DEPARTMENT OF ECONOMICS
OxCarre
Oxford Centre for the Analysis of Resource Rich Economies

Manor Road Building, Manor Road, Oxford OX1 3UQ
Tel: +44(0)1865 281281 Fax: +44(0)1865 271094
oxcarre@economics.ox.ac.uk www.oxcarre.ox.ac.uk

OxCarre Research Paper 157

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

Frederick van der Ploeg

OxCarre

Direct tel: +44(0) 1865 281281 E-mail: oxcarre@economics.ox.ac.uk

SECOND-BEST CARBON TAXATION IN THE GLOBAL ECONOMY

The Green Paradox and Carbon Leakage Revisited

Frederick van der Ploeg, University of Oxford[ℜ]

ABSTRACT

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, social damages from greenhouse gases drop if the fall in oil supply and cumulative emissions is strong enough. If the current carbon tax is set too low, the second-best future carbon tax is set below the first best too 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 price carbon 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

JEL codes: D62, D90, H22, H23, Q31, Q38, Q54

March 2015, revised January 2016

Correspondence address:

Department of Economics, Manor Road Building, Oxford, OX1 3UQ, U.K.

Email: rick.vanderploeg@economics.ox.ac.uk

[ℜ] Also affiliated with the Laboratory Economic Performance and the Environment, St. Petersburg State University, 199034 Russia and the VU University Amsterdam, the Netherlands. Support from the BP funded OxCARRE and from the European Research Council (FP7-IDEAS-ERC Grant No. 269788) are gratefully acknowledged. I thank Niko Jaakkola, Gerard van der Meijden, Till Requate and two anonymous referees for their detailed and very helpful comments on earlier versions and thank Peter Neary, Rüdiger Pethig, Armon Rezai, Partha Sen, Tony Venables, Sweder van Wijnbergen and Cees Withagen for helpful discussions on general equilibrium effects of carbon taxes.

1. Introduction

Badly designed climate policy can be counter-productive. For example, the Green Paradox states that politicians that put off carbon taxation bring oil consumption forward and thus accelerate global warming (Sinn, 2008). However, a future carbon tax also cuts the total amount of fossil fuel that is burnt and thus cuts cumulative carbon 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 a third of oil, half of gas and over four fifths of coal reserves must be left unburnt for global warming to stay below 2 degrees Celsius (McGlade and Ekins, 2015). Much of this debate on climate policy is cast in partial equilibrium. Our objective is to adopt a general equilibrium perspective taking full account of the repercussions in global markets for final goods, bonds and fossil fuel. To explain the cumulative burnt fossil fuel and carbon emissions, we model exploration investment (Gaudet and Laserre, 1988; Cairns, 1990).

We want to deepen understanding of second-best policy reform starting from a sub-optimal situation as well as global and unilateral second-best optimal carbon taxes. We distinguish oil-importing and of oil-exporting countries with homothetic, symmetric preferences.[1] Types of reform that we consider are politicians shying away from carbon taxation by putting it off and using renewable energy subsidies. We also derive and discuss second-best optimal policies when other countries including fossil fuel producers are unwilling to price carbon at the appropriate level and discuss second-best responses if there are third oil-importing countries that do not engage in climate policies.

Our contributions concerning *second-best policy reform* are as follows. First, we show that announcing to tax carbon in the future boosts current oil demand and carbon emissions. This is the so-called *weak* Green Paradox effect (Gerlagh, 2011). We show that this effect is stronger if the price elasticities of current and future oil demand are large and those of oil exploration and oil supply are small. We show that this 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 social damages from greenhouse gases is further mitigated by locking more carbon in the earth as a result of curbing oil exploration. If the net effect of a future carbon tax on social damages from greenhouse gases is positive, one has a *strong* Green Paradox effect (Gerlagh, 2011). We show that this occurs

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

if the ecological discount rate is large enough while the price elasticity of oil demand is high and that of oil supply is small. Despite such a strong Green Paradox, oil-importing countries might still improve their welfare due to the import tariff and intertemporal terms of trade benefits of a higher future carbon tax.

Second, we show that, if the condition holds for a future carbon tax to induce a strong Green Paradox, an asset holding tax on oil exporters boosts welfare and is thus a good alternative. But, if oil supply reacts strongly to oil prices and demand not, a future carbon tax boosts welfare but an asset tax does not. Third, we show that subsidizing renewable energy induces weak Green Paradox effects and locks up more carbon in the long run provided renewables are a good enough substitute for oil. For future renewable subsidies these effects are attenuated in general equilibrium. In case there is an abundant and cheap alternative to fossil fuel (coal), we give conditions for which the weak Green Paradox effect is reversed (cf., Michielsen, 2014) and for which oil exporters benefit from climate policy at the expense of coal producers (cf., Coulomb and Henriet, 2015).

Fourth, we establish that introducing a carbon tax that grows at a rate equal to the rate of interest does not affect the intertemporal patter of oil extraction if oil reserves are given. If carbon taxes rise at a faster rate than the interest rate, weak Green Paradox effects occur and social damages from greenhouse gases increase; carbon taxes that rise slower than that curb these social damages. But if oil supply is elastic, a carbon tax that rises at a rate equal to the interest rate cuts current oil extraction and cuts exploration investment, oil reserves, cumulative carbon emissions and social damages from greenhouse gases.

Our contributions concerning *second-best optimal policies* are as follows, where we use as our benchmark the global first-best carbon taxes that are set to the Pigouvian social costs of carbon (the present value of marginal global warming damages). We first show that, if for political reasons the current carbon tax is pegged below the Pigouvian tax, the global second-best optimal future carbon taxes are below the first-best globally optimal carbon taxes to mitigate weak 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 rise slower than the rate of interest and thus induce no weak Green Paradox effects. We then show that if carbon taxes are set unilaterally by the oil-importing countries, they exceed the global first-best taxes as they contain an import tariff component. We also show 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 discuss the time inconsistency of unilateral second-best optimal carbon taxes, which results from the pure rents inherent in future reserves. Unilateral reneging implies that carbon taxes are pushed up at an even greater welfare cost to oil-exporting countries.

Finally, our contributions relating to *carbon leakage* if there are third countries that pursue inadequate climate policy are as follows.[2] We show that both contemporaneous and intertemporal carbon leakage strengthen the weak Green Paradox effect as non-Kyoto countries that do not price carbon enough raise current and future carbon emissions in response to a future unilateral carbon tax. We show that social damages from greenhouse gases fall if oil supply responds more to prices than current oil demand of the Kyoto and non-Kyoto countries and if the ecological discount rate is small, but welfare of the Kyoto countries rises by more due to rent-grabbing effects. We also show that the intertemporal terms of trade effect on unilateral welfare is proportional to the future trade balance of the Kyoto countries. Finally, we derive the globally altruistic and the unilateral second-best optimal carbon taxes for the Kyoto countries given that the non-Kyoto countries price carbon below the Pigouvian social cost of carbon. The former are set too low, especially if more of the burden of carbon taxes is shifted to oil exporters and the oil consumed by non-Kyoto countries is large relative to that consumed by Kyoto countries. The unilateral exceed the globally altruistic second-best optimal carbon taxes.

Our contributions owe a lot to Eichner and Pethig (2011), who offer a general equilibrium analysis of the Green Paradox and carbon leakage within the context of a two-period, three-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 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, but show that with identical preferences and no investment in physical capital a future carbon tax unambiguously reduces the interest rate and attenuates the weak Green Paradox effect.

[2] Earlier studies on carbon leakage are Elliott et al. (2010), Elliot et al. (2012), Fischer and Salant (2013), Elliott and Fullerton (2014), Eichner and Pethig (2011, 2013), Ritter and Schopf (2014) and Sen (2015).

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 weak and strong Green Paradox and carbon leakage and easy-to-interpret formulae for the global first-best, global second-best 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 identical coefficients of intergenerational inequality aversion)[3].

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

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 and climate policies. Our model is as in van der Meijden et al. (2015), but we use duality theory to derive and interpret the comparative statics of climate policy reform and their welfare effects as well as to derive explicit expressions for the global and unilaterally second-best and first-best optimal climate policies. Section 3 thus extends van der Meijden et al. (2015) by determining not just the signs but also giving explicit expressions for the partial and general equilibrium effects on carbon emissions, social damages from greenhouse gases and global welfare of changes in current and future carbon taxes. This highlights the crucial roles of the price elasticities of the supply and demand for oil in each period and also the role of the ecological discount rate for the signs and magnitudes of these effects. Sections 4 and 6 extend van der Meijden et al. (2015) by deriving explicit expressions for the first-best carbon taxes and the global and unilaterally second-best optimal carbon taxes, respectively. Section 5 extends van der Meijden et al. (2015) by deriving the quantitative effects of an asset holding tax and a renewable energy subsidy, and showing the effects of coal on global warming and the Green Paradox. Section 7 extends the analysis to a three-country framework.

