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Summary

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Keywords: Climate Policy, Carbon Leakage, Directed Technical Change, International Trade

JEL Classification: F18, O33, Q54, Q55

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Abstract

A common critique to the Kyoto Protocol is that the reduction in emissions of CO_2 by countries who comply with it will be (partly) offset by the increase in emissions on the part of other countries (carbon leakage). This paper analyzes the effect of technical change on carbon leakage in a two-country model where only one of the countries enforces an exogenous cap on emissions. Climate policy induces changes in relative prices, which cause carbon leakage through a *terms-of-trade effect*. However, these changes in relative prices in addition affect the incentives to innovate in different sectors. We allow entrepreneurs to choose the sector for which they innovate (directed technical change). This leads to a counterbalancing *induced-technology effect*, which always reduces carbon leakage. We therefore conclude that the leakage rates reported in the literature so far may be too high, as these estimates neglect the effect of relative price changes on the incentives to innovate.

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1 Introduction

An important threat to climate policy is that actions undertaken without universal participation may prove to be ineffective: any partial agreement to reduce emissions, for example of carbondioxide, will be undermined by the behaviour of countries outside the agreement.[1] Standard economic theory suggests that these countries may have several incentives to increase their emissions. In the first place, the relative price for carbon-intensive goods could increase as global supply falls due to the emission constraint. This gives countries outside the coalition incentives to expand their production of these goods

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[1] Carbondioxide (CO_2) is the greenhouse gas with the highest global warming contribution and most of its anthropogenic emissions are directly related to fossil fuel use. Therefore most of the economics literature on climate policy focuses on CO_2. For simplicity, we also call the global pollutant in this paper carbon or carbondioxide; our analysis, however, applies to any uniformly mixing transboundary pollutant.

and export them to signatory countries (*terms-of-trade* effect). Secondly, a lower price for fossil fuels, due to the reduced demand from the constrained economies, could induce substitution towards this type of fuels in countries without a carbon constraint. Thirdly, if damage costs from the global pollutant are strictly convex in global emissions, marginal environmental costs will decrease in unconstrained countries and emission levels may be revised upwards. For all these reasons, emissions in unconstrained countries can increase and off-set the reductions secured by the agreement participants, a phenomenon known as *carbon leakage*.

In this paper we study the role of technical change in determining carbon leakage. As discussed above, climate policy affects relative prices of both goods and factors, inducing carbon leakage through what we called the terms-of-trade effect. However, these relative price changes also affect the incentives to innovate in different sectors, causing a counterbalancing *induced-technology effect*. As this effect is ignored in the existing literature on carbon leakage, the degrees of leakage that have been reported so far may be too high, partly explaining the negative attitude of policy makers towards unilateral climate policy.

Our aim in this paper is to isolate the effects of the regime of technical change on carbon leakage. To this end, we model two countries that are perfectly symmetric as refers to preferences, technology and endowments. We only allow them to differ in one crucial respect: one country imposes a binding emission cap, while the other remains unconstrained. We are thus able to compare the effects of an exogenous unilateral emission constraint on the choice of pollution in the foreign country for two different regimes of endogenous technical change. The first regime reflects the 'traditional' way of modelling technical change as increasing total factor productivity. We show that in this case carbon leakage will occur through the terms-of-trade effect described above. However, climate policy also changes the relative prices of inputs. This in turn will affect the relative profitability of innovating for the clean or dirty industry and hence the relative development of technology in the two industries.[2] Therefore, we model a second regime of technical change, in which new inventions can be aimed at the industry that gives the highest profits, and technical change may benefit one of the productive factors more than the other (directed technical change). We show that, in this case, the induced changes in the *composition* rather than in the level of technology always reduce carbon leakage relative to the alternative scenario. Moreover, we hint at the possibility that, for high values of the price elasticity of carbon-based energy, induced technical change leads to negative leakage rates.

Our paper contributes to a growing literature on carbon leakage by highlighting the role of directed technical change in this framework.

The problem of carbon leakage has been widely studied in the context of the Kyoto Protocal using Computable General Equilibrium (CGE) models. These models generally report leakage rates (the percentage of reduction in emissions that is offset by an increase in emissions by countries outside the Protocol) ranging from 5% to 20% (see, for example, the survey in Burniaux and Martins 2000), although some papers find leakage rates as high as 41% (Light, Kolstad, and Rutherford 2000). In a recent paper Babiker (2005) even

[2]Newell, Jaffe, and Stavins (1999) study the effect of energy prices and government regulations on energy-efficiency innovation. They show that, for the products studied, changes in energy prices affect the direction of innovation for some products and that they induce changes in the subset of technically feasible models offered for sale. The authors conclude that "the endogeneity of the direction or composition of technological change is surely at least as significant [as] the overall pace of technological change" (p. 971). Popp (2002) shows that energy prices (including the effect of environmental policy) positively and quickly affect environmentally friendly innovations.

finds a leakage rate of 130% for one of his scenarios: in this case the Kyoto Protocol would lead to an increase in global carbondioxide emissions. These differences in estimates stem from differences in assumptions with respect to the degree of international market integration, substitution and supply elasticities, and market structure. Although CGE models do allow for both international and sectoral disaggregations, we feel that they fall short of the mark, since they do not take into account the effects of climate policy on technical change, and the feedbacks on emissions.

Another rich strand of literature addresses asymmetric international environmental policy from a public economics point of view (e.g. Barrett 1994, Carraro and Siniscalco 1998, Hoel 1991). Stressing the roles of free-riding incentives and strategic behaviour among nations, but abstracting from both technical change and international trade, this literature concludes that emissions among countries are strategic substitutes and that unilateral climate policy will lead to leakage of emissions.

Copeland and Taylor (2005) show, among other things, that in the presence of international trade and environmental preferences, a country's response to a rest-of-world emissions reduction is ambiguous. In their static two-good, two-factor, K-country model without technical change, this result follows from allowing for income and substitution effects on the consumption side to offset the terms-of-trade effect on the production side. The mechanism underlying their result therefore differs from ours, both in terms of modelling and in terms of economic content.

Golombek and Hoel (2004) study the effect of international spillovers of abatement technology on leakage, using a static partial equilibrium two-country, one-good model with transboundary pollution. In each country a central planner chooses research and development (R&D) expenditures and abatement levels to minimize total costs that include environmental damages. Research activities lead, by assumption, to reductions in abatement costs, while international technology spill-overs allow technology to diffuse across borders at no cost. Hence, the authors effectively build in their model a mechanism that counteracts the free-riding incentives underlined by previous literature. In our model, on the other hand, the nature of technical change is endogenous, as it is itself driven by profit incentives, and depends on the characteristics of production.

