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Carbon Leakage Revisited: Unilateral Climate Policy with Directed Technical Change*

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Abstract

The increase in carbondioxide emissions by some countries in reaction to an emission reduction by countries with climate policy (carbon leakage) is seen as a serious threat to unilateral climate policy. Using a two-country model where only one of the countries enforces an exogenous cap on emissions, this paper analyzes the effect of technical change that can be directed towards the clean or dirty input, on carbon leakage. We show that, as long as technical change cannot be directed, there will always be carbon leakage through the standard *terms-of-trade effect*. However, once we allow for directed technical change, a counterbalancing *induced technology effect* arises and carbon leakage will generally be lower. Moreover, we show that when the relative demand for energy is sufficiently elastic, carbon leakage may be negative: the technology effect induces the unconstrained region to voluntarily reduce its own emissions.

JEL Classification: F18, O33, Q54, Q55.

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1 Introduction

An important threat to climate policy is that actions undertaken without universal participation may prove ineffective: any partial agreement to reduce emis-

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sions (of carbon dioxide, for example¹) will be undermined by the behaviour of countries outside the agreement. Standard economic theory suggests that these countries may indeed have several incentives to increase their polluting emissions. In the first place, the relative price for carbon-intensive goods could increase giving countries outside the coalition incentives to expand their production of these goods and export them to signatory countries (terms-of-trade effect). Secondly, a lower fossil fuel price due to the reduced demand from the constrained economies could induce substitution towards fossil fuels in countries without a carbon constraint. Third, if damage costs from the global pollutant are strictly convex in the total emission level, marginal environmental costs can decrease in unconstrained countries and emissions 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*.

That carbon leakage will arise as a consequence of a partial climate change policy effort is widely accepted by economists. Yet so far the role of technical change has been grossly underestimated in this debate. This paper fills this gap. We demonstrate that allowing for endogenous differences in rates of technical change across sectors reduces the degree of carbon leakage and can be conducive to a reversal of the conclusions sketched above. In particular, we show that endogenous technical change *per se* is not enough to reverse the pattern of carbon leakage. Only when the direction (not just the level) of innovation responds to profit incentives can such a reversal occur.

We present a two country framework in which innovations occur endogenously as a result of research investment. We compare the effects of an exogenously imposed emission constraint in one of the countries on the choice of pollution in the other for two different regimes of 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. In the second regime, 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. Climate policy will change the relative prices of inputs and hence the relative profitability of inventing for the clean or dirty industry.² In this case carbon leakage is generally reduced and can even become negative.

Our aim in this paper is to isolate the effects of the regime of technical change

¹Carbon dioxide (CO₂) is the greenhouse gas with the highest global warming contribution since it is both emitted in large amounts and has a low decay rate. Therefore most of the economics literature on climate policy focuses on CO₂. For simplicity we call the global pollutant in this paper carbon or carbon dioxide as well, yet our analysis applies to any other greenhouse gas associated with energy production or fossil fuel extraction, like methane.

²Popp (2002) and Newell et al. (1999), among others, show that energy prices (including the effect of environmental policy) positively affect environmentally friendly innovations.

on carbon leakage. To do this we assume that our two countries are perfectly symmetric as refers to preferences, technology and endowments. We only allow them to differ in one crucial respect: one of them imposes an exogenously given binding emission cap, while the other remains unconstrained. In this way we obtain the necessary degree of asymmetry in environmental policy without having to postulate differences in fundamentals that would cloud our analysis. Using this setup we decompose the effects of unilateral policy in a standard *terms-of-trade effect* and an additional *induced technology effect* and address their relative sizes.

The problem of carbon leakage has been widely studied using Computable General Equilibrium (CGE) models to assess the consequences of the Kyoto Protocol. These models generally report leakage rates ranging from 5% to 20% (see e.g. Burniaux and Oliveira Martins (2000)), although some papers find leakage rates as high as 60% (Light et al. (2000)). Babiker (2005) even 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 arise because of different assumptions in the degree of international market integration, substitution and supply elasticities, and market structure. Although CGE models allow for both international and sectoral disaggregations, they do not take into account the effect of climate policy on technical change.

