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Green Innovation and Economic Growth in a North-South Model

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Abstract

If one region of the world switches its research effort from dirty to clean technologies, will other regions follow? To investigate this question we built a North-South model that combines insights from directed technological change and quality ladder endogenous growth models. We allow researchers in the South to create business-stealing innovations. We found that (i) after the North switches from dirty to clean technologies, the growing value of clean markets will motivate technology firms in the South to follow the switch; however this result is conditional on the North being sufficiently large. (ii) If the two regions invest research effort to different sectors and the outputs of the two sectors are gross substitutes, then the long run growth rates in both regions are smaller than if the global research effort were to be invested in one sector. (iii) If the North switches to R&D in clean technologies, the benevolent central planner in the South would ensure that all South R&D switches too, unless the planner's discount rate is high.

Keywords: directed technological change; green growth; endogenous growth model; cross-country spillovers; unilateral climate policy; green R&D subsidies,

JEL: O33, O41, O44, Q55, Q56

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1 Introduction

The problem of greenhouse gases (GHG) is usually considered an example of the tragedy of the commons. Given that emissions are produced by all economies, an effort to limit emissions by a single region will only have a minor effect on the total stock of GHG in the atmosphere and thus cannot prevent potential environmental disaster caused by the greenhouse effect. A single region does not have any incentive to adopt measures mitigating climate change if they are costly. Furthermore, even a coalition of countries cannot prevent the stock of emissions from rising if one significant economy outside the coalition continues emitting, for instance, because it has a different belief about the likelihood of the greenhouse effect occurring or because it could benefit from climate change.

In this paper we show that a unilateral effort by a single region or a coalition of regions can trigger a global emissions reduction if R&D effort in this region increases the value of the market for clean technologies. Fast growth of the market's value will induce a shift of research effort in all remaining regions towards the development of these technologies. The redirection of global research effort will then provide economic incentives for all producers to adopt clean technologies and curb emissions, even in the absence of emissions taxes in the regions of the producers.

Our argument is built on the Shumpeterian notion of business-stealing innovations: by investing effort, a technology firm in one region has a chance to capture a market built by the competitor in another region. Suppose that one region with strong R&D potential builds up the market of clean technologies. Then the researchers in other regions will have incentive to jump on the same technological platform and work on the innovations for the same technologies since successful innovations will allow them to capture a valuable market.

This pattern of cross-region technological competition has been seen before. One example is the competition in automobile industry: developed by manufacturers in US, Japanese manufacturers partly captured the market through process innovations in '60s and '70s (Cusumano 1988). A more recent example is the fierce competition in the market for smartphones between Korean and US developers. In each case, competition led to declining production costs as well as product improvements and fast market growth. One may expect that a similar competition for improvements in the clean technologies could be induced by appropriately designed policy.

To formalise our argument we developed a Directed Technological Change (DTC) model for two regions of the world: North and South. Each region has its own R&D sector with researchers who have to choose between developing technologies for the clean or the dirty sectors. By allowing for R&D to be performed in the South, we depart from the usual setup of the North-South model, whereby the North is a technological leader and the South imitates the innovations of the North. For the purpose of this paper, "North" is the label for a coalition of countries with ambitious climate goals, while "South" signifies countries with solely economic objectives. Even though environmentalism traditionally has tended to go hand in hand with economic maturity and technological advancement, in recent decades one can observe a rapid growth of the R&D sector in large emerging, less-environmentally ambitious economies (see Dechezlepretre et al. 2011)

The DTC framework has been widely used to study the role of technological progress in climate change mitigation and resource depletion (see André and Smulders 2014, Aghion et al. 2016 and the survey by Fischer and Heutel 2013). Several studies applied the framework in a two-region setting. The work that is closest to ours is the study by Acemoglu et al. (2014), who assume that innovations are generated in the North and could be imitated by researchers in the South. They demonstrate that a policy supporting green technologies in the North can induce imitation of green technologies in the South and thus reduce global emissions. The major novelty in our model with respect to Acemoglu et al. (2014) is that we allow researchers in the South to develop their own innovations.

The innovation in the South was introduced by Hemous (2016), Ravetti et al. (2016) and van den Bijgaart (2017). These studies explored which policies in the North could change the incentives for Southern researchers by changing the demand for the output of the clean and dirty sectors in the South. They did not consider the possibility that the North and South can trade clean and dirty technologies because they did not aim to study the direct competition between researchers in the two regions. In contrast, in our model we assume that the two regions cannot trade with the intermediate goods they produce but they can trade with the technologies used in the two sectors (machines). This assumption could correspond to a case in which clean and dirty good is electricity from renewable and non-renewable sources. Although electricity cannot be traded in large quantities across long distances, the trade of and competition on the markets for electricity generating technologies can play a significant role in the transition to a low-carbon.

In order to capture the competition between the research sectors in the two regions, we replaced the R&D specification in the standard DTC model by Acemoglu et al. (2012) with a specification based on the quality ladder models by Grossman and Helpman (1991) and Aghion and Howitt (1992).[1] In other words, rather than having intellectual property rights expire after one period, the researcher retains those rights in perpetuity but loses the market when a competitor develops a better innovation. The interest of competitors in capturing the market grows with the value of that market. Since value of the market is built by successive innovations, the Northern innovations in the clean sector encourage firms in South to direct R&D towards the markets in the same sector.

2 The model

We specify a two-region (North-South) model in which the production of a final good demands the use of intermediate goods, one of which is clean and the other dirty. Production of intermediate goods involves labor, which is in fixed supply; sector-specific resources, either clean or dirty; and specialized machines, for which the blueprints are developed through research. Research occurs in both regions, but blueprints from a foreign region may not always be adapted for domestic use. The researcher is allowed to allocate his or her research effort across varieties within a clean or dirty sector. We assume that the arrival of innovation follows a Poisson process with a constant arrival rate (i.e., the expected number of innovations per unit of research effort and per unit of time). Every innovation is materialised in the form of a new blueprint. The researcher holds the property rights to the blueprint forever. However, as we will demonstrate, he or she loses the market when a new innovation arrives. The model is solved in continuous time; i.e., the time periods are not separated.

[1] Greaker et al. (2012) propose a similar combination of DTC framework and the quality ladder set-up. However, they do not consider any interaction between technology firms in the North and South.

The primary goal of the model is to understand what the incentives are for researchers in the South region to switch from dirty to clean technologies if this switch has already taken place in the North region. Therefore, in the following set-up we will take the perspective of the South, with its economy being the "domestic" economy and the North economy viewed as the "foreign" economy. The macroeconomic variables for the foreign economy will be marked with index f.