Although the two-period analysis has been used before to study the economics of climate change in partial equilibrium (e.g., Michielsen, 2014) and in general equilibrium (e.g., Eichner and Pethig, 2011, 2013; Ritter and Schopf, 2014; van der Meijden et al., 2015), it must be realized that this is merely a theoretical albeit useful metaphor. Climate change

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

after all stretches out decades and centuries ahead. This poses ethical issues related to intergenerational justice and social discounting as well as climate uncertainties (e.g., Dasgupta, 2008; Gollier, 2012). Period one can be viewed as covering the next twenty years or so and period two as covering the future from then on. Given that fossil fuel has to be phased out in the next fifty years or so, this may not be so unrealistic. The merit of the two-period setup is, however, that it gives clear-cut analytical results that are policy relevant.[4] First-period relative to second-period oil extraction can be viewed as a proxy for the speed of oil extraction in an infinite-horizon context. Of course, there is a theoretical literature that studies small continuous-time, infinite-horizon partial equilibrium models of weak and strong Green Paradox effects and first-best optimal policies (e.g., Gerlagh, 2011; van der Ploeg and Withagen, 2012; Fischer and Salant, 2013; Coulomb and Henriet, 2015) and their general equilibrium extensions (van der Ploeg and Withagen, 2014). Furthermore, tractable discrete-time, infinite-horizon general equilibrium models of growth and the first-best optimal carbon tax have been developed, albeit with bold assumptions (Golosov et al., 2014),[5] and large numerical integrated assessment models (e.g., Nordhaus, 2014; Stern, 2007; Böhringer et al., 2014ab) have multiple periods too. But these infinite-horizon models yield in contrast to our two-period model no analytical insights on second-best optimal policies and typically lack the forward-looking dynamics of scarce and exhaustible fossil fuel resources underlying the weak Green Paradox effect.

Our model consists of an oil-exporting and an oil-importing country called Industria. There is an international market for a homogenous final good produced in Industria, an international bonds market, and an international oil market. All markets operate under perfect competition. Cumulative carbon emissions are endogenous, since initial oil reserves depend on initial investment in exploration. The only variable production factor in Industria is oil; other factors such as land, labour or capital are fixed (see Appendix A for a discussion of investment in physical capital). Preferences are homothetic and identical for Industria and the oil-exporting country. There are no bonds at the start and none left at the end. Apart from climate externalities, there are no other market failures or distorting taxes. Our second-best analysis starts from the premise of government failure.

[4] There is a big literature that addresses climate change issues such as carbon leakage in *one-period*, small-open-economy or multi-country models (e.g., Copeland, 1994; Copeland and Taylor, 1994, 1995; Elliott et al., 2010, 2012; Bayliss et al., 2013, 2014; Elliott and Fullerton, 2014; Sen, 2015).

[5] These are logarithmic utility, Cobb-Douglas production, exponential damages, 100 percent depreciation of physical capital in each period and a very simple two-box carbon cycle.

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. Since *e* is the minimum cost of financing one unit of private utility U, we have $C_1 + \delta C_2 = e(\delta)U$ 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.

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*. The consumer price of oil, $q_t \equiv p_t + \tau_t$ in period *t* consists of the world producer price of oil, p_t, plus a specific carbon tax, τ_t. Oil demands 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 defined as $\varepsilon_t^D \equiv -q_t R'(q_t)/R_t > 0, t = 1, 2.$ Let *Y* denote the present value of income (wealth) and $T \equiv \tau_1 R_1 + \delta \tau_2 R_2$ denote rebated carbon tax revenue. The present-value budget constraint of Industria is then given by $e(\delta)U = Y \equiv F(R_1) - q_1 R_1 + \delta\left[F(R_2) - q_2 R_2\right] + T.$

The Hicksian demand function $C_2 = e'(\delta)U$ and the present-value budget constraint $Y = eU = C_1 + \delta C_2$ 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. The oil-exporting country

The oil-exporting country chooses initial oil exploration investment J to maximize the present value of its profits or its national income, $Y^* \equiv p_1 R_1 + \delta^* p_2 R_2 - J$, subject to the oil depletion constraint $R_1 + R_2 = S(J)$, where *S* denotes initial oil reserves and δ^* is the relative price of future final goods in the oil-exporting country. We suppose diminishing returns from oil exploration, so that $S'(J) > 0$ and $S''(J) < 0.$ We thus get the familiar Hotelling rule for the producer price of oil, $p_2 = (1+r^*)p_1 = p_1/\delta^*$, and the optimality condition for exploration investment, $p_1 S'(J) = 1.$ From this we can solve for

$J = J(p_1),\ J'(p_1) = -1/p_1^2 S''(J) > 0,$ and $S = S(p_1).$ We define the oil supply elasticity as $\varepsilon^S \equiv p_1 S'(p_1)/S > 0.$ Final goods consumption in period one, $C_1^* = \left[1-\theta(\delta^*)\right]Y^*,$ and in period two, $C_2^* = \theta(\delta^*)Y^*/\delta^*,$ and private utility $U^* = Y^*/e(\delta^*)$ follow from the present-value budget constraint $C_1^* + \delta^* C_2^* = Y^*(p_1) = p_1 S - J$ 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 the oil-exporting country, hence $r = r^*$ and $\delta = \delta^*$. Equilibrium on the international oil market requires that all oil supplies are depleted either today or in the future, so that

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

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, which gives

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

Global private welfare is utilitarian, so that it is given by $U+U^*$ and inequality aversion across the two countries is zero. Global welfare Φ is defined as global private welfare minus social damages from greenhouse gases Ω:

(3) $$\Phi \equiv U + U^* - \Omega \ \text{ with } \ \Omega = \chi(R_1+\beta S),$$

where $0 < \beta \le 1$ is the ecological discount factor and $\chi > 0$ is the marginal damage coefficient for greenhouse gases. The ecological discount rate $(1-\beta)/\beta$ includes the rate of decay of atmospheric carbon and thus exceeds the social discount rate. The social discount rate is lower than the private discount rate if it is deemed unethical to discount welfare of future generations (e.g., Stern, 2007) or prudent to use a lower discount rate in face of climate uncertainties (e.g., Gollier, 2012). It differs from the market interest rate *r*. Following Gerlagh (2011), a policy change (such as introducing a small future carbon tax) that boosts current carbon emissions, $R_1,$ and accelerates global warming is called a *weak* Green Paradox and if this policy change also curbs social damages from greenhouses, $\Omega,$ it is called a *strong* Green Paradox.

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 the following expressions for the change in the current producer price of oil, the current consumer price of oil, oil reserves and current oil extraction, respectively:

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

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. They indicate what fraction of the current and future carbon tax is borne by the oil-exporting country rather than by Industria.

For a given world interest rate, the expression for Υ^I indicates that the burden of a current carbon tax is shifted more to the oil-exporting country if the price elasticities of oil supply and future oil demand are small relative to that of current oil demand (i.e., 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 carbon taxes, equation (4) implies that $-1 < dp_1 / d\tau_1 = -(1-\Upsilon^I) = -R_1\varepsilon_1^D / \left(R_1\varepsilon_1^D + R_2\varepsilon_2^D + S\varepsilon^S\right) < 0.$ This clearly shows that more of the current carbon tax is borne by Industria if oil demand is relatively elastic and oil supply is not.

A future carbon tax is partially shifted to oil producers too, so the world producer price of oil falls today and via the Hotelling logic in the future too. The future consumer price of oil increases, so future oil demand falls. Current oil demand rises on account of the drop 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 the price elasticity of future oil demand (at zero carbon taxes, one has $0 < \Upsilon^G = \delta R_2 \varepsilon_2^D / (R_1 \varepsilon_1^D + R_2 \varepsilon_2^D + S\varepsilon^S) < 1$). 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 equations (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 the condition for final goods markets to be in equilibrium (2) gives

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

where

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

Intuitively, for a given current producer price of oil p_1, a higher current carbon tax cuts 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 current consumer price of oil q_1, given τ_1, also postpones demand for final goods and thus also requires a higher interest rate to restore equilibrium in world markets for final goods.

3.3. General Equilibrium Comparative Statics

Combining the conditions for equilibrium in world oil markets (4) and in final goods markets (5), we obtain the general equilibrium comparative statics for the current producer and consumer prices of oil:

(6) $$dp_1 = -(1-\Gamma^I) d\tau_1 - \Gamma^G d\tau_2 \quad \text{and} \quad dq_1 = \Gamma^I d\tau_1 - \Gamma^G d\tau_2,$$

where $\Gamma^I \equiv \Upsilon^I - p_1\Upsilon^G\Gamma^1$ and $\Gamma^G \equiv \dfrac{\Upsilon^D}{\Upsilon^D + p_1\Upsilon^G}\Upsilon^G$. The change in the world interest rate is

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

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 (4) 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, with the power utility function $U(C_1, C_2) =$ $\left[\dfrac{(1+\rho)C_1^{1-1/\varepsilon^I} + C_2^{1-1/\varepsilon^I}}{(2+\rho)(1-1/\varepsilon^I)}\right]^{1/(1-1/\varepsilon^I)}$, we have a constant elasticity of intertemporal substitution in which case $\Upsilon^D \to \infty$ as $\Theta'(r)/\Theta = \delta\varepsilon^I \to \infty$ and thus $\Gamma^1 \to 0, \Gamma^2 \to 0, \Gamma^I \to \Upsilon^I$ and $\Gamma^G \to \Upsilon^G$ as $\varepsilon^I \to \infty$ (see Appendix B). As it becomes very easy to substitute current for future consumption, the general equilibrium comparative statics approach the partial equilibrium comparative statics.

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

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

Hence, the current consumer price of oil and the world interest rate increase in the current carbon tax but always decrease in the future carbon tax.