The rest of the paper develops as follows. We introduce the model in section 2. In section 3 we present equilibrium conditions for the four versions of our model: with and without unilateral climate policy, and with and without directed technical change. Section 4 contains the main results of the paper. We first introduce the terms-of-trade effect and study carbon leakage when entrepreneurs cannot aim new technologies to one of the sectors; we then focus on carbon leakage under directed technical change and show how the induced technology effect changes the results found before. We conclude in section 5.

2 The Model

Our economy consists of two countries, c and u, that have identical production technologies and endowments, while only differing in their environmental policies.[3] We assume that country c (for *constrained*) imposes a binding cap on polluting emissions. We focus on a situation of free trade noting that, as long as the two countries do not differ in environmental policies, there will be no actual scope for trade.

[3] In this paper we are only interested in the effect of climate policy on technology and in the ensuing production choices. We therefore do not discuss growth rates or welfare. Since in addition we assume balanced trade, (intertemporal) preferences play no role and the consumption side of the model is redundant.

In each country, final output Y is obtained as a CES aggregate of two (intermediate) goods, Y_E and Y_L, with an elasticity of substitution equal to ε:

$$Y^r = \left[(Y_E^r)^{\frac{\varepsilon-1}{\varepsilon}} + (Y_L^r)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{1}$$

where $r = c, u$ is the country index.[4] We assume that good Y_E is produced using energy (E) and a specialized set of differentiated machines. The range of types of machines available to produce energy intensive goods is indicated by N_E. Instead, Y_L is produced using labour (L_L) and a different set of machines, whose range is indicated by N_L. Following Acemoglu (2002), the production functions for the intermediate goods are as follows:

$$Y_E^r = \frac{1}{1-\beta} \left(\int_0^{N_E} k_E^r(i)^{(1-\beta)} di \right) (E^r)^{\beta}, \tag{2}$$

and

$$Y_L^r = \frac{1}{1-\beta} \left(\int_0^{N_L} k_L^r(i)^{(1-\beta)} di \right) (L_L^r)^{\beta}, \tag{3}$$

where $\beta \in (0,1)$ and $k_j^r(i)$ is the amount of machines of type i employed in sector $j = L, E$ in country r. Both intermediate goods are traded internationally.

To produce each type of machines, producers need a blueprint invented by the R&D sector, as will be discussed below. We assume that machines developed to complement one factor of production cannot be usefully employed in the other sector and that blueprints can be traded internationally. Accordingly, N_E and N_L represent global levels of technology and producers in each country can use all machine types globally available for their sector. For a given state of technology, that is for given N_E and N_L, both (2) and (3) exhibit constant returns to scale. However, when N_E and N_L grow due to R&D activities the returns will be increasing at the aggregate level.[5]

We assume that in each country an amount of labour equal to $\overline{L}$ is inelastically supplied at each point in time and that it is immobile across countries. Labour can either be employed in the production of the labour intensive good Y_L or in the production of energy:

$$\overline{L} = L_L^r + L_E^r, \tag{4}$$

where L_E^r is the amount of labour in energy production in country r. As in Babiker (2005), we assume that energy has to be produced using labour and some fixed factor. Consequently there are decreasing returns to labour in energy production:

$$E^r = (L_E^r)^{\phi}, \tag{5}$$

where $\phi \in (0,1)$. Energy generation causes emissions of carbondioxide. We assume that CO_2 emissions, Z, are proportional to the amount of energy produced, so that $Z = E$.

When country c introduces a binding constraint on the amount of carbondioxide emitted, it *de facto* imposes a cap on the amount of labour allocated to energy production. Indeed, when Z^c is the maximum amount of emissions permitted at any point in time, the allocation of labour in country c must satisfy $L_E^c = (Z^c)^{1/\phi}$.

The last part of our model consists of the process of technical change. We consider two alternative possibilities in this paper: technical change can either be 'undirected'

[4]For simplicity, we set the share parameters in the CES to one, as they will only introduce an additional constant term in the expressions.

[5]In other words, our model exhibits endogenous growth through variety expansion. See for example Grossman and Helpman (1991).

or 'directed'. With *undirected* or 'traditional' technical change, prospective innovators invest in the development of blueprints whenever it is profitable to do so, yet they cannot choose the sector they want to develop a new machine for. Instead, we assume that the newly developed blueprint will be energy-complementing with probability $\gamma \in (0,1)$ and it will be labour-complementing with probability $(1-\gamma)$. As a consequence the (expected) relative marginal productivity is constant, as is common in traditional (one-sector) models of endogenous growth.[6]

Using a lab-equipment specification for the process of technical change, we assume that investing one unit of the final good in R&D generates ν new innovations.[7] The total number of innovations in this case will therefore develop according to:

$$\dot{N} = \nu \left(R^c + R^u \right), \tag{6}$$

where R^r indicates total R&D investment by country r, and a dot on a variable represents its time derivative, i.e. $\dot{x} = \mathrm{d}x/\mathrm{d}t$.

The second regime of technical change that we consider is *directed* technical change.[8] In this case prospective innovators, besides deciding upon the amount of their R&D outlays, are able to choose the sector they want to target their innovation efforts to. Hence they will invent new machines for the sector that promises the highest returns. The development of new types of machines takes place according to the following production functions:[9]

$$\dot{N}_E = \nu \left(R^c_E + R^u_E \right), \tag{7}$$

$$\dot{N}_L = \nu \left(R^c_L + R^u_L \right). \tag{8}$$

A new blueprint must be developed before the innovator can sell it to producers, thus the costs of R&D are sunk. As a consequence, machine producers must wield some monopoly power in the market for machines, in order to recoup the development costs. For this we assume that an innovator is awarded a global patent for her invention and that patents are perfectly enforced in both countries. As a result, each innovation will take place only once and no international overlap in blueprints occurs.[10]

Furthermore, we simplify the analysis by assuming that machine production is local, that is innovators license their blueprints to one producer in each region, so that blueprints are traded across countries, but machines are not.

3 The Equilibrium

In this section we derive the general equilibrium allocation of labour. We first derive a necessary condition for equilibrium on the goods and factor markets. For the model

[6]Hence, with undirected technical change the relative level of technology in the two sectors, N_E/N_L, is exogenous and constant. Moreover, since N_E/N_L equals $\gamma/(1-\gamma)$, any value of N_E/N_L can be calibrated by an appropriate choice of the probability γ.

[7]See Rivera-Batiz and Romer (1991).

[8]The seminal work in this field is due to Daron Acemoglu. See, for example, Acemoglu (2002).

[9]For simplicity we assume that R&D is equally productive in the two sectors. Relaxing this assumption introduces a constant in the expressions that follow, but does not alter our qualitative results.

