its profits or its national income, $Y^* \equiv p_1R_1 + \delta^* p_2R_2 - J,$ subject to the oil depletion constraint $R_1 + R_2 = S(J),$ where S denotes initial oil reserves. We suppose diminishing returns from oil exploration, so that $S'(J) > 0$ and $S''(J) < 0.$ We thus get the familiar Hotelling rule, $p_2 = (1+r^*)p_1 = p_1/\delta^*,$ and the optimality condition for exploration investment, $p_1S'(J) = 1.$ From this we get $J = J(p_1),$ $J'(p_1) = -1/p_1{}^2S''(J) > 0,$ and $S = S(p_1).$ We define the oil supply elasticity as $\varepsilon^S \equiv p_1S'(p_1)/S > 0.$ Oilrabia's final goods consumption $C_1^* = \left[1-\theta(\delta^*)\right]Y^*$ and $C_2^* = \theta(\delta^*)Y^*/\delta^*,$ follow from the present-value budget constraint $C_1^* + \delta^*C_2^* = Y^*(p_1) = p_1S - J$ with $Y^{*}{}'(p_1) = S > 0.$

2.3. Equilibrium and Welfare

Perfect international capital markets imply that the interest rate is the same in Industria and Oilrabia ($r = r^*$ and $\delta = \delta^*$). Equilibrium on the international oil market requires

$$(1) \qquad R_1(p_1+\tau_1) + R_2\left((1+r)p_1+\tau_2\right) = S(p_1).$$

The markets for present and future final goods must be in equilibrium too. Walras's law implies that it suffices that the ratio of future to current demand, $\Theta(r),$ equals the ratio of future to current supply of final goods:

$$(2) \qquad \frac{C_2+C_2^*}{C_1+C_1^*} = \frac{\theta(r)}{1-\theta(r)}(1+r) \equiv \Theta(r) = \frac{F\left(S(p_1)-R_1(p_1+\tau_1)\right)}{F\left(R_1(p_1+\tau_1)\right)-J(p_1)}, \quad \Theta'(r) > 0.$$

We suppose that global welfare Φ is utilitarian and additive in private welfare and the green welfare loss $\Omega,$ where the latter is the present value of cumulative carbon emissions:

$$(3) \qquad \Phi = C + C^* - \Omega, \quad \Omega \equiv \chi(R_1 + \beta S), \quad \chi > 0.$$

Here $0 < \beta \le 1$ is the ecological discount factor including the effect of growth in damages. Utilitarian welfare implies zero inequality aversion across the two countries.

3. Comparative Statics and Welfare Effects

We first solve the oil market equilibrium condition (1) for p_1 in terms of r, τ_1 and τ_2, then solve the final goods market equilibrium (2) for r in terms of p_1 and τ_1, and then combine the two by solving for p_1 and r in general equilibrium. All other variables then follow.

3.1. Partial Equilibrium in the Oil Market: Tax Incidence and the Green Paradox

Total differentiation of the condition for equilibrium in the world oil market (1) yields:

$$\begin{gathered} dp_1 = -(1-\Upsilon^I)d\tau_1 - \Upsilon^G(d\tau_2 + p_1 dr), \quad dq_1 = \Upsilon^I d\tau_1 - \Upsilon^G(d\tau_2 + p_1 dr), \\ dS = \frac{S}{p_1}\varepsilon^S dp_1, \quad dR_1 = -\frac{R_1}{q_1}\varepsilon_1^D dq_1, \end{gathered} \tag{4}$$

where $0 < \Upsilon^I \equiv \dfrac{\frac{R_2}{\delta q_2}\varepsilon_2^D + \frac{S}{p_1}\varepsilon^S}{\frac{R_1}{q_1}\varepsilon_1^D + \frac{R_2}{\delta q_2}\varepsilon_2^D + \frac{S}{p_1}\varepsilon^S} < 1$ and $0 < \Upsilon^G \equiv \dfrac{\frac{R_2}{q_2}\varepsilon_2^D}{\frac{R_1}{q_1}\varepsilon_1^D + \frac{R_2}{\delta q_2}\varepsilon_2^D + \frac{S}{p_1}\varepsilon^S} < 1.$ Here $1-\Upsilon^I$ and Υ^G are the tax incidence coefficients for the current and future carbon tax, respectively, and indicate what fraction of each tax is borne by oil producers.

For a given world interest rate, the expression for Υ^I indicates that the burden of a current carbon tax is shifted more to Oilrabia if the price elasticities of oil supply and future oil demand are small relative to that of current oil demand (small ε^S and ε_2^D, large ε_1^D). Less of the incidence of carbon taxes is then borne by Industria's consumers. If evaluated at zero taxes, (4) becomes $-1 < dp_1 / d\tau_1 = -(1-\Upsilon^I) = -R_1\varepsilon_1^D / \left(R_1\varepsilon_1^D + R_2\varepsilon_2^D + S\varepsilon^S\right) < 0.$

A future carbon tax is partially shifted to oil producers too, so the world producer price of oil falls via the Hotelling logic both in the future and today. The future consumer price of oil will increase, so future oil demand falls. Current oil demand rises on account of the fall in the current oil price. Current carbon emissions thus rise and global warming accelerates, which is the weak Green Paradox effect. The expression for Υ^G implies that the effect on the current oil price is large if price elasticities of current oil demand and supply are small relative to that of future oil demand (at zero taxes $0 < \Upsilon^G = \delta R_2\varepsilon_2^D / (R_1\varepsilon_1^D + R_2\varepsilon_2^D + S\varepsilon^S)$ <1). The boost to current oil demand and carbon emissions is large if the price elasticities of current and future oil demand are large and that of oil supply is small (as $dR_1 / d\tau_2 = q_1\varepsilon_1^D\Upsilon^G / R_1 > 0$). So if oil exploration and reserves adjust easily downwards in anticipation of a future carbon tax (high ε^S) and price elasticities of oil demand are small (low ε_1^D and ε_2^D), the weak Green Paradox effect is small. From (4) we note that a higher world interest rate depresses the consumer oil price and thus speeds up oil extraction.

3.2. Partial Equilibrium in the World Market for Final Goods

Total differentiation of (2) yields

$$(5) \qquad \Upsilon^D dr = dp_1 + (1-\Upsilon^S)d\tau_1 = dq_1 - \Upsilon^S d\tau_1,$$

where $0 < \Upsilon^S \equiv \dfrac{\left(\Theta + \dfrac{q_2}{p_1}\right) S\varepsilon^S}{\left(\Theta + \dfrac{q_2}{p_1}\right) S\varepsilon^S + \left(\Theta + \dfrac{q_2}{q_1}\right) R_1\varepsilon_1^D} < 1$ and $\Upsilon^D \equiv \dfrac{(C_1 + C_1^*)\Theta'(r)}{\left(\Theta + \dfrac{q_2}{p_1}\right) S\varepsilon^S + \left(\Theta + \dfrac{q_2}{q_1}\right) R_1\varepsilon_1^D} > 0.$

Intuitively, for a given p_1, a higher current carbon tax curbs current relative to future production of final goods. The price of future final goods δ thus has to fall to shift demand for final goods from the present to the future and restore equilibrium on world markets for final good and bonds. This corresponds to a rise in the world interest rate. A higher price of oil, given τ_1, has the same effects and also requires a higher interest rate to restore equilibrium in world markets for final goods.

3.3. General Equilibrium Comparative Statics

Combining (4) and (5), we obtain the general equilibrium comparative statics:

$$(6) \qquad dp_1 = -(1-\Gamma^I)d\tau_1 - \Gamma^G d\tau_2, \quad dq_1 = \Gamma^I d\tau_1 - \Gamma^G d\tau_2,$$

where $\Gamma^I \equiv \Upsilon^I - p_1\Upsilon^G\Gamma^1$ and $\Gamma^G \equiv \dfrac{\Upsilon^D}{\Upsilon^D + p_1\Upsilon^G}\Upsilon^G$, and

$$(7) \qquad dr = \Gamma^1 d\tau_1 - \Gamma^2 d\tau_2$$

where $\Gamma^1 \equiv \dfrac{\Upsilon^I - \Upsilon^S}{\Upsilon^D + p_1\Upsilon^G}(>)0$ and $\Gamma^2 \equiv \dfrac{\Upsilon^G}{\Upsilon^D + p_1\Upsilon^G} > 0.$ If evaluated at zero carbon taxes, we readily find that $\Upsilon^I > \Upsilon^S$ and thus $\Gamma^1 > 0$ and $\Gamma^I < \Upsilon^I$. We make the mild assumption that these inequalities hold in the range of carbon taxes that we will consider.

Comparing (6) and (4) we see that in general equilibrium less of a current carbon tax is borne by consumers in Industria than in partial equilibrium ($0 < \Gamma^I < \Upsilon^I < 1$) as such a tax pushes up the interest rate, which shifts oil depletion from the future to the present. Note that (6) boils down to the partial equilibrium result (1) if the world interest rate does not respond to carbon taxation, which is the case for very large values of the elasticity of intertemporal substitution ε^I. Indeed, for power utility functions $\Upsilon^D \to \infty$ as $\Theta'(r)/\Theta = \delta\varepsilon^I \to \infty$ and thus $\Gamma^I \to \Upsilon^I$ and $\Gamma^G \to \Upsilon^G$ as $\varepsilon^I \to \infty$ (see Appendix B).

With exogenous oil exploration and reserves ($\varepsilon^S = 0$), equations (6) and (7) simplify to:

$$(8) \qquad dq_1 = \Upsilon^D dr = \Gamma^I (d\tau_1 - \delta d\tau_2), \quad \Gamma^G = \delta\,\Gamma^I, \quad \Upsilon^S = 0.$$

4. The Green Paradox Revisited

Carbon taxation is unpopular, so we first consider the politically more palatable option of postponing carbon taxation and then that of taxing assets of oil producers and subsidizing renewable energy. We also show the effects of a carbon-intensive, cheap and abundant alternative (coal) to oil.

4.1. Postponed Carbon Taxation

It helps to distinguish three effects of an anticipated future carbon tax.

A. *Weak Green Paradox effect*: The future carbon tax depresses the current and future producer price of oil as some of the burden is shifted to oil exporters. This brings oil production and carbon emissions forward and accelerates global warming. As we have already seen, these weak Green Paradox effects are stronger if the price elasticity of oil supply is low and those of oil demand are high.

B. *Intertemporal terms of trade effect*: The relative fall in future supply of goods caused by the future carbon tax pushes up the future price of final goods (the intertemporal terms of trade) and unit expenditure *e*. The cut in the interest rate induces oil producers to produce less today and more tomorrow as it makes it in the margin less attractive to extract another barrel of oil. This attenuates the Green Paradox effect and thus mitigates the acceleration of global warming (comparing (6) and (7), we see that $\Gamma^G < \Upsilon^G$).[3]

C. *Putting out of business effect*: The higher future carbon tax cuts the current and future producer prices of oil and thus curbs oil exploration investment, reserves and cumulative

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[3] If one were to allow for investment in physical capital, this would reduce this attenuation of the weak Green Paradox effect and may even reverse it (cf. van der Meijden, et al., 2015 and Appendix A).

carbon emissions, especially if the price elasticity of oil exploration is high. In contrast to the weak Green Paradox effect, this curbs global warming and benefits green welfare.