We will first derive the demand for intermediate goods and for technologies. Then we will show how the profit of technology firm in one sector depends on revenue of that sector and how the revenue depends on the path of technologies. Finally, we will discuss how the change in technology over time depends on the allocation of researchers across sectors. We postpone the discussion of consumption dynamics and welfare until section 6. While consumption dynamics matter for the central planners optimization, they are irrelevant for the decisions of individual researchers.

2.1 Domestic production

Final good and the demand for intermediate goods

In line with the standard Directed Technological Change model, we assume that the final good is produced using two types of intermediate goods (dirty and clean), which are gross substitutes. Specifically, we assume the Constant Elasticity of Substitution production function,

$$Y = \Phi \left(Y_c^{\frac{\epsilon-1}{\epsilon}} + Y_d^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}},$$

where Y_{ct} and Y_{dt} denote clean and dirty intermediate goods, $\epsilon > 1$ is the elasticity of substitution between the two goods, and Φ is the sector-neutral productivity parameter. All variables are expressed in per capita terms.

The final good producer takes the prices of its output as well as the prices of inputs as given. We take the price of the final good as the numeraire. The producer's optimisation problem can then be stated as

$$\max_{Y_c, Y_d} \Phi \left(Y_c^{\frac{\epsilon-1}{\epsilon}} + Y_d^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}} - P_c Y_c - P_d Y_d.$$

The first-order conditions for the optimum define the demand curves for the clean and dirty intermediate goods:

$$\Phi^{\frac{\epsilon-1}{\epsilon}} Y^{\frac{1}{\epsilon}} Y_j^{\frac{\epsilon-1}{\epsilon}} = P_j Y_j. \tag{1}$$

We will use the symbol "ˆ" to denote the value of prices or quantities in the clean sector relative to their value in the dirty sector., i.e. for any variable x, $\hat{x} = \frac{x_c}{x_d}$. Then the above translates into

$$\hat{p}_j^{-\epsilon} = \hat{Y}_j, \tag{2}$$

implying a simple log-linear relative demand curve.

Production of intermediate goods.

The production of intermediate good $j \in \{c, d\}$ requires labour (L_j), natural resources (R_j) and a composite of machines (X_j):

$$Y_j = R_j^{\alpha_2} L_j^{1-\alpha} X_j^{\alpha_1},$$

with $\alpha = \alpha_1 + \alpha_2$.

We consider the clean and dirty goods to use different natural resources (e.g., renewable energy and coal), which have constant unit costs c_c and c_d, respectively (expressed in terms of the final good), and no scarcity rents.

The technology composite is formed of a range of machines: $\ln X_j = \int_0^1 \ln(A_{ij} Z_{ij})\, di$, where Z_{ij} is a machine of the variety i devoted to sector j, and each machine is characterised by its own productivity parameter A_{ij}. The number of varieties of machines is normalised to unity (the predictions of the model do not change if we replace the unity with a positive parameter). The machine of variety ij can be either supplied by domestic producers (delivering Z_{hij}) or imported (at quantity Z_{mij}). Domestic and imported machines are perfect substitutes, i.e. $Z_{ij} = Z_{hij} + Z_{mij}$. Let A_{ij} denote the productivity of the best machine available on the market ij. The best technology could be either domestic or foreign. The production and characteristics of the machines are described in the subsequent sub-section.

We assume that the intermediate goods producers take all prices as given. If w_t denotes wages (which must be equal in both sectors as we assume free flow of labor) and p_{hij} (p_{mij}) is the price of a machine ij from a domestic (foreign) producer, then the optimisation problem for the representative firm in the intermediate good sector is

$$\max_{Z_j,R_j,L_j} \quad P_j R_j^{\alpha_2} L_j^{1-\alpha} X_j^{\alpha_1} - c_j R_j - wL - \int_0^1 p_{hij} Z_{hij} di - \int_0^1 p_{mij} Z_{mij} di$$

subject to $\ln X_j = \int_0^1 \ln (A_{ji} Z_{ji})\, di$, $Z_{ij} = Z_{hij} + Z_{mij}$ and the non-negativity constraints.

The first-order conditions give the demand for labor, resources and each machine variety:

$$\alpha_2 P_j Y_j = R_j c_j \tag{3}$$

$$(1-\alpha) P_j Y_j = L_j w \tag{4}$$

$$\alpha_1 P_j Y_j = Z_{ij} p_{ij} \tag{5}$$

where p_{ij} is the price of the machine that is chosen by the firm at market ij. The intermediate producer always chooses the machine with the lowest quality-adjusted price. If $\frac{p_{hij}}{A_{hij}} \leq \frac{p_{mij}}{A_{mij}}$, i.e. the quality-adjusted price of the domestic machine is lower than the one proposed by its foreign competitor, then $Z_{ij} = Z_{hij}$, $Z_{mij} = 0$, and $p_{ij} = p_{hij}$. Otherwise, $Z_{ji} = Z_{mji}$, $Z_{hji} = 0$, and $p_{ij} = p_{mij}$.

We assume that the machines and the final good are tradable and the intermediate goods are not tradable. If a region is a net importer of machines, it must be a net exporter of the final good.

Labor and wages

Domestic labor supply is fixed at L. Although it is perfectly substitutable across sectors, it is not mobile internationally. By summing the demand for labor in (4) for the two sectors, we can show that total compensation to labor is a constant fraction of GDP:

$$wL = (1-\alpha) Y. \tag{6}$$

Because we consider all variables in per capita terms, labor can be normalized to unity.

Generation of blueprints and prices of machines

The representation of the technology and innovation market follows that of the quality ladder in Grossman and Helpman (1991). We assume that the technology firms own the blueprints to produce a machine of variety ij characterised by some quality level (A). In contrast to the original DTC model by Acemoglu et al. (2012), the firms do not lose the property rights of the blueprint after one period. Instead, the firm will lose the market when another firm comes up with an innovation in the same market. An innovation results in a new blueprint, which allows the newcomer to produce a machine with a quality level that is higher than the previous best available technology by a factor $(1+\gamma)$. As a result, the newcomer captures the entire market for machine of variety ij.

An innovation is created by researchers hired by a technology firm. As in the original Grossman-Helpman model, we assume that the arrival of innovations is random and follows the Poisson process: the number of innovations per unit of research effort and per unit of time is distributed according to the Poisson distribution with the arrival rate λ.

