Carbon Taxes and Green Subsidies in a World Economy*

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Abstract

We examine positive and normative questions that arise with the joint use of carbon taxes and green subsidies in an open economy. Moving from autarky to free trade induces countries to introduce green subsidies and reduce carbon taxes, in order to reduce foreign emissions. In contrast to the "leakage" effect of carbon taxes, green subsidies are associated with "reverse leakage," as they decrease emissions both at home and abroad, and as a consequence, the availability of green subsidies tends to be good for global welfare. International climate agreements (ICAs) seek to increase carbon taxes, but the effect on green subsidies is more nuanced. An ICA removes green subsidies, even though they exert 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. We also consider the welfare implications of lobbying from the fossil and green energy sectors. In a noncooperative setting, we find that pressures from the fossil lobby tend to reduce welfare, whereas pressures from the green lobby tend to increase welfare. We also find that in the presence of lobbying, an ICA can decrease welfare relative to the noncooperative equilibrium, even if it changes carbon taxes and green subsidies toward their efficient levels.

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1 Introduction

The global landscape of climate policy instruments includes both carbon pricing and green subsidies. Nearly a quarter of global greenhouse gas (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 increase the share to 41 percent and a total of $192 billion (Taylor 2020).[1]

Alongside the shifting set of energy and climate policies is a well-established fossil fuel lobby and a growing lobby advocating for the clean energy sector. In the United States, for example, the oil and gas sector had annual federal lobbying expenditures of $153 million in 2024, and the renewable energy sector had expenditures of $63 million, more than doubling since 2020 (Open Secrets 2025). Increasingly, lobbyists are also participants in international climate negotiations, with those registered at the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) increasing from hundreds to thousands in recent years (Kluger 2023).

Motivated by this policy landscape, this paper addresses positive and normative questions that arise when governments can use both carbon pricing and green subsidies. There is an expansive literature on policy instrument choice in the fields of environmental and climate economics, but much of the emphasis is on mechanisms for pricing emissions, whereas far less attention has been given to green subsidies, and even less to the interactions between the two. The reason stems from standard intuitions about how green subsidies are not a targeted instrument for addressing environmental externalities and therefore are considered second-best, unless justified on the basis of other market failures, including innovation and knowledge spillovers, among others. A starting point of the present paper, however, is to show that the standard intuition does not in fact apply in an open-economy setting, where green subsidies play a more subtle and interesting role than previously recognized.

We address questions that fit into three broad areas. First, in a noncooperative scenario, how do governments choose carbon taxes and green subsidies, how do these choices differ relative to a closed-economy setting, and what are their welfare implications? Second, we examine the role of international cooperation when both instruments are available, asking whether international agreements should seek to promote, discourage, or even ignore green subsidies. Third, we

[1] Not included in these estimates is the U.S. Inflation Reduction Act (IRA) of 2022, which included provisions initially estimated at $271 billion in green energy subsidies over 10 years (CBO 2022), with more recent estimates having put the magnitudes at $700 billion or more (CBO 2024; Bistline, Mehrotra and Wolfram 2023). More recently, however, the One Big Beautiful Bill Act of 2025 repealed many of the IRA provisions and has left others uncertain.

consider how the presence of lobbying in the two 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 clean energy, which does not.[2] The two policy instruments that we focus on throughout most of the paper are production taxes on fossil energy (or "carbon taxes") and production subsidies on clean energy (or "green subsidies"), but we later consider the implications of allowing for additional policy instruments, namely trade and consumption instruments.[3] 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).

The first set of results relates to the noncooperative choices of carbon taxes and green subsidies. We find that an open-economy setting 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 welfare rationale for green subsidies, even in the presence of a fossil energy lobby that resists the use of carbon taxes.

Intuition follows from recognizing that a country benefits from reducing emissions at home and abroad, but it can only set domestic policy. One tool to target foreign emissions is to reduce the carbon tax, as this reduces the foreign price of fossil energy, and an additional tool to accomplish the same objective is to introduce a green subsidy. Interestingly, green subsidies are used in spite of the fact that reducing carbon taxes is a more direct tool to affect the foreign price of fossil fuels, thus the "targeting principle" has no bite in this setting. Rather, the principle that applies is the desirability of spreading out distortions over different margins, in this case over the two energy sectors. We also show that the interaction between carbon taxes and green subsidies provides a further reason for countries to reduce carbon taxes in an open-economy setting—namely, to reduce the domestic distortion in the clean energy sector that the green subsidy causes.

While reducing carbon taxes and introducing green subsidies are tools that a government uses jointly to reduce foreign emissions, they differ fundamentally in their impact on domestic and global emissions, with green subsidies having decidedly more benign effects. Reducing a carbon tax leads to lower foreign emissions but higher domestic emissions—this is the flip-side of

[2]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 research and development externalities and learning by doing spillovers. We nevertheless discuss possible interactions among market failures in the conclusion.

[3]We focus on carbon taxes as the mechanism for carbon pricing, but we note that price and quantity instruments, including emissions trading systems, are equivalent in competitive settings, thus our results extend to the case where governments can use carbon pricing (more generally) and green subsidies.

the well known "leakage" effect. And when both governments do this, global emissions increase. In contrast, a green subsidy leads to lower emissions both at home and abroad, because it reduces the price of fossil energy in both countries—an effect that we label "reverse leakage." As a consequence, when both governments use green subsidies, global emissions are reduced.

The reverse-leakage effect of green subsidies and the interaction effect described just above are at the basis of our next finding: in a noncooperative setting, global welfare is higher if green subsidies are available than if they are not, provided the reduction in carbon taxes induced by the introduction of green subsidies is not too large. At a broad level, this suggests there is no fundamental reason to be worried about the noncooperative use of green subsidies: the availability of green subsidies tends to increase global efficiency, and its only adverse effect is not due to the subsidies themselves, but rather, to the consequent reduction in carbon taxes that governments enact to counter the domestic distortions that subsidies create.

As highlighted above, moving from autarky to free trade leads to lower carbon taxes in both countries. This constitutes an adverse welfare effect of trade, and we show that it can lead to overall losses from trade. While our symmetric setup rules out the standard gains from trade, it isolates a potentially important distortionary effect of trade that occurs through the induced reduction in the equilibrium carbon taxes.

Our second set of results pertains 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 would remove them. Intuitively, this result suggests that a gradual ICA may increase green subsidies before decreasing them. To explore this possibility, we consider a simple dynamic extension of the model where policies are subject to adjustment frictions. In this case, we find that an ICA will indeed increase green subsidies before decreasing them, if adjustment frictions are relatively more severe for carbon taxes than for green subsidies. We emphasize that the kind of adjustment frictions we consider could never generate a non-monotonic time path if the policy were one-dimensional: the non-monotonicity is a consequence of the interaction between carbon taxes and green subsidies.

The model also has something interesting to say about the optimal scope of an ICA. We find that an ICA focused only on carbon taxes is sufficient to achieve global efficiency if and only if countries are symmetric. On the other hand, an ICA focused only on green subsidies can never achieve global efficiency. These results suggest two points. The first is that an ICA that only covers carbon taxes, which is often the focus of the literature on ICAs, is inefficient if green subsidies are available and countries are asymmetric. The second and perhaps more subtle point is that, in the presence of contracting costs, an incomplete agreement that focuses only on carbon taxes may be optimal if countries are not too asymmetric, because it is worth incurring the costs of contracting over green subsidies only if countries are sufficiently asymmetric.

Our third set of results speaks to the welfare implications of lobbying. In a noncooperative scenario, we find that the fossil and green energy 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, 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, whereas decreasing carbon taxes has negative international externalities.

We then consider how a politically-pressured ICA changes welfare relative to the noncooperative equilibrium. We show that, regardless of the lobbying pressures, the only role of the ICA is to correct the global climate externality, and under plausible conditions, the ICA moves carbon taxes and green subsidies closer to their efficient levels. Nevertheless, we find that an ICA can decrease welfare. In particular, 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 increases carbon taxes to correct the climate externality, and this will increase production of green energy and therefore exacerbate the distortion in the green energy sector even further.

Finally, we discuss how the availability of trade and consumption taxes in the energy sectors, in addition to production instruments, may affect our analysis. Focusing on the production-cum-trade instrument kit and on the unilateral welfare-maximizing policies, we make two main observations. First, if trade policy is unconstrained, a country will choose trade instruments in both energy sectors and a Pigouvian tax on fossil energy, but if trade instruments are constrained to some degree, perhaps because of preexisting trade agreements, a country will choose a mix of trade and production instruments in both energy sectors. We emphasize that, regardless of any constraints on trade instruments, green energy policies—in the form of trade and/or production instruments—continue to be used in addition to fossil energy policies to reduce foreign emissions, even though the latter are the more targeted instruments for this objective. Second, green-energy and fossil-energy policies continue to have sharply different "side effects," with the former more benign than the latter. In particular, a change in green-energy policy that reduces foreign emissions will also lower domestic and global emissions, whereas a change in fossil-energy policy that reduces foreign emissions will increase domestic emissions and possibly global emissions as well.

Relation to the literature. Our broad contribution to the literature is to consider the joint implications of carbon taxes and green subsidies in an open-economy setting—both when governments act noncooperatively and when ICAs are available—as well as the welfare impacts of lobbying from fossil and green energy interests.

Questions about policy instrument choice have a long tradition in environmental and climate economics (e.g., Weitzman 1974; Baumol and Oats 1988; Goulder and Parry 2008; Kotchen 2024), but most papers in the literature focus on tradeoffs associated with choosing between instruments in closed economies. Fischer (2017) considers green subsidies in an open economy with a political preference for domestic production, but the model does not consider carbon taxes nor interactions between fossil and green energy sectors. There are a few studies that consider carbon taxes and green subsidies, but in these papers green subsidies are motivated by innovation spillovers rather than climate externalities (e.g., Gerlagh et al. 2009; Acemoglu et al. 2012, 2016), and they focus on a closed economy. Also in this strand of literature, Aidt (1998) considers the joint determination of multiple environmental policies in the presence of multiple lobbies in a closed economy, highlighting the potential welfare benefits of countervailing lobbying.

More closely related to our analysis is a working paper (which we became aware of only recently) by Kay (2024). He considers an open-economy setup with a good that can be produced with "clean" and "dirty" production processes (in addition to a numeraire good). He examines the optimal unilateral policy and finds that it includes a tax on the dirty process and a subsidy to the clean process, a finding related to our first result. Our setting is more general, however, and we address a broader set of questions. Our model has two final goods and two energy sectors, where the energy inputs are themselves traded and can have different degrees of substitutability (or complementarity), and more importantly, we consider the welfare consequences of green subsidies, the role of ICAs, and the implications of lobbying from the two energy sectors.

There is also a literature that focuses on linkages between climate policy (or more generally environmental policy) and trade policy, with contributions emphasizing unilateral policies (Markusen 1974; Copeland and Taylor 1995; Copeland 1996; Hoel 1994; Fischer and Fox 2012; Keen and Kotsogiannis 2014; Balistreri et al. 2019; Kortum and Weisbach 2024; Weisbach et al. 2023; Brunel and Levinson 2025) and the interaction between trade policy and environmental agreements (Barrett 2003; Nordhaus 2015; Maggi 2016; Harstad 2024; Farrokhi and Lashkaripour 2025). 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 optimal scope of international agreements (Horn, Maggi, and Staiger 2010), international regulatory agreements under lobbying (Maggi and Ossa 2023), and the relationship between trade agreements and domestic policies (Bagwell and Staiger 2001). None of these papers, however, consider 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 discusses implications of allowing for trade and consumption taxes. Section 7 concludes.

2 A closed economy

We begin with a closed economy to lay out 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 from labor and a specific factor with constant returns to scale. Labor is in fixed supply, denoted L, and we assume it is large enough to guarantee positive consumption of good B in equilibrium.

