Carbon Taxes and Green Subsidies in a World Economy*

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Abstract

To address the growing threat of climate change, countries have agreed to transition away from fossil fuels and significantly increase renewable energy. This paper examines positive and normative questions that arise with the joint use of carbon taxes and green energy subsidies in a world economy, allowing for lobbying pressures from the fossil and green energy sectors. The open economy setting provides a unilateral welfare rationale for the use of green subsidies, owing to a "reverse leakage" effect, whereby green subsidies can reduce fossil fuel output both at home and abroad. International climate agreements (ICAs) will always seek to increase carbon taxes, but the effect on green subsidies is more nuanced. An ICA removes green subsidies, even though they have positive international externalities at the noncooperative equilibrium. If, however, policies can only be changed gradually, an ICA may start by increasing subsidies before decreasing them over time. When we consider the welfare impacts of lobbying, we find that in the noncooperative scenario, pressures from the fossil lobby tend to reduce welfare, while pressures from the green lobby tend to increase welfare. We also find that in the presence of lobbying pressures, an ICA can decrease welfare relative to the noncooperative equilibrium, even though its only purpose is to correct climate externalities and it changes carbon taxes and green subsidies toward their efficient levels.

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1 Introduction

Decarbonization of the world's energy systems is necessary to reduce greenhouse gas (GHG) emissions enough to meet internationally agreed upon targets to limit global warming (IPCC 2022). At the most recent Conference of the Parties to the United Nations Framework Convention on Climate Change, world leaders agreed to pursue two main objectives for achieving this goal (UNFCCC 2023). The first is to transition away from fossil fuels, and the second is to triple global renewable energy capacity by 2030.

The global landscape of climate policy instruments includes both carbon pricing and green subsidies. Nearly a quarter of global GHG emissions are regulated through carbon pricing, with national and sub-national policies that include direct pricing through carbon taxes and indirect pricing through emissions trading systems (World Bank 2024). Direct subsidies to renewable sources of energy were estimated at $166 billion worldwide in 2017, comprising 26 percent of all direct energy subsidies, and forecasts for 2030 reach $192 billion, increasing to 41 percent of the total (Taylor 2020). Not included in these estimates, however, is the U.S. Inflation Reduction Act of 2022, which includes provisions initially estimated at $271 billion in green energy subsidies over 10 years (CBO 2022), with more recent estimates putting the magnitudes at $700 billion or more (CBO 2024; Bistline, Mehrotra, and Wolfram 2023).

Alongside the shifting landscape of energy and climate policy is a well-established fossil fuel lobby and a growing lobby advocating interests of the clean energy sector. In the United States, for example, the oil and gas sector had annual federal lobbying expenditures of $130 million on average over the last decade, and the renewable energy sector had expenditures of $60 million in 2023, more than doubling since 2020 (Open Secrets 2024). Increasingly, lobbyists are also participants in UNFCCC climate negotiations, with those registered from the fossil fuel sector growing from the hundreds to the thousands in the last three years (Kluger 2023).

Motivated by this policy landscape, this paper addresses positive and normative questions that arise with the simultaneous use of carbon pricing and green (i.e., clean energy) subsidies. We first examine the noncooperative choices of carbon pricing and green subsidies and how these depend on the countries' openness to trade. We then examine the role of international cooperation in a setting where both instruments are operational, asking whether international agreements should seek to promote or discourage green subsidies. Finally, we analyze how the presence of lobbying from the fossil and green energy sectors affects unilateral and cooperative policies, and what this implies for global welfare.

The basic structure of our model is a competitive, two country setting. There is a final good that uses energy as an input, along with an outside good. There are two forms of energy: fossil fuel, which generates a global externality, and green energy, which does not.[1] The two policy instruments that we focus on throughout most of the paper are a production tax on fossil energy (i.e., a carbon tax) and a subsidy on green energy, but we later consider the implications of allowing also trade and consumption taxes. We allow for political economy considerations, and in particular, the fossil and green energy sectors can lobby policymakers a' la Baldwin (1987) and Grossman and Helpman (1994). Our key results fit broadly into three areas.

Noncooperative policies.—The first set of results relate to the noncooperative choice of carbon taxes and green subsidies in a global economy. We find that an open economy can provide a unilateral welfare rationale for the use of green subsidies. This result stands in contrast to the case of a closed economy, where there is no rationale for green subsidies, even in the presence of a fossil energy lobby that resists the use of carbon taxes. In an open economy, green subsidies provide an additional channel to affect the world price of fossil energy and therefore reduce its output in foreign countries. While carbon taxes are associated with "leakage," which diminishes their unilateral efficiency, green subsidies have a "reverse leakage" effect: the induced reduction in the home country's fossil fuel output is associated with further reductions abroad. This occurs because the induced change in the price of fossil fuel is the same both at home and abroad, unlike that for a carbon tax. We also show that green subsidies can provide a reason beyond leakage for countries to reduce carbon taxes in an open economy setting—to reduce the domestic distortion in the clean energy sector— and that the reduction in carbon taxes induced by openness to trade creates the possibility of losses from trade.

International cooperation.—The second set of results pertain to international cooperation on carbon taxes and green subsides. We focus first on the question of whether international climate agreements (ICAs) should seek to increase or decrease green subsidies in a setting where carbon taxes are available too. A key insight is that green subsidies exert positive international externalities at the noncooperative equilibrium, even though a welfare maximizing ICA will remove them. An implication of this result is that a gradual ICA may increase green subsidies before decreasing them. Indeed, we find that in a simple dynamic extension of the model where policies are subject to adjustment frictions, if such frictions are relatively more severe for carbon taxes than for green subsidies, then the ICA will increase green subsidies before reducing them. An additional result relates to the optimal scope of

[1] We focus throughout the paper on the global externality of climate change and not on other market failures that might be at play, including those associated with technological innovation and diffusion, such as R&D externalities and learning by doing spillovers. Later in the paper, however, we will briefly discuss how these other market failures might affect the analysis.

an ICA. We find that an ICA focused only on carbon taxes leads to global efficiency if countries are symmetric, whereas one focused only on green subsidies can never achieve global efficiency. This result suggests that in the presence of contracting costs (such as costs of negotiation, enforcement, or both), an incomplete agreement that focuses only on carbon taxes may be optimal if countries are not too asymmetric, or put differently, the costs of contracting over green subsidies may only be worth it if countries are sufficiently asymmetric.

Welfare implications of lobbying.—The third set of results speak to the welfare implications of lobbying. In a noncooperative scenario, we find that the fossil and green lobbies have strongly asymmetrical effects on welfare. Strengthening the fossil lobby decreases welfare, as long as the green lobby is not too strong. In sharp contrast, we find that strengthening the green lobby increases welfare, provided it does not get too strong. This result is directly related to the feature that increasing green subsidies starting from the noncooperative equilibrium generates positive international externalities, while decreasing carbon taxes has negative international externalities. We then consider how a politically-pressured ICA changes welfare relative to the noncooperative equilibrium. Regardless of the lobbying pressures, the only role of the ICA is to correct the global climate externality, and the ICA moves carbon taxes and green subsidies toward their efficient levels. Nevertheless, we find that the ICA can decrease welfare. This can happen in the presence of a strong green lobby. The reason is that a strong green lobby can extract a large green subsidy and hence cause an over-production distortion in the green sector at the noncooperative equilibrium. An ICA then seeks to correct the climate externality by increasing carbon taxes, which will increase production of green energy and exacerbate the distortion in the green energy sector even further.

While our baseline model focuses on production taxes/subsidies, in a later section we consider also consumption and trade taxes. If a government can use production and consumption taxes, it will still use a green production subsidy, but lower in magnitude than absent consumption taxes. The intuition is that it is optimal to spread the policy distortion across all instruments. We then consider a scenario where governments can use production and trade taxes, but the latter are constrained by pre-existing trade agreements. In particular, we examine the optimal choice of policies in a world where export subsidies are banned (as they are in reality by the GATT-WTO) and tariffs are subject to caps. Focusing on green energy policies, we find that, if a country has a comparative advantage or a slight comparative disadvantage in the green sector, it will use a green production subsidy, just as in our baseline model. On the other hand, if a country has a strong comparative disadvantage in the green sector, if the tariff cap is binding it will supplement the tariff with a green production subsidy, otherwise it will only use a tariff.

Our broad contribution to the literature is to consider carbon taxes and green subsidies in a global economy, with global externalities and lobbying, both in a noncooperative scenario and when ICAs are available. Questions about policy instrument choice have a long tradition in environmental economics (e.g., Weitzman 1974; Baumol and Oats 1988; Goulder and Parry 2008), but most papers in this literature focus on the tradeoffs associated with choosing between instruments, in closed economies, and with welfare maximization rather than political economy. Aidt (1998) does consider the way that countervailing lobbies affect the politically optimal level of environmental taxes, but the analysis is limited to a closed economy. Fischer (2017) considers green subsidies in an open economy with a political preference for domestic production, but the model does not consider carbon taxes or the interactions between green and fossil energy sectors.

There are a few studies that consider carbon taxes and green subsidies, such as Gerlagh et al. (2009) and Acemoglu et al. (2012), but in a settin where green subsidies are motivated by research and development spillovers rather than climate externalities. Moreover, they do not focus on the implications of international trade or lobbying, nor do they consider the role of ICAs relative to a noncooperative scenario.

There is also a literature that focuses on linkages between climate (or more generally transboundary pollution) and trade policy, with contributions emphasizing unilateral policies (Markusen 1974; Copeland 1996; Hoel 1996; Fischer and Fox 2012; Keen and Kotsogiannis 2014; Balistreri et al. 2019; Kortum and Weisbach 2021; Weisbach et al. 2023) and the potential for trade policy as a tool to incentivize participation in environmental agreements (Barrett 2003; Nordhaus 2015; Farrokhi and Lashkaripour 2023). In contrast to our model, these papers have little or no focus on a green energy sector, and they do not consider lobbying.

Other related papers consider the relationship between trade agreements and domestic policies (Bagwell and Staiger 2001), questions about the scope of international agreements (Horn, Maggi, and Staiger 2010), and international regulatory agreements under lobbying (Maggi and Ossa 2023). None of these papers, however, considers fossil and green energy policies in a setting with trade, a global climate externality, and lobbying.

The remainder of the paper is organized as follows. Section 2 develops the model setup in a closed economy. Section 3 considers the noncooperative scenario with open economies and welfare maximizing governments. Section 4 considers the role of ICAs. Section 5 considers lobbying and its welfare implications. Section 6 extends the analysis to allow for consumption taxes and trade taxes. Section 7 concludes.

2 A closed economy

We begin with a closed economy to lay out the basic features of the model and establish some benchmark results.

We assume perfect competition. There are two final good sectors, A and B. Good A is produced from fossil fuels (F), green energy (G) and labor with constant returns to scale. Good B is the numeraire good, produced one-for-one from labor. The energy inputs F and G are each produced with labor and a specific factor with constant returns to scale. Labor is in fixed supply, denoted L and assumed to be sufficiently large to guarantee positive consumption of good B in equilibrium,

Production of fossil fuels generates an environmental externality, which we assume to be linear: $E = \alpha y^F$, where y^F is the output of fossil fuels and α captures the marginal damages due to climate change.[2] Preferences are quasilinear and take the form $x^B + U(x^A) - E$, where x^j is consumption of good $j = A, B$, with $U' > 0$ and $U'' < 0$.