Another rich strand of literature has addressed asymmetric climate policy from a public economics point of view (see e.g. Barrett (1994), Carraro and Siniscalco (1998), and 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 emissions leakage.

Two recent papers show that a reversal in the direction of carbon leakage is possible in models with either technical change or international trade. Golombek and Hoel (2004) present a static partial equilibrium two-country one good model with transboundary pollution. In each country a central planner chooses R&D expenditures and abatement levels to minimize total costs that include environmental damages. Since positive international technology spillovers are assumed to reduce abatement costs, the authors effectively build in their model a mechanism that counteracts the free-riding incentives shown by previous literature. Under appropriate conditions this mechanism is sufficient to generate negative leakage (an increase in abatement) in the foreign country, following an increase in abatement at home. Although the end result is the same, our contribution differs from theirs in many respects. In the first place there are no free-riding incentives in our framework. The incentives to expand emissions arise purely from changes in the terms-of-trade. Moreover, and more poignantly, we do not assume *a priori* that technical change always leads to cleaner technology. In our model the na-

ture of technical change is itself driven by profit incentives and depends on the characteristics of production.

Copeland and Taylor (2005) show, among other things, that in the presence of international trade, a country's response to a rest-of-world emissions reduction is ambiguous. In their static two-good, two-factor, K-country model (modified to take into account polluting emissions) 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. Hence the mechanism underlying their result is different from ours, both in terms of modelling and of economic content.

The paper develops as follows. We introduce the model in section 2 and present the general equilibrium conditions for both the model with and without unilateral climate policy, with and without directed technical change, in section 3. Section 4 first studies carbon leakage when entrepreneurs cannot aim new technologies to one of the sectors and introduces the terms-of-trade effect. 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, and only differ in their environmental policies. We assume that country c (for *constrained*) imposes a binding cap on polluting emissions.³ 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.

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 :

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

where $r = c, u$ is the country index. We assume that good Y_E is produced using energy and a specialized set of differentiated machines, of which a set of mass N_E is available. Instead Y_L is produced using labour (L_L) and a different set of machines, whose mass is indicated by N_L . Following Acemoglu (2002), the

³In this paper we focus on production decisions for given environmental policy. Since we do not discuss growth rates or welfare and assume balanced trade, (intertemporal) preferences play no role. Hence the consumption side of the model is redundant and we only present the production side.

production functions for the intermediate goods are as follows:

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

and

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

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 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.⁴

We assume that in each country an amount of labour equal to \bar{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:

$$\bar{L} = L_L^r + L_E^r, \quad (4)$$

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:

$$E^r = (L_E^r)^\phi, \quad (5)$$

where $\phi \in (0, 1)$.

Energy generation causes emissions of carbondioxide. We assume that CO₂ emissions, Z , are proportional to the amount of energy produced, so that

$$Z = E. \quad (6)$$

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: $L_E^c = (Z^c)^{1/\phi}$.

⁴In other words, our model exhibits endogenous growth through variety expansion in the machines sector. See, for example, Grossman and Helpman (1991).

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’ 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 with probability $\gamma \in (0, 1)$ the newly developed blueprint will be energy-complementing and with probability $(1 - \gamma)$ it will be labour-complementing. As a consequence the (expected) relative marginal productivity is constant, as is common in traditional (one-sector) models of endogenous growth. The relative size of the set of machines available in the two sectors, $N_E/N_L = \gamma/(1 - \gamma)$, can be pinned down by an opportune choice of the probability γ . 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.⁵ The total number of innovations in this case will therefore be given by:

$$\dot{N} = \nu (R^c + R^u), \quad (7)$$

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

The second type of technical change regime that we consider is *directed* technical change.⁶ In this case prospective innovators, besides deciding 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:⁷

$$\dot{N}_E = \nu (R_E^c + R_E^u), \quad (8)$$

$$\dot{N}_L = \nu (R_L^c + R_L^u). \quad (9)$$

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 costs of obtaining the license on the blueprint. For this, we assume that an innovator will obtain 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 there is no international overlap in blueprints.