Consider a domestic technology firm that has just made an innovation for machine ij. Now the firm, which we label as the "newcomer" has to compete with the incumbent firm in the market ij. We assume that this competition takes the Bertrand form. The incumbent cannot lower its price below average cost, which we assume is constant and equal to ψ. The newcomer offers a price that is epsilon lower than $(1+\gamma)\,\psi$ and wins the competition. This implies that in equilibrium, $p_{hij} = (1+\gamma)\,\psi$. If the newcomer is a foreign firm generating an adaptable innovation, then exactly the same logic applies and $p_{mij} = (1+\gamma)\,\psi$. Using (5), this implies that the demand for machines is given by

$$Z_{ij} = \frac{\alpha_1 P_j Y_j}{(1+\gamma)\,\psi} \tag{7}$$

In other words, demand for the best machine is proportional to total revenue in the relevant intermediate good sector.

The instantaneous profit of a newcomer from the domestic market is given by

$$\pi_j = (p_{hij} - \psi) Z_{ij} = \gamma\psi \frac{\alpha_1}{(1+\gamma)\psi} (P_j Y_j) = \frac{\gamma}{1+\gamma} \alpha_1 P_j Y_j \tag{8}$$

and the expected instantaneous profit of a newcomer from the foreign market is given by

$$\omega \pi_j^f = \omega \left(p_{mij}^f - \psi \right) Z_{ij}^f = \omega \frac{\gamma}{1+\gamma} \alpha_1 P_j^f Y_j^f \tag{9}$$

where superscript f is used to denote the variable for the foreign economy.

Note that since the profit is the same for every variety i, the researchers will be indifferent when choosing to work on any of the varieties within intermediate sector j. Progress in each sub-sector will therefore be equally likely.

The symmetry between profits in sub-sectors ij is necessary for a tractable solution of the model. In our model, this symmetry emerges from the micro-foundations of the model. In contrast, the same symmetry in the original DTC model by Acemoglu et al (2012) was bought with a rather strong assumption on the random allocation of researchers. In that model, the researchers could choose whether they want to work on technologies in the dirty or clean sectors, but once this choice was made, they could not choose which particular technology ij they wished to work on.

In section 2.2, we detail how competition in the technology sector influences the allocation of researchers and the growth rate.

Equilibrium revenues of the dirty and clean sectors

The revenues of the intermediate sector can be expressed as a function of the intermediate prices and total output by using (1):

$$P_j Y_j = Y P_j^{-(\epsilon-1)} \Phi^{\epsilon-1}$$

This expression implies that, for a given level of output, a drop in the price of an intermediate good will increase its revenues as long as the two intermediate goods are gross substitutes ($\epsilon > 1$).

Next, using a duality of cost function and production, we can express the price of an intermediate good as:

$$P_j = \Omega A_j^{-(1-\alpha_1)} c_j^{\alpha_2} w^{1-\alpha}, \tag{10}$$

where $\Omega = \alpha_2^{-\alpha_2} \left(\frac{\alpha_1}{(1+\gamma)\psi}\right)^{-\alpha_1} (1-\alpha)^{-(1-\alpha)}$ is a constant. The condition reflects the negative effect of a productivity improvement in sector j on the price of the intermediate good supplied by this sector.

From the labour market equilibrium (6), normalised wages are $w = (1-\alpha)\,Y$. Combining this with equation (10), we can then express the revenue in sector j as a function of total GDP, the cost of resources, and the technology used in sector j. The revenue in sector j is proportional to:

$$P_j Y_j \propto A_j^{\varphi_1} c_j^{-(\epsilon-1)\alpha_2} Y^{(1-\varphi)}, \tag{11}$$

where $\varphi_1 = (1-\alpha_1)(\epsilon-1)$ and $\varphi = (1-\alpha)(\epsilon-1)$. Throughout the paper we assume that the two goods are sufficiently substitutable to ensure that dirty resource use (which is proportional to dirty sector revenue) declines when all research effort is channeled to the clean sector, i.e. $\varphi > 1$. This condition mirrors the condition on elasticity of substitution in the Acemoglu et al. (2012) paper.

Total output can be derived by summing the left and right hand sides of (11) over the two sectors and noting that $P_c Y_c + P_d Y_d = Y$. This results in

$$Y \propto \left(A_c^{\varphi_1} c_c^{-(\epsilon-1)\alpha_2} + A_d^{\varphi_1} c_d^{-(\epsilon-1)\alpha_2}\right)^{\frac{1}{\varphi}} \tag{12}$$

Using (11) we can also express revenues as

$$p_j Y_j = \sigma_j Y \tag{13}$$

where

$$\sigma_j \equiv \frac{p_j Y_j}{Y} = \frac{\left(A_j^{1-\alpha_1} c_j^{-\alpha_2}\right)^{\epsilon-1}}{\left(A_d^{1-\alpha_1} c_d^{-\alpha_2}\right)^{\epsilon-1} + \left(A_c^{1-\alpha_1} c_c^{-\alpha_2}\right)^{\epsilon-1}} \tag{14}$$

is the share of sector j in the total output.

To summarise the analysis to this point, we have demonstrated that the profit of a technology firm is proportional to the total revenue of that sector (equation 8) and that the revenue is determined by the level of GDP and the distance between the clean and dirty technologies, A_c/A_d (equations 13 and 14). If the clean and dirty intermediates are gross substitutes then an increase in the distance leads to an increase in the share of the clean sector and, if Y_t is kept constant, an increase in the revenue of the sector and the profit for clean technology owners. Next, we will examine the equilibrium allocation of researchers and show that the technological growth paths depend on the allocation of researchers across the sectors.

2.2 Research, technological innovation, and growth

We assume that the number of researchers in the two regions is fixed. The population of foreign researchers is normalized to unity ($\mu_f = 1$). The population of domestic researchers is given by μ, which therefore also represents the ratio of domestic to foreign researchers. The share of the researcher populations working on the technologies in the clean sector is given by s at home and s_f abroad. In this section, we focus on the determinants of the researcher shares devoted to clean technologies.

Technology paths

Let $A_j(t)$ stand for the geometric average of technologies in sector j at time t raised to the power $\frac{\alpha_1}{1-\alpha_1}$:

$$\ln(A_j(t)) = \frac{\alpha_1}{1-\alpha_1} \int \ln(A_{ij}(t))\, di.$$

Differentiating this with respect to time,

$$\frac{d \ln(A_j(t))}{dt} = \frac{\alpha_1}{1-\alpha_1} \int \frac{d \ln(A_{ij}(t))}{dt} di.$$

As noted earlier, the intermediate producers purchase the best available technology, irrespective of whether it was developed at home or abroad. However, we take into account that not every foreign innovation can be successfully adapted to the domestic market. In particular, we assume that the probability of successful adaptation is given by ω.