4. First-Best Climate Policy

The first-best carbon taxes maximize global welfare (3) and typically require lump-sum financed side payments. The taxes boost private welfare of Industria and depress social damages from greenhouse gases at the expense of the oil-exporting country, but global welfare rises compared with the no-policy scenario. It follows that Industria can indeed compensate the oil-exporting country, and both can then 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. The first-best carbon taxes must be set to the Pigouvian social costs of carbon which are defined as the present discounted values of marginal damages from burning one additional unit of carbon today (cf., Stern, 2007; Nordhaus, 2014; Golosov et al., 2014).

Proposition 1: *The first-best global carbon taxes,* τ_t^{FB}*, are set to the Pigouvian taxes,* τ_t^P *:*

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

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

The first-best carbon taxes decrease with the ecological discount rate and are independent of the stock of fossil fuel reserves. With $\varepsilon^S = 0$ *and full exhaustion, any carbon tax path including (9)-(10) that satisfies* $\tau_1 - \delta\tau_2 = \chi e$ *achieves the first best.*

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

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

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

(11) $$d(U+U^*) = \frac{\tau_1 dR_1 + \delta\tau_2 dR_2}{e}.$$

The marginal change in global welfare (net of social damages from greenhouse gases) is

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

The first-best global carbon taxes (9) and (10) ensure that this marginal change is zero. Equations (9) and (10) are necessary conditions for an optimum. With concave utility and production functions these conditions are also sufficient. □

We can use equations (6) and (12) to obtain the marginal change in global welfare:

$$(12') \qquad d\Phi = -\left[\left(\frac{\tau_1 - \delta\tau_2}{e} - \chi\right)\frac{R_1}{q_1}\varepsilon_1^D \Gamma^I + \left(\frac{\delta\tau_2}{e} - \chi\beta\right)\frac{S}{p_1}\varepsilon^S(1-\Gamma^I)\right]d\tau_1 + \left[\left(\frac{\tau_1 - \delta\tau_2}{e} - \chi\right)\frac{R_1}{q_1}\varepsilon_1^D - \left(\frac{\delta\tau_2}{e} - \chi\beta\right)\frac{S}{p_1}\varepsilon^S\right]\Gamma^G d\tau_2.$$

The first-best taxes (9) and (10) also follow from setting (12′) to zero. To ensure that the first-best optimum is a maximum, the second-order optimality condition must be satisfied. This requires that the Hessian matrix corresponding to (12′) is strictly negative definite.

The first-best Pigouvian carbon taxes (9) and (10) 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 private utility *e*.[6] The current carbon tax is thus high if *e* is high and the world interest rate is low. The future carbon tax also responds directly to the interest rate, so in general the future carbon tax is high if the world interest rate is high.[7] With a fixed 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 a current carbon tax, $\tau_1 = \chi e,$ or a future carbon subsidy, $-\tau_2 = (1+r)\chi e$). However, if it is not optimal to fully exhaust the fixed reserves ($R_1 + R_2 < S$), the first-best taxes are determinate and given by (9) and (10).

Our main concern in this paper is not first best, but *policy reform* and *second-best optimal policies*. Policy reform is concerned with how welfare can be improved from a sub-optimal situation (e.g., zero carbon taxes) by introducing a small carbon tax, a small asset holding subsidy, a renewable energy subsidy, or a rising path of carbon taxes. This type of policy reform analysis typically has business as usual (doing nothing) as its benchmark and underlies the burgeoning literature on the Green Paradox. It is the focus of Section 5. Section 6 is concerned with constraints on the set of policy instruments that prevent first-best policies from being attained. It thus deals with second-best optimal carbon taxes, both

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[6] If climate damages are multiplicative, $\Phi = \ln(U + U^*) - \bar{\chi}(R_1 + \beta S)$ with $\bar{\chi} > 0,$ not additive as in (3), Propositions 2 and 4 are unaffected and the first-best carbon taxes in Proposition 1 become (9) and (10) with χ replaced by $\chi = \bar{\chi}(U + U^*).$ First-best carbon taxes are then thus proportional to global wealth, $e(U + U^*),$ and rise in line with growth of the global economy (cf. Golosov et al., 2014).

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

from a global and a unilateral perspective. For this we are also interested in comparing them with the benchmark that results from the global first-best optimal carbon taxes.

5. Policy Reform: The Green Paradox Revisited

Carbon taxation is notoriously unpopular. Politicians therefore try to shift the burden of pricing carbon to the future, to tax assets of foreign oil exporters or to subsidize renewable energy, all of which will be analysed below. We also discuss the effects on carbon emissions of a carbon-intensive, cheap and abundant alternative (coal) to oil. Finally, we discuss the effects of introducing a rising path for the carbon tax. Our benchmark for these policy reform exercises is business as usual with no climate policies in place.

5.1. Postponed Carbon Taxation

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

A. *Weak Green Paradox effect (i.e., increase in* R_1*)*: 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 (i.e., fall in r)*: The relative fall in future supply of goods caused by the future carbon tax pushes up the future price of final goods and depresses the world interest rate. This induces oil exporters to sell less today and more tomorrow as it makes it in the margin less attractive to extract another barrel of oil. This weakens the weak Green Paradox effect and thus mitigates the acceleration of global warming (comparing equations (6) and (7), we see that $\Gamma^G < \Upsilon^G$).[8]

C. *Out of business effect (i.e., drop in J and S)*: The higher future carbon tax cuts the current and future producer prices of oil and thus curbs oil exploration investment, reserves and cumulative 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 social damages from greenhouse gases.

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

Since from equation (11) the marginal change in private global welfare is zero if evaluated at initial carbon taxes, i.e., $d(U+U^{*})=0,$ and equation (12) indicates that the marginal change in global welfare is $d\Phi=-d\Omega=-\chi(dR_{1}+\beta dS)$ at zero initial carbon taxes, the effect of a future carbon tax on global welfare is the opposite of that on social damages:

$$(13)\qquad \left.\frac{d\Phi}{d\tau_{2}}\right|_{\tau_{1}=\tau_{2}=0}=-\left.\frac{d\Omega}{d\tau_{2}}\right|_{\tau_{1}=\tau_{2}=0}=-\chi\left(\frac{dR_{1}}{d\tau_{2}}+\beta\frac{dS}{d\tau_{2}}\right)=\frac{\chi}{p_{1}}\left(\beta S\varepsilon^{S}-R_{1}\varepsilon_{1}^{D}\right)\Gamma^{G}.$$

From equation (13) we see that introduction of a global carbon tax deteriorates global welfare and increases the social damages from greenhouse gases if $R_{1}\varepsilon_{1}^{D}>\beta S\varepsilon^{S}$ holds. In that case, there is a *strong* Green Paradox (Gerlagh, 2011) as the adverse weak Green Paradox effects dominate the beneficial effects of putting oil producers out of business and curbing cumulative carbon emissions as the price elasticity of current oil demand is high relative to that of oil reserves and the ecological discount rate is high (low β). Hence, if oil reserves and cumulative emissions do not respond much to prices, $\varepsilon^{S}<(R_{1}/S)\varepsilon_{1}^{D}/\beta,$ one has a *strong* Green Paradox effect as a future carbon tax boosts social damages from greenhouse gases. Conversely, if oil supply is relatively more sensitive to price than oil demand and the ecological discount rate is small, then social damages from greenhouse gases and global welfare increase. Note that if oil exporters have little room for manoeuvre, i.e., if oil supply is relatively inelastic and oil demand is relatively elastic (high Γ^{G}), the marginal effect of the future carbon tax on global welfare is amplified.

More generally, if we start out from a situation of non-zero carbon taxes, we can show from equation (12) that the effect of a future carbon tax on global welfare is given by $\frac{d\Phi}{d\tau_{2}}=\left[(\tau_{2}^{P}-\tau_{2})\frac{\delta S\varepsilon^{S}}{ep_{1}}+(\tau_{1}-\delta\tau_{2}-\chi e)\frac{R_{1}\varepsilon_{1}^{D}}{ep_{1}}\right]\Gamma^{G}$ instead of (13). This expression confirms that starting from the global first-best carbon taxes (9) and (10), the marginal change in global welfare is zero. In general, starting from positive carbon taxes that are closer to the Pigouvian first-best taxes reduces the effect of a future global carbon tax on global welfare. Fossil fuel subsidies are prevalent throughout the world economy (Coady et al., 2015), hence initial carbon taxes are negative and the positive effects on global welfare via curbing reserves and locking up more carbon are amplified.[9]

However, even if there is a strong Green Paradox effect with an increase in social damages from greenhouse gases and a fall in global welfare, this does not mean that Industria's welfare (i.e., $U-\Omega=\Phi-U^*$) needs to fall. This can be seen from the marginal change in Industria's welfare (using the relationship $\Gamma^2/\Gamma^G=1/\Upsilon^D$):

$$(13') \quad \left.\frac{d(U-\Omega)}{d\tau_2}\right|_{\tau_1=\tau_2=0} = -\chi\left(\frac{dR_1}{d\tau_2}+\beta\frac{dS}{d\tau_2}\right)-\frac{dU^*}{d\tau_2}=\left[\frac{\chi}{p_1}\left(\beta S\varepsilon^S-R_1\varepsilon_1^D\right)+\underbrace{\frac{S}{e}}_{\text{tariff}}+\underbrace{\frac{\theta\delta U^*}{\Upsilon^D}}_{\text{ITT term}}\right]\Gamma^G.$$

Comparing (13′) with (13), we see two extra terms. The first one, *S*/*e*, reflects the import tariff benefits of a higher future tax. Industria can grab part of the oil exporter's revenue from selling oil reserves, *S*, on world markets by adding to the future carbon tax an import tariff component and boosting Industria's welfare at the expense of the oil exporter. The second term, $\theta\delta U^*/\Upsilon^D$, reflects the boost to the intertemporal terms of trade (ITT = δ) resulting from a higher future carbon tax. This arises from this policy depressing relative supply of future final goods, which demands a boost to the price of future final goods, δ, to restore equilibrium in final goods markets. This pushes up the cost of private utility, *e*, and thus erodes the real value of the oil-exporter's wealth and boosts Industria's welfare.