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.

⁵See Rivera-Batiz and Romer (1991).

⁶The seminal work in this field is due to Daron Acemoglu. See, for example, Acemoglu (2002).

⁷For 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.

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 with undirected technical change, this condition gives the general equilibrium amount of labour in energy production. For the model with directed technical change, instead, we need to take another step and study the equilibrium in 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

We start by assuming that technology levels N_E and N_L are given, and focus on the goods market. 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:

$$\frac{Y_E^{dr}}{Y_L^{dr}} = \left(\frac{p_E}{p_L} \right)^{-\varepsilon}, \quad (10)$$

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 they trade at no cost, so throughout the paper prices indicate international ones.

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 .⁸

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 $k_j(i)$:

$$k_E^r(i) = \left(\frac{p_E}{p_{k_E(i)}} \right)^{1/\beta} E^r \quad \text{and} \quad k_L^r(i) = \left(\frac{p_L}{p_{k_L(i)}} \right)^{1/\beta} L_L^r. \quad (11)$$

By the same token, from the first-order conditions with respect to primary inputs,

⁸Throughout 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.

we can derive the (inverse) local demand for energy and labour:

$$w_E = \frac{\beta}{1-\beta} p_E \left(\int_0^{N_E} k_E^r(i)^{(1-\beta)} di \right) (E^r)^{\beta-1}, \quad (12)$$

$$w_L = \frac{\beta}{1-\beta} p_L \left(\int_0^{N_L} k_L^r(i)^{(1-\beta)} di \right) (L_L^r)^{\beta-1}. \quad (13)$$

As mentioned before, the holder of a patent licenses production to 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. Each monopolist maximizes her profits subject to the appropriate demand function in (11). 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 1.⁹

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,

$$Y^w = p^{(1-\beta)/\beta} S^w N. \quad (14)$$

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 and we define the global relative factor supply as $S^w \equiv (E^c + E^u) / (L_L^c + L_L^u)$. Superscript w indicates that the variable concerned represents a global (world) amount or ratio.

Equalling relative supply (14) and relative demand (10) yields the market clearing relative price for intermediate goods, for given technology:

$$p = (NS^w)^{-\beta/\sigma}, \quad (15)$$

where we define $\sigma \equiv 1 + (\varepsilon - 1)\beta$. From (15) we see that a higher level of technology in the dirty goods sector, 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 (11) into the inverse demand functions for energy (12) and labour (13), we obtain an expression for the relative factor rewards. Using this and the market clearing relative price for intermediate goods (15), we get the following expression for the relative factor rewards for given technology:

$$w = N^{(\sigma-1)/\sigma} (S^w)^{-1/\sigma}. \quad (16)$$

⁹Notice that machines are equally productive in intermediate goods' production and all 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, in fact we may write: $\int_0^{N_j} k_j(i)^{(1-\beta)} di = N_j k_j^{(1-\beta)}$, for $j = E, L$.

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 (16) 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. Hence, the effect of the technology ratio on relative factor rewards depends on whether relative energy demand is elastic or inelastic.¹⁰

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 as given. An energy producer can employ labour (at a unit cost of w_L) to produce and sell her output at the prevailing market price w_E . This simple maximization problem yields the following first-order condition, which expresses an unconstrained country's demand for labour in energy production as a function of relative factor prices:

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

Equalizing this expression and (16) we find an expression representing the equilibrium allocation of labour by country u , for a given technology ratio N and for given energy production in the other country:

$$\phi^{-\sigma} N^{1-\sigma} \left[(L_E^c)^\phi (L_E^u)^{\sigma(1-\phi)} + (L_E^u)^{\phi(1-\sigma)+\sigma} \right] + L_E^c + L_E^u = 2\bar{L}. \quad (17)$$