2.1 Laissez-faire equilibrium

We now characterize the market equilibrium in the absence of policy. First note that, since the numeraire good is produced one-for-one from labor, the wage is $w = 1$. Demand for the final good A is defined implicitly by $U'(x^A) = p$, and we denote it simply as as $d(p)$. Consumer surplus is denoted $CS(p)$, and it follows that $\frac{dCS}{dp} = -d(p)$.

Next we derive the supply and demand functions for energy inputs, before turning to the market conditions that determine energy prices. The supply functions for inputs are straightforward given the assumed specific factor technology. Total returns to the specific factor in sector $i = F, G$ depend only on the corresponding price p^i (and the fixed wage, $w = 1$). We can therefore write the total returns to the specific factor in sector i as $\pi^i(p^i)$, which can be interpreted as producer surplus. The supply function for each input can be written as $y^i(p^i) = \frac{d\pi^i}{dp^i}$, where the equality follows by Hotelling's lemma.

Before turning to the input demand functions, it is convenient to define unit input requirements, or "input coefficients." These represent the (optimized) amount of each input used to produce one unit of the final good A. For the two energy inputs, we write these functions as $a^F(p^F, p^G)$ and $a^G(p^G, p^F)$, recalling that $w = 1$. Each input coefficient is decreasing in its own price. We assume the energy inputs are substitutes, meaning that $\frac{\partial a^i}{\partial p^j}$ is positive, and that the own-price effect is greater than the cross-price effect, so that $\left|\frac{\partial a^i}{\partial p^i}\right| > \frac{\partial a^i}{\partial p^j}$. The input coefficient for labor is similarly written as $a^L\left(p^F, p^G\right)$. With these functions established, it

[2] The parameter α can be interpreted as the amount of carbon dioxide per unit of fissil output multiplied by the climate damages per unit of carbon dioxide.

is also useful to define the unit cost function for final good A:

$$c(p^F, p^G) = p^F a^F \left(p^F, p^G\right) + p^G a^G \left(p^G, p^F\right) + 1 \cdot a^L \left(p^F, p^G\right),$$

where by the envelope theorem $\frac{\partial c}{\partial p^i} = a^i(\cdot)$. The zero-profit condition in sector A implies $p = c(p^F, p^G)$.

We can now write all demand functions for the final good and energy inputs in terms of the input prices only. These functions can be interpreted as "general equilibrium demand functions," because they take into account the downstream changes in the price of the final good. Using the zero profit condition, demand for the final good A can be written as $d(p) = d\left(c(p^F, p^G)\right) \equiv \tilde{d}(p^F, p^G)$, which is clearly decreasing in both prices, as $d(p)$ is decreasing and $c(p^F, p^G)$ is increasing in both arguments. The input demand functions for $i = F, G$ can then be expressed as

$$d^i \left(p^i, p^j\right) \equiv a^i \left(p^i, p^j\right) \tilde{d} \left(p^i, p^j\right). \tag{1}$$

Note that the own-price effect $\frac{\partial d^i}{\partial p^i}$ is negative, because an increase in p^i reduces the input coefficient a^i and decreases the final good demand $\tilde{d}$. However, the cross-price effect $\frac{\partial d^i}{\partial p^j}$ can take either sign, because the input substitution effect $\frac{\partial a^i}{\partial p^j}$ is positive while the downstream demand effect $\frac{\partial \tilde{d}}{\partial p^j}$ is negative. In what follows, we say that input i is a substitute (complement) for input j if $\frac{\partial d^i}{\partial p^j} > 0$ (< 0). The case in which the two forms of energy are substitutes is perhaps more plausible and intuitive, so throughout the paper we will focus on this case, unless otherwise noted.[3]

Three conditions determine the market prices p, p^F and p^G. The first, and already mentioned, is the zero profit condition for the final good, $p = c(p^F, p^G)$. The other two conditions are the market clearing conditions in the energy input sectors: $d^i(p^i, p^j) = y^i(p^i)$ for $i = F, G$.

[3] We note that the case of equilibrium substitutes or complements relates to empirically estimable elasticities. The cross price effect can be written as $\frac{\partial d^i}{\partial p^j} = \frac{\partial a^i(\cdot)}{\partial p^j}\tilde{d}(\cdot) + a^i(\cdot)\frac{\partial \tilde{d}(\cdot)}{\partial p^j}$. Multiplying both sides of this equation by $\frac{p^j}{d^i}$ and recognizing that $a^i = \frac{d^i}{\tilde{d}}$, it follows that input i is a substitute for input j if and only if $\varepsilon_{a^i p^j} > \theta_j \varepsilon_{\tilde{d}}$, where $\varepsilon_{a^i p^j}$ is the elasticity of the energy input i coefficient with respect to a change in the price of energy input j, θ_j is factor j's cost share in the final good industry, and $\varepsilon_{\tilde{d}}$ is the elasticity of the final good demand with respect to its own price (defined positively). While determining whether the condition holds is ultimately an empirical question, the case of substitutes seems plausible for at least two reasons. First, for many final goods the cost share of energy θ_j is much lower than one, and second, some final goods with large energy inputs, such as electricity, tend to have inelastic demand, hence a low $\varepsilon_{\tilde{d}}$. We note that assumptions about the elasticity of substitution and the price elasticity of final goods demand play an important role in recent papers on the macroeconomics of climate policy (Golosov et al. 2014; Hassler and Krusell 2018; Hassler et al. 2021; Casey, Jeon, and Traeger 2023)

2.2 Energy policy

We consider two policy instruments: a specific production tax on F, denoted t, which we will often refer to as a "carbon tax," and a specific production subsidy on G, denoted s, which we will refer to as a "green subsidy." Although we focus on production taxes throughout most of the paper, we later extend the analysis to allow for consumption taxes on inputs and final goods as well as trade taxes.

The aim of this section is to characterize how changes in t and s affect equilibrium prices. Let p^i and q^i denote the consumer and producer prices for energy input i, respectively. Hence we have price wedges $q^F = p^F - t$ and $q^G = p^G + s$. Market clearing in the input markets requires

$$d^F(p^F, p^G) = y^F(p^F - t)$$

and

$$d^G(p^G, p^F) = y^G(p^G + s),$$

and this system defines $p^F(t, s)$ and $p^G(t, s)$.

Differentiating this system and solving for dp^F and dp^G we can derive the following results, which are proved in the Appendix.

Remark 1. The within-sector effects of policies satisfy consumer price effects of $0 < \frac{dp^F}{dt} < 1$ and $-1 < \frac{dp^G}{ds} < 0$ and therefore producer price effects of $\frac{dq^F}{dt} < 0$ and $\frac{dq^G}{ds} > 0$.

This implies within-sector effects of policies that are intuitive: an increase in the carbon tax increases p^F, and an increase in the green subsidy decreases p^G. Moreover, because pass-through is incomplete, the within-sector producer prices move in the opposite direction.

The next set of results relate to cross-sector effects:

Remark 2. The cross-sector effects of policies satisfy: (i) $\frac{dp^G}{dt} = \frac{dq^G}{dt} > 0$ if and only if G is a substitute for F, and (ii) $\frac{dp^F}{ds} = \frac{dq^F}{ds} < 0$ if and only if F is a substitute for G.

Note that the cross-sector effects of policies are the same for consumer and producer prices. It is intuitive that the sign of the cross-sector effects of policies is determined by whether the two sources of energy are substitutes or complements. As noted previously, we will focus on the case of substitutes throughout most of the paper: in this case, a carbon tax increases the price of G, and a green subsidy decreases the price of F.[4]

[4] It may be helpful to discuss briefly the special case in which F and G are perfect substitutes. In this case, the production function for A is linear in the total amount of energy, the consumer price of F and G must be the same, say $p^F = p^G \equiv p^E$ (where E denotes energy), the unit cost function for A is $c(p^E, 1)$, the zero-profit condition implies $p = c(p^E, 1)$, demand for A is $d(p) = d(c(p^E, 1)) \equiv \tilde{d}(p^E)$, and the market clearing condition for energy is $d^E(p^E) = y^F(p^E - t) + y^G(p^E + s)$. Differentiating this, we find $dp^E = \frac{y^{G'} ds - y^{F'} dt}{d^{E\prime} - y^{F'} - y^{G'}}$. Note that s and t have different impacts on the consumer price of energy if the supply functions have different

2.3 Welfare maximization

It is natural in this setting to define welfare as aggregate indirect utility: $Income + CS - E$. Note that $Income = \pi^F + \pi^G + L + R$, where π^i is producer surplus in sector i, L is labor income and R is government revenue. The welfare function can therefore be written as $W = CS + \pi^F + \pi^G + R - E$, where we ignore L because it is constant. Expanding this expression to include the role of prices and policy, we have

$$W = CS(c(p^F, p^G)) + \pi^F(p^F - t) + \pi^G(p^G + s) + ty^F(p^F - t) - sy^G(p^G + s) - \alpha y^F(p^F - t), \quad (2)$$

where $p^F = p^F(s,t)$ and $p^G = p^G(s,t)$. We assume the welfare function is concave in s and t. Choosing t and s to maximize welfare yields the following result.

Remark 3. In a closed economy, the welfare maximizing policies are $t = \alpha$ and $s = 0$.

These policies follow immediately from the first-order conditions and are intuitive (see the Appendix). The tax is set at the Pigouvian level, and given no other externality, there is no need for a subsidy.

2.4 Political economy

We model lobbying in Baldwin-Grossman-Helpman fashion, by specifying a politically weighted objective function of the form

$$\Omega = W + \gamma^F \pi^F + \gamma^G \pi^G, \quad (3)$$

where $\gamma^F, \gamma^G \geq 0$ capture the strength of the respective lobbies. The "politically efficient" policies that maximize this objective function have additional terms compared to those without lobbying:

$$t = \alpha - \gamma^F \frac{y^F}{y^{F\prime}} \text{ and } s = \gamma^G \frac{y^G}{y^{G\prime}}. \quad (4)$$

An immediate implication of this result is that lobbying by the F sector alone cannot rationalize a second-best green subsidy in a closed economy.[5] This finding runs contrary to a

slopes. Using this, and recalling that $q^F = p^E - t$ and $q^G = p^E + s$, we find $dq^F = \frac{y^{G\prime} ds + \left(y^{G\prime} - d^{E\prime}\right) dt}{d^{E\prime} - y^{F\prime} - y^{G\prime}}$, with a similar expression holding for dq^G. Note that both a carbon tax and a green subsidy decrease q^F, but intuitively a green subsidy has a smaller impact than a carbon tax. All of our qualitative results can be shown to hold in the case of perfect substitutes.

[5] This result is somewhat more general because it does not depend on the linear specification in (3). If the politically weighted objective takes the form $\Omega = W + \phi(\pi^F)$, where $\phi' > 0$, it is direct to verify that the politically efficient subsidy is still $s = 0$.

frequently made argument that green subsidies are a second-best policy if a fossil fuel lobby opposes a carbon tax. We record this result with:

Remark 4. In a closed economy, existence of a G lobby is necessary and sufficient to rationalize a green subsidy, $s > 0$.

