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Abstract

We determine the core characteristics of a climate coalition's optimal policies in a dynamic two-country directed technical change framework. Unilateral policies alter the structure of production and thereby innovation incentives across countries. Whenever feasible, optimal policies implement sustainable growth by directing global innovation to the nonpolluting sector. If nonparticipants drive global innovation, this requires policies relocating clean production to nonparticipants. A calibration exercise suggests that the US or EU alone are too small to implement sustainable growth. A coalition of Annex I countries that signed the Kyoto protocol can implement sustainable growth, yet required tax rates are very high.

1 Introduction

In June 1992, at the Earth Summit in Rio, the UNFCCC was opened for signature. The objective of the convention was to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN, 1992). Twenty-two years since, increased scientific evidence for climate change further strengthened the call to reduce greenhouse gas emissions. The outcomes of climate negotiations since Rio have been disappointing however. Where UNFCCC membership is near universal, the Kyoto protocol, which is the most important agreement linked to the UNFCCC, has never been ratified by the US. In addition, Japan, New Zealand, Russia and Canada have not taken on any second round targets under the protocol. Subsequent rounds of negotiations, from Bali to Prague, were unsuccessful in establishing a universal treaty with binding limits on emissions. As a

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consequence, attention has shifted to 'incomplete agreements' and policy actions adopted by a more limited number of countries. Examples are the European Emission Trading System, launched in 2005 and operational in 28 countries, but also individual countries' and states' actions such as Germany's Energiewende and California's Global Warming Solutions Act.

A global climate agreement is however still viewed as preferable to such unilateral policies. The main reason is that unilateral policies cause carbon leakage. Carbon leakage is the increase in emissions in nonparticipatory countries, as a consequence of emission-reducing policies in participatory countries. For example, a restriction of carbon intensive good production will increase the global price of these goods, which in turn increases production of these goods in nonparticipatory countries. Carbon leakage reduces the effectiveness, and thereby increases the cost, of unilateral policies in reducing emissions vis-à-vis the global solution (Babiker, 2005; Burniaux and Martins, 2012).[1]

Unilateral policies also affect nonparticipant's future emissions through technical change. By altering the structure of production across countries, unilateral policies affect innovation decisions in nonparticipatory countries. More specifically, policies that increase the price of carbon intensive goods encourage production and thereby innovation in these goods in these countries. Unless 'clean' sector innovation in the participatory countries is sufficiently strong, global innovation will be directed at the 'dirty' sector, increasing future emissions.

In this paper, we assess the conditions under which unilateral policies lead to sustainable growth globally, in the sense of curbing future emission growth, especially in foreign countries not adhering to climate policies. For foreign countries to substitute away from dirty goods, the clean good must be a sufficiently strong substitute, and sufficiently advanced relative to the dirty good. Sustainable growth thus requires inducing clean innovation. If the participatory countries dominate global innovation, i.e. if these countries are more innovative than non-participatory countries, clean growth is straighforwardly implemented through domestic innovation subsidies. If instead, the direction of global growth is determined in the non-paticipatory countries, sustainable growth require policies that, in the short run, increase the world market price of the clean good relative to the dirty good, turning the foreign countries in clean exporters, and encouraging clean innovation in these countries. Whether the participatory countries can sufficiently steer global innovation depends on the initial productivity of clean and dirty technologies, and the relative size of the coalition in terms of output. A large coalition with more advanced clean technology is more likely able to unilaterally implement sustainable growth.

The policy advice to stimulate foreign clean innovation runs counter to the intuitive advice based on the static perspective. The static view seeks the most (welfare) cost-effective solution to reduce emissions, given the state of technology, and will always opt for domestic emission reductions increasing the competitiveness of the foreign dirty sector. With foreign innovations driving global growth, such policies will reduce current emissions, but, by encouraging dirty innovation in foreign, fail to prevent emission growth and never implement sustainable growth.

Calibrating our stylized model, we find that the US or EU alone are too small to unilaterally direct flobal innovation efforts towards sustainable growth. Even though a coalition of Annex B countries with binding

[1] See also Markusen (1975), Hoel (1996), Copeland and Taylor (2004), Levinson and Taylor (2008) and van der Werf and Di Maria (2012).

targets does not drive global innovation, it is sizable enough to redirect innovation outside this coalition and thereby global long-run growth to the clean sector. The calibrated tax rates required in such a case however are very high: the tax rate on dirty intermediate input use exceeds 100%, corresponding to approximately 1700 $/tCO2. Larger coalitions require lower taxes to implement sustainable growth.

Our formal model builds on the Acemoglu et al. (2012) two-sector framework of directed technical change in the presence of an environmental externality. In this framework, final goods are produced using two intermediates. The production of the dirty intermediate causes carbon emissions, which reduce future utility. Scientists innovate in the sector with the greatest expected return. We extend the framework with a second country, allow for free trade in intermediate goods, assume no international enforcement of patent rights, and full and immediate international technology spillovers. These assumptions are strong, yet provide us with a clear setup to point at the core mechanisms.

The result that implementing sustainable growth may require increasing the price of the clean intermediate in the short run follows from directed technical change, the presence of carbon leakage and the importance of locality in innovation decisions. The result resembles the finding in Acemoglu (1998, 2002), who shows that profit-motivating scientists have an incentive to develop technologies for goods that are (relatively) expensive, in high demand, and technologically advanced. Acemoglu (1998) also pointed at the important role of international property rights protection, determining the market scientists face. Our framework combines an environmental and innovation market failure; firms do not appropriate the full social return of their innovations. Jaffe et al. (2005) argue that in this context, optimal policies comprise both a tax on pollution, and an innovation subsidy. This subsidy should redirect scientists to where their social value is greatest. Using formal modeling, Gerlagh et al. (2009) and Acemoglu et al. (2012) confirm this insight and show that with directed technical change a temporary subsidy redirecting scientists to the clean sector may be sufficient to prevent emissions from accumulating to dangerous levels.[2]

Empirical evidence for directed technical change is presented by Newell et al. (1999), who provide evidence for a positive responsive of energy-efficiency improvements to energy prices, and Popp (2002) and Aghion et al. (2012), who, using patent data, confirm that high energy prices and a large stock of existing knowledge of clean technologies spur the development of such technologies.[3] As noted above, in a static framework, the unilateral implementation of a carbon tax may cause carbon leakage. Directed technical change will then affect the degree of carbon leakage in the long run (Golombek and Hoel, 2004; Gerlagh and Kuik, 2007; Di Maria and Smulders, 2005; Di Maria and van der Werf, 2008; Hemous, 2012). In determining optimal unilateral environmental policies, this effect should be taken into account. Apart from Hemous (2012), the literature had so far not recognized that such optimal policies may require the non-participatory country to become a clean good exporter. The different outcomes reflect different basic of assumptions. Golombek and Hoel (2004) assume R&D to be always pollution-saving and Di Maria and Smulders (2005) abstract from foreign innovation. Gerlagh and Kuik (2007) and Di Maria and van der Werf (2008) posit that patents are perfectly enforced internationally which implies that innovation becomes independent of industry location. Hemous (2012) adopts a two-country framework with directed technical

[2] Aghion and Howitt (2009) reached the same conclusion in a similar, yet simplified analysis.

[3] Also Acemoglu and Linn (2004) and Hanlon (2011) find evidence for directed technical change in the pharmaceutical sector and the cotton textile industry in 19th century Britain, respectively.

change closely related to the framework presented in this paper. The countries trade in polluting and non-polluting goods, where the former is produced using a combination of 'clean' and 'dirty' inputs. To redirect the world economy to a sustainable growth trajectory, innovation in this dirty input must be halted.

Important contrasts between Hemous (2012) and this paper remain however. Hemous (2012) takes countries as equally innovative and abstracts from international technology spillovers in his core framework. We assume positive technology spillovers and allow for asymmetries in the size of the labor force and the number of scientists across countries. By abstracting from asymmetries in countries' innovation potential and labor force, Hemous (2012) cannot consider the role that these parameters play as core determinants of both the optimal policy set and the ability to unilaterally redirect the global economy to a more sustainable growth trajectory. Lastly, we contribute to the literature by explicitly contrasting optimal policy under exogenous and endogenous technical change.

The paper proceeds as follows. Section 2 presents the model, and Section 3 solves for its equilibrium. Section 4 discusses optimal unilateral policies, and under what conditions a sustainable growth path can be unilaterally implemented. Section 5 includes a calibration of the model and several numerical results. Section 6 discusses alternative modeling assumptions and Section 7 concludes. Several proofs are presented in Appendix A.

2 The model

This section introduces the basic framework. We extend the Acemoglu et al. (2012) framework to two countries, where the countries home, h, and foreign, f, can equally be regarded as internally coordinating regions. Each country $k \in \{h, f\}$ is endowed with a fixed amount of effective labor L_k, which is an increasing function of the population size of the country. Similarly, the inelastic supply of effective scientists, s_k, increases in the number of researchers in country k. This setup allows for a flexible interpretation when calibrating the model. Throughout the paper we refer to L_k as labor and s_k as the number of scientists in country k.

Preferences and production In each country, a representative household at time t maximizes intertemporal utility

$$U_{kt} = u\left(\mathbf{c_{kt^+}}, \mathbf{E_{t^+}}\right) \tag{1}$$

where $\mathbf{c_{kt^+}} = \{c_{kt}, c_{kt+1} ..., c_{k\infty}\}$ and $\mathbf{E_{t^+}} = \{E_t, E_{t+1}, ..., E_\infty\}$ are vectors of household final good consumption and the global pollutant stock. Utility is increasing in consumption at a decreasing rate, and falling in the pollutant stock at an increasing rate. We assume there exists some finite level of the emission stock $\bar{E} > 0$ such that reaching this level is infinitely costly in terms of utility: $\lim_{E_v \to \bar{E}} u\left(\mathbf{c_{kt}}, \mathbf{E_{t^+}}\right) = -\infty$ for some $v \geq t$. The utility function above is very general,[4] and for the analysis below there is no need to further specify its functional form. The core property used of the utility function is that allowing the pollutant

[4]The utility function used in Acemoglu et al. (2012) is a more specific version of (1).

stock to grow over time until some $E_v \geq \bar{E}$ is infinitely costly, and therefore always optimal to avoid. The remainder of the analysis will focus on unilateral policies that satisfy this neccesary condition for policy optimality.

Households consume a final good Y_{kt}, which is produced competitively using clean, c, and dirty, d, intermediate goods according to

$$(2) \qquad Y_{kt} = \left(Y_{kct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{kdt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}},$$

where $\varepsilon \in (0,\infty)$ is the elasticity of substitution between the two intermediates and Y_{kjt} is the quantity of intermediate $j \in \{c,d\}$ used in country k final good production. Throughout this paper, we assume the two intermediates are substitutes ($\varepsilon > 1$), i.e. the clean intermediate provides a service similar to the dirty intermediate and can therefore substitute for the dirty intermediate and the functions it performs. Referring to examples such as solar energy versus energy from nonrenewables, and the development of alternative, more energy-efficient production methods, this is likely the empirically relevant case.[5] Intermediate goods are freely traded, so intermediate goods market clearing requires

$$(3) \qquad Y_{hjt} + Y_{fjt} = \tilde{Y}_{hjt} + \tilde{Y}_{fjt}$$

for both $j \in \{c,d\}$ where $\tilde{Y}_{kjt}$ denotes country k production. We assume trade is balanced at every point in time:

$$(4) \qquad p_{dt}\left(Y_{kdt} - \tilde{Y}_{kdt}\right) + p_{ct}\left(Y_{kct} - \tilde{Y}_{kct}\right) = 0,$$

where p_{jt} is the intermediate j world market price. Intermediate goods are competitively produced according to the following production function, using labor, L_{kjt}, and a continuum of sector-specific machines, x_{kjit}, of quality A_{kjit}:

$$(5) \qquad \tilde{Y}_{kjt} = L_{kjt}^{1-\alpha-\beta} \int_0^1 A_{kjit}^{1-\alpha} x_{kjit}^{\alpha} di,$$

where $i \in [0, 1]$ denotes the machine type, $\alpha, \beta \in (0,1)$ and $\alpha + \beta < 0$.[6] Labor is perfectly mobile across sectors, but immobile across countries, so that labor market clearing requires

$$(6) \qquad L_{kct} + L_{kdt} = L_k.$$

Each machine is either competitively supplied or produced by a profit-maximizing monopolist; it can not be traded internationally. The production of each machine requires $\psi > 0$ units of the final good Y_{kt} and is

[5] This is confirmed by the recent results in Papageorgiou et al. (2013).