[10]Di Maria and Smulders (2004) also deal with directed technical change in an open-economy framework, but develop a North-South model to explain pollution-haven effects. They focus on the asymmetry of intellectual property rights' protection: since patents are not protected in the South all innovation takes place in the North. As a consequence the relevant market for innovators is the northern one, and the technology developed is inadequate to the factor composition in the South. Hence, the level of emissions in the South might increase once international trade in goods is allowed.

with undirected technical change, this condition gives the general equilibrium amount of labour in energy production. For the model with directed technical change we need to take another step and also study the equilibrium on the market for innovations. Joint consideration of these two conditions will give the general equilibrium allocation under directed technical change.

3.1 Equilibrium on the goods and factor markets

The market for the final good is perfectly competitive and we choose the final good's price as the numeraire. It follows that a necessary condition for the optimal demand for labour- and energy-intensive goods is that the marginal product of each intermediate good equals its price. From (1) we get, in relative terms:

$$\frac{Y_E^{dr}}{Y_L^{dr}} = \left(\frac{p_E}{p_L}\right)^{-\varepsilon}, \tag{9}$$

where p_j is the price of good Y_j, $j = E, L$. Notice that we introduced a superscript d to indicate demand and avoid confusion with supply in (2) and (3). Prices will be equalized across the two regions since countries are either symmetric or trade at no cost.

Producers of the intermediate good Y_j maximize profits taking prices and technology as given. In particular, they choose the amount of inputs taking as given the prices of their output (p_j), of the primary input they use (w_j) and of the machines they use ($p_{k_j(i)}$ for a machine of type i complementing factor j), and the range of available machines N_j.[11]

Using (2) and (3) we can derive the local demand for a machine of type i in each sector from the first-order conditions with respect to each type of machine $k_j(i)$:

$$k_E^r(i) = \left(\frac{p_E}{p_{k_E(i)}}\right)^{1/\beta} E^r \quad \text{and} \quad k_L^r(i) = \left(\frac{p_L}{p_{k_L(i)}}\right)^{1/\beta} L_L^r. \tag{10}$$

By the same token we can derive the (inverse) local demand for energy and labour from the first-order conditions with respect to primary inputs:

$$w_E = \frac{\beta}{1-\beta} p_E \left(\int_0^{N_E} k_E^r(i)^{(1-\beta)} di\right) (E^r)^{\beta-1}, \tag{11}$$

$$w_L = \frac{\beta}{1-\beta} p_L \left(\int_0^{N_L} k_L^r(i)^{(1-\beta)} di\right) (L_L^r)^{\beta-1}. \tag{12}$$

As mentioned before, the holder of a patent licenses production to only one producer in each region. Consequently, local producers act as monopolists on their local market. We assume that the production of machines in both sectors entails a constant marginal cost equal to ω units of the final good, and that machines depreciate immediately after use. Each monopolist maximizes her profits subject to the appropriate demand function in (10). As a result, each monopolistic producer will set her price as a constant mark-up over marginal cost, that is $p_{k_j(i)} = \omega/(1-\beta)$. Letting $\omega = 1-\beta$ for convenience, we can set the price of machines in both sectors equal to 1.[12]

[11] Throughout the paper we will refer to energy (E) and labour used in the production of Y_L (L_L) as primary inputs, although in the model labour is the only "truly" primary input.

[12] Notice that all machines are equally productive in intermediate goods production and entail the same cost. Thus, the amount of each machine used in sectorial production will be the same, k_j say. This symmetry simplifies the structure of the sectorial production functions as we may write: $\int_0^{N_j} k_j(i)^{(1-\beta)} di = N_j k_j^{(1-\beta)}$, for $j = E, L$.

Using this result we obtain an expression for the relative supply of goods that depends on relative prices, relative (primary) factors supplies and relative technology,

$$Y^w = p^{(1-\beta)/\beta} S^w N. \tag{13}$$

In the remainder of the paper we define variables without a subscript as ratios, with the convention that the variables at the numerator refer to the energy sector E. Hence, we refer to $N \equiv N_E/N_L$ as the (global) technology ratio. Moreover, we let the global relative factor supply be $S^w \equiv (E^c + E^u) / (L_L^c + L_L^u)$, and define the world relative supply of intermediate goods as $Y^w \equiv (Y_E^c + Y_E^u) / (Y_L^c + Y_L^u)$. Superscript w indicates that the variable concerned represents a global (world) amount or ratio.

Equating relative supply (13) and relative demand (9) yields the market clearing relative price for intermediate goods, for given technology:

$$p = (NS^w)^{-\beta/\sigma}, \tag{14}$$

where we define $\sigma \equiv 1 + (\varepsilon - 1)\beta$. From (14) we see that a higher level of technology in the sector for energy intensive goods, or a higher relative supply of energy decreases the relative price of the dirty good.

We now turn to the market for factors. Substituting machine demands (10) into the inverse demand functions for energy (11) and labour (12), we obtain an expression for the relative factor rewards. Using this and the market clearing relative price for intermediate goods (14), we get the following expression for the relative factor rewards for given technology:

$$w = N^{(\sigma-1)/\sigma} (S^w)^{-1/\sigma}. \tag{15}$$

The relative price of energy decreases with energy supply, while the effect of the technology ratio N depends on whether σ is larger or smaller than unity. Solving equation (15) for S^w gives $S^w = N^{\sigma-1} w^{-\sigma}$, which informs us that σ is the elasticity of relative factor demand with respect to their relative price. As will be discussed later, the effect of the technology ratio on relative factor rewards depends on whether relative energy demand is elastic or inelastic.[13]

To fully characterize the equilibrium on the goods and factor markets for given technology, we need to determine the way in which labour is allocated between production of the labour intensive intermediate good and energy production. As noted in section 2, when country c faces a binding emission constraint, the amount of labour in energy production is exogenously determined by the cap, $L_E^c = (Z^c)^{1/\phi}$. In an unconstrained country however, each energy producer chooses the amount of labour so as to maximize her profits, subject to the production function in (5) and taking prices w_L and w_E as given. This gives an unconstrained country's demand for labour in energy production as a function of relative factor prices:

$$w = \frac{1}{\phi \left(L_E^r\right)^{\phi-1}}.$$

Equating this expression and (15) we find an expression representing the equilibrium allocation of labour in country u, for a given technology ratio N and for given energy production in the other country:

$$\phi^{-\sigma} N^{1-\sigma} \left[(L_E^c)^{\phi} (L_E^u)^{\sigma(1-\phi)} + (L_E^u)^{\phi(1-\sigma)+\sigma} \right] + L_E^c + L_E^u = 2\overline{L}. \tag{16}$$

[13] From the definition of σ as $1 + (\varepsilon - 1)\beta$, it is clear that $\sigma \gtrless 1 \Leftrightarrow \varepsilon \gtrless 1$. Thus relative factor demand is elastic if and only if intermediate goods are gross substitutes in the production of the final good, and inelastic if and only if they are gross complements.