Recall that the number of innovations per unit of research effort and per unit of time is distributed according to the Poisson distribution with the Poisson arrival rate, λ. This implies that in the clean sector, on average there are $\lambda\mu s$ improvements per unit of time delivered by domestic researchers and $\lambda\omega s_f$ domestically applicable improvements delivered by the foreign research sector [2]. Due to the law of large numbers, there are $\mu\lambda s + \lambda\omega s_f$ varieties that are improved by a factor $1+\gamma$ at every instance of time. This means that the growth of A_j is given by

$$g_j(t) \equiv \frac{d\ln(A_j(t))}{dt} = \frac{\alpha_1}{1-\alpha_1}\left(\mu\lambda s_j(t) + \lambda\omega s_j^f(t)\right)\gamma \tag{15}$$

The value of a blueprint

As noted in the previous section, innovation is associated with the loss of monopoly power on the part of the owner of the previous blueprint. This effect is known in the endogenous growth literature as the *business-stealing effect*: On the one hand, the innovator captures the entire value of the market and thus benefits from all previous innovations; on the other hand, the innovator only receives the dividend until the next incremental innovation arrives and captures the full value again.

The presence of the effect was one of the central features in the models of Grossman and Helpman (1991) and of Aghion and Howitt (1992). The size of the effect determined whether decentralised innovation effort is higher or lower than is socially optimal. In our model, we are not concerned with the total amount of innovation effort but rather its distribution across sectors. Here also the role of the business-stealing effect is central: as we will see, the possibility of winning the market encourages innovators in the South to operate in the same sector as innovators in the North.

We will first examine the length of the time period between a blueprint invention and a successive innovation in the same market. For simplicity, we will limit our analysis to a balanced growth path (BGP). Along the BGP s, s_f and the growth rates of productivities in the two sectors are constant.

Note that since the innovators are indifferent between working on any variety within

[2] Recall that the number of researchers in North is normalised to unity

sector j, they distribute their effort equally across all varieties. Given that the number of innovations per unit of time and per unit of research effort is distributed Poisson, the distribution of the time interval between two successive innovations in the clean sector is exponential with the parameter $\lambda(\mu s + \omega s_f)$. Hence, if a firm innovated at time t, the probability that competitors would not come up with any successful innovation in the same market by time τ is $e^{-\lambda\left(\mu s+\omega s_f\right)(\tau-t)}$. By the same logic the probability that a successful domestic firm is present in the foreign market at τ is given by $\omega e^{-\lambda\left(\mu\omega s+s_f\right)(\tau-t)}$. The value of the blueprint in sub-sector i in the clean sector is then given by

$$v_{ic}(t) = \int_{\tau=t}^{\infty} \pi_c(\tau)\, e^{\left(-\rho-\lambda\left(\mu s+\omega s_f\right)\right)(\tau-t)} + \omega \int_{\tau=t}^{\infty} \pi_c^f(\tau)\, e^{\left(-\rho-\lambda\left(\mu\omega s+s_f\right)\right)(\tau-t)}$$

where ρ denotes the discount rate used by a firm.

This can be also expressed as

$$v_{ic}(t) = \pi_c(t)\,\Gamma_c(t) + \pi_c^f(t)\,\Gamma_c^f(t) \qquad (16)$$

where

$$\Gamma_c = \int_{\tau=t}^{\infty} \frac{\pi_c(\tau)}{\pi_c(t)} e^{-\rho-\lambda\left(\mu s+\omega s_f\right)(\tau-t)} d\tau,$$

and

$$\Gamma_c^f = \omega \int_{\tau=t}^{\infty} \frac{\pi_c^f(\tau)}{\pi_c^f(t)} e^{-\rho-\lambda\left(\mu\omega s+s_f\right)(\tau-t)} d\tau.$$

The term Γ can be interpreted as the discounted sum of expected profits relative to the current profit. One could also interpret Γ as the expected length of the interval with the monopoly rent adjusted for the growth of the profit and the discount rate.

Using the growth rate of profit derived from equations 8 and 11, Γ_c can be expressed as

$$\Gamma_c(s, s_f) = \int_{\tau=t}^{\infty} e^{-\chi\left(s,s_f,g\right)(\tau-t)}$$

where $\chi(s, s_f, g) = \rho + (1-\gamma\alpha_1(\epsilon-1))\,\lambda(\mu s + \omega s_f) + (\varphi-1)\,g$. In order to ensure that the value of technology firm is finite, we assume that $\gamma\alpha_1(\epsilon-1) < 1$. If the condition is satisfied, $\chi > 0$ and the integral in Γ_c is finite.

Incentives for researchers in the long run

The BGP growth rate of the economy, g, can be derived from equation (12):

$$g = \frac{1-\alpha_1}{1-\alpha} \left(\sigma_c g_c + \sigma_d g_d \right), \tag{17}$$

Since along the BGP the growth rates of the technologies must be constant, the shares of the sector must either be constant, approach unity or approach zero asymptotically. In either case, as t goes to infinity, g coverges to a positive constant; $\chi(s, s_f, g)$ converges to a strictly positive constant; and Γ_c approaches its finite and strictly positive limit given by $1/\chi(s, s_f, g)$. The same argument applies to $\Gamma_c^f(s, s_f)$, $\Gamma_d(s, s_f)$ and $\Gamma_d^f(s, s_f)$.

Since Γ's are constant in the long run, v_c grows (or vanishes) together with π_c and π_{cf}. Combining this result and the previous results enables us to relate the growth of v_c with the path of technologies and the allocation of researchers. The larger the number of researchers in the clean sector, the faster the progress of a clean technology, growth of the revenue of the sector, and profits, and value of the innovation.

Note that while the value of the market is built by all researchers who worked on a given technology in the past, at any point in time that value is fully captured by only one researcher: the one who came up with the most recent innovation. This business stealing will result in a gravitational force that pulls researchers into one sector. Every researcher will wish to work in the sector that has accommodated a large number of researchers in the past.

3 Research allocation and technical change

We have established how the opportunity to winning the technology supply to an ever increasing market creates a strong gravitational pull for researchers. In the context of our two-region model, this pull implies that the shift of North researchers to clean sector will build up the value of this sector in the long run and thus generate an incentive for researchers in the South to follow the switch. We will formally present this argument in the next two sections.

3.1 Symmetric regions

We will first analyse the simplest case when the two regions are symmetric – at least in the sense that they have the same labour force, the same prices of resources, c's, and the same sector-neutral productivity, Φ. We also assume that $\omega = 1$ (adaptation is perfect), and that the initial values of A's are the same in both regions. Since all technologies are available for any producer in any region, the two regions will be characterised by the same levels of A_c and A_d and, therefore, with the same output and sector shares. Finally, and most importantly, we assume that the number of researchers in both regions is equal, that is $\mu = 1$. In subsection 3.2 we will consider a more complex case when the regions are asymmetric and when the above assumptions are relaxed.