Production of fossil fuels generates a negative externality, which we assume is linear: $E = \alpha y^F$, where y^F is the output of fossil fuels, and α captures the marginal damages due to climate change. The parameter α can be interpreted as the product of the carbon dioxide (CO_2) emissions per unit of fossil energy and the climate damages per unit of CO_2.[4] We assume that production of green energy generates no externality. 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 examine the market equilibrium in the absence of policy. Because the numeraire good B 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. 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 total returns to the specific factor in sector i as $\pi^i(p^i)$,

[4] Our results would be the same if consumption rather than production of F generated the externality, as consumption is equal to production in a closed economy. In an open economy, which we turn to in Section 3, whether there is a production or consumption externality does not matter for the optimal and equilibrium levels of a given policy instrument. This is because we consider a global climate externality, and global production equals global consumption. The only case in which the nature of the externality may matter is if a government must for some reason choose between consumption and production instruments; in this case the nature of the externality can affect the choice of instrument. But if governments can use both instruments, the distinction is immaterial.

which can be interpreted as producer surplus. Moreover, 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 energy 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 given the input prices. 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 clearly decreasing in its own price. We assume $\frac{\partial a^j}{\partial p^i} > 0$, which means that increasing the price of one energy input leads to a more intensive use of the other energy input.[5] The input coefficient for labor can be similarly written as $a^L\left(p^F, p^G\right)$. With these functions established, it is also useful to define the unit cost function for final good A:

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

Note that the envelope theorem implies $\frac{\partial c}{\partial p^i} = a^i(\cdot)$, and 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 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 decreases both the input coefficient a^i and the final good demand $\tilde{d}$. However, the cross-price effect $\frac{\partial d^i}{\partial p^j}$ can in general take either sign, because an increase in p^j increases a^i but decreases the final good demand $\tilde{d}$. We say that input i is a "substitute" for input j if $\frac{\partial d^i}{\partial p^j} > 0$, and similarly, we say that input i is a "complement" for input j if $\frac{\partial d^i}{\partial p^j} < 0$. The case where the two forms of energy are substitutes is more plausible and intuitive, so throughout the paper we focus on this case, unless otherwise noted.[6]

[5] This assumption is standard in the context of "clean" and "dirty" inputs, including fossil and green energy (e.g., Acemoglu et al. 2012). Note that some papers in the literature refer to this as "substitutability" between inputs, but we will use a different definition of input substitutability, which incorporates a general-equilibrium effect through the price of the final good, as we explain below.

[6] We note that the case of substitutes or complements relates to empirically estimable elasticities. The cross-

Finally, three conditions determine the market prices (p, p^F, 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 are market clearing conditions in the energy input sectors: $d^i(p^i, p^j) = y^i(p^i)$ for $i = F, G$.

2.2 Energy policy

We consider two policy instruments. First is a specific production tax on F, denoted t, which we refer to as a "carbon tax." Second is a specific production subsidy on G, denoted s, which we refer to as a "green subsidy." Although we focus on production instruments in our baseline model, we later discuss the implications of allowing for trade and consumption instruments.

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

$$d^F(p^F, p^G) = y^F(p^F - t) \tag{2}$$

and

$$d^G(p^G, p^F) = y^G(p^G + s), \tag{3}$$

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

As we show in the Appendix, the within-sector effects of policies on consumer and producer prices satisfy: (i) $0 < \frac{\partial p^F}{\partial t} < 1$ and $-1 < \frac{\partial p^G}{\partial s} < 0$; and (ii) $\frac{\partial q^F}{\partial t} < 0$ and $\frac{\partial q^G}{\partial s} > 0$. These effects are intuitive, as an increase in the carbon tax increases the consumer price of F, and an increase in the green subsidy decreases the consumer price of G. Then, since pass-through in this setting is incomplete, the within-sector producer prices move in the opposite direction.

In the Appendix we also show that the cross-sector effects of policies satisfy: (i) $\frac{\partial p^G}{\partial t} = \frac{\partial q^G}{\partial t} > 0$ if and only if G is a substitute for F; and (ii) $\frac{\partial p^F}{\partial s} = \frac{\partial q^F}{\partial s} < 0$ 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 cross-sector effects is dictated by whether the two sources of energy are substitutes or complements. As noted previously, we will focus on

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 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 $\varepsilon_{\tilde{d}}$. It turns out that assumptions about the elasticity of substitution and the price elasticity of final goods demand play an important role in papers on the macroeconomics of climate policy (Golosov et al. 2014; Hassler and Krusell 2018; Hassler et al. 2021; Casey, Jeon, and Traeger 2023).

the case of substitutes throughout most of the paper, in which case a carbon tax increases p^G, and a green subsidy decreases p^F.

Before proceeding, we point out that a special case of our model is one where the green energy subsidy can be interpreted as an "abatement subsidy" that lowers the cost of adopting a cleaner production process. In particular, if the two energy inputs are perfect substitutes, and they are the only inputs for good A (i.e., no labor is needed), they can be re-interpreted as two alternative processes (one dirty, one clean) to produce the final good. In this case, we can interpret y^F (resp., y^G) as the amount of good A produced with the dirty (resp., clean) process, and the green subsidy as a policy that lowers the cost of the clean process.[7]

2.3 Welfare maximization

We now examine the welfare maximizing policies. It is natural in this setting to define welfare as aggregate indirect utility: $Income + CS - E$. Decomposing further we have $Income = \pi^F + \pi^G + L + R$, where 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

$$W = CS(c(p^F, p^G)) + \pi^F(p^F - t) + \pi^G(p^G + s) + ty^F(p^F - t) - sy^G(p^G + s) - \alpha y^F(p^F - t), \quad (4)$$

where $p^F = p^F(t, s)$ and $p^G = p^G(t, s)$ satisfy the market clearing conditions. We assume the welfare function is concave in t and s.

The unique welfare-maximizing policies are $t = \alpha$ and $s = 0$, as we show in the Appendix: the tax is set at the Pigouvian level, and given no other externality, there is no welfare rationale for a green subsidy.[8]

It is worth emphasizing that this result holds even if F and G are perfect substitutes, and in particular, a carbon tax is strictly superior to a green subsidy even in this case. The intuition is the following. While the carbon tax increases the price of F relative to G, thereby inducing reallocation from F to G, it also increases the price of the energy intensive final good A relative to other final goods, thereby driving resources away from A. In contrast, while the green subsidy also changes the price of F relative to G, it *reduces* the price of A relative to other final goods, and hence leads to overproduction of the energy intensive final good.[9]

[7] We note that, in this special case, our model becomes similar to the setup of pollution taxes and abatement subsidies in Kay (2024).

[8] Although we focus on production instruments, the same result would apply to consumption instruments, because there is an equivalence between production and consumption instruments in a closed-economy setting.

[9] We can examine the case of perfect substitutes more formally. In this case, the consumer price of F and G must be the same, say $p^F = p^G \equiv p^\epsilon$, where ϵ denotes energy. Let $a^\epsilon(p^\epsilon)$ denote the input coefficient for energy and $c(p^\epsilon)$ the unit cost function for A, so the zero-profit condition implies $p = c(p^\epsilon)$. Demand for A

2.4 Political economy

We model lobbying in a similar way as Baldwin (1987) and Grossman and Helpman (1994). In particular, we specify a politically weighted objective function of the form

$$\Omega = W + \gamma^F \pi^F + \gamma^G \pi^G, \tag{5}$$

where $\gamma^F, \gamma^G \geq 0$ capture the strength of the respective lobbies. It is direct to show that the "politically efficient" policies that maximize (5) are:

$$t = \alpha - \gamma^F \frac{y^F}{y^{F'}} \quad \text{and} \quad s = \gamma^G \frac{y^G}{y^{G'}}. \tag{6}$$

As (6) shows, the politically-efficient policies differ from the welfare-maximizing policies ($t = \alpha$ and $s = 0$) by additional terms that reflect the strength of lobbying. In each sector, the lobbying parameter γ^i interacts with the inverse semi-elasticity of supply $y^i/y^{i'}$. Intuitively, if the supply function is more rigid (i.e., $y^i/y^{i'}$ is greater) the deadweight loss from distorting the policy is lower, thus it is less costly to distort the policy in the direction favored by the lobby.

Note that if only the F sector has political influence, i.e., $\gamma^F > 0$ and $\gamma^G = 0$, the green subsidy is zero. Thus the model implies that lobbying by the F sector alone cannot rationalize a second-best green subsidy in a closed economy.[10] This finding runs contrary to a frequently made argument that green subsidies are a second-best policy if a fossil fuel lobby opposes carbon taxes. We record this finding as follows:

Remark 1. *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 lies in 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.[11]

is $d(p) = d(c(p^\epsilon)) \equiv \tilde{d}(p^\epsilon)$, demand for energy is $d^\epsilon(p^\epsilon) = a^\epsilon(p^\epsilon)\tilde{d}(p^\epsilon)$, and the market clearing condition for energy is $d^\epsilon(p^\epsilon) = y^F(p^\epsilon - t) + y^G(p^\epsilon + s)$. Now, differentiating this expression, we find $dp^\epsilon = \frac{y^{G'} ds - y^{F'} dt}{d^{\epsilon'} - y^{F'} - y^{G'}}$, and it is clear that t and s have different impacts on p^ϵ if the supply functions have different slopes. Then, using the equation for dp^ϵ, along with the identity $q^F = p^\epsilon - t$, we can write $dq^F = \frac{y^{G'} ds + (y^{G'} - d^{\epsilon'}) dt}{d^{\epsilon'} - y^{F'} - y^{G'}}$, with a similar expression holding for dq^G. Note that both t and s decrease q^F, but we can see that t has a larger impact than s, even if the supply functions have the same slope. This result underlies the intuition provided in the main text. All of our qualitative results throughout the paper can be shown to hold in the case of perfect substitutes.

[10] This result is even somewhat more general because it does not depend on the linear specification in (5). 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 $s = 0$.

[11] 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 that make carbon taxes costly can lead to green subsidies. For

Finally, we note that the inverse supply semi-elasticities $\frac{y^i}{y^{i'}}$ in (6) depend on the equilibrium producer prices, and therefore on energy 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 assume $\frac{y^i(q^i)}{y^{i'}(q^i)}$ 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. Under this assumption, it is easy to show that increasing the strength of a lobby changes both policies in the direction preferred by that lobby. More specifically, strengthening the F lobby decreases both t and s (but never turns s negative), and strengthening the G lobby increases both s and t (but never raises t above α).

3 Open economies: the noncooperative setting

We now turn to an open-economy setup with two countries, Home and Foreign. Our basic model focuses 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 are nevertheless due to the *potential* for trade. Terms-of-trade effects would modify most of our results in obvious directions, yet make them less transparent. We will, however, point out the implications of terms-of-trade effects when discussing trade policy in Section 6. We assume that the numeraire good B and the two energy inputs can be costlessly traded, but we will later discuss the implications of trade costs for energy. Finally, we assume the final good A is not tradable, but the results would be essentially unchanged if it were.[12]

A key feature of the open-economy setup is that each country experiences a global externality $E = \alpha(y^F + y^{*F})$, where an asterisk denotes the Foreign country.[13] We initially put aside political economy, by setting $\gamma^F = \gamma^G = 0$, but we will examine the effects of lobbying in the open-economy setup in Section 5. In this section, we solve for policies that maximize global welfare, before turning to the Nash equilibrium and consideration of how trade affects welfare.

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 $C^{F'}(t) > 0$ 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.

[12]If good A were tradable, the location of its production would be indeterminate, but this is immaterial for welfare, and all other results would be unchanged.

[13]We reiterate that assuming a production externality, rather than a consumption externality, has no consequence for our main results, even in an open-economy setting, because global consumption is equal to global production. In particular, the source of the externality has no effect on the optimal levels of the policy instruments. See also footnote 4.

Home's welfare is given by

$$\begin{aligned} W =& CS(c(p^F, p^G)) + \pi^F(p^F - t) + \pi^G(p^G + s) + ty^F(p^F - t) - sy^G(p^G + s) \\ & - \alpha[y^F(p^F - t) + y^{*F}(p^F - t^*)], \end{aligned} \tag{7}$$

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 equations define p^F and p^G as functions of the four policies (t, s, t^*, s^*), and the domestic producer prices must satisfy $q^F = p^F - t$ and $q^G = p^G + s$ for Home, where there is an analogously defined set of equations for Foreign. Note, however, that consumer prices remain the same across countries and can be interpreted as world prices in this setting.

In the open-economy setting, changes in policy have the same qualitative effects on prices as in the closed-economy setting of Section 2.2. The only difference is in the magnitudes: the effects on consumer prices are smaller because each country has a smaller impact on world prices. This, in turn, also means that the within-sector effects of policies on producer prices are greater.

Defining global welfare as the sum of the two countries' welfare, $W^W \equiv W + W^*$, the global-welfare maximizing policies can be found by simply solving the closed-economy problem with twice the marginal climate damages. The solution has a familiar form: $t = 2\alpha$ and $s = 0$. Intuitively, the globally optimal carbon tax in each country is now equal to the global marginal damages, and because there is no other source of market failure, the globally optimal green subsidies are equal to zero.

3.1 Nash equilibrium policies

We now consider the optimal unilateral policies, beginning with an intuitive discussion of one important difference between carbon taxes and green subsidies. Suppose Home wants to reduce the domestic producer 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. 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.[14] The green subsidy, in contrast, has what we

[14] Markusen (1975) is an early paper that identifies the leakage effect in the context of transboundary pollution, and Hoel (1994) is the first to consider the issue specifically in the context of climate change.

refer to as a "reverse leakage" effect, as an increase in s decreases both the domestic producer price and world price of fossil energy (because $\frac{\partial p^F}{\partial s} = \frac{\partial q^F}{\partial s}$), causing a decrease in both Home and Foreign emissions. We now examine the implications of this distinction between the two policy instruments, studying the jointly optimal choice of t and s, their interaction, and the symmetric Nash equilibrium.