The intuition for this result can be traced to the targeting principle, whereby a regulator seeking to transfer surplus to the F sector will do it through the most efficient means only—that is, a reduction in t, possibly going so far as to turn the carbon tax into a fossil fuel subsidy.[6]

Note that the inverse supply semi-elasticities $\frac{y^i}{y^{i'}}$ depend on the equilibrium producer prices, which in turn depend on policies. At various junctures in the paper we will consider the comparative-static effects of changes in the political parameters γ^F and γ^G. To ensure that the indirect effects of these changes through the supply semi-elasticities do not outweigh their direct effects, we make the reasonable assumption that $\frac{y^i(q^i)}{y^{i'}(q^i)}$ is (weakly) increasing in q^i for $i = F, G$. This condition is satisfied, for example, if the supply functions are linear or constant-elasticity. With this assumption, along with the producer price results in Remark 1, we find intuitively that a stronger F lobby results in a lower t, and a stronger G lobby results in a higher s. And furthermore, we can sign the cross-sector effects of changes in lobby strengths: we find that, if F and G are substitutes, strengthening the F lobby decreases s (but never turns it negative), and strengthening the G lobby increases t (but never raises it above α).

3 Open economies

We now consider an open economy setup with two countries, Home and Foreign. We assume no trade costs and focus on the case of symmetric countries, which implies no trade and hence no terms-of-trade effects at a symmetric equilibrium. Many of the key effects that arise in our open economy setup are nevertheless due to the *potential* for trade. Terms-of-trade effects would affect most of our results in obvious directions, making them less transparent. But we will point out the implications of terms-of-trade effects when relevant.

A key feature of the open economy setup is that each country now experiences a global externality $E = \alpha(y^F + y^{*F})$, where an asterisk denotes the Foreign country. We begin without political economy, that is, setting $\gamma^F = \gamma^G = 0$, but reintroduce lobbying later in

[6]While in this paper we focus on lobbying, and we have shown that an F lobby cannot rationalize a green subsidy, other kinds of political considerations can. For example, electoral politics related to ideological opposition to carbon taxes could play a role, and we might consider a politically weighted objective function of the form $W(t, s) - C^F(t)$, where $C^{F'} > 0$ represents the marginal political cost associated with a carbon tax. In this case, it is straightforward to verify that $s > 0$ if F is a substitute for G.

the paper. In this section, we also solve for the set of policies that maximize global welfare, before turning to the Nash equilibrium and consideration of how trade affects welfare.

Welfare of Home is given by

$$\begin{aligned} W =& CS(c(p^F, p^G)) + \pi^F(p^F - t) + \pi^G(p^G + s) + ty^F(p^F - t) - sy^G(p^G + s) \\ &- \alpha[y^F(p^F - t) + y^{*F}(p^F - t^*)], \end{aligned} \tag{5}$$

where the consumer prices p^i for $i = F, G$ must satisfy the market clearing conditions

$$d^F(p^F, p^G) + d^{*F}(p^F, p^G) = y^F(p^F - t) + y^{*F}(p^F - t^*)$$

and

$$d^G(p^G, p^F) + d^{*G}(p^F, p^G) = y^G(p^G + s) + y^{*G}(p^G + s^*).$$

These define the consumer prices as a function of the four policies (t, t^*, s, s^*), and the domestic producer prices must satisfy $q^F = p^F - t$ and $q^G = p^G + s$ for both Home and Foreign. Note that consumer prices can also be interpreted as the world prices.

In this open economy setup, changes in policy have the same qualitative effect on prices as those identified in the closed economy. In particular, the results of Remarks 1 and 2 hold in the open economy as well. The only difference is that the magnitudes are smaller—exactly half the size starting at a symmetric market equilibrium—as each country has a smaller impact on the world prices.

The policies that maximize global welfare $W^W \equiv W + W^*$ also have a familiar solution.[7]

Remark 5. In the open economy setup, the global-welfare maximizing policies in each country are $t = 2\alpha$ and $s = 0$.

The globally optimal carbon tax in each country is now equal to the global marginal damages (i.e., the global social cost of carbon), and because there is no other source of market failure, the globally optimal subsidies are equal to zero.

3.1 Nash equilibrium policies

We now consider the incentives associated with unilateral policies, beginning with an intuitive discussion of one way in which they differ between t and s. Suppose Home wants to reduce the domestic price of fossil energy q^F in order to reduce the climate externality. This can be accomplished by an increase in the carbon tax, as we showed with the closed economy.

[7] The solution to this problem can be arrived at by simply solving the closed economy problem with twice the marginal climate damages.

What differs in the open economy setting is "leakage," as the increase in t also increases the world price p^F and therefore Foreign emissions. The green subsidy, in contrast, has a "reverse leakage" effect, as an increase in s decreases both the domestic and world price of F (because $\frac{dp^F}{ds} = \frac{dq^F}{ds}$), causing a decrease in both Home and Foreign emissions. We now examine this intuition more rigorously, studying the jointly optimal choice of both instruments, their interaction, and the symmetric Nash equilibrium.

We begin with Home's unilateral choice of t and s to maximize (5). With a bit of algebra, the first-order conditions simplify to

$$\frac{\partial W}{\partial t} = -\left(m^F \frac{\partial p^F}{\partial t} + m^G \frac{\partial p^G}{\partial t}\right) + (t-\alpha) y^{F'} \frac{\partial q^F}{\partial t} - \alpha y^{*F'} \frac{\partial p^F}{\partial t} - s y^{G'} \frac{\partial q^G}{\partial t} = 0 \tag{6}$$

and

$$\frac{\partial W}{\partial s} = -\left(m^F \frac{\partial p^F}{\partial s} + m^G \frac{\partial p^G}{\partial s}\right) + (t-\alpha) y^{F'} \frac{\partial q^F}{\partial s} - \alpha y^{*F'} \frac{\partial p^F}{\partial s} - s y^{G'} \frac{\partial q^G}{\partial s} = 0, \tag{7}$$

where $m^i = d^i - y^i$ denotes Home imports of input i. First note that with symmetric countries there is no trade in equilibrium, so the first term in parentheses is equal to zero in (6) and (7). To gain intuition for how the open economy level of policies differ from those in a closed economy, we can start by evaluating the first-order conditions at the closed economy policies ($t = \alpha$ and $s = 0$), yielding $\frac{\partial W}{\partial t} < 0$ and $\frac{\partial W}{\partial s} > 0$. This suggests that Home wants to lower its carbon tax relative to the closed economy optimum ($t = \alpha$) and introduce a green subsidy. The term $-\alpha y^{*F'} \frac{\partial p^F}{\partial t} < 0$ in equation (6) captures the leakage effect, which provides a marginal disincentive for use of the carbon tax. In contrast, the term $-\alpha y^{*F'} \frac{\partial p^F}{\partial s} > 0$ in equation (7) captures the reverse leakage effect, which provides a marginal incentive for use of the green subsidy. An additional effect worth noting is the last term in (6), $-s y^{G'} \frac{\partial q^G}{\partial t} < 0$, which reflects another disincentive for using a carbon tax: with a positive green subsidy, a higher tax exacerbates the inefficient distortion in the G sector.

Using the first-order conditions above, it is straightforward to solve for the symmetric Nash equilibrium policies. Setting trade equal to zero and solving the system for t and s, we find:

$$t^N = \alpha \left(2 - \Phi \frac{\partial q^G}{\partial s}\right) \tag{8}$$

and

$$s^N = -\alpha \Phi \frac{\partial q^F}{\partial s} \cdot \frac{y^{F'}}{y^{G'}}, \tag{9}$$

where $\Phi = \left[\frac{\partial q^F}{\partial s}\frac{\partial q^G}{\partial t} - \frac{\partial q^G}{\partial s}\frac{\partial q^F}{\partial t}\right]^{-1} > 0$.[8] It is also straightforward to verify that $\Phi\frac{\partial q^G}{\partial s} > 1$, which implies $t^N < \alpha$. And recalling that $\frac{\partial q^F}{\partial s} < 0$, we can then state:

Proposition 1. *At a symmetric Nash equilibrium, each country chooses (i) $t < \alpha$, and (ii) $s > 0$ if and only if F is a substitute for G.*

Notice that the carbon tax is not only less then 2α because of standard free riding effect—it is less than α. Contributing to this result are the leakage effect and the incentive to reduce the G sector distortion.

The most important insight of Proposition 1, however, is that in an open economy setting, the green subsidy is used as an additional instrument to reduce the foreign supply of F. Recall that in a closed economy, a G lobby was necessary and sufficient to rationalize use of a subsidy. Our analysis here shows that, if F and G are substitutes, an open economy provides a unilateral welfare rationale for a green subsidy, in contrast to that of a closed economy, where the welfare maximizing subsidy is set to zero.[9] The fundamental intuition is that, in an open economy, a country reduces the carbon tax because of the leakage, but this creates an opportunity to use a green subsidy to lower the world price of F; and it is worth it because the subsidy distortion is second-order, whereas lowering the world price of F (with $t < \alpha$) generates a first-order benefit.

It is perhaps surprising that the targeting principle does not have bite here: a green subsidy is unilaterally optimal even though a more direct tool to lower p^F is a reduction in the carbon tax. Rather, the principle that applies here is the desirability of spreading out distortions over different margins, in this case over the two energy sectors.

It is also worth noting that, even though both a reduction in t and an increase in s serve to decrease production of F in the Foreign country, the two strategies have a fundamentally different nature. Reducing t is a "beggar thy neighbor" strategy, because it leads to lower Foreign emissions but higher domestic emissions, with a net increase in global climate damages. To see this, consider a setting where carbon taxes are the only available instrument, and Home reduces t unilaterally form an initial condition of symmetry. The global change in climate damages is then given by $\alpha y^{F'}\left(\frac{\partial q^F}{\partial t} + \frac{\partial p^F}{\partial t}\right) = \alpha y^{F'}\left(2\frac{\partial p^F}{\partial t} - 1\right) < 0$, where the sign follows because incomplete pass-through implies $\frac{\partial p^F}{\partial t} < \frac{1}{2}$. On the other hand, a green subsidy, assuming it is the only available instrument, leads to lower emissions for both Home

[8]To verify that $\Phi > 0$, it is convenient to rewrite the expression in terms of consumer prices, and recall that at a symmetric equilibrium the effect of policy changes on consumer prices have half the magnitude as those in a closed economy. Then using the expressions for price changes in the Appendix (see proof of Remarks 1 and 2), one can establish the sign of Φ.

[9]Note that if F is a complement for G, the sign of the subsidy is negative, meaning that countries tax production of G.

and Foreign, thereby resulting in lower global damages. Underlying the difference between the two policies is the leakage and reverse leakage effects previously described.