[6] For $\beta \to 0$, the production function approaches the intermediates production function in Acemoglu et al. (2012), where, in equilibrium, output is CRS to labor. With international trade, price or productivity differences across countries then lead to a specialization of (at least) one country in the production of a single good (Ricardian trade). Our results are robust to the case where $\beta = 0$ (detailed proofs available on request).

equal across sectors and machine varieties, so the monopolist maximizes $\pi_{kjit} = x_{kjit}\left(p_{kjit} - \psi p_{kt}\right)$ where p_{kjit} is the time t price for machine kji and p_{kt} country k final good price.

Innovation The economy advances through improvements in machine quality. At the beginning of every period, each scientist decides what sector to innovate in. Within this sector, the scientist is randomly allocated to one machine, and each machine is allocated to at most one scientist. If innovation is successful, the new machine quality is $1+\gamma > 1$ times the quality in the previous period and the scientist receives a 1-period patent for his achievements. We assume property rights are not enforced across borders, so upon a successful innovation, the scientist can only profitably sell its patent to a local machine producer. In the other country this improvement will be copied immediately and the particular machine will be competitively supplied. As a consequence, a home scientist's innovation decision is independent of foreign machine demand (and vice versa) and machine quality is equal across countries at all times.[7] If innovation is not successful, no patent is granted and the machine will be competitively supplied with the previous period quality. Hence, sector j average machine quality, which will later be referred to as sector j technology progresses according to

(7) $$A_{jt} = A_{jt-1}\left(\gamma z s^W_{jt} + 1\right),$$

where we define

(8) $$A_{jt} \equiv \int_0^1 A_{jit} di$$

and $s^W_{jt} \equiv s_{hjt} + s_{fjt}$. z is the scientist's probability of success in innovation which, for simplicity, we assume to be equal across countries and sectors. Market clearing for scientists reads

(9) $$s_{kct} + s_{kdt} = s_k.$$

Environment Emissions are caused by the production of the dirty intermediate. For simplicity, we assume a single, global level of the emission stock and a common emission intensity of dirty good production in home and foreign. The emissions stock evolves according to

(10) $$E_{t+1} = f\left(\mathbf{Y^W_{dt^-}}\right),$$

where $\mathbf{Y^W_{dt^-}} = \left\{\tilde{Y}^W_{jt}, \tilde{Y}^W_{jt-1}, \ldots, \tilde{Y}^W_{jt-\infty}\right\}$, $\tilde{Y}^W_{jt} \equiv \tilde{Y}^W_{hjt} + \tilde{Y}^W_{fjt}$ and $f_{\tilde{Y}^W_{jv}} \geq 0$ for $v \leq t$ with strict inequality for $v = t$. The emission stock at time $t+1$ is increasing in time t dirty good production. The stock may be persistent, implying that also dirty good production from some time $v < t$ positively affects the time $t+1$ emission stock. The above law of motion of the emission stock encompasses both the specification by Acemoglu et al. (2012), and the alternative form proposed by Hourcade et al. (2012), which is more closely based on

[7] Section 5 discusses the robustness of the main argument under alternative assumptions regarding technology spillovers.

the climate science models.

3 Equilibrium

This section solves for the equilibrium of the model. We consider three types of policies. The first is a tax on the production, or output, of clean or dirty intermediates, such that the cost of using intermediate inputs equals $p_{jt}\tau_{kjt}$. Second, a government may implement a tax on the use of intermediates as inputs, on either, or both intermediates. This tax reduces the price intermediate input producers receive for their intermediates to $p_{jt}\tilde{\tau}_{kjt}^{-1}$. Lastly, a sector-specific subsidy to innovation, at a rate $q_{kjt}-1$, may be introduced. In addition to the environmental externality, the model features a market failure in monopoly distortions. For convenience, we assume that in both countries, monopoly distortions have been corrected for by the appropriate subsidy granted to machine users. This would amount to a subsidy rate of $(1-\alpha)$ on machines supplied by monopolists. Throughout the exposition, we abstract from subsidies on intermediate production and input use, focusing on positive taxes instead. We first solve for the static equilibrium, and evaluate how the unilateral introduction of input and output taxes affect demand and supply for given technologies. Next, we determine scientists innovation decisions and the effect of unilateral carbon taxes and innovation subsidies thereon. In order to focus the analysis on the divergence of policies in home and foreign, we abstract from foreign taxes and subsidies: $\tilde{\tau}_{fjt} = \tau_{fjt} = q_{fjt} = 1$ for both $j \in \{c, d\}$.

3.1 The static equilibrium

Final good producers maximize their input mix by equating the marginal return to intermediate Y_{kjt} to its tax-inclusive price $\tau_{kjt}p_{jt}$. Using (2), country k relative demand for intermediates reads

$$\frac{Y_{kct}}{Y_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{-\varepsilon}\left(\frac{\tau_{kct}}{\tau_{kdt}}\right)^{-\varepsilon}. \tag{11}$$

Introducing a positive intermediate input tax on the dirty intermediate will, given the world market relative price p_{ct}/p_{dt}, increase the demand for the clean intermediate relative to dirty. The final good price in country k then equals $p_{kt} = \left(p_{ct}^{1-\varepsilon}\tau_{kct}^{1-\varepsilon} + p_{dt}^{1-\varepsilon}\tau_{kdt}^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}$. Global relative demand for intermediates will naturally lie between Y_{hct}/Y_{hdt} and Y_{fct}/Y_{fdt}. Using trade balance, (4), we find

$$\frac{Y_{ct}^W}{Y_{dt}^W} = \left(\frac{p_{ct}}{p_{dt}}\right)^{-\varepsilon} F, \tag{12}$$

where $Y_{jt}^W \equiv Y_{hjt} + Y_{fjt}$ is world demand for intermediate j and F is a factor that adjusts for the individual countries intermediate input taxes, and the relative size of each country's demand.[8] This factor is falling in τ_{hct}/τ_{hdt}: the introduction of a dirty intermediate input tax in home reduces global relative demand for this intermediate. Whenever $\tau_{hct}/\tau_{hdt} < 1$, i.e. whenever home's relative tax on dirty intermediates exceeds

[8] More specifically, F is defined by $F \equiv \frac{I^R + V^R}{I^R(\tau_{hct}/\tau_{hdt})^{\varepsilon} + V^R}$ with $I^R \equiv \frac{p_{ct}\tilde{Y}_{hct} + p_{dt}\tilde{Y}_{hdt}}{p_{ct}\tilde{Y}_{fct} + p_{dt}\tilde{Y}_{fdt}}$ and $V^R \equiv \frac{(\tau_{hct}/\tau_{hdt})^{\varepsilon} + (p_{ct}/p_{dt})^{1-\varepsilon}}{1 + (p_{ct}/p_{dt})^{1-\varepsilon}}$.

foreign's we find $Y_{hct}/Y_{hdt} > Y^W_{ct}/Y^W_{dt} > Y_{fct}/Y_{fdt}$. If home is large relative to foreign (i.e. it produces a large share of global output), Y^W_{ct}/Y^W_{dt} will be relatively close to Y_{hct}/Y_{hdt}.[9] This is intuitive, as in this case, home demand represents a large share of global demand.

Intermediate producers demand machines until the marginal return to machines equals the machine price. With optimal machine subsidies, the cost of a machine to intermediate good producers always equals machine production cost, ψp_{kt}. By (5) equilibrium demand for machine ji in country k reads

$$x_{kjit} = p_{kt}^{-\frac{1}{1-\alpha}} p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}} A_{jit} \left(\frac{\alpha}{\psi}\right)^{\frac{1}{1-\alpha}}. \tag{13}$$

Intermediate output taxes affect machine demand directly. By reducing the marginal return to machine use, they reduce machine demand for given world intermediate prices. Also positive intermediate input taxes are detrimental for machine demand, as they increase the price of final output, and thereby machine production cost and prices. Profit-maximizing monopolists charge a constant markup over marginal cost. This gives a revenue per machine of $\psi p_{kt}/\alpha$, which, using (13), pins down profits for the machine-producing monopolist at

$$\pi_{kjit} = (1-\alpha)\, p_{kt}^{-\frac{\alpha}{1-\alpha}} p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}} A_{jit} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}. \tag{14}$$

Machine profits are increasing in machine demand, which is increasing in machine productivity, A_{jit} and the marginal return to machine use, $p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}}$. Labor is mobile across sectors, yet not across countries, and its allocation is determined by where it earns the greatest marginal return. By (5) and (13) the marginal return to labor in sector j reads

$$MRL_{kjt} = (1-\alpha-\beta)\, p_{kt}^{-\frac{\alpha}{1-\alpha}} p_{jt}^{\frac{1}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{1}{1-\alpha}} L_{kjt}^{-\frac{\beta}{1-\alpha}} A_{jt} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}. \tag{15}$$

The marginal return to labor in a sector is falling in the amount of labor employed in this sector. Labor market equilibrium then requires marginal return to be equalized across sectors. This gives

$$\frac{L_{kct}}{L_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{\beta}} \left(\frac{\tilde{\tau}_{kct}}{\tilde{\tau}_{kdt}}\right)^{-\frac{1}{\beta}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\beta}} \tag{16}$$

Finally, using (5) and (13), production of intermediate j in country k reads

$$\tilde{Y}_{kjt} = p_{kt}^{-\frac{\alpha}{1-\alpha}} p_{jt}^{\frac{\alpha}{1-\alpha}} \tilde{\tau}_{kjt}^{-\frac{\alpha}{1-\alpha}} L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}} A_{jt} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}. \tag{17}$$

[9] If $I^R \to 0$, the framework approaches a single-country model where home is the sole country, and $F \to (\tau_{hct}/\tau_{hdt})^{-\varepsilon}$ which gives $Y^W_{ct}/Y^W_{dt} \to Y_{hct}/Y_{hdt}$. Likewise, if $I^R \to \infty$, we have $F \to 1$ and $Y^W_{ct}/Y^W_{dt} \to Y_{fct}/Y_{fdt}$.

which gives global relative supply

$$\frac{\tilde{Y}_{ct}^W}{\tilde{Y}_{dt}^W} = \frac{A_{ct}}{A_{dt}} \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{\alpha}{1-\alpha}} \frac{K \tilde{\tau}_{hct}^{-\frac{\alpha}{1-\alpha}} L_{hct}^{\frac{1-\alpha-\beta}{1-\alpha}} + L_{fct}^{\frac{1-\alpha-\beta}{1-\alpha}}}{K \tilde{\tau}_{hdt}^{-\frac{\alpha}{1-\alpha}} L_{hdt}^{\frac{1-\alpha-\beta}{1-\alpha}} + L_{fdt}^{\frac{1-\alpha-\beta}{1-\alpha}}} \tag{18}$$

where we define $K \equiv (p_{ht}/p_{ft})^{-\frac{\alpha}{1-\alpha}}$. Global relative intermediates supply is a function of relative productivity, A_{ct}/A_{dt}, intermediates prices, p_{ct}/p_{dt}, and the labor allocation. The greater clean sector productivity, higher clean intermediate prices and the more labor is employed in this sector, the larger the relative supply of clean intermediates. Domestic labor is corrected by two factors. The first, K, corrects for differences in machine prices across countries. If home imposes a tax on either intermediate input, this factor will be below unity: due to the net taxation of intermediates, machines will be more expensive, and machine use per unit of labor will be lower. Hence, output per unit of labor in home will fall short of output per unit of labor in foreign. In a similar manner, a high intermediate output tax in sector j, will reduce the use of machines and output per unit of labor in this sector.