In this expression we allow for the possibility that each country chooses a different level of labour in energy production. It is clear that, as long as no binding emission cap is introduced, a symmetric expression holds for country c. In this case, given that countries are identical, they will choose the same equilibrium amount of labour in energy production so that we can rewrite the above expression, letting $L_E^u = L_E^c = L_E$, as

$$\phi^{-\sigma} N^{1-\sigma} L_E^{\phi(1-\sigma)+\sigma} + L_E = \overline{L}. \quad (17)$$

Here L_E is the amount of labour employed in energy production in each country, when both countries are unconstrained.

In sum, when country c faces a binding emission constraint, its emissions, energy generation and amount of labour in energy producion are determined by the cap. Yet expression (16) still holds for the unconstrained country, u, and solves (implicitly) for the amount of labour in energy production in the unconstrained region for given N.

As we saw in section 2 the technology ratio N is constant when technical change is undirected. Consequently, in this case equations (16) and (17) determine the general equilibrium allocation of labour. However, for the case of directed technical change we need to study the equilibrium on the market for innovations to determine the general equilibrium allocation of labour.

3.2 Equilibrium on the market for innovations

Under directed technical change innovators choose both the amount and the direction of their innovation efforts. Quite naturally they will invest in the sector which is expected to yield the highest rate of return. Using (10), the instantaneous profits are given by the following expressions:

$$\pi_E = \beta p_E^{1/\beta} E^w \quad \text{and} \quad \pi_L = \beta p_L^{1/\beta} L_L^w. \quad (18)$$

At each point in time, then, the direction of innovation will be determined by relative profits: $\pi = p^{1/\beta} S^w$. This expression clearly shows that the entrepreneurs' choice of the sector to invest in is determined by the relative price of the intermediate goods (the *price effect*) and by the relative amount of factors to which a machine type is complementary (the *market-size effect*). In particular, for given technology, a decrease in energy supply leads to a reduction in relative profits through the market size effect and to an increase through the price effect, see (14). Which of the two effects prevails depends on the elasticity σ, as will be discussed later.

Each potential innovator maximizes the net present value of the stream of future profits that she expects to enjoy over time. Along the balanced growth path of the economy, profits will not change over time,[14] and, since entry is free in the R&D sector, we know that the value of an innovation cannot exceed its cost (see (7) and (8)). Moreover, along the balanced growth path both types of innovation must occur at the same time, leading to the following no-arbitrage equation for the research sector:

$$\pi_E \nu = \pi_L \nu.$$

Substituting the appropriate expression for profits from (18), this can be rearranged to read,

$$p^{1/\beta} S^w = 1. \quad (19)$$

[14]We define a balanced growth path as a situation in which prices are constant and N_E and N_L grow at the same constant rate.

This no-arbitrage equation enables us to solve for the equilibrium level of the technology ratio N. Indeed, using the expression for relative prices in (14), we may solve (19) for N, obtaining the following expression for the balanced growth path equilibrium ratio of technology levels in the two sectors:

$$N = (S^w)^{\sigma-1}. \tag{20}$$

From this expression we see that, as noted above, the effect of a decrease in energy supply on the direction of technical change, that is on whether N increases or decreases, depends on the size of σ. When labour- and energy-intensive goods are gross complements in final goods production ($\sigma < 1$), the price effect in (18) outweighs the market size effect and a decrease in energy supply induces an increase in the range of energy complementary machines. However, when $\sigma > 1$ the result is reversed and the reduction in energy supply induces an increase in the range of labour-complementary machines.

3.3 General equilibrium under directed technical change

In the previous sections we have derived equilibrium conditions for the goods and factor markets and for the market for innovations. We are now ready to derive the general equilibrium allocation of labour for the model with directed technical change, as it obtains when both markets are in equilibrium at the same time.[15]

Substituting (20) into (16) yields the general expression for the equilibrium under directed technical change:

$$\phi^{1/(\sigma-2)}\left[\left(L_E^c\right)^{\phi}\left(L_E^u\right)^{(\phi-1)/(\sigma-2)} + \left(L_E^u\right)^{(\phi(\sigma-1)-1)/(\sigma-2)}\right] + L_E^c + L_E^u = 2\overline{L}. \tag{21}$$

Interpreting L_E^c as the constrained level of labour used in energy generation in country c following the introduction of an emissions cap, this expression solves for L_E^u in the unconstrained country under directed technical change.

Alternatively, assuming that no environmental policy is in place, we can interpret (21) as one of the two (symmetric) expressions that determine the equilibrium level of $L_E^c = L_E^u = L_E$ under directed technical change. Substituting L_E for the country specific variables yields the following expression:

$$\phi^{1/(\sigma-2)} L_E^{(\phi(\sigma-1)-1)/(\sigma-2)} + L_E = \overline{L}. \tag{22}$$

The above equations summarize the long-run equilibrium of our model with and without unilateral climate policy, under directed technical change. Indeed, they solve implicitly for the optimal level of L_E^u (L_E, respectively), from which we can immediately derive all the other variables of the model.

4 Unilateral climate policy and carbon leakage

We now turn to the analysis of the effects of unilateral climate policy, in terms of carbon leakage, across different regimes of technical change. To compare different scenarios, we

[15] It is possible to show that the model has an interior stable equilibrium for $\sigma \in (0, (1+\phi)/\phi)$. The stability of the equilibrium requires that in the (L_E, N) plane the line depicting the goods market equilibrium (16) is steeper than the no-arbitrage equation (20), at the point of intersection. The details of the existence and stability discussion are available from the authors upon request.

need to start from a common baseline. The natural baseline to choose is the long-run equilibrium of the model with directed technical change when both countries are unconstrained, equation (17). This baseline is characterized by the (symmetric) equilibrium level of labour devoted to energy generation L_E and by the corresponding (endogenous) technology ratio N. In order to have comparable baselines across technology regimes, we need to choose γ, the probability for an innovator to end up with an energy-complementing blueprint, such that $\gamma/(1-\gamma) = N$ equals the level prevailing under directed technical change, see Section 2.

Starting from this common equilibrium, we introduce an emissions constraint in one of the countries and study the degree of carbon leakage that occurs along the balanced growth path. We first study carbon leakage when technical change is undirected. Then we move on to the model with directed technical change and discuss how and why the results from this model differ from the model with 'traditional' endogenous growth.