In the symmetric case, equation (16) reduces to

$$\hat{v}_t = \frac{v_{ct}}{v_{dt}} = \hat{\Gamma}_c \hat{\pi}_c;$$

i.e. the relative value of the innovation at time t is given by the relative profit at time t scaled by the factor $\hat{\Gamma}$.

Along the BGP, $\hat{\Gamma}$ is constant and can be expressed as:

$$\hat{\Gamma}(s, s_f) = \frac{\rho + \{\lambda(2 - s - s_f)\} - [\alpha_1(\epsilon - 1)\gamma\lambda(2 - s - s_f)] + (\varphi - 1)g(s, s_f)}{\rho + \{\lambda(s + s_f)\} - [\alpha_1(\epsilon - 1)\gamma\lambda(s + s_f)] + (\varphi - 1)g(s, s_f)} \tag{18}$$

Thus $\hat{v}$ will change over time along with $\hat{\pi}$, which (using 8, 11 and 15) can be expressed as

$$\hat{\pi}(s, s_f) = \hat{A}(t)^{\varphi_1}\hat{c}^{-(\epsilon-1)\alpha_2} = \hat{A}_0^{\varphi_1}\hat{c}^{-(\epsilon-1)\alpha_2}\left(\frac{e^{\gamma\lambda\left(s+s_f\right)t}}{e^{\gamma\lambda\left(2-s-s_f\right)t}}\right)^{\alpha_1(\epsilon-1)} \tag{19}$$

Depending on the allocation of researchers the relative value can stay constant, increase exponentially over time or approach zero asymptotically.

Researchers' incentives

Since we assume a free entry of technology firms, the zero profit condition will imply that the compensation (or wage) for researchers will be equal to the expected return to research. The return to research in sector j is given by $\lambda v_{ijt} + \xi_j$, where ξ_j denotes the research subsidy for technologies in sector j. The subsidy is financed from a lump-sum tax on consumers in order to avoid any distortionary effect from taxes.

A researcher compares the wages in the two sectors and allocates its entire research effort to the clean sector if and only if $v_{ict} + \frac{\xi_c}{\lambda} > v_{idt} + \frac{\xi_d}{\lambda}$. Note that in this specification, for any parameter values, the government always has the possibility to incentivise the movement of all researchers to either sector, simply by choosing the appropriate levels of research subsidies in the two sectors.

Suppose now that the government of the foreign country (i.e. the North region) increases subsidies for clean research in order to shift researchers to this sector and away from the dirty sector. We are interested in the consequence of this shift for the allocation of researchers in the South. We distinguish between four types of effects.

First, observe that an increase of s_f will increase the business-stealing effect in the clean sector and decrease the size of this effect in the dirty sector. In other words, more researchers working in the clean sector implies that the likelihood of a successful innovation of a competitor in this sector increases and thus the innovator can enjoy its profit for a shorter period. Also, fewer competitors in the dirty sector implies a lower risk of losing the market in this sector. We marked this effect with curly brackets in (18) above.

Second, note that when a firm has a monopoly in the market of variety i in the clean sector, the unit productivity of other varieties in that sector will grow at the rate $\gamma\lambda\left(s + s_f\right)$. This means that, although some researchers in the clean sector will be aiming at stealing the market i, the remaining researchers will be working on improving other varieties. These improvements will increase the share of the clean sector and the revenue for variety i. This effect is marked with square brackets in (18).

Third, s_f will influence the value of blueprints in both sectors through its effect on the aggregate growth rate. If the new allocation of research implies a slower growth of the economy, this effect will depress the blueprint values in both the dirty and the clean sectors. This effect is captured in the change of the term $g(s, s_f)$ in equation (18).

Finally, the most important effect for the long run is framed in the exponential terms in equation (19). The more researchers are working in the clean sector, the larger is the value of the businesses operating in this sector. This implies more benefit from capturing one of such businesses in the event of a successful innovation. Conversely, fewer researchers in the dirty sector implies slower growth of that sector and less benefits from capturing the dirty industry in the long run. Note that, contrary to the first three effects, which change the *level* of the blueprint's value (through the changes in the BGP level of $\hat{\Gamma}$), the last effect changes the *growth rate* of the blueprint's value. As a result, this last effect will always dominate the other effects and determines the relative value of the blueprint in the long run, as t approaches infinity.

To reverse this result, either factor $\hat{\Gamma}$ would need to decline at the exponential rate or the growth of productivity would need to reach the limit. An exponential decline in $\hat{\Gamma}$ would mean that in the long run innovators would enjoy their dividends for infinitesimally short period of time, which is hard to imagine. Theoretically, in our model $\hat{\Gamma}$ could decline due to an increase in the business-stealing rate, $\lambda(s + s_f)$, which could be caused by an increase in the number of researchers. However, the inflow of researchers into the sector must stop at some point because the number of researchers in the entire economy is fixed.

The second possibility is the limit on the growth of productivity. In our model, the exponential growth of productivity under constant number of researchers is driven by the assumption on spillovers (see Jones 1995). Although this assumption is standard in endogenous growth models (Aghion Howitt (1992), Grossman and Helpman (1991), Romer (1991)), theoretically it is possible that the growth will die out at some point e.g. because researchers will find it more and more difficult to improve clean technologies (this is known as the fishing out effect). If there is an upper bound on the productivity (e.g. the floor cost of every potential clean technology) then the argument made above will fail.

Researchers' choices

Although the switch of foreign researchers in the North to the clean sector will also have a positive effect on the value of clean blueprints in the long run in the South, this effect may not be sufficiently strong to guarantee the switch of researchers in the South. We clarify the conditions for the Southern switch in the following proposition:

Proposition 1 *Allocation of Southern researchers when there is no South government and the two regions are symmetric:*

If at time $t = 0$ all researchers in the South work in the dirty sector and if all researchers in the North work on clean technologies, then in the long run the Southern researchers will stay in the dirty sector if and only if

$$A_{c0}^{\varphi_1} c_c^{-\alpha_2(\epsilon-1)} \leq A_{d0}^{\varphi_1} c_d^{-\alpha_2(\epsilon-1)}$$

Otherwise, in the long run all researchers will work in the clean sector.

Proof. The "if" part: When all Southern researchers are working in the dirty sector ($s = 0$), then the condition above implies that

$$\frac{2\left(A_{c0}^{\varphi_1} e^{-\alpha_1(\epsilon-1)\gamma\lambda t}\right) c_c^{-\alpha_2(\epsilon-1)}}{\rho + \lambda - \alpha_1(\epsilon-1)\gamma\lambda + (\varphi-1)\, g(0,1)}$$

$$\leq \frac{2\left(A_{d0}^{\varphi_1} e^{-\alpha_1(\epsilon-1)\gamma\lambda t}\right) c_d^{-\alpha_2(\epsilon-1)}}{\rho + \lambda - \alpha_1(\epsilon-1)\gamma\lambda + (\varphi-1)\, g(0,1)}$$

where $g(0,1)$ is the growth of the final output under $s = 0$ and $s_f = 1$. Hence, the value of the clean blueprint is lower than the value of the dirty blueprint so no one has an incentive to move from the dirty sector to the clean sector. Since the research effort is equally split between the two sectors ($s_f = 1 - s = 1/2$), the two sectors grow at exactly the same rate and the condition holds in all subsequent periods.