Consider Home's choice of t and s to maximize (7). With a bit of algebra, the first-order conditions for Home can be written as

$$\frac{\partial W}{\partial t} = -\left(m^F \frac{\partial p^F}{\partial t} + m^G \frac{\partial p^G}{\partial t}\right) + (t-\alpha) y^{F'} \frac{\partial q^F}{\partial t} - \alpha y^{*F'} \frac{\partial p^F}{\partial t} - s y^{G'} \frac{\partial q^G}{\partial t} = 0 \tag{8}$$

and

$$\frac{\partial W}{\partial s} = -\left(m^F \frac{\partial p^F}{\partial s} + m^G \frac{\partial p^G}{\partial s}\right) + (t-\alpha) y^{F'} \frac{\partial q^F}{\partial s} - \alpha y^{*F'} \frac{\partial p^F}{\partial s} - s y^{G'} \frac{\partial q^G}{\partial s} = 0, \tag{9}$$

where $m^i = d^i - y^i$ denotes Home imports of input i. Note that at a symmetric Nash equilibrium there is no trade, so the first term in parentheses is equal to zero in (8) and (9).

To gain intuition for how the equilibrium policies in an open economy differ from those in a closed economy, let us evaluate $\frac{\partial W}{\partial t}$ and $\frac{\partial W}{\partial s}$ at the autarky equilibrium, where both countries choose their closed-economy policies ($t = \alpha$ and $s = 0$) and there is no trade. This yields $\frac{\partial W}{\partial t} < 0$ and $\frac{\partial W}{\partial s} > 0$, suggesting that Home wants to lower its carbon tax relative to the closed-economy optimum ($t < \alpha$) and introduce a green subsidy ($s > 0$). The term $-\alpha y^{*F'} \frac{\partial p^F}{\partial t} < 0$ in (8) 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 (9) captures the reverse leakage effect, which provides a marginal incentive for use of the green subsidy. Consistent with this intuition, below we show that at a symmetric Nash equilibrium each country sets the carbon tax below α and chooses a positive green subsidy.

It is also worth noting how the two policies interact with each other. First focus on Home's optimal carbon tax. The last term in (8), $-s y^{G'} \frac{\partial q^G}{\partial t} < 0$, indicates that a green subsidy introduces another disincentive for using a carbon tax: when a positive green subsidy is in place, a higher carbon tax exacerbates the distortion in the G sector. Together with our observations above, this suggests that at a Nash equilibrium the carbon tax is lower than the global optimum 2α for three reasons: first, the standard free-riding effect, captured by the fact that the optimal carbon tax in a closed economy is α rather than 2α; second, the leakage effect due to the openness to trade; and third, the interaction effect due to the green subsidy. Next focus on the impact of t on the optimal choice of s. Here the interaction effect is captured by the term $(t-\alpha) y^{F'} \frac{\partial q^F}{\partial s}$ in (9). Noting that $\frac{\partial q^F}{\partial s} = \frac{\partial p^F}{\partial s} < 0$, this means that setting the carbon tax below α strengthens the incentive to use a green subsidy, because the subsidy mitigates the overproduction distortion in the F sector caused by the low carbon tax.

Using the first-order conditions above and unpacking the price derivatives, it is easy to write down expressions for the symmetric Nash equilibrium policies. Setting trade equal to zero and solving the system for t and s, we find

$$t^N = \alpha(2 - \Phi_t) \quad \text{and} \quad s^N = \alpha\Phi_s, \tag{10}$$

where Φ_t and Φ_s are terms that depend only on the derivatives of the supply and demand functions.[15] It is straightforward to verify that $\Phi_t > 1$, and that $\Phi_s > 0$ if and only if F is a substitute for G, so we can 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.*

As discussed above, the carbon tax is less then α because of the standard free riding effect, the leakage effect, and the incentive to reduce the G sector distortion. The most important insight of Proposition 1, however, is that if F is a substitute for G, an open economy provides a unilateral welfare rationale for a green subsidy, in contrast to a closed economy, where the welfare maximizing subsidy is zero.[16]

The fundamental intuition is that in a global economy a country has two tools to reduce the production of F in the Foreign country. The first, more direct, tool is reducing the carbon tax below its closed-economy level α. But an additional tool is to introduce a green subsidy, and this is worth doing because a further reduction in p^F generates a first-order benefit (since $\alpha > 0$), whereas the distortion from a small green subsidy is second-order. Moreover, as discussed above, the reduction of the carbon tax below α increases the incentive for using the green subsidy even further.

Readers might wonder why 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. The principle that applies, however, is the desirability of spreading out distortions over different margins, in this case over the two energy sectors. If we think of the reduction of t below α as an implicit subsidy to the F sector, Home balances the distortions of the implicit F subsidy and the explicit G subsidy in order obtain the first-order benefit of reducing Foreign emissions.

An important observation is that, even though both a reduction in t and an increase in s serve

[15]In particular, $\Phi_t = 1 + \left(y^{G'} - 2\frac{\partial d^G}{\partial p^G}\right) y^{F'} \phi^{-1}$ and $\Phi_s = 2\frac{\partial d^F}{\partial p^G} y^{F'} \phi^{-1}$, where $\phi = y^{F'} y^{G'} - 4\left(\frac{\partial d^F}{\partial p^G}\frac{\partial d^G}{\partial p^F} - \frac{\partial d^F}{\partial p^F}\frac{\partial d^G}{\partial p^G}\right) - 2\left(\frac{\partial d^G}{\partial p^G} y^{F'} + \frac{\partial d^F}{\partial p^F} y^{G'}\right) > 0$.

[16]Note that if F is a complement for G, the sign of the subsidy is negative, meaning that countries tax production of G. But as noted previously, we focus on the case of substitutes throughout the paper.

to decrease Foreign's production of F, the two strategies differ fundamentally in their impact on Home's production of F and on global emissions. 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 what happens if Home reduces t unilaterally from an initial condition of symmetry: the global change in climate damages is given by $\alpha\left(y^{F'}\frac{\partial q^F}{\partial t} + y^{*F'}\frac{\partial p^F}{\partial t}\right) = \alpha y^{F'}\left(2\frac{\partial p^F}{\partial t} - 1\right)$, which is negative because $\frac{\partial p^F}{\partial t} < \frac{1}{2}$.[17] As a consequence, when both countries engage in the strategy of lowering carbon taxes, global climate damages increase even more. On the other hand, consider an increase in Home's green subsidy. Since $\frac{\partial q^F}{\partial s} = \frac{\partial p^F}{\partial s} < 0$, the green subsidy lowers the price of F both in the Foreign country and at Home, resulting in lower emissions in both countries and thereby lower global damages. Moreover, when both countries use green subsidies, global damages decrease even more. The intuition underlying this stark difference between the two policies lies in the leakage and reverse leakage effects previously described.

Before proceeding, we make an observation about trade costs, which we have abstracted from thus far. The presence of moderate trade costs would not interfere with the main insights developed above, but empirically one might argue that green energy is less tradeable than fossil fuels. Our observation is that, even if we made green energy non-tradeable, keeping the rest of the model unchanged, Proposition 1 would still hold. Intuitively, if G is non-tradeable but F is tradeable, a green subsidy will still depress the world price of F, because it induces substitution from F to G in the domestic market. While in this case the effect on the world price of F is quantitatively weaker relative to the setting with tradeable G, it will still be unilaterally optimal to use a green subsidy.

3.2 The welfare effect of green subsidies

A natural next question to consider is how the availability of green subsidies affects global welfare. Specifically, we examine how welfare changes if we go from the Nash equilibrium in a scenario where only carbon taxes are available to the Nash equilibrium where green subsidies are available too. One interpretation of this thought experiment might be that green subsidies become feasible because of exogenous changes in the political environment. Another interpretation is that we might be interested in knowing whether an international agreement that bans green subsidies is a good idea.

As a first step, we define $t^N(s)$ as the symmetric Nash equilibrium carbon tax conditional on a symmetric green subsidy s: this is the symmetric t that solves the first-order condition in

[17] The inequality $\frac{\partial p^F}{\partial t} < \frac{1}{2}$ follows from the fact that in the symmetric open-economy setup, the effects of policy changes on consumer prices have exactly half the magnitude of those in a closed economy, where we have already established there is incomplete passthrough.

(8) evaluated at a symmetric s. Note that $t^N(0)$ is the Nash equilibrium tax when subsidies are not available, and $t^N(s^N)$ is the Nash equilibrium tax when subsidies are available. To get a sense for how $t^N(s)$ changes with s, consider the first-order condition in (8). The direct effect of an increase in s is to induce a reduction in the unilateral carbon tax in order to mitigate the domestic distortion in the G sector, as described above. But an increase in s can also have indirect effects through changes in the price derivatives, and these can either strengthen or weaken (or even potentially overturn) the direct effect. To focus on the direct effects, and to get traction on the potential welfare consequences of green subsidies, we focus in this subsection on the case of linear supply and demand in the F and G sectors, noting that this implies all price derivatives are constant. In this case, we find the slope of $t^N(s)$ by differentiating (8):

$$t^{N'}(s) = \frac{y^{G'}}{y^{F'}} \cdot \frac{\frac{\partial q^G}{\partial t}}{\frac{\partial q^F}{\partial t}} < 0. \tag{11}$$

The intuition for why $t^N(s)$ is decreasing simply carries over from the preceding discussion: as green subsidies increase, countries respond by lowering their unilateral carbon taxes, and the sole reason for doing so is to mitigate the increase in the domestic G-sector distortion.

Turning now to global welfare, we start by introducing some new notation. If $W(s, s^*, t, t^*)$ and $W^*(s, s^*, t, t^*)$ denote Home and Foreign welfare as functions of all policies, we let $W^W(s, t) \equiv W(s, s, t, t) + W^*(s, s, t, t)$ denote global welfare as a function of the *symmetric* tax and subsidy. To compare welfare at the Nash equilibrium without subsidies with welfare at the Nash equilibrium with subsidies, we evaluate the change in $W^W(s, t^N(s))$ as s moves from 0 to s^N. We have

$$\frac{dW^W(s, t^N(s))}{ds} = \frac{\partial W^W}{\partial s} + \frac{\partial W^W}{\partial t} \cdot t^{N'}(s). \tag{12}$$

Integrating the derivative in (12) from 0 to s^N yields the welfare effect of making green subsidies available. Here we provide an intuitive discussion of this effect, relegating details to the Appendix as a formal proof to the next remark.

Consider introducing a small symmetric subsidy starting from the Nash equilibrium with only carbon taxes. This has a positive direct welfare effect, that is, $\frac{\partial W^W}{\partial s} > 0$. Intuitively, as we highlighted above, an increase in green subsidies generates a first-order improvement by reducing global emissions. While the subsidies create G-sector distortions, these are second-order because we are starting from $s = 0$, and this means that the emergence of green subsidies in itself is good for welfare. But each country also accompanies the green subsidy with a reduction in its carbon tax in order to mitigate the domestic G-sector distortion ($t^{N'}(s) < 0$), and since carbon taxes are already inefficiently low from a global welfare perspective, $\frac{\partial W^W}{\partial t} > 0$, this adjustment has a negative effect on welfare. Can the indirect effect through the reduction in carbon taxes overturn the beneficial welfare effect of green subsidies? In principle it can, if the reduction in t "overreacts" to the increase in s, but we now highlight two different sufficient conditions under which this does not happen.

The first, intuitive one is that $t^{N'}(s)$ is sufficiently small. This is the case if carbon taxes have little effect on the price of G, which in turn is the case if $\frac{\partial d^G}{\partial p^F}$ is small. But note that this condition works only if, at the same time, the reverse cross-price effect $\frac{\partial d^F}{\partial p^G}$ is relatively large, because we need s^N to be relatively large. Hence this sufficient condition relies on strong asymmetry in the degree of substitutability between F and G, and while useful for the purposes of intuition, it is perhaps less plausible when thinking about two energy inputs that are likely more symmetric in their substitutability. The second sufficient condition is based on a more natural setting where the degree of substitutability between F and G is symmetric. More specifically, we can show that if F and G have symmetric demand and supply derivatives, $\frac{dW^W(s,t^N(s))}{ds}$ is positive for all s between 0 and s^N, and hence welfare is higher when both carbon taxes and green subsidies are available relative to the scenario where only carbon taxes are available. We record these results as follows:

Remark 2. *Global welfare is higher in the Nash equilibrium with green subsidies than in the Nash equilibrium without green subsidies, as long as the reduction in carbon taxes induced by the introduction of green subsidies is not too large. This is guaranteed if demand and supply for F and G are linear, and either of the following sufficient conditions holds: (i) $\frac{\partial d^G}{\partial p^F}$ is sufficiently small relative to $\frac{\partial d^F}{\partial p^G}$, or (ii) F and G have symmetric demand and supply derivatives: $\frac{\partial d^G}{\partial p^G} = \frac{\partial d^F}{\partial p^F}$, $\frac{\partial d^G}{\partial p^F} = \frac{\partial d^F}{\partial p^G}$ and $y^{F'} = y^{G'}$.*

We emphasize that condition (ii), which as argued above is the more natural of the two, is stronger than necessary: in particular, the result continues to hold if inputs are not too asymmetric and demand/supply are not too nonlinear.

