Who Gains and Who Loses by Fossil-Fuel Taxes and Caps: Importers Versus Exporters

By

Jon Strand
World Bank
Development Economics Group
Washington DC 20433

and

Department of Economics
University of Oslo

e-mail: jstrand1@worldbank.org

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Abstract

We study tax and cap policies for reducing global fossil-fuel consumption when fossil-fuel consumer and producer countries are distinct. The total fuel tax is then the sum of a producer/exporter and a consumer/importer tax. Tax policy is driven by a global externality caused by fossil-fuel consumption, and by a strategic motive. Each of the two groups can impose taxes or caps; and each group benefits from taxing, and loses by not taxing. With *full policy coordination within and between the two groups*, the total fuel tax is Pigovian, but it matters to exporters and importers how tax revenues are shared. A global cap-and-trade scheme to limit carbon emissions from fossil fuels can also implement this solution. When the exporter and importer groups *coordinate their policies within but not across groups*, the total tax is set *above* the Pigou level. A cap-and-trade scheme then *strictly worse* for importers than setting a tax. The reason is that exporters' optimal response to a quota is to set a higher tax, leaving importers worse off.

Key words: fossil-fuel taxes; greenhouse-gas emissions; Pigou taxation; optimal tariffs; cap-and-trade schemes; Nash Equilibrium.

JEL classification: H23; Q31; Q41; Q54; Q58.

> "Rather than complain that the Middle East is getting so much oil money, we can put some of the money into America's pockets (by taxing petroleum)." (From interview with Kenneth Rogoff, previous IMF Chief Economist, in *Foreign Policy*, January 8, 2008.)

1. Introduction

In this paper, we discuss the following questions: What levels of fossil-fuel taxes would countries that primarily consume fossil fuels, and countries that primarily produce such fuels, set, with full tax coordination *within*, but not *between,* the two groups? What are implications for welfare, in aggregate and for each group? What are implications for one group of not taxing fossil fuels? And does it matter whether fossil-fuel consumption is constrained through taxes, or through a cap-and-trade scheme? Such issues are highly relevant in the context of greenhouse gas (GHG) emissions control, and for energy security of importers.[1] There is today a sharp divide between producing and consuming countries, at least in the oil market, making the distinction between exporters and consumers highly relevant. The OECD and high-growth Asian economies are large importers; OPEC and the former Soviet Union large exporters. These two blocks have sharply opposing interests in the oil market, as well as the gas market. Within each block there is substantial cooperation, which may easily be thought to expand further. OPEC already provides a high degree of exporter coordination, which may be strengthened if importers find it advantageous to cooperate in their pricing of fossil fuels. The latter may become reality as soon as the main fossil-fuel consuming countries initiate more serious coordinated action to limit GHGs.

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[1] The approach in this paper is more directly relevant to oil market than to that for the other fossil fuels, coal and natural gas; these fuels tend to be consumed more in the country of production, and market structure is more complicated, in particular for natural gas which often involves long-run price contracts due to heavy specific infrastructure investments in pipelines.

Given that consumer and producer countries for fossil fuels are separate, the overall fuel tax, relevant for controlling carbon emissions, is the sum of taxes set by producer and consumer countries. Fossil-fuel taxes then play two roles. One is to correct for global externalities caused by carbon emissions.[2] In a world where producers and consumers are one, the optimal worldwide tax is Pigovian, set to equal the global marginal emission cost.[3] A second, strategic, motivation for taxing petroleum however enters when importers and exporters have conflicting interests. It then matters greatly to the two groups how taxes are divided among them: When consumer countries tax more, a greater share of market rent flows to these countries and a smaller share to producer countries; and vice versa when producer countries tax more. This in turn strongly affects the incentives to tax, for each block.

To discuss these issues we consider a highly stylized model where fossil fuels are demanded by atomistic consumers, and supplied by atomistic producers, demand and supply functions are linear in the fuel price, producer countries do not consume fossil fuels, while consumer countries do not produce them. Fuel-exporting countries are subject to supply from atomistic producers, but can set the export fuel tax and thus the export price.[4] We first (in Section 2) derive the overall efficient solution, under full cooperation and coordination of policies both within and across the two blocks. Section 3 then studies the non-cooperative

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[2] We are here ignoring the local externalities caused by petroleum consumption, which can in principle be corrected for by taxes and regulations in the countries themselves.

[3] This abstracts from the difficult problem of agreeing on a correct value of the externality. We here also abstract from problems due to the environmental problem being due to a stock externality, while emissions are a current flow.

[4] This approach abstracts from many of the specifics of considering fossil fuels as an exhaustible resource; see Newbery (2005) and the discussion below.

Nash equilibrium (NE) where policies are coordinated within each blocks, but not across blocks. The outcomes under these two possible equilibiria are compared to the no-tax solution, in Section 4, which perhaps best describes the actual situation today.[5] We also consider, in Section 5, the Stackelberg solution where the importer is the leader in fossil-fuel tax policy, and the exporter is a follower. In Section 6 we study cases where importing countries, instead of taxing, may limit their fossil-fuel consumption by setting a cap on fuel imports, corresponding to an emissions quota for greenhouse gases.

Section 7 further illustrates the welfare effects for importer and exporter countries of the various solutions, by studying two fully parameterized (but highly stylized) numerical examples. We there include a discussion of welfare implication for each group (consumer or producer countries) of failing to tax when the other party taxes optimally; and for importers, of choosing cap-and-trade solutions instead of an optimal tax. While stylized, these examples realistically illustrate of how welfare effects for the two groups can be ranked, under different solutions, important for practical policy. Section 8 concludes the analysis. We here point out that most of the main results are likely to survive a variety of model changes in the direction of more realism.

Most existing literature on fossil-fuel taxation considers environmental and strategic motivations separately. Much of this literature considers petroleum as non-renewable, and with competitive price time path subject to Hotelling's (1931) rule. Dasgupta and Heal (1979) showed that a proportional tax on the resource rent (with no extraction costs, the resource price) need not affect the optimal extraction profile of producers. Newbery (1976),

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[5] However, to the extent that OPEC directly affects the oil price, it may in the context of our model be relevant to consider this as a producer tax.

and later Karp and Newbery (1991a, b), showed that the solution can be complex and involve time inconsistency problems, as announced tax plans are not always credible.[6]

Taxing petroleum for environmental purposes is studied by many including Jorgenson, Slesnick and Wilcoxen (1992), Nordhaus (1993) and Nordhaus and Yang (1996); and with exhaustibility considerations added, by Sinclair (1992, 1994) and Ulph and Ulph (1994, 1997). The latter papers find the optimal petroleum tax to be either above or below the Pigovian level, and increasing or falling over time. In Ulph and Ulph (1994), the tax falls when the price path nears the backstop price (and the market price then does most of the "work" of deterring consumption). A more recent focus is on interactions between fossil-fuel taxes and GHG emissions abatement. Goulder and Mathai (2000) show that the optimal tax is then likely to rise over time. Hoel (1996) and Rosendahl (2004) show that optimal carbon taxes may differ across countries and sectors, due to trade and technological considerations. Keen and Strand (2007) discuss an optimal tax mix comprising of both an ad valorem tax (on goods utilizing fossil fuel inputs) and a specific fuel tax, with weights depending e g on governments' revenue concerns versus their externality concerns. Zhang (1997) studies producer petroleum taxes to extract maximum rent. Geroski, Ulph and Ulph (1987) consider market power (by OPEC) explicitly. None of these contributions however considers strategic taxation by consumer countries, or for distributing rents between consumers and producers.