3.2 How does trade affect welfare?

Our comparison between closed and open economies prompts an additional question: How does trade affect welfare? The analysis above shows that opening up trade induces both countries to reduce carbon taxes, and this intuitively is bad for welfare. On the other hand, trade induces countries to use green subsidies, which may be beneficial. Intuitively, if the own-sector effects of policies are stronger than cross-sector effects, the adverse effect may dominate. In what follows we examine this intuition more formally. Of course, since we are abstracting from comparative advantage in our symmetric country setup, we are abstracting from standard gains from trade, so our analysis should be interpreted as isolating the impacts that trade has on welfare through the induced changes in climate policies.

We solve for the change in world welfare $W^W = W + W^*$, evaluated at the optimal policies for a closed economy ($t = \alpha$ and $s = 0$). This yields

$$dW^W = -\alpha y^{F'} \left[\frac{\partial q^F}{\partial (t = t^*)} dt + \frac{\partial q^F}{\partial (s = s^*)} ds \right], \tag{10}$$

where the notation makes clear that we are considering the effect of changing policies in both Home and Foreign. We have established above that each country will reduce t, and this has a negative effect on global welfare. With the possibility for subsidies, however, both countries will increase s, and this has a positive effect on global welfare. While in general the net effect could go either way, equation (10) shows that it must be negative if the own-sector effect of the carbon tax, $\frac{\partial q^F}{\partial t}$, is sufficiently stronger than the cross-sector effect of the subsidy, $\frac{\partial q^F}{\partial s}$.[10] Although equation (10) is evaluated locally at $t = \alpha$ and $s = 0$, the insight applies more generally on the path to the Nash equilibrium. The reason is that the welfare gain from increasing the green subsidy is diminished further as s becomes positive and increases, due to the increasing inefficiency of the G sector distortion. We therefore find the following:

Proposition 2. *Trade decreases welfare if* $\left|\frac{\partial q^F}{\partial s}\right|$ *is sufficiently small relative to* $\left|\frac{\partial q^F}{\partial t}\right|$.

Notice that, if subsidies are not available, in this setting with symmetric countries trade will always decrease welfare. Hence a more optimistic interpretation of Proposition 2 is that

[10] It turns out that dW^W in (10) has the opposite sign as the change in global climate damages. To see this, note that global climate damages are $2\alpha y^F(q^F)$, and differentiating this expression holding $t = t^*$ and $s = s^*$ yields $-2dW^W$.

models that take into account the endogeneity of carbon taxes but ignore the possibility of green subsidies may understate the gains from trade (or overstate the losses from trade).

4 International climate agreements

In this section, we turn to the analysis of welfare maximizing ICAs. We begin with the observation that a welfare maximizing ICA eliminates green subsidies even though subsidies exert positive international externalities at the noncooperative equilibrium. We then consider an interesting implication of this result: gradual ICAs may increase green subsidies before decreasing them. Finally, we show how an ICA that focused only on carbon taxes can be globally efficient, whereas one that focuses only on subsidies cannot.

4.1 International externalities from green subsidies

We model ICAs in the simplest possible way, by assuming that governments choose carbon taxes and green subsidies jointly to maximize global welfare, $W + W^*$.[11] We have already established the solution to this problem in Remark 5: $t = 2\alpha$ and $s = 0$ in both countries. Compared to the noncooperative solution, an ICA therefore increases the tax from $t < \alpha$ and decreases the subsidy from $s > 0$.

It is interesting to note that, despite the ICA pushing the policies in opposite directions, both t and s have positive international externalities at the noncooperative equilibrium. While this is well-known for a carbon tax, the result is more subtle for a green subsidy. To show it formally, we take the derivative of Home's welfare with respect to Foreign's subsidy and evaluate it at the symmetric Nash equilibrium:

$$\left.\frac{\partial W}{\partial s^*}\right|_{NE} = (t-\alpha)y^{F'}\frac{\partial q^F}{\partial s^*} - \alpha y^{*F'}\frac{\partial q^F}{\partial s^*} - sy^{G'}\frac{\partial q^G}{\partial s^*} > 0, \tag{11}$$

assuming as usual that F is a substitute for G. The first two terms capture the beneficial effect of avoided climate damages to Home: the first is because Foreign's subsidy reduces Home's production of F, and Home's carbon tax is below the country-level marginal damage α; the second is because Foreign's subsidy reduces its own production of F. The third term captures a more subtle, beneficial effect of Foreign's subsidy on Home through reduction of

[11] We are implicitly assuming that countries have access to international transfers. Even though explicit cash transfers are rarely observed in the context of international negotiations in general, governments have many ways to compensate each other, so this assumption seems reasonable. We also note that climate finance is beginning to play an important role as a form of international transfers in the negotiation of ICAs. At any rate, in our baseline model with symmetric countries such transfers are unnecessary.

the over-production distortion in Home's G sector, which in turn is due to Home's green subsidy (noting that $\frac{\partial q^G}{\partial s^*} = \frac{\partial p^G}{\partial s} < 0$). All three effects push in the same direction, so we can state:

Proposition 3. *The welfare maximizing ICA removes green subsidies even though they exert positive international externalities at the noncooperative equilibrium.*

How can we reconcile the statement that green subsidies have positive international externalities at the Nash equilibrium with the fact that global efficiency requires their complete removal? First note that this could never happen if the policies were one-dimensional: for example, if green subsidies were the only available policy instruments, they would have positive international externalities at the Nash equilibrium, and an ICA would increase them.

What underlies Proposition 3 is the interaction between the two policy instruments. Figure 1 illustrates the logic behind this result. With symmetric countries, we can focus on symmetric policies s and t. The $t^C(s)$ curve shows the globally optimal (symmetric) carbon tax as a function of the (symmetric) green subsidy, that is, the value of t that solves the first-order condition $\frac{\partial W^W(t,s)}{\partial t} = 0$ for a given s, where $W^W(t, s)$ denotes world welfare as a function of the symmetric policies t and s. Similarly, the $s^C(t)$ curve shows the globally optimal green subsidy as a function of the carbon tax, that is, the value of s that solves $\frac{\partial W^W(t,s)}{\partial s} = 0$ for a given t. The global-welfare maximizing policies are therefore given by the intersection of the two curves at point C.

The symmetric Nash equilibrium policies correspond to point N. As established above, green subsidies are positive at the Nash equilibrium, so point N lies Northwest of point C. We also know that the international externality from green subsidies at the Nash equilibrium is positive, that is, $\frac{\partial W}{\partial s^*}\Big|_{NE} > 0$. It is easy to see that this implies $\frac{\partial W^W}{\partial (s=s^*)}\Big|_{NE} > 0$,[12] and therefore point N must lie below the $s^C(t)$ curve. This reconciles the two statements in Proposition 3: in Figure 1, if s is increased locally starting from the Nash point while holding t fixed, so that we move up vertically from point N, global welfare increases, but nevertheless, maximizing global welfare requires moving from point N to point C, with subsidies being reduced to zero.[13]

[12] To see this, note that $\frac{\partial W^W}{\partial (s=s^*)}\Big|_{NE} = \left(\frac{\partial W}{\partial s} + \frac{\partial W}{\partial s^*} + \frac{\partial W^*}{\partial s^*} + \frac{\partial W^*}{\partial s}\right)\Big|_{NE} = \left(\frac{\partial W}{\partial s^*} + \frac{\partial W^*}{\partial s}\right)\Big|_{NE} > 0$, where $\frac{\partial W}{\partial s} = \frac{\partial W^*}{\partial s^*} = 0$ at the Nash equilibrium follows from optimality of the unilateral subsidy choices.

[13] In Figure 1 we show $t^C(s)$ and $s^C(t)$ as linear functions for illustrative purposes. While this will hold with linear supply and demand, the key qualitative features of the figure hold more generally. In particular, it can be shown that, if F and G are substitutes, concavity of $W^W(t, s)$ implies that (i) locally around point C, the curves $t^C(s)$ and $s^C(t)$ are strictly decreasing, with $t^C(s)$ steeper than $s^C(t)$, and (ii) $t^C(s)$ and $s^C(t)$ cross exactly once. Finally, as noted already, the observation that s has a positive international externality at the Nash equilibrium implies that the $s^C(t)$ curve, and therefore also the $t^C(s)$ curve, must be to the northeast of N.

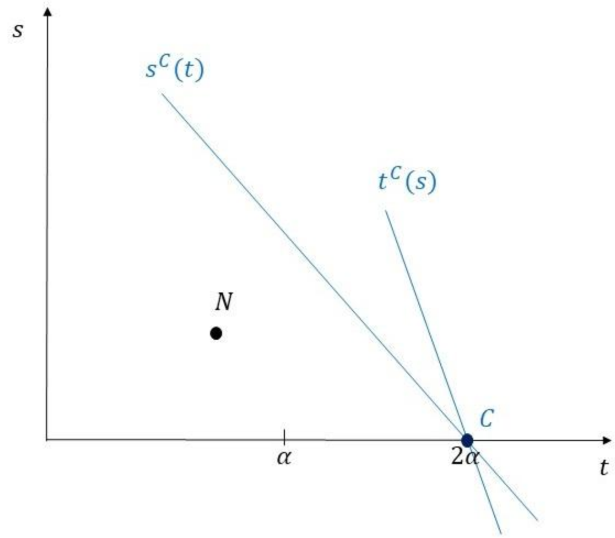

Figure 1: Noncooperative and cooperative policies in an open economy

4.2 Gradual agreements

Suppose there are frictions in the adjustment of policies, so that an ICA must change policies gradually. In this case, how will taxes and subsidies change over time? The result of Proposition 3 that green subsidies exert positive intenational externalities at the Nash equilibrium, even though efficiency requires their complete removal, suggests that it might be optimal for a gradual ICA to increase green subsidies before reducing them. Suppose for a moment that policies can only be changed marginally from the Nash equilibrium. Since the gradient of the welfare function evaluated at the Nash policy levels points northeast (see Figure 1), the steepest welfare increase is achieved by increasing both t and s. Thus a "local" ICA would increase subsidies, while the full ICA would remove them, suggesting that a gradual ICA may change subsidies non-monotonically.

We examine gradual agreements more formally with a simple dynamic variation of the model where ICAs are constrained to change policies gradually. Our approach is not to *explain* gradualism in international agreements, but only to explore its implications for the time path of taxes and subsidies. While this means we model gradualism in an admittedly ad-hoc manner, the simple setup is useful to establish how the direction of change for optimal green subsidies can be non-monotonic We consider a continuous-time setting and assume policies must be changed at finite speed starting from the Nash levels. The "speed limits" are finite, but can be arbitrarily high, and they can differ across policy instruments. We have in mind that it may be politically costly to change environmental policies very quickly. For example, a government may need to build political support for an increase in carbon taxes, and this may take time, perhaps because voters need convincing that climate change is a serious problem and requires government intervention.[14]

Formally, let $z \in [0, \infty)$ denote time, $s(z)$ and $t(z)$ the time paths of policies, taken to be symmetric across countries, and ρ the discount rate. The speed limits are represented by the constraints $|\dot{s}(z)| \leq \overline{u}_s$ and $|\dot{t}(z)| \leq \overline{u}_t$, with $\overline{u}_s, \overline{u}_t > 0$. Recalling that (s^N, t^N) denotes the (symmetric) Nash equilibrium policies, the optimization problem can be written as

$$\begin{aligned} & \max_{s(z),t(z)} \int_0^\infty e^{-\rho z} W^W(s(z), t(z)) dz \\ s.t. \quad & |\dot{s}(z)| \leq \overline{u}_s, \left|\dot{t}(z)\right| \leq \overline{u}_t \\ & s(0) = s^N, t(0) = t^N. \end{aligned}$$

This problem can be solved with standard optimal control techniques, the details of which we present in the Appendix. Here we provide an intuitive discussion. Consider two opposite extremes: one where only t is subject to a speed limit, and the one where only s is subject to a speed limit. In the first case, $\overline{u}_t$ is finite and $\overline{u}_s$ is infinite. Referring back to Figure 1, it is intuitive for the optimal subsidy to increase at time zero from the Nash level to $s^C(t^N)$, and then for the policy vector to move down the $s^C(t)$ curve (with a speed dictated by $\overline{u}_t$) until reaching the first-best point C. In this case, the ICA increases the subsidy before decreasing it, while the tax increases monotonically. In the second case, where $\overline{u}_t$ is infinite and $\overline{u}_s$ is finite, it is optimal for t to increase at time zero from the Nash level to $t^C(s^N)$, and then for the policy vector to move along the $t^C(s)$ curve until reaching point C. In this case, therefore, the ICA changes both policies monotonically.