In equilibrium, the labor allocation and intermediate prices are jointly determined by global intermediate goods market equilibrium, (3), (12) and (18), and labor market equilibrium, through (6) and (16). Using these conditions, the laissez-faire equilibrium can be solved in a rather straightforward manner. Next, we summarize the effect of unilateral policies on the equilibrium labor allocation, prices, and the pattern of trade.

Laissez-faire equilibrium In laissez-faire, no intermediate input or output taxes are introduced: $\tilde{\tau}_{kjt} = \tau_{kjt} = 1$ for both $k \in \{h, f\}$ and $j \in \{c, d\}$. As a consequence, producers and consumers face identical prices in both countries. Global relative intermediate demand will equal relative intermediate demand in the individual countries:

$$\frac{Y_{ct}^W}{Y_{dt}^W} = \frac{Y_{kct}}{Y_{kdt}} \text{ and } \frac{Y_{ct}^W}{Y_{dt}^W} = \left(\frac{p_{ct}}{p_{dt}}\right)^{-\varepsilon}, \tag{19}$$

and by (11) and (16)-(18), we find the relative supply of intermediates

$$\frac{\tilde{Y}_{ct}^W}{\tilde{Y}_{dt}^W} = \frac{\tilde{Y}_{kct}}{\tilde{Y}_{kdt}} \text{ and } \frac{\tilde{Y}_{ct}^W}{\tilde{Y}_{dt}^W} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1-\beta}{\beta}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\beta}}. \tag{20}$$

Equilibrium relative prices then equal

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{-\frac{1-\alpha}{1+(\varepsilon-1)\beta}}. \tag{21}$$

Since $\varepsilon > 1$, the relative price is falling in the relative productivity: advancements in clean productivity reduce the price of clean intermediates relative to dirty intermediates. From (16) and (21) we derive the equilibrium labor allocation:

$$\frac{L_{kct}}{L_{kdt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}}, \tag{22}$$

where $\sigma \equiv (1-\alpha)(\varepsilon-1) > 0$. As both consumers and intermediate good producers face identical prices across countries, no strict gains from trade exists, and we assume no trade will take place.[10] Equations (6), (17), (21) and (22) then determine country k clean, dirty and final good production

$$\begin{aligned} \tilde{Y}_{kct} &= \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1-\beta-\varepsilon(1-\alpha-\beta)}{\sigma}} A_{ct}^{\frac{\varepsilon(1-\alpha)}{1+(\varepsilon-1)\beta}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \\ \tilde{Y}_{kdt} &= \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1-\beta-\varepsilon(1-\alpha-\beta)}{\sigma}} A_{dt}^{\frac{\varepsilon(1-\alpha)}{1+(\varepsilon-1)\beta}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \\ \text{and } Y_{kt} &= \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1+(\varepsilon-1)\beta}{\sigma}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}, \end{aligned} \tag{23}$$

where by the absence of trade $\tilde{Y}_{kjt} = Y_{kjt}$.

Unilateral policy Equilibrium relative prices, as well as the production and consumption of intermediate and final goods are less straightforward to derive if home implements intermediate input or output taxes. We can however draw the following conclusion regarding the pattern of trade:

Lemma 1. *Define $T_{ht} \equiv (\tau_{hct}/\tau_{hdt})^{-\varepsilon\frac{\beta}{1-\beta}} (\tilde{\tau}_{hct}/\tilde{\tau}_{hdt})$. If $T_{ht} > (<)1$, home is a dirty (clean) intermediate exporter, and foreign is a clean (dirty) intermediate exporter. If $T_{ht} = 1$, no trade takes place and, for given technologies, unilateral policies leave equilibrium relative prices and foreign demand, supply and labor allocation unaffected.*

Proof Let $p^R_{kt} \equiv p_{kct}/p_{kdt}$ be the country k equilibrium relative price under autarky and $p^R_t \equiv p_{ct}/p_{dt}$ the world equilibrium relative price. By (11), (16) and (17), $p^R_{ht} = (A_{ct}/A_{dt})^{-\frac{1-\alpha}{1+\beta(\varepsilon-1)}} T_{ht}^{\frac{1-\beta}{1+\beta(\varepsilon-1)}}$ and $p^R_{ft} = (A_{ct}/A_{dt})^{-\frac{1-\alpha}{1+\beta(\varepsilon-1)}}$. If $T_{ht} > 1$, $p^R_{ht} > p^R_{ft}$ which implies that in our free trade equilibrium we must have $p^R_{ht} > p^R_t > p^R_{ft}$. Compared to the autarky case, the lower relative price will increase home demand for the clean relative to the dirty intermediate, yet reduce home supply of clean relative to dirty intermediates. Hence, home becomes a clean intermediate importer and a dirty intermediate exporter. Similarly, if $T_{ht} < 1$, in autarky, $p^R_{ht} < p^R_{ft}$, so $p^R_{ht} < p^R_t < p^R_{ft}$ and home exports the clean intermediate. If $T_{ht} = 1$, opening up to trade does not affect equilibrium relative prices, labor allocation, demand or supply. No trade takes place and unilateral policies leave foreign unaffected.■

[10] This assumption can be substantiated by allowing for arbitrarily small trade costs.

T_{ht} is a measure of the degree to which home distorts intermediates demand relative to supply. By implementing a net tax on dirty production ($\tilde{\tau}_{hct} < \tilde{\tau}_{hdt}$), home reduces the return to dirty relative to clean intermediates production, distorting its supply in favor of clean intermediates. Similarly, implementing a net tax on dirty consumption ($\tau_{hct} < \tau_{hdt}$), distorts home demand is in favor of clean intermediates. If T_{ht} equals unity, the demand and supply distortions cancel out. In this case, the introduction of the tax does not affect equilibrium relative prices, and no trade will take place. If T_{ht} is below unity, the distortion of production in favor of clean intermediates is larger than the shift in consumption towards clean intermediates. As a consequence, at laissez-faire prices, relative supply of clean intermediates exceeds relative demand. Equilibrium is then re-established by a fall in p_{ct}/p_{dt}, which increases relative clean intermediate demand globally, and causes foreign to become a dirty intermediate exporter.

3.2 The dynamic equilibrium

Scientists decide upon in which sector to innovate based on profit expectations. As scientists receive a 1-period patent, they only take the next period into account. Scientists are randomly allocated to a machine, which gives expected machine quality if successful $(1+\gamma)A_{jt-1}$. Accounting for the probability of success, z, and noting that unsuccessful scientists will not make a profit, by (14), expected profits for a country k scientist innovating in sector j read

$$\Pi_{kjt} = z(1+\gamma)(1-\alpha)\, p_{kt}^{-\frac{\alpha}{1-\alpha}}\, p_{jt}^{\frac{1}{1-\alpha}}\, \tilde{\tau}_{kdt}^{-\frac{1}{1-\alpha}}\, L_{kjt}^{\frac{1-\alpha-\beta}{1-\alpha}}\, A_{jt-1} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}},$$

which, by (16), gives relative expected profits

$$\frac{\Pi_{kct}}{\Pi_{kdt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}} \left(\frac{\tilde{\tau}_{kct}}{\tilde{\tau}_{kdt}}\right)^{-\frac{1}{1-\alpha}} \left(\frac{L_{kct}}{L_{kdt}}\right)^{\frac{1-\alpha-\beta}{1-\alpha}} \frac{A_{ct-1}}{A_{dt-1}} \frac{q_{kct}}{q_{kdt}}, \tag{24}$$

where $q_{fjt} = 1$ for both $j \in \{c, d\}$. If relative expected profits exceed unity in country k, research in the clean sector is more profitable than in the dirty sector. As a consequence, country k scientists will relocate from the dirty to the clean sector. Similarly, if $\Pi_{kct}/\Pi_{kdt} < 1$, scientists relocate to the dirty sector. We assume that, if a scientist is indifferent, it innovates in the clean sector. Analogous to Acemoglu et al. (2012), we can identify price, market size and technology effects. The price effect is due to p_{ct}/p_{dt}: a high relative price in sector j increases demand for machines and machine profits in this sector. This effect must however be corrected for output taxes, which reduce the net return to intermediates production in a sector. Hence, a relatively high output tax in sector j reduces the incentive to innovate in this sector. To the contrary a high innovation subsidy, q_{kjt}, encourages innovation in sector j. Next, innovation in a sector is favorable if this sector employs a large share of labor. This is called the market size effect. The final effect is the technology effect: the more advanced a sector's technology, A_{jt-1}, the greater the expected benefits from further improvements.

Again, we can solve for the laissez-faire equilibrium and the equilibrium under unilateral policies.

Laissez-faire equilibrium In the laissez-faire equilibrium, in addition to $\tilde{\tau}_{kjt} = \tau_{kjt} = 1$ we have $q_{kjt} = 1$ for both $k \in \{h, f\}$and $j \in \{c, d\}$. Using (21) and (7), we reduce (24) to

$$\frac{\Pi_{kct}}{\Pi_{kdt}} = \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{\sigma}{1+(\varepsilon-1)\beta}} \left(\frac{\gamma z s_{ct}^W + 1}{\gamma z s_{dt}^W + 1}\right)^{-\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{1+(\varepsilon-1)\beta}}, \tag{25}$$

where $s_{jt}^W \equiv s_{hjt} + s_{fjt}$. As $\sigma > 0$, innovation favors the more advanced sector, which reinforces initial patterns of development are reinforced. Suppose that at time 0, dirty technologies are relatively advanced (A_{c0}/A_{d0} is low), such that the majority of time 1 scientists innovates in the dirty sector. By (7), dirty technologies grow faster than clean, which implies that the next period, again, a majority of scientists are active in this sector.

Multiple equilibrium scientist allocations may arise if $(\varepsilon - 1)(1 - \alpha - \beta) > 1$. In this case, relative expected profits are increasing in the share of scientists innovating in this sector. This is due to the following. The more scientists innovate in the clean sector, given A_{ct-1}/A_{dt-1}, the larger A_{ct}/A_{dt}. A greater A_{ct}/A_{dt} implies that the relative price for the clean intermediate, p_{ct}/p_{dt}, will be lower. This reduces the return to clean innovation and thereby Π_{kct}/Π_{kdt}. However, a larger A_{ct}/A_{dt} also implies more labor will be employed in the clean sector, which encourages additional clean sector innovation. If $(\varepsilon - 1)(1 - \alpha - \beta) > 1$, the latter effect dominates and an increase in the number of scientists active in a sector will further encourage research in this sector. As a consequence, multiple equilibria, where all scientists innovate in either the clean, or the dirty sector, may arise. Whenever this is the case, i.e. whenever both $s_{ct}^W = 0$ and $s_{ct}^W = s^W$ is an equilibrium, where $s^W \equiv s_h + s_f$, we assume scientists coordinate on the 'clean equilibrium' with $s_{ct}^W = s^W$.