The work most closely related to ours considers strategic aspect of fossil-fuel taxation. Bergstrom (1982) considered strategic tax setting by independent petroleum importing countries, facing either a competitive petroleum supply or a monopoly exporter, while

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[6] See also Newbery (2005), who also derives estimates of optimal tariffs on petroleum, under different assumptions about price elasticities of demand for petroleum.

ignoring environmental costs and the possibility that exporters may tax.[7] Bergstrom found that the full burden of an importer excise tax then falls on the exporter.[8] Similar results were found by Karp and Newbery (1991b), and Amundsen and Schöb (1999); in the latter paper the strategic and environmental tax motivations are combined, and some conclusions similar to ours; e g that rent capture arguments may lead to optimal taxes in excess of Pigou taxes for fuel importers. More recently, Liski and Tahvonen (2004) have studied what is in effect a dynamic version of our Nash Equilibrium model in Section 3, but where only importers tax fossil fuels. They derive results similar to ours for this case, in particular, the optimal tax set by importers exceeds the Pigou tax when the environmental externality is "small", but is below this level when the externality is sufficiently "great". They also show that when the environmental problem is "small", and at the same time leads the importer group to adopt a coordinated fossil-fuel tax policy, the environmental "problem" can turn out to be gainful for importers; a similar result can be shown here, as commented in the final Section 8 below.

2. Optimized world welfare

We start with a basic case where a unified world government sets fossil-fuel taxes to maximize world welfare. Consider a stylized world economy where consuming countries do not supply and supplying countries do not consume fossil fuels. Heroically, utility from

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[7] Bergstrom however does consider the strategic relationship between taxes set by importers and a monopolistic exporter, thus leading up to an analysis akin to ours in section 5.3 below.

[8] This result is largely due to the combined assumptions of exhaustibility of the fossil-fuel resource and zero extraction cost, which leads to a shift in the equilibrium future price path for the resource when an importer tax is imposed. In our formulation, extraction costs play a key role, while exhaustibility is ignored.

petroleum consumption can be aggregated into a quadratic utility function in overall world fossil-fuel consumption, R,[9]

(1) $$W_1 = R - \frac{1}{2}\gamma R^2 - pR - c_1 R,$$

where γ is a positive coefficient, p is the fossil-fuel price facing importing countries, and c_1 is the negative (climate-related) externality associated with petroleum consumption for the consumer country group.[10] In importing countries, fossil fuels are demanded by many small and competitive agents, who maximize[11]

(2) $$V_1 = R - \frac{1}{2}\gamma R^2 - (p+t)R$$

with respect to R, yielding the first-order condition

(3) $$1 - p - t = \gamma R$$

On the producer side, consider a single country (or unified country group) with the following function representing welfare, related to petroleum production and use:

(4) $$W_2 = \Pi_2 + sR - c_2 R.$$

Petroleum producers' profits are given by

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[9] This assumption in effect embeds additional assumptions that will not be discussed further here; in particular, all consumers of petroleum, in all consumer countries must be facing a uniform petroleum price, and all must behave atavistically in their respective markets. We are also, equally heroically, disregarding all distributional concerns, within or between countries.

[10] When c_1 represents the greenhouse-gas related damage, it will typically involve a stock externality, as there will be an externality cost due to current emissions for all future periods. Such an interpretation of c is here permissible given that climate effects are linear in emissions, and with an infinite horizon and constant interest (and discount) rate. Then, in addition, damages from future emissions will be independent of the stock of accumulated GHG emissions, at any given time.

[11] With n countries and N demanders of fossil fuels in each country, the externality effect as a result of ones own demand for fossil fuels, will be of the order c/nN, which vanishes when N is large.

(5) $$\Pi_2 = (p-s)R - p_0 R - \frac{1}{2}\phi R^2 ,$$

where sR is income from the proportional producer excise tax, and c_2R represents negative emissions externalities for the exporter. Fossil fuels suppliers are atomistic, maximizing profits taking the producer price, p-s, as given. This yields the (linear) supply function

(6) $$p = p_0 + s + \phi R ,$$

where $\phi > 0$ represents the (inverse) supply sensitivity of petroleum output.[12] Arguably, c_2 is small relative to c_1; in today's world petroleum consumer countries are, overwhelmingly, those concerned with the possible damage due to carbon emissions. From (3) and (6), the equilibrium export price, p, is found as a function of s and t, as follows:

(8) $$p = \frac{\gamma}{\gamma+\phi}(p_0 + s) + \frac{\phi}{\gamma+\phi}(1-t) .$$

Net world welfare from petroleum production and consumption is found adding (1) and (4), yielding

(9) $$W = R - p_0 R - \frac{1}{2}\gamma R^2 - \frac{1}{2}\phi R^2 - c_1 R - c_2 R .$$

Maximizing (9) with respect to R, the tax instruments implementing this solution are now found as[13]

(11) $$z = c_1 + c_2 ,$$

simply the Pigou tax. This is the globally efficient petroleum tax, but the split of taxes between a producer-country tax (s) and a consumer-country tax (t) is indeterminate. One way

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[12] The supply function (6) is derived in Appendix 1 below.

[13] See Appendix 1 for a derivations of all analytical solutions in this section.

to determine this split is to consider the symmetric Nash bargaining (NB) solution between importers and exporters, with the no-trade solution as status-quo point. This yields:

$$t = c_1 - \frac{\gamma - \phi}{2} R^*, s = c_2 + \frac{\gamma - \phi}{2} R^* , \tag{16}$$

where R* is first-best fuel consumption. In particular, when Φ = γ (demand and supply are equally sensitive to price), the NB solution prescribes t = c_1, and s = c_2: taxes are split in proportion to externalities suffered, for the two country groups. In more general cases, the group with the more flexible demand/supply response to price is to set its tax rate higher than its respective externality, while the other party sets its tax lower.

3. The Nash equilibrium (NE) solution

Consider now a *non-cooperative* model where each of the two blocks sets its tax optimally from its own point of view, taking the other group's tax as given. Otherwise the model is as in Section 2. For importers, the only instrument is a fossil-fuel tax on which they agree. Maximizing W_1 with respect to t, taking (3), (8) and s as given, is found to yield[14]

$$t = \frac{\gamma + \phi}{\gamma + 2\phi} c_1 + \frac{\phi}{\gamma + 2\phi} (1 - p_0 - s) . \tag{19}$$

Producer countries maximize W_2 with respect to s, taking (6), (8), and t as given, resulting in the following solution for s:

$$s = \frac{\gamma + \phi}{2\gamma + \phi} c_2 + \frac{\gamma}{2\gamma + \phi} (1 - p_0 - t) \tag{25}$$

(19) and (25) reveal that t and s are *strategic substitutes*: when t (s) is higher, s (t) is smaller but by less. Intuitively, a higher s implies that there is less to gain for importers by raising

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[14] See Appendix 2 for more discussion of analytical results for the NE case.

taxes as there is less net rent to be extracted per unit of importer tax. s and t are now found solving (19) and (25) simultaneously:

$$t = \frac{(2\gamma + \phi)c_1 + \phi(1 - p_0 - c_2)}{2(\gamma + \phi)}. \tag{29}$$

$$s = \frac{(\gamma + 2\phi)c_2 + \gamma(1 - p_0 - c_1)}{2(\gamma + \phi)} \tag{30}$$

From (29)-(30), each of s and t is a weighted sum of two terms, an externality cost term (c_1 for consumers, c_2 for producers), and an "optimal tariff" term. The "optimal tariff" terms matter for each party as a monopolistic (for s) or monopsonistic (for t) element in supply or demand. s increases in c_2 and falls in c_1, and vice versa for t. Note that s is affected relatively more by strategic factors when γ is greater, and fuel demand is relatively insensitive to price. Exporting countries may the extract more rent by increasing the tax component in the supply price. t is, correspondingly, affected more when ϕ is greater (and importing countries can increase the importer tax without prompting a large negative supply response).