The "only if" part: If the condition is violated, then clean blueprints are more valuable than the dirty blueprint and researchers flow from the dirty to the clean sector. However, in this case, the growth of productivity in the dirty sector (from (15) equal to $\frac{\alpha_1}{1-\alpha_1}\gamma\lambda(1-s)$) is slower than the growth in the clean sector (from (15) equal to $\frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(1+s\right)$). The increase in technological distance will incentivise more researchers to switch to the clean sector. As the technological distance keeps increasing, $\hat{\pi}$ must grow without limit. Since $\hat{\Gamma}$ is bounded from below (since both, Γ_c and Γ_d are bounded from below and from above), this implies that in the long run the value of the dirty blueprints relative to the value of the clean blueprint is falling and reaches zero asymptotically. Consequently, in the long run all researchers work in the clean sector. The BGP with $s<1$ is not possible. QED. ■

The proposition above shows that if North commits to putting all its research in the clean sector, in the long run there are two possible balanced growth paths: one with all Southern researchers choosing the clean sector (s=1) and one with all Southern researchers choosing the dirty sector ($s=0$).

The proposition implies that if the accumulation of knowledge stock in the dirty sector is sufficiently advanced (A_d is large), and if the Southern government is absent, then the world economy will follow a balanced growth path with the two sectors growing at the same pace. The reason why the switch in the North is not propagated in the South is that the positive effect of foreign switch is offset by the lock-in effect in the South. In the symmetric model with an equal number of researchers in the South and in the North, these two effects will be exactly equal to each other. To change the balanced growth path we would need the former force to be at least marginally larger than the latter force. This case will be discussed in the case of asymmetric regions in the subsequence section.

3.2 Asymmetric regions

Let us now drop the assumption of the symmetry between regions. In other words, we allow the workforce (L), the population of researchers (μ) and sector-neutral productivity (Φ) to vary across regions. In addition, we allow $\omega\leq1$; that is, we take into account that not every innovation developed in one region can be successfully adapted to the economy of the other region. We will view the allocation of researchers from the perspective of the South (thus all variables indexed with f will refer to the value for North), and we will consider the case in which all Northern researchers work in the clean sector, $s_f=1$.

In the asymmetric case, the unit productivities for the two sectors, A_c and A_d will differ between the two regions. In particular, while the domestic unit productivities follow the processes described in equation (15), the unit productivities abroad will follow

$$g_c^f = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(\mu\omega s + s_f\right) \tag{20}$$

$$g_d^f = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(\mu\omega\left(1-s\right) + 1 - s_f\right) \tag{21}$$

The value of a blueprint in sector j will be given by:

$$v_j = \pi_j \Gamma_j + \pi_j^f \Gamma_j^f \tag{22}$$

Along the BGP, the evolution of π_j and π_j^f will be determined by the paths of technologies and the growth rate of GDP:

$$\pi_j \propto (A_j)^{\varphi_1} c_j^{-(\epsilon-1)\alpha_2} Y^{(1-\varphi)}$$

$$\pi_j^f \propto (A_j^f)^{\varphi_1} c_j^{-(\epsilon-1)\alpha_2} Y_f^{(1-\varphi)} \left(\frac{L_f}{L}\right)^{(1-\varphi)}$$

where Y_f is the foreign GDP per capita.

Meanwhile, $\Gamma_j\left(s, s_f\right)$ and $\Gamma_j^f\left(s, s_f\right)$ will stay constant or approach their positive and finite limit.

We can now state the key results predicted by the model.

Proposition 2 *Suppose that all researchers in the North work on clean technologies. The balanced growth path with some Southern researchers in the dirty sector is only possible when number of researchers in the South is larger than the number of researchers in the North; i.e.* $\mu \geq 1$.

Proof. Suppose that $s_f = 1$ and $\mu < 1$. We will show that the long run growth of the value of the clean blueprint must be larger than the growth of the value of the dirty blueprint. Thus the BGP with constant $s < 1$ is not feasible.

First, we will consider the BGP with $s = 0$ (all Sothern researchers working in the dirty sector). Afterwards, we will consider the BGPs with $s \in (0, 1)$.

The value of the clean blueprint is determined by equation 22. Since along the BGP, Γ 's are constant, the first term in this expression grows at the growth rate of $A_c^{\varphi_1} Y^{(1-\varphi)}$ given by

$$\alpha_1 (\epsilon - 1) \gamma \lambda \omega - (\varphi - 1) g \tag{23}$$

The second term grows at the growth rate of $A_{fc}^{\varphi_1} Y_f^{(1-\varphi)}$ given by

$$\alpha_1 (\epsilon - 1) \gamma \lambda - (\varphi - 1) g_f \tag{24}$$

In the long run, the growth of total output is determined by the growth of the fastest-growing sector: if sector j grows faster than the other sector, σ_j, the share of sector j in total output approaches unity and thus the growth of output is determined by the growth of that sector in the long run. In the case of the foreign economy, if $\mu < 1$ the clean sector is always the fastest sector and thus $g_f = \frac{\alpha_1}{1-\alpha} \gamma \lambda$. Then 24 reduces to $\frac{\alpha_1}{1-\alpha} \gamma \lambda$. In the case of the domestic economy, we have to distinguish between the two cases. If $\mu \leq \omega$, then $g_c \geq g_d$, $g = \frac{\alpha_1}{1-\alpha} g_c = \frac{\alpha_1}{1-\alpha} \gamma \lambda \omega$ and 23 reduces to $\frac{\alpha_1}{1-\alpha} \gamma \lambda \omega$. If $\mu > \omega$, then $g_c < g_d$ and $g = \frac{\alpha_1}{1-\alpha} g_d = \frac{\alpha_1}{1-\alpha} \gamma \lambda \mu > \frac{\alpha_1}{1-\alpha} \gamma \lambda \omega$. In this case the expression in 23 must be smaller than $\frac{\alpha_1}{1-\alpha} \gamma \lambda \omega$

In both cases ($\mu \leq \omega$ and $\mu > \omega$), in the long run the first term in 22 evaluated for the clean sector grows slower than the second term and thus the long run growth rate of the value of the blueprint in the clean sector is equal to $\frac{\alpha_1}{1-\alpha} \gamma \lambda$.