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

$$\phi^{-\sigma} N^{1-\sigma} L_E^{\phi(1-\sigma)+\sigma} + L_E = \bar{L}. \quad (18)$$

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 production are determined

¹⁰From the definition of σ as $1 + (\varepsilon - 1)\beta$, it is clear that $\sigma \geq 1 \Leftrightarrow \varepsilon \geq 1$. 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.

by the cap. In this case $L_E^c = (Z^c)^{1/\phi}$. Yet expression (17) still holds for the unconstrained country, u , and it solves (implicitly) for the amount of labour in energy production in the unconstrained region for given N .

As discussed in section 2, when technical change is undirected the technology ratio N is constant. Consequently, in this case equations (17) and (18) determine the general equilibrium allocation of labour. Under directed technical change, however, N is endogenous and entrepreneurs have to decide for which sector to invent new machines. For this specification of 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 (11), the instantaneous profits are given by the following expressions:

$$\pi_E = \beta p_E^{1/\beta} E^w \quad \text{and} \quad \pi_L = \beta p_L^{1/\beta} L_L^w. \quad (19)$$

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 (15). 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. Expressing this in standard dynamic programming equations gives $r(t)V_j(t) - \dot{V}_j(t) = \pi_j(t)$, where V_j is the value of an innovation in sector $j = E, L$. This expression relates the present discounted value of developing an innovation, V_j , to instantaneous profits and it allows for the flow of profits to change over time through the "capital gain" term \dot{V}_j . Along the balanced growth path of the economy, profits will not change over time so \dot{V}_j must be zero.¹¹ Since entry is free in the R&D sector, we know that the value of an innovation cannot exceed its cost (see (8) and (9)) so that $V_j \leq 1/\nu$ in each sector. Moreover, along the balanced growth path both types of innovation must occur at the same time, so that $V_j = 1/\nu$ in both sectors. From this we can

¹¹We 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.

derive the following no-arbitrage equation for the research sector:

$$\pi_E v = \pi_L v,$$

which, after substituting for profits from (19), can be rearranged to read

$$p^{1/\beta} S^w = 1. \quad (20)$$

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 (15), we may solve (20) for N , obtaining the following expression for the balanced growth path equilibrium ratio of technology levels in the two sectors:

$$N = (S^w)^{\sigma-1}. \quad (21)$$

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 (19) 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 allocation 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.¹²

Substituting (21) into (17) yields the general expression for the equilibrium under directed technical change:

$$\phi^{1/(\sigma-2)} \left[(L_E^c)^\phi (L_E^u)^{(\phi-1)/(\sigma-2)} + (L_E^u)^{(\phi(\sigma-1)-1)/(\sigma-2)} \right] + L_E^c + L_E^u = 2\bar{L}. \quad (22)$$

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.

¹²It 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 (17) is steeper than the no-arbitrage equation (21), at the point of intersection. The details of the existence and stability discussion are available from the authors upon request.

Alternatively, assuming that no environmental policy is in place, we can interpret (22) 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:

$$\phi^{1/(\sigma-2)} L_E^{(\phi^{(\sigma-1)-1})/(\sigma-2)} + L_E = \bar{L}. \quad (23)$$

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 be able to compare different scenarios, we 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 (22). This baseline is characterized by the (symmetric) equilibrium level of labour devoted to energy generation L_E and by the corresponding technology ratio N . In order to have comparable baselines across technology regimes, we choose γ , the probability for an innovator to end up with an E -complementing blueprint in the undirected technical change version of the model, such that $\gamma/(1-\gamma) = N$. 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. In terms of our model, there is carbon leakage whenever $L_E^u > L_E$. 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 the 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 (18) and (17) and rearrange to find:

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

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 $L_E^u > L_E$. \square

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.¹³ 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 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.