The aggregate tax, z = s+t, given by

$$z = \frac{1}{2}(c_1 + c_2 + 1 - p_0). \tag{31}$$

z simply equals half of the Pigou rate ($c = c_1+c_2$), plus half of $1-p_0$ (in the example, equal to consumers' willingness to pay for the first unit of fuel). A meaningful solution requires $1-p_0$ greater than c (perhaps substantially so); thus $z > c$. The NE fuel tax thus exceeds the Pigou level.[15] Intuitively, the strategic motive for taxing turns out to overwhelm the externality-related motive, with the particular parameterization assumed here (linear demand and supply

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[15] This conclusion is obviously contingent on $1-p_o > c$. With a more general formulation of the demand function, and with extremely high this need not hold.

functions). While not entirely general, we argue that the case considered is realistic, in a climate policy context today.[16]

4. No taxes

A benchmark for comparison to the optimal and NE tax solutions is the no-tax case (s=t=0). This may correspond more closely to today's actual situation. Taxation is then, obviously, sub-optimal, and fossil-fuel consumption excessive. Aggregate welfare is then also lower than with optimal taxation. This case is however not obviously worse than the NE solution. Welfare in the NE case is found to be greater than welfare in the no-tax case in our specified model given that $c > (1-p_0)/3$, which is far from clear.[17] While no justification for a zero-tax solution; this reminds us that non-cooperative NE taxation, with producers versus consumers and when taken to the limit, is here generally excessive and could be a quite long way from optimal.

5. Stackelberg solution with importer as leader

In some cases, the tax setting game may be better viewed as having one party as a natural leader, e g because it is first in establishing a tax policy. The other party may then need to react to the leader's policy, in setting its tax. A natural equilibrium concept is then the Stackelberg equilibrium, with either the petroleum importer or exporter group as leader. Appendix 4 formally analyzes the importer leadership case. The main results are as expected, namely that the importer tax, t, is higher than in the NE case, while the exporter tax, s, is lower. s is however lowered by only a fraction of the initial increase in t, so that the total tax, z = t+s, is increased. This is due to the strategic substitutability of t and s: the importer group,

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[16] See Appendix 2 for a further elaboration.

[17] See Appendix 3 for a derivation, and Section 7 for numerical examples.

in setting its tax, will consider the strategic response of the exporter group, which is to respond with a lower tax; this prompts more aggressive tax setting by importers. The resulting allocation is even less efficient than under NE. The leader (importer) gains relative to the NE, while the follower loses by more than this gain, for an overall aggregate loss. The case with the exporter as the first mover is parallel; only with the exporter now gaining and the importer losing.

6. Quantity strategies for the importer

In this section we discuss two cases where the importer chooses a *quantitative* consumption target for fossil fuels, instead of a tax. The importer is then presumed to implement the allocation of fossil-fuel among consumers, using tradable emission quotas that are auctioned freely among these. The main scheme for controlling carbon emissions under the Kyoto Protocol, the European Union emissions trading scheme, EU ETS, is of this general type, albeit with some differences.[18] We assume that exporters impose no petroleum taxes. Next, we assume that the exporter responds to the quantitative scheme by setting optimal ad valorem export taxes.

6.1 Importer cap-and-trade scheme with no exporter taxes

In this case, the importing country group simply sets its quota at the optimal solution for R given s=0 in the NE case. Licenses to buy R (or emit the corresponding carbon amount) can be viewed as auctioned off among demanders. The equilibrium auction price, q(0), will then equal the tax derived from (6) given s = 0.

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[18] One main difference is the current lack of auctioning of emission permits under EU ETS, with 95 percent of emission rights being given away to firms for free. Another difference is that the EU ETS only comprises a fraction (less than half) of carbon emissions in the European Union.

The importer government's quota sales revenue must equal the tax revenue from an optimal importer tax, from (6). This also yields the same income for consumer-country governments, in the former case through the importer excise tax on petroleum; in the current case, by auctioning off quotas costing the same as the tax.

6.2 Importer cap-and-trade schemes with optimal exporter taxes

This is arguably a more realistic, and interesting, case. Here, exporters respond to an importer cap by setting their fossil-fuel tax optimally. This case is studied analytically in Appendix 5. When the importer sets a quota for total imports of fossil fuels, the importer's demand for fossil fuels becomes perfectly inelastic to price (for prices not exceeding the clearing price). This gives the exporter maximal monopoly power to set its fossil-fuel tax and thus price. We show in Appendix 5 that this leads to one of two possible solutions. The first, more interesting, solution is identical to the solution under an optimal exporter tax and no importer taxes. The exporter then sets its tax such that the equilibrium quota price for carbon emissions rights is reduced to zero. The second (less interesting) is the no-trade solution, where the importer imports and consumes no fossil fuels whatsoever.[19] Both these solutions are bad for the importer: the two are the *worst for the importer group* among possible outcomes discussed in this paper, as also illustrated in the numerical examples in Section 7 below. Note however that the solution with trade and importer quotas may still be attractive in an *aggregate welfare* sense; it always fares better than the NE solution, and may even be first best.

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[19] Technically, this solution can be viewed as an artifact following from the special assumptions made about the importer demand function for fossil fuels, whereby demand is capped at a (relatively low) maximum demand price. This solution is discussed technically in Appendix 5; it however does not receive (nor warrants) much emphasis in the ensuing discussion.

In conclusion, a purely quantitative constraint is less attractive than a tax as viewed by importers, given that exporters respond optimally to such a policy. This may immediately appear as a surprise, as the fossil-fuel tax is replaced by a quota trading system that is presumed to mimic the tax scheme. The common perception is that a tax and a cap-and-trade scheme, both "optimal" by fossil-fuel consumers, are equivalent in such cases. But equivalence holds only when exporters respond competitively to the policies of importers. When exporters act in a unified way, they are not competitive. The strategic behavior of exporters will then differ in the two cases, the seller being more aggressive in the quantitative case than in the tax case, setting a higher exporter tax, and extracting a larger share of overall rent. In consequence, importers can do no better than to impose a quota corresponding to a zero tax, resulting in lower utility than when setting an optimal tax.

Note however that while the resulting solution here is very unattractive for *importers*, it is still generally more efficient *overall* than the NE solution, and may even as a special case be first best (as illustrated in Appendix 5, and example 2 below).

7. Two Numerical Examples

The purpose of this section is to illustrate the solutions discussed in previous section, with the use of two fully specified examples. To emphasize the differences in climate impacts and attitudes between the importing and exporting block, we will set c_1= c, $c_2 = 0$: negative impacts of climate change are felt only in importing countries. To simplify we also set $\gamma = \phi = 1$ in both examples (demand and supply are equally sensitive to price changes). The difference between the two examples lies in the value of petroleum consumption relative to the environmental externality it causes. We also set $p_0 = 0$, implying that there are no extraction costs at the lower support of the cost distribution.

In example 1, we set c = 1/3, which implies that the maximum value of a unit of petroleum consumption is three times the value of the externality caused. From (1.11) in Appendix 2, this corresponds to p = c in the NE case; the externality is here “very serious”. In example 2 we assume c = 1/6, implying that the externality is less (only half as) serious relative to the value of fossil-fuel consumption, From, (1.11), p = 2.5c in the NE case.

Example 1

The examples we consider have 9 alternative solutions: a) the NE; b) the Stackelberg solution, c) optimal t for importers given s = 0; d) the optimal s for exporters given t = 0; e) the optimal C-A-T solution for importers given s = 0; f) the optimal C-A-T solution for importers given optimal s response; g) the overall optimal (Pigou) tax solution with importers only taxing; h) the Pigou solution with exporters only taxing; and i) the no-tax solution. Solutions c) and e) are generically identical; as are solutions d) and f) (also for example 2 below). In example 1, the two latter are identical also to case h. We thus have 6 distinct cases. In example 1, as noted, c = 1/3, implying that the externality is “serious” relative to the value of the petroleum resource.