4.1 Carbon Leakage under undirected technical change

Carbon leakage occurs when the unconstrained region increases its emissions in reaction to a reduction in emissions by the other country (i.e. when $L_E^u > L_E$). Intuitively it would seem clear that there should always be some carbon leakage: when a country exogenously reduces its supply of energy by introducing a limit to the amount of emissions, the energy intensive good becomes scarcer on its domestic market, giving rise to an increase in its relative price. This creates some scope for trade: the unconstrained economy now enjoys a comparative advantage in the production of the dirty good and will expand its production thereof. As a consequence L_E^u and hence emissions Z^u increase. We call this the *terms-of-trade effect* of a unilateral emission constraint. This result indeed holds in the case of undirected technical change, as formalized by the following proposition.

Proposition 1. *When technical change is undirected, carbon leakage will always be positive along the balanced growth path.*

Proof. Take the ratio of (17) and (16) and rearrange to find:

$$\left(\frac{L_E^{\phi}}{(L_E^u)^{\phi} + (L_E^c)^{\phi}}\right)^{-1/\sigma} \left(\frac{2\overline{L} - L_E^c - L_E^u}{\overline{L} - L_E}\right)^{-1/\sigma} = \left(\frac{L_E}{L_E^u}\right)^{1-\phi}.$$

Assume that $L_E^u \leq L_E$. Then the right hand side is larger than or equal to one while the left hand side is smaller than one. So we have a contradiction, hence $L_E^u > L_E$. □

We illustrate this result in Figure 1, where the dark dashed line represents emissions (or equivalently energy production) in each country when both are unconstrained. The amount of emissions by the unconstrained country when the other country faces a binding emission constraint, under undirected technical change is represented by the solid black line.[16] The figure clearly shows that emissions in the unconstrained region always increase following the introduction of the cap. In addition, we see that the amount of energy produced in the unconstrained region is declining with σ, the elasticity of relative demand for energy with respect to its relative price. The higher this elasticity, the

[16]The figures in this paper are obtained from numerical simulations, using as baseline parameters values: $\overline{L} = 1$, $\phi = 0.4$, and $\sigma \in (0, 3.5)$. For each value of σ the corresponding value for N for the model with directed technical change were computed and the appropriate γ calibrated such that both models start from the same baseline. We conducted numerous robustness checks for the local results derived in Propositions 2 and 4. In all cases the qualitative results were unchanged. For the sake of graphical clarity, the graphs are plotted over a smaller range for σ.

lower the demand for energy in the constrained economy following the imposition of the constraint, hence the lower the export-led increase in energy generation.

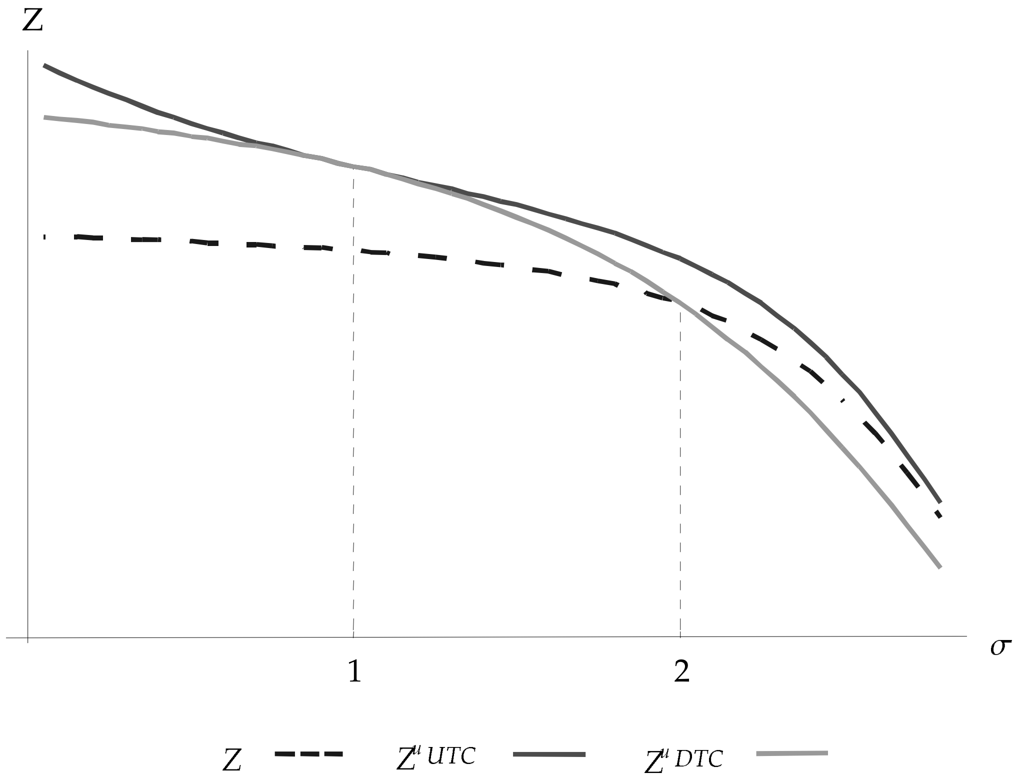

Figure 1: *Emissions in the unconstrained model (Z), in the constrained model under undirected technical change ($Z^u UTC$), and under directed technical change ($Z^u DTC$)*

When technical change is endogenous but undirected, unilateral climate policy is undermined by emission increases by unconstrained countries. However, it seems intuitively clear that changes in relative prices *cœteris paribus* will not lead to an increase in global emissions. Climate policy will shift production to the unconstrained country (proposition 1), but the increase in the relative price of the carbon intensive good will at the same time lead to a reduction in global energy demand. To address this formally, we use a log-linearized version of our model, which we derive in Appendix A, to obtain the following result:

Proposition 2. *When technical change is undirected, global emissions will always decrease following a marginal tightening of the emission constraint.*

Proof. In section A.2 of the Appendix, we show that we can write a change in global energy production (emissions) $\widetilde{E^w}$ as:

$$\widetilde{E^w} = \frac{(1-\eta)\,\phi\,(1-\phi)\,\sigma + \chi\phi\eta\frac{L_E^u - L_E^c}{L_E^u}}{(1-\phi)\,\sigma + \eta\phi + \chi}\widetilde{L_E^c}. \tag{23}$$

The denominator and the first term in the numerator are positive. Moreover, from Proposition 1 and the definition of a binding cap we have $L_E^u > L_E > L_E^c$. It follows that also the second term at the numerator is positive. Hence $\widetilde{E^w}/\widetilde{L_E^c} > 0$. □

Although this proposition refers to the linearized version of the model, our numerical simulations suggest that the results also hold for the non-linearized model, as illustrated in Figure 2. Here we present the leakage rate, defined as the ratio of the induced increase in emissions in the unconstrained country and the emission reduction in the constrained region, i.e. $\left[(L_E^u)^\phi - (L_E)^\phi\right] \Big/ \left[(L_E)^\phi - (L_E^c)^\phi\right]$, as a function of σ. The leakage rate for the case of undirected technical change is represented by the dark line. As the figure shows, the leakage rate is always positive, but less than 1.