Since both these extra terms in equation (13′) are positive, the gain in Industria's welfare unambiguously exceeds the drop in social damages from greenhouse gases from the credible announcement of a future carbon tax.

Proposition 2: *Introducing a future carbon tax boosts current oil use and accelerates global warming, especially if the price elasticities of oil demand are large and that of oil supply is small. This effect is mitigated by the drop in the world interest rate, especially if intertemporal substitution is weak. Social damages from greenhouse gases rise if and only if* $R_1\varepsilon_1^D>\beta S\varepsilon^S$ *holds. 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.*

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[9] Post-tax fossil fuel subsidies (including the failure to price global warming at the appropriate price) take up about 5 trillion dollars or 6.5 percent of world GDP in 2013 and 13-18 percent of GDP in emerging and developing Asia, the Middle East, North Africa and Pakistan and the Common Wealth of Independent States (Coady et al., 2015). The biggest subsidies are for coal, which per energy unit harm global warming most.

5.2. 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 $r^* = r - \upsilon.$ In that case, Industria gets rebated in lump-sum fashion the amount $T \equiv \tau_1 R_1 + \delta\tau_2 R_2 + \upsilon(p_1 R_1 - J - C_1^*).$ 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 social damages is in fact 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* curbs social damages from greenhouse gases. This can be seen from $d\Omega / d\upsilon = -\chi R_1\varepsilon_1^D\Gamma^G < 0.$ A future carbon tax, in contrast, then always boosts social damages from greenhouse gases. However, if oil supplies respond strongly to oil prices and current oil demand does not and if the ecological discount rate is small, we have $\beta S\varepsilon^S > R_1\varepsilon_1^D$ and thus establish that an asset holding tax is counter-productive whilst in contrast a future carbon tax cuts social damages from greenhouse gases.

Using $dU^* = \frac{S}{e^*}dp_1 + \delta^*\theta^*U^*(dr - d\upsilon)$ 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 $\theta^*\delta^*U^* = C_2^*,$ we find that the effect of an unilateral asset holding tax on Industria's private welfare (evaluated at zero taxes) is

$$(13'') \quad \left.\frac{d(U-\Omega)}{d\upsilon}\right|_{\tau_1=\tau_2=\upsilon=0} = \chi\Gamma^G\left(R_1\varepsilon_1^D - \beta S\varepsilon^S\right) + \frac{\Upsilon^D}{\Upsilon^D + p_1\Upsilon^G}\left(C_2^* - \Upsilon^G\frac{p_1 S}{e^*}\right).$$

It has been pointed out a long time ago, in a setting with exogenous oil supply, $\varepsilon^S = 0$, and no social damages from greenhouse gases, $\chi = 0,$ that 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 condition to $\varepsilon^S \geq 0$ as equation (13″) then implies that Industria's welfare falls if $\Upsilon^G p_1 S / e^* > C_2^*$ which will be the case if $\Upsilon^G = \frac{R_2}{q_2}\varepsilon_2^D / \left(\frac{R_1}{q_1}\varepsilon_1^D + \frac{R_2}{\delta q_2}\varepsilon_2^D + \frac{S}{p_1}\varepsilon^S\right)$ 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. With social damages from greenhouse gases, the term $\chi \Gamma^G R_1 \varepsilon_1^D > 0$ in (13″) implies that it is less likely that an asset holding tax depresses Industria's welfare.

Proposition 3: *A tax on the oil exporter' asset holdings has the opposite effects of a future carbon tax and is effective if a future carbon tax harms global welfare, and vice versa.*

5.3. Does Subsidizing Renewable Energy Induce Green Paradox Effects?

It is know that subsidizing renewable energy in an infinite-horizon setting, where renewables are *perfect* substitutes for fossil fuel also leads to weak Green Paradox effects and brings the switch to the carbon-free era forward (e.g., van der Ploeg and Withagen, 2012). To see how this works in our two-period setup with *imperfect* substitution, let the final goods production function in period t depend on oil and renewable energy, i.e., $F(R_t, B_t),$ where B_t is renewable energy use supplied at fixed cost b_t. Energy demands follow from the marginal productivity conditions $F_{R_t} = q_t$ and $F_{B_t} = b_t,$ so that oil demands depend on the costs of oil and renewable energy and are given by $R_t = R(q_t, b_t), t = 1, 2.$ Renewable energy is a gross substitute for oil if the cross price elasticity, defined as $\varepsilon_t^B \equiv b_t R_{b_t}(q_t, b_t) / R_t,$ is positive and a gross complement if it is negative. The oil market equilibrium condition (1) becomes $R_1(p_1 + \tau_1, b_1) + R_2\left((1+r)p_1 + \tau_2, b_2\right) = S(p_1),$ which gives an extra term, $\Upsilon_1^B db_1 + \Upsilon_2^B db_2,$ in expression (4). We thus get the following effect on the current oil price:

(4′) $$dp_1 = -(1-\Upsilon^I)d\tau_1 - \Upsilon^G(d\tau_2 + p_1 dr) + \Upsilon_1^B db_1 + \Upsilon_2^B db_2,$$

where $\Upsilon_t^B \equiv R_t q_2 \varepsilon_t^B \Upsilon^G / (b_t R_2 \varepsilon_2^D), t = 1, 2.$ Hence, a renewable energy subsidy (lower b_1 or b_2) depresses the current price of oil and causes a weak Green Paradox effect, i.e., R_1 rises and current carbon emissions rise whilst more carbon is locked up, i.e., S falls, only if renewable energy and fossil fuel are gross substitutes, i.e., if $\varepsilon_t^B > 0$. It is easy to demonstrate that the general equilibrium effects of a future renewable energy subsidy (lower b_2), like those of a future carbon tax, are weakened due to a drop in the world interest rate. If renewable energy is a complement to oil, i.e., $\varepsilon_t^B < 0$, subsidizing renewables decelerates oil extraction and global warming.

Proposition 4: *Subsidizing renewable energy accelerates global warming in the short run but locks up more carbon in the long run if it is a gross substitute for fossil fuel, but if it is a gross complement it decelerates global warming and locks up less carbon in the long run. Future subsidies depress the world interest rate and attenuate these effects.*

Papageorgiou et al. (2015) estimate the elasticity of substitution between fossil fuel and renewable energy to be 2 for the electricity generating sector and almost 3 for the non-energy sectors, which suggest that the two types of energy are gross substitutes and thus that renewable energy subsidies will in practice induce weak Green Paradox effects.

5.4. Does Coal Reverse the Green Paradox?

Renewable energy is hardly used, but coal is abundant, cheap and used a lot despite strong adverse effects on global warming. In contrast to oil which is exhaustible, we suppose that coal is in unlimited supply at constant marginal cost and is an imperfect substitute or complement to oil. Denoting coal use with X_t and the user cost of one unit of coal by d_t, we write oil demand as function of the user costs of oil and coal: $R_t = R(q_t, d_t), t = 1, 2.$ We define the cross price elasticity of oil demand with respect to the cost of coal as $\varepsilon_t^X \equiv d_t R_{d_t}(q_t, d_t) / R_t, t = 1, 2.$ Let $\lambda > 1$ indicate the carbon emissions intensity of coal relative to that of oil when using one unit of energy and let d denote the production cost of coal. The user cost of coal is then $d_t = d + \lambda \tau_t.$ One can show that this changes the partial equilibrium effect of the future carbon tax on the current price of oil from $-\Upsilon^G$ in (4) 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, i.e., if $\varepsilon_2^X < 0,$ especially as coal is relatively more carbon-intensive than carbon, $\lambda > 1,$ but also amplifies the drop in exploration investment and cumulative carbon emissions. Conversely, coal attenuates or possibly reverses the weak Green Paradox effect if coal is a gross substitute for oil, i.e., if $\varepsilon_2^X > 0.$ There is reversal of the weak Green Paradox effect 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), but here it also boosts reserves and cumulative carbon emissions.

If there is reversal, p_1 rises and the oil exporter's income is boosted at the expense of coal producers. This has been coined the Grey Paradox (Coulomb and Henriet, 2015)[10] and occurs in our setup 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 5: *The increase in current carbon emissions and drop in cumulative carbon emissions resulting from a future carbon tax are amplified if coal is a gross complement to oil, but weakened or reversed if coal is a gross substitute for oil. The Grey Paradox occurs if coal is cheap and carbon intensive and if coal is a good substitute for oil.*

5.5. Effects of Introducing a Growing Carbon Tax

A balanced introduction of carbon taxes lets the carbon tax grow at the rate of interest. This implies $d\tau_2 = (1+r)d\tau_1 > 0$ and $d\Delta = 0$. If oil reserves do not respond to prices (i.e., $\varepsilon^S = 0$), this policy does not affect the intertemporal pattern of oil extraction, carbon emissions or welfare (see equation (8) with $d\tau_1 = \delta d\tau_2$) as the burden of carbon taxes is fully borne by the oil-exporting country. If the carbon taxes rise at a faster rate than the Hotelling rule suggests, $d\Delta = d\tau_2 - (1+r)d\tau_1 > 0$ and $dq_1 = \left[\Gamma^I - (1+r)\Gamma^G\right] d\tau_1 - \Gamma^G d\Delta$ from equations (6) and (7) or $dq_1 = -\Gamma^G d\Delta < 0$ if $\varepsilon^S = 0$ as from equation (4) we have $\Upsilon^G = \delta\Upsilon^I$. The current consumer price of oil thus falls, current oil extraction rises and global welfare drops by $d\Phi = -\chi dR_1 = -\chi\varepsilon_1^D (R_1 / q_1)\Gamma^G d\Delta$ from equation (12) if $dS = 0$ and $\tau_1 = \tau_2 = 0.$ Hence, global welfare worsens if $d\Delta > 0$ and the carbon tax rises too fast.