In Table 1, aggregate utility of the two parties is, obviously, greatest in the Pigou (first-best) case. Aggregate welfare is lowest in the Stackelberg case, followed by the NE and no-tax cases (the two are are identical in this particular case: NE output being too low, and no-tax output being equally too high). The (identical) cases where the importer faces no exporter tax (s=0) and sets either an optimal tax or C-A-T scheme, are intermediate in welfare terms. Welfare for importers is however highest here, and lowest for exporters, among all solutions considered. This numerical example implies a special case where optimal s facing t =0 (or a C-A-T scheme) yields the Pigou solution and thus maximal welfare. Still, this solution is the worst possible for importers (but correspondingly, the by far best for exporters). This illustrates in a rather extreme way that a cap-and-trade is unfavorable for importers, in cases where exporters react to a c-a-t scheme by selecting an optimal tax.[20]

Table 1: Numerical examples, assuming c = 1/3

Variable	Model alternative					
	NE	Stackelberg	Optimal t; or C-A-T, s=0	t=c, s=0	t=0, s = c; or C-A-T, optimal s	t=s=0
T	1.5c	1.71c	1.67c	c	0	0
S	0.5c	0.43c	0	0	c	0
z=s+t	2c	2.14c	1.67c	c	c	0
p	c	0.86c	0.67c	c	2c	1.5c
q = p+t	2.5c		2.33c	2c	2c	1.5c
R	0.5c	0.43	0.67c	c	c	1.5c
W_1	$0.38c^2$	$0.40c^2$	$0.67c^2$	$0.5c^2$	$-0.5c^2$	$-0.38c^2$
W_2	$0.38c^2$	$0.28c^2$	$0.22c^2$	$0.5c^2$	$1.5c^2$	$1.13c^2$
W	$0.75c^2$	$0.68c^2$	$0.89c^2$	c^2	c^2	$0.75c^2$

It is also of some interest to consider how the distribution of welfare between the two country groups is altered, when taxation is optimal (t+s = c) and t and s change in opposite directions. An interesting starting observation is then that welfare is spilt equally between the parties given that each party sets its tax equal to the externality it faces (thus t=c_1, and s=c_2; in our numerical example, t=c, and s=0). As noted in Section 3 above, this also corresponds to a Nash bargaining (NB) solution for the two parties in our particular example (with c = c_1

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[20] Note that in these cases welfare of importers is negative, implying that they would have been better off with no petroleum consumption whatsoever. This is a feature that clearly questions the viability of the c-a-t solution in this case. From Appendix 5, the appropriate solution for importers is then rather to set the cap at zero, with zero resulting welfare (thus choosing the other corner solution discussed there). The solution with no importer taxes is here still fully viable; the fact that welfare is negative in this case is less problematic (presuming only that importer countries do not have policy instruments available to limit petroleum imports).

and $\gamma = \phi$), with the no-trading solution as the status quo or impasse point.[21] One might also argue that, as a normative conclusion, importers "ought to" be the only ones to impose taxes, given that the NB solution is considered "fair".[22]

Example II

In our second example we retain all assumptions for example I, except that we set $1\text{-}p_0 = 6c$. The value of the externality is then only half, relative to its value in example I. Most of the results are now quite similar to those under example I, with some slight differences. One is that welfare is now positive for importers in all solutions (both parties are now always better off trading than not). Anther difference is that t = 0 or C-A-T facing an optimal s is now no longer first-best: in this case petroleum consumption is now lower than first best and implies the same aggregate welfare as the no-tax solution. Here, moreover, the NE yields strictly lower welfare than the no-tax solution, confirming our theoretical result given in Appendix 3.

A final point needs to be made on the welfare implications of alternative policies. Consider two additional cases: a) no environmental externalities; and b) a "small" environmental externality c for the importer block. Assume that in both cases, exporters coordinate their policies optimally. Moreover, assume that in case a) importer impose no taxes (as the only reason for doing so, would be as a protective tariff which may not be allowed), while in case b) importers are led to implement an optimal import tax, corresponding to the NE solution (in this case, we may assume, the importer is entitled to

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[21] One here easily realizes that this turns out to be the NB solution also when the NE solution is taken as the status quo point, the reason being that utilities to the two parties are the same in the NE solution, and thus incremental utilies the same going to the NB solution.

[22] Remember, more generally from (16) above, that when $\gamma = \phi$, the NB solution prescribes taxes to be imposed in proportion to the externality suffered by the respective party, so that $t = c_1$, and $s = c_2$.

"call" the entire tax an environmental tax, regardless of the actual level of the externality). It is then easy to demonstrate (numerically, with parametric assumptions as in the examples above) that welfare for importers is greater in case b) than in case a). In other words, the existence of a (limited) environmental problem leads to a better overall solution for importers, when accompanied by an improved tax policy. This is not surprising: we have seen that when the environmental problem is "small", the strategic motive dominates tax setting; an improvement in tax policy will then easily outweigh the disadvantage of the environmental externality.[23]

Table 2: Numerical examples when c = 1/6

Variable	Model alternative						
	NE	Stackelberg	Optimal t or C-A-T, s=0	t=c, s=0	t=0, s=c	t=s=0	t=0 or C-A-T, optimal s
T	2.25c	2.79c	2.67c	c	0	0	0
S	1.5c	1.07c	0	0	c	0	2c
Z=s+t	3.75c	3.86c	2.67c	c	c	0	2c
P	2.5c	2.14c	1.67c	2.5c	3.5c	3c	4c
Q = p+t	4.75c	4.93c	4.33c	3.5c	3.5c	3c	4c
R	1.25c	1.07c	1.67c	2.5c	2.5c	3c	2c
W_1	$2.34c^2$	$2.49c^2$	$4.17c^2$	$3.13c^2$	c^2	$1.5c^2$	0
W_2	$2.34c^2$	$1.72c^2$	$1.39c^2$	$3.13c^2$	$5.63c^2$	$4.5c^2$	$6c^2$
W	$4.69c^2$	$4.21c^2$	$5.56c^2$	$6.25c^2$	$6.25c^2$	$6c^2$	$6c^2$

8. Conclusions and discussion

We have studied a model where countries consuming and countries producing fossil fuels are separate, with full cooperation *within* each block, but possibly with no cooperation *between* blocks. In such a world, the overall fossil-fuel tax is the sum of the tax imposed by

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[23] A similar result is shown by Liski and Tahvonen (2004).

the exporter, and that imposed by the importer. For each of the two blocks, not only the aggregate tax matters (which determines the solution's environmental efficiency properties), but also what tax level is set by each block. We start, in Section 2, by considering overall efficient tax setting, where the sum of exporter and importer taxes equals the Pigou tax. One way to implement this solution is through (symmetric) Nash bargaining (NB) between importer and exporter countries. With symmetric demand and supply responses, the NB solution implies that importers and exporters tax according to the marginal externality suffered by each. In the numerical examples studied in Section 7, such a rule gives a higher welfare to each party, than either a NE tax rule, or a no-tax rule. The best solution for any one given party (among solutions considered in the examples), however, is where this party (the exporter or importer group of countries) taxes optimally from its perspective, and the opposite party does not tax at all. This is at the same time the worst possible solution for party that does not tax.