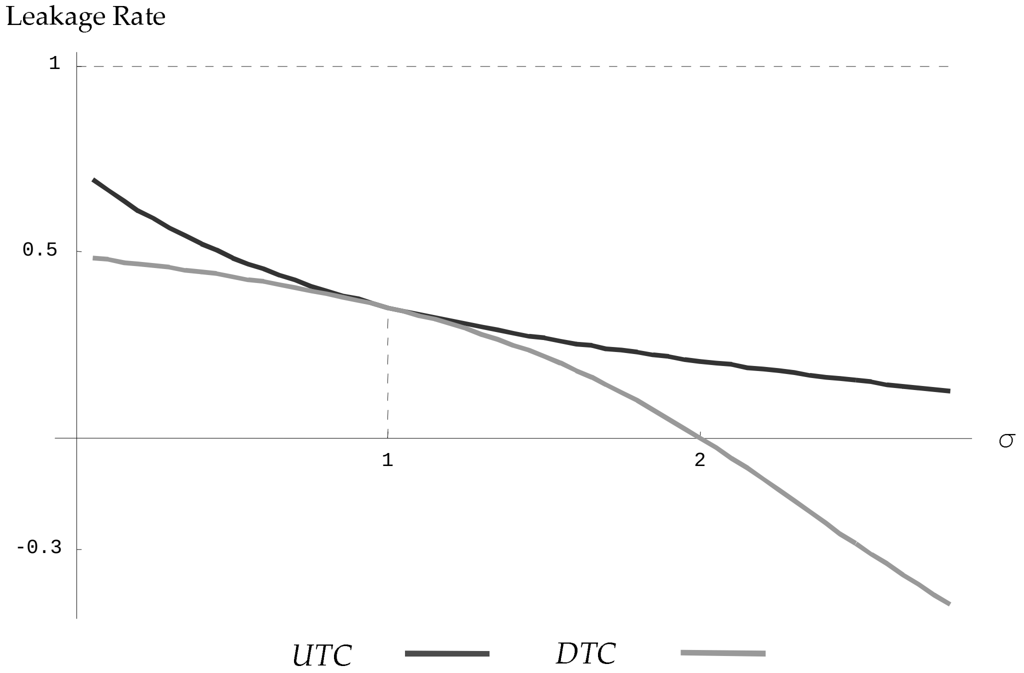

Figure 2: *Leakage rate under undirected (UTC) and directed (DTC) technical change*

4.2 Carbon leakage under directed technical change

In this section we focus on the central point of our analysis and derive our main results comparing the effects of an emission cap across regimes of technical change. We start by noting that allowing for directed technical change effectively provides the economy with an additional instrument to cope with the consequences of the introduction of a binding cap in the constrained country. Changes in the composition of technology may enable the unconstrained country to meet the increased demand for energy intensive goods while diverting less labour from its relatively more productive use in the Y_L sector. This is what we call the *induced-technology effect* of a unilateral emission constraint. We will show that this effect has the opposite sign to the terms-of-trade effect introduced above and hence tends to reduce carbon leakage.

We can compare the two versions of the model using the Le Chatelier principle (see e.g. Silberberg 1990). Taking the total differential of (16) and rearranging we can write the total effect of a change in the emission cap on emissions in the unconstrained country as:

$$\left.\frac{\partial L_E^u}{\partial L_E^c}\right|_{DTC} = \left.\frac{\partial L_E^u}{\partial L_E^c}\right|_{UTC} + \frac{\partial L_E^u}{\partial N}\frac{\mathrm{d}N}{\mathrm{d}L_E^c}, \tag{24}$$

where DTC indicates directed technical change and UTC undirected technical change. We can interpret this expression as saying that the overall effect of the cap when allowing for directed technical change (the left hand side) can be decomposed in a *terms-of-trade effect*, represented by the first term at the right-hand side, and a *induced-technology effect*, the remaining term. Whether these two effects act in the same direction or not ultimately determines under which regime we can expect leakage to be higher. In order to draw any conclusion, we need to sign the components of the above equation.

We know from Proposition 1 that the first term on the right-hand side is always negative. For the second term, let us consider first the case where $\sigma < 1$. From (20) we see that $\mathrm{d}N/\mathrm{d}L_E^c < 0$. On the other hand, from (16) it is clear that when N (and hence $N^{1-\sigma}$) increases, L_E^u must decline to satisfy the equation, *cœteris paribus*. Thus, $\partial L_E^u/\partial N < 0$. This shows that the last term at the right-hand side of (24) is positive for $\sigma < 1$. A symmetric argument holds when the relative energy demand is elastic, i.e. when $\sigma > 1$. In this case both derivatives are positive, and so is their product.

To complete our discussion, notice that when σ equals unity N is independent of S^w and always equal to 1. Equation (20) shows that in this case the technology levels N_E and N_L are the same in the long-run equilibrium across regimes of technical change. As a consequence expressions (16) and (21) in this case coincide and there is no difference between the models with directed and undirected technical change. This is due to the fact that when $\sigma = 1$, our CES specification in (1) reduces to a Cobb-Douglas production function, in which case technical change will always be neutral to the inputs concerned.[17] We summarize this discussion in the following result:

Proposition 3. *For $\sigma \neq 1$ carbon leakage will be smaller with directed technical change than with undirected technical change. For $\sigma = 1$ it will be identical across regimes.*

Proof. In text. □

With this result we have shown that the induced-technology effect works against the standard terms-of-trade effect, and lowers the amount of carbon leakage that would occur when technical change is not directed. Figure 1 shows the two effects. The pure terms-of-trade effect can be read from the upwards shift of emissions from the dashed dark line (the model without a cap) to the dark solid line (the model with a cap and undirected technical change). The induced technology effect is summarized by the move from the solid black line to the light gray one (the model with a cap and directed technical change). Indeed, the amount of emissions is lower when technical change is directed, with the exception of the case of Cobb-Douglas technology.

Another interesting question is whether the induced-technology effect can more than offset the terms-of-trade effect and lead to a situation where carbon leakage is negative. Figure 1 shows that an affirmative answer is in order. Indeed, the curve representing emissions under directed technical change (the light curve) dips below the graph of the baseline case (the dashed curve), as σ gets larger. The following proposition makes it formal:[18]

Proposition 4. *When technical change is directed, carbon leakage due to a marginal tightening of the emission constraint will be positive for $\sigma < 2$, zero for $\sigma = 2$, and negative for $\sigma > 2$.*

[17] Notice that, formally, we would need share parameters summing up to one in (1) to obtain a constant-returns-to-scale Cobb-Douglas production function as ε (and hence σ) goes to 1.