Since the marginal change in private global welfare is zero at initial taxes, $d(C+C^*)=0$), the effect of a future carbon tax on global welfare is the same as that on green welfare:

$$(9) \qquad \left.\frac{d\Phi}{d\tau_2}\right|_{\tau_1=\tau_2=0} = -\left.\frac{d\Omega}{d\tau_2}\right|_{\tau_1=\tau_2=0} = -\chi\left(\frac{dR_1}{d\tau_2}+\beta\frac{dS}{d\tau_2}\right) = \frac{\chi}{p_1}\left(\beta S\varepsilon^S - R_1\varepsilon_1^D\right)\Gamma^G.$$

Introduction of a global carbon tax thus improves global welfare if $R_1\varepsilon_1^D < \beta S\varepsilon^S$ holds. Hence, the adverse weak Green Paradox effects are dominated by the beneficial effects of putting oil producers out of business and curbing cumulative carbon emissions if the price elasticity of current oil demand is low relative to that of oil exploration and oil supply and the ecological discount rate is low (high β). If oil reserves and cumulative carbon emissions do not respond much to prices, $\varepsilon^S < (R_1/S)\varepsilon_1^D/\beta,$ a future carbon tax harms global and green welfare. This is called a *strong* Green Paradox (Gerlagh, 2011). But a strong Green Paradox does not mean that Industria's welfare ($C-\Omega=\Phi-C^*$) needs to fall. This follows from the marginal change in Industria's welfare (using $\Gamma^2/\Gamma^G=1/\Upsilon^D$):

$$(9') \left.\frac{d(C-\Omega)}{d\tau_2}\right|_{\tau_1=\tau_2=0} = -\chi\left(\frac{dR_1}{d\tau_2}+\beta\frac{dS}{d\tau_2}\right)-\frac{dC^*}{d\tau_2} = \left[\frac{\chi}{p_1}\left(\beta S\varepsilon^S - R_1\varepsilon_1^D\right)+\underset{\text{tariff}}{\frac{S}{e}}+\underset{\text{ITT term}}{\frac{\theta\delta C^*}{\Upsilon^D}}\right]\Gamma^G.$$

The first extra term reflects the import tariff benefits of a higher future tax. The second one reflects the boost to the intertemporal terms of trade (ITT = δ) and the cost of utility, *e*, which erodes the real value of Oilrabia's wealth and boosts Industria's welfare. Since both these extra terms are positive, the gain in Industria's welfare unambiguously exceeds the gain in green welfare from the credible announcement of a future carbon tax.

Proposition 1: *Introducing a future carbon tax boosts current oil use and accelerates global warming if the price elasticities of oil demand are large and that of oil supply is small. This effect is curbed by the drop in the interest rate, especially if intertemporal substitution is weak. Green welfare falls if and only if* $R_1\varepsilon_1^D > \beta S\varepsilon^S$ *. However, even if there is such a strong Green Paradox, Industria's welfare might rise if the import tariff and intertemporal terms of trade benefits of a future carbon tax are strong enough.*

4.2. Merits of an Asset Holding Tax on Oil Producers

Sinn (2008) argues for an asset holding tax υ on oil-producing countries if carbon taxes are infeasible, so $r^* = r - \upsilon$ and Industria gets rebated $T \equiv \tau_1 R_1 + \delta \tau_2 R_2 + \upsilon (p_1 R_1 - J - C_1^*)$. Such a tax increases the current price of oil and slows down current oil extraction and carbon emissions, hence has no adverse weak Green Paradox effects. But an asset holding tax also induces more oil exploration so that less fossil fuel is trapped in the earth and cumulative carbon emissions increase. At zero taxes, the effect of an asset holding tax on global and green welfare is the opposite of that of a future carbon tax: $d\Phi / d\upsilon = -d\Omega / d\upsilon$ $= -\chi \left(\beta S \varepsilon^S - R_1 \varepsilon_1^D \right) \Gamma^G$. Sinn (2008) considered inelastic oil supplies in which case an asset holding tax *always* boosts green welfare, $-d\Omega / d\upsilon = \chi R_1 \varepsilon_1^D \Gamma^G > 0$. A future carbon tax then always depresses green welfare due to the weak Green Paradox effect. However, if oil supplies respond strongly to oil prices and current oil demand does not and if the ecological discount rate is small ($\beta S \varepsilon^S > R_1 \varepsilon_1^D$), we establish that an asset holding tax is counter-productive whilst a future carbon boosts green welfare.

Using $dC^* = \frac{S}{e^*} dp_1 + \delta^* \theta^* C^* (dr - d\upsilon)$ with $dp_1 = -(1 - \Gamma^I) d\tau_1 - \Gamma^G (d\tau_2 - p_1 d\upsilon)$ and $dr = \Gamma^1 d\tau_1 - \Gamma^2 (d\tau_2 - p_1 d\upsilon)$ and also using $\theta^* \delta^* C^* = C_2^*$, we find the effect of an unilateral asset holding tax on Industria's private welfare (evaluated at zero taxes):

$$(9'') \quad \left. \frac{d(C - \Omega)}{d\upsilon} \right|_{\tau_1 = \tau_2 = \upsilon = 0} = \chi \Gamma^G \left(R_1 \varepsilon_1^D - \beta S \varepsilon^S \right) + \frac{\Upsilon^D}{\Upsilon^D + p_1 \Upsilon^G} \left(C_2^* - \Upsilon^G \frac{p_1 S}{e^*} \right).$$

It has been pointed out a long time ago that, with exogenous oil supply, $\varepsilon^S = 0$, an asset holding tax can *decrease* Industria's private welfare if the price elasticity of current oil demand is small and that of future oil demand is large (van Wijnbergen, 1985). We can generalize this for $\varepsilon^S \geq 0$ as (10′) implies that Industria's welfare falls if $\Upsilon^G p_1 S / e^* > C_2^*$ or $\Upsilon^G = \frac{R_2}{q_2} \varepsilon_2^D / \left(\frac{R_1}{q_1} \varepsilon_1^D + \frac{R_2}{\delta q_2} \varepsilon_2^D + \frac{S}{p_1} \varepsilon^S \right)$ is large. This occurs if the price elasticities of current oil demand and oil supply are small and that of future oil demand is large.

4.3. Does Subsidizing Renewable Energy Induce Green Paradox Effects?

Subsidizing renewable energy can also lead to weak Green Paradox effects if renewables are perfect substitutes for fossil fuel and the switch to the carbon-free era is brought forward (e.g., van der Ploeg and Withagen, 2012). To see how this works with *imperfect* substitution, let final goods production in period *t* be $F(R_t, B_t),$ where B_t is renewable energy use supplied at fixed cost b_t. Energy demands follow from $F_{R_t} = q_t$ and $F_{B_t} = b_t,$ so $R_t = R(q_t, b_t), t = 1, 2.$ Renewable energy is a gross substitute for oil if the cross price elasticity $\varepsilon_t^B \equiv b_t R_{b_t}(q_t, b_t) / R_t$ is positive and a gross complement if it is negative. An extra term, $\Upsilon_1^B db_1 + \Upsilon_2^B db_2,$ emerges in (4), where $\Upsilon_t^B \equiv R_t q_2 \varepsilon_t^B \Upsilon^G / (b_t R_2 \varepsilon_2^D), t = 1, 2.$ We thus see that a weak Green Paradox emerges (i.e., p_1 falls) only if renewable energy and fossil fuel are gross substitutes (i.e., $\varepsilon_t^B > 0$).The general equilibrium effects are again attenuated due to a fall in the world interest rate. If renewable energy is a complement to oil ($\varepsilon_t^B < 0$), subsidizing renewables decelerates oil extraction and global warming.

4.4. Does Coal Reverse the Green Paradox?

Renewable energy is hardly used in the global economy. However, coal is abundant, cheap and still used a lot despite relatively strong adverse effects on global warming. We assume here that, in contrast to oil which is exhaustible, coal is in unlimited supply at a constant marginal cost and is an imperfect substitute for or a complement to oil. Denoting coal use with X_t and the user cost of one unit by $d_t,$ oil demand is $R_t = R(q_t, d_t), t = 1, 2.$ The cross price elasticities of oil demand with respect to the cost of coal are $\varepsilon_t^X \equiv d_t R_{d_t}(q_t, d_t) / R_t, t = 1, 2.$ Let $\lambda > 1$ indicate the carbon emissions intensity of coal relative to that of oil and *b* the production cost of coal, then the user cost of coal is $b_t = b + \lambda \tau_t.$ This changes the partial equilibrium effect of the future carbon tax on the current price of oil from Υ^G to $(\varepsilon_2^D - q_2 \lambda \varepsilon_2^X / d_2) \Upsilon^G / \varepsilon_2^D.$ The presence of cheap, abundant coal thus amplifies the weak Green Paradox effect if it is a gross complement to oil, but attenuates or possibly reverses it if coal is a gross substitute for oil. Also, the weak Green Paradox effect is reversed if $\lambda q_2 \varepsilon_2^X > \varepsilon_2^D d_2$ in which case a future carbon tax boosts the current price of oil and cuts current carbon emissions (cf., Michielsen, 2014). The boost to Oilrabia's income at the expense of coal producers has been coined the Grey Paradox

(Coulomb and Henriet, 2015).[4] It occurs if the user cost of coal is relatively low compared with that of oil (low d_2/q_2), coal is much more carbon intensive than oil (high λ), the own price elasticity of oil demand is low, and the cross price of elasticity of oil with respect to coal is high.

Proposition 2: *A tax on oil producers' asset holdings has the opposite effects of a future carbon tax, so is effective if a future carbon tax harms global welfare and vice versa. Subsidizing renewable energy leads to a weak Green Paradox if it is gross substitute for fossil fuel, but if it is a gross complement it decelerates global warming. Coal strengthens the weak Green Paradox of a future carbon tax if it is a complement to fossil fuel, but weakens or reverses it if coal is a gross substitute for fossil fuel. The Grey Paradox occurs if coal is relatively cheap and carbon intensive and a good substitute for fossil fuel.*

5. Effects of Introducing a Growing Carbon Tax

A balanced introduction of carbon taxes has the carbon tax growing at the rate of interest (i.e., $d\tau_2 = d\left[(1+r)\tau_1\right] > 0$ and $d\Delta = 0$). If oil reserves do not respond to prices ($\varepsilon^S = 0$), this policy does not affect the intertemporal pattern of oil extraction, carbon emissions or welfare (see (8)). The burden of carbon taxes is thus fully borne by oil producers.

If the carbon taxes rise at a faster rate than the rate of interest or Hotelling rate (i.e., $d\Delta = d\tau_2 - (1+r)d\tau_1 > 0$), we get $dq_1 = \left[\Gamma^I - (1+r)\Gamma^G\right]d\tau_1 - \Gamma^G d\Delta$ from (6) and (7). This boils down to $dq_1 = -\Gamma^G d\Delta < 0$ if $\varepsilon^S = 0,$ since then from (4) $\Upsilon^G = \delta\Upsilon^I.$ The current consumer price of oil thus falls, current oil extraction rises and global welfare drops by $d\Phi = -\chi dR_1 = -\chi\varepsilon_1^D (R_1/q_1)\Gamma^G d\Delta.$ Hence, welfare worsens if the carbon tax rises too fast.

If oil supply does adjust (i.e., $\varepsilon^S > 0$), then from (6)-(7) a balanced carbon tax hike gives

$$(10)\qquad \left.\frac{dq_1}{d\tau_1}\right|^{\substack{\textit{balanced}\\ \textit{tax hike}}} = \Gamma^I - (1+r)\Gamma^G = \frac{\left[\Upsilon^I - (1+r)\Upsilon^G\right]\Upsilon^D + p_1\Upsilon^S\Upsilon^G}{\Upsilon^D + p_1\Upsilon^G} > 0$$

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[4] This study uses an infinite horizon, partial equilibrium framework with inelastic supply of oil reserves and perfect substitution between oil and coal at any given point of time. Substitution, however, occurs intertemporally due to endogenous changes in the timing of the transition from using only coal to only oil.

where $0 < \Upsilon^I - (1+r)\Upsilon^G = S\varepsilon^S / (R_1\varepsilon_1^D + R_2\varepsilon_2^D + S\varepsilon^S) < 1$ (evaluated at zero initial taxes). A balanced carbon tax hike thus boosts the current consumer oil price and curbs current oil extraction. It also curbs the current producer price of oil and thus curbs oil exploration and reserves as $\left.\frac{dp_1}{d\tau_1}\right|^{\substack{balanced \\ tax\ hike}} = -\frac{\left[1-\Upsilon^I + (1+r)\Upsilon^G\right]\Upsilon^D + p_1(1-\Upsilon^S)\Upsilon^G}{\Upsilon^D + p_1\Upsilon^G} < 0.$ Both the cut in current carbon emissions and the cut in cumulative carbon emissions boost green welfare.