When technical change is endogenous but undirected, unilateral climate policy is undermined by emission increases by unconstrained countries. The question now arises whether unilateral climate policy can even induce an increase in global emissions, as for example in Babiker (2005). To address this question, 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.*

¹³The figures in this paper are obtained from numerical simulations, using as baseline parameters values: $\bar{L} = 1$, $\phi = 0.4$, and $\sigma \in (0, 3.5)$. Furthermore for each value of σ the appropriate value for N for the model without directed technical change is computed such that both models start from the same baseline. We performed numerous robustness checks without qualitative changes in the results. For the sake of graphical clarity the graphs are plotted over a smaller range for σ .

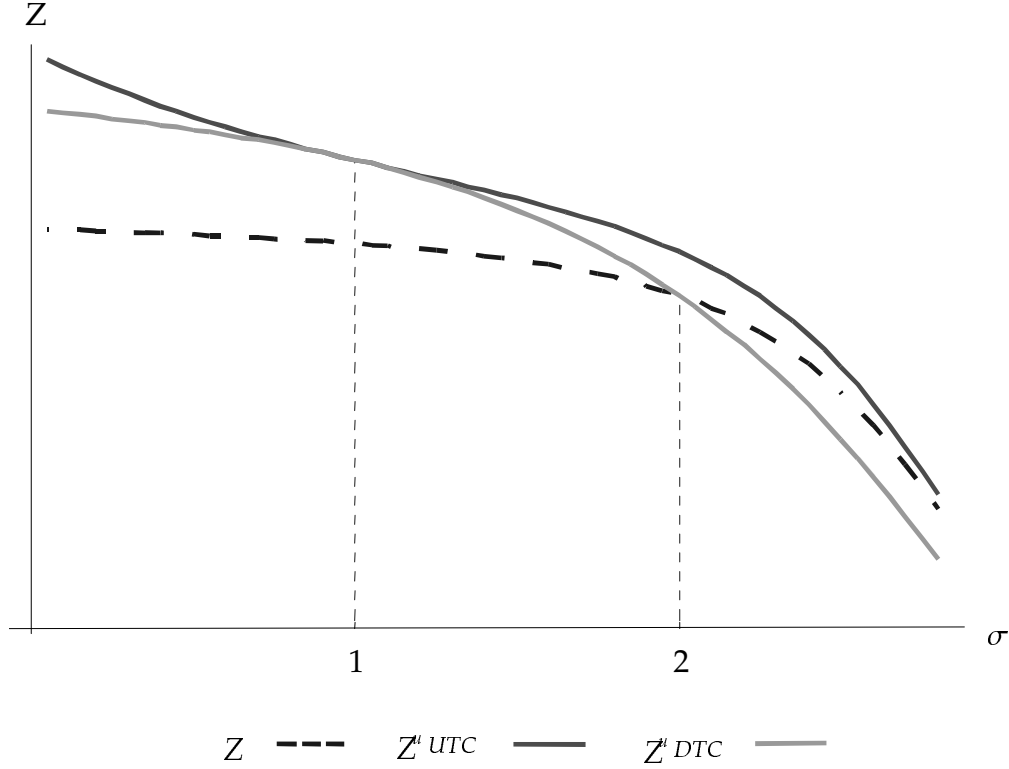


Figure 1: Emissions in the unconstrained model (Z), in the constrained model under undirected technical change ($Z^u\text{UTC}$), and under directed technical change ($Z^u\text{DTC}$)

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:

$$\widetilde{E}^w = \frac{(1 - \eta) \phi (1 - \phi) \sigma + v \phi \eta \frac{L_E^u - L_E^c}{L_E^u} \widetilde{L}_E^c}{(1 - \phi) \sigma + \eta \phi + v} \widetilde{L}_E^c. \quad (24)$$

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 $\widetilde{E}^w / \widetilde{L}_E^c > 0$. \square

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 between the induced increase in emissions in the unconstrained country and the emission reduction in the constrained region, i.e. $\frac{(L_E^u)^\phi - (L_E)^\phi}{(L_E)^\phi - (L_E^c)^\phi}$, 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.