Lets now consider the dirty sector. The first term in expression 22 evaluated for the dirty sector will grow at the rate

$$\alpha_1 (\epsilon - 1) \gamma \lambda \mu - (\varphi - 1) \frac{\alpha_1}{1-\alpha} \gamma \lambda \max \{\mu, \omega\} \leq \frac{\alpha_1}{1-\alpha} \gamma \lambda \mu < \frac{\alpha_1}{1-\alpha} \gamma \lambda$$

The second term in expression (22) evaluated for the dirty sector will grow at the rate

$$\alpha_1 (\epsilon - 1) \gamma \lambda \omega \mu - (\varphi - 1) \frac{\alpha_1}{1-\alpha} \gamma \lambda < \frac{\alpha_1}{1-\alpha} \gamma \lambda \omega \mu < \frac{\alpha_1}{1-\alpha} \gamma \lambda$$

Thus, the value of a blueprint in dirty sector will grow slower than the value of a blueprint in the clean sector. This implies that at some point in time the value of the clean blueprint overtakes the value of the dirty blueprint and some researchers move to the clean sector. This would violate the condition that s stays constant over time.

When $s \in (0,1)$ (i.e. some, but not all Southern researchers work in the clean sector) then the productivity in the clean sector grows faster and the productivity in the dirty sector grows slower than in the case of $s = 0$. Now the growth of the value of the clean blueprint cannot be smaller than $\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(1+\omega\mu s\right)$ while the growth of the value of the dirty blueprint cannot be larger than $\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(1-s\right)\mu$. Thus, the value of clean blueprints will again grow faster than the value of dirty blueprints. When the former value overtakes the latter, researchers will switch, violating the conditions that s stays constant along the BGP.

■

The proposition brings important implications for the effectiveness of the policy to support the dirty sector in the South. When the number of researchers in the South is smaller than that of the North, there is no constant (and finite) research subsidies ξ_d and ξ_c which could keep researchers in the South in the dirty sector in the long run.

Note also that the balanced growth path with all Southern researchers working in the clean sector is possible for any parameter μ. To understand this, observe that when $s = 1$, then the growth of π_c, which is equal to $\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$, as well as the growth of π_c^f, which is equal to $\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\omega\mu+1\right)$, is positive. Meanwhile the growth of π_d, which is equal to $-\left(\varphi-1\right)g$ and π_c^f, which is equal to $-\left(\varphi-1\right)g_f$, must be negative. This implies that if A_c is sufficiently high to ensure that all researchers work in the clean sector, the economy will follow the balanced growth path with $s = 1$.

As a result, the government in the South is always able to incentivise its researchers to switch. Indeed, all that is needed is a temporary subsidy ξ_c, which ensures that researchers work in the clean sector, to allow A_c to grow sufficiently large. In the long run, the subsidy can be withdrawn, once the lock-in effect works in favour of the clean sector.

4 The consequences for long run growth

In this subsection we will explore the long run growth rate of the Southern economy when all researchers in both regions work in the clean sector ($s = s_f = 1$) and when the research effort is split: researchers in the North work in the clean sector and researchers in the South work in the dirty sector ($s = 0$, $s_f = 1$). In the former case the growth of productivity in the clean and dirty sector can be derived using 15 as $g_c = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\left(\mu + \omega\right)$ and $g_d = 0$, respectively. Inserting it into the expression for GDP growth in 17, we obtain

$$g = \frac{\alpha_1}{1-\alpha}\left(\sigma_c \gamma\lambda\left(\mu + \omega\right)\right)$$

Notice that in the long run the clean sector will dominate in the economy (i.e. $\sigma_{ct} \equiv \frac{P_{ct}Y_{ct}}{Y_t} = \frac{\left(A_{ct}^{1-\alpha_1} c_{ct}^{-\alpha_2}\right)^{\epsilon-1}}{\left(A_{dt}^{1-\alpha_1} c_{dt}^{-\alpha_2}\right)^{\epsilon-1} + \left(A_{ct}^{1-\alpha_1} c_{ct}^{-\alpha_2}\right)^{\epsilon-1}} \to 1$). Therefore the expression above implies that the long run growth of the Southern economy is given by $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\mu + \omega\right)$.

In the case of a split ($s = 0$, $s_f = 1$), the two sectors will grow at the rates, $g_c = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\omega$ and $g_d = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\mu$. When this is inserted in the expression for growth, we obtain

$$g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\sigma_c\omega + \sigma_d\mu\right)$$

Since along this balanced growth path, productivity in the dirty sector grows faster than in the clean sector,[3] in the long run the dirty sector will dominate the economy, implying that the long run growth of the Southern economy is given by $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu$. This is strictly smaller than in the case of all research effort concentrated in the clean sector.

Proposition 3 *The long run growth of the economy is always larger if researchers from the two regions work in the same sector than if the research effort is split between the two sectors.*

Proof. In the text. ■

Consumption will differ from GDP due to exports (necessary to purchase the foreign technologies) and imports (financed by the sale of domestic technologies abroad). It can be

[3]Recall from proposition 2 that for the balanced growth path with $s = 0$, it must be that $\mu > 1 > \omega$ and hence $g_c = \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\omega < \frac{\alpha_1}{1-\alpha_1}\gamma\lambda\mu = g_d$

shown, however, that when both regions work on clean technologies ($s = s_f = 1$) the growth rate of consumption cannot be smaller than the growth rate of domestic economy given by $\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$. If the research effort is split ($s = 0$, $s_f = 1$), consumption cannot grow faster than $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu$ (see Appendix A1).

5 Implications for emissions

The next step is to examine the use of dirty resources along the two possible balanced growth paths. By combining 3 with 11 and 12, we can find that the equilibrium level of the use of the dirty resource is given by

$$R_d = constant * \left[\frac{\left(A_d^{\varphi_1} c_d^{\alpha_2(1-\epsilon)}\right)}{\left(A_d^{\varphi_1} c_d^{\alpha_2(1-\epsilon)}\right) + \left(A_c^{\varphi_1} c_c^{\alpha_2(1-\epsilon)}\right)}\right]^{\frac{\varphi-1}{\varphi}} \left(A_d c_d^{-1}\right)^{\frac{1-\alpha_1}{1-\alpha}}$$

When all researchers in the world work in the clean sector, the growth of A_d is equal to zero. On the other hand, A_c exhibits constant growth. The expression inside the square brackets goes to zero asymptotically when the dirty and clean goods are gross substitutes ($\epsilon > 1$ and so $\varphi_1 > 0$). This will translate into a decline of R_d towards zero as long as $\varphi > 1$. In other words, the technological progress in the clean sector will lead to a decline of use of dirty resources only if the elasticity of substitution between clean and dirty goods is high enough to ensure that $\varphi = (\epsilon - 1)(1 - \alpha) > 1$. This condition mirrors the condition on elasticity of substitution in the Acemoglu et al. (2012) paper.