Proposition 3: *Introducing a hike in carbon taxes that rises at a rate equal to the interest rate is neutral if oil reserves are given. Introducing carbon taxes that rise faster than this induce Green Paradox effects and curb welfare; carbon taxes that rise slower improve welfare (* $d\Phi = -\chi\varepsilon_1^D(R_1/q_1)\Gamma^G d\Delta$ *). If oil supply is elastic, a balanced hike pushes up the current consumer price of oil as in (8) and curbs the current rate of oil extraction. It also depresses cumulative extraction and carbon emissions, and boosts green welfare.*

6. Globally Optimal Carbon Taxation

6.1. First Best

The first-best global carbon taxes maximize global welfare Φ defined in (3) and may require lump-sum financed side payments. Private welfare of Industria falls and green welfare rises at the expense of Oilrabia, but global welfare rises compared with the no-policy scenario. It follows that Industria can indeed compensate Oilrabia and both can be better off. The side payments ensure that it is feasible to implement a uniform carbon tax throughout the global economy, which is optimal from a global perspective.

Proposition 4: *The first-best global carbon taxes,* τ_t^{FB}*, are set to the Pigouvian taxes,* τ_t^P *:*

(11) $$\tau_1^{FB} = \tau_1^P \equiv (1+\beta)\chi e,$$

(12) $$\tau_2^{FB} = \tau_2^P \equiv \frac{\beta}{\delta}\chi e = \left(\frac{1+r}{1+\rho}\right)\chi e.$$

The first-best taxes are the present discounted values of marginal global warming damages. They decrease with the ecological discount rate, are proportional to the unit cost of real consumption, and are independent of the stock of fossil fuel reserves. The first-

best outcome has no Green Paradox effects. With $\varepsilon^S = 0$ *and full exhaustion, any carbon tax path including (11)-(12) that satisfies* $\tau_1 - \delta\tau_2 = \chi e$ *achieves the first best.*

Proof: Totally differentiating $C + C^* = \left[F(R_1) + \delta F(R_2) - J\right]/e,$ we get

$$d(C+C^*) = \frac{q_1 dR_1 + \delta q_2 dR_2 + F(R_2)d\delta - dJ}{e} - (C+C^*)\theta\frac{d\delta}{\delta} = \frac{\tau_1 dR_1 + \delta\tau_2 dR_2}{e} +$$

$\left[\delta F(R_2) - e(\delta)(C+C^*)\theta\right]\dfrac{d\delta}{\delta e}$ as $p_1 dR_1 + p_2\delta dR_2 - dJ = p_1 dS - dJ = 0.$ Equilibrium in the final goods markets, i.e., (2), implies that the term in square brackets vanishes, so that

$$(13) \qquad d(C+C^*) = \frac{\tau_1 dR_1 + \delta\tau_2 dR_2}{e}.$$

Hence, the change in global welfare is

$$(14) \qquad d\Phi = d(C+C^*) - \chi(dR_1 + \beta dS) = \left(\frac{\tau_1 - \delta\tau_2}{e} - \chi\right)dR_1 + \left(\frac{\delta\tau_2}{e} - \chi\beta\right)dS.$$

The first-best global carbon taxes ensure that this marginal change is zero. Since $\Delta = -\chi e/\delta < 0,$ the first best displays no Green Paradox effects. □

The first-best Pigouvian carbon taxes are higher if a lower ecological discount rate is used (higher value of β). They are also proportional to the marginal damage coefficient χ and to the unit cost of real consumption e.[5] The current carbon tax is thus high if e is high and the world interest rate is low. However, the future carbon tax also responds directly to the rate of interest, so in general the future carbon tax is high if the world interest rate is high.[6] The carbon taxes are credibly set before the level of costly oil exploration is determined. Hence, there is no incentive to burn less oil than has been explored. However, if it is optimal to fully exhaust a fixed and exogenous level of oil reserves ($R_1 + R_2 = S$), only $\tau_1 - \delta\tau_2 = \chi e$ must hold and the path of first-best taxes is indeterminate (e.g., the first best can be reached with either (11) and (12), a current carbon tax, $\tau_1 = \chi e,$ or a future carbon

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[5] If climate damages are multiplicative, $\Phi = \ln(C + C^*) - \bar{\chi}(R_1 + \beta S), \quad \bar{\chi} > 0,$ not additive as in (3), Propositions 1 and 3 are unaffected and the first-best carbon taxes in Proposition 3 become (11) and (12) with $\chi = \bar{\chi}(C + C^*).$ First-best carbon taxes are thus proportional to global wealth, $e(C + C^*),$ and rise in line with growth of the global economy (cf. Golosov et al., 2014).

[6] With power utility functions we have that e/δ falls with δ and rises with r (see Appendix B).

subsidy, $-\tau_2 = (1+r)\chi e$). If it is not optimal to fully exhaust a fixed and exogenous level of reserves ($R_1 + R_2 < S$), the first-best taxes are determinate and given by (11) and (12).

6.2. Second Best

If for political reasons the current carbon tax is set too low, we show that the second-best optimal future carbon tax which respects this constraint is below the future Pigouvian carbon tax too. This credibly announced future carbon tax is designed to mitigate the adverse Green Paradox effects; the argument that the future carbon must be set higher than the Pigouvian tax to compensate for insufficient carbon taxation today is thus incorrect.

Proposition 5: *If the current carbon tax is pegged too low,* $\tau_1 = \overline{\tau}_1 < \tau_1^P$, *the second-best optimal future carbon tax given this constraint is set too low also:*

$$(15) \qquad \tau_2^{SB} = \tau_2^P - \frac{p_1 R_1 \varepsilon_1^D}{q_1 S \varepsilon^S + p_1 R_1 \varepsilon_1^D} \left(\frac{\tau_1^P - \overline{\tau}_1}{\delta} \right) < \tau_2^{FB} = \tau_2^P .$$

Proof: The marginal change in global welfare (14) can be expressed as:

$$(14') \qquad d\Phi = -\frac{R_1}{q_1 e}\left[\tau_1 - \tau_1^P - \delta(\tau_2 - \tau_2^P) \right] \varepsilon_1^D dq_1 + \frac{S}{p_2 e}(\tau_2 - \tau_2^P)\varepsilon^S (dq_1 - d\tau_1).$$

Note that this expression vanishes if carbon taxes are set at Pigouvian levels. Using $d\tau_1 = 0,\ \ dq_1 = -\Gamma^G d\tau_2$ from (6) and (14′), we get (15) from $d\Phi = 0.$ □

Recalling Propositions 1 and 3, a postponed or too rapidly rising carbon tax has adverse weak Green Paradox effects on short-run carbon emissions but beneficial welfare effects on curbing oil supply and cumulative emissions. The net effect on green welfare is negative if the price elasticity of oil demand is large and that of oil supply is small. In that case, the future carbon tax is also set rather more below the Pigouvian carbon tax to mitigate adverse weak Green Paradox effects, especially if the current carbon tax is fixed much below the Pigouvian tax. With fixed reserves ($\varepsilon^S = 0$) and a zero current carbon tax, $\Delta = \tau_2^P - \tau_1^P / \delta = -(1+r)\chi e < 0,$ the second-best optimal carbon tax avoids any weak Green Paradox effects. This is achieved with a future carbon *subsidy* ($\tau_2^{SB} = \tau_2^P - \tau_1^P / \delta < 0$ as in the first best). If the current carbon tax is pegged at a higher level or oil supply responds to prices, a future carbon tax may be needed.

Like credibly announced future carbon taxes, renewable subsidies accelerate global warming (see Section 4.2) but also lock up more fossil fuel and curb cumulative carbon emissions. One can also derive the optimal second-best carbon taxes if politicians prefer subsidies for carbon-free renewables to pricing carbon (over and above what might be necessary to internalize market failures in the production of renewables). The optimal second-best carbon taxes in the presence of such subsidies are then also set below what they would have been in the first best without these subsidies.

7. Unilaterally Optimal Carbon Taxation: Clobbering the Oil Barons

If Industria does not care about the welfare of Oilrabia, it maximizes $C - \Omega = \Phi - C^*$ and imposes carbon taxes unilaterally at the expense of Oilrabia in the absence of a global climate deal. The optimal taxes will contain Pigouvian correction terms, but also terms that reflect the capturing of oil rents and that correspond to changes in the intertemporal terms of trade. Before looking at this, suppose that the global first-best carbon taxes are in place. Marginal changes in carbon taxes then leave global welfare unaffected (dΦ = 0) but do affect Oilrabia's welfare, $C^* = (p_1 S - J)/e(\delta),$ as can be seen from (using (6) and (7)):

$$(16) \qquad dC^* = \frac{S}{e}dp_1 + \delta\theta C^* dr = -\left[\underbrace{\frac{S}{e}(1-\Gamma^I)}_{+ve} - \underbrace{\delta\theta C^*\Gamma^1}_{(+ve)}\right]d\tau_1 - \left[\underset{+ve}{\frac{S}{e}\Gamma^G} + \underbrace{\delta\theta C^*\Gamma^G / \Upsilon^D}_{+ve}\right]d\tau_2.$$

Starting from first-best carbon taxes, we have a zero-sum game in the margin as the marginal boost to Industria's welfare is exactly equal to the fall in Oilrabia's welfare:

$$(17) \qquad d(C - \Omega)\Big|_{\substack{\tau_1 = \tau_1^{FB} \\ \tau_2 = \tau_2^{FB}}} = -dC^*.$$

Expressions (16)-(17) highlight two effects of raising carbon taxes above their first best:

A. *Grabbing the pure rents from oil exporters*: The producer price of oil (p_1) falls either via usual tax shifting for a current carbon tax (by the amount $1-\Gamma^I$) or via the Green Paradox effect for a future carbon tax (by the amount Γ^G), both modified for induced changes in the interest rate. This implies a pure transfer of rents from Oilrabia to Industria, which is large if the real value of oil reserves (*S/e*) is large. It curbs Oilrabia's welfare

(C^*), as can be seen from the first term in each of the two of square brackets in (16), and thus boosts the private component of Industria’s welfare (C), as can be seen from (17).

B. *Change in the intertemporal terms of trade*: A marginally higher current carbon tax depresses current output and induces an incipient current excess demand for final goods, which is cleared by a higher price of current final goods. This shows up in a higher world interest rate (r), a lower intertemporal terms of trade (δ) and a lower unit cost of utility (e). Oilrabia’ welfare thus receives a boost that is proportional to Oilrabia’s consumption of future final goods (i.e., $\delta\theta C^*\Gamma^1 = \delta^2 C_2^*\Gamma^1 / e$), which curbs Industria’s welfare (17).

A marginally higher future carbon tax depresses future output and induces a future excess demand for final goods, so that the price of future final goods has to rise to restore equilibrium (higher δ) and thus the unit cost of utility (e) rises. As a result, Oilrabia’ welfare erodes (by $\delta\theta C^*\Gamma^G / \Upsilon^D = \delta^2 C_2^*\Gamma^G / e\Upsilon^D$), which boosts Industria’s welfare from (17). This general equilibrium effect does not occur in partial equilibrium or if intertemporal substitution is very strong ($\varepsilon^I \to \infty$ and $\Upsilon^D \to \infty$).