Section 3 studies a non-cooperative tax-setting game between the two blocks, where each block sets an individually optimal fuel excise tax, resulting in a non-cooperative Nash equilibrium (NE). We show that the NE implies overall excessive taxation, as a strategic tax motivation more than counteracts an under-taxation propensity, from a purely environmental motivation. Thus, NE fossil-fuel consumption is too small: both parties would gain by taxing less, but the NE dictates that the individually rational tax set by each is higher.

Our other main objective was to study a cap-and-trade (c-a-t) scheme for limiting importers' fuel consumption, and compare this to an import tax. In Section 6, the attractiveness of a c-a-t scheme for the importer is found to be highly dependent on the exporter reaction to a quantitative demand limitation. When there is no strategic reaction (here, no exporter tax), a c-a-t solution is favorable for the importer; it coincides with a solution where the importer taxes optimally, while the exporter does not tax. In the more realistic case where the exporter reacts strategically, and optimally, a c-a-t scheme for limiting fossil-fuel consumption, and thus GHG emissions, is very unfavorable for the importer; in fact, the worst among all policies considered. The reason is that an optimizing exporter then benefits by setting the export tax so high that the quota market in importer countries clears, and the quota price driven to zero. The solution is then the same as when the exporter sets an optimal tax, and the importer no tax. This shows, importantly, that the equivalence between a cap-and-trade scheme and a tax scheme for fossil-fuel consumer countries, which holds when no country or block of countries wields market power, does not carry over to the case where exporter countries as a group do wield such power, by setting coordinated taxes. Our analysis has thus exposed another potentially limiting aspect of c-a-t schemes for GHG emissions reductions, relative to a tax scheme; adding to other limitations.[24]

There is today no unified taxation policy for fossil fuels by major importers; indeed, hardly any taxation whatsoever of such fuels, with (imperfect) exceptions such as motor-fuels taxation in Europe, and the EU-ETS trading scheme for limiting greenhouse gas emissions under the Kyoto Protocol. The Protocol implies a positive cost of carbon emissions, but its ability to significantly constrain overall fossil-fuel consumption (and

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[24] See discussions and references in IMF (2008).

emissions) is questionable.[25] Our analysis should be a wake-up call for those, in particular in oil-importing countries, who might think there is little to gain by taxing fossil fuels.

While our model is stylized, we still argue that it is useful in a policy context. First, consuming and producing countries do form two natural blocks in terms of their fossil-fuel consumption, at least for oil; see Table 3. The consuming block comprises largely OECD plus most of Asia; the producing block consists of the Middle East, the former Soviet Union, and (a few) countries in Africa and Latin America. Imports by the former block, and exports by the latter block, are each about half of world production. Two major importers, the United States and China, have substantial oil production; but both have large and growing oil imports, and have their main interests solidly, and increasingly, on the demand side.

The model can readily be extended in several directions.

1) *Including fossil-fuel production by importers, and consumption by exporters*. This is more relevant when also other fossil fuels than oil, coal and natural gas (with a much higher degree of self-sufficiency among main producers), are incorporated into the analysis. The main conclusions, it is easily seen, still broadly stand. One difference is that importer taxes will be less potent for reducing both own demand, and exporter supply. The effects of tax setting will be "diluted", leading to a smaller strategic component, and a greater environmental component, in tax setting. Another difference relates to the effect of a cap-and-trade scheme for the importer group, which will apply to a mix of imported and self-produced fossil fuels.

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[25] There are several problems with the ETS. One of these is the high degree of free allocation of emission quotas to past emitters (at least 95 percent in the current trading period; and at least 90 percent for the 2008-2012 period), providing high windfall gains to emitters and robbing governments of potential tax revenue; see Goulder (2002) and OECD (2004). As argued by Böhringer and Lange (2005) and Rosendahl (2008), perhaps even more damaging is the system's lack of ability to deliver carbon reductions over time, since future free quotas tend to depend on current emissions, and are expected to do so in the future.

The demand function directed toward exporters will then no longer be completely inelastic, but still less elastic than under a tax. Our main result, that a tax is preferable to a cap for importers, would stand.

2) *Dynamic analysis*. Our analysis is static, while fossil-fuel extraction causing climate change is inherently dynamic, in two ways: fossil fuels is a limited, exhaustible resource; and greenhouse gas emissions are accumulated gradually over time. Exhaustibility makes supply less elastic in response to factors (such as taxes) that affect fossil-fuel demand. This *strengthens* some of our key results. Most importantly, it permits importers to extract even more rent from fossil-fuel producers when taxing fuels.[26] Moreover, taxes are an even better instrument for importers relative to a cap-and-trade quota scheme (since the latter still permits exporters, operating in coordinated fashion, to extract maximum rent from the importer group).

3) *Non-competitive behavior of fossil-fuel producers*. In our model, individual suppliers in exporter countries are taken to behave competitively, which can of course be questioned. OPEC, representing most oil exporters, actively attempts to regulate oil supply, but directly only in a limited way, through variable supply from Saudi Arabia who acts as an effective leader of this group.[27] Our model does in fact assume monopolistic supply behavior from fossil-fuel exporters as a group, but with clear limits on what strategic instruments can be

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[26] Bergstrom (1982) shows that an importer-imposed tax is, in effect, fully paid for by exporters through lower rents to the latter, given that supply is fully inflexible in the long run.

[27] In recent years OPEC has, arguably, functioned more as an intertemporal regulator of supply than as a general suppressor, or has at least attempted to do so. Over the three years up to the present (June 2008), with growing demand and price levels, the group has generally not restricted supply, apart via an unwillingness by Saudi Arabia to *increase* supply.

used: only the export price can be manipulated by exporters, not supply directly.[28] A dynamic analysis would further complicate this picture. Dynamic bilateral monopoly games between producer and consumer cartels can be complicated; in particular, taxation and output response schemes can be more elaborate.[29] Still, there are limits to the exercise of market power by a resource monopolist, in particular under a finite resource constraint and constant marginal cost. Bergstrom (1982) has shown for such cases, that essentially all the monopoly surplus can be taxed away by consumer countries using a constant unit tax through time. Under similar cost assumptions, a well-known result by Stiglitz (1976) shows that a monopolist will choose the perfectly competitive extraction (and price) path, in the same way as under competition, only given that the demand elasticity for the resource is constant.[30] This indicates that many of our basic results are likely to survive when fossil-fuel producers are non-competitive. The topic still clearly warrants further analysis, in particular, focusing on cases with increasing extraction costs, and relating the analysis to the price and supply strategies by OPEC and other major exporters.[31] This work should also make room for other energy markets (such as those for biofuels) interacting with the oil market.[32]

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[28] Appendix 6 however considers a case where exporters have direct control of both price and supply; this leads to greater market power for exporters.

[29] Other papers that study such issues (but without going into the issue of bilateral taxation) are Salo and Tahvonen (2001), and Rubio and Escriche (2001).

[30] In other cases, Stiglitz shows, the extraction path by a monopolist is either less rapid (when the demand elasticity is increasing in price) or more rapid (with decreasing demand elasticity).

[31] In particular, with increasing extraction costs and thus vanishing rents as the extraction period draws to a close, as e g in Heal (1976), Hoel and Kverndokk (1996), a monopolist could have more market power as total supply can more easily be manipulated. This case warrants more study.

[32] Note also that the classical view of petroleum as an exhaustible resource may be challenged by development of new cost-competitive energy sources, such as biofuels, with the same functions as oil.

4) *More general model specification*, including with respect to functional forms. Our assumption that the fossil-fuel supply and demand functions are both linear is not particularly realistic. A linearization may be appropriate when changes in demand and supply are small, which is not granted here. On the other hand, we will argue, most of our qualitative results (in particular, the comparison of welfare levels, in Tables 1-2) are not likely to be much affected. One issue may change when the linear structure is abandoned: it is no longer clear that the strategic motive will dominate over the environmental motive in tax setting. One might easily end up with a conclusion similar to Liski and Tahvonen (2004), that the overall optimal NE tax is, after all, below the Pigou rate.