These examples suggest that if the adjustment friction is more important for t than for s, so that $\overline{u}_t/\overline{u}_s$ is small, then the ICA should increase s initially and then reduce it, whereas in the opposite case, the ICA should decrease s monotonically. This intuition turns out to

[14] Gradualism can also be rationalized, under some conditions, when there are costs of adjustment in the reallocation of resources across sectors. As Mussa (1984) argues, in this case gradualism may be politically efficient if the government places a higher weight on the owners of specific factors that need to be reallocated. Maggi and Rodriguez-Clare (2007) consider a setting with similar features as the one discussed by Mussa, but it is interesting to note that their setting does not give rise to a gradual reduction of tariffs starting from the noncooperative equilibrium. In their setting, the first phase of liberalization consists of an abrupt drop in the tariff from the noncooperative level to the one that maximizes political efficiency given the initial allocation of capital. The reason is that the government can compensate the import-competing lobby for its losses with a side transfer. Only subsequently, as capital starts flowing out of the import sector, does the tariff decreases further in a gradual way, following the (static) politically-efficient level as a function of the evolving allocation of capital. But a simple modification of that setting could provide a micro-foundation for the gradualism in policy changes that we assume here: if the government is not allowed to transfer money to the lobbies (while lobbies can contribute money to the government), then the only way to mitigate the losses to the F lobby as the ICA increases the carbon tax might be to do it gradually, as this gives time to the specific-factor owners to move out of the F sector. Exploration of this possible micro-foundation for policy gradualism is the subject of work in progress.

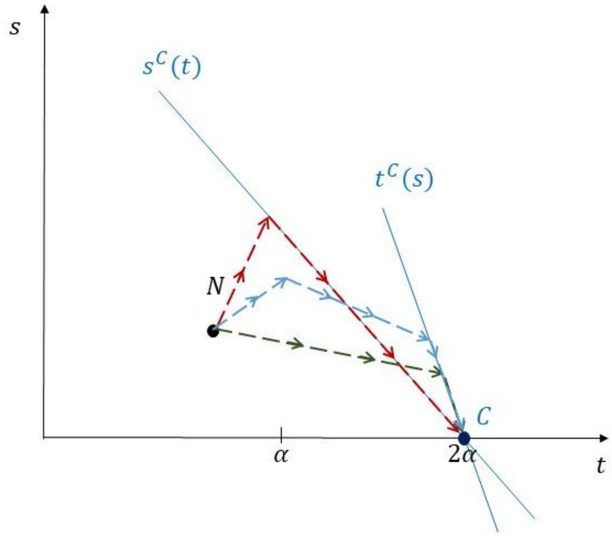

Figure 2: The optimal gradual agreement

be correct. Indeed, we show that there exist two thresholds ν_0 and ν_1 such that the optimal path of the policy vector is as follows: (a) If $\overline{u}_t/\overline{u}_s < \nu_0$, the policy vector moves from the Nash point in the northeast direction until it hits the $s^C(t)$ curve, and then slides along this curve until reaching the first-best point C. This case is depicted as the red path in Figure 2. (b) If $\nu_0 < \overline{u}_t/\overline{u}_s < \nu_1$, the policy vector initially moves northeast, then turns southeast before crossing the $s^C(t)$ curve, eventually hitting the $t^C(s)$ curve and following it until reaching C, as shown in blue in Figure 2. (c) If $\overline{u}_t/\overline{u}_s > \nu_1$, the policy vector moves southeast until it hits the $t^C(s)$ curve and follows it until reaching C, as shown in green in Figure 2.

Noting that in both cases (a) and (b) the subsidy increases before it decreases, while in case (c) the subsidy decreases monotonically, we can state the following:

Proposition 4. *There exists a threshold ν_1 such that: (i) If $\overline{u}_t/\overline{u}_s < \nu_1$, the ICA increases green subsidies before reducing them; (ii) If $\overline{u}_t/\overline{u}_s > \nu_1$, the ICA decreases green subsidies monotonically.*

We note that the speed limits can be arbitrarily high, that is, only the relative speed limits matter for the qualitative structure of the optimal path. In other words, the result holds even if policies can be changed fast, as long as they cannot be changed instantaneously.

Note that adjustment frictions of the kind we model here could never give rise to a non-monotonic time path if the policy were one-dimensional: the policy would move gradually from the starting point to the optimal point, but in a monotonic way. The non-monotonicity is a consequence of the interaction between the two policies. It is also worth emphasizing that the logic behind Proposition 4 is not simply the standard notion that green subsidies are a second-best policy if carbon taxes are constrained. Rather, the result stems from the more subtle feature that green subsidies exert positive international externalities at the non-cooperative equilibrium. To make this clear, suppose for a moment that the starting policy levels were not the Nash levels (s^N, t^N), but, for example, a point inside the cone between the $s^C(t)$ and $t^C(s)$ curves in Figure 2. In this region, subsidies exert negative international externalities, and as a consequence, the optimal path would entail a monotonic reduction of s regardless of $\overline{u}_t/\overline{u}_s$.

Finally, the implications of Proposition 4 appear consistent with the observation that current ICAs implicitly encouraged governments to promote green subsidies, as noted with UNFCCC objectives for renewable energy at the outset of the paper. If viewed through the lens of the model, this might be the first phase of an optimal path that would eventually reduce green subsidies and rely heavily on carbon taxes. According to the model, this two-phase approach might be efficient if policies can only be changed gradually, with carbon taxes facing stronger adjustment frictions than green subsidies.

4.3 Scope of the ICA

We now return to the static model to make a point about the scope of ICAs. We have thus far assumed an ICA that includes provisions for both t and s. But the inclusion of both instruments within the scope of an ICA may increase the costs of negotiation, enforcement, or both. This raises the question of whether it might be worthwhile for an ICA to focus only on t or only on s.

Let us begin with an ICA that focuses only on t. To illustrate a key feature of the result, we relax for the moment the assumption that $\alpha = \alpha^*$. It is clear that global efficiency requires $t = \alpha + \alpha^*$ and $s = 0$ in both countries. We now ask: if the ICA simply sets the tax at its first best level $t = \alpha + \alpha^*$ and leaves subsidies at the governments' discretion, how will governments choose their unilateral subsidies? We focus on Home without loss of generality. We impose $t = \alpha + \alpha^*$, write down the first-order condition for Home's subsidy and evaluate at $s = 0$:

$$\left.\frac{\partial W}{\partial s}\right|_{t=\alpha+\alpha^*, s=0} = \left(\alpha^* y^{F'} - \alpha y^{*F'}\right) \frac{\partial q^F}{\partial s}. \tag{12}$$

This expression is equal to zero if countries are symmetric, and this implies that countries will respond with zero subsidies, thereby responding in a way that is globally efficient.[15] Equation (12) nevertheless shows that the result no longer holds with asymmetry in marginal

[15] While we continue to assume countries are symmetric in all ways other than possibly for $\alpha \neq \alpha^*$, we use different notation for Home and Foreign supply of F in equation (12) to facilitate intuition.

damages. In particular, Home will want a green subsidy if $\alpha^* < \alpha$, and a green tax (i.e., $s < 0$) otherwise. To see why Home would want a green subsidy if $\alpha^* < \alpha$, notice that the consequent decrease in q^F has two effects reflected in equation (12). The first term captures the marginal cost of a decrease in q^F due to the fact that, given $t = \alpha + \alpha^*$, from Home's unilateral perspective its fossil sector is being overtaxed by α^*; and the second term captures Home's marginal benefit of reducing Foreign's supply of fossil energy. If the latter effect outweighs the former (i.e., if $\alpha^* < \alpha$), then Home wants a green subsidy.

Reversing the question above, we may ask: Might countries choose the globally optimal taxes if the ICA constrains only the subsidies at $s = 0$? The answer in this case is clearly no, for reasons described previously: the standard free riding effect and leakage, both of which would cause countries to set taxes less than their domestic marginal damages. We summarize these two results as follows.

Proposition 5. *An ICA that focuses only on carbon taxes leads to global efficiency if and only if countries are symmetric. On the other hand, an ICA that focuses only on green subsidies can never achieve global efficiency.*

This result suggests that in the presence of contracting costs, such as costs of negotiating and/or enforcing policy commitments, an incomplete agreement that focuses only on carbon taxes may be optimal if countries are not too asymmetric. Or viewed from a different perspective, it may be worth incurring the costs of contracting over green subsidies only if countries are sufficiently asymmetric.[16]

5 The effects of lobbying

We now introduce lobbying to our open economy setup and focus on two questions: How does lobbying affect the welfare of countries at the noncooperative equilibrium? And what are the welfare effects of ICAs in the presence of lobbying?

5.1 Welfare effects of lobbying in the noncooperative scenario

We assume for simplicity that the political parameters $\gamma^F, \gamma^G \geq 0$ are the same in both countries. Solving for the symmetric Nash equilibrium policies, we find

$$t^N = \alpha \left(2 - \Phi \frac{\partial q^G}{\partial s} \right) - \gamma^F \frac{y^F(q_N^F)}{y^{F\prime}(q_N^F)} \tag{13}$$

[16]For a paper that examines the optimal scope of trade agreements in the presence of contracting costs, although in a different setting, see Horn et al. (2010).

and

$$s^N = -\alpha\Phi\frac{\partial q^F}{\partial s}\cdot\frac{y^{F'}(q_N^F)}{y^{G'}(q_N^G)} + \gamma^G\frac{y^G(q_N^G)}{y^{G'}(q_N^G)}, \tag{14}$$

where q_N^i denotes the producer price for input i at the Nash equilibrium policies.[17] These expressions are a generalization of the policies in equations (8) and (9): the first term of each expression corresponds to the unilateral welfare-maximizing level of the policy, and the second term captures the impact of lobbying.