Effects A and B operate in the same direction for a *future* carbon tax, so that Industria’ welfare rises unambiguously if this tax is increased above the first best. But when raising the *current* carbon tax above the first best, the boost to Industria’ welfare from putting Oilrabia out of business is dampened by the negative intertemporal terms of trade effect.

We now show that the unilateral second-best optimal carbon taxes set by Industria consist of a Pigouvian part, a pure import tariff part, and positive and negative intertemporal terms of trade corrections for the future and current carbon tax, respectively.

Proposition 6: *The unilateral second-best optimal carbon taxes set by Industria consist of a Pigouvian and an import tariff component which includes opposing intertemporal terms of trade effects of the future and current carbon tax:*

$$(18) \qquad \tau_1^U = \tau_1^P + \frac{p_1}{\varepsilon^S}\left(1 + \frac{\theta\delta e C^*}{S}\frac{\Upsilon^G\Upsilon^S}{\Upsilon^D}\right) - \frac{q_1}{\varepsilon_1^D}\frac{\theta\delta e C^*}{R_1}\frac{\Upsilon^G(1-\Upsilon^S)}{\Upsilon^D},$$

$$(19) \qquad \tau_2^U = \tau_2^P + \frac{p_2}{\varepsilon^S}\left(1 + \frac{\theta\delta e C^*}{S}\frac{\Upsilon^G\Upsilon^S}{\Upsilon^D}\right) > \tau_2^P + \frac{p_2}{\varepsilon^S} > \tau_2^{FB} = \tau_2^P.$$

Proof: See Appendix C.

Expression (19) of Proposition 6 states that the unilateral second-best optimal future carbon tax consists of the *Pigouvian tax* $\tau_2^P = \beta\chi e / \delta$ from (11) and a *specific import tariff*, which consists of the two parts in the round brackets in (18) and (19).

A marginally higher future carbon tax curbs the current oil price (weak Green Paradox) which corresponds to a transfer of pure rents and boosts Industria's welfare at the expense of Oilrabia. This first part of the specific import tariff is the pure partial equilibrium import tariff p_2 / ε^S, (or the usual ad valorem import tariff $1/\varepsilon^S$) and maximizes the capture of Oilrabia's Hotelling oil rents for a given interest rate (and consumer price of oil). This part of the tariff is high if the future oil price is high and Oilrabia cannot easily adjust its oil reserves downwards in response to a future carbon tax (low ε^S). In accordance with the Ramsey principle of taxation, the unilateral carbon tax is pushed a lot above the first-best carbon tax if the price elasticities of oil exploration and oil reserves are small. With inelastic oil supply all rents will be captured.

Recalling the discussion of (16) above, a marginally higher future carbon tax requires a rise in the ITT (δ) and the unit cost of utility (e) which erodes Oilrabia's welfare and boosts that of Industria. This positive *intertemporal terms of trade* (ITT) effect makes it attractive to raise the future tax above its partial equilibrium level as reflected by the second part of the future tariff (as $\theta\delta e C^* \Upsilon^G \Upsilon^S / S \Upsilon^D > 0$) which pushes up the future tariff above its partial equilibrium value (p_2 / ε^S).This general equilibrium adjustment of the import tariff is small if oil reserves are large, the weak Green Paradox effect is small, and oil exploration and reserves do not react much to changes in reserves and thus the interest rate does not fall much (large S, small Γ^G and Υ^S).

Expression (18) of Proposition 6 splits up the unilaterally optimal current carbon tax into four components. The first one is the Pigouvian tax (τ_1^P). The second and third ones are the current pure import tariff and the positive ITT correction for the future carbon tax. In line with the Hotelling logic these equal the present value of the future ones. The fourth component corresponds to the negative ITT correction for the current carbon tax. This is negative and inversely proportional to the price elasticity of current oil demand. It reflects that a marginally higher current carbon tax lowers the ITT (δ) and the cost of private welfare (e), which boosts the real value of Oilrabia's wealth and lowers Industria's private welfare. This fourth part of the current carbon tax tilts the tax path from the present to the future. From $\frac{\Upsilon^S}{\Upsilon^D} = \frac{\left(\Theta + \frac{q_2}{p_1}\right) S\varepsilon^S}{(C_1 + C_1^*)\Theta'(r)}$ and $\frac{1-\Upsilon^S}{\Upsilon^D} = \frac{\left(\Theta + \frac{q_2}{q_1}\right) R_1\varepsilon_1^D}{(C_1 + C_1^*)\Theta'(r)}$, the ITT effects of the future carbon tax are large if the price elasticity of oil supply is small; and the ITT effects of the current tax are large if the price elasticity of current oil demand is large. Both ITT effects are large if intertemporal substitution is weak as $\Theta / \Theta' = (1+r)/\varepsilon^I$ (Appendix B).

If the elasticity of intertemporal substitution is very large ($\varepsilon^I \to \infty$), the ITT effects disappear and (18) and (19) boil down to the partial equilibrium expressions $\tau_1^U = \tau_1^P + p_1 / \varepsilon^S > \tau_1^{FB}$ and $\tau_2^U = \tau_2^P + p_2 / \varepsilon^S > \tau_2^{FB}$. If oil exploration is not very price sensitive (small ε^S), the pure tariff will dominate the negative ITT effects of the future carbon tax and the current carbon tax will be set below the partial equilibrium level, especially if the Green Paradox effect is strong and intertemporal substitution weak: $\tau_1^U \cong \tau_1^P + \frac{p_1}{\varepsilon^S} - \theta\delta e C^* \Upsilon^G \frac{q_1\Theta + q_2}{(C_1 + C_1^*)\Theta\delta\varepsilon^I} < \tau_1^P + \frac{p_1}{\varepsilon^S}$ and $\tau_2^U \cong \tau_2^P + p_2 / \varepsilon^S > \tau_2^{FB}$. The pure import tariff part is then large as it is easy to extract revenue. If the taxes become large enough, the carbon tax has to be set just below the level that creams off all oil rents. The unilateral second-best optimal carbon taxes harm global welfare but curb oil exploration and cumulative emissions more than the first-best taxes (provided the ITT effect of the current carbon tax is not too large). This indicates the conflicting interests of Industria and Oilrabia: oil exporters are put out of business by carbon taxes and import tariffs.

Finally, the unilateral second-best optimal policies (18) and (19) require pre-commitment to an announced path of carbon taxes but Industria has an incentive to renege and push up future carbon taxes even more once exploration investment has taken place. Once this investment has been sunk, all remaining oil rents are fixed in period 2 and Industria can tax them away by raising τ_2^R to just under C_2^* / R_2 as, once in period 2, Oilrabia must sell all remaining oil $S - R_1$ and taxes are non-distorting. This boosts Industria' welfare and curbs Oilrabia' welfare with green and global welfare unchanged.[7]

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[7] Industria would tax away the rents in period one too, so Oilrabia does not invest in oil exploration at all. With recurring oil exploration investment (see Appendix A), no commitment leads to under-investment (cf. Fischer, 1980) except if reputation is built for not regening (Kreps and Wilson, 1982ab; Backus and Driffill, 1985ab). Futures markets and storage also curb time inconsistency problems (Maskin and Newbery, 1990).

8. Extension: Oil-Importing Countries that Opt Out of Carbon Taxes

If some non-Kyoto oil-importing countries *N* do not price carbon, it is of interest to investigate the effects of unilateral carbon taxes by the Kyoto countries *K* on carbon leakage (cf. Eichner and Pethig, 2011, 2013; Richter and Schopf, 2014; Sen, 2015) and to derive the unilateral second-best optimal carbon taxes to be set by the Kyoto countries *K*.[8] With identical, homothetic preferences for the three countries, equilibrium on the world markets for oil and final goods requires:

$$(1') \qquad R_1^K(p_1+\tau_1)+R_1^N(p_1)+R_2^K\left((1+r)p_1+\tau_2\right)+R_2^N\left((1+r)p_1\right)=S(p_1),$$

$$(2') \qquad \begin{gathered}(C_2^K+C_2^N+C_2^*)/(C_1^K+C_1^N+C_1^*)=\Theta(r)=\\ \frac{F_2^K\left(S(p_1)-R_1^K(p_1+\tau_1)-R_1^N(p_1)-R_2^N\left((1+r)p_1\right)\right)+F_2^N\left(R_2^N\left((1+r)p_1\right)\right)}{F_1^K\left(R_1^K(p_1+\tau_1)\right)+F_1^N\left(R_1^N(p_1)\right)-J(p_1)},\end{gathered}$$

where $q_t^K=q_t,\, q_t^N=p_t,\, \tau_t^K=\tau_t>0,\, \tau_t^N=0,\, t=1,2.$ The solution for p_1 and r is (6)-(7), where the new expressions for $\Upsilon^I, \Upsilon^G, \Upsilon^S$ and Υ^D are in Appendix D. If Υ^D is negative, there is reversal of the Green Paradox effect (negative intertemporal carbon leakage). We focus at the case $\Upsilon^D>0$ which holds if effects are evaluated at a zero future tax ($\tau_2=0$).

8.1. Carbon Leakage and the Green Paradox

We see from (1′) and (2′) that a *current* carbon tax is partially shifted to Oilrabia (with constant elasticities and evaluated at zero taxes, we get $0<1-\Upsilon^I=R_1^K\varepsilon^D/S(\varepsilon^D+\varepsilon^S)<1$), so that the current consumer price of price falls in *N* and rises in *P*. We thus have positive carbon leakage as emissions in *N* rise, both today and in the future.[9] A *future* unilateral

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[8] Non-participating countries do not levy a pure import tariff on oil. We focus at unilateral taxes and abstract from cooperative and non-cooperative setting of tariffs (cf., Bergstrom, 1982; Brander and Djajic, 1983). Our analytical 2-period, 3-country general equilibrium analysis complements related empirical analysis (e.g., Elliott et al., 2010; Elliot et al., 2012; Fischer and Salant, 2013; Elliott and Fullerton, 2014) and numerical infinite-horizon analysis (e.g., Ryszka and Withagen, 2015). A typical estimate is that 20% of carbon reductions in *P* leaks away due to higher emissions in *N* (e.g., Elliott, et al., 2010). Simulations with numerical general equilibrium models show that, differentiating emission taxes by manipulating the terms of trade yields only small efficiency gains ((Böhringer et al., 2014a) and with OPEC as the dominant producer, leakage through the oil market can become negative (Böhringer et al., 2014b).

[9] If there is an internationally mobile clean factor that is in fixed supply and *P* and *N* goods are imperfect substitutes but factor substitution is strong, *negative* carbon leakage can occur (Baylis et al, 2014; Elliott and Fullerton, 2014), since the taxed region substitutes away from fossil fuel to the clean factor, so that the other region shrinks as less of the clean factor is available. Interestingly, for all cases with negative carbon leakage, a unilateral carbon tax results in a welfare loss; however, with positive carbon leakage a unilateral tax can boost welfare (Baylis et al., 2013). Negative carbon leakage can also occur if, as a result of a carbon tax in *P*, *N* becomes richer and thus pursues a more stringent climate policy (Copeland and Taylor, 2005).

carbon tax is also partially shifted to Oilrabia ($0 < \Upsilon^G = R_2^K \varepsilon^D / S(\varepsilon^D + \varepsilon^S) < 1$), especially if participating countries use more fossil fuel and emit more carbon than non-participating countries. This weak Green Paradox effect is attenuated in general equilibrium by the fall in the world interest rate ($\Gamma^G < \Upsilon^G$). Hence, the consumer price of oil in *K* falls today and rises in the future but the producer price of oil rises both today and in the future. The weak Green Paradox effect of a rise in current carbon emissions by *K* is attenuated by a fall in the world interest rate but the adverse effects are reinforced by intertemporal and contemporaneous carbon leakage as oil extraction and carbon emissions by *N* rise both now and in the future. Still, the increase in current carbon emissions by *K* and in current and future emissions by *N* are not fully offset by *K*'s cut in future carbon emissions, since the fall in the producer price of oil curbs oil exploration and the total amount of explored oil reserves. Hence, despite the short-run increase in *K*'s and *N*'s current carbon emissions and in *N*'s future carbon emissions, cumulative emissions must fall. The condition for introducing a future carbon tax by *K* to improve global welfare or green welfare is now $R_1^K \varepsilon_1^{KD} + R_1^N \varepsilon_1^{ND} < \beta S \varepsilon^S$. The adverse weak Green Paradox ($R_1^K \varepsilon_1^{KD}$) and adverse intertemporal carbon leakage ($R_1^N \varepsilon_1^{ND}$) effects must thus be less than the beneficial effects of trapping more fossil fuel in the earth ($\beta S \varepsilon^S$) for global and green welfare to rise.