Table 3: Oil production and consumption by major regions. 2003.
Figures in million tons.

Major area	Oil consumption	Oil production	Oil imports	Oil exports
European Union	621	122	578	87
North America	808	310	552	50
OECD Pacific	341	24	332	15
China	251	169	91	8
Rest Asia	343	152	261	71
Total, mainly oil importing regions	2364	777	1814	231
Middle East	180	1040	18	878
Former USSR	130	488	52	410
Africa	97	373	39	315
Latin America	164	312	57	205
Total, mainly oil exporting regions	571	2213	166	1808

Source: International Energy Agency (2006).

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Technical Appendix: Analytical Results

A1. First-best solutions

Consider the following aggregate consumer-country utility function for fossil-fuel consumption

(1) $$W_1 = R - \frac{1}{2}\gamma R^2 - pR - c_1 R,$$

where $\gamma > 0$, p = fossil fuel import price, c_1 = (climate-related) externality associated with fossil-fuel consumption for importing countries. Consider an importer excise tax t, leaving the consumer price at p+t. Fossil fuels are imported by many small agents, each of whom behaves competitively. The worldwide public demanding fossil fuels maximize

(2) $$V_1 = R - \frac{1}{2}\gamma R^2 - (p+t)R$$

with respect to R, yielding the first-order condition

(3) $$R = \frac{1-p-t}{\gamma}$$

A single producer country or region has welfare function

(4) $$W_2 = \Pi_2 + sR - c_2 R,$$

where Π_2 is net profit of petroleum producers, sR is excise tax revenue, and c_2R negative emissions externalities for the exporter. Net profits of producers are

(5) $$\Pi_2 = (p-s)R - p_0 R - \frac{1}{2}\phi R^2.$$

Maximizing (5) with respect to R yields the fossil-fuel supply function

(6) $$p = p_0 + s + \phi R.$$

ϕ (> 0) here represents the (inverse) supply sensitivity of petroleum output. s is the unit producer excise tax. $p_0+s > 0$; thus the supply elasticity is less than unit.

Solving (3) and (6) for R and p yields

(7) $$R = \frac{1-p_0-s-t}{\gamma+\phi}$$

(8) $$p = \frac{\gamma}{\gamma + \phi}(p_0 + s) + \frac{\phi}{\gamma + \phi}(1 - t).$$

Assumed now that tax policy is decided by a unified world government setting petroleum taxes to maximize world welfare. World welfare, given by

(9) $$W = R - p_0 R - \frac{1}{2}\gamma R^2 - \frac{1}{2}\phi R^2 - c_1 R - c_2 R,$$

is then maximized with respect to z, yielding

(10) $$R = \frac{1 - p_0 - c_1 - c_2}{\gamma + \phi}.$$

Invoking (7), the optimality condition for the aggregate petroleum tax can be expressed as

(11) $$t + s = z = c_1 + c_2,$$

the Pigou tax. The split of the overall petroleum tax, between a producer-country tax (s) and a consumer-country tax (t), is arbitrary in implementing the efficient solution.

With non-cooperative Nash tax setting by each group of consumers and producers, the "Pigou aspect" of the tax is reduced to exactly half. Nash fossil-fuel taxes however serve an additional rent-extraction purpose for the respective governments, contributing to an overall Nash tax in excess of the Pigou level.

Maximized aggregate world welfare equals

(12) $$W = \frac{(1 - p_0 - c)^2}{2(\gamma + \phi)}.$$

Only the sum t+s is here determined, not t and s individually. The surplus split from fossil-fuel trading between exporter and importer countries, is then indeterminate. We now consider one particular solution to this problem, namely the Nash bargaining solution where the importer and exporter bargain over the net surplus from trading, and given that the disagreement point is the no-trading solution. This is extreme but may be thought of as arising as an impasse solution (as bargaining is progressing), and where the bargaining solution results in higher utilities for both parties than the case where an outside option is exercised. Arguably, the natural outside option here is the NE solution.

The Nash maximand is

(13) $$NP = W_1W_2 = \left((1-p-c_1)R-\frac{1}{2}\gamma R^2\right)\left((p-p_0-c \ -\frac{1}{2}\phi R^2\right)$$

Maximizing NP with respect to R and p yields the optimal values R* and p*, found from

(14) $$\frac{dNP}{dR} = 0 \Leftrightarrow R^* = \frac{1-p_0-c_1-c_2}{\gamma+\phi}$$

(15) $$\frac{dNP}{dp} = R(W_1-W_2) = 0 \Leftrightarrow W_1 = W_2$$

From (7), we now have t+s = c_1+c_2 = c, confirming that the aggregate taxes conform to the Pigou solution in this case.

Using (6), we may derive the following solutions for t and s:

(16) $$t = c_1 + \frac{\phi-\gamma}{2}R^*, s = c_2 + \frac{\gamma-\phi}{2}R^*.$$

The solution for p* is

(17) $$p^* = p_0 + \frac{1}{2}(1-p_0-c_1+c_2)$$

(16) first shows that when demand and supply are equally sensitive to price ($\gamma = \phi$), the symmetric NB solution implies t = c_1, s = c_2, and thus that importers and exporters both implement taxes which equal the externality felt by each respective party, which in turn corresponds to an overall first-best solution.

When Φ is large relative to γ (implying that supply is relatively insensitive to price, while demand is relatively sensitive), t > c_1 so that the importer, as part of this solution, will tax relatively more than the importers' share of total externality damage, while exporters will tax correspondingly less.

A2. Nash equilibrium (NE) fossil-fuel taxes

The importer solution

An authority representing all importing countries sets t to maximize W_1 in (1), given the private-sector response represented by (7)-(8). This yields the first-order condition

(18) $$\frac{dW_1}{dt}=(1-\gamma R-p-c_1)\left(-\frac{1}{\gamma+\phi}\right)+R\frac{\phi}{\gamma+\phi}=0\,.$$

Inserting for R and p, we derive the following NE importer tax:

(19) $$t=\frac{\gamma+\phi}{\gamma+2\phi}c_1+\frac{\phi}{\gamma+2\phi}(1-p_0-s)\,.$$

The optimized values for R, p, and W_1 are:

(20) $$R=\frac{1}{\gamma+2\phi}(1-p_0-s-c_1)$$

(21) $$p=\frac{\gamma+\phi}{\gamma+2\phi}(p_0+s)+\frac{\phi}{\gamma+2\phi}(1-c_1)$$

(22) $$W_1=\frac{1}{2(\gamma+2\phi)}(1-p_0-s-c_1)^2\,.$$

W_1 decreases in s; i.e., higher petroleum taxation by producer countries lowers maximized net utility of petroleum consumption (including the negative externality from carbon emissions) for consumer countries. Clearly, consumer countries prefer producers to set a low petroleum tax.

When $c_2 = 0$, all negative externalities of petroleum use are suffered by consumers. In this case, the Pigouvian tax equals c_1. When fossil-fuel demand is linear, $1-p_0$ expresses consumer valuation (net of production costs) of the first unit of petroleum consumed. We must then have $1-p_0 > c_1$: otherwise petroleum would not be an economically meaningful good.[33] Then from (19), $t > c_1$. Thus, the importer tax, given no producer tax, exceeds the Pigou rate.