Now consider the comparative-static effects of changes in the political parameters γ^F and γ^G on the equilibrium policies. We can distinguish between the direct and indirect effects of changes in γ^F and γ^G on the equilibrium policy levels. Consider for example increasing the strength of the F lobby, γ^F: the direct effect is a decrease in the carbon tax, as can be seen in (13). This decrease in t will then have indirect effects through two channels. The first is through the supply levels y^F and y^G. Decreasing t pushes up q^F and pushes down q^G, thus boosting output of F and reducing output of G; this in turn further decreases t and reduces s. The second channel operates through the price derivatives (e.g. $\frac{\partial q^i}{\partial s}$) and the supply slopes ($y^{F'}$ and $y^{G'}$), to the extent that supply and demand functions are nonlinear. In what follows, to make our results sharper and more transparent, we assume that the indirect effects through the second channel cannot outweigh the other effects outlined above. This is satisfied for example if demand and supply functions are linear. In this case, it is easy to see that increasing the power of a lobby has the intuitive effect of changing both policies in the direction desired by that lobby: more specifically, an increase in γ^F reduces both the carbon tax and the green subsidy, and an increase in γ^G leads to a larger green subsidy and a higher carbon tax.

We can now turn to the welfare effects of lobbying. We first state our result and then provide some intuition.

Proposition 6. *(i) Strengthening the F lobby reduces welfare, provided the G lobby is not too strong; (ii) Strengthening the G lobby increases welfare, provided the G lobby does not get too strong.*

This result states that, in our open economy setting, the F and G lobbies have strongly asymmetric effects on welfare, with the former looking more ominous than the latter. To understand this result, note that the change in global welfare is given by $dW^W = \frac{\partial W^W}{\partial t}dt + \frac{\partial W^W}{\partial s}ds$, where it should be kept in mind that the policy changes are symmetric in the two

[17] Here we write the producer prices as explicit arguments of y^i and $y^{i'}$ as it will prove useful later in the paper when making comparisons between the Nash and cooperative policies.

countries. Now recall from our previous discussion of Figure 1 that the Nash point N absent lobbying lies below the $s^C(t)$ curve. It follows that if the G lobby is not too strong, the point N continues to lie below the $s^C(t)$ curve and this helps to understand part (i) of Proposition 6. In this region, we have $\frac{\partial W^W}{\partial t} > 0$ and $\frac{\partial W^W}{\partial s} > 0$, where the latter inequality is due the positive international externality of the subsidy. Then since strengthening the F lobby reduces t and s, it follows that it decreases welfare. To understand part (ii) of Proposition 6, note again that, regardless of the strength of the F lobby, the N point is below the $s^C(t)$ curve as long as the G lobby is not too strong. Hence because strengthening the G lobby increases s and t, it follows immediately that it increases welfare.

Intuitively, the reason why the F lobby tends to be bad for welfare and the G lobby tends to be good for welfare is closely related to the way that green subsidies have positive international externalities at the noncooperative equilibrium, even though efficiency requires their removal. This implies that, starting from the noncooperative equilibrium absent lobbying, an increase in t and s is good for welfare, and this is exactly what a *moderate* G lobby achieves. On the other hand, the F lobby pushes policies in the opposite direction, which is bad for welfare. Nevertheless, if the G lobby becomes too strong it no longer brings about welfare benefits. In particular, if green subsidies are large enough that the Nash point N in Figure 1 lies above the $s^C(t)$ curve, then $\frac{\partial W^W}{\partial s} < 0$, and a further strengthening of the G lobby will reduce welfare, as the greater distortion from s outweighs the welfare gain from increasing t.[18]

5.2 Can ICAs decrease welfare?

We now consider how lobbying impacts the formation of an ICA, and in particular, we ask whether a politically-pressured ICA can decrease welfare relative to the noncooperative equilibrium. Note that this is a very different question from the one considered in the previous subsection. There we examined how changes in the political parameters affect welfare in the noncooperative equilibrium. Here we hold the political parameters constant and examine how an ICA changes welfare relative to the noncooperative equilibrium.

We assume the ICA sets the policy levels t and s to maximize the sum of the governments' (politically-adjusted) payoffs, denoted $\Omega^W \equiv \Omega + \Omega^*$. Letting t^C and s^C denote the policies

[18] We note that the results discussed here are predicated on the assumption that lobbies are symmetric across countries. While introducing asymmetry opens the door to other possibilities, the direct welfare effect of changing a lobby's strength in a single country is qualitatively similar. For example, a stronger F lobby at Home lowers t and s at Home, and both changes are bad for global welfare assuming the G lobby is not too strong. If this direct effect dominates the indirect effects, the qualitative result identified above should continue to hold.

that maximize Ω^W, it is straightforward to verify that

$$t^C = 2\alpha - \gamma^F \frac{y^F(q_C^F)}{y^{F\prime}(q_C^F)} \text{ and } s^C = \gamma^G \frac{y^G(q_C^G)}{y^{G\prime}(q_C^G)}, \tag{15}$$

where q_C^i denotes the respective equilibrium producer price at the cooperative policies. Note that the cooperative policies differ from the noncooperative policies in (13) and (14) in two respects. The first is the absence of the terms that capture the unilateral environmental motive for policies (these are the terms that contain Φ). The second is that the inverse supply semi-elasticities $\frac{y^i}{y^{i\prime}}$ are evaluated at different producer prices, q_C^i versus q_N^i.

Before considering the welfare effects of an ICA, we first examine two related positive questions: What motivates an ICA in a politically-pressured environment, or more specifically, what international policy externalities does it address? And how does the ICA change policies relative to the noncooperative equilibrium?

To the first question, we can show that, in our symmetric setting with no terms-of-trade motives for policies, the ICA is motivated entirely by the international environmental externalities, and there is no "international political externality" for the ICA to address. To see this, shut down the environmental externality by setting $\alpha = 0$, and note that the Nash and cooperative policies coincide, comparing (13) and (14) to the equations in (15), implying no scope for an ICA. Underlying this result is the fact that production subsidies (or reductions in production taxes) are the targeted instruments for the purpose of redistribution to lobbies. Loosely speaking, a change in the Foreign production instruments cannot "help" the Home government politically, because Home can already help itself by choosing its own production instruments in a politically optimal way.[19]

Our second question calls for a comparison between the Nash policies (t^N, s^N) in (13) and (14) and the cooperative policies (t^C, s^C) in (15). We can distinguish between direct and indirect effects of the ICA on policies. The direct effect of the ICA is that it removes the terms that capture the unilateral environmental motive for policies, thus increasing t by $\alpha\Phi\frac{\partial q^G}{\partial s}$ and decreasing s by $\alpha\Phi\frac{\partial q^F}{\partial s}\frac{y^{F'}}{y^{G'}}$. The indirect effect is that these policy changes affect the producer prices and hence the supply semi-elasticities, which feed back into the equilibrium policy levels. One simple condition that ensures that the indirect effect does not outweigh the direct effect is that the supply semi-elasticities not vary too much with the producer prices. Under this assumption, we can state:

Remark 6. Regardless of lobbying pressures, the ICA increases t and decreases s, moving

[19]This result stands in interesting contrast with the results in Maggi and Ossa (2023). There, governments choose standards and production instruments are not available, implying that standards do have international political externalities at the noncooperative equilibrium.

them closer to their Pigouvian levels: $t^N < t^C < 2\alpha$ and $s^N > s^C > 0$.

Note by the expressions in (15) that the ICA can never push the carbon tax above its Pigouvian level (2α), and likewise, it can never push the green subsidy below its Pigouvian level (zero). Hence a politically-pressured ICA that increases carbon taxes and decreases green subsidies will do so only part-way toward their Pigouvian levels.

We now turn to the normative question of the welfare effects of a politically-pressured ICA. The analysis thus far has established that, even in the presence of lobbying, the only purpose of an ICA in our setting is to address the global environmental externalities, and that the ICA moves carbon taxes and green subsidies in the direction of their Pigouvian levels. These observations might suggest that the ICA must increase welfare relative to the noncooperative equilibrium, but we now show this is not necessarily the case.

To examine the welfare effect of the ICA, we consider the directional derivative of global welfare as we move from the Nash policies (t^N, s^N) to the cooperative policies (t^C, s^C). We let $\nabla W^W|_{N\to C}$ denote this derivative, $\Delta t \equiv t^C - t^N > 0$, and $\Delta s \equiv s^C - s^N < 0$. Solving for the derivative, we can write

$$\begin{aligned}
\nabla W^W|_{N\to C} &= \frac{\partial W^W}{\partial(t=t^*)} + \frac{\partial W^W}{\partial(s=s^*)} \cdot \frac{\Delta s}{\Delta t} \\
&= \left[\underbrace{-(t-2\alpha)y^{F'} \frac{\partial q^F}{\partial(t=t^*)}}_{\text{net env benefit}} \underbrace{-sy^{G'} \frac{\partial q^G}{\partial(t=t^*)}}_{\text{higher } G \text{ distortion}} \right] \\
&+ \left[\underbrace{-(t-2\alpha)y^{F'} \frac{\partial q^F}{\partial(s=s^*)}}_{\text{net env loss}} \underbrace{+sy^{G'} \frac{\partial q^G}{\partial(s=s^*)}}_{\text{lower } G \text{ distortion}} \right] \cdot \frac{\Delta s}{\Delta t},
\end{aligned} \tag{16}$$

This expression is useful because the total change in world welfare caused by the ICA is the integral of the above derivative over the straight line between (t^N, s^N) and (t^C, s^C). The first square bracket on the right-hand side is the marginal welfare effect of the increase in the (symmetric) tax, recalling that our notation implies we are changing policies symmetrically in both countries. This includes the net environmental benefit due to the reduction in q^F, and the cost of the overproduction distortion in the G sector, due to the fact that the increase in t boosts q^G. Note that the latter effect is more sizable when the G lobby is stronger, because in this case s is larger in both the N and C equilibria, and hence at any point in between. The second square bracket is the marginal welfare effect of the decrease in the (symmetric) subsidy. This includes the environmental loss due to the increase in q^F, and the benefit of reducing the overproduction distortion in the G sector. Finally, the last term outside the brackets reflects the direction of the policy change:

$$\frac{\Delta s}{\Delta t} = \frac{\alpha\Phi\frac{\partial q^F}{\partial s}\cdot\frac{y^{F'}}{y^{G'}} - \gamma^G \Delta\left(\frac{y^G}{y^{G'}}\right)}{\alpha\Phi\frac{\partial q^G}{\partial s} + \gamma^F\Delta\left(\frac{y^F}{y^{F'}}\right)}, \tag{17}$$

where $\Delta\left(\frac{y^i}{y^{i'}}\right) \equiv \frac{y^i(q_N^i)}{y^{i'}(q_N^i)} - \frac{y^i(q_C^i)}{y^{i'}(q_C^i)}$ for input $i = F, G$.