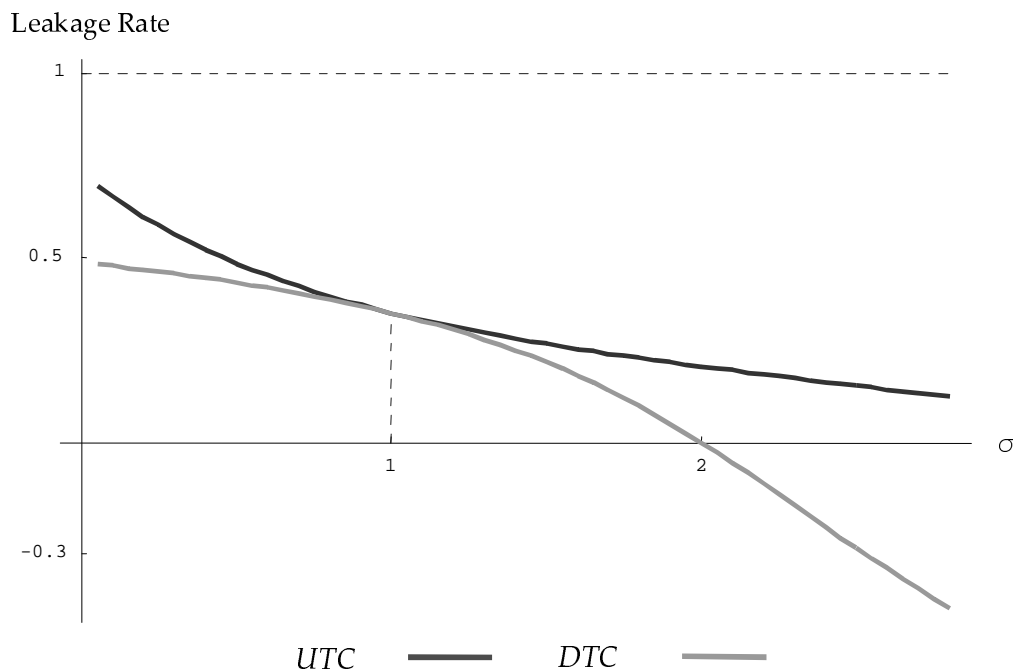


Figure 2: Leakage rate under undirected and directed technical change

4.2 Carbon leakage under directed technical change

In this section we focus on the central point of our analysis and compare 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. Thus we may expect that this additional degree of freedom will lead to a reduction in emissions by the unconstrained country, and hence in the degree of carbon leakage, compared to the case of undirected technical change. Indeed, we will show that the relative productivity of energy adjusts in such a way that, compared to the case where technical change is undirected, less energy is demanded. 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.

Comparing the two versions of the model boils down to an exercise in comparative statics for a maximization problem (profit maximization by energy generators), when one binding constraint is removed (N is free to adjust in the directed technical change case). A natural way to address this problem is through the Le Chatelier principle. Taking the total differential of (17) and rearranging we can write the total effect of a change in the emission cap on emissions in the unconstrained country as:

$$\left. \frac{\partial L_E^u}{\partial L_E^c} \right|_{DTC} = \left. \frac{\partial L_E^u}{\partial L_E^c} \right|_{UTC} + \frac{\partial L_E^u}{\partial N} \frac{dN}{dL_E^c}, \quad (25)$$

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 (21) we see that $dN/dL_E^c < 0$. On the other hand, from (17) it is clear that when N (and hence $N^{1-\sigma}$) increases, L_E^u must decline to satisfy the equation, *ceteris paribus*, thus $\partial L_E^u / \partial N < 0$. This shows that the last term at the right-hand side of (25) 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 their product is still positive.

To complete our discussion, notice that when σ equals unity N is independent of S^w and always equal to 1, see (21), showing that 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 (17) and (22) 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. 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. □

This result shows that the induced technology effect works against the standard terms-of-trade effect, and lowers the amount of carbon leakage that would occur when entrepreneurs cannot target new inventions to labour or energy. 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). As expected, the amount of emissions is lower when technical change is directed, with the exception of the case of Cobb-Douglas technology.