As has been noted above, the intial level of technologies will determine the innovation decision in laissez-faire. In the remainder of the paper, we assume the following:

Assumption 1. $\frac{A_{c0}}{A_{d0}} < \min\left\{\left(\gamma z s^W + 1\right)^{\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{\sigma}}, \left(\gamma z s^W + 1\right)^{-\frac{1-(\varepsilon-1)(1-\alpha-\beta)}{\sigma}}\right\}$,

Assumption 1 ensures that in the absence of intervention, for any scientist allocation, $\Pi_{kc1}/\Pi_{kd1} < 1$ for both $k \in \{h, f\}$: scientists in both countries start innovating in the dirty sector only, A_{ct}/A_{dt} falls over time and innovation continues to take place in the dirty sector only. By (23) and (10), the persistent growth in A_{dt} causes $\tilde{Y}_{hdt} + \tilde{Y}_{fdt}$ and the emission stock, E_t, to grow over time. As a consequence, $E_\nu \geq \bar{E}$ at some finite time ν, which implies $U_{kt} = -\infty$. Given the high cost of $E_\nu \geq \bar{E}$, there is a strong call for a social planner to curb emission growth. This result is symmetric to Propositions 1 and 2 in Acemoglu et al. (2012).

Unilateral policy Using innovation subsidies, q_{hjt}, home can, in a rather straightforward manner, redirect its scientists to the clean or dirty sector. Such subsidies affect foreign scientists' innovation incentives through the terms s_{ct}^W and s_{dt}^W. This can best be seen if home does not implement any intermediate input or output taxes, in which case (25) applies for foreign. For example, suppose home uses subsidies to increase s_{hct} at the expense of s_{hdt}. Given the scientist allocation in foreign, s_{ct}^W rises and s_{dt}^W falls. Here, if $(\varepsilon - 1)(1 - \alpha - \beta) > 1$, this increase in s_{hct} will increase foreign scientists' incentive to innovate in the clean sector. If instead $(\varepsilon - 1)(1 - \alpha - \beta) < 1$, substitution will take place and, if feasible, any increase in s_{hct} will be countered by an equivalent decrease in s_{fct}. If $(\varepsilon-1)(1-\alpha-\beta)=1$, foreign innovation is independent of the home allocation of scientists, and thereby of q_{hjt}.

Also intermediate input and output taxes affect scientists' innovation decisions, in both home and foreign. Substituting (16) in (25) we find

$$\frac{\Pi_{kct}}{\Pi_{kdt}}=\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{\beta}}\left(\frac{\tilde{\tau}_{kct}}{\tilde{\tau}_{kdt}}\right)^{-\frac{1}{\beta}}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{1-\alpha}{\beta}}\left(\frac{\gamma z s^W_{ct}+1}{\gamma z s^W_{dt}+1}\right)^{\frac{1-\alpha-\beta}{\beta}}\frac{q_{kct}}{q_{kdt}} \tag{26}$$

In home, a net tax on dirty intermediate output ($\tilde{\tau}_{hct}/\tilde{\tau}_{hdt}<1$) encourages innovation in the dirty sector. For given relative prices, this tax reduces the return to dirty intermediate production, which, both directly and through reduced labor use in this sector, reduces demand for dirty machines and hence the profits that flow from dirty machine varieties. Relative to the dirty sector, clean sector innovation has become more profitable. As established above, unilateral policies may alter global equilibrium relative prices. An increase in the price of the clean intermediate increases demand for clean machines and profits in the clean sector. This effect is present not only in home, but also in foreign. Hence, as the following Lemma establishes, home can affect the foreign scientists' innovation decision through equilibrium relative prices.

Lemma 2. *Let $T_{ht}\equiv(\tau_{hct}/\tau_{hdt})^{-\frac{\varepsilon}{1-\beta}}(\tilde{\tau}_{hct}/\tilde{\tau}_{hdt})$ and take s_{hjt} as given. If $T_{ht}>(<)1$ the incentive for foreign scientists to innovate in the clean sector is increased (reduced) relative to laissez-faire. If $T_{ht}=1$, unilateral policies do not affect foreign scientist' incentives.*

Proof For a given s_{hjt}, A_{ct-1}/A_{dt-1}, and s_{fct} equal to its laissez-faire level of zero, we know A_{ct}/A_{dt}. Lemma 1 established that, for given A_{ct}/A_{dt}, if $T_{ht}>1$, p_{ct}/p_{dt} will rise above the laissez-faire level. By (26), this will increase the relative return to clean innovation in foreign, increasing the incentive for its scientists to innovate in the clean sector. Likewise, if $T_{ht}<(=)1$, p_{ct}/p_{dt} falls (is unchanged), and so is Π_{fct}/Π_{fdt}. ■

Lemma 2 implies that in addition to a 'static' leakage channel, we can identify a 'dynamic' leakage channel. Carbon taxes which cause the relative price of dirty intermediates to rise, trigger higher supply of dirty intermediates in foreign, as compared to the case without such taxes. This, well-known, effect of carbon tax policies is called leakage. We refer to this leakage as static, as it takes technologies as given. The increase in the relative price of dirty intermediates also affects technologies. By Lemma 2, a fall in p_{ct}/p_{dt} increases the incentive to innovate in the dirty sector. This may increase the number of foreign scientists in the dirty sector,[11] which increases next-period A_d, and therefore, for given policies, next-period emissions. This leakage channel, running through innovation incentives, is what we call the dynamic leakage channel.

[11] Foreign innovation in the dirty sector will rise, unless the initial equilibrium satisfies either of the following requirements: 1) All foreign scientists innovate in dirty, or 2) All foreign scientists innovate in clean and, given the initial scientist allocation and despite the fall in p_{ct}/p_{dt}, $\Pi_{fct}/\Pi_{fdt}\geq 1$ still.

4 Sustainable growth and unilateral policies

The previous section establishes that in laissez-faire the emission stock exceeds levels considered as extremely harmful in finite time. This section assesses whether unilateral policies can redirect the economy to a more sustainable growth trajectory. As defined below, the emission stock will always be below the threshold level of $\bar{E}$ on such a trajectory.

Definition 1. *On a sustainable growth path, $E_\nu < \bar{E}$ for all ν.*

As allowing the emission stock to pass the level of $\bar{E}$ is considered infinitely costly, if feasible, the social planner will always implement a sustainable growth trajectory.

4.1 Unilateral implementation of a sustainable growth path

At time t, home can unilaterally implement a sustainable growth path if intermediates are so-called 'strong substitutes',[12] $\bar{E}$ is sufficiently large, and if it can implement policies that redirect the majority of scientists to the clean sector:

Lemma 3. *Home can unilaterally implement a sustainable growth path at time t if $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $\bar{E}$ is sufficiently large, and there exist unilateral policies that implement $s^W_{ct} > s^W_{dt}$.*

Proof See Appendix. ■

Though the mathematical proof is tedious, the argument is immediate. Home can always engineer an equilibrium in which it eliminates all domestic demand for, and supply of, dirty intermediates. In this equilibrium, no trade takes place, and global dirty intermediates production equals its production, and demand, in foreign, at the laissez-faire (autarky) level. As it turns out, for given technologies, this equilibrium minimizes global emissions.[13] Thus, to prevent global emissions from rising over time, preventing foreign demand for dirty intermediates from rising is key. Advances in dirty technologies increase foreign demand for dirty intermediates by increasing income and by reducing the price of dirty relative to clean intermediates. Clean technology improvements reduce foreign dirty intermediate demand, as long as the substitution effect from relatively cheaper clean intermediates (see (21)) outweighs the income effect from increased output. This is the case if $\varepsilon > (1-\beta)/(1-\alpha-\beta)$. If $\varepsilon = (1-\beta)/(1-\alpha-\beta)$, Y_{fdt} is independent of A_{ct}. Implementing a sustainable growth path thus requires $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$ and sufficiently faster growth in A_{ct} than A_{dt}. This can only be implemented if home can, at time t, redirect the majority of global scientists to the clean sector. If home is unable to do so, A_c/A_d falls over time, which increases the relative return to dirty sector innovation, rendering home unable to redirect a sufficient number of scientists in any future period. Absent of further policies, implementing a sustainable growth path implies that in finite time, no further dirty machine improvements will be made. If $\varepsilon > (1-\beta)/(1-\alpha-\beta)$, this implies $E_\infty = 0$.

[12] We borrow the notion of strong substitutes from (see Acemoglu et al., 2012), yet for $\beta > 0$ our definition is slightly different.

[13] Reducing foreign dirty intermediate demand below the laissez-faire level in (23) requires increasing the price of dirty relative to clean intermediates, which would increase foreign (and hence global) supply of these intermediates beyond the laissez-faire level.

Finally, even if in the long run, pollution can be halted or eliminated, E_t might still rise initially, so $\bar{E}$ must be sufficiently large for the stock of emissions to remain below this level along the process.

The next step in the analysis is to determine under what conditions home can indeed unilaterally implement $s_{ct}^W > s_{dt}^W$. Here we distinguish two cases. In the first case, home inhabits the majority of scientists. In the second case, home and foreign are either equally innovative, or foreign scientists outnumber those in home.

4.1.1 Home inhabits majority of scientists

If home inhabits the majority of scientists, i.e. if $s_h > s_f$, the domestic social planner can always redirect a sufficient number of scientists by offering an innovation subsidy to scientists in the clean sector. An alternative is to reduce the returns to dirty innovation by taxing the production of dirty intermediates. In the absence of innovation subsidies or output taxation, a dirty intermediate input tax may redirect home scientists to the clean sector. By reducing global demand for dirty intermediates, such a tax causes the world market price of dirty intermediates to fall, causing a fall in the expected return to dirty innovation (see (24)). Using innovation subsidies or dirty output taxes, at any point in time, home can implement $s_c^W > s_d^W$, causing A_c/A_d to grow. As a growing A_c/A_d increases relative profits, this policy intervention is only necessary for a limited period of time, and also foreign scientists will, as of some point in time, start innovating in the clean sector.

Proposition 1 *If $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $s_h > s_f$, and $\bar{E}$ is sufficiently large, unilateral policies can redirect the global economy to a sustainable growth path. Such (temporary) policies correspond to a clean innovation subsidy, or a tax on dirty intermediates production, or both. Alternatively, a tax on dirty intermediate inputs may be capable of redirecting home scientists to the clean sector.*

Proof In text. ■

4.1.2 Home inhabits minority of scientists

Implementing a sustainable path requires redirecting foreign scientists to the clean sector if $s_h \leq s_f$. To redirect these scientists, home must, for any scientist allocation, implement policies that increase the world market price of clean intermediates. In response to this price increase, foreign will expand the size of its clean sector at the expense of dirty, increasing foreign scientists' incentives to innovate in the clean sector. These policies thus cause negative leakage, and turn foreign in a clean intermediate exporter. An example of such a policy is a net tax on dirty intermediate inputs, which increases home, and hence global, demand in favor of clean intermediates. Alternatively, home could introduce a net tax on clean intermediate production, which reduces home supply of this intermediate. In both cases, the increase in clean intermediates demand net of supply will increase the price of clean intermediates relative to dirty. Unilateral policies that cause positive carbon leakage and turn foreign in a dirty intermediate exporter will *not* implement sustainable growth. Any expansion of dirty intermediates production in foreign will encourage foreign innovation in this sector, which is the exact opposite of what home aims to achieve.