The effect of a future unilateral carbon tax by *K* on *K*'s welfare is (see Appendix D): [10]

$$(20) \qquad \frac{d(C^K - \Omega)}{d\tau_2} = \left[\frac{\chi}{p_1}\left(\beta S \varepsilon^S - R_1^K \varepsilon_1^{KD} - R_1^N \varepsilon_1^{ND} \right) + \frac{R_1^K + R_2^K}{e} + \frac{\delta^2}{e \Upsilon^D}\left\{ F_2^K(R_2^K) - C_2^K \right\} \right] \Gamma^G .$$

The first term in square brackets indicates the effect on green welfare. The second term indicates the rent-grabbing effect of a lower producer oil price on *K*'s welfare at the expense of Oilrabia's welfare (*N*'s welfare also increases). The third term results from the ITT effect of the induced lower interest rate and higher unit cost of utility on Industria's welfare at the expense of Oilrabia's and *N*'s welfare. This term is proportional to *K*'s future trade balance, so that is positive if *K* has a future trade surplus and negative if *K* has a future trade deficit. The tariff component thus makes a future carbon tax more attractive

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[10] Equation (20) for the 3-country model extends equation (9′) for the 2-country model discussed in Section 4.1, since $\theta \delta C^*$ in (9′) equals $\delta^2 C_2^* / e = \delta^2 \left\{ F(R_2) - C_2 \right\} / e$ as from the future goods market equilibrium condition Oilrabia's future consumption must equal Industria's future trade balance in the 2-country model.

from *K*'s perspective than purely ecological considerations, and the ITT effect makes it even more (less) attractive if *K* has a future trade surplus (deficit).

Proposition 7: *The fall in future carbon emissions in countries that unilaterally announce the introduction of a future carbon tax is partially offset by higher future and current emissions of non-participating countries (contemporaneous and intertemporal carbon leakage, respectively). Green welfare increases if and only if* $R_1^K \varepsilon_1^{KD} + R_1^N \varepsilon_1^{ND} < \beta S \varepsilon^S$. *Since the rent-grabbing effect of a future carbon tax levied by the Kyoto countries hurts welfare of non-Kyoto oil-importing and oil exporters, unilateral welfare can rise despite a strong Green Paradox effect. The intertemporal terms of trade effect on unilateral welfare is proportional to the future trade balance of the Kyoto countries.*

8.2. **Second Best: Global Altruism**

If all oil-importing countries participate in Kyoto and price carbon, the globally first-best optimal carbon taxes are uniform and given by (11) and (12). However, if there are non-Kyoto countries which do not charge carbon or peg carbon prices too low, $\tau_t^N = \overline{\tau}_t^N < \tau_t^P$, $t = 1, 2,$ the Kyoto countries' carbon taxes that maximize global welfare will be called the second-best *globally altruistic* unilateral taxes. Abstracting from the intertemporal terms of trade effects due to changes in the world interest rate, i.e., $\Upsilon^D, \varepsilon^I \to \infty,$ the globally altruistic taxes are (see (A18) in Appendix D for the general equilibrium expressions):

$$(21) \qquad \tau_1^{K,GA} = \tau_1^P - (1-\Upsilon^I)\left(\frac{(\tau_1^P - \overline{\tau}_1^N)R_1^N \varepsilon_1^{ND} / q_1^N + (\tau_2^P - \overline{\tau}_2^N)R_2^N \varepsilon_2^{ND} / q_2^N}{R_1^K \varepsilon_1^{KD} / q_1^K}\right)\Lambda < \tau_1^{FB} = \tau_1^P,$$

$$(22) \qquad \tau_2^{K,GA} = \tau_2^P - \Upsilon^G\left(\frac{(\tau_1^P - \overline{\tau}_1^N)R_1^N \varepsilon_1^{ND} / q_1^N + (\tau_2^P - \overline{\tau}_2^N)R_2^N \varepsilon_2^{ND} / q_2^N}{\delta R_2^K \varepsilon_2^{KD} / q_2^K}\right)\Lambda < \tau_2^{FB} = \tau_2^P,$$

with

$$0 < \Lambda \equiv \frac{(p_1 / q_1^K)R_1^K \varepsilon_1^{KD} + (p_2 / q_2^K)R_2^K \varepsilon_2^{KD} + (p_1 / q_1^N)R_1^N \varepsilon_1^{ND} + (p_2 / q_2^N)R_2^N \varepsilon_2^{ND} + S\varepsilon^S}{(p_1 / q_1^N)R_1^N \varepsilon_1^{ND} + (p_2 / q_2^N)R_2^N \varepsilon_2^{ND} + S\varepsilon^S} < 1,$$

$1-\Upsilon^I \equiv (1-\Upsilon^{G,N}/\delta)(1-\Upsilon^{I,K}) + (\Upsilon^{G,K}/\delta)(1-\Upsilon^{I,N})$ and $\Upsilon^G \equiv (1-\Upsilon^{I,N})\Upsilon^{G,K} + \Upsilon^{I,K}\Upsilon^{G,N}$.

The globally altruistic carbon taxes set by *K* are second best as *N* taxes carbon too low, hence they are lower than the first-best taxes. The current carbon tax is lower if more of its burden is shifted to oil producers (low Υ^I); the future carbon tax is lower if the weak

Green Paradox effect is stronger (high Υ^G). From (21) and (22) we also expect the downward biases in globally altruistic carbon taxes to be bigger if the oil consumed by non-Kyoto countries is large relative to the oil consumed by Kyoto countries.

8.3. Unilateral Second-Best Optimal Carbon Taxation

From the perspective of the Kyoto countries, they can do better if they unilaterally maximize their own welfare as this allows them to levy a tariff to capture some of the rents of the oil-producing countries. The Kyoto countries' carbon taxes that maximize $C^K - \Omega = \Phi - (C^N + C^*)$ will be called the *unilateral second-best optimal* carbon taxes. Abstracting from intertemporal terms of trade effects, these are (see (A20)-(A21) in Appendix D for the general equilibrium expressions):

$$(23) \quad \tau_1^{K,U} = \tau_1^P + (1-\Upsilon^I)\left[\frac{q_1^K(R_1^K + R_2^K) - (\tau_1^P - \overline{\tau}_1^N)R_1^N\varepsilon_1^{ND}/q_1^N - (\tau_2^P - \overline{\tau}_2^N)R_2^N\varepsilon_2^{ND}/q_2^N}{R_1^K\varepsilon_1^{KD}/q_1^K}\right]\Lambda,$$

$$(24) \quad \tau_2^{K,U} = \tau_2^P + \Upsilon^G\left[\frac{q_2^K(R_1^K + R_2^K) - (\tau_1^P - \overline{\tau}_1^N)R_1^N\varepsilon_1^{ND}/q_1^N - (\tau_2^P - \overline{\tau}_2^N)R_2^N\varepsilon_2^{ND}/q_2^N}{\delta R_2^K\varepsilon_2^{KD}/q_2^K}\right]\Lambda.$$

These unilateral second-best carbon taxes exceed the globally altruistic taxes, especially if oil producers bear most of the burden (see (A22)-(A23) in Appendix D). This occurs if the tax incidence coefficient $1-\Upsilon^I$ is large and the weak Green Paradox effect Υ^G is large. The drop in welfare of oil producers and non-Kyoto countries is then larger. These taxes exceed the Pigouvian taxes if the rent-grabbing effects dominate the free-riding effects of *N*. The ITT effects for the future carbon tax would add positive terms to (23) and (24) and the ITT effects for the current tax a negative term to (23) (cf. Proposition 6).

Proposition 8: *Abstracting from intertemporal terms of trade effects, the globally altruistic carbon taxes (21)-(22) are set below the first- best carbon taxes (12)-(13), especially if oil producers bear a lot of the burden, the Green Paradox effect is strong, and a bigger fraction of emitting countries price carbon too low. The unilateral second-best carbon taxes (23)-(24) are set above the globally altruistic carbon taxes. They are set above the Pigouvian taxes if the rent-grabbing effects dominate carbon free-riding effects.*

Countries may implement border tax adjustments to price carbon embedded in imports from non-Kyoto countries but general equilibrium changes in prices will blunt such second-best instruments (e.g., Lockwood and Whalley, 2010; Elliot et al., 2010).

8.4. Strategic Behaviour

Our analysis can be extended to study strategic interactions. Consider a 3-country world with two symmetric oil-importing countries, say *A* and *B*, and an oil-exporting country. If *A* and *B* set carbon taxes non-cooperatively, the Nash equilibrium with commitment follows from solving the current and future reaction functions (akin to (23)-(24)). This induces too low carbon taxes compared with the cooperative outcome, since climate externalities will not be fully internalized due to free-rider problems and rent-grabbing from oil producers will be less effective. To analyse such issues properly, one needs to allow for asymmetries in stages of economic development and asymmetries in the vulnerabilities to global warming damages of *K* and *N* to explain why some countries wish to implement lower carbon taxes than other countries.

One can also allow for strategic behaviour of oil producers. If they can exercise monopoly power on world markets, they will raise prices to capture some of the climate rents of oil importers just like oil importers cream off part of the Hotelling rents of oil exporters.[11] One might conjecture that this limits the scope for rent-grabbing and externality-correcting carbon taxes, so the carbon taxes will be attenuated.[12]

9. Concluding remarks

There may be political imperatives to postponing current carbon taxation. But fossil fuel extraction and carbon emissions are brought forward as a result of introducing a future carbon tax, especially so if a relatively large part of the burden of the tax is borne by fossil fuel producers. Such weak Green Paradox effects harm green welfare. Its effects are attenuated by the lower interest rate which results from a higher intertemporal terms of trade necessary to restore equilibrium on the markets for final goods. This attenuation of the weak Green Paradox is more prominent if intertemporal substitution is weak. Such a future carbon tax also means that the oil barons are put out of business as more of fossil fuel reserves are left abandoned, so cumulative carbon emissions are less. A strong Green Paradox (a fall in green welfare) occurs if the price elasticity of the supply of fossil fuel reserves is small relative to that of fossil fuel demand and the ecological discount rate is

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[11] In fact, oil-exporting countries can also levy export tariffs (cf. Copeland, 1994).

[12] Earlier studies of such Nash games are partial equilibrium with linear (Tahvonen, 1995; 1996; Wirl, 1995; Rubio and Escriche, 2001; Liski and Tahvonen, 2004) or more general oil demand (Kagan et al., 2015), but the objective would be to study such strategic interactions in general equilibrium.

high. Even with a strong Green Paradox effect, welfare of oil-importing countries can rise due to the import tariff and intertemporal terms of trade benefits of a future carbon tax.

An asset holding tax has the opposite effects on green welfare as an anticipated carbon tax. If oil supply does not respond much to oil prices compared to oil demand and the ecological discount rate is large, the short-run rise in oil use and carbon emissions (weak Green Paradox) of an anticipated carbon tax dominate the effects of curbing cumulative carbon emissions and green welfare falls (strong Green Paradox). An asset tax then curbs current emissions and boosts green welfare despite higher cumulative emissions. Conversely, if oil supply is much more responsive to oil prices than oil demand and the ecological discount rate is small, the positive welfare effect of an anticipated carbon tax via lower cumulative emissions dominates the adverse effect of higher short-run emissions. An asset holding tax then depresses green welfare (no strong Green Paradox).