If oil supply does respond to prices (i.e., $\varepsilon^S > 0$), then from equations (6)-(7) a balanced carbon tax hike gives the following effect on the current consumer price of oil:

$$(14) \qquad \left.\frac{dq_1}{d\tau_1}\right|^{\substack{\text{balanced} \\ \text{tax hike}}} = \Gamma^I - (1+r)\Gamma^G = \frac{\left[\Upsilon^I - (1+r)\Upsilon^G\right]\Upsilon^D + p_1\Upsilon^S\Upsilon^G}{\Upsilon^D + p_1\Upsilon^G} > 0$$

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

[10] 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. But substitution occurs intertemporally due to changes in the timing of the transition from the phase using only coal to the phase using only oil.

oil extraction. It also cuts the current producer price of oil and thus curbs oil exploration and reserves, since we have $\left.\frac{dp_1}{d\tau_1}\right|^{\text{balanced}}_{\text{tax hike}} = -\frac{\left[1-\Upsilon^I + (1+r)\Upsilon^G\right]\Upsilon^D + p_1(1-\Upsilon^S)\Upsilon^G}{\Upsilon^D + p_1\Upsilon^G} < 0.$ The cuts in current and cumulative carbon emissions lead to a drop in social damages from greenhouse gases and a boost to global welfare.

Proposition 6: *Introducing a hike in carbon taxes that rises at a rate equal to the interest rate is neutral if oil reserves are given. A faster hike induces weak Green Paradox effects and curbs welfare; a slower hike increases global 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 equation (8) and curbs the current rate of oil extraction. It also depresses cumulative extraction and carbon emissions, and cuts social damages from greenhouse gases.*

6. Second-Best Optimal Carbon Taxation

We now turn to second-best aspects of optimal climate policies. We first discuss what the optimal future second-best carbon tax from a global perspective is if the current carbon tax is set sub-optimally low. We then discuss what the optimal future second-best carbon tax is from Industria's perspective. We show that an import tariff component has to be added to the carbon tax, so that some of the rent of the oil-exporting country can be grabbed.

6.1. Second Best from a Global Perspective

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 set 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 7: *If the current carbon tax is pegged too low,* $\tau_1 = \overline{\tau}_1 < \tau_1^P$*, the second-best optimal future carbon tax with credible commitment given this constraint is too low too:*

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

If commitment is infeasible, the second-best optimal future carbon tax is zero.

Proof: The marginal change in global welfare (12′) with $d\tau_1 = 0$ boils down to

$$(12'') \quad d\Phi = \left[\left(\frac{\overline{\tau}_1 - \delta\tau_2}{e} - \chi \right) \frac{R_1}{q_1} \varepsilon_1^D - \left(\frac{\delta\tau_2}{e} - \chi\beta \right) \frac{S}{p_1} \varepsilon^S \right] \Gamma^G d\tau_2.$$

Using $\tau_1^P = (1+\beta)\chi e$ from (9), we can use (12″) together with $d\Phi = 0$ to get (15). To ensure a maximum, we require $\partial \left[\left(\frac{\overline{\tau}_1 - \delta\tau_2}{e} - \chi \right) \frac{R_1}{q_1} \varepsilon_1^D - \left(\frac{\delta\tau_2}{e} - \chi\beta \right) \frac{S}{p_1} \varepsilon^S \right] / \partial\tau_2 < 0.$ □

Recalling Propositions 2 and 6, a postponed or too rapidly rising carbon tax causes, in contrast to the global first-best carbon taxes of Proposition 1[11], an adverse weak Green Paradox effect on short-run carbon emissions. But such a policy also yields a long-run boost to welfare from curbing oil supply and cumulative carbon emissions. The net effect on social damages from greenhouse gases is positive if the price elasticity of oil demand is large and that of oil supply is small. In that case, the future carbon tax is set rather more below the Pigouvian carbon tax to mitigate adverse weak Green Paradox effects if the current carbon tax is fixed much below the Pigouvian tax. With fixed reserves ($\varepsilon^S = 0$), we have $\Delta \equiv \tau_2^{SB} - \overline{\tau}_1 / \delta = \tau_2^P - \tau_1^P / \delta = -\chi e / \delta < 0$ and thus the second-best optimal policy avoids weak Green Paradox effects completely. If the current carbon tax is wholly absent, equation (15) indicates that this is achieved with a future carbon *subsidy* (so that $\tau_2^{SB} = -\chi e / \delta < 0$ 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 but also lock up more fossil fuel and curb cumulative carbon emissions (see Section 5.3). One can demonstrate in an IAM with scarce fossil fuel that the second-best optimal subsidies for renewables exceed whatever might be necessary to internalize market failures in the production of renewables (Rezai and van der Ploeg, 2016).

6.2. Time inconsistency of the global second-best optimal future carbon tax

The global second-best optimal future carbon tax (15) if the current carbon tax is pegged too low requires that policy makers can make a *credible* commitment to this future policy

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[11] The first-best carbon taxes (9) and (10) imply $\Delta = \tau_2 - \tau_1 / \delta = -\chi e / \delta < 0,$ hence Propositions 2 and 6 indicate that there is no weak Green Paradox effect.

change. This implies that private agents in the economy at the beginning of period one believe that the future carbon tax (15) announced by policy makers at that time will indeed be levied in period two with perfect certainty and act accordingly. This is a strong assumption and requires a credible commitment mechanism to ensure that policy makers once period two arrives do not renege and unexpectedly deviate from their announced policies and thereby surprise and falsify expectations of private agents. Indeed, if private agents believe that the announced future carbon tax will be levied, but policy makers decide nevertheless to re-optimize at the beginning of period two, the future carbon tax will be brought back to zero. The reason is that, once period two has arrived, future oil use and carbon emissions, R_2, are completely given by oil reserves minus current oil use, $S-R_1$, which are fixed by that time, and therefore there is no compelling reason for policy makers to tax carbon in period two. If private agents believe that announcements about future carbon taxes are incredible due to this incentive to renege and policy makers cannot credibly pre-commit, it makes no sense for policy makers to try to levy a carbon tax in the future. The second-best optimal future carbon tax without pre-commitment is thus zero.

6.3. Second Best from Industria's Perspective: Clobbering the Oil Exporters

If Industria does not care about the welfare of the oil-exporting country, it maximizes its own welfare $U-\Omega=\Phi-U^*$ and imposes carbon taxes unilaterally at the expense of the oil-exporting country. The optimal carbon taxes 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 we derive these in Proposition 8, suppose that the global first-best carbon taxes are in place. Marginal changes in carbon taxes then leave global welfare unaffected ($d\Phi=0$) but do affect the oil-exporting country's welfare, $U^*=(p_1S-J)/e(\delta)$, as (using equations (6) and (7)) can be seen from

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

Starting from first-best carbon taxes, we have a zero-sum game as the marginal boost to Industria's welfare exactly equals the marginal drop in the oil-exporting country's welfare:

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

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

A. *Grabbing 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 the oil-exporting country to Industria, which is large if the real value of oil reserves (*S/e*) is large. It curbs the oil-exporting country's welfare (U^*), as can be seen from the first term in each of the two square brackets in equation (16), and thus boosts the private component of Industria's welfare (U), as can be seen from equation (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), lower intertemporal terms of trade (δ) and lower unit cost of private utility (e). The oil exporter's welfare thus receives a boost that is proportional to its consumption of future final goods (i.e., $\delta\theta U^*\Gamma^1 = \delta^2 C_2^*\Gamma^1 / e$), which curbs Industria's welfare (17).

In contrast, 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 private utility (e) rises. As a result, the oil-exporting country's welfare erodes (by $\delta\theta U^*\Gamma^G / \Upsilon^D = \delta^2 C_2^*\Gamma^G / e\Upsilon^D$), 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's welfare rises unambiguously if this tax is increased above the first best. But when raising the *current* carbon tax marginally above the first best, the boost to Industria's welfare from putting the oil-exporting country out of business is dampened by the negative intertemporal terms of trade effect.

We now derive the unilateral second-best optimal carbon taxes set by Industria.

Proposition 8: *The unilateral second-best optimal carbon taxes set by Industria consist of a Pigouvian, a pure import tariff, and positive and negative intertemporal terms of trade corrections for the future and current carbon tax, respectively:*

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

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

Proof: See Appendix C.

Expression (19) of Proposition 8 states that the unilateral second-best optimal future carbon tax consists of the *Pigouvian tax* $\tau_2^P = \beta\chi e / \delta$ as given in (10) and a *specific import tariff*, which consists of the two parts in the round brackets in equations (18)-(19).