[18] Although this proposition represents a local result, all our simulations confirm this pattern for the model in levels.

Proof. In section A.3 of the Appendix we use the log-linearized model to show that, around the equilibrium, we may write:

$$\frac{\widetilde{L_E^u}}{\widetilde{L_E^c}} = \frac{(\sigma-2)\left((1-\eta)\,\phi+\chi\frac{L_E^c}{L_E^u}\right)}{(2-\sigma)\,(\eta\phi+\chi)+1-\phi}. \tag{25}$$

As discussed in the Appendix, a necessary condition for a stable equilibrium is that the term at the denominator is positive. Moreover, the second term in parenthesis at the numerator is always positive. Hence, around a stable equilibrium, we have $\widetilde{L_E^u}/\widetilde{L_E^c} \gtreqless 0$ whenever $\sigma \gtreqless 2$. □

This proposition says that, when technical change is directed, the induced-technology effect can outweigh the terms-of-trade effect, provided that the relative demand for energy is sufficiently elastic. Whether σ larger than two is a plausible case is a difficult issue to assess. In our model energy, E, implicitly stands for energy generated from fossil fuels rather than energy *tout-court*, as its generation directly causes the emissions of carbondioxide. It is safe to assume that the price elasticity of carbon-based energy is higher than the price elasticity of energy *per se*, as it is easier to substitute from fossil to non-fossil fuels, than from energy to other inputs. Thus, the demand elasticity of energy intensive goods may be quite high in our model. However, its exact value, and hence the plausibility of the negative leakage result, remains an open empirical question.

The results in propositions 3 and 4 are driven by two mechanisms. To analyze these mechanisms we first show how the composition of technology is affected by the introduction of the cap. Successively we address the interaction between changes in N, the level of σ, and relative factor productivity, to understand the labour allocation decision in the unconstrained country.

The composition of technology evolves according to the relative profitability of R&D in the different sectors. As noted in section 3.2, the final effect of introducing a cap (i.e. a change in S^w) on relative profits will depend on both the change in the relative market size and the change in relative prices. Climate policy reduces the amount of energy produced and hence decreases the potential size of the market for new energy-complementing innovations. At the same time, it makes energy scarcer, thereby rising the price of energy and making an innovation for the energy intensive good more valuable. Whether the negative market size effect or the positive price effect dominates depends on σ, the elasticity of the relative demand for energy with respect to its relative price. Since in the long-run equilibrium the technology ratio is given by (20), we see that whenever $\sigma < 1$ the price effect dominates and the introduction of a cap will induce an increase in N. When $\sigma > 1$ on the other hand, the market size effect dominates and N decreases. This yields a relation between N and σ such as the one plotted in Figure 3, where the gray line represents the ratio of technology under directed technical change and the dark one depicts the case of undirected technical change.

Recalling from (15) that relative factor productivity for the constrained model can be written as,

$$w = N^{(\sigma-1)/\sigma}(S^w)^{-1/\sigma},$$

we clearly see that, for given N, the effect of the cap is to unambiguously increase the relative productivity of energy since it initially becomes scarcer on the global market, and thus to increase pollution in the unconstrained country. Consequently, leakage is always positive when the technology ratio is given. Once we allow N to change in response to economic incentives, some form of induced energy-saving technical change occurs. The

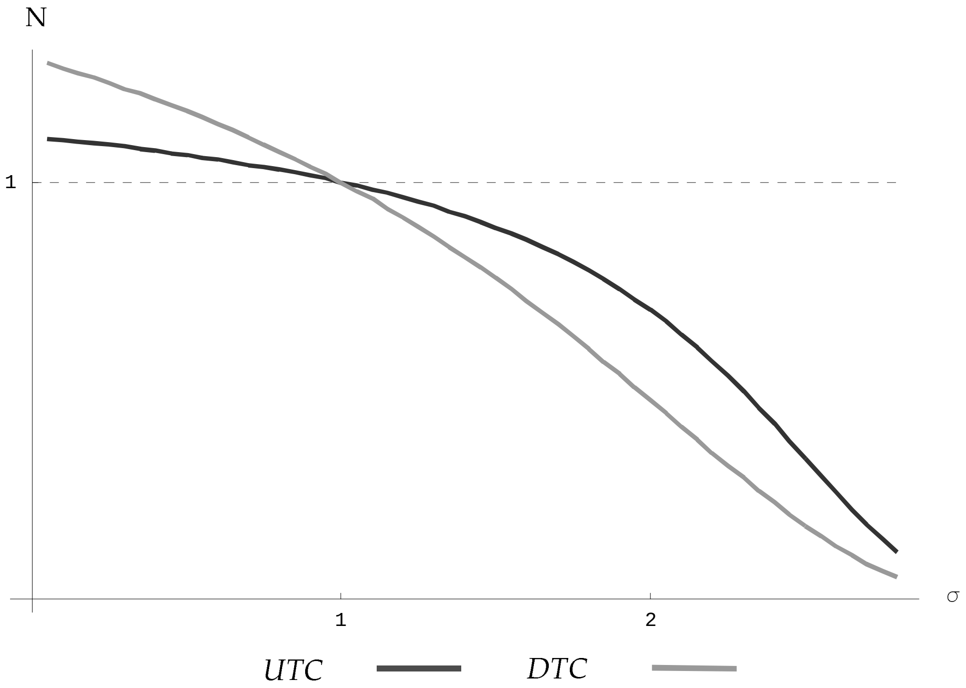

Figure 3: *Technology ratios (N) under undirected and directed technical change*

expression above shows how the effect of a change in the technology ratio on relative factor productivity depends on σ. Indeed, when $\sigma < 1$, N is higher than in the case of undirected technical change (see Figure 3). In this case $N^{(\sigma-1)/\sigma}$ is lower, and the increase in relative productivity induced by the cap is counteracted by the change in technology. The same result can be obtained for $\sigma > 1$, in which case both N and $N^{(\sigma-1)/\sigma}$ are below their baseline levels. As a result the induced change in technology ($N^{(\sigma-1)/\sigma}$) mitigates the terms-of-trade effect (which works through $(S^w)^{-1/\sigma}$). Taking into account the effect that changes in relative prices, induced by the introduction of unilateral climate policy, have on the incentives to innovate for the energy-intensive or labour-intensive industries hence unambiguously leads to lower leakage rates.

To determine which of the two effects will be stronger, we substitute (20) in (15) to obtain the general equilibrium relative factor productivity:

$$w = (S^w)^{\sigma-2}.$$

Evidently, as long as $\sigma < 2$ the decrease in the factor ratio induced by the cap will lead to an increase in the relative productivity of energy and leakage will be positive (but lower than under undirected technical change). When $\sigma > 2$ instead, the decrease in S^w will reduce the relative productivity of energy. The change in the technology ratio is so strong that it will more than compensate for the terms-of-trade effect, and the unconstrained country will voluntarily decrease its emissions.