The broad message suggested by the analysis above is that there is no fundamental reason to worry about the welfare consequences of "green subsidy wars": the noncooperative use of green subsidies tends to increase global welfare relative to a scenario where green subsidies are not available The only adverse welfare effect that does arise is not due to the subsidies in themselves, but rather, to the induced reduction in carbon taxes that governments enact to counter the subsidy-induced domestic distortions.

3.3 How does trade affect welfare?

In the previous subsection we examined how the availability of green subsidies affects welfare within an open-economy setting. A related but distinct question is: how does trade affect welfare, relative to autarky? Recall from Section 2.3 that green subsidies are not used under autarky, so in this case we also need to compare the Nash equilibrium with carbon taxes and green subsidies to a scenario without green subsidies, but in the latter scenario carbon taxes are set at their autarky level ($t = \alpha$).

As we highlighted above, opening up to trade induces both countries to reduce carbon taxes, and this in itself is bad for welfare, but it also induces countries to introduce green subsidies, which may enhance welfare. In what follows, we examine how these two forces play out in shaping the welfare impacts of trade. Of course, since we are abstracting from comparative advantage in our symmetric setup, we are not accounting for 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.

Since countries are symmetric, when countries open up to trade there is still no trade in equilibrium, but policies change. We therefore need to examine the change in world welfare $W^W = W + W^*$ when policies change from their autarky levels ($t = t^* = \alpha$ and $s = s^* = 0$) to their Nash equilibrium levels ($t = t^* = t^N$ and $s = s^* = s^N$). To account for how symmetric changes in polices affect prices in what follows, we let $\widetilde{q}^F(t, s)$ denote the equilibrium producer price of F as a function of the *symmetric* tax and subsidy.[18]

We start with the change in world welfare caused by a small and symmetric reduction in t and increase in s, starting from their respective autarky levels. Differentiating $W^W(t, s)$ and evaluating at the autarky policies, it is direct to verify that

$$dW^W\big|_{autarky} = -\alpha y^{F'} \frac{\partial \widetilde{q}^F}{\partial t} dt - \alpha y^{F'} \frac{\partial \widetilde{q}^F}{\partial s} ds. \tag{13}$$

The first term is the welfare effect of a small reduction in t starting from autarky; this is negative because $\frac{\partial \widetilde{q}^F}{\partial t} < 0$ and $dt < 0$. The second term is the welfare effect of a small increase in s starting from autarky; this is positive because $\frac{\partial \widetilde{q}^F}{\partial s} < 0$ and $ds > 0$. The net effect can take either sign in general, depending on the magnitude of the cross-price effect relative to the own effect ($\frac{\partial \widetilde{q}^F/\partial s}{\partial \widetilde{q}^F/\partial t}$) and on the magnitude of the tax reduction relative to the subsidy increase ($\frac{dt}{ds}$).[19] But it is intuitive and easy to show that moving from autarky to free trade must decrease welfare if the cross-sector effect of the subsidy, $\left|\frac{\partial \widetilde{q}^F}{\partial s}\right|$, is sufficiently small relative to the own-sector effect of the carbon tax, $\left|\frac{\partial \widetilde{q}^F}{\partial t}\right|$, for the relevant range of prices.

The intuition for this result is as follows. First note that, if $\left|\frac{\partial \widetilde{q}^F}{\partial s}\right|$ is small, the Nash subsidy s^N is small, because the whole reason a government wants to use a green subsidy in

[18] The derivatives of a price with respect to symmetric policy changes map into the derivatives of that price with respect to unilateral policy changes as follows. Denoting $q^F(t, t^*, s, s^*)$ and $p^F(t, t^*, s, s^*)$ respectively as the equilibrium producer and consumer price of F as a function of all policies, we have $\frac{\partial \widetilde{q}^F}{\partial s} = 2\frac{\partial q^F}{\partial s}$ and $\frac{\partial \widetilde{q}^F}{\partial t} = 2\frac{\partial p^F}{\partial t} - 1 = 2\frac{\partial q^F}{\partial t} + 1 < 0$, where the inequality is due to the fact that $\frac{\partial p^F}{\partial t} < \frac{1}{2}$.

[19] It is interesting to note that the welfare change in (13) maps directly into the change in global climate damages ($2\alpha y^F$). Differentiating this yields $d(2\alpha y^F) = 2\alpha y^{F'}(\frac{\partial \widetilde{q}^F}{\partial t} dt + \frac{\partial \widetilde{q}^F}{\partial s} ds)$. Clearly this has the opposite sign as (13), so global welfare decreases if and only if global climate damages increase.

the open economy is to influence the world price of F. In this case, the welfare effect of the green subsidies is dominated by the welfare effect of the reduction in the carbon taxes. This means that we can sign the overall welfare change by ignoring the change in the subsidy and focusing just on the reduction in the carbon tax. Second, while equation (13) shows that a local reduction in t starting from the autarky level α reduces welfare, lowering t further from α increases emissions and therefore produces an even greater welfare loss: it is direct to verify that $\frac{dW^W}{dt} = y^{F'}(t-2\alpha)\frac{\partial\widetilde{q}^F}{\partial t}$, which is negative for $t < 2\alpha$, thus confirming that welfare keeps going down as we lower t further below α.

Note that, in terms of primitives of the model, the condition that $\frac{\partial\widetilde{q}^F/\partial s}{\partial\widetilde{q}^F/\partial t}$ is sufficiently small translates into the cross-price sensitivity of the demand for the F input, $\left|\frac{\partial d^F}{\partial p^G}\right|$, being sufficiently small relative to the corresponding own-price sensitivity, $\left|\frac{\partial d^F}{\partial p^F}\right|$. We therefore state the result as follows:

Remark 3. *Trade reduces welfare in each country if the cross-price effect* $\left|\frac{\partial d^F}{\partial p^G}\right|$ *is sufficiently small relative to the own-price effect* $\left|\frac{\partial d^F}{\partial p^F}\right|$ *for the relevant range of prices.*

It is interesting to relate Remark 3 to Remark 2. The former compares welfare under the Nash policies ($t = t^N$, $s = s^N$) with welfare under the autarky policies ($t = \alpha$, $s = 0$), while the latter compares welfare under the Nash policies ($t = t^N$, $s = s^N$) with welfare under the Nash taxes in the absence of subsidies ($t = t^N(0)$, $s = 0$). These comparisons are similar except that the autarky level of the tax is higher than the Nash level of the tax absent subsidies ($\alpha > t^N(0)$), as our discussion above makes clear. It is because of this difference in the tax level that the two comparisons may well yield opposite answers. For example, suppose that the demand and supply for F and G are linear and symmetric, with the own-price sensitivity of demand much larger than the cross-price sensitivity of demand. In this case, the conditions for Remark 2 and Remark 3 are both satisfied, and therefore, making green subsidies available in the open-economy setting is good for welfare, while moving from autarky to free trade (which also leads to the emergence of green subsidies) is bad for welfare.

4 International climate agreements

We now turn to the analysis of global-welfare maximizing ICAs. We begin by showing that a global-welfare maximizing ICA eliminates green subsidies even though subsidies exert positive international externalities at the noncooperative equilibrium. We then show an interesting implication of this result: in a simple dynamic variation of our model, where policies can only be changed gradually, ICAs may increase green subsidies before decreasing them. Finally, we show that an ICA focused only on carbon taxes can be globally efficient, but only if countries are symmetric, whereas an ICA focused only on green subsidies can never achieve efficiency.

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, $W^W = W + W^*$.[20] We have already established in Section 3 that the solution to this problem is $t = 2\alpha$ and $s = 0$ in both countries. Compared to the noncooperative solution in Proposition 1, an ICA increases carbon taxes and removes green subsidies.

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, evaluated at the symmetric Nash equilibrium:

$$\left.\frac{\partial W}{\partial s^*}\right|_{NE} = (t-\alpha)y^{F'}\frac{\partial q^F}{\partial s^*} - \alpha y^{*F'}\frac{\partial q^{*F}}{\partial s^*} - sy^{G'}\frac{\partial q^G}{\partial s^*} > 0 \tag{14}$$

where $\frac{\partial q^{*F}}{\partial s^*} = \frac{\partial q^F}{\partial s^*} < 0$, and the sign follows from the assumption 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 a reduction of the over-production distortion in Home's G sector. This follows because Home's green subsidy is distorting, and the increase in Foreign's subsidy lowers the world price of G, 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 2. *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 removal? It is helpful to first note that this could never happen with a one-dimensional policy. For ex-

[20]The assumption that the ICA maximizes a utilitarian global welfare function is natural with symmetric countries. More generally, this approach implicitly assumes access to international transfers. While explicit transfers are rarely observed in the context of international negotiations in general, climate finance is beginning to play an important role as a form of international transfers in the negotiation of ICAs.

ample, 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.

Underlying Proposition 2 is the interaction between the two policy instruments. Figure 1 illustrates the logic. With symmetric countries, we can focus on symmetric policies for both t and s. The $t^C(s)$ curve shows the globally optimal (symmetric) carbon tax as a function of any (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. 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. At the Nash equilibrium, as established above, green subsidies are positive and carbon taxes are lower than α, 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, $\frac{\partial W}{\partial s^*}\Big|_{NE} > 0$, as shown in (14). And it is easy to see that this implies $\frac{\partial W^W}{\partial s}\Big|_{NE} > 0$, and therefore point N must lie below the $s^C(t)$ curve.[21] Figure 1 can therefore be used to see why green subsidies have positive externalities at the Nash equilibrium, yet an ICA would remove them. If green subsidies are increased locally starting from the Nash point while holding carbon taxes fixed, so that we move up vertically from point N, global welfare increases; nevertheless, maximizing global welfare requires moving from point N to point C, with subsidies reduced to zero.[22]

4.2 Gradual agreements

We now consider an interesting implication of the previous result that green subsidies exert positive international externalities at the Nash equilibrium, even though efficiency requires their complete removal. Suppose there are frictions to the adjustment of policies, so that an ICA must change policies gradually. In this case, how will carbon taxes and green subsidies change over time? The result of Proposition 2 suggests that it might be optimal for a gradual ICA to increase green subsidies before reducing them. To elaborate further on this intuition, suppose for a moment that policies can only be changed marginally from the Nash equilibrium.

[21] To see this, note that $\frac{\partial W^W}{\partial s}\Big|_{NE} = \left(\frac{\partial W}{\partial s} + \frac{\partial W}{\partial s^*} + \frac{\partial W^*}{\partial s^*} + \frac{\partial W^*}{\partial s}\right)\Big|_{NE} = \left(\frac{\partial W}{\partial s^*} + \frac{\partial W^*}{\partial s}\right)\Big|_{NE} > 0$, which follows because $\frac{\partial W}{\partial s} = \frac{\partial W^*}{\partial s^*} = 0$ by unilateral optimality at the Nash equilibrium.

[22] In Figure 1, we show $t^C(s)$ and $s^C(t)$ as linear functions for illustrative purposes. While this holds with linear supply and demand, the key qualitative features of the figure also 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) the curves $t^C(s)$ and $s^C(t)$ are strictly decreasing locally around point C, 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.

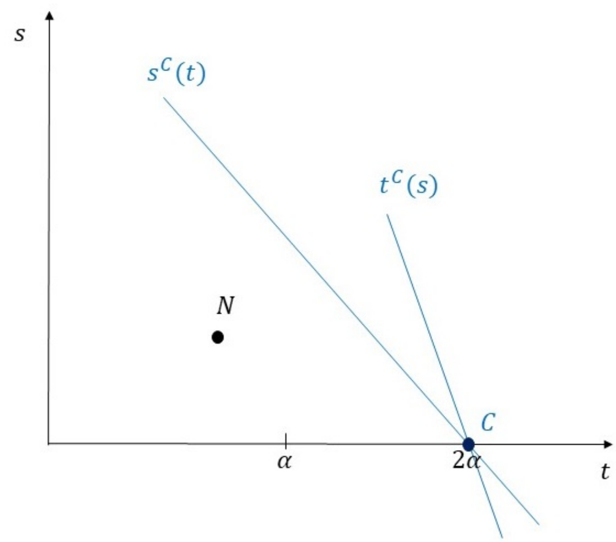

Figure 1: Noncooperative and cooperative policies in an open economy

Since the gradient of the welfare function evaluated at the Nash policies 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 now 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, this makes for a simple and transparent setup that shows how optimal green subsidies can change non-monotonically over time.[23] The only dynamic aspect we introduce in the model is a friction in the adjustment of policies, thus we abstract from other relevant dynamic aspects such as the distinction between the stock of CO_2 in the atmosphere and the flows of emissions. This will help us focus more sharply on the implications of policy gradualism.