The different terms in equation (16) suggests a way in which the ICA might decrease welfare. Consider a strong G lobby (i.e., large γ^G) that causes a large green subsidy s. Then if the cross-sector effect $\frac{\partial q^G}{\partial t}$ is nonegligible, the ICA might decrease welfare, because the carbon tax increase brought about by the ICA causes a substantial worsening of the distortion in the G sector.[20] In fact, the ICA is guaranteed to reduce welfare if, in addition to the conditions just mentioned, the ICA does not reduce the green subsidy by much (i.e., Δs is small), so that the last two terms in (16) are muted. This is the case, for example, if supply semi-elasticities are constant (so that $\Delta\left(\frac{y^G}{y^{G'}}\right) = 0$) and $\frac{\partial q^F}{\partial s}$ is small, as shown in the numerator of (17). At a broad level, the two key elements that make the ICA more likely to decrease welfare are (*i*) a strong G lobby, and (*ii*) asymmetric cross-sector effects of policies on prices, with $\frac{\partial q^G}{\partial t}$ larger than $\frac{\partial q^F}{\partial s}$.

The following proposition states conditions under which the ICA can have adverse welfare effects:

Proposition 7. *The ICA can decrease welfare if γ^G is large and $\frac{\partial q^G}{\partial t}$ is large relative to $\frac{\partial q^F}{\partial s}$.*

While the possibility of a welfare-reducing ICA may be surprising in light of Remark 6 and the discussion that precedes it, we emphasize that a variety of alternative conditions will guarantee that the ICA increases welfare. For example, if both γ^F and γ^G are small, the ICA must increase welfare. This is true also if γ^F is large, so that t^N is much lower than 2α, or if both cross-sector effects, $\frac{\partial q^F}{\partial s}$ and $\frac{\partial q^G}{\partial t}$, are small, in which case the ICA has effects similar to that in a setting absent the G sector.

Finally, it is important to recall that we have shut down terms-of-trade motives for an ICA, by focusing on the case of symmetric countries. Introducing a terms-of-trade motive could affect the welfare impacts of the ICA in interesting ways. Even though preventing terms-of-trade manipulation by governments tends to be good for welfare in a standard setting without environmental externalities, this is not necessarily the case in our setting

[20] In the discussion here, we refer to the relative magnitudes of price changes, e.g. $\frac{\partial q^j}{\partial t}$, without carrying around the more cumbersome notation for symmetric changes in policy, e.g. $\frac{\partial q^j}{\partial(t=t^*)}$, noting that statements about the relative magnitudes of the former apply to the latter as well.

here. For example, focus on carbon taxes. As is well known in the literature on terms-of-trade motivated agreements (Grossman and Helpman 1995; Bagwell and Staiger 1999), the politically efficient policy levels do not reflect terms-of-trade effects. On the other hand, in the noncooperative scenario here, a country that exports fossil fuels will want to increase its carbon tax—other things equal—for terms-of-trade manipulation purposes, and this may mitigate the "under-taxing" incentives we highlighted above. Thus, intuitively, the welfare gains from an ICA might be lower (or the welfare losses might be higher) than absent terms-of-trade effects.

6 What about trade and consumption taxes?

In this final section, we discuss how some of our main results are likely to change if we allow for trade taxes or consumption taxes in the energy sectors.[21] It is well known that, if all instruments are unconstrained and can be costlessly used, a combination of production and trade instruments is equivalent to a combination of production and consumption instruments. In reality, however, trade taxes are constrained by existing trade agreements, and consumption taxation may be administratively costly, thus making it meaningful to consider both policy packages. We start by considering trade instruments in addition to production instruments.

6.1 Trade taxes

In this section we consider a government's choice of production and trade taxes when the latter are constrained in ways that reflect long-standing GATT-WTO rules. In particular, the GATT imposed a strict ban on export subsidies a long time ago, and the WTO has imposed caps on import tariffs that are on average very low.[22] In addition to this, a multitude of free trade areas and customs unions have all but eliminated trade restrictions among their member countries, in part because of the strictures of GATT's Article XXIV.[23].

Here we take the constraints on trade instruments as pre-determined when governments

[21] We can also allow for a tax on the final good A, but since this good is not traded, production taxes are equivalent to consumption taxes in this sector. We can show that a tax on A is redundant, and we therefore ignore it in what follows.

[22] The treatment of export taxes in the GATT-WTO is more complex. Export taxes are generally allowed, but a number of WTO accession agreements, and most notably the one involving China in 2001, include disciplines on export taxes. We also note that most free trade areas and customs unions prohibit trade taxes among their member countries. And some countries, including the United States, have banned export taxes by constitution.

[23] GATT's Article XXIV states that preferential trade agreements are allowed only if they eliminate substantially all trade barriers between member states.

choose their climate policies. Ideally, a richer model would explain the constraints on trade instruments from first principles, but here we take them as given.[24] We will assume that export subsidies are not available and tariffs are subject to caps. We take the tariff caps as given but do not impose any structure on them, and we will consider both the case where they are binding and the case where they are not.[25]

While in the previous sections we focused mostly on the case of symmetric countries to make our points more transparent, in this discussion it is natural to allow for asymmetric countries, so that there is trade in equilibrium. We will refer to a country as a "natural" importer (exporter) of a given commodity if that country imports (exports) that commodity under laissez-faire. In the interest of space, we focus our discussion on Home's welfare-maximizing policies assuming that the foreign government is passive.

To build intuition, we start by considering the benchmark case where trade instruments are unconstrained. In this case, it is easy to show that the optimal unilateral policy is to impose a production tax equal to α in the F sector and use trade instruments in both the F and G sectors, refraining from using production instruments in the G sector. In particular, each country will use trade policy for two purposes: (i) to manipulate terms-of-trade (TOT) and (ii) to reduce the world price of F in order to reduce emissions in the other country. The TOT motive pushes both countries toward trade taxes in each energy sector. The environmental motive, on the other hand, pushes policies in different directions depending on the direction of the trade flow: in each energy sector, this motive pushes an exporter toward an export subsidy and an importer toward an import tax.

The logic above implies that a natural exporter of energy (whether green or fossil) will subsidize exports if the environmental motive outweighs the TOT motive, and will tax exports in the opposite case.

On the other hand, the optimal trade policy for a natural importer of energy is more subtle, because the environmental policy motive can turn a natural importer into an exporter. Intuitively, the only way to significantly reduce the world price of F may be to induce exports with an export subsidy. Thus, if under laissez-faire a country imports a small amount in a given energy sector, the TOT motive for a tariff is weak, so the environmental motive may call for an export subsidy that turns the country into an exporter in that sector. A strong natural importer of energy, however, will tax imports, both for TOT and environmental reasons.

[24] We note that there is no widely accepted theoretical explanation for the GATT ban on export subsidies. See for example Maggi (2014) for a survey of the relevant literature.

[25] In reality the constraints on trade policy imposed by the WTO are imperfectly enforceable, and governments sometimes knowingly violate them (as recent events reminded us), but this arguably carries significant costs.

Now let us revisit the optimal unilateral policies in a world where export subsidies are banned and tariffs are capped. Let us focus on the green energy sector.

Using the logic above, if a country has a comparative advantage or a slight comparative disadvantage in the G sector, so that the optimal unconstrained policy is an export subsidy, since this instrument is banned it will resort to the next best instrument, which is a green production subsidy, just as in our basic model. On the other hand, if a country has a strong comparative disadvantage in the G sector, so that the optimal unconstrained policy is a tariff, then if the tariff cap is binding it will supplement the tariff with a green production subsidy, otherwise it will only use a tariff. In the F sector something similar will happen, except that the optimal production tax is shifted up by α.

Finally, while our model has only two countries, it suggests an insight regarding regional trade agreements. Suppose a country is involved in a free trade area or a customs union, so that it can use trade restrictions with some trading partners but not with others. Then there are two distinct environmental motives for policy: decreasing the price of F in the countries that are part of the same regional trade agreement(s), and decreasing the price of F in the rest of the world. The first of these two objectives cannot be pursued with trade policy, so this creates a unilateral motive for reducing the carbon tax and rolling out a green subsidy, while the second of these objectives can be pursued in part with trade policies, as discussed above, to the extent that they do not run afoul of WTO constraints.

6.2 Consumption taxes

In a world where trade taxes and subsidies are severely constrained, it is natural to consider the possibility for consumption taxes. We start by considering a setting where consumption taxes are unconstrained, and then discuss possible limitations to the use of these instruments. And again, we focus on the unilateral welfare-maximizing choice of policies.

Suppose the Home government can freely use production taxes and consumption taxes (but not trade taxes), with the Foreign government passive. It is not hard to show that the optimal unilateral policy entails: (i) a carbon tax lower than α and a consumption tax on F; (ii) a production subsidy coupled with an equal-rate consumption tax on G. This policy package implements the same allocation as the optimal (unconstrained) combination of production and trade taxes that we considered above, but with production subsidies and consumption taxes, rather than border policies, in the G sector. Note that the production subsidy in the G sector will be lower in magnitude than in our baseline model with only production instruments. The intuition is that it is optimal to spread the policy distortion across all instruments, so that it is still optimal to subsidize green energy but the magnitude of the subsidy is smaller than absent consumption taxes.

Several authors (for example Weisbach et al., 2023) have argued that the scope for consumption taxes in the energy sector may be limited by significant administrative costs. For example, if green energy and fossil-fuel energy are both inputs to produce electricity, the government will have to collect differential taxes on purchases of the two forms of energy from the electricity producer, and this may be costly to administer and monitor. To the extent that the use of consumption taxes is limited by administrative costs, intuitively the production instruments in the F and G sectors will become more important, and we will get closer to the production-instrument-only setting of our basic model.

7 Conclusion

In this paper, we have developed a simple and tractable model to examine positive and normative questions that arise with the simultaneous use of carbon pricing and green subsidies in an open economy setting with global climate externalities. The basic and key elements of our model are a final good that uses use two forms of energy inputs—fossil fuel, which generates a global externality, and green energy, which does not—and both energy sectors can exert political pressure through lobbying. The model generates novel insights around three broad questions: How does the availability of both carbon taxes and green subsides affect the unilateral choices of each instrument? When it comes to international cooperation, should ICAs seek to increase or decrease green subsidies, or even ignore them entirely? Finally, what are the welfare consequences of lobbying by the fossil and green energy sectors on the noncooperative and cooperative setting of policies?

We have made a number of simplifying assumptions throughout the paper in order to make the results sharp. Relaxing some of these assumptions may enable the model to address further interesting questions. For example, we have focused on global climate damages as the only source of market failure, but green subsidies can also be motivated by R&D externalities, external economies of scale or learning by doing spillovers. These other market failures would provide an "industrial policy" rationale for green subsidies that could interact in interesting ways with the climate change rationale that our basic model focuses on. Another frutiful direction of extension of our model would be to allow for asymmetries across countries, both in the structure of supply and demand – and hence comparative advantage – and in the countries' valuations of global climate damages. Doing so may help illuminate, for example, why some countries rely more on carbon pricing and others rely more on green subsidies (Clausing and Wolfram 2023), and may generate different policy implications for developed and developing countries.

8 Appendix

8.1 Proof of Remarks 1 and 2

We let subscripts denote partial derivatives with respect to the corresponding argument. It is first useful to prove that the assumptions $a_2^i > 0$ and $a_2^i < |a_1^i|$ for $i = F, G$ are sufficient to establish $d_2^F d_2^G - d_1^G d_1^F < 0$. Differentiating the general equilibrium demand functions in (1) and rearranging, we have

$$d_2^F d_2^G - d_1^G d_1^F = \left(a_2^F a_2^G - a_1^F a_1^G\right) \tilde{d}\tilde{d} + \left(a_2^F a^G - a_1^G a^F\right) \tilde{d}_1 \tilde{d} + \left(a^F a_2^G - a^G a_1^F\right) \tilde{d}_2 \tilde{d} < 0$$

where the first term is negative because the own-price effect is greater, and $a_2^F, a_2^G > 0$ ensures the second two terms are negative.