5 Concluding remarks

The refusal of the United States to ratify the Kyoto Protocol is seen by many as a serious threat to the Protocol's effectiveness. If a coalition of technologically advanced (and hence fossil-fuel dependent) economies decides to voluntarily reduce its emissions of carbondioxide, this will increase the price of dirty goods within this coalition. Hence, unconstrained countries, such as the US, might benefit from increasing their production of dirty goods and exporting them to coalition members, thereby offsetting the decrease in emissions by the ratifying countries (carbon leakage).

Since environmental policy affects relative prices and hence relative profitability of inventing for the clean or dirty goods industry, however, the effects of the direction of technical change on carbon leakage cannot be ignored. In this paper we studied the effects of directed technical change on carbon leakage when a technologically advanced country is outside the coalition.

To shed light on this issue we have compared the results of a model where technology levels in the clean and dirty goods sector are allowed to develop differently (directed technical change) with those derived from a model of 'traditional' endogenous technical change. We have shown that taking into account the effects of relative price changes on the incentives to innovate always leads to lower leakage rates than when this induced technology effect is ignored. We have also discussed the possibility that the direction of carbon leakage can be reversed. When the elasticity of the demand for carbon-based energy is sufficiently high, the change in technology due to the emission constraint is such that it becomes optimal for the unconstrained country to cut back on its emissions. Whether this latter situation constitutes a plausible scenario remains a matter of empirical investigation.

The advocates of the Kyoto Protocol and other forms of unilateral climate policy may find some support in our results: our result shows that, given that the applied literature on carbon leakage abstracts from the direction of technical change, the leakage rates proposed in the current debate might prove to be overestimated. As a consequence, unilateral climate policy might turn out to be more effective than generally considered.

Ratifying countries, in particular, might be relieved by our conclusions. Indeed, their efforts to reduce polluting emissions will be undone by the reactions of others to a lesser extent than often suggested. Moreover, we also hint at the (theoretical) possibility that when the demand for carbon-based energy is sufficiently elastic, the ratifiers' efforts could even be compounded by the emissions reduction undertaken by the unconstrained countries and global emissions could decrease.

The degree to which the mechanisms highlighted here can change current estimates of carbon leakage depends on the elasticities of the model. Our theoretical conclusions need to be assessed through quantitative methods, first and foremost using CGE models that incorporate directed technical change, and therefore sector-specific data on technical progress. Building such a model, and finding the necessary data, however, constitutes a formidable challenge for future research.

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A Appendix: the log-linearized model

In this appendix we (log-)linearize the model around the steady state and derive several results.

A.1 Deriving the log-linearized model

The linearized version of the goods market equilibrium condition (16) reads:

$$(\sigma - 1)\, \widetilde{N} = [(1-\phi)\,\sigma + \eta\phi + \chi]\, \widetilde{L_E^u} + \left[(1-\eta)\,\phi + \chi \frac{L_E^c}{L_E^u}\right] \widetilde{L_E^c}, \tag{A.1}$$

where a tilde, $\widetilde{\ }$, over a variable denotes a small percentage change, and where we have used the following definitions:

$$\eta \equiv \frac{(L_E^u)^\phi}{(L_E^u)^\phi + (L_E^c)^\phi} \in (0,1), \text{ and } \chi \equiv \frac{L_E^u}{2\overline{L} - L_E^c - L_E^u}. \tag{A.2}$$

The percentage changes in L_E^u and L_E^c denote any marginal change in the respective variable. For example, a decrease in L_E^c (that is a $\widetilde{L_E^c} < 0$) from $L_E^c = L_E$ would represent the introduction of a marginal emissions cap in the country, while a decrease from any $L_E^c < L_E$ would represent any marginal tightening of an existing cap.

When we linearize the equilibrium condition for the market for innovations, (20), we find:

$$\widetilde{N} = (\sigma - 1)\left((1-\eta)\,\phi + \chi \frac{L_E^c}{L_E^u}\right)\widetilde{L_E^c} + (\sigma - 1)\,(\eta\phi + \chi)\,\widetilde{L_E^u}. \tag{A.3}$$

A.2 Appendix to Proposition 2

We can write total energy generation, or emissions, as $E^w = (L_E^u)^\phi + (L_E^c)^\phi$. Taking logs and differentiating yields the following representation in growth rates: $\widetilde{E^w} = \eta\phi\widetilde{L_E^u} + (1-\eta)\,\phi\widetilde{L_E^c} < 0$, where we have used the definition of η from (A.2).

From (A.1), setting $\widetilde{N} = 0$ due to the undirectedness of technical change, we can solve for L_E^u. Using this to substitute in the expression for the change in total emissions above and rearranging, we find:

$$\frac{\widetilde{E^w}}{\widetilde{L_E^c}} = \frac{(1-\eta)\,\phi\,(1-\phi)\,\sigma + \chi\phi\eta\frac{L_E^u - L_E^c}{L_E^u}}{(1-\phi)\,\sigma + \eta\phi + \chi}. \tag{A.4}$$

A.3 Appendix to Proposition 4

To find (25), substitute (A.3) into (A.1) and rewrite to find:

$$\frac{\widetilde{L_E^u}}{\widetilde{L_E^c}} = \frac{(\sigma - 2)\left((1-\eta)\,\phi + \chi\frac{L_E^c}{L_E^u}\right)}{(2-\sigma)\,(\eta\phi + \chi) + 1 - \phi}. \tag{A.5}$$

The denominator of this expression will be positive around any stable equilibrium. Indeed, the dynamics of the system require that at any stable equilibirum the slope of the goods market equilibrium condition be steeper than the R&D equilibrium condition in the (L_E, N) space. The relevant slopes can be easily derived from (A.1) and (A.3). For $\sigma < 1$ the stability condition discussed above requires:

$$\left.\frac{\widetilde{N}}{\widetilde{L_E^u}}\right|_{GME} = \frac{(1-\phi)\sigma + \eta\phi + \chi}{\sigma - 1} < \left.\frac{\widetilde{N}}{\widetilde{L_E^u}}\right|_{R\&DE} = (\sigma - 1)(\eta\phi + \chi),$$

where the subscripts GME and $R\&DE$ indicate the goods markets and the R&D market equilibrium conditions, respectively. The sign of the inequality is reversed for the case when $\sigma > 1$. Since in both cases one can easily verify that the stability condition simplifies to

$$(2-\sigma)\,(\eta\phi + \chi) + 1 - \phi > 0,$$

we have established our claim.

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