We consider a continuous-time setting and assume policies starting at Nash levels must be

[23]Without developing micro-foundations for gradualism, we point to at least two reasons why it might arise. First, it may take time to build political support for policy reform. For example, a government may need to build 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. Indeed, there is ample evidence to support this idea, meaning that it can be politically costly to change policy too quickly, especially with respect to carbon taxes (Drews and van den Bergh 2015; Egan and Mullin 2017; Dechezleprêtre et al. 2025). Second, gradualism would arise with a "conservative social welfare function" (Corden, 1974; Deardorff, 1987) that exhibits aversion to sudden losses for any group in society. This in turn would occur, for example, if the social planner is utilitarian and individual utility functions display loss aversion and increasing sensitivity to losses. In this case, gradualism would arise because changes in t and s necessarily imply losses for some individuals in society.

changed at finite speeds. The "speed limits" can be arbitrarily high and can differ across policy instruments. Let $z \in [0, \infty)$ denote time, $s(z)$ and $t(z)$ the time paths of policies, taken to be symmetric across countries, and δ the discount rate. The speed limits are represented by the constraints $|\dot{s}(z)| \leq \overline{u}_s$ and $\left|\dot{t}(z)\right| \leq \overline{u}_t$, 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

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

This problem can be solved with standard optimal control techniques, the details of which we include in the Appendix. Here we provide an intuitive discussion. To simplify the analysis we assume that demand and supply functions are linear, but below we explain how our result extends to the nonlinear case.

Consider two opposite extremes: one where only t is subject to a speed limit, and 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 $s^C(t^N)$, after which the policy vector moves 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 to $t^C(s^N)$, after which the policy vector moves along the $t^C(s)$ curve until reaching point C. In this case, the ICA changes the levels of 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 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 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:

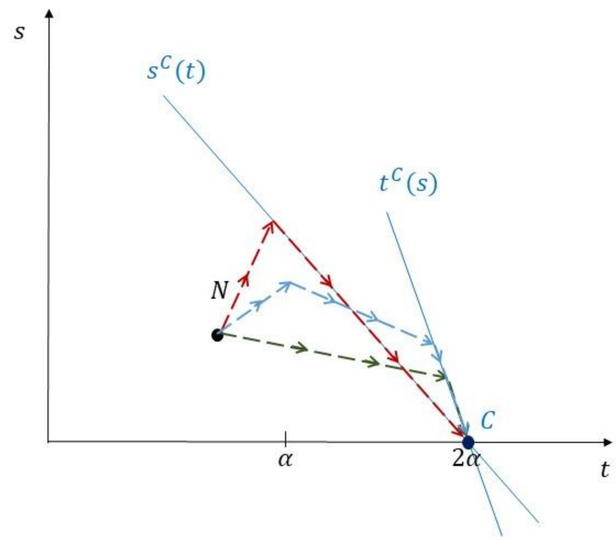

Figure 2: Possible time paths of the optimal gradual agreement

Proposition 3. *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.*

Recalling that the speed limits can be arbitrarily high, we emphasize that only the relative speed limits matter for the qualitative structure of the optimal path. That is, the result holds even if policies can be changed fast, as long as they cannot be changed instantaneously.[24]

It is worth emphasizing 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 and monotonically from the starting point to the optimal end point. The non-monotonicity is a consequence of the interaction between the two policies, though not because green subsidies are a second-best policy if carbon taxes are constrained. Rather, the result stems from the more subtle logic behind Proposition 2 that green subsidies exert positive international externalities at the noncooperative 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 $\overline{u}_t/\overline{u}_s$.

We conclude with an observation on the potential policy relevance of Proposition 3. The non-

[24]As mentioned above, Proposition 3 assumes that demand and supply functions are linear. More generally, even if they are nonlinear, it is easy to show that if $\overline{u}_t/\overline{u}_s$ is sufficiently small then the ICA increases green subsidies before reducing them, and if $\overline{u}_t/\overline{u}_s$ is sufficiently large then the ICA decreases green subsidies monotonically. The intuition for this is the same as the one provided above in the main text, noting that the argument does not rely on linearity of the $s^C(t)$ and $t^C(s)$ curves.

monotonicity result appears consistent with the way the United Nations Framework Convention on Climate Change encourages governments to promote green subsidies.. 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 more heavily on carbon taxes in the future. As we have shown, the two-phase approach may be efficient if policies can only be changed gradually, with carbon taxes facing stronger adjustment frictions than green subsidies.[25]

4.3 Scope of the ICA

We now return to our static model, and consider questions about the scope of ICAs. We have thus far assumed an ICA that includes provisions for both carbon taxes and green subsidies. But the inclusion of both instruments within the scope of an ICA may increase the costs of negotiation, enforcement, or both. One might therefore be concerned with the inefficiencies that arise when an ICA focuses only on carbon taxes or only on green subsidies, as these may determine whether it is worthwhile for an ICA to focus only on one or the other.

Let us begin with an ICA that focuses only on t in both countries. To illustrate a key feature of the result, we relax for the moment the assumption that $\alpha = \alpha^*$, that is, the marginal damages of emissions can differ between countries. 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 in both countries, $t = \alpha + \alpha^*$, and leaves subsidies to each governments' discretion, how will governments choose their unilateral subsidies?

We focus on Home without loss of generality. Imposing $t = t^* = \alpha + \alpha^*$, we derive the first-order condition for Home's subsidy and evaluate it at $s = s^* = 0$:

$$\left.\frac{\partial W}{\partial s}\right|_{t=t^*=\alpha+\alpha^*,s=s^*=0} = \left[\alpha^* y^{F'}(q^F) - \alpha y^{F'}(q^{*F})\right] q_s^F, \tag{15}$$

where we used the fact that, even if $\alpha^* \neq \alpha$, given symmetric policies there is no trade in equilibrium, and $q_s^{*F} = q_s^F$. To aid intuition below, the notation above distinguishes between the domestic and foreign producer price of F, even though they are equal given symmetric policies.

The expression in (15) is clearly equal to zero if $\alpha = \alpha^*$, as symmetric policies imply $q^F = q^{*F}$. Therefore, if countries are symmetric, they will respond with zero subsidies to an

[25]We note that the possibility of temporary green subsidies, when available along with carbon taxes, has been shown elsewhere in the literature, but for a very different reason. Acemoglu et al. (2012) find that temporary clean energy subsidies are optimal in a model of endogenous and directed technical change. Underlying their result are positive externalities associated with green energy research and development. Our results show that a similar non-motonicity of green energy subsidies over time is possible without technological change and based on the environmental externality of fossil energy alone.

ICA that fixes carbon taxes at their first best levels, thereby responding in a way that is globally efficient.

Equation (15) nevertheless shows that the result no longer holds with asymmetry in marginal damages. In particular, Home will want a green subsidy if $\alpha^* < \alpha$, and a green tax (i.e., $s < 0$) otherwise. To see why intuitively, notice that if Home increases its subsidy from zero, the consequent decrease in the price of F has two effects reflected in equation (15). The first term captures the marginal cost of a decrease in the price of F due to the fact that the F sector is being overtaxed from Home's unilateral perspective by α^*. 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 now ask: Might countries choose the globally optimal taxes if the ICA constrains only the subsidies at $s = s^* = 0$? 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 lower than their domestic marginal damages. Notice that, if the ICA can only constrain green subsidies, taking into account that governments will then choose their carbon taxes unilaterally, the ICA can in general do better than setting subsidies at zero. This does not, however, change the fact that such an ICA cannot achieve global efficiency, which entails zero subsidies and the Pigouvian carbon taxes. We summarize these findings as follows.

Proposition 4. *An ICA that focuses only on carbon taxes (and fixes them at their first-best level) leads to global efficiency if countries are symmetric. On the other hand, an ICA that focuses only on green subsidies can never achieve global efficiency.*

The analysis above suggests two insights. The first one is that an ICA that focuses on carbon taxes alone, which is often the emphasis in the literature on ICAs, will be inefficient if subsidies are available and countries are asymmetric. The second, perhaps more surprising, insight is that the inefficiency of an ICA that ignores green subsidies is small if countries are close to symmetric. This in turn 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.

5 The effects of lobbying

We now introduce lobbying into our open-economy setup and focus on two questions related to welfare. First, we consider how lobbying affects the welfare of countries in the noncooperative scenario. Broadly speaking, we find that the F lobby tends to be bad for welfare, whereas the

G lobby tends to be good for welfare. This strong asymmetry is due to the openness between the two economies, and contrasts with the case of a closed economy, where introducing either the F or G lobby is bad for welfare. Second, we consider the welfare effects of an ICA in the presence of lobbying, relative to the noncooperative equilibrium. Despite the fact that, even under lobbying, the only purpose of an ICA in this setting is to correct climate externalities, we show that a politically-pressured ICA can decrease welfare in the presence of a strong G lobby.

5.1 Welfare effects of lobbying in the noncooperative setting

We assume for simplicity that the political parameters γ^F,$\gamma^G \geq 0$ are the same in both countries, though we discuss the implications of relaxing this assumption below. Solving for the symmetric Nash equilibrium policies, which are a straightforward generalization of (10), we find

$$t^N = \alpha\left(2-\Phi_t\right) - \gamma^F \frac{y^F(q_N^F)}{y^{F'}(q_N^F)} \quad \text{and} \quad s^N = \alpha\Phi_s + \gamma^G \frac{y^G(q_N^G)}{y^{G'}(q_N^G)}, \tag{16}$$

where q_N^i denotes the producer price for energy input i at the Nash equilibrium, and the terms Φ_t and Φ_s are defined as in footnote 15.[26] Referring back to (10), it is clear that the first term of each expression captures the unilateral environmental motive for each policy, and the second term captures the impact of lobbying.

Now consider the comparative-static effects of changing the political parameters γ^F and γ^G (symmetrically in the two countries). We can distinguish between the direct and indirect effects of these changes on the equilibrium policy levels. Consider, for example, increasing the strength of the F lobby: the direct effect is a decrease in the carbon tax, as can be seen in (16). Indirect effects of the decrease in t then arise through two channels because of the change in prices. The first is through the supply levels. Decreasing t increases q^F and decreases q^G, and this boosts y^F and reduces y^G, which in turn further decreases t and reduces s. This first indirect effect therefore reinforces the direct effect. The second channel operates through the slopes of the demand and supply functions, which in turn affect the terms Φ_t and Φ_s. In what follows, to make our results sharper and more transparent, we simply assume that this second indirect effect cannot outweigh the other effects outlined above. This is satisfied, for example, if demand and supply functions are linear.[27] In this case, it is easy to see that increasing the power of a lobby changes both policies in the lobby's desired direction: an increase in γ^F reduces both t

[26] Here we write the producer prices as explicit arguments of y^i and $y^{i'}$ $(i = F, G)$ as it will prove useful later in this section when making comparisons between the Nash and cooperative policies. We also note that there is a slight abuse of notation in (16), because Φ_t and Φ_s in general depend on prices, and the equilibrium prices are different with and without lobbying.

[27] Recall from footnote 15 that the expressions for Φ_t and Φ_s contain supply and demand slopes. If demand and supply functions are linear, Φ_t and Φ_s are constant.

and s, and an increase in γ^G increases both s and t.

We now turn to the welfare effects of lobbying, first stating our result and then providing some intuition.