Now, differentiating the market clearing conditions, we can solve for the change in prices due to changes in policy. In doing so, it is helpful to define $\Theta = d_2^F d_2^G - (d_1^F - y^{F\prime})(d_1^G - y^{G\prime}) < 0$, where the sign follows because $d_2^F d_2^G - d_1^G d_1^F < 0$. The within-sector effect of a change in t is

$$\frac{dp^F}{dt} = \frac{(d_1^G - y^{G\prime})y^{F\prime}}{\Theta},$$

and it follows that $0 < \frac{dp^F}{dt} < 1$. For a change in s, we have

$$\frac{dp^G}{ds} = \frac{-(d_1^F - y^{F\prime})y^{G\prime}}{\Theta},$$

and it follows that $-1 < \frac{dp^G}{ds} < 0$. These two conditions prove Remark 1.

Turning to the cross-sector effects, we have

$$\frac{dp^G}{dt} = \frac{-y^{F\prime} d_2^G}{\Theta}$$

and

$$\frac{dp^F}{ds} = \frac{d_2^F y^{G\prime}}{\Theta}.$$

Hence $\frac{dp^G}{dt} >$ if and only if G is a substitute for F, and $\frac{dp^F}{ds} < 0$ if and only if F is a substitute for G. These conditions prove Remark 2.

8.2 Proof of Remark 3

Differentiating (2) with respect to t and s yields the first-order conditions:

$$\frac{\partial W}{\partial t} = \underbrace{-d(\cdot)\left(a^F\frac{\partial p^F}{\partial t} + a^G\frac{\partial p^G}{\partial t}\right)}_{-y^F\frac{\partial p^F}{\partial t} - y^G\frac{\partial p^G}{\partial t}} + y^F\cdot\left(\frac{\partial p^F}{\partial t} - 1\right) + y^G\cdot\frac{\partial p^G}{\partial t} + y^F + (t-\alpha)y^{F\prime}\left(\frac{\partial p^F}{\partial t} - 1\right) - sy^{G\prime}\cdot\frac{\partial p^G}{\partial t} = 0$$

$$\frac{\partial W}{\partial s} = \underbrace{-d(\cdot)\left(a^F\frac{\partial p^F}{\partial s} + a^G\frac{\partial p^G}{\partial s}\right)}_{-y^F\frac{\partial p^F}{\partial s} - y^G\frac{\partial p^G}{\partial s}} + y^F\cdot\frac{\partial p^F}{\partial s} + y^G\cdot\left(\frac{\partial p^G}{\partial s} + 1\right) + (t-\alpha)y^{F\prime}\cdot\frac{\partial p^F}{\partial s} - y^G - sy^{G\prime}\cdot\left(\frac{\partial p^G}{\partial s} + 1\right) = 0$$

The under-braces follow from the market clearing conditions $y^F = a^F\tilde{d}$ and $y^G = a^G\tilde{d}$. Further simplifying the first-order conditions, we obtain

$$\frac{\partial W}{\partial t} = (t-\alpha)y^{F\prime}\frac{\partial q^F}{\partial t} - sy^{G\prime}\frac{\partial q^G}{\partial t} = 0$$

$$\frac{\partial W}{\partial s} = (t-\alpha)y^{F\prime}\frac{\partial q^F}{\partial s} - sy^{G\prime}\frac{\partial q^G}{\partial s} = 0.$$

The solution is clearly $t = \alpha$ and $s = 0$, and this proves Remark 3.

8.3 Proof of Proposition 4

In this proof we focus for simplicity on the case where $t^C(s)$ and $s^C(t)$ are linear, but it is not hard to extend the argument to the more general case.

We treat t and s as the state variables and let $u_s = \dot{s}$ and $u_t = \dot{t}$ be the control variables. The Lagrangian can be written as

$$L = e^{-\rho z}W(s(z), t(z)) + \lambda_t u_t + \lambda_s u_s$$

where λ_t and λ_s are the costate variables associated with the corresponding state variables. The necessary conditions for an optimum are:

(i) $(u_t, u_s) \in \arg\max L$ s.t. $|u_s| \leq \overline{u}_s$ and $|u_t| \leq \overline{u}_t$ (control optimality);

(ii) $\dot{\lambda}_t = -\frac{\partial L}{\partial t}$, $\dot{\lambda}_s = -\frac{\partial L}{\partial s}$ (costate equations)

(iii) $\lambda_t(\infty) = \lambda_s(\infty) = 0$ (transversality conditions)

(iv) $\dot{s} = u_s$, $\dot{t} = u_t$ (state equations);

(v) $s(0) = s^N, t(0) = t^N$ (initial conditions).

Maximizing L with respect to the control variables yields

$$u_t \left\{ \begin{array}{ccc} = -\overline{u}_t & \text{if} & \lambda_t < 0 \\ = \overline{u}_t & \text{if} & \lambda_t > 0 \\ \in [-\overline{u}_t, \overline{u}_t] & \text{if} & \lambda_t = 0 \end{array} \right\}$$

and

$$u_s \left\{ \begin{array}{ccc} = -\overline{u}_s & \text{if} & \lambda_s < 0 \\ = \overline{u}_s & \text{if} & \lambda_s > 0 \\ \in [-\overline{u}_s, \overline{u}_s] & \text{if} & \lambda_s = 0 \end{array} \right\}$$

The costate equations are

$$\dot{\lambda}_t = -e^{-\rho z} \cdot W_t(s,t)$$
$$\dot{\lambda}_s = -e^{-\rho z} \cdot W_s(s,t)$$

Given that welfare is concave in (s,t), it can be shown that the above conditions are also sufficient. Our method is to guess-and-verify the solution to the above conditions. In particular, we first guess a solution that corresponds to the red path in Figure 2, and show that this solution satisfies the optimality conditions if $\overline{u}_s/\overline{u}_t$ is above a certain threshold ν_1. Then we guess a solution that corresponds to the green path in Figure 2, and show that it satisfies the optimality conditions if $\overline{u}_s/\overline{u}_t$ is below a threshold $\nu_0 < \nu_1$. And finally we show that if $\nu_0 < \overline{u}_s/\overline{u}_t < \nu_1$ then the policy vector must follow the blue path in Figure 2.

1. Our initial guess is the following:

- $t(z)$ increases at speed $\overline{u}_t$ until it hits 2α;

- $s(z)$ increases at speed $\overline{u}_s$ until the policy vector hits the s^C curve, then decreases at speed $\overline{u}_t \cdot \left|\frac{ds^C}{dt}\right|$, so that the policy vector $(s(z), t(z))$ moves down along the s^C curve, until it hits$(0, 2\alpha)$, and then stays constant;

- $\lambda_t(z)$ solves the differential equation $\dot{\lambda}_t(z) = -e^{-\rho z} W_t(s(z), t(z))$ s.t. $\lambda_t(z_0) = 0$ for the time interval $z \in [0, z_0]$, where $(s(z), t(z))$ is the policy path described above and z_0 is the time when the policy vector hits $(0, 2\alpha)$. Then λ_t stays constant at zero for $z \geq z_0$.

- $\lambda_s(z)$ solves the differential equation $\dot{\lambda}_s(z) = -e^{-\rho z} W_s(s(z), t(z))$ s.t. $\lambda_s(z_1) = 0$ for the time interval $z \in [0, z_1]$, where $(s(z), t(z))$ is the policy path described above and z_1 is the time when the policy vector hits the s^C curve.

It is easy to see that the solution above satisfies the optimality conditions if and only if the speed at which s needs to change along the s^C curve, which is $\overline{u}_t \cdot \left|\frac{ds^C}{dt}\right|$, satisfies the speed limit for s, that is $\overline{u}_t \cdot \left|\frac{ds^C}{dt}\right| < \overline{u}_s$, or $\frac{\overline{u}_s}{\overline{u}_t} > \left|\frac{ds^C}{dt}\right| \equiv \nu_1$.

2. Next suppose $\frac{\overline{u}_s}{\overline{u}_t} < \left|\frac{ds^C}{dt}\right|$, so that the solution above is not viable. We guess the following solution:

- $t(z)$ increases at speed $\overline{u}_t$ until the policy vector hits the t^C curve, then increases at speed $\overline{u}_s \cdot \left|\frac{dt^C}{ds}\right|$, so that the policy vector moves down along the t^C curve, until it hits $(0, 2\alpha)$;

- $s(z)$ decreases at speed $-\overline{u}_s$ until it hits zero;

- $\lambda_t(z)$ solves $\dot{\lambda}_t(z) = -e^{-\rho z} W_t(s(z), t(z))$ s.t. $\lambda_t(z_0') = 0$ for the time interval $z \in [0, z_0']$, where z_0' is the time when the policy vector hits the t^C curve. Then λ_t stays constant at zero for $z \geq z_0'$.

- $\lambda_s(z)$ solves $\dot{\lambda}_s(z) = -e^{-\rho z} W_s(s(z), t(z))$ s.t. $\lambda_s(z_1') = 0$ for the time interval $z \in [0, z_1']$, where z_1' is the time when the policy vector hits $(0, 2\alpha)$.

Note that $\lambda_s(z)$ starts negative, initially decreases, reaches a minimum when the policy vector crosses the s^C curve, and then increases until it hits zero. Also note that this solution satisfies the speed constraint when the policy vector moves along the t^C curve. This speed condition is $\left|\frac{dt^C}{ds}\right| . \overline{u}_s < \overline{u}_t$, but this is implied by $\frac{\overline{u}_s}{\overline{u}_t} < \left|\frac{ds^C}{dt}\right|$ because, as we argued in the main text, $\left|\frac{ds^C}{dt}\right| < \frac{1}{\left|\frac{dt^C}{ds}\right|}$. But for this solution to be viable, the policy vector must hit the t^C curve above the first best point $(0, 2\alpha)$. This requires $\frac{\overline{u}_s}{\overline{u}_t} < \frac{s^N}{t^N} \equiv \nu_0 < \nu_1$.

3. Finally suppose $\nu_0 < \overline{u}_s/\overline{u}_t < \nu_1$. In this case, the solution is qualitatively the same as in case 2 from some point in time $z = \hat{z}$ onwards, but there is an initial phase $[0, \hat{z}]$ where $\lambda_s(z)$ is positive and decreasing, crossing zero at $z = \hat{z}$, and then following a similar path as in case 2. And correspondingly, $s(z)$ increases at speed $\overline{u}_s$ until $z = \hat{z}$, then flips and starts decreasing, and then follows a similar path as in case 2. The paths for t and λ_t are qualitatively the same as in case 2. The flipping time $\hat{z}$ will be chosen in such a way that the costate variable λ_s is zero at $z = \hat{z}$, follows the path dictated by the differential equation $\lambda_s = -\frac{\partial L}{\partial s}$, and hits zero again when the policy vector hits $(0, 2\alpha)$.

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