We also show that a weak Green Paradox emerges if, instead of pricing carbon, renewable energy is subsidized and is a gross substitute for fossil fuel. If renewable energy and oil are gross complements, subsidizing renewables decelerates global warming. Coal which is abundant and cheap but much more carbon intensive than oil amplifies the weak Green Paradox if it is a gross complement to oil, but attenuates or even reverses it if it is a gross substitute. Reversal of the weak Green Paradox effect implies a boost to the current price of oil and the national income of oil-exporting countries at the expense of coal producers. It occurs if coal is relatively cheap but dirty, the own price elasticity of oil demand is low, and the cross price of elasticity of oil with respect to coal is high. Hence, if the carbon tax hits coal much more than oil, the oil barons can benefit if oil substitutes a lot for coal.

A carbon tax that grows at the same rate as the world rate of interest does not affect the intertemporal pattern of fossil fuel extraction if fossil fuel reserves are fixed. Faster rising carbon taxes then give rise to Green Paradox effects and harm green welfare; slower rising carbon taxes boost green welfare. If fossil fuel exploration and reserves respond to prices, even a balanced carbon tax hike depresses cumulative emissions and boosts green welfare.

The first-best global carbon taxes equal the Pigouvian taxes: the present value of marginal climate damages. They rise slower than the rate of interest and do not generate a weak Green Paradox. If the current carbon tax is set below the Pigouvian tax, the second-best optimal future carbon tax is not set above the Pigouvian carbon tax to compensate for a too low current carbon tax. It must be set below the Pigouvian carbon tax to mitigate adverse weak Green Paradox effects, especially if the price elasticity of current oil demand is large and of oil supply is small.

Unilateral second-best optimal carbon taxes exceed the first-best taxes as they include an import tariff component, which is designed to capture part of the Hotelling rents and thus put the fossil fuel barons out of business. This import tariff component is bigger if exploration investments are not very sensitive to fossil fuel prices. The future unilateral second-best optimal carbon tax rises by more than the unilaterally optimal current carbon tax relative to the first best due to opposing intertemporal terms of trade effects. Unilateral carbon taxes are harmful and can lower global welfare. Once exploration investment is sunk, there is an incentive to renege and push carbon taxes up even more in the future at the expense of the oil barons. Despite the adverse effects of excessive unilateral carbon taxes, they lock up more fossil fuel and curb global warming. In this sense, import tariffs are an environmentalist’s best friend.

If some countries importing fossil fuel do not price carbon or price carbon too low, the weak Green Paradox effect caused by a unilateral future carbon tax is reinforced by intertemporal carbon leakage. Both carbon leakage and the weak Green Paradox effect are less strong if the incidence of carbon taxes falls less on fossil fuel producers. Green welfare thus increases if the price elasticity of oil supply is large relative to that of oil current demand. Unilateral welfare can increase despite a fall in green welfare, since the rent-grabbing effect improves welfare at the expense of the oil-exporting and non-participating oil-importing countries due to a lower producer price of oil. Furthermore, the intertemporal terms of trade effect on unilateral welfare is proportional to the future trade balance of the Kyoto countries.

The globally altruistic current and future optimal carbon taxes are set below the first-best taxes, especially if oil producers bear a lot of the burden and the weak Green Paradox effect is strong. Ignoring intertemporal terms of trade effects, the unilateral second-best optimal carbon taxes exceed the globally altruistic taxes, but they are set above the Pigouvian taxes if the rent-grabbing effects are stronger than the free-riding effects resulting from non-Kyoto countries pricing carbon too low.

An open question is why some countries do not pursue climate policy. Although poorer countries might a less ambitious climate policy and specialize more in pollution-intensive goods (Copeland and Taylor, 1994),[13] political obstacles also differ across countries. Focusing on national commitments to a uniform global carbon price instead of emission cuts might help (Nordhaus, 2013; Weitzman, 2014). Second-best public finance issues also need to be taken more seriously. For example, without lump-sum finance globally optimal carbon taxes are 8-30 percent lower than without distorting capital taxes (Barrage, 2014). Without commitment and with distorting capital taxes, unilateral optimal carbon taxes are too low from a global perspective (Schmitt, 2014). Strategic interactions also need further study. From a policy perspective it is crucial that more understanding is gained on how to convince countries to stop using coal. More must be done to understand the obstacles that must be removed (such as fossil fuel subsidies) to get the world economy to use less coal (e.g., Collier and Venables, 2014). Finally, more must be done on games resulting from oil importers investing in renewables and oil exporters using limit pricing to keep these alternatives out (e.g., Jaakkola, 2015).

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[13] Free trade raises pollution if incomes differ substantially across countries (Copeland and Taylor, 1995).

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Appendix A: Investment in Physical Capital and Recurring Oil Exploration

Here we sketch how our analysis can be modified to allow for investment in physical capital in the first period *I*, which boosts production in the second period, $F(I,R_2)$. Investment in physical capital and future oil demand follow from the efficiency conditions $F_I(I,R_2)=1+r$ and $F_{R_2}(I,R_2)=q_2,$ so $I=I(r,q_2)$ and $R_2=R_2(q_2,r)$. With oil exploration investment at the start of the second period J_2 as well as at the start of the first period $J_1,$ so reserves are $S(J_1)$ at the start of period one and $S(J_1)+A(J_2,J_1)$ at the start of period two. The additional amount of reserves explored at the start of period two typically decreases in first-period exploration efforts as it is harder to explore if a lot of oil has already been explored ($A_{J_1}(J_2,J_1)\leq 0$), which is akin to the more familiar assumption of stock-dependent extraction costs. The Hotelling rule is unaffected, but efficiency of oil exploration investment now demands $p_1\left[S'(J_1)+A_{J_1}(J_2,J_1)\right]=1$ and $(1+r)p_1A_{J_2}(J_2,J_1)=1.$ This gives $J_1=J_1(p_1,r)$ and $J_2=J_2(p_1,r),$ and thus $S=S(p_1,r)$ and $A=A(p_1,r).$ Equilibrium conditions for the oil and final goods markets thus become:

(A1) $R_1(p_1+\tau_1)+R_2\left((1+r)p_1+\tau_2,r\right)=S\left(p_1,r\right)+A\left(p_1,r\right),$

(A2) $\Theta(r)=\dfrac{F\left(S(p_1,r)+A(p_1,r)-R_1(p_1+\tau_1)\right)-J_2(p_1,r)}{F\left(R_1(p_1+\tau_1)\right)-I(r,(1+r)p_1+\tau_2)-J_1(p_1,r)},$

where $J_{1r}=S_r=0$ if $A_{J_1}(J_2,J_1)=0.$ Propositions 1 and 2 are affected by these extensions. Ignoring J_2 and the cross-price effects in investment, we see that Υ^D in (5) increases to $\Upsilon^D=\left[(C_1+C_1^*)\Theta'(r)-\Theta I'(r)\right]/\left[\left(\Theta+q_2/p_1\right)S\varepsilon^S+\left(\Theta+q_2/q_1\right)R_1\varepsilon_1^D\right]$ and thus Γ^G in (6) increases also. Hence, the weakening of the Green Paradox effect in general equilibrium stated in Proposition 1 is curbed. Van der Meijden et al. (2015) confirm this more generally and also show that capital market repercussions can induce amplification of Green Paradox effects if oil importers are more impatient than oil exporters; reversal requires them to be more patient (and the elasticities of intertemporal substitution and factor substitution to be low). Anticipated carbon tax increases green welfare more easily than in Proposition 1, since second-period exploration investment falls too.

Totally differentiating $C+C^*=\left[F(R_1)+\delta F(R_2)-I-J_1-\delta J_2\right]/e(\delta),$ we get

$$d(C+C^*)=\frac{q_1dR_1+\delta q_2dR_2+\left[F(R_2)-J_2\right]d\delta-dI-dJ_1-\delta dJ_2}{e(\delta)}$$

$$-(C+C^*)\theta\frac{d\delta}{\delta}=\frac{\tau_1 dR_1+\delta\tau_2 dR_2}{e}+\left[\delta F(R_2)-J_2-e(\delta)(C+C^*)\theta\right]\frac{d\delta}{\delta e}$$

as $p_1 dR_1+p_2\delta dR_2-dJ_1-\delta J_2=p_1(dS+dA)-dJ_1-\delta dJ_2=0.$ Equilibrium in the final goods markets (A6) implies that the last term in square brackets vanishes, so that the change in global private welfare is given by (13) as before and global welfare by

$$\text{(A3)}\qquad d\Phi=d(C+C^*-\Omega)=\left(\frac{\tau_1-\delta\tau_2}{e}-\chi\right)dR_1+\left(\frac{\delta\tau_2}{e}-\chi\beta\right)(dS+dA).$$

The first-best optimal carbon taxes (11)-(12) in Proposition 4 are thus unaffected. From $C^*=\left[p_1(S+A)-J_1-\delta J_2\right]/e(\delta),$ we get the change in Oilrabia's welfare:

$$dC^*=\frac{S+A}{e}(dq_1-d\tau_1)+\delta\theta C^* dr=$$

$$\text{(A4)}\qquad \left[\underbrace{-\frac{S+A}{e}(1-\Gamma^I)}_{-ve}+\underbrace{\delta\theta C^*\Gamma^1}_{(+ve)}\right]d\tau_1-\left[\underbrace{\frac{S+A}{e}\Gamma^G+\delta\theta C^*\Gamma^2}_{+ve}\right]d\tau_2.$$

The unilaterally optimal carbon taxes follow from maximizing $d(\Phi-C^*)$:

$$\text{(A5)}\qquad \tau_1^U=\tau_1^P+\frac{p_1}{\varepsilon^S}\left(1+\frac{\theta\delta eC^*}{S+A}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\right)-\frac{q_1}{\varepsilon_1^D}\frac{\theta\delta eC^*}{R_1}\frac{\Gamma^2(1-\Upsilon^S)}{\Gamma^G},$$

$$\text{(A6)}\qquad \tau_2^U=\tau_2^P+\frac{p_2}{\varepsilon^S}\left(1+\frac{\theta\delta eC^*}{S+A}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\right)>\tau_2^P+\frac{p_2}{\varepsilon^S}>\tau_2^{FB}=\tau_2^P.$$

This extends (18)-(19) in Proposition 6. Exploring a further amount of oil reserves curbs the positive ITT adjustment for the future carbon tax whereas the strengthening of the Green Paradox resulting from investment in physical capital curbs both the ITT effects.

Appendix B: Power and Logarithmic Present-Value Utility Functions

The power present-value utility function $C=\left[\frac{(1+\rho)C_1^{1-1/\varepsilon^I}+C_2^{1-1/\varepsilon^I}}{(2+\rho)(1-1/\varepsilon^I)}\right]^{1/(1-1/\varepsilon^I)}$ has a constant elasticity of intertemporal substitution $\varepsilon^I>0$ where $\varepsilon^I\neq 1$ and a constant private discount rate $\rho > 0$. The ecological discount rate $(1-\beta)/\beta$ is typically lower than the private discount rate. This utility function is a monotonic transformation of the more usual utility function $C_1^{1-1/\varepsilon^I}+\frac{1}{1+\rho}C_2^{1-1/\varepsilon^I}$, and thus preserves the preference ordering. The corresponding unit expenditure function is $e(\delta) = \left[\left(\frac{1}{1+\beta}\right)\left(1+\beta^{\varepsilon^I}\delta^{1-\varepsilon^I}\right)^{\frac{1}{\varepsilon^I}}\right]^{\varepsilon^I/(1-\varepsilon^I)}$. This implies $\theta = \delta / \left\{\delta + \left[(1+\rho)\delta\right]^{\varepsilon^I}\right\}$, $\Theta = \left[1/\delta(1+\rho)\right]^{\varepsilon^I}$ and $\Theta'(r) = \delta\,\Theta\varepsilon^I > 0.$ If $\varepsilon^S = 1,$ we get the logarithmic present-value utility function $C = C_1^{\frac{1+\rho}{2+\rho}} C_2^{\frac{1}{2+\rho}}$ which has $e(\delta) = \left(\frac{2+\rho}{1+\rho}\right)\left(\frac{\delta}{1+\rho}\right)^{\frac{1}{2+\rho}}$ with $\theta = \frac{1}{2+\rho}$, $\Theta = \frac{1+r}{1+\rho}$ and $\Theta'(r) = \frac{1}{1+\rho} > 0.$ The intertemporal substitution dominates (falls short of) the income effect if ε^I > 1 (< 1). With logarithmic utility these effects cancel out exactly.