Proposition 5. *(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 potentially more concerning than the latter. To understand part (i) of Proposition 5, note first that the change in global welfare is given by $dW^W(t,s) = \frac{\partial W^W}{\partial t}dt + \frac{\partial W^W}{\partial s}ds$. Now recall from our previous discussion of Figure 1 that the Nash policy vector N absent lobbying lies below the $s^C(t)$ curve. It follows that, if the G lobby is not too strong, the Nash policy vector in the presence of lobbying continues to lie below the $s^C(t)$ curve. This is illustrated in Figure 3, where the point $N(\gamma^F, \gamma^G)$ indicates the Nash equilibrium policies under lobbying. 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 to the positive international externality from the subsidy. It therefore follows that strengthening the F lobby, which reduces t and s, decreases welfare. This change is indicated in Figure 3 by the brown arrow, which points Southwest. To understand part (ii) of Proposition 5, note again that, regardless of the F lobby's strength, the point $N(\gamma^F, \gamma^G)$ is below the $s^C(t)$ curve as long as the G lobby is not too strong. Hence strengthening the G lobby, which increases s and t, increases welfare. This change is indicated in Figure 3 by the green arrow, which points Northeast.[28]

Intuitively, the reason why the F lobby tends to be bad for welfare while the G lobby tends to be good is closely related to the fact—pointed out previously—that green subsidies have positive international externalities at the noncooperative equilibrium. 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.[29]

Finally, it is worth emphasizing that the sharp asymmetry between the welfare effects of the two lobbies is due to the openness of the two economies. To highlight the contrast between

[28]If, however, the G lobby is very strong, the green subsidies will be large, and it is therefore possible that the point $N(\gamma^F, \gamma^G)$ will lie above the $s^C(t)$ curve. In this case, $\frac{\partial W^W}{\partial s} < 0$, and further strengthening of the G lobby will reduce welfare, as the greater distortion from s outweighs the welfare gain from increasing t.

[29]We note that the results discussed here are predicated on the assumption that lobbies are symmetric between 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 results identified above continue to hold.

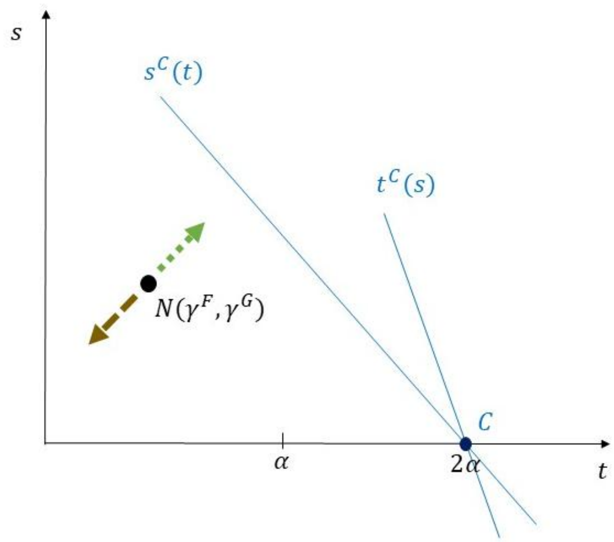

Figure 3: Effect of lobbying in the noncooperative setting

the impact of lobbying under open economies and under autarky, consider a simpler thought experiment than the one considered above: let us introduce a single lobby starting from a no-lobbying scenario. In a closed economy, introducing either the F or G lobby alone is bad for welfare, because in the absence of lobbying, policies are set at their welfare maximizing levels. In the open-economy setting, however, introducing the G lobby alone can mitigate the inefficiency of the Nash equilibrium policies, whereas introducing the F lobby alone exacerbates it.

5.2 The welfare effects of a politically-pressured ICA

We now consider how lobbying impacts the formation of an ICA, and in particular, we focus on 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 maintain the assumption that the ICA sets the policy levels t and s to maximize the sum of the government payoffs, which are now given by the politically-adjusted welfare functions Ω and Ω^*, thus the ICA now maximizes $\Omega^W \equiv \Omega + \Omega^*$. It is straightforward to verify that the policies that maximize Ω^W are

$$t^C = 2\alpha - \gamma^F \frac{y^F(q_C^F)}{y^{F'}(q_C^F)} \quad \text{and} \quad s^C = \gamma \frac{y^G(q_C^G)}{y^{G'}(q_C^G)}, \tag{17}$$

where q_C^i denotes the equilibrium producer price induced by the cooperative policies for energy input $i = F, G$. The cooperative policies in (17) differ from the noncooperative policies in (16) in two respects. First is the absence of the terms that capture the unilateral environmental motive for policies (these are the terms that contain Φ_t and Φ_s). Second is that the inverse supply semi-elasticities are evaluated at q_C^i rather than q_N^i.

Before analyzing the welfare effects of an ICA, we first examine two related questions: What motivates an ICA in a politically-pressured environment, or more specifically, what international 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, only the international environmental externalities motivate the ICA. To see this, we can shut down the environmental externality by setting $\alpha = 0$, take the derivative of Home's welfare with respect to Foreign's policies, and evaluate the conditions at the symmetric Nash equilibrium to find $\frac{\partial \Omega}{\partial t^*}\big|_{NE} = \frac{\partial \Omega}{\partial s^*}\big|_{NE} = 0$. Thus there are no international policy externalities to address, and hence no scope for an ICA, when $\alpha = 0$. This is confirmed by comparing (16) and (17) with $\alpha = 0$, in which case the Nash and cooperative polices coincide. 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 Foreign's production instruments cannot "help" the Home government politically, because Home can already help itself by choosing its own production instruments in a politically efficient way. It is worth noting that this result contrasts with some other models in the literature that consider politically-pressured international agreements.[30]

Our second question calls for a comparison between the Nash policies (t^N, s^N) in (16) and the cooperative policies (t^C, s^C) in (17). We can distinguish between direct and indirect effects of the ICA on t and s. The direct effect is that the ICA removes the terms in expression (16) that capture the unilateral environmental motive for policies, thus increasing t by the amount $\alpha\Phi_t$ and decreasing s by the amount $\alpha\Phi_s$. The indirect effect is that these policy changes affect producer prices and hence the supply semi-elasticities, which feed back into the equilibrium policy levels. To make our point in the simplest way, we focus on the case where the direct effect dominates the indirect effect, which is guaranteed for example if the supply

[30]For example, in Maggi and Ossa's (2023) model of international regulatory cooperation, agreements are motivated by international political externalities. The reason is that governments choose standards in a setting where production instruments are not available. Standards are not the targeted instruments for the purpose of redistribution to lobbies, and as a consequence, they do have international political externalities at the noncooperative equilibrium. Another example is given by models of tariff agreements where export interests are politically organized but export subsidies are not available (e.g., Grossman and Helpman, 1995; Ornelas, 2005; Bagwell and Staiger, 2011): in such settings, tariffs exert international political externalities at the noncooperative equilibrium, because a government is not able to redistribute toward its export lobbies through export subsidies.

semi-elasticities do not vary too much with prices. In this case, which is a natural one to consider but not necessary for our analysis that follows, the ICA changes both policies toward their Pigouvian levels:

Remark 4. *Suppose supply semi-elasticities do not vary too much with prices. Then, regardless of lobbying pressures, the ICA increases t and decreases s, moving them closer to their Pigouvian levels: $t^N < t^C \leq 2\alpha$ and $s^N > s^C \geq 0$.*

Note that the expressions in (17) imply 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. To this end, we consider the derivative of the global welfare function $W^W(t,s)$ as we move from the symmetric Nash policies (t^N, s^N) to the symmetric cooperative policies (t^C, s^C) following a straight line. Letting $s = \hat{s}(t) \equiv s^N + \frac{s^N - s^C}{t^C - t^N} \cdot \left(t^N - t\right)$ denote this straight line, and recalling that $\widetilde{q}^i(t,s)$ denotes the equilibrium producer price of energy input $i = F, G$ as a function of the symmetric tax and subsidy, we can write the following derivative of global welfare as we move from the noncooperative to the cooperative level of policies:

$$\begin{aligned} \frac{dW^W(t,\hat{s}(t))}{dt} =& \frac{\partial W^W}{\partial t} - \frac{\partial W^W}{\partial s} \cdot \frac{s^N - s^C}{t^C - t^N} \\ =& 2\left[\underbrace{(t-2\alpha)y^{F'}\frac{\partial \widetilde{q}^F}{\partial t}}_{\text{net env benefit}} \underbrace{-sy^{G'}\frac{\partial \widetilde{q}^G}{\partial t}}_{\text{higher } G \text{ distortion}}\right] - 2\left[\underbrace{(t-2\alpha)y^{F'}\frac{\partial \widetilde{q}^F}{\partial s}}_{\text{net env loss}} \underbrace{-sy^{G'}\frac{\partial \widetilde{q}^G}{\partial s}}_{\text{lower } G \text{ distortion}}\right] \cdot \frac{s^N - s^C}{t^C - t^N}. \end{aligned} \tag{18}$$

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. This includes the net environmental benefit due to the reduction in the price of F, and the cost of the overproduction distortion in the G sector, due to the fact that the increase in t boosts the price of 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 scenarios, 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 the price of F, and the benefit of reducing the overproduction distortion in the G sector. Finally, notice that

$$t^C - t^N = \alpha\Phi_t + \gamma^F \Delta\left(\frac{y^F}{y^{F'}}\right) \quad \text{and} \quad s^N - s^C = \alpha\Phi_s - \gamma^G \Delta\left(\frac{y^G}{y^{G'}}\right) \tag{19}$$

where $\Delta\left(\frac{y^i}{y^{i'}}\right) \equiv \frac{y^i(q^i_N)}{y^{i'}(q^i_N)} - \frac{y^i(q^i_C)}{y^{i'}(q^i_C)}$ for energy type $i = F, G$.

The different terms in equation (18) suggest a way in which the ICA might decrease welfare. Consider a strong G lobby (i.e., large γ^G) that causes a large Nash green subsidy s^N. Then if the cross-sector effect $\frac{\partial \tilde{q}^G}{\partial t}$ is non-negligible, the carbon tax increase brought about by the ICA causes a substantial worsening of the distortion in the G sector. The ICA is then guaranteed to reduce welfare if it does not reduce the green subsidy by much (i.e., $s^N - s^C$ is small), so that the effect of the second term in brackets in (18) is muted. This is the case, for example, if the cross-sector effect of the subsidy $\frac{\partial \tilde{q}^F}{\partial s}$ is small (in which case it can easily be shown that Φ_s is small) and the supply semi-elasticities do not vary much with the producer price (so that $\Delta\left(\frac{y^G}{y^{G'}}\right)$ is small). Notice that, if γ^G is large enough and $s^N - s^C$ is small enough, $\frac{dW^W(t,\hat{s}(t))}{dt}$ is negative all the way as we move from (t^N, s^N) to (t^C, s^C), thus ensuring that the ICA reduces welfare. Finally, we also note that in this example, the condition for Remark 4 is satisfied, so the ICA moves s and t toward their Pigouvian levels.

Our next proposition summarizes the key point of the above discussion. Even if an ICA only serves to address environmental externalities and it moves policies toward their Pigouvian levels, we find that:

Proposition 6. *Under lobbying, the ICA can decrease welfare relative to the noncooperative equilibrium, and this will occur if γ^G is large enough and $s^N - s^C$ is small enough.*

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

6 What about trade and consumption instruments?

In this final section, we discuss how allowing for trade and consumption instruments in the energy sectors may affect the key insights of the preceding analysis. If all instruments are unconstrained and can be costlessly used, it is well-known that a combination of production and trade instruments is equivalent to a combination of production and consumption instruments. In reality, however, trade instruments are constrained by existing trade agreements (or by the threat of retaliation), and consumption instruments can be administratively costly, thus making it meaningful to consider both policy packages. We proceed in this section with an intuitive discussion, rather than providing a formal analysis.

6.1 Trade instruments

We begin with the joint use of production and trade instruments. While in previous sections we focused mostly on the case of symmetric countries to make our points more transparent, it is natural here to consider asymmetric countries, as this enables trade to emerge in equilibrium. To keep things simple, we focus on the unilateral welfare-maximizing policies and on making two main observations. First, if trade policy is unconstrained, a country will choose trade instruments in both energy sectors along with a Pigouvian carbon tax on fossil energy, but if trade instruments are constrained to some degree, a country will choose a mix of trade and production instruments in both energy sectors. Importantly, G-sector policies—which may now consist of trade and/or production instruments—continue to be used in addition to F-sector policies to reduce foreign emissions, even though the latter are the more targeted instruments for this objective. Second, G-sector policies continue to have more beneficial "side effects" than F-sector policies. In particular, a G-sector policy change that reduces foreign emissions will also lead to lower domestic and global emissions, while an F-sector policy change that reduces foreign emissions will lead to higher domestic emissions and, under some conditions, higher global emissions.

We start with the benchmark case where trade instruments are unconstrained, and then consider an (arguably more realistic) scenario where trade instruments are constrained at least in part by trade agreements. In the former case, it is easy to show that Home's optimal unilateral policy for any fixed Foreign 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. The targeting principle provides an intuition. The unilateral policy intervention has three objectives: reduce domestic emissions, reduce Foreign emissions, and manipulate terms of trade (TOT). Reducing domestic emissions is best achieved with a production tax on F; reducing Foreign emissions requires a reduction in the foreign producer price of F, and this is best achieved with trade policy; and manipulating TOT is also best achieved with trade policy.