Now one final question needs to be addressed: can the induced technology effect more than off-set 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 one) dips below the graph of the baseline case (the dashed curve), as σ gets larger. The following proposition makes it formal:¹⁴

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 $\sigma > 2$.*

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

$$\frac{\widetilde{L}_E^u}{\widetilde{L}_E^c} = \frac{(\sigma - 2) \left((1 - \eta) \phi + \nu \frac{L_E^c}{L_E^u} \right)}{(2 - \sigma) (\eta \phi + \nu) + 1 - \phi}. \quad (26)$$

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 $\widetilde{L}_E^u / \widetilde{L}_E^c \gtrless 0$ whenever $\sigma \gtrless 2$. \square

When technical change is directed, the induced technology effect can thus outweigh the terms-of-trade effect, provided that the relative demand for energy is sufficiently elastic. The introduction of an emission cap in one country increases the relative demand for Y_E in the other. To serve the increased demand, producers in the unconstrained country can only expand energy generation and hence emissions when technology ratio N is given. When relative technology is free to change however, as is the case when technical change is directed, it will adjust to the new relative factor supply and reduce the amount of energy necessary to satisfy the demand for the energy-intensive good.

¹⁴Although this proposition represents a local result, all our simulations confirm this pattern for the model in levels.

The results in proposition 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, thus N will increase whenever relative profits π rise. 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 more scarce, 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 (21), 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.

These differences in technology composition across versions of the model determine the differences in the relative productivity of energy and labour, that ultimately drive the results of this section. Recalling from (16) 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 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 $(S^w)^{-1/\sigma}$).

To determine which of the two effects will be stronger, we substitute (21) in

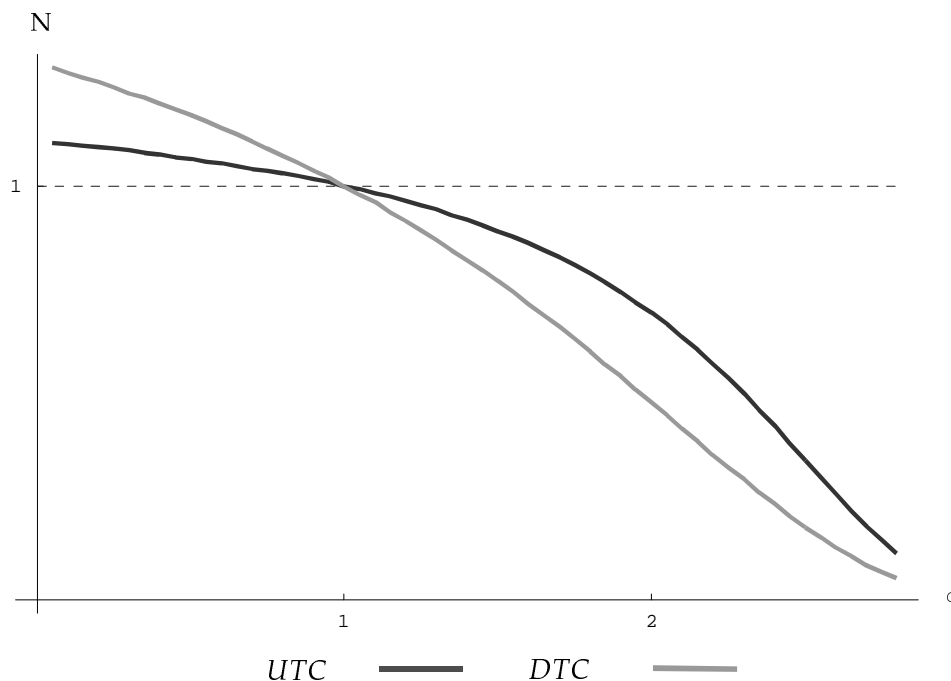


Figure 3: *Technology ratios (N) under undirected and directed technical change*

(16) 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 Conclusions

The refusal of the United States to ratify the Kyoto Protocol is seen by many as a serious threat to the Protocol's effectiveness. Most economists would indeed argue that if a coalition of technologically advanced (and hence fossil-fuel dependent) economies decides to voluntarily reduce its emissions of carbon dioxide, this will increase the price of dirty goods within this coalition while the world price of fossil fuels may fall due to the lower demand from the coalition. Hence