Appendix C: Proof of Proposition 6

Using (14′) and (16), we get the marginal change in Industria's welfare:

(A7)
$$\begin{aligned} d(C-\Omega) = d(\Phi - C^*) = \left[1 - \frac{\tau_2 - \tau_2^P}{p_2}\varepsilon^S\right]\frac{S}{e}d\tau_1 - \delta\theta C^*(\Gamma^1 d\tau_1 - \Gamma^2 d\tau_2) \\ -\left\{\left[1 - \frac{\tau_2 - \tau_2^P}{p_2}\varepsilon^S\right]\frac{S}{e} + \frac{R_1}{q_1 e}\left[\tau_1 - \tau_1^P - \delta(\tau_2 - \tau_2^P)\right]\varepsilon_1^D\right\}(\Gamma^I d\tau_1 - \Gamma^G d\tau_2). \end{aligned}$$

The optimality conditions for the unilateral carbon taxes are:

(A8)
$$\begin{aligned} \frac{\partial(C-\Omega)}{\partial\tau_1} = -\left\{\left[1 - \frac{1}{p_2}(\tau_2 - \tau_2^P)\varepsilon^S\right]\frac{S}{e} + \frac{R_1}{q_1 e}\left[\tau_1 - \tau_1^P - \delta(\tau_2 - \tau_2^P)\right]\varepsilon_1^D\right\}\Gamma^I \\ -\delta\theta C^*\Gamma^1 + \left[1 - \frac{1}{p_2}(\tau_2 - \tau_2^P)\varepsilon^S\right]\frac{S}{e} = 0, \end{aligned}$$

(A9)
$$\begin{aligned} \frac{\partial(C-\Omega)}{\partial\tau_2} = \left\{\left[1 - \frac{1}{p_2}(\tau_2 - \tau_2^P)\varepsilon^S\right]\frac{S}{e} + \frac{R_1}{q_1 e}\left[\tau_1 - \tau_1^P - \delta(\tau_2 - \tau_2^P)\right]\varepsilon_1^D\right\}\Gamma^G \\ +\delta\theta C^*\Gamma^2 = 0. \end{aligned}$$

Multiplying (A8) with Γ^G and (A9) with Γ^I, adding the two equations, and simplifying, we get $-\delta\theta C^*\Gamma^1\Gamma^G + \left[1 - \frac{1}{p_2}(\tau_2 - \tau_2^P)\varepsilon^S\right]\frac{S}{e}\Gamma^G + \delta\theta C^*\Gamma^2\Gamma^I = 0$ or $\left[1 - \frac{1}{p_2}(\tau_2 - \tau_2^P)\varepsilon^S\right]\frac{S}{e}\Gamma^G + \delta\theta C^*\Gamma = 0,$ where $\Gamma \equiv \Gamma^I\Gamma^2 - \Gamma^G\Gamma^1.$ Using (6) and (7), we get $\Gamma \equiv \Gamma^I\Gamma^2 - \Gamma^G\Gamma^1 = \Gamma^2\Upsilon^S > 0,$ $\Gamma^2/\Gamma^G = \Upsilon^G/\Upsilon^D > 0$ and thus arrive at equation (19) in Proposition 6.

Rewriting (A9) as $\frac{S}{e}+\frac{R_1}{q_1 e}(\tau_1-\tau_1^P)\varepsilon_1^D+\delta\theta C^*\frac{\Gamma^2}{\Gamma^G}=\left(\frac{1}{p_2}\frac{S}{e}\varepsilon^S+\frac{\delta R_1}{q_1 e}\varepsilon_1^D\right)(\tau_2-\tau_2^P)$

$=\left(\frac{1}{p_2}\frac{S}{e}\varepsilon^S+\frac{\delta R_1}{q_1 e}\varepsilon_1^D\right)\left(1+\frac{\theta\delta eC^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\right)\frac{p_2}{\varepsilon^S}$ where we used (19). This gives

$$\text{(A10)}\quad \tau_1^U=\tau_1^P+\left(\frac{\frac{1}{p_2}\frac{S}{e}\varepsilon^S+\frac{\delta R_1}{q_1 e}\varepsilon_1^D}{\frac{R_1}{q_1 e}\varepsilon_1^D}\right)\left(1+\frac{\theta\delta eC^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\right)\frac{p_2}{\varepsilon^S}-\frac{q_1S}{R_1\varepsilon_1^D}\left(1+\frac{\theta\delta eC^*}{S}\frac{\Gamma^2}{\Gamma^G}\right)=$$

$$\tau_1^P+\frac{p_1}{\varepsilon^S}+\frac{q_1S}{R_1\varepsilon_1^D}+\left(\delta+\frac{q_1S}{R_1\varepsilon_1^D}\frac{\varepsilon^S}{p_2}\right)\frac{\theta\delta eC^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\frac{p_2}{\varepsilon^S}-\frac{q_1S}{R_1\varepsilon_1^D}\left(1+\frac{\theta\delta eC^*}{S}\frac{\Gamma^2}{\Gamma^G}\right),$$

$$\text{(A11)}\quad \tau_1^P+\frac{p_1}{\varepsilon^S}+\theta\delta eC^*\left[\left(\delta+\frac{q_1S}{R_1\varepsilon_1^D}\frac{\varepsilon^S}{p_2}\right)\frac{1}{S}\Upsilon^S\frac{p_2}{\varepsilon^S}-\frac{q_1}{R_1\varepsilon_1^D}\right]\frac{\Gamma^2}{\Gamma^G}.$$

Using $\Gamma^2/\Gamma^G=\Upsilon^G/\Upsilon^D>0$ from (6) and (7), this can be rewritten as

$$\text{(A12)}\quad \tau_1^U=\tau_1^P+\frac{p_1}{\varepsilon^S}+\theta\delta eC^*\frac{p_1}{S\varepsilon^S}\frac{\Upsilon^G\Upsilon^S}{\Upsilon^D}-\theta\delta eC^*\frac{q_1}{R_1\varepsilon_1^D}(1-\Upsilon^S)\frac{\Upsilon^G}{\Upsilon^D},$$

which corresponds to expression (18) in Proposition 6. □

Appendix D: Three-Country Analysis

Tax Incidence and (Reversal of) Green Paradox

Total differentiation of (1′) yields the tax incidence and Green Paradox coefficients:

$$\text{(A13)}\quad 0<1-\Upsilon^I=R_1^K\varepsilon_1^{KD}/q_1^K\Lambda^{OME}<1\quad\text{and}\quad 0<\Upsilon^G=R_2^K\varepsilon_2^{KD}/q_2^K\Lambda^{OME}<1,$$

where $\Lambda^{OME}\equiv\frac{R_1^K}{q_1^K}\varepsilon_1^{KD}+\frac{R_1^N}{q_1^N}\varepsilon_1^{ND}+\frac{R_2^K}{\delta q_2^K}\varepsilon_2^{KD}+\frac{R_2^N}{q_2^N}\varepsilon_2^{ND}+\frac{S}{p_1}\varepsilon^S>0.$ Total differentiation of equation (2′) for equilibrium on the final goods markets yields:

$$\text{(A14)}\quad 0<1-\Upsilon^S=\left(\Theta+\frac{q_2}{p_1}\right)R_1^K\varepsilon_1^{KD}/\Lambda^{GME}<1,\quad \Upsilon^D=\left[(C_1^K+C_1^N+C_1^*)\Theta'(r)-\tau_2\delta R_2^N\varepsilon_2^{ND}\right]/\Lambda^{GME}.$$

where $\Lambda^{GME}\equiv\left(\Theta+\frac{q_2}{p_1}\right)S\varepsilon^S+\left(\Theta+\frac{q_2}{q_1}\right)R_1^K\varepsilon_1^{KD}+\left(\Theta+\frac{q_2}{p_1}\right)R_1^N\varepsilon_1^{ND}+\frac{\tau_2}{p_1}R_2^N\varepsilon_2^{ND}>0.$

At zero taxes and with constant demand elasticities, $1-\Upsilon^I=R_1^K\varepsilon^D/S(\varepsilon^D+\varepsilon^S)$, $\Upsilon^G=\delta R_2^K\varepsilon^D/S(\varepsilon^D+\varepsilon^S)$ and $\Lambda^{GME}\equiv(\Theta+1+r)(S\varepsilon^S+(R_1^K+R_1^N)\varepsilon^D>0.$ For high and positive $\tau_2R_2^N\varepsilon_2^{ND}/p_1$, low intertemporal substitution and elastic enough oil demand, Υ^D

and Γ^G become negative which reverses the Green Paradox effect (i.e., negative intertemporal carbon leakage) in case of a future carbon tax. Effectively, part of the emission reduction in *K* leaks away to *N* instead of to the present. We focus at the case where Υ^D and Γ^G are positive. A sufficient condition is that $\tau_2 = 0$ as then $\Upsilon^D > 0.$

Note that $\Gamma^2 = \Gamma^G / \Upsilon^D > 0$ and $\Gamma^2\Gamma^I - \Gamma^1\Gamma^G = \Gamma^2\Upsilon^S \geq 0.$

Welfare Analysis

Since $d(eC^*) = Sdp_1$ and $d(eC^N) = -(R_1^N + R_2^N)dp_1 + \left[F(R_2^N) - p_2R_2^N\right]d\delta,$ the marginal change in the total welfare of Oilrabia and non-participating countries is

$$\text{(A15)} \quad \begin{aligned} d(C^N + C^*) = &\left[-\left(\frac{S - R_1^N - R_2^N}{e}\right)(1 - \Gamma^I) + \frac{\delta^2}{e\Upsilon^D}\left\{C_2^N + C_2^* - F(R_2^N)\right\}\Gamma^1\right]d\tau_1 \\ &-\left[\frac{S - R_1^N - R_2^N}{e} + \frac{\delta^2}{e\Upsilon^D}\left\{C_2^N + C_2^* - F(R_2^N)\right\}\right]\Gamma^G d\tau_2. \end{aligned}$$

The first terms in the square brackets correspond to the damage to Oilrabia net of the gain to the non-participating countries of a drop in the real price of oil cause by higher carbon taxes. The second terms in the square brackets correspond to the positive and negative intertemporal terms of trade effects of the current and future carbon tax, respectively.