The more subtle part of the policy package just described is the fact that trade policy is used in *both* energy sectors, even though trade intervention in the F sector is the most direct way to affect the Foreign price of F. The intuition is similar to that developed previously in the setting with production instruments only. The ideal targeted instrument to reduce Foreign emissions would be to directly tax Foreign producers of F, but this is not available to the Home government. From a unilateral point of view, therefore, trade policy provides the next best instrument to target this margin, and using instruments in both energy sectors allows Home to spread out the distortion caused by trade policy.[31]

It is well known, however, that the GATT-WTO bans export subsidies and imposes caps on import tariffs. Furthermore, a multitude of free trade areas and customs unions have all but eliminated tariffs among member countries.[32] So how might the optimal unilateral policies differ in a world where trade policies are constrained by pre-existing trade agreements?

Consider first the extreme case where trade instruments are constrained at zero. In this case, Home will engage in policy substitution and use production instruments to affect world prices, both for environmental reasons (reducing the world price of F) and for TOT reasons (reducing the world price of imports and increasing the world price of exports). Intuitively, if α is large enough, the environmental motive dominates, and Home will introduce a green production subsidy and reduce the carbon tax below α. In this case, the pattern of results is qualitatively similar to that in our symmetric setup of Section 3.

If trade instruments are partially constrained, Home will engage in partial policy substitution, using a production instrument in the G sector and changing the level of the carbon tax from α. In general, because of the interaction between the environmental and TOT motives, s could be positive or negative, and t could be lower or higher than α, but one can show that if α is large enough and some regularity conditions are satisfied, s will be positive and t will be lower than α.[33]

The preceding discussion makes clear that, regardless of any constraints on trade policy, there is a unilateral environmental rationale for intervening in the G sector: through production instruments, trade instruments, or both. The next important point is that, regardless of whether Foreign emissions are targeted with trade and/or production instruments, doing so through G-sector policies has beneficial side effects (due to reverse leakage), whereas doing so through F-sector policies has adverse side effects (due to leakage). This contrast is an immediate implication of the differential effects on Home and Foreign producer prices of F. Policies in the G sector affect the domestic and Foreign producer price of F in the same direction, whereas policies in the F sector affect producer prices of F in opposite directions.

[31] We note that the optimal unconstrained trade instruments can in general be taxes or subsidies, depending on the direction of the trade flow in each sector and on how the TOT motive for trade intervention compares with the environmental motive.

[32] As recent events have reminded us, the constraints on trade policy imposed by trade agreements are imperfectly enforceable, and governments sometimes knowingly violate them, but this arguably carries significant costs, in part because of the possibility of retaliation.

[33] More specifically, assume α is large enough and consider an exogenous and proportional reduction of the trade taxes/subsidies in the F and G sectors, starting from their unconstrained optimal levels. It can be shown that this leads to $s > 0$ and $t < \alpha$, at least if demand and supply functions are sufficiently close to linear. The reason for this condition is the following. As the trade taxes/subsidies move exogenously from their unconstrained optimal levels to zero, t moves from α to a lower level and s moves from zero to a strictly positive level, but if demand and supply functions are highly nonlinear, we cannot rule out non-monotonicity of these paths, because of indirect effects that operate through the slopes of demand and supply.

To be more concrete, consider the effect of import tariffs. First suppose Home imposes a tariff in the F sector. This will reduce the Foreign producer price of F, while increasing the domestic producer price, thereby leading to higher emissions at Home. Furthermore, global emissions may well increase as a result of a tariff on F, and will definitely increase if the passthrough rate of the tariff is sufficiently close to one.[34] In light of recent empirical studies that find high passthrough rates for U.S. tariffs, often close to one (e.g., Fajgelbaum and Khandelwal, 2022), this suggests that trade intervention in the F sector may well be detrimental from the global climate point of view. Now consider an import tariff in the G sector. This will reduce the producer price of F both at home and abroad, thereby leading to lower emissions in both countries, just as we found for a green production subsidy. As a consequence, an import tariff in the G sector can only decrease global emissions.

The statements above generalize in a straightforward way to export and production subsidization. Suppose first that Home exports F and consider a unilateral increase in Home's export subsidy (or equivalently, a reduction in the export tax) for F. In our setting, this reduces the world price of F and hence Foreign's emissions, and at the same time it increases the domestic price of F, thus increasing Home's emissions. And if the passthrough rate of this policy change to the domestic price of F is sufficiently close to one, global emissions will increase. On the other hand, if the same export policy change occurs in the G sector, it will decrease the price of F in both countries, thus reducing emissions at home and abroad.

Finally consider a unilateral increase in Home's production subsidy (or equivalently, a reduction in the production tax) for F. Again, this leads to a reduction in Foreign emissions and an increase in Home emissions, and global emissions will increase if the rate of passthrough of the subsidy to the domestic producer price is sufficiently close to one.[35] On the other hand, if the analogous policy change occurs in the G sector, this will decrease emissions in both countries.

In sum, the general insight here is that, depending on the constraints that apply to trade instruments, a government may lean more on trade or production instruments to control foreign emissions, but regardless, G-sector policies continue to have beneficial side effects for the global

[34]To see this, note that global emissions can be written as $y^F\left(\rho^F - t + \tau\right) + y^{*F}\left(\rho^F - t^* + \tau^*\right)$, where ρ^F denotes the world price (which is a function of all policies), so the effect of the tariff τ on global emissions is $\frac{\partial\left(y^F + y^{*F}\right)}{\partial\tau} = y^{F'} \cdot \left(\frac{\partial\rho^F}{\partial\tau} + 1\right) + y^{*F'} \cdot \frac{\partial\rho^F}{\partial\tau}$. Note that the passthrough rate of the tariff to the domestic price is given by $\frac{\partial q^F}{\partial\tau} = \frac{\partial\left(\rho^F - t + \tau\right)}{\partial\tau} = \frac{\partial\rho^F}{\partial\tau} + 1$. Hence if the passthrough rate is close to one, then $\frac{\partial\rho^F}{\partial\tau}$ is small and global emissions increase.

[35]The rate of passthrough to the domestic producer price is defined simply as the extent to which the export subsidy or production subsidy translates into an increase in the domestic producer price. Note that, in the limit case of a small open economy, an export subsidy has a passthrough rate of one to both the domestic and consumer price, while a production subsidy has a passthrough rate of one only to the domestic producer price (and zero to the domestic consumer price). Also note that the thought experiment we are considering here is a bit different from the one we considered in Section 3.1, although the basic insight is similar: there we considered the implications of symmetric changes in production taxes/subsidies in both countries, while here we are considering unilateral policy changes in the Home country.

environment, whereas F-sector policies do not.

6.2 Consumption instruments

In a world where trade instruments are constrained, it is natural to consider the possibility for consumption taxes. We start with the case in which consumption taxes are unconstrained, and then discuss the implications of possible limitations to their use. We again focus on the unilateral welfare-maximizing choice of policies.

Suppose Home can freely use production and consumption instruments (but not trade instruments), holding Foreign policies constant. In this case, the optimal unilateral policy entails: (i) a production tax lower than α and a consumption tax in the F sector; and (ii) a production subsidy coupled with an equal-rate consumption tax in the G sector. This policy package implements the same allocation as the optimal (unconstrained) combination of production and trade instruments described in the previous section, but with production and consumption instruments instead. In this case, it is also worth noting that the production subsidy in the G sector will be lower in magnitude than in our baseline model with production instruments only. Intuition for this difference follows from the desire to spread the policy distortion across all instruments: it is still optimal to subsidize green energy, but the magnitude of the subsidy is smaller than absent consumption taxes.

An important observation worth highlighting is that intervention in the G sector (production subsidies and consumption taxes) remains optimal even though fossil energy can be taxed both at the production and consumption margins. Here again the reason lies in the desirability of spreading the policy distortion across all margins, where the aim is to reduce the producer price of fossil energy abroad.

Some nevertheless argue that significant administrative costs may limit the scope for consumption taxes in the energy sector (e.g., Weisbach et al. 2023). For example, if green and fossil energy are both inputs to produce electricity, the government will need to collect differential taxes on purchases of the two forms of energy from electricity producers, and this may be costly to administer and monitor. Moreover, when it comes to energy, the number of downstream consumers is significantly greater than the number of upstream producers, which can further increase the administrative costs of implementing consumption instruments compared to production instruments (Metcalf and Weisbach 2009).

Finally, to the extent that the use of consumption taxes is limited by administrative costs, or other constraints, production instruments in the F and G sectors will become more important. This policy shifting is intuitive because the more consumption taxes are constrained, the closer we get to the production-instrument-only setting of our basic model.

7 Conclusion

In this paper, we develop a simple and tractable model to examine positive and normative questions that arise with the joint use of carbon pricing and green subsidies in an open-economy setting with global climate externalities. At the core of our model is a final good that uses use two forms of energy inputs—fossil fuel, which generates a global externality, and green energy, which does not. The model generates novel insights around three broad questions: How does the availability of both carbon taxes and green subsides affect the noncooperative choices of these policies, and what are the welfare implications of these choices? When it comes to international cooperation, should ICAs seek to increase or decrease green subsidies, or even ignore them entirely? And what are the welfare consequences of lobbying by the fossil and green energy sectors in the open-economy setting?

We find that countries have a unilateral incentive to use green subsidies, in addition to reducing carbon taxes, in order to control foreign emissions, and that green subsidies are associated with a beneficial "reverse leakage" effect, which stands in contrast to the leakage effect of carbon taxes. As a consequence of the reverse-leakage effect, the availability of green subsidies tends to be good for global welfare in a noncooperative setting. When it comes to international cooperation, an ICA removes green subsidies, even though they exert 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 setting the fossil lobby tends to be bad for welfare, while the green lobby tends to be good for welfare. We also find that in the presence of lobbying, an ICA can decrease welfare relative to the noncooperative equilibrium, even if it moves carbon taxes and green subsidies toward their efficient levels.

We have made a number of simplifying assumptions throughout the paper in order to make the results sharp. Relaxing some of these assumptions in future research would enable the model to address further interesting and policy relevant questions. We have, for example, focused on global climate damages as the only source of market failure, but green subsidies can also be motivated by research and development externalities, external economies of scale, and learning by doing spillovers. These other market failures would provide an "industrial policy" rationale for green subsidies, and they could interact in interesting and potential important ways with the climate change rationale of our basic model.

Another potentially fruitful direction for extending our model would be to allow for asymmetries across countries, and in particular, asymmetries across countries in the valuation of climate damages, in the power of lobbies, and in the structure of supply and demand, which determines comparative advantage. Doing so may help illuminate, for example, why some countries rely more on carbon pricing and others on green subsidies (Clausing and Wolfram 2023), and it may identify different policy implications for developed and developing countries. Finally, a model with heterogeneous countries could be used to examine questions related to climate finance in the form of international transfers, potentially in form of green subsidies, which are topics that do not emerge in our model with symmetric countries.

8 Appendix

8.1 Price effects of policies in a closed economy

Differentiating the market clearing conditions (2) and (3), we can solve for the change in prices due to changes in policy.

It is first helpful to define $\Theta \equiv \frac{\partial d^F}{\partial p^G}\frac{\partial d^G}{\partial p^F} - (\frac{\partial d^F}{\partial p^F} - y^{F'})(\frac{\partial d^G}{\partial p^G} - y^{G'}) < 0$, where the sign follows because $\frac{\partial d^F}{\partial p^G}\frac{\partial d^G}{\partial p^F} - \frac{\partial d^F}{\partial p^F}\frac{\partial d^G}{\partial p^G} < 0$. The latter inequality follows by differentiating the general equilibrium demand functions in (1) for $i = F, G$, rearranging terms, and using the fact that $\frac{\partial a^F}{\partial p^G}\frac{\partial a^G}{\partial p^F} - \frac{\partial a^F}{\partial p^F}\frac{\partial a^G}{\partial p^G} < 0$ because the Hessian matrix of the cost function is negative semi-definite.

The price changes can then be written as

$$dp^F = \frac{\left(\frac{\partial d^G}{\partial p^G} - y^{G'}\right) y^{F'}\, dt + \frac{\partial d^F}{\partial p^G} y^{G'}\, ds}{\Theta} \tag{20}$$

$$dp^G = -\frac{\left(\frac{\partial d^F}{\partial p^F} - y^{F'}\right) y^{G'}\, ds + \frac{\partial d^G}{\partial p^F} y^{F'}\, dt}{\Theta}. \tag{21}$$

Focusing on the within-sector effects, these expressions immediately prove that $0 < \frac{\partial p^F}{\partial t} < 1$ and $-1 < \frac{\partial p^G}{\partial s} < 0$, and therefore incomplete pass-through. Turning to the cross-sector effects, the price changes also imply that $\frac{\partial p^G}{\partial t} >$ if and only if G is a substitute for F, and $\frac{\partial p^F}{\partial s} < 0$ if and only if F is a substitute for G. This proves our claims on the within-sector and cross-sector effects of policies.