unconstrained countries, such as the US, can produce dirty goods at a lower cost and export them to coalition members, thereby offsetting the decrease in emissions from the coalition (carbon leakage).

While the literature on carbon leakage has largely overlooked the role of technical change, we believe that including the endogenous development of technology into the analysis is key to understanding the long-run reactions to unilateral climate policy. In this paper we have studied the problem of carbon leakage when a technologically advanced country is outside the coalition focussed on the effects of directed technical change. Allowing technology levels in the clean and dirty goods sector to develop differently, we have compared the results with those derived from a model of 'traditional' endogenous technical change. From an environmental point of view we have obtained comforting results: directed technical change always lowers the incentive to pollute for the unconstrained country. Indeed, with directed technical change, unilateral climate policy may even induce the unconstrained region to reduce its emissions, when the relative demand for energy is elastic enough. Moreover we have shown that unilateral climate policy will always be effective to some degree, as the leakage rate will always be less than 100%.

In the light of these results some of the concerns voiced by critics of the Kyoto Protocol may be unjustified. Ratifying countries, in particular, should be relieved by our conclusions: their efforts to reduce polluting emissions will be undone by the reactions of others to a lesser extent than often suggested. Moreover, whenever the demand for polluting goods is elastic enough, the ratifiers' efforts will even be reinforced by the emissions reduction undertaken by the unconstrained countries and global emissions will decrease.

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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 (17) reads:

$$(\sigma - 1) \tilde{N} = [(1 - \phi) \sigma + \eta \phi + \nu] \tilde{L}_E^u + \left[(1 - \eta) \phi + \nu \frac{L_E^c}{L_E^u} \right] \tilde{L}_E^c, \quad (\text{A.1})$$

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

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

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 $\tilde{L}_E^c < 0$) 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, (21), we find:

$$\tilde{N} = (\sigma - 1) \left((1 - \eta) \phi + \nu \frac{L_E^c}{L_E^u} \right) \tilde{L}_E^c + (\sigma - 1) (\eta \phi + \nu) \tilde{L}_E^u. \quad (\text{A.3})$$

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: $\tilde{E}^w = \eta \phi \tilde{L}_E^u + (1 - \eta) \phi \tilde{L}_E^c < 0$, where we have used the definition of η from (A.2).

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

$$\frac{\tilde{E}^w}{\tilde{L}_E^c} = \frac{(1 - \eta) \phi (1 - \phi) \sigma + \nu \phi \eta \frac{L_E^u - L_E^c}{L_E^u}}{(1 - \phi) \sigma + \eta \phi + \nu}. \quad (\text{A.4})$$

A.3 Appendix to Proposition 4

To find (26), substitute (A.3) into (A.1) and rewrite to find:

$$\frac{\widetilde{L}_E^u}{\widetilde{L}_E^c} = \frac{(\sigma - 2) \left((1 - \eta) \phi + \nu \frac{L_E^c}{L_E^u} \right)}{(2 - \sigma) (\eta \phi + \nu) + 1 - \phi}. \quad (\text{A.5})$$

The denominator of this expression will be positive around any stable equilibrium. Indeed, the dynamics of the system require that the slope of the goods market equilibrium condition be steeper than the R&D equilibrium condition in the (L_E, N) space. From (A.1) and (A.3) we get that this condition requires:

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

where the subscripts *GME* and *R&DE* indicate the goods markets and the R&D market equilibrium conditions, respectively. Since the condition above simplifies to

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

we have established our claim.