Since at zero taxes $d(C^K + C^N + C^*) = 0,$ equation (20) follows from (A15) and $C_2^N + C_2^* - F_2^N(R_2^N) = F_2^K(R_2^K) - C_2^K$ with $d\tau_1 = 0$ and $d(C^K - \Omega) = -d(\Omega + C^N + C^*).$

The marginal change in global welfare is

$$\text{(A16)} \quad \begin{aligned} d\Phi &= (\tau_1 dR_1^K + \delta\tau_2 dR_2^K)/e - \chi\left[d(R_1^K + R_1^N) + \beta dS\right] = \\ &\left(\frac{\tau_1 - \tau_1^P}{e}\right)d(R_1^K + R_1^N) + \delta\left(\frac{\tau_2 - \tau_2^P}{e}\right)d(R_2^K + R_2^N) - \left(\frac{\tau_1}{e}\right)dR_1^N - \delta\left(\frac{\tau_2}{e}\right)dR_2^N. \end{aligned}$$

The first-best and globally altruistic carbon taxes

From (A16) we see that with zero non-participating countries, all countries across the globe set the same carbon taxes and thus the first-best optimal carbon taxes equal the Pigouvian taxes. With non-Kyoto countries setting non-zero carbon taxes too, the marginal change in global welfare is

$$\text{(A17)}\quad \begin{aligned} d\Phi = & -\left(\frac{\tau_1^K-\tau_1^P}{e}\right)\frac{R_1^K}{q_1^K}\varepsilon_1^{KD}dq_1^K+\left(\frac{\tau_1^N-\tau_1^P}{e}\right)\frac{R_1^N}{q_1^N}\varepsilon_1^{ND}dq_1^N \\ & -\delta\left(\frac{\tau_2^K-\tau_2^P}{e}\right)\frac{R_2^K}{q_2^K}\varepsilon_2^{KD}dq_2^K-\delta\left(\frac{\tau_2^N-\tau_2^P}{e}\right)\frac{R_2^N}{q_2^N}\varepsilon_2^{ND}dq_2^N. \end{aligned}$$

Suppose that the non-Kyoto countries set carbon taxes too low, $\tau_t^N=\overline{\tau}_t^N<\tau_t^P,\ t=1,2,$ and that the Kyoto countries set their carbon taxes in a second-best optimal fashion. We first consider the situation where the Kyoto countries are globally altruistic and maximize global welfare Φ. Using $dq_t^i=dp_t+d\tau_t^i,\ t=1,2,\ i=K,N,\ \ dp_2=p_1dr+(1+r)dp_1,$ (6) and (7), we get from (A17) the first-order conditions for the Kyoto countries:

$$\begin{aligned} \frac{d\Phi}{d\tau_1^K}= & -\left(\frac{\tau_1^K-\tau_1^P}{e}\right)\frac{R_1^K}{q_1^K}\varepsilon_1^{KD}\Gamma^{I,K}+\left(\frac{\overline{\tau}_1^N-\tau_1^P}{e}\right)\frac{R_1^N}{q_1^N}\varepsilon_1^{ND}(1-\Gamma^{I,N})+\left(\frac{\tau_2^K-\tau_2^P}{e}\right)\frac{R_2^K}{q_2^K}\varepsilon_2^{KD}(1-\Gamma^{I,K}) \\ & -\left[\delta\left(\frac{\tau_2^K-\tau_2^P}{e}\right)\frac{R_2^K}{q_2^K}\varepsilon_2^{KD}\Gamma^{1,K}+\delta\left(\frac{\overline{\tau}_2^N-\tau_2^P}{e}\right)\frac{R_2^N}{q_2^N}\varepsilon_2^{ND}\Gamma^{1,N}\right]p_1+\left(\frac{\overline{\tau}_2^N-\tau_2^P}{e}\right)\frac{R_2^N}{q_2^N}\varepsilon_2^{ND}(1-\Gamma^{I,N})=0, \end{aligned}$$

and

$$\begin{aligned} \frac{d\Phi}{d\tau_2^K}= & \left(\frac{\tau_1^K-\tau_1^P}{e}\right)\frac{R_1^K}{q_1^K}\varepsilon_1^{KD}\Gamma^{G,K}+\left(\frac{\overline{\tau}_1^N-\tau_1^P}{e}\right)\frac{R_1^N}{q_1^N}\varepsilon_1^{ND}\Gamma^{G,N}-\delta\left(\frac{\tau_2^K-\tau_2^P}{e}\right)\frac{R_2^K}{q_2^K}\varepsilon_2^{KD} \\ & +\left[\delta\left(\frac{\tau_2^K-\tau_2^P}{e}\right)\frac{R_2^K}{q_2^K}\varepsilon_2^{KD}\left\{p_1\Gamma^{2,K}+(1+r)\Gamma^{G,K}\right\}+\delta\left(\frac{\overline{\tau}_2^N-\tau_2^P}{e}\right)\frac{R_2^N}{q_2^N}\varepsilon_2^{ND}\left\{p_1\Gamma^{2,N}+(1+r)\Gamma^{G,N}\right\}\right]=0, \end{aligned}$$

where the superscripts *K* and *N* for $\Gamma^I,\Gamma^G,\Gamma^1$ and Γ^2 refer to the expressions for the *K* and *N* countries reflecting the different carbon taxes that are levied in countries *K* and *N*.

To get the globally altruistic optimal carbon taxes set by the Kyoto countries, we define $\tilde{\tau}_t^N\equiv\tau_t^P-\overline{\tau}_t^N,\ t=1,2,$ rewrite these first-order conditions and solve the following system of simultaneous equations:

$$\text{(A18)}\quad \begin{pmatrix}\tau_1^{K,GA}-\tau_1^P \\ \tau_2^{K,GA}-\tau_2^P\end{pmatrix}=\frac{Aa}{\det(A)}\ \text{ with } a\equiv\begin{pmatrix}\tilde{\tau}_1^N\dfrac{R_1^N}{q_1^N}\varepsilon_1^{ND}(1-\Gamma^{I,N})+\tilde{\tau}_2^N\dfrac{R_2^N}{q_2^N}\varepsilon_2^{ND}(1-\Gamma^{I,N}-\delta p_1\Gamma^{1,N}) \\ \tilde{\tau}_1^N\dfrac{R_1^N}{q_1^N}\varepsilon_1^{ND}\Gamma^{G,N}+\delta\tilde{\tau}_2^N\dfrac{R_2^N}{q_2^N}\varepsilon_2^{ND}\left[p_1\Gamma^{2,N}+(1+r)\Gamma^{G,N}\right]\end{pmatrix},$$

$$\text{and }\ A\equiv\begin{pmatrix}\delta\dfrac{R_2^K}{q_2^K}\varepsilon_2^{KD}\left[p_1\Gamma^{2,K}+(1+r)\Gamma^{G,K}-1\right] & -\dfrac{R_2^K}{q_2^K}\varepsilon_2^{KD}(1-\Gamma^{I,K}-\delta p_1\Gamma^{1,K}) \\ -\dfrac{R_1^K}{q_1^K}\varepsilon_1^{KD}\Gamma^{G,K} & -\dfrac{R_1^K}{q_1^K}\varepsilon_1^{KD}\Gamma^{I,K}\end{pmatrix}.$$

The unilateral second-best optimal carbon taxes

We use (A15) and *K*'s first-order conditions to get the unilateral second-best optimal taxes that maximize $C^K - \Omega = \Phi - (C^N + C^*)$, including the import tariff and ITT terms, from:

$$\text{(A19)} \begin{pmatrix} \tau_1^{K,U} - \tau_1^P \\ \tau_2^{K,U} - \tau_2^P \end{pmatrix} = \frac{A(a+b)}{\det(A)},\ b \equiv \begin{pmatrix} -(R_1^K + R_2^K)(1-\Gamma^{I,N}) + \delta^2 \left[C_2^N + C_2^* - F(R_2^N) \right] \Gamma^{1,N} \\ -\left[R_1^K + R_2^K + \frac{\delta^2}{\Upsilon^D} \left\{ C_2^N + C_2^* - F(R_2^N) \right\} \right] \Gamma^{G,N} \end{pmatrix}.$$

Since $\det(A) = \frac{R_1^K}{q_1^K} \varepsilon_1^{KD} \frac{R_2^K}{q_2^K} \varepsilon_2^{KD} \left[\delta \Gamma^{I,K}(1 - p_1 \Gamma^{2,K}) + \Gamma^{G,K}(\delta p_1 \Gamma^{1,K} - 1) \right]$, we have:

$$\text{(A20)} \quad \tau_1^{K,U} = \tau_1^{K,GA} + \frac{q_1^K}{R_1^K \varepsilon_1^{KD}} \left\{ \frac{\delta \left[p_1 \Gamma^{2,K} + (1+r)\Gamma^{G,K} - 1 \right] b_1 - (1 - \Gamma^{I,K} - \delta p_1 \Gamma^{1,K}) b_2}{\delta \Gamma^{I,K}(1 - p_1 \Gamma^{2,K}) + \Gamma^{G,K}(\delta p_1 \Gamma^{1,K} - 1)} \right\},$$

$$\text{(A21)} \quad \tau_2^{K,U} = \tau_2^{K,GA} + \frac{q_2^K}{R_2^K \varepsilon_2^{KD}} \left[\frac{\Gamma^{I,K} b_2 + \Gamma^{G,K} b_1}{\delta \Gamma^{I,K}(1 - p_1 \Gamma^{2,K}) + \Gamma^{G,K}(\delta p_1 \Gamma^{1,K} - 1)} \right].$$

Special case: no intertemporal terms of trade effects

If $\Upsilon^D \to \infty$, $\det(A) / (\frac{R_1^K}{q_1^K} \varepsilon_1^{KD} \frac{R_2^K}{q_2^K} \varepsilon_2^{KD}) = \delta \Gamma^{I,K} - \Gamma^{G,K} = \frac{R_1^N \varepsilon_1^{ND} + R_2^N \varepsilon_2^{ND} + S\varepsilon^S}{p_2 \Lambda^{OME,K}}$, so that

$$\tau_1^{K,GA} = \tau_1^P + \frac{\delta \left[(1+r)\Upsilon^{G,K} - 1 \right] a_1 - (1 - \Upsilon^{I,K}) a_2}{\frac{R_1^K}{q_1^K} \varepsilon_1^{KD} (R_1^N \varepsilon_1^{ND} + R_2^N \varepsilon_2^{ND} + S\varepsilon^S)} p_2 \Lambda^{OME,K} \quad \text{and}$$

$\tau_2^{K,GA} = \tau_2^P - (\Upsilon^{I,K} a_2 + \Upsilon^{G,K} a_1) p_2 \Lambda^{OME,K} / \left[R_2^K \varepsilon_2^{KD} (R_1^N \varepsilon_1^{ND} + R_2^N \varepsilon_2^{ND} + S\varepsilon^S) / q_2^K \right]$. Since $a = \left(\tilde{\tau}_1^N \frac{R_1^N}{q_1^N} \varepsilon_1^{ND} + \tilde{\tau}_2^N \frac{R_2^N}{q_2^N} \varepsilon_2^{ND} \right) \begin{pmatrix} 1 - \Upsilon^{I,N} \\ \Gamma^{G,N} \end{pmatrix}$ and $b = -(R_1^K + R_2^K) \begin{pmatrix} 1 - \Upsilon^{I,N} \\ \Upsilon^{G,N} \end{pmatrix}$, we get (21) and (22) with $\Lambda \equiv p_1 \Lambda^{OME,K} / (R_1^N \varepsilon_1^{ND} + R_2^N \varepsilon_2^{ND} + S\varepsilon^S)$ for the globally altruistic taxes. Alsio,

$$\text{(A22)} \quad \tau_1^{K,U} = \tau_1^{K,GA} + (1 - \Upsilon^{I,N}) q_1^K (R_1^K + R_2^K) \Lambda / R_1^K \varepsilon_1^{KD} > \tau_1^{GA},$$

$$\text{(A23)} \quad \tau_2^{K,U} = \tau_2^{K,GA} + \Upsilon^{G,N} q_2^K (R_1^K + R_2^K) \Lambda / \delta R_2^K \varepsilon_2^{KD} > \tau_2^{GA}.$$

Note that (A22) and (A23) indicate that the unilateral second-best optimal carbon taxes exceed the globally altruistic carbon taxes. Using (21)-(22) in (A24)-(A25) we get (23) and (24) for the second-best unilateral taxes.