Whether home can unilaterally implement a sustainable growth path depends on the size of its labor force relative to foreign's, and initial technologies. First, if the home country is relatively large in terms of its labor force, home produces a large share of global intermediates. This implies that home can implement large shifts in global intermediates supply, and thereby large changes in equilibrium relative prices. Put differently, a large country has greater control over prices and corresponding allocation of production across countries. This is beneficial, as redirecting foreign scientists may require sizable increases in the size of the clean sector in foreign. Second, if clean technologies are relatively advanced, the size of the clean sector, and thereby the return to clean innovation is relatively high to begin with. Hence, a smaller shift in the price equilibrium is required to suffiently increase the return to clean innovation in foreign. Hence, we can prove the following

Proposition 2 *If $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$ and $s_h \leq s_f$, for a sufficiently large $\bar{E}$, L_h/L_f and A_{ct-1}/A_{dt-1}, unilateral policies can, at time t, redirect the global economy to a sustainable growth path. Such policies reduce the relative price of dirty intermediates relative to laissez-faire.*

Proof See Appendix. ■

4.2 Myopic policies

A social planner may not recognize the endogeneity of technical change and thereby fail to take the effect of its policies on innovation in general, and foreign innovation in particular, into account. In such a situation, the social planner implements myopic policies. Myopic policies are unilateral policies that are optimal under the (false) presumption that innovation is exogenous. Concerning such policies, we can prove the following[14]

Proposition 3 *Myopic policies increase the global relative price of dirty intermediates relative to laissez-faire.*

Proof See Appendix. ■

The rationale behind Proposition 3 runs as follows. Because of the negative welfare effects of emissions due to dirty intermediates production, the myopic policymaker aims to reduce global dirty intermediates supply relative to laissez-faire. A reduction in global dirty intermediates supply implies an equivalent drop in global use of dirty intermediates in final output. This latter drop causes consumption, and thereby utility losses. For a given level of pollution reduction, the social planner faces three options. First, it can implement policies that leave equilibrium relative intermediate prices, p_{ct}/p_{dt}, and thereby foreign demand for and supply of dirty intermediates, unaffected. In this case, the full reduction, and accompanying utility loss, comes at the expense of domestic consumers. Second, home can increase the price of dirty intermediates relative to clean. As a consequence, demand for dirty intermediates falls in foreign. Carbon leakage will occur however: foreign dirty intermediate producers respond to the higher dirty intermediate price by increasing their production. Third, if home reduces the price of dirty intermediates relative to

[14]Even though the maximization problem changes slightly, Proposition 3 continues to hold if the domestic government (falsely) presumes property rights are perfectly enforced internationally.

clean, foreign dirty intermediate demand increases relative to the laissez-faire equilibrium. So, to reach the emission reduction goal, home must reduce the use of dirty intermediates in final goods production in excess of the reduction goal, and utility losses are increased relative to the case with an unchanged price ratio. This third option can thus never be optimal: home will never implement policies that reduce the world market price of the dirty intermediate and foreign production of dirty intermediates. Also, one can show that the first option is suboptimal: home prefers to share the utility losses from reduced dirty intermediate consumption with foreign.

As myopic policies do not account for the effect of production taxes on technological change, the above policy is independent of the number of scientists in the two countries. From Proposition 2, the next corollary follows

Corollary 1 *If* $\varepsilon \geq \frac{1-\beta}{1-\alpha-\beta}$, $s_f > s_h$ *and* L_h/L_f *and* A_{ct-1}/A_{dt-1} *sufficiently large, myopic policies are inconsistent with optimal policies.*

Proof By Proposition 2, if $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$, $s_f > s_h$ and $\bar{E}$, L_h/L_f and A_{ct-1}/A_{dt-1} sufficiently large, unilateral policies can redirect the economy to a sustainable growth path. Such policies reduce the relative price of dirty intermediates vis-a-vis laissez faire. By Proposition 3, myopic policies implement the opposite: an *increase* in the relative price of dirty intermediates. ■

This contradiction between myopic and optimal policies can have far-reaching consequences. Under myopic policies, the share of labor employed in foreign dirty intermediates production will increase, so, by (24) and Assumption 1, all foreign scientists continue to innovate in the dirty sector. If foreign inhabits the majority of scientists, such policies will not implement this sustainable growth path even if the conditions in Proposition 2 were satisfied, this would have been feasible and hence optimal.

5 Calibration

Up to this point, the analysis of unilateral policies has been analytical, allowing us to draw qualitative conclusions only. In this section, we perform a simple calibration exercise and address more quantitative issues. By seeing the model at work, it enhances our understanding of its implications and allows us to draw additional conclusions related to what coalitions are capable of implementing sustainable growth, the level of the required tax rates for sustainability, and short-run effects of unilateral policies. Given the strong assumptions of our framework, the simple trade structure, and the fact it only includes 2 abstract sectors, the exercise below should mostly be interpreted as a first inquiry into the economic significance of the mechanism at work.

5.1 Parameter values

To allow the reader to compare our framework to Acemoglu et al. (2012), parameters are chosen in line with their framework. This implies we choose $\alpha+\beta = 1/3$, $\gamma z = 0.02$, $\psi = \alpha$ and $L^W = 1$ and $s^W = 1$. We have no reliable priors regarding the appropriate size of β. The model has been run for several $\beta' s$. Qualitatively, results are independent of the β selected. With the exception of the level of required taxes, also quantitatively, differences are small. To keep the exposition short we only report on the case of $\beta = 1/30$.[15] Acemoglu et al. (2012) use three different values for the elasticity of substitution between clean and dirty varieties: 3, 5 and 10. Several researchers (Pelli, 2011; Hourcade et al., 2012; Papageorgiou et al., 2013) regard these elastiticies of substitution as (too) high. To acknowledge this critique, we select the lowest value of the three values: $\varepsilon = 3$.[16] For these parameter values, the condition $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$ is always satisfied. Throughout we assume that $\bar{E}$ is suffienctly high such that, if home can implement a growth path that prevents dirty output from rising in the long run, this growth path is sustainable. This implies we abstract from the question whether growth can be redirected sufficiently fast. One could reinterpret this as answering the question whether there exists some emission concentration level $E' < \infty$, that we are able to avoid.

5.2 Results

Figure 1 plots the combinations of L_h/L_f and A_{ct-1}/A_{dt-1} that allow home to implement a sustainable growth path as of time t if $s_h \leq s_f$. In line with our analytical result, given L_h/L_f, a larger A_{ct-1}/A_{dt-1} makes it more likely home can implement a sustainable growth trajectory. For A_{ct-1}/A_{dt-1} close to zero, i.e. clean technology that is very basic compared to dirty, no unilateral policy will be able to redirect the economy to a sustainable growth trajectory. To the contrary, if A_{ct-1}/A_{dt-1} exceeds the level implied by Assumption 1, growth is already sustainable in laissez-faire, and no policy is required to implement such a growth trajectory. Similarly, given A_{ct-1}/A_{dt-1}, the greater L_h/L_f, the more likely home can redirect foreign scientists to the clean sector. The rationale is immediate: home redirects foreign scientists through taxation policies which increases the world price of the clean intermediate. The larger home, the larger share it represents of the world economy, and the larger the effect of home taxation on the global equilibrium.

Figure 1: Minimum country size for implementing sustainable growth if $s_h \leq s_f$

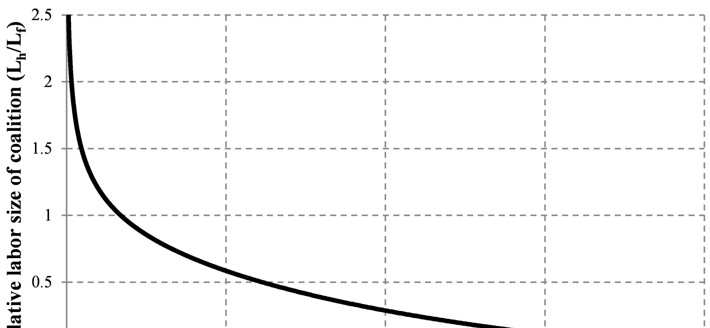
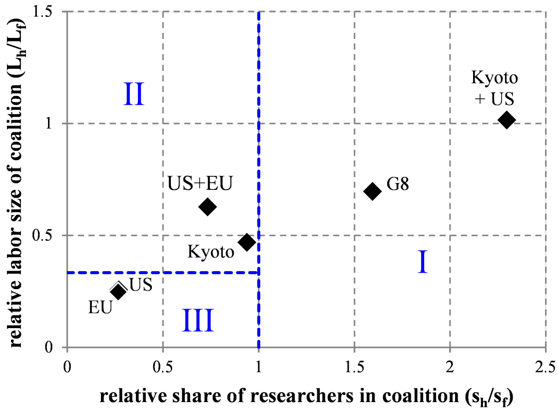


Figure 1 applies as long as $s_h \leq s_f$, yet is independent of the exact levels of s_h and s_f. This may

[15] Results for alternative $\beta's$ are available on request.
[16] This value is in line with the findings by Papageorgiou et al. (2013).

seem counterintuitive at first, but is a direct consequence of the fact that home and foreign scientists are perfect substitutes, with equal productivity, in innovation (see (7)). Figure 2 maps several coalitions in $(L_h/L_f, s_h/s_f)$-space, where coalitions' size in terms of relative labor and scientists are calibrated using WEO GDP and WIPO patent data. Taking $A_{ct-1}/A_{dt-1} = 0.45$, the ratio consistent with IEA statistics[17], we can identify three areas. In area I, $s_h > s_f$ and Proposition 1 applies: the coalition dominates global innovation and can implement sustainable growth by redirecting its own scientists to the clean sector. Examples of such coalitions are the countries with binding targets under the Kyoto treaty (henceforth referred to as the Kyoto coalition)[18] plus the US, or a coalition of G8 countries. Also area II coalitions, such as the Kyoto coalition or a coalition of the EU and US, can implement sustainable growth. However, because $s_h \leq s_f$, these coalitions must redirect *foreign* innovation to the clean sector. The smaller coalitions in area III cannot implement sustainable growth. These are the coalitions that are insufficiently innovative to redirect global growth by redirecting domestic scientists only, but also too small to redirect foreign scientists to the clean sector. The EU and US find themselves in this situation (note that in the figure, the EU and US are hard to distinguish).[19]

Figure 2: Coalitions that can (I and II) and cannot (III) implement sustainable growth



For area I coalitions, a clean innovation subsidy is sufficient to redirect the majority of scientists to the clean sector. If the coalition does not inhabit the majority of scientists, but is sufficiently large (area II coalitions), taxes on clean intermediate output, and/or dirty intermediate inputs are required to implement a sustainable growth trajectory. Figure 3 takes a closer look at such tax rates. It depicts the minimum taxes required on clean intermediate output for different levels of L_h/L_f, given $A_{ct-1}/A_{dt-1} = 0.45$ and the tax rate on dirty intermediate inputs. A clean output tax below zero should be interpreted as the negative of the dirty output tax. From Figure 3 we learn that the larger the country, the lower the tax rate required to

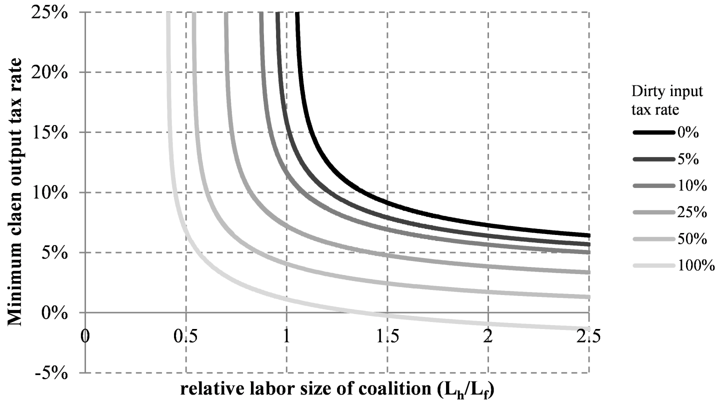
[17] We use the 2013 ratio between global energy use from renewable and nonrenewable sources to approximate for A_{ct-1}/A_{dt-1}.