A marginally higher *future* carbon tax curbs the current oil price, which corresponds to a transfer of pure rents and boosts Industria's welfare at the expense of the oil-exporting country. 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 the oil-exporting country's Hotelling oil rents for a given interest rate (and consumer price of oil). This pure import tariff component is high if the future oil price is high and the oil-exporting country 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 private utility (e) which erodes the oil-exporting country'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 $\theta\delta e U^*\Upsilon^G\Upsilon^S / S\Upsilon^D > 0$) and 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 (i.e., for large S, small Γ^G and small Υ^S).

Expression (18) of Proposition 8 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, p_1 / ε^S, and the positive ITT correction for the future carbon tax, $p_1\theta\delta e U^* \Upsilon^G \Upsilon^S / (\varepsilon^S S \Upsilon^D)$, exactly as discussed for the future carbon tax (19) except that in line with the Hotelling logic ($p_1 = \delta p_2$) these now are the present values of the future pure import tariff and ITT corrections. The fourth component corresponds to the ITT correction for the current carbon tax (i.e., $-\frac{q_1}{\varepsilon_1^D}\frac{\theta\delta e U^*}{R_1}\frac{\Upsilon^G(1-\Upsilon^S)}{\Upsilon^D}$). This correction 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 the oil-exporting country's wealth and lowers Industria's private welfare. This fourth part of the current carbon tax tilts the tax path towards 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; 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 $\Theta / \Theta' = (1+r) / \varepsilon^I$ (see Appendix B). However, if intertemporal substitution becomes very strong ($\varepsilon^I \to \infty$), the ITT effects vanish and equations (18) and (19) boil down to the partial equilibrium expressions $\tau_1^U = \tau_1^P + p_1 / \varepsilon^S > \tau_1^{FB}$ and $\tau_2^U = \tau_2^P + p_2 / \varepsilon^S > \tau_2^{FB}$, respectively,

If oil exploration is not very price sensitive (small ε^S), the pure tariff can dominate the negative ITT effects of the future carbon tax in which case the current carbon tax will be set below the partial equilibrium level, especially if the Green Paradox effect is strong and intertemporal substitution weak: $\tau_1^U \cong \tau_1^P + \frac{p_1}{\varepsilon^S} - \theta\delta e U^* \Upsilon^G \frac{q_1\Theta + q_2}{(C_1 + C_1^*)\Theta\delta\varepsilon^I} < \tau_1^P + \frac{p_1}{\varepsilon^S}$ and $\tau_2^U \cong \tau_2^P + p_2 / \varepsilon^S > \tau_2^{FB}$. The pure tariff part is then large as it is easy to extract revenue.

Strictly speaking, there is an upper limit to the carbon taxes given by expressions (18) and (19), because the taxes cannot be larger than 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 helps in the fight against global warming and highlights the conflicting interests as oil exporters are more put out of business.

6.4. Time inconsistency of the unilateral second-best optimal carbon taxes

The unilateral second-best optimal policies (18) and (19) are time inconsistent just like the global second-best optimal future carbon tax (15). They also require pre-commitment by policy makers to ensure that policy announcements about an announced path of carbon taxes are credible. If private agents wrongly believe that Industria will stick to its promises about the future carbon tax, Industria has an incentive to renege and *push up* future carbon taxes even more once exploration investment has taken place. This is a stark difference with the time inconsistency of the global second-best optimal future carbon tax (15), which is in fact *brought down* to zero if policy makers interested in global welfare were to re-optimize. The point is now that, once exploration investment has been sunk, remaining oil rents are fixed in period 2 and Industria can tax them all away by raising the future carbon tax, τ_2^R, to just under C_2^* / R_2 as, once in period two, the oil-exporting country must sell all remaining oil $S - R_1$ and carbon taxes have become non-distorting. This rent grabbing boosts Industria's welfare and curbs the oil-exporting country's welfare with social damages from greenhouse gases and global welfare unchanged.[12]

7. Third Oil-Importing Countries that Opt Out of Carbon Taxes

Let there now be multiple oil-importing countries: some denoted by K price carbon (called the Kyoto countries) and others denoted by N are third countries that do not price carbon (called the non-Kyoto countries). We then investigate the effects of unilateral carbon taxes set by the Kyoto countries on carbon emissions in the third non-Kyoto countries. If emissions in non-Kyoto countries increase, we have *carbon leakage*. Eichner and Pethig (2011) show the effects of unilateral tightening of present and future carbon caps within the context of a three-country model.[13] Their analysis differs from our analysis in the

[12] Working backwards according to the logic of the principle of dynamic programming, it then follows that Industria has an incentive to tax away all the rents in period one too. As oil exporters realize this, they do not invest in oil exploration at all. In a generalization of our model with recurring oil exploration investment (Appendix A), no commitment leads to under-investment in exploration (cf. Fischer, 1980).

[13] Ritter and Schopf (2014) extend the three-country model of Eichner and Pethig (2011) to stock-dependent extraction costs. Eichner and Pethig (2013) use a two-country model to study flattening of global emissions using unilateral carbon caps. Sen (2015) uses a two-country model and shows that the effect of a cut in unilateral emissions depends on whether the resource is paid at or above marginal cost.

following respects: they study unilateral caps whilst we study the effects of unilateral changes in present and future carbon taxes if a subset of countries conducts no or inadequate climate policy; we use duality theory and get comparative statics results which readily yield welfare effects; they have a fixed supply of oil and a zero supply elasticity whilst we allow for oil exploration and an endogenous supply of oil; and we derive the unilateral second-best optimal carbon taxes to be set by the Kyoto countries as well as the comparative statics effects of small changes in present and future carbon taxes.[14]

With identical, homothetic preferences for the three countries, equilibrium on the world market for oil and the world market for final goods corresponds to the conditions

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

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

where $q_t^K=q_t,\, q_t^N=p_t,\, \tau_t^K=\tau_t>0$ and $\tau_t^N=0,\, t=1,2.$ The solution for p_1 and r is given by equation (6), i.e., $dq_1=\Gamma^I d\tau_1-\Gamma^G d\tau_2$, and equation (7), i.e., $dr=\Gamma^1 d\tau_1-\Gamma^2 d\tau_2$, where the new expressions for $\Upsilon^I,\Upsilon^G,\Upsilon^S$ and Υ^D and thus for $\Gamma^I,\Gamma^G,\Gamma^1$ and Γ^2 are derived in Appendix D. If Υ^D is negative, reversal of the weak Green Paradox effect occurs. This can be viewed as *negative* intertemporal carbon leakage and echoes the result of Eichner and Pethig (2011) that in a three-country context with $\varepsilon^S=0$ unilateral tightening of a future carbon cap does not always necessarily lead to a rise in current carbon emissions and a weak Green Paradox effect. However, we focus at the case $\Upsilon^D>0$ which can be shown to hold if effects are evaluated at a zero future tax ($\tau_2=0$). Eichner and Pethig (2011) find that unilateral tightening of the carbon cap in period one works in the opposite manner to tightening the cap in period two. The equation for the

[14] Non-Kyoto oil-importing 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 two-period, three-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 *K* 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., 2014) and with OPEC as the dominant producer, leakage through the oil market can become negative (Böhringer et al., 2014).

consumer price of oil in period one given in equation (6), $dq_1 = \Gamma^I d\tau_1 - \Gamma^G d\tau_2$, indicates that our model with $\varepsilon^S > 0$ yields the same property as long as Γ^I and Γ^G are positive, which equation (A13) shows is the case if $\Upsilon^D > 0$ holds.

7.1. Carbon Leakage and the Green Paradox

We see from (1′) and (2′) that a *current* carbon tax is partially shifted to the oil-exporting country (evaluated at zero taxes, $-1 < \partial dp_1 / \partial\tau_1 = -(1-\Upsilon^I) = -R_1^K \varepsilon^D / S(\varepsilon^D + \varepsilon^S) < 0$), The resulting fall in the current producer price of oil is large and the increase in the consumer price of oil is small if oil demand of the Kyoto countries is large compared to that of the non-Kyoto countries. In that case, the drop in current oil demand and carbon emissions in the Kyoto countries is relatively small. However, the increase in current oil demand and current carbon emissions in the non-Kyoto countries is relatively large and the Hotelling logic indicates that there is also a relatively large increase in future oil demand and emissions in both the Kyoto and non-Kyoto countries. This implies that then there is large and positive carbon leakage, both today and in the future.[15]

A *future* unilateral carbon tax is also partially shifted to the oil exporter ($-1 < \partial p_1 / \partial\tau_2 = -\Upsilon^G = -R_2^K \varepsilon^D / S(\varepsilon^D + \varepsilon^S) < 0$), especially if the Kyoto countries *K* use relatively more oil and emit relatively more carbon than the non-Kyoto countries *N*. This weak Green Paradox effect is attenuated in general equilibrium by the fall in the world interest rate (as $\Gamma^G < \Upsilon^G$). Hence, the consumer price of oil in the Kyoto countries 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 the Kyoto countries is attenuated by a fall in the world interest rate but the adverse effects are reinforced by intertemporal and contemporaneous carbon leakage as oil use and carbon emissions by the non-Kyoto oil-importing countries rise both now and in the future. Still, the increase in current carbon emissions by the Kyoto countries and in current and future emissions by the non-Kyoto oil-importing countries are not fully offset by the Kyoto countries’ cut in future carbon

[15] If there is an internationally mobile clean factor that is in fixed supply and *K* 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 *K*, *N* becomes richer and thus pursues a more stringent climate policy (Copeland and Taylor, 2005).