The producer solution

The producer country maximizes W_2 with respect to s, taking the supply function (6) from individual producers, the price relation (8), and the importer-determined tax rate, t, as given. The first-order condition for this problem is

(23) $$\frac{dW_2}{ds}=(p-p_0-\phi R-c_2)\left(-\frac{1}{\gamma+\phi}\right)+R\frac{\gamma}{\gamma+\phi}=0\,,$$

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[33] In more realistic cases, the demand function is linear only as an approximation in the neighborhood of equilibrium, and not globally. The condition, under which t exceeds the Pigou level, is then that the value of the first petroleum unit as calculated from the linearized demand function, exceed the marginal externality cost; which will also hold unless c_1 is extremely large.

which yields the following condition for optimal R in this case:

(24) $$R = \frac{p - p_0 - c_2}{\gamma + \phi}.$$

(6), (8) and (24) solve for R, p and s, taking t as exogenous, as follows:

(25) $$s = \frac{\gamma}{2\gamma + \phi}(1 - p_0 - t) + \frac{\gamma + \phi}{2\gamma + \phi}c_2$$

(26) $$p = \frac{\gamma + \phi}{2\gamma + \phi}(1 - t) + \frac{\gamma}{2\gamma + \phi}(p_0 + c_2)$$

(27) $$R = \frac{1 - p_0 - t - c_2}{2\gamma + \phi}.$$

Maximized welfare of petroleum producers is given by an expression similar to (22):

(28) $$W_2 = \frac{1}{2(2\gamma + \phi)}(1 - p_0 - t - c_2)^2$$

We here see that producer utility decreases in the importer-country tax.

Overall NE solution

We may now solve (19) and (25) simultaneously for t and s. The solutions are

(29) $$t = \frac{(2\gamma + \phi)c_1 + \phi(1 - p_0 - c_2)}{2(\gamma + \phi)}.$$

(30) $$s = \frac{(\gamma + 2\phi)c_2 + \gamma(1 - p_0 - c_1)}{2(\gamma + \phi)}$$

Each of s and t is a weighted sum of an externality cost (c_1 for importers setting t, and c_2 for producers setting s), and a strategic (or "optimal tariff") term. s increases in c_2 and falls in c_1, and vice versa for t. s falls in c_1 since s falls in t (from (25), and higher c_1 raises t.

As for the second (strategic) component, s is affected relatively more by strategic factors when γ is greater (petroleum demand is relatively insensitive to price, by (3)), while t is affected more when ϕ is greater (petroleum supply is insensitive to price, by (6)).

The total tax, z = s+t, is given by

(31) $$z = \frac{1}{2}(c_1 + c_2 + 1 - p_0).$$

In (31), the total tax equals half of aggregate externalities plus 1-p_0 (the difference between maximum demand price (=1) and minimum supply price (=p_0); or, alternatively, net willingness to pay for the first unit of petroleum consumption). Since the relative weight to 1-p_0 is greater here, z is greater than t in (19) (for s=0), or s in (25) (for t=0). Obviously then also, z exceeds the Pigou level.

Solutions for the producer price p, petroleum output R, importer and exporter welfare, W_1 and W_2, and aggregate world welfare, $W = W_1+W_2$, are found as

$$p=\frac{1}{2}(1+p_0-c_1+c_2) \tag{32}$$

$$R=\frac{1-p_0-c_1-c_2}{2(\gamma+\phi)} \tag{33}$$

$$W_1=\frac{\gamma+2\phi}{8(\gamma+\phi)^2}(1-p_0-c_1-c_2)^2 \tag{34}$$

$$W_2=\frac{2\gamma+\phi}{8(\gamma+\phi)^2}(1-p_0-c_1-c_2)^2 \tag{35}$$

$$W=W_1+W_2=\frac{3}{8}\frac{(1-p_0-c_1-c_2)^2}{\gamma+\phi}\,. \tag{36}$$

Welfare of the two blocks is affected very similarly by changes in the externality coefficients c_1 and c_2; but more differently by changes in the response parameters ϕ and γ, with importers (exporters) being more affected by a change in the export supply (import demand) response.

Comparing (36) to (12), aggregate welfare in the (excessive-tax) Nash case equals ¾ of maximized welfare.

A question to be elaborated is how general is of our result that the strategic component of the NE tax always overwhelms the “Pigou component”. Our assumption of linear fossil-fuel demand in price over its entire domain is restrictive. With a more general demand function (where demand would not vanish for high prices), one might open up for externality costs to play a more dominant role in setting the importer tax. Such cases have been studied by Liski and Tahvonen (2004), with unilateral taxation by importers (but where exporters react strategically). They point out that when the environmental externality is sufficiently serious, the optimal importer tax could below the Pigou level (which when viewed from importers would equal c_1 in our model). Liski and Tahvonen interpret this as amounting to a subsidy to imports (in the sense that when the tax is considered to consist of a full Pigou component plus a strategic component, the latter is negative).

While such a case is theoretically possible, we argue that it is not relevant in practice. Consider a (hypothetical) case where c = 1-p_0 (so that the externality component would be exactly equivalent to the strategic component, in terms of factors affecting the NE price). Using (32), this would imply that the total externality as fraction of the equilibrium NE export price of fossil fuels equal (1-p_0)/(1-c_1), which would generally exceed unity. This is not realistic for oil in today's market. To exemplify, consider an oil export price of US\$100 per barrel (lower than today's level, in July 2008), equivalent to about US\$850/tC, or about US\$250 per ton CO_2; and where the marginal externality cost for importers would need to generally exceed this level. This could clearly be unrealistic today.

A3. The no-tax solution

In this case, fossil-fuel consumption and price, R and p, are given by (3) and (7) setting s = t = 0. Welfare of importers and producers, and aggregate welfare, are

(39) $$W_1 = \frac{\gamma}{2}\frac{(1-p_0)^2}{(\gamma+\phi)^2} - c_1\frac{1-p_0}{\gamma+\phi}$$

(40) $$W_2 = \frac{\phi}{2}\frac{(1-p_0)^2}{(\gamma+\phi)^2} - c_2\frac{1-p_0}{\gamma+\phi}$$

(41) $$W = W_1 + W_2 = \frac{1}{2}\frac{(1-p_0-2c)(1-p_0)}{(\gamma+\phi)}$$

Aggregate welfare is now lower than with optimal taxation. Denoting optimal welfare (from (12)) by W*, and welfare in the current case by W(0), respectively, the loss is

(42) $$W^* - W(0) = \frac{c^2}{2(\gamma+\phi)}.$$

This loss is proportional to the square of the externality, corresponding to a standard "Harberger triangle".

A more interesting welfare comparison is between no taxes and the non-cooperative Nash case. With welfare W(N) in the Nash case (from (36)), we find

(43) $$W(N) > W(0) \Leftrightarrow 1 - p_0 < 3c.$$

In our example, only when the aggregate externality cost is above this particular threshold is aggregate world welfare greater in the Nash solution than in the no-tax solution. This threshold can be high; note that $1\text{-}p_0$ is society's net valuation of the first unit of petroleum consumed. The world society might then be better off with no fossil-fuel taxation, than with non-cooperative consumer-producer Nash taxation as derived from our model.

On the other hand, given that one party does not tax, it is always beneficial for the other party to tax, both in a social (potential Pareto) sense and privately. When producer countries do not tax petroleum, the optimal consumer-country tax is given by (19) (with s = 0). The welfare gain from such a unilateral optimal tax instead of a zero tax equals

(44) $$W(N;0) - W(0) = (\phi(1-p_0) + (\gamma+\phi)c_1)^2,$$

which is always positive.

A4. Stackelberg equilibrium with importer group as leader

The tax setting game is now viewed as not played out simultaneously, but instead with one party as natural leader, e g because it is first in establishing a tax policy. The other party may then need to react to the leader's policy, in setting its tax. One then needs to consider Stackelberg solutions, with either the petroleum importer or exporter group as leader. We formally analyze only the importer-country leadership case; the case with the exporter as the first mover is parallel.