[18] This Kyoto coalition includes the EU countries, Australia, Belarus, Iceland, Japan, New Zealand, Russia, Turkey, Switzerland and Ukraine (no data was seperately available for Monaco). This corresponds to all Annex I parties excluding Canada and the US (see http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php).

[19] This conclusion no longer applies for very high β. In that case the calibrated labor size of the US and EU just pass the level required for implementing sustainable growth.

implement a sustainable growth trajectory. This is intuitive, a given tax rate has a larger effect on world supply and demand, and hence world relative prices, if the country where this tax is introduced is larger. Also, if the tax rate on dirty intermediate consumption is already high, a lower tax rate on clean intermediate production is required to redirect a sufficient number of foreign scientists to the clean sector. For the Kyoto coalition, tax rates are very high. For example, with a 100% tax on dirty intermediate inputs, the minimum tax required on clean intermediate output is 8%. If we reduce the tax on the use of dirty intermediate to 50%, unilaterally implementing sustainable growth is no longer feasible. In terms of numbers, a 100% tax on dirty intermediates would correspond to a tax of 1700 \$/tCO2.[20] This result raises the question whether the unilateral implementation of a sustainable growth trajectory is politically feasible.

Figure 3: Minimum tax rates for implementing sustainable growth



The next table illustrates the short run implications of unilateral policies implementing a sustainable growth path. By raising the relative price of clean intermediates, unilateral policies do not only encourage clean innovation in foreign, but also the demand for dirty intermediates. Put differently, policy has a dynamic effect on emission through redirecting innovation and altering A_{ct}/A_{dt}, but also a direct effect for given A_{ct}/A_{dt}.[21] As a consequence, we cannot exclude the possibility of short-run emission increases. Table 1 depicts the short run effect of policies from Figure 3 on global dirty intermediate output. It breaks down the full effect from unilateral policies into an innovation and the tax effect. Here, the innovation effect is defined as the effect of redirecting innovation on emissions, and the tax effect the effect of policies on emissions, given that all scientists innovate in the clean sector.

The effect of unilateral policies on short-run pollution turns out to be highly dependent on the specifics of the tax policies implemented. The fact that policies encourage innovation in the clean sector reduces dirty output in the short run. In addition to this innovation effect on global dirty output, the tax rates implemented may then either cause an additional reduction or increase in global emissions in the short run.

[20] In the model, a region's CO2 intensity of GDP is equal to $\xi Y_{kdt}/p_{kt}Y_{kt}$ where ξ is ton CO2 per unit of dirty intermediate output. Assuming laissez-faire, parameter values as described in the text, and world CO2 intensity of 0.44 kg/GDP, this allows us to compute $p_{dt}(\tau_{hdt}-1)/\xi$, the tax in \$/tCO2.

[21] Note again the timing of events. Time t policy is observed or anticipated by scientists s_{kt}, which by (7) affects technology, A_{jt}, and thereby time t output and pollution.

Table 1: Short run global emission effect of unilateral policies for $L_h/L_f = 1.5$

dirty input tax rate	clean output tax rate	full effect	innovation effect	tax effect
0%	9%	-1%	-3%	2%
5%	8%	-4%	-3%	-1%
10%	7%	-7%	-3%	-4%
25%	5%	-15%	-3%	-12%
50%	2%	-26%	-3%	-23%

A reduction is more likely the larger the dirty intermediate input tax. This is intuitive, as given the relative intermediates prices implemented by the policies, such a tax reduces home, and thus global demand for dirty intermediates. Table 1 displays the effects only for $L_h/L_f = 1.5$, yet qualitatively, it holds for any L_h/L_f. From Table 1, the full effect is always negative: also in the short run, unilateral policies reduce pollution. The size of the innovation effect however, strongly depends on the rate of innovation in society ($\gamma z s^W$). The lower this rate, the smaller the innovation effect. With a positive effect of unilateral taxation on short-run dirty intermediate production, a smaller innovation effect may turn the total effect of unilateral policies on pollution positive in the short run.

6 Alternative modeling assumptions

Sustainable growth requires innovation to be clean in the long run. The unilateral implementation of a positive carbon tax causes production of the polluting intermediate to relocate to the foreign country, and thereby increases the incentive for foreign scientists to direct their research to this dirty sector. Hence, such a unilateral tax may be unsuccessful in implementing a sustainable growth trajectory. In such a case, as stated in Proposition 2, an opposite policy, which reduces the relative price of the dirty intermediate in the short run, can in fact be optimal. Although counter-intuitive at first sight, the rationale is clear: such a policy causes production of the clean intermediate to relocate to foreign, which increases the incentive for clean innovation in this country. The allocation of foreign scientists is especially relevant if they are numerous compared to home scientists: in this case they are the main factor determining innovation worldwide. The above result is core to the paper, yet established under a strong set of assumptions: immediate technology spillovers and the absence of international property rights protection. This section contains a short discussion of alternative assumptions, commonly used in the literature, and some initial insights how these may affect this papers core results.

Di Maria and van der Werf (2008) present a 2-country framework of trade, induced technical change and unilateral environmental policy wherein property rights are perfectly enforced internationally. Under this assumption, the return to innovation in a sector is independent of the location of intermediates production and, abstracting from innovation subsidies, home and foreign scientists face identical innovation incentives. As a consequence, with perfect international property rights protection, we find Proposition 2 no longer applies. Perfect international property rights enforcement is however a very strong assumption too.

Typically, licensing a patent abroad entails some additional adjustment or trade cost, and one may find the probability of success in innovation enhanced by learning spillovers from local industries. A more realistic assumption would be that scientists are responsive to global production, but more so to local production.[22] This expands home's set of policy options that encourage clean innovation in foreign. As a consequence, we find a weakened version of Proposition 2 to apply, where home *might* have to become a dirty intermediate exporter to redirect the economy to a sustainable growth tax if $s_h < s_f$.

Closely related to the assumption regarding international property rights protection is our assumption of immediate technology spillovers. Even though, in the absence of such spillovers, the effects of policy measures will become dependent of the (differences between) country-specific technology levels, core insights are only slightly altered. To implement a sustainable growth trajectory, unilateral policies must redirect the majority of *foreign* scientists to the clean sector by increasing the size of foreign's clean sector. So, under this assumption, Proposition 2 and Corollary 1 apply for any $s_f > 0$. This assertion is confirmed by Hemous (2012), who finds that to unilaterally redirect the world economy to a sustainable growth trajectory, in the long run, scientists in the unrestricted country must innovate in clean, or nonpolluting machines. Similarly, Proposition 2 and Corollary 1 are upheld in the intermediate case, where technologies require time to diffuse. Here, in the long run, the country with the largest knowledge base determines the direction of growth

7 Conclusion

In its aim to reduce emissions a climate coalition typically implements policies that increase the world price of carbon intensive goods. This causes nonparticipants to expand their carbon intensive goods production and carbon leakage to occur. In addition to this, well-known, static result, we identify a 'dynamic' leakage channel. The expansion of carbon intensive sectors will induce nonparticipant innovation in these sectors, inducing future emission growth. As we show, this mechanism can have far-reaching consequences with regard to optimal unilateral policies. Most notably, if nonparticipants drive global innovation, policies that cause carbon leakage cannot prevent a continuing increase in global emissions. In this setting, unilateral policies that sufficiently reduce the short run price of polluting goods and turn the coalition in a polluting good exporter, redirect nonparticipants' innovation to the nonpolluting sector and implement sustainable growth. The coalition is more likely able to realize sustainable growth if it represents a large share of global demand and if clean technologies are relatively advanced initially. The directedness of growth as well as the importance of industry location for innovation are crucial determinants of optimal policies. A social planner who fails to account for these will always implement policies that cause positive leakage, and may therefore fail to achieve sustainable growth.

Naturally, results from a stylized model do not directly carry over to real-world policy implications. The core insight that as unilateral action affects innovation incentives, the innovation potential outside the

[22]For example, one can redefine expected innovation profits as $\Pi_{kjt} = \mathrm{E}\left[\pi_{kjit} + \chi\pi_{-kjit}\right]$ where E is the expectations operator, $-k$ refers to the country other than k and $\chi \in [0, 1]$ is a measure of international property right enforcement, expressed as the share of profits in (14) a scientist captures if it sells its patent to a machine producer in the other country. As long as $\chi < 1$, foreign scientists are more responsive to local production.

coalition may be a major determinant of optimal policies may well be relevant though. A quick glance at the data reveals that three of the most innovative nations have no binding targets, or did not ratify the Kyoto treaty.[23] As innovators in these nations will, for a large part, determine the world's long-run growth trajectory, their incentives should be taken into account in the design of environmental policies. In this light, the US and EU imposition of tariffs and minimum prices on Chinese solar panels may not only be harmful to the environment in the short run, but may also have unfavorable long-run repercussions.[24] A simple calibration exercise confirms this picture: a coalition of countries with binding targets under the Kyoto treaty is insufficiently innovative to implement sustainable growth without redirecting non-Kyoto innovation. They are capable of doing the latter, albeit at the cost of very high tax rates on use of polluting goods. Increasing the size of the coalition would allow for reduced tax rates.

It is highly likely that unilateral policies remain relevant for the foreseeable future. Past performance is of course no guarantee for future results, but chances are that, like in the past decades, the UNFCCC will continue to be unsuccessful in establishing a universal climate treaty with binding limits on emissions. And even if a global agreement is reached, not all countries may implement the same set of policy measures. Developing countries or countries whose industries would be a particularly hurt by the implementation of stringent environmental policies may only cooperate conditional on certain provisions in the agreement. Differential policies across different (groups of) countries could affect trade patterns and insights regarding unilateral policies can be extended to such cases.

Further research could investigate the empirical relevance of this paper's argument by assessing the relationship between carbon leakage and the spatial distribution of innovation over time. It could also contribute to formalizing the discussion regarding the results' sensitivity to modeling assumptions, as presented in Section 5. Alternatively, the model could be extended by endogenizing the foreign country's policy decision and its response to domestic policies. Finally, the size of the research bases in both countries is crucial, yet taken fully exogenous. An interesting array of further research could be to endogenize the number of scientists in a country, and determine how this endogenization affects optimal policy decisions.

Appendix

A Proofs

To save on notation, all proofs use the following definitions for relative intermediates prices $p_t^R \equiv p_{ct}/p_{dt}$, relative technology $A_t^R \equiv A_{ct}/A_{dt}$, relative labor $L_w^R \equiv L_h/L_f$ and $L_{kt}^R \equiv L_{kct}/L_{kdt}$, and relative final goods prices $p_{wt}^R \equiv p_{ht}/p_{ft}$. Likewise, we define relative taxes $\tilde{\tau}_{kt}^R \equiv \tilde{\tau}_{kct}/\tilde{\tau}_{kdt}$ and $\tau_{kt}^R \equiv \tau_{kct}/\tau_{kdt}$, relative global intermediates production $\tilde{Y}_t^{WR} \equiv \tilde{Y}_{ct}^W/\tilde{Y}_{dt}^W$ and demand $Y_t^{WR} \equiv Y_{ct}^W/Y_{dt}^W$, and relative expected profits $\Pi_{kt}^R \equiv \Pi_{kct}/\Pi_{kdt}$. Finally, $p_t^{R,LF}$ is defined as the laissez-faire equilibrium relative price, where (21) gives $p_t^{R,LF} = \left(A_t^R\right)^{-\frac{1-\alpha}{1+(\varepsilon-1)\beta}}$.