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 current carbon emissions by the Kyoto and non-Kyoto oil-importing countries and the increase in future carbon emissions by non-Kyoto countries, cumulative carbon emissions must fall. The condition for introducing a future carbon tax by the Kyoto countries to improve global welfare and cut social damages from greenhouse gases can readily be shown to be $R_1^K \varepsilon_1^{KD} + R_1^N \varepsilon_1^{ND} < \beta S \varepsilon^S$. The adverse weak Green Paradox and adverse intertemporal carbon leakage effects, the size of which is measured by $R_1^K \varepsilon_1^{KD}$ and $R_1^N \varepsilon_1^{ND}$, respectively, must thus be less than the beneficial effects of trapping more fossil fuel in the earth, the size of which is measured by $\beta S \varepsilon^S$ and increases in the price elasticity of oil supply and decreases in the ecological discount rate, for global welfare to rise and social damages from greenhouse gases to fall.

The effect of a future unilateral carbon tax by the Kyoto countries on their welfare net of social damages from greenhouse gases is (see Appendix D): [16]

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

The first term in square brackets indicates the negative effect of the future carbon tax on social damages from greenhouse gases. The second term is the beneficial rent-grabbing effect which results from the drop in the producer oil price on the welfare of the Kyoto countries and goes at the expense of the welfare of the oil-exporting country. Note that the welfare of the third non-Kyoto oil-importing countries also increases. The third term corresponds to the ITT effect which results from the drop in the world interest rate and the associated rise in the unit cost of private utility on the welfare of the Kyoto countries. This term is proportional to the future trade balance of the Kyoto countries, so that the effect on welfare is positive if these countries have a future trade surplus and negative if they have a future trade deficit with the rest of the world. The tariff component thus makes a future carbon tax more attractive from the Kyoto countries' perspective than purely ecological

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[16] Equation (20) for the three-country model extends equation (13′) for the two-country model discussed in Section 4.1, since $\theta \delta U^*$ in equation (13′) equals $\delta^2 C_2^* / e = \delta^2 \left\{ F(R_2) - C_2 \right\} / e$ as from the future goods market equilibrium condition the oil-exporting country's future consumption must equal Industria's future trade balance in the two-country model.

considerations, and the ITT effect makes it even more (less) attractive if the Kyoto countries have a future trade surplus (deficit) with the rest of the world.

Proposition 9: *The fall in future carbon emissions in countries that unilaterally announce the introduction of a future carbon tax is partially offset by higher current emissions in those countries (weak Green Paradox) and by higher future and current emissions of non-Kyoto countries (contemporaneous and intertemporal carbon leakage). Social damages from greenhouse gases fall 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 countries and the oil-exporting country, unilateral welfare of Kyoto countries 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.*

7.2. **Second Best: Global Altruism**

If all oil-importing countries participate in Kyoto and price carbon, the globally first-best optimal carbon taxes are uniform throughout the globe and given by equations (9) and (10). However, if there are non-Kyoto oil-consuming countries which do not price carbon or peg carbon taxes sub-optimally low, i.e., $\tau_t^N = \bar{\tau}_t^N < \tau_t^P,\ t = 1, 2,$ the Kyoto countries' carbon taxes that maximize global welfare are referred to as 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 equation (A18) in Appendix D for the general equilibrium expressions):

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

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

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

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

The globally altruistic carbon taxes set by the Kyoto countries are second best as the non-Kyoto countries price carbon too low, hence these second-best carbon taxes are set to a lower value than the first-best taxes. The current carbon tax is lower if more of its burden is shifted to the oil-exporting country (low Υ^I); the future carbon tax is lower if the weak Green Paradox effect is stronger (high Υ^G). From equations (21) and (22) we also see that the downward biases in globally altruistic carbon taxes are bigger if the oil consumed by non-Kyoto countries is large relative to the oil consumed by Kyoto countries and the non-Kyoto countries price carbon much lower than the social cost of carbon.

7.3. 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 on top of the carbon taxes to capture some of the rents of the oil-producing countries. The Kyoto countries' carbon taxes that maximize $U^K - \Omega = \Phi - (U^N + U^*)$ are referred to as the *unilateral second-best optimal* carbon taxes. Abstracting from intertemporal terms of trade effects, these are (see equations (A20)-(A21) in Appendix D for the general equilibrium expressions):

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

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

These unilateral second-best carbon taxes exceed the globally altruistic taxes, and by a larger amount if the oil-exporting country bears most of the burden (as can be seen from inspecting equations (23) and (24) and the expression for Λ). 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 the oil-exporting country and the non-Kyoto oil-importing countries is then larger. These taxes exceed the Pigouvian taxes if the rent-grabbing effects dominate the free-riding effects of the non-Kyoto countries. The ITT effects for the future carbon tax would add positive terms to equations (23) and (24) and the ITT effects for the current tax a negative term to equation (23) (cf. Proposition 8).

Proposition 10: *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 exporters bear a lot of the burden, the weak 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 carbon 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. Conclusion

Our core results are summarized in Table 1. There may be political imperatives to postpone current carbon taxation rather than levying the first-best optimal carbon taxes. Introducing a postponed (or a too rapidly rising) carbon tax then induces weak Green Paradox effects. In general equilibrium this is mitigated by a drop in the world interest rate, especially if intertemporal substitution is weak (compare second and first columns of Table 1). We have shown that introducing a future carbon tax curbs social damages from greenhouse gases and boosts global welfare if the price elasticity of oil supply is large and that of oil demand is small and the ecological discount rate is small. The effect of putting fossil fuel producers out of business then dominates the effect of accelerated global warming. If this is not the case, social damages increase and global welfare falls, thus yielding a strong Green Paradox. Even with a strong Green Paradox, the import tariff and intertemporal terms of trade effects of a postponed carbon tax can if they are strong enough lead to a net boost to the welfare of the oil-importing countries. An asset holding subsidy has opposite effects to a postponed carbon tax and is thus effective in putting oil producers out of business and fighting global warming if the latter induces a strong Green Paradox (third row of Table 1). Since renewables are typically a gross substitute for fossil fuel, subsidizing them accelerate global warming in the short run but locks up more carbon and cuts ultimate global warming (fourth row).

If there are oil-importing countries that do not pursue climate policy, the fall in future carbon emissions in the Kyoto countries that unilaterally announce a future carbon tax is partially offset by higher future and current emissions of non-Kyoto countries as a result of contemporaneous and intertemporal carbon leakage, respectively. Social damages from greenhouse gases fall if the price elasticities of current and future oil demand for the Kyoto countries are small, the price elasticity of oil supply is large and the ecological discount rate is small. If this is not the case, there is a strong Green Paradox. Welfare of oil- importing countries can then nevertheless increase due to the rent-grabbing effect of a future carbon tax at the expense of oil exporters.

Table 1: Effects of Climate Policies relative to Business as Usual

	First-best carbon taxes	Second-best: postponed carbon taxes	Second-best: asset holding tax	Second-best: future renewable subsidy
Current world price of oil:				
for producer	–	–	+	–
for consumer	+	–	+	–
Future world price of oil:				
for producer	–	–	+	–
for consumer	+	+	+	–
World interest rate	+	–	+	–
Carbon emissions:				
current	–	+	–	+
cumulative	–	–	+	–
social damages	–	+/–	–/+	+/–
Welfare:				
Industria - private	+	+/–	–/+	+/–
oil exporter – private	–	–	–	–
global – private	+	0	0	0
global – total	+	–/+	+/–	–/+
Third non-Kyoto countries:				
current carbon emissions	+	+	–	+
future carbon emissions	+	+	–	+
welfare	+	+	–	+

Key: The last column assumes that renewable energy is a gross substitute for fossil fuel.

Apart from policy reform, we have investigated the second-best optimal future carbon tax in situations that current carbon taxation is inadequate and commitment is feasible. This future tax is then set below the Pigouvian social cost of carbon to limit weak Green Paradox effects. If supply is not very sensitive to prices, the optimal response may even be to subsidize carbon. If policy makers cannot commit to their announcements about future climate policies, the global second-best optimal carbon taxes are zero. If oil-importing countries are interested in their own welfare instead of global welfare and can pre-commit, they increase their carbon taxes with an import tariff component. The unilateral second-best optimal current and future carbon taxes also include negative and positive intertemporal terms of trade corrections, respectively. These policies are also time inconsistent and thus require pre-commitment too. Reneging implies that future carbon taxes are pushed up once exploration investment has taken place.

With third non-Kyoto countries setting carbon prices sub-optimally low, the globally altruistic second-best carbon taxes set by the Kyoto countries are below the first-best taxes especially so if non-Kyoto countries consume a lot of oil compared to the Kyoto countries. For the current carbon tax this is especially so if more of its burden is shifted to oil producers and for the future carbon tax if the weak Green Paradox effect is stronger. If the Kyoto countries unilaterally maximize their own welfare, their carbon taxes include a tariff to capture some of the oil rents which is larger if oil producers bear more of the burden. These unilateral second-best carbon taxes exceed the Pigouvian taxes if these rent-grabbing effects dominate the free-riding effects of the non-Kyoto oil-importing countries.

We conclude with the remark that a good understanding of second-best issues is crucial for understanding why climate policy does or does not work in practice. We have focused on *exogenous* political constraints on the set of policy instruments. Future work must *explain* the political constraints that lead national governments to shy away from current carbon taxation or use renewable subsidies instead of using the full range of instruments.