As in the NE, the exporter tax can be found from (25), where t is now taken as observable by the exporter when setting s. The importer however now takes not s, but rather the schedule (16), providing a reaction function of s to the setting of t, as given. The first-order condition for the importer is then:

$$\frac{dW_1}{dt} = (1-\gamma R - p - c_1)\left(-\frac{1}{\gamma+\phi}\right) + R\left(\frac{\gamma}{2\gamma+\phi} + \frac{\phi}{\gamma+\phi}\right) = 0 \tag{45}$$

which yields

$$R = \frac{2\gamma+\phi}{(3\gamma+\phi)(\gamma+\phi)}(1-p-c_1)\,. \tag{46}$$

(46), together with (6), (7) and (25) now solve for R, p, s and t. For t and s we find:

$$t = \frac{(2\gamma+\phi)^2}{(\gamma+\phi)(5\gamma+2\phi)}c_1 + \frac{(\gamma+\phi)^2+\gamma\phi}{(\gamma+\phi)(5\gamma+2\phi)}(1-p_0-c_2) \tag{47}$$

$$s = \frac{(\gamma+\phi)(5\gamma+2\phi)-\gamma(2\gamma+\phi)}{(\gamma+\phi)(5\gamma+2\phi)}c_2 + \frac{\gamma(2\gamma+\phi)}{(\gamma+\phi)(5\gamma+2\phi)}(1-p_0-c_1)\,. \tag{48}$$

To compare these tax rates with the NE, we compare the coefficient before the last term in (48) to the corresponding coefficient in (29). The former is greater, implying that t is greater, and s lower, in the Stackelberg case. This is intuitive: the leader (here, the importer country group) uses its strategic advantage to set a higher tax, thus inducing the follower (the producer country group) to set a lower tax (since taxes are strategic substitutes); this is advantageous for the leader as its utility is a decreasing function of the follower's tax.

The aggregate tax z, and output R, are now

$$z = s+t = \frac{2\gamma+\phi}{5\gamma+2\phi}c + \frac{3\gamma+\phi}{5\gamma+2\phi}(1-p_0) \tag{49}$$

$$R = \frac{2\gamma+\phi}{(5\gamma+2\phi)(\gamma+\phi)}(1-p_0-c_1-c_2)\,. \tag{50}$$

z now has more weight to $1-p_0$, and less weight to the externality $c = c_1+c_2$, than in the NE. The aggregate tax is then higher than in the NE, since $1-p_0 > c$. To understand why, consider consumer countries, first, setting t unilaterally, higher than the NE level in (29). Producer countries react to this by reducing s below the NE level; but this reduction is less than the initial increase in t.

The corresponding solution with producers as leaders and consumer countries as followers is not derived analytically. One easily finds it to be parallel, with the two parties in opposite roles. E g, the formula for the aggregate tax, z, will be the same as in (49) only with coefficients γ and ϕ switching places; and now the exporter tax is higher, and the importer tax lower, than in the Nash case.

Generally, being a leader is advantageous as it permits setting a higher tax than in the NE, which has the effect of reducing the follower's tax below the Nash level; the latter response is exactly what is favorable for the leader.

A5. Importer cap-and-trade scheme with optimal exporter tax

In this case exporters set their excise tax optimally, in response to an importer cap. Assume that the importer quota equals R(Q). Consider two sub cases: a) fossil-fuel supply equals R(Q); and b) supply is less than R(Q).

In case a, exporter countries prefer fossil-fuel output to equal at least R(Q). With no importer tax (t=0), the exporter would, from (1.9), ideally produce R(0) given by

(51) $$R(0) = \frac{1-p_0-c_2}{2\gamma+\phi}.$$

Given $R(Q) \leq R(0)$, R(Q) will be the realized output (since the exporter would not voluntarily choose a lower level). (7) (with t=0) must still hold, since importer-country petroleum demand must be exactly realized at equilibrium; and since exporters will set the highest possible level of s corresponding to such an equilibrium. s will be given by

(52) $$s = 1-p_0-(\gamma+\phi)R(Q),$$

set to exactly clear the petroleum market in importer countries. As a result, the equilibrium price in the quota market in importer countries equals zero.

In deriving its optimal level of R(Q), the importer knows that s will be adjusted to its highest possible level for any given R(Q), from (52). The output price faced by the importer will depend on the import cap, and equal

(53) $$p = 1-\gamma R(Q).$$

To derive R(Q) set by importer countries (within the restriction R(Q) ≤ R(0)), importers maximize (1) with respect to R(Q), taking p as given from (52). This results in the modified expression for importer welfare, W_1:

$$W_1 = \frac{1}{2}\gamma(R(Q))^2 - c_1 R(Q)\,. \tag{54}$$

This expression is strictly convex in R(Q). The importer's optimal strategy is a corner solution, setting R(Q) either at zero (i e, consume no petroleum), or at its highest possible level given R(Q) ≤ R(0). Disregarding the former case, R(0) is optimal for importers. Importer-country utility is in this case the same as with t=0 and s given from (25).

Intuitively, when the importer sets a petroleum quota, petroleum demand is perfectly inelastic to price (for prices not exceeding the clearing price of petroleum). This in turn gives the exporter maximal monopoly power to set its petroleum tax and thus price, driving it up to the level that eliminates net rents at the margin for importer-country consumers.

Considering the numerical examples in Section 7, we find in example I that the no-trade solution is preferable for the importer to the cap-and-trade solution with optimal exporter tax response. Arguably this is unrealistic; it probably gives too little marginal value to fossil-fuel consumption at low consumption levels.

A6. Exporters set output price and quantity

In the final case considered, we assume that the exporter holds a more powerful role than in the analysis above, by controlling both the export price of fossil fuels, and its supply. We study a simple case where the exporter simply fixes the export price, and supplies the amount necessary to fulfill demand at this price. The exporter is then no longer constrained by a fuel supply function; supply is directly under government control. The exporter sets p, and supplies output necessary to sustain this price. The importer sets t, as in Section 3.

We discuss two cases. In the first, all variables are determined simultaneously. For given t, the optimal level of R for the exporter, with an associated clearing price p, is then still given by (27). The relationship between p and R is determined from (3) since, once R and t are given, (3) determines the clearing price p.[34] To determine t, the importer can be viewed as maximizing (1) with respect to R, taking p as a constant. This yields

$$R = \frac{1 - p - c_1}{\gamma}\,, \tag{55}$$

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[34] Another way to put this is to say that the exporter will always charge the highest price at which the total quantity of R would be sold to importers; this must be optimal for the exporter, since otherwise it would have selected a lower level of R.

assuming that this is feasible (R from (55) must not exceed the exported quota). Since (3) must still hold, t=c_1, implying that the importer tax is Pigouvian. From (27), the output quantity R set by the exporter is then given by

(56) $$R = \frac{1 - p_0 - c_1 - c_2}{2\gamma + \phi}.$$

R is now higher than in the simultaneous Nash tax setting case, in section 2. The reason is that t is set lower in this case. The strategic motivation for taxing petroleum is here taken away from the importer, who now taxes in a standard Pigou way. The utility of the exporter is also higher.

When the exporter is a Stackelberg leader in setting p and R, the solution is the same as in the simultaneous Nash case. This follows because t is the same (in both cases Pigovian, since t does not depend on any aspect of exporter policy). For given t, the optimal exporter action is unique.

In the second case, the importer is allowed to set t before the exporter sets its price and associated output. Now the exporter must take t as given when setting its petroleum output R, and can then do no better than choosing R according to (27). But this yields the Stackelberg solution in Section 5. There is then nothing to gain for the exporter by having the ability to set p and R independently.