[23] WIPO (2012) shows that China, the US and Japan belong to the 5 most innovative countries (by patent, trademark and industrial design counts) worldwide, where China is the fastest growing.

[24] See New York Times (2012) and Bloomberg (2013).

A.1 Proof to Lemma 3

As E_t is increasing in $\tilde{Y}_{dv}^{W}$ for $v < t$ and, absent of environmental policy, growth in $\tilde{Y}_{d}^{W}$ is strictly positive, implementing a sustainable growth path (see Definition 1) requires curbing growth in global dirty intermediates production. The proof then proceeds in two steps. First we determine $Y_{dt}^{W,MIN}$, which is defined as the minimum equilibrium global dirty intermediates demand for given technologies. If, asymptotically, $Y_{dt}^{W,MIN}$ grows, so must Y_{d}^{W} and hence $\tilde{Y}_{d}^{W}$. The next step is to determine under what conditions growth in $Y_{dt}^{W,MIN}$ is weakly negative. In the remainder of the proof, we define Y_{kjt}^{LF} and $\tilde{Y}_{kjt}^{LF}$ as the country k laissez-faire equilibrium demand and supply of intermediate j.

Lemma A1 $Y_{dt}^{W,MIN} = Y_{fdt}^{LF}$

Proof For given technologies, both foreign demand and supply of dirty intermediates are solely a function of p_t^R. By (6), (16), (17), and $\tilde{\tau}_{fjt} = \tau_{fjt} = 1$ for both $j \in \{c,d\}$ foreign supply of dirty intermediates reads

$$\tilde{Y}_{fdt} = \left(\left(p_t^R\right)^{1-\varepsilon}+1\right)^{\frac{\alpha}{\sigma}} \left(1+\left(p_t^R\right)^{\frac{1}{\beta}}\left(A_t^R\right)^{\frac{1-\alpha}{\beta}}\right)^{-\frac{1-\alpha-\beta}{1-\alpha}} A_{dt} L_f^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}.$$

$\tilde{Y}_{fdt}$ is falling in p_t^R and any policy in home that reduces p_t^R increases foreign supply of dirty intermediates. Next, using (4), (6), (11), (16) and (17) we have

$$Y_{fdt} = \left(\left(p_t^R\right)^{1-\varepsilon}+1\right)^{\frac{\alpha-\sigma}{\sigma}} \left(1+\left(p_t^R\right)^{\frac{1}{\beta}}\left(A_t^R\right)^{\frac{1-\alpha}{\beta}}\right)^{\frac{\beta}{1-\alpha}} A_{dt} L_f^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}.$$

Here, one can show that whenever $p_t^R > p_t^{R,LF}$, Y_{fdt} is increasing in p_t^R. Now take the following thought experiment. Suppose home can freely set any p_t^R, and under the condition that p_t^R is an equilibrium, choose any level for Y_{hjt} and $\tilde{Y}_{hjt}$. If home sets $p_t^R = p_t^{R,LF}$, $\tilde{Y}_{fdt} = \tilde{Y}_{fdt}^{LF} = Y_{fdt}^{LF} = Y_{fdt}$. Home can eliminate its domestic demand and supply of dirty intermediates, and $\tilde{Y}_{dt}^{W} = \tilde{Y}_{fdt}^{LF}$. If instead, home sets $p_t^R < p_t^{R,LF}$, we find $\tilde{Y}_{fdt} > \tilde{Y}_{fdt}^{LF}$ and $\tilde{Y}_{fdt} > Y_{fdt}$. Home can eliminate its domestic supply of dirty intermediates, but for $p_t^R > p_t^{R,LF}$ to be an equilibrium, it must demand dirty intermediates. Hence, we have $\tilde{Y}_{dt}^{W} > \tilde{Y}_{fdt}^{LF}$ for $p_t^R > p_t^{R,LF}$. Finally, if home sets $p_t^R > p_t^{R,LF}$, we find $\tilde{Y}_{fdt} < \tilde{Y}_{fdt}^{LF} = Y_{fdt}^{LF} < Y_{fdt}$. Now, home can eliminate its domestic demand for dirty intermediates, but for this to be an equilibrium, it must produce and export a positive amount of dirty intermediates. Now $\tilde{Y}_{dt}^{W} = Y_{dt}^{W} > Y_{fdt}^{LF} = \tilde{Y}_{fdt}^{LF}$. So, $\tilde{Y}_{dt}^{W}$ is minimized at $\tilde{Y}_{dt}^{LF}$ with $p_t^R = p_t^{R,LF}$. Up to now, this was a mere thought experiment. However, home can in fact implement $\tilde{Y}_{dt}^{W,MIN}$ by setting $\tilde{\tau}_{hdt} = \tau_{hdt} = \infty$ with any $\tilde{\tau}_{hct}, \tau_{hct} < \infty$. In this case, home will neither demand, nor supply dirty intermediates. Since home only produces and consumes clean intermediates, no trade will take place, and foreign intermediate and final goods producers will face the laissez-faire (autarky) price. ■

By Lemma A1 and (23), minimum global dirty intermediates supply reads

$$Y_{dt}^{W,MIN} = \left(A_{ct}^{\frac{\sigma}{1+(\varepsilon-1)\beta}} + A_{dt}^{\frac{\sigma}{1+(\varepsilon-1)\beta}}\right)^{\frac{1-\beta-\varepsilon(1-\alpha-\beta)}{\sigma}} A_{dt}^{\frac{\varepsilon(1-\alpha)}{1+(\varepsilon-1)\beta}} L_k^{\frac{1-\alpha-\beta}{1-\alpha}} \left(\frac{\alpha}{\psi}\right)^{\frac{\alpha}{1-\alpha}}$$

By (7), $A_{jt} - A_{jt-1} \geq 0$ for both j with strict inequality for at least one $j \in \{c, d\}$. $Y_{dt}^{W,MIN}$ is always increasing in A_{dt}, increasing in A_{ct} if $\varepsilon < (1-\beta)/(1-\alpha-\beta)$, constant in A_{ct} if $\varepsilon = (1-\beta)/(1-\alpha-\beta)$ and falling in A_{ct} if $\varepsilon > (1-\beta)/(1-\alpha-\beta)$. If A_{ct} and A_{dt} grow at equal rates (A_t^R is constant), Y_{dt}^{MIN} rises. So implementing a $Y_{dt}^{W,MIN}$ that is constant or falling over time requires $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$ and a growing A_t^R. By the following, home can only implement a growing A_t^R if it can implement $s_c^W > s_d^W$ at time t. If home cannot implement $s_{ct}^W > s_{dt}^W$, we have $s_{ct}^W \leq s_{dt}^W$, $A_{t-1}^R \geq A_t^R$. Whenever $A_{t-1}^R \geq A_t^R$, for given policies, the incentive to innovate in the clean sector is either equal or reduced, which implies that home will be unable to implement $s_c^W > s_d^W$ at any point in the future. As A^R is constant or falling, $Y_{dt}^{W,MIN}$ grows over time, and home cannot implement a sustainable growth path. If however, home implements $s_{ct}^W > s_{dt}^W$, by (7), $A_{t-1}^R < A_t^R$. With unchanged policies, the incentive to innovate in the clean sector is increased, and home can implement $s_{cv}^W > s_{dv}^W$ for any $v > t$. A^R continues to rise and in finite time, all scientists innovate in the clean sector. In the long run, Y_{dt}^{MIN} falls (if $\varepsilon > (1-\beta)/(1-\alpha-\beta)$) or remains constant (if $\varepsilon = (1-\beta)/(1-\alpha-\beta)$). In either case, $\bar{E}$ must be sufficiently high to ensure $E_t < \bar{E}$ for all t. ■

A.2 Proof to Proposition 2

By Lemma 1, home can only implement a sustainable growth path at time t if $\varepsilon \geq (1-\beta)/(1-\alpha-\beta)$, $\bar{E}$ is sufficiently high and it can implement $s_{ct}^W > s_{dt}^W$. By Assumption 1, absent of environmental policies, $s_{fct} = 0$. So if $s_f > s_h$, home must redirect a sufficient number of foreign scientists to the clean sector to implement $s_{ct}^W > s_{dt}^W$. Home achieves this if it implements policies such that $\Pi_{ft}^R = L_{ft}^R \left(\frac{\gamma z s_{ct}^W + 1}{\gamma z s_{dt}^W + 1}\right)^{-1} \geq 1$ or some $Z_t \equiv \frac{\gamma z s_{ct}^W + 1}{\gamma z s_{dt}^W + 1} > 1$, where we use (17) and (24). Hence we need $L_{ft}^R \geq Z_t > 1$. Then by (16) we can rewrite this condition to $p_t^R \geq Z_t^\beta \left(A_t^R\right)^{\alpha-1}$. This is true if in equilibrium, for $p_t^R = Z_t^\beta \left(A_t^R\right)^{\alpha-1}$, we have world relative demand for clean greater or equal to relative supply, or $Y_{ct}^{WR} \geq \tilde{Y}_{ct}^{WR}$. Now at $p_t^R = Z_t^\beta \left(A_t^R\right)^{\alpha-1}$, by (6), (16) and (18), we find

$$\tilde{Y}_t^{WR} = \frac{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{\left(\tilde{\tau}_{ht}^R\right)^{\frac{1-\beta}{\beta}} + Z_t} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t\left(\tilde{\tau}_{ht}^R\right)^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \left(A_t^R\right)^{1-\alpha} Z_t^{1-\beta}, \tag{27}$$

where

$$X_t \equiv \left(\frac{1 + Z_t \left(\tilde{\tau}_{ht}^R\right)^{-\frac{1}{\beta}}}{1 + Z_t}\right)^{-\frac{1-\alpha-\beta}{1-\alpha}} \frac{1 + Z_t \left(\tilde{\tau}_{ht}^R\right)^{-\frac{1-\beta}{\beta}}}{1 + Z_t} \tilde{\tau}_{hdt}^{-\frac{\alpha}{1-\alpha}}, \tag{28}$$

and we know

$$p_{wt}^R = \left(\tau_{hdt}^{1-\varepsilon} \frac{\left(p_t^R\right)^{1-\varepsilon} \left(\tau_{ht}^R\right)^{1-\varepsilon} + 1}{\left(p_t^R\right)^{1-\varepsilon} + 1}\right)^{\frac{1}{1-\varepsilon}}. \tag{29}$$

Using additionally (12) and (17) we have

$$Y_t^{WR} = \frac{\left(\tau_{ht}^R\right)^{-\varepsilon}\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}\left(\tau_{ht}^R\right)^{-\varepsilon}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^{\sigma}\left(\tau_{ht}^R\right)^{-\varepsilon}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \left(A_t^R\right)^{\varepsilon(1-\alpha)} Z_t^{-\varepsilon\beta}. \tag{30}$$

The question we adress is under what conditions it is feasible for home to implement $Y_t^{WR} \geq \tilde{Y}_t^{WR}$ for $p_t^R = Z_t^{\beta}\left(A_t^R\right)^{\alpha-1}$. Here, home has four policy choices: the levels of the two intermediate output taxes, and the two intermediate input taxes. Regarding these policy choices, we first put forward the following Lemma.