8.2 Welfare maximizing policies in a closed economy

Differentiating (4) with respect to t and s yields the first-order conditions:

$$\begin{aligned}\frac{\partial W}{\partial t} =& \underbrace{-d(\cdot)\left(a^F\frac{\partial p^F}{\partial t} + a^G\frac{\partial p^G}{\partial t}\right)}_{-y^F\frac{\partial p^F}{\partial t} - y^G\frac{\partial p^G}{\partial t}} \\ &+ y^F \cdot \left(\frac{\partial p^F}{\partial t} - 1\right) + y^G \cdot \frac{\partial p^G}{\partial t} + y^F + (t-\alpha)y^{F'}\left(\frac{\partial p^F}{\partial t} - 1\right) - sy^{G'} \cdot \frac{\partial p^G}{\partial t} = 0\end{aligned}$$

$$\begin{aligned}\frac{\partial W}{\partial s} =& \underbrace{-d(\cdot)\left(a^F\frac{\partial p^F}{\partial s} + a^G\frac{\partial p^G}{\partial s}\right)}_{-y^F\frac{\partial p^F}{\partial s} - y^G\frac{\partial p^G}{\partial s}} \\ &+ y^F \cdot \frac{\partial p^F}{\partial s} + y^G \cdot \left(\frac{\partial p^G}{\partial s} + 1\right) + (t-\alpha)y^{F'} \cdot \frac{\partial p^F}{\partial s} - y^G - sy^{G'} \cdot \left(\frac{\partial p^G}{\partial s} + 1\right) = 0.\end{aligned}$$

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

$$\frac{\partial W}{\partial t} = (t-\alpha)\, y^{F'} \frac{\partial q^F}{\partial t} - s y^{G'} \frac{\partial q^G}{\partial t} = 0$$

$$\frac{\partial W}{\partial s} = (t-\alpha)\, y^{F'} \frac{\partial q^F}{\partial s} - s y^{G'} \frac{\partial q^G}{\partial s} = 0.$$

The unique solution is $t = \alpha$ and $s = 0$, as claimed in the text.

8.3 Proof of Remark 2

Expanding on equation (12) in the main text, we have

$$\begin{aligned}\frac{dW^W(s, t^N(s))}{ds} =& 2\left((t-2\alpha)y^{F'}\frac{\partial \widetilde{q}^F}{\partial s} - s y^{G'}\frac{\partial \widetilde{q}^G}{\partial s}\right) \\ &+ 2\left((t-2\alpha)y^{F'}\frac{\partial \widetilde{q}^F}{\partial t} - s y^{G'}\frac{\partial \widetilde{q}^G}{\partial t}\right)\frac{y^{G'}}{y^{F'}} \cdot \frac{\frac{\partial \widetilde{q}^G}{\partial t}}{\frac{\partial \widetilde{q}^F}{\partial t} - 1},\end{aligned} \tag{22}$$

where we have expressed $t^{N'}(s)$ in (11) using the relationships $\frac{\partial q^G}{\partial t} = \frac{1}{2}\frac{\partial \widetilde{q}^G}{\partial t}$ and $\frac{\partial q^F}{\partial t} = \frac{\partial p^F}{\partial t} - 1 = \frac{1}{2}\frac{\partial \widetilde{p}^F}{\partial t} - 1 = \frac{1}{2}\left(\frac{\partial \widetilde{q}^F}{\partial t} + 1\right) - 1 = \frac{1}{2}\left(\frac{\partial \widetilde{q}^F}{\partial t} - 1\right)$.

Evaluating the change in global welfare at $s = 0$, the expression simplifies to

$$\left.\frac{dW^W(s, t^N(s))}{ds}\right|_{s=0} = 2(t-2\alpha)y^{F'}\left(\frac{\partial \widetilde{q}^F}{\partial s} + \frac{\partial \widetilde{q}^F}{\partial t} \cdot \frac{\frac{\partial \widetilde{q}^G}{\partial t}}{\frac{\partial \widetilde{q}^F}{\partial t} - 1} \cdot \frac{y^{G'}}{y^{F'}}\right), \tag{23}$$

which is positive if and only if the term in parentheses is negative. Substituting in for the price derivatives, which are equal to those in the closed economy (see 20 and 21) because of the symmetric policy changes, the condition for an increase in welfare at $s = 0$ can be rewritten as $\frac{\frac{\partial \widetilde{q}^F}{\partial t} - 1}{\frac{\partial \widetilde{q}^F}{\partial t}} > \frac{\frac{\partial d^G}{\partial p^F}}{\frac{\partial d^F}{\partial p^G}}$. Since incomplete pass-through implies that the left-hand side is greater than 2, a sufficient condition for this inequality to hold is $2\frac{\partial d^F}{\partial p^G} > \frac{\partial d^G}{\partial p^F}$, which is clearly satisfied if $\frac{\partial d^G}{\partial p^F} = 0$ or $\frac{\partial d^F}{\partial p^G} = \frac{\partial d^G}{\partial p^F}$.

We now consider further increases in s. Note that, because (22) is linear in s, if it is positive at both end points $s = 0$ and $s = s^N$, it is positive everywhere in between. Hence we need only evaluate (22) at s^N, which we can write as

$$\left.\frac{dW^W(s,t^N(s))}{ds}\right|_{s=s^N} = \left.\left(\frac{\partial W}{\partial s}+\frac{\partial W^*}{\partial s}+\frac{\partial W}{\partial s^*}+\frac{\partial W^*}{\partial s^*}\right)\right|_{s=s^*=s^N,t=t^*=t^N}$$
$$+\, t^{N'}(s^N)\left.\left(\frac{\partial W}{\partial t}+\frac{\partial W^*}{\partial t}+\frac{\partial W}{\partial t^*}+\frac{\partial W^*}{\partial t^*}\right)\right|_{s=s^*=s^N,t=t^*=t^N}$$

Recall that $W(\cdot)$ and $W^*(\cdot)$ are defined as functions of all policies, unlike $W^W(\cdot)$, and at the Nash equilibrium $\frac{\partial W}{\partial s}=\frac{\partial W}{\partial t}=\frac{\partial W^*}{\partial s^*}=\frac{\partial W^*}{\partial t^*}=0$. The previous expression therefore simplifies to

$$\left.\frac{dW^W(s,t^N(s))}{ds}\right|_{s=s^N} = \left.\left(\frac{\partial W^*}{\partial s}+\frac{\partial W}{\partial s^*}\right)\right|_{s=s^*=s^N,t=t^*=t^N} + t^{N'}(s^N)\left.\left(\frac{\partial W^*}{\partial t}+\frac{\partial W}{\partial t^*}\right)\right|_{s=s^*=s^N,t=t^*=t^N} \tag{24}$$

It is direct to verify that

$$\left.\frac{\partial W}{\partial s^*}\right|_{s=s^*=s^N,t=t^*=t^N} = (t^N-2\alpha)y^{F'}\frac{\partial q^F}{\partial s} - s^N y^{G'}\frac{\partial p^G}{\partial s} = s^N y^{G'}$$

and

$$\left.\frac{\partial W}{\partial t^*}\right|_{s=s^*=s^N,t=t^*=t^N} = (t^N-2\alpha)y^{F'}\frac{\partial p^F}{\partial t} + \alpha y^{F'} - s^N y^{G'}\frac{\partial q^G}{\partial t} = t^N y^{F'}.$$

Recognizing that symmetry implies $\frac{\partial W^*}{\partial s}=\frac{\partial W}{\partial s^*}$ and $\frac{\partial W^*}{\partial t}=\frac{\partial W}{\partial t^*}$, we can substitute these expressions, along with $t^{N'}(s)$ from (11), into (24) to obtain

$$\left.\frac{dW^W(s,t^N(s))}{ds}\right|_{s=s^N} = 2y^{G'}\left(s^N + t^N\frac{\frac{\partial q^G}{\partial t}}{\frac{\partial q^F}{\partial t}}\right). \tag{25}$$

Because $\frac{\partial q^G}{\partial t}=\frac{\partial p^G}{\partial t}=\frac{\partial d^G}{\partial p^F}y^{F'}\Theta^{-1}$ (see 21), the expression above is positive if $\frac{\partial d^G}{\partial p^F}$ is sufficiently small, and this completes the proof of the first sufficient condition in Remark 2.

To complete the proof of the second condition, first note that if the demand and supply derivatives are symmetric across the G and F sectors, then $\frac{\partial q^F}{\partial t}=-\frac{\partial q^G}{\partial s}$ and $\frac{\partial q^F}{\partial s}=-\frac{\partial q^G}{\partial t}$. Using these relationships, the Nash equilibrium policies can be written as $t^N=2\alpha+\frac{\alpha\frac{\partial q^F}{\partial t}}{\left(\frac{\partial q^F}{\partial t}\right)^2-\left(\frac{\partial q^F}{\partial s}\right)^2}$ and $s^N=-\frac{\alpha\frac{\partial q^F}{\partial s}}{\left(\frac{\partial q^F}{\partial t}\right)^2-\left(\frac{\partial q^F}{\partial s}\right)^2}$, where $\left(\frac{\partial q^F}{\partial t}\right)^2-\left(\frac{\partial q^F}{\partial s}\right)^2>0$ because we already established that $t^N<\alpha$ and $s^N>0$. Substituting the expressions for t^N and s^N into (25), we find that a sufficient condition for welfare to increase is $\frac{\partial q^F}{\partial t}\frac{\partial p^F}{\partial t}-\left(\frac{\partial q^F}{\partial s}\right)^2<0$, which is clearly satisfied.

8.4 Proof of Proposition 3

The assumption of linear demand and supply functions implies that $t^C(s)$ and $s^C(t)$ are linear. 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

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

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

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

$$u_s \begin{Bmatrix} = -\overline{u}_s & \text{if} & \lambda_s < 0 \\ = \overline{u}_s & \text{if} & \lambda_s > 0 \\ \in [-\overline{u}_s, \overline{u}_s] & \text{if} & \lambda_s = 0 \end{Bmatrix}.$$

The costate equations are

$$\begin{aligned} \dot{\lambda}_t &= -e^{-\delta z} \cdot \tfrac{\partial W(s,t)}{\partial t} \\ \dot{\lambda}_s &= -e^{-\delta z} \cdot \tfrac{\partial W(s,t)}{\partial s}. \end{aligned}$$

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 it 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 $\nu_0 < \nu_1$. 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.

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 $\dot{\lambda}_t(z) = -e^{-\delta z} \cdot \frac{\partial W(s(z),t(z))}{\partial t}$ 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 $(0, 2\alpha)$, and then λ_t stays constant at zero for $z \geq z_0$;

- $\lambda_s(z)$ solves the differential equation $\dot{\lambda}_s(z) = -e^{-\delta z} \cdot \frac{\partial W(s(z),t(z))}{\partial s}$ 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, $\overline{u}_t \cdot \left|\frac{ds^C}{dt}\right| \leq \overline{u}_s$, or $\frac{\overline{u}_s}{\overline{u}_t} \geq \left|\frac{ds^C}{dt}\right| \equiv \nu_1$.

Next suppose that $\frac{\overline{u}_s}{\overline{u}_t} < \left|\frac{ds^C}{dt}\right|$, 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 $\dot{\lambda}_t(z) = -e^{-\delta z} \cdot \frac{\partial W(s(z),t(z))}{\partial t}$ 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, and then λ_t stays constant at zero for $z \geq z_0'$;

- $\lambda_s(z)$ solves $\dot{\lambda}_s(z) = -e^{-\delta z} \cdot \frac{\partial W(s(z),t(z))}{\partial s}$ 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 $\left|\frac{dt^C}{ds}\right| \cdot \overline{u}_s \leq \overline{u}_t$, 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, $\left|\frac{ds^C}{dt}\right| < \left|\frac{dt^C}{ds}\right|^{-1}$. But for this solution to be viable, the policy vector must hit the t^C curve above the first-best point $(0, 2\alpha)$, and this requires $\frac{\overline{u}_s}{\overline{u}_t} \leq \frac{s^N}{t^N} \equiv \nu_0 < \nu_1$.

Now suppose $\nu_0 < \overline{u}_s/\overline{u}_t < \nu_1$. In this case, the solution is qualitatively the same as that 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, following 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 $(0, 2\alpha)$.

Finally, the above arguments imply that there exists a threshold ν_1 such that, if $\overline{u}_t/\overline{u}_s < \nu_1$, the ICA increases green subsidies before reducing them, and if $\overline{u}_t/\overline{u}_s > \nu_1$, the ICA decreases green subsidies monotonically, as stated in the proposition.

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