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Appendix A: Investment in Physical Capital and Recurring Oil Exploration

Here we sketch how 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 decreases in first-period exploration efforts if it is harder to explore if a lot of oil has already been explored (i.e., $A_{J_1}(J_2, J_1) \le 0$), which is akin to the 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 $(1+r)p_1 A_{J_2}(J_2, J_1) = 1.$ 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 3-6 are unaffected 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 2 is curbed. Van der Meijden et al. (2015) confirm this more generally and also show that capital market repercussions can even 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 taxation curbs social damages from greenhouse gases more easily than in Proposition 2, because second-period exploration investment falls too.

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

$$d(U + U^*) = \frac{q_1 dR_1 + \delta q_2 dR_2 + \left[F(R_2) - J_2\right] d\delta - dI - dJ_1 - \delta dJ_2}{e(\delta)}$$

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

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 (11) as before and global welfare by

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

The first-best optimal carbon taxes (9)-(10) in Proposition 1 are thus unaffected. From $U^*=\left[p_1(S+A)-J_1-\delta J_2\right]/e(\delta),$ we get the change in the oil exporter's welfare:

(A4) $$dU^*=\frac{S+A}{e}(dq_1-d\tau_1)+\delta\theta U^* dr=$$
$$\left[\underbrace{-\frac{S+A}{e}(1-\Gamma^I)}_{-ve}+\underbrace{\delta\theta U^*\Gamma^1}_{(+ve)}\right]d\tau_1-\left[\underbrace{\frac{S+A}{e}\Gamma^G+\delta\theta U^*\Gamma^2}_{+ve}\right]d\tau_2.$$

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

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

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

This extends (18)-(19) in Proposition 8. Exploring a further amount of oil reserves curbs the positive ITT adjustment for the future carbon tax whereas the strengthening of the weak Green Paradox due to investment in physical capital curbs both the ITT effects.

Appendix B: Power and Logarithmic Present-Value Utility Functions

The power present-value utility function $U(C_1,C_2)=\left[\frac{(1+\rho)C_1^{1-1/\varepsilon^I}+C_2^{1-1/\varepsilon^I}}{(2+\rho)(1-1/\varepsilon^I)}\right]^{1/(1-1/\varepsilon^I)}$ has a constant elasticity of intertemporal substitution $\varepsilon^I>0$ where $\varepsilon^I\neq1$ 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 $U=C_1^{\frac{1+\rho}{2+\rho}}C_2^{\frac{1}{2+\rho}}$ 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 8

Using equations (12′) and (16), we see that the marginal change in Industria's welfare is

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

The optimality conditions for the unilateral carbon taxes are

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

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

Multiplying (A8) with Γ^G and (A9) with Γ^I, adding the two equations, and simplifying, we get $-\delta\theta U^*\Gamma^1\Gamma^G+\left[1-\frac{1}{p_2}(\tau_2-\tau_2^P)\varepsilon^S\right]\frac{S}{e}\Gamma^G+\delta\theta U^*\Gamma^2\Gamma^I=0$ or $\left[1-\frac{1}{p_2}(\tau_2-\tau_2^P)\varepsilon^S\right]\frac{S}{e}\Gamma^G$ $+\delta\theta U^*\Gamma=0,$ 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 8.

Rewriting (A9) as $\frac{S}{e}+\frac{R_1}{q_1 e}(\tau_1-\tau_1^P)\varepsilon_1^D+\delta\theta U^*\frac{\Gamma^2}{\Gamma^G}=\left(\frac{1}{p_2}\frac{S}{e}\varepsilon^S+\frac{\delta R_1}{q_1 e}\varepsilon_1^D\right)(\tau_2-\tau_2^P)$ $=\left(\frac{1}{p_2}\frac{S}{e}\varepsilon^S+\frac{\delta R_1}{q_1 e}\varepsilon_1^D\right)\left(1+\frac{\theta\delta eU^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\right)\frac{p_2}{\varepsilon^S}$ where we used equation (19). This gives

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

(A10) $$\tau_1^P+\frac{p_1}{\varepsilon^S}+\frac{q_1 S}{R_1\varepsilon_1^D}+\left(\delta+\frac{q_1 S}{R_1\varepsilon_1^D}\frac{\varepsilon^S}{p_2}\right)\frac{\theta\delta eU^*}{S}\frac{\Gamma^2\Upsilon^S}{\Gamma^G}\frac{p_2}{\varepsilon^S}-\frac{q_1 S}{R_1\varepsilon_1^D}\left(1+\frac{\theta\delta eU^*}{S}\frac{\Gamma^2}{\Gamma^G}\right)=$$

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

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

(A11) $$\tau_1^U=\tau_1^P+\frac{p_1}{\varepsilon^S}+\theta\delta eU^*\frac{p_1}{S\varepsilon^S}\frac{\Upsilon^G\Upsilon^S}{\Upsilon^D}-\theta\delta eU^*\frac{q_1}{R_1\varepsilon_1^D}(1-\Upsilon^S)\frac{\Upsilon^G}{\Upsilon^D},$$

which corresponds to expression (18) in Proposition 8. To ensure a maximum, we require that the second-order condition of optimality is satisfied. □

Appendix D: Three-Country Analysis

Tax Incidence and possible reversal of the weak Green Paradox effect

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

(A12) $0<1-\Upsilon^I=R_1^K\varepsilon_1^{KD}/q_1^K\Lambda^{OME}<1$ and $0<\Upsilon^G=R_2^K\varepsilon_2^{KD}/q_2^K\Lambda^{OME}<1,$

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

(A13) $0<1-\Upsilon^S=\left(\Theta+\frac{q_2}{p_1}\right)R_1^K\varepsilon_1^{KD}/\Lambda^{GME}<1,\quad \Upsilon^D=\left[(C_1^K+C_1^N+C_1^*)\Theta'(r)-\tau_2\delta R_2^N\varepsilon_2^{ND}\right]/\Lambda^{GME}.$

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 $\tau_2 R_2^N \varepsilon_2^{ND} / p_1$, low intertemporal substitution and elastic enough oil demand, Υ^D and Γ^G become negative which reverses the weak Green Paradox effect (i.e., negative intertemporal carbon leakage) in case of a future carbon tax. Effectively, part of the emission reduction in the Kyoto countries leaks away to the non-Kyoto oil-importing countries instead of to the present. We focus at the case where Υ^D and Γ^G are positive. A sufficient condition for this is that $\tau_2 = 0$ holds 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

(A14) $d(eU^*) = Sdp_1$ and $d(eC^N) = -(R_1^N + R_2^N)dp_1 + \left[F(R_2^N) - p_2 R_2^N\right]d\delta,$

the marginal change in the total welfare of the oil-exporting and non-Kyoto countries is

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

The first terms in the square brackets correspond to the damage to the oil-exporting country net of the gain to the non-Kyoto countries of a drop in the real price of oil caused 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 $d(U^K + U^N + U^*) = 0$, 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 $d(U^K - \Omega) = -d(\Omega + U^N + U^*)$.

The marginal change in global welfare is given by

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

The first-best and globally altruistic carbon taxes

From equation (A16) we see that with no non-Kyoto countries, all countries across the globe set the same carbon taxes and thus the first-best optimal carbon taxes equal the Pigouvian taxes (i.e., the social costs of carbon). With non-Kyoto countries setting non-zero carbon taxes too, the marginal change in global welfare is

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

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 $dq_t^i = dp_t + d\tau_t^i, t = 1,2, i = K, N,$ $dp_2 = p_1 dr + (1+r)dp_1,$ (6) and (7), we get from equation (A17) the first-order conditions for the Kyoto countries:

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

and

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

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

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:

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

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

We suppose that the second-order optimality conditions for this problem are satisfied, so that the carbon taxes for the Kyoto countries (A18) indeed correspond to a maximum.

The unilateral second-best optimal carbon taxes

We use (A15) and the first-order conditions for the Kyoto countries to get the unilateral second-best optimal taxes that maximize $U^K - \Omega = \Phi - (U^N + U^*)$, 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 obtain the following expressions for the Kyoto countries' unilateral second-best optimal carbon taxes:

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

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

To ensure that the taxes (A20) and (A21) indeed yield a maximum for the welfare of the Kyoto countries, we suppose that the second-order optimality conditions are satisfied.

Special case: no intertemporal terms of trade effects

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

$$\text{(A22)} \quad \tau_1^{K,GA} = \tau_1^P + \frac{\delta \left[(1+r)\Upsilon^{G,K} - 1 \right] a_1 - (1 - \Upsilon^{I,K}) a_2}{\frac{R_1^K}{q_1^K} \varepsilon_1^{KD} (R_1^N \varepsilon_1^{ND} + R_2^N \varepsilon_2^{ND} + S\varepsilon^S)} p_2 \Lambda^{OME,K} \quad \text{and}$$

$$\text{(A23)} \quad \tau_2^{K,GA} = \tau_2^P - (\Upsilon^{I,K} a_2 + \Upsilon^{G,K} a_1) p_2 \Lambda^{OME,K} / \left[R_2^K \varepsilon_2^{KD} (R_1^N \varepsilon_1^{ND} + R_2^N \varepsilon_2^{ND} + S\varepsilon^S) / q_2^K \right].$$

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 expressions (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 and expressions (23) and (24) for the unilateral second-best optimal carbon taxes.