Lemma A2: To maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, home must set $\tau_{hct} = \tilde{\tau}_{hdt} = 1$.

Proof: By (29), multiple levels of τ_{ht}^R support a given p_{wt}^R. We use this property to show that to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, we never have $\tau_{ht}^R > 1$. First, as long as p_{wt}^R is given, $\tilde{Y}_t^{WR}$ is independent of output taxes τ_{jht}, yet Y_t^{WR} is falling in τ_{ht}^R. Hence, for a given p_{wt}^R, to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, one must minimize τ_{ht}^R. However, to maintain this p_{wt}^R, any reduction in τ_{ht}^R requires both a reduction in τ_{hct} and an increase in τ_{hdt}.[25] As we require $\tau_{hjt} \geq 1$, $\tau_{ht}^R > 1$ implies $\tau_{hct} > 1$ and a reduction in τ_{ht}^R while maintaining p_{wt}^R is always feasible. If $\tau_{ht}^R \leq 1$ however, we may have $\tau_{hct} = 1$ (which we will later see is indeed the case), and further reductions in τ_{ht}^R may not be feasible. Thus, we conclude that maximizing $Y_t^{WR} - \tilde{Y}_t^{WR}$ implies $\tau_{ht}^R \leq 1$.

Next by (28), multiple levels of $\tilde{\tau}_{ht}^R$ support a given X_t. We use this property to show that to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, we never have $\tilde{\tau}_{ht}^R > 1$. First, for a given X_t, $\tilde{Y}_t^{WR}$ is falling in $\tilde{\tau}_{ht}^R$ and Y_t^{WR} is independent of X_t. Hence, for a given X, to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, one must maximize $\tilde{\tau}_{ht}^R$. However, to maintain a given X_t, any increase in $\tilde{\tau}_{ht}^R$ requires a reduction in $\tilde{\tau}_{hdt}$. For $\tilde{\tau}_{ht}^R \leq 1$, one can show that for given X_t, an increase in $\tilde{\tau}_{ht}^R$ requires an increase in $\tilde{\tau}_{hdt}$. Hence, one can always increase $\tilde{\tau}_{ht}^R$ if $\tilde{\tau}_{ht}^R \leq 1$. Hence, to maximize $Y_t^{WR} - \tilde{Y}_t^{WR}$, one will never set $\tilde{\tau}_{ht}^R < 1$. For $\tilde{\tau}_{ht}^R > 1$, the relationship between $\tilde{\tau}_{ht}^R$ and $\tilde{\tau}_{hdt}$ turns ambiguous, and one may hit the restriction $\tilde{\tau}_{hdt} \geq 1$.

We now have established that the combination of some $\tau_{ht}^R \leq 1$ and $\tilde{\tau}_{ht}^R \geq 1$ maximizes $Y_t^{WR} - \tilde{Y}_t^{WR}$. Now, given τ_{ht}^R, $Y_t^{WR} - \tilde{Y}_t^{WR}$ is maximized by minimizing p_{wt}^R. Above, we found that for given τ_{ht}^R, p_{wt}^R is increasing in τ_{hdt}. Hence, the $\tau_{ht}^R \leq 1$ we set must be set such that τ_{hdt} is minimized, which is the case if we set $\tau_{hct} = 1$. Additionally, given $\tilde{\tau}_{ht}^R$, $Y_t^{WR} - \tilde{Y}_t^{WR}$ is maximized by maximizing X, where X is falling in $\tilde{\tau}_{hdt}$. Hence, the $\tilde{\tau}_{ht}^R \geq 1$ we set must be set such that τ_{hdt} is minimized, which is the case if we set $\tilde{\tau}_{hdt} = 1$. ■

Next using $\tilde{\tau}_{hdt} = \tau_{hct} = 1$, and (27) and (30), $Y_t^{WR} \geq \tilde{Y}_t^{WR}$ implies

$$Z_t^{-(1+(\varepsilon-1)\beta)} \geq G,$$

[25] More specifically we have $\frac{d\tau_{hct}}{d\tau_{hdt}} = -\left(p_t^R\right)^{\varepsilon-1}\left(\tau_{ht}^R\right)^{\varepsilon}$

with

$$G \equiv \frac{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma \tau_{hdt}^\varepsilon} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\tau_{hdt}^\varepsilon \left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma}{1+Z_t^{\beta(1-\varepsilon)}\left(A_t^R\right)^\sigma \tau_{hdt}^\varepsilon} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \frac{\tilde{\tau}_{hct}^{-\frac{1-\beta}{\beta}} \left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t \tilde{\tau}_{hct}^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1}{\left(p_{wt}^R\right)^{-\frac{\alpha}{1-\alpha}} \frac{1+Z_t}{1+Z_t \tilde{\tau}_{hct}^{-\frac{1-\beta}{\beta}}} \left(L_w^R\right)^{\frac{1-\alpha-\beta}{1-\alpha}} X_t + 1} \left(A_t^R\right)^{-\sigma}.$$

Then, using $\tilde{\tau}_{hct} \geq 1$ and $\tau_{hdt} \geq 1$, we can show $dG/dL_w^R < 0$ and $dG/dA_t^R < 0$. As, for a given Z_t, $dA_t^R/dA_{t-1}^R > 0$, this implies $dG/dA_{t-1}^R < 0$. Hence, the greater L_h/L_f and the greater A_{ct-1}/A_{dt-1}, the more likely home can implement equilibrium relative prices p_{ct}/p_{dt} that exceed the level required to suffienctly increase the production of clean intermediates in the foreign country, and thereby redirect foreign scientists to the clean sector. ■

A.3 Proof to Proposition 3

The myopic social planner chooses the paths of machine production, x_{kjit}, labor allocation, L_{hct}, and relative intermediates prices, p_t^R that maximize intertemporal utility U_{kt} subject to $c_{ht} = \frac{1}{\bar{L}_h + \bar{s}_h}\left[Y_{ht} - \psi\left(\sum_j \int_0^1 x_{hjit} di\right)\right]$, (2), (3), and (6) for $k = h$, (10) and, by (3), $Y_{hjt} = IM_{jt}\left(p_t^R\right) + \tilde{Y}_{hjt}$ where $IM_{jt}(p_t) \equiv \tilde{Y}_{fjt}\left(p_t^R\right) - Y_{fjt}\left(p_t^R\right)$, while taking the path of technology as given. First, define $\lambda_{ht} = \frac{\partial U_{ht}}{\partial c_t}\frac{\partial c_t}{\partial Y_{ht}}$ as the shadow value of one unit of final output, and $\lambda_{hjt} = \lambda_{ht}\frac{\partial Y_{ht}}{\partial Y_{hjt}}$ as the shadow value of input j in final output production. Similarly, we take $\lambda_{hEt} = \frac{\partial U_{ht}}{\partial \mathbf{E}_{t+}}\frac{\partial \mathbf{E}_{t+}}{\partial \tilde{Y}_{dt}^W}$ as the shadow value of emissions at time t. Here, we have $\lambda_{ht}, \lambda_{hjt} > 0$ and $\lambda_{hEt} < 0$. The FOC with respect to L_{hct} implies that the social planner allocates labor according to

$$(\lambda_{hdt} + \lambda_{hEt})\frac{\partial \tilde{Y}_{hdt}}{\partial L_{hdt}} = \lambda_{hct}\frac{\partial \tilde{Y}_{hct}}{\partial L_{hct}}.$$

The FOC with respect to p_t^R then gives that in the optimum

$$\lambda_{hdt}\frac{\partial IM_{dt}}{\partial p_t^R} + \lambda_{hct}\frac{\partial IM_{ct}}{\partial p_t^R} + \lambda_{hEt}\frac{\partial \tilde{Y}_{fdt}}{\partial p_t^R} = 0. \tag{31}$$

In the market equilibrium, the final output producer equates the relative return to clean and dirty input use to its marginal cost: $\frac{\partial Y_{ht}/\partial Y_{hct}}{\partial Y_{ht}/\partial Y_{hct}} = p_t^R \tau_{ht}^R$ (see (11)) Similarly, by labor mobility, the return to labor is equal across sectors (see (15)): $p_{dt}\tilde{\tau}_{hdt}^{-1}\frac{\partial \tilde{Y}_{hdt}}{\partial L_{hdt}} = p_{ct}\tilde{\tau}_{hct}^{-1}\frac{\partial \tilde{Y}_{hct}}{\partial L_{hct}}$. This gives us that in the optimum, we must have $p_t^R \tau_{ht}^R = \frac{\lambda_{hct}}{\lambda_{hdt}}$ and $p_t^R\left(\tilde{\tau}_{ht}^R\right)^{-1} = \frac{\lambda_{hct}}{\lambda_{hdt}+\lambda_{hEt}}$. From here we derive the optimal tax wedge

$$\frac{\lambda_{hdt}}{\lambda_{hdt} + \lambda_{hEt}} = \left(\tilde{\tau}_{ht}^R \tau_{ht}^R\right)^{-1} > 1.$$

The environmental externality calls for a net tax on dirty intermediates output and/or input. The greater the environmental externality, the more negative λ_{hEt} and hence the larger dirty taxes are called for. The optimal use of policy tools depends on foreign's response. By balanced trade, we have $p_t^R IM_{ct} + IM_{dt} = 0$

for any p_t^R, which implies $IM_{ct} + p_t^R \frac{\partial IM_{ct}}{\partial p_t^R} + \frac{\partial IM_{dt}}{\partial p_t^R} = 0$. Using this in addition to the above results, allows us to rewrite (31) to

$$\tau_{ht}^R \left(\tilde{\tau}_{ht}^R \tau_{ht}^R - 1\right)^{-1} \left(\tilde{\tau}_{ht}^R - \left(1 + \frac{IM_{ct}}{\partial IM_{dt}/\partial p_t^R}\right)\right) + \frac{\partial Y_{fdt}/\partial p_t^R}{\partial IM_{dt}/\partial p_t^R} = 0.$$

From here, we can show that the social planner will never set $p_t^R \geq p_t^{LF}$. From the definition of IM_{dt}, and by $\partial \tilde{Y}_{fdt}/\partial p_t^R < 0$ and $\partial Y_{fdt}/\partial p_t^R > 0$ we know $\frac{\partial Y_{fdt}/\partial p_t^R}{\partial IM_{dt}/\partial p_t^R} \in (-1, 0)$. Hence we know that in the optimum $\tau_{ht}^R \left(\tilde{\tau}_{ht}^R \tau_{ht}^R - 1\right)^{-1} \left(\tilde{\tau}_{ht}^R - \left(1 + \frac{IM_{ct}}{\partial IM_{dt}/\partial p_t^R}\right)\right) < 1$, or $\tau_{ht}^R \left(1 + \frac{IM_{ct}}{\partial IM_{dt}/\partial p_t^R}\right) > 1$. For $p_t^R \geq p_t^{LF}$, we have $IM_{ct} \geq 0$, which by $\partial IM_{dt}/\partial p_t^R < 0$ implies we require $\tau_{ht}^R > 1$. By Lemma 1, to set $p_t^R \geq p_t^{LF}$, $T_{ht} = \left(\tau_{ht}^R\right)^{-\frac{\varepsilon}{1-\beta}} \tilde{\tau}_{ht}^R$ must be greater than or equal to unity. With $\tau_{ht}^R > 1$, this implies we need $\tilde{\tau}_{ht}^R > 1$. However, this gives $\tilde{\tau}_{ht}^R \tau_{ht}^R > 1$ which contradicts the requirement on the optimal tax wedge. ■

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