By contrast, in the balanced growth path with all Southern researchers working in the dirty sector, productivity in the dirty sector grows faster than productivity in the clean sector. In this situation, the term within the square brackets approaches unity. Consequently, in the long run, the use of dirty resource grows exponentially at the rate $\frac{1-\alpha_1}{1-\alpha} g_d = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu > 0$. This last result does not depend on the elasticity of substitution between the two goods.

6 Social optima in the South

In the analysis until now we have assumed the absence of governmental subsidies in the South. Notice that in our specification either government can always choose the pair ξ_c and ξ_d which flips the sign of $(v_{ict} + \xi_c) - (v_{idt} + \xi_d)$ in any direction. This means that the governments always have a possibility to induce a switch of research to either sector. In this section we will demonstrate that if the Southern government has a low discount rate, it will have an incentive to introduce subsidies and move the economy to the balanced growth path with South researchers working in the same sector as researchers in the North. If the government is impatient, the optimal decision of the government in the South depends on the initial distance between technologies as well as the speed at which Southern firms can capture the clean markets.

6.1 Welfare

We assume that the welfare of the South is determined solely by the sum of the discounted flow of consumption

$$W = \int_0^\infty e^{-\rho\tau} C(\tau) d\tau$$

Purposefully, we assume that welfare does not depend on the quality of the environment in order to highlight the purely economic incentives of the government in the South. We also assume no economic damages due to climate change. If the planner in South takes into account the damages, the planner will have additional incentives to encourage innovation in clean sector. In this paper, we consider the extreme case in which the planner in South does not have these additional incentives, for instance, because the planner does not believe in anthropogenic climate change.

In each instance of time, consumption is determined by

$$C = (1 - \alpha) Y + \Pi + \Pi^f \tag{25}$$

where $(1 - \alpha) Y$ is labor compensation, Π is the aggregated profit domestic firms made on the domestic markets and Π^f is the aggregated profit domestic firms made on the foreign markets.

Total output is given by equation 12 (restated below for convenience)

$$Y \propto \left(A_c^{\varphi_1} c_c^{-(\epsilon-1)\alpha_2} + A_d^{\varphi_1} c_d^{-(\epsilon-1)\alpha_2}\right)^{\frac{1}{\varphi}}$$

We assume that at time $t = 0$, all clean technologies are owned by Northern firms while all dirty technologies are owned by Southern firms.

If at time $t = 0$ all researchers in the South switch from dirty to clean R&D ($s = s_f = 1$) then at time τ,

$$\Pi(\tau) = \phi_c(\tau)\frac{\gamma}{1+\gamma}\alpha_1 P_c(\tau)Y_c(\tau) + \frac{\gamma}{1+\gamma}\alpha_1 P_d(\tau)Y_d(\tau) \tag{26}$$

$$\Pi^f(\tau) = \phi_c^f(\tau)\frac{\gamma}{1+\gamma}\alpha_1 P_c^f(\tau)Y_c^f(\tau) + \frac{\gamma}{1+\gamma}\alpha_1 P_d^f(\tau)Y_d^f(\tau) \tag{27}$$

where ϕ_c (ϕ_c^f) is the fraction of clean technologies owned by domestic firms in domestic (foreign) markets (recalling that $\phi_d = \phi_d^f = 1$). In section 6.4 we show that ϕ_c is constant along the BGP and given by $\frac{\mu}{\mu+\omega}$. Similarly, $\phi_c^f = \frac{\omega\mu}{1+\mu\omega}$.

If all researchers in the South stay in the dirty sector, then

$$\Pi(\tau) = \frac{\gamma}{1+\gamma}\alpha_1 P_d(\tau)Y_d(\tau) \tag{28}$$

$$\Pi^f(\tau) = \frac{\gamma}{1+\gamma}\alpha_1 P_d^f(\tau)Y_d^f(\tau) \tag{29}$$

Welfare depends both directly and indirectly on the discount rate, which affects not only the present value of consumption along the path but also the choice of the path of specialization.

6.2 Optimal path for a patient South

When the discount rate is sufficiently low, the planner will always choose the path with the faster long run growth of consumption. Here, we formalize the argument.

As argued above in the case of a switch to clean R&D, $\sigma_c \to 1$ and $\sigma_c^f \to 1$. Hence, we can choose a point of time τ^* such that for $\tau > \tau^*$, $\sigma_c \approx 1$, $\sigma_c^f \approx 1$ and consumption grows at constant rate which cannot be smaller than the growth of the domestic economy given by $g(1,1) = \frac{\alpha_1}{1-\alpha}\gamma\lambda(\mu+\omega)$. Thus, the South's welfare can be written as

$$\begin{aligned} W_0(1,1) &= \int_0^{\tau^*} e^{-\rho\tau} C(\tau;1,1)\, d\tau + \int_{\tau^*}^{\infty} e^{-(\rho - g(1,1))\tau} C(\tau^*;1,1)\, d\tau \\ &= \int_0^{\tau^*} e^{-\rho\tau} C(\tau;1,1)\, d\tau + \frac{C(\tau^*;1,1)}{\rho - g(1,1)} \end{aligned}$$

By analogous argument, we can express welfare when Southern researchers stay in the dirty sector as:

$$W_0(0,1) = \int_0^{\tau^*} e^{-\rho\tau} C(\tau;0,1)\, d\tau + \frac{C(\tau^*;0,1)}{\rho - g(0,1)}$$

To ensure that all integrals converge, we assume that $\rho > g(1,1) = \frac{\alpha_1}{1-\alpha}\gamma\lambda(\mu+\omega)$. For this reason, the terms in $W_0(1,1)$ and $W_0(0,1)$ are finite. However, we can make the term $\frac{c_{\tau^*}(1,1)}{\rho - g(1,1)}$ arbitrarily large by choosing a ρ that is sufficiently low (i.e. sufficiently close to $\frac{\alpha_1}{1-\alpha}\gamma\lambda(\mu+\omega)$). In turn, the term $\frac{c_{\tau^*}(0,1)}{\rho - g(0,1)}$ is bounded by $\frac{c_{\tau^*}(0,1)}{g(1,1) - g(0,1)} = \frac{c_{\tau^*}(0,1)}{\frac{\alpha_1}{1-\alpha}\gamma\lambda\omega}$. This implies that we can find ρ^* such that for every $\rho < \rho^*$, $W_0(1,1) > W_0(0,1)$.

We summarise the result of this sub-section in the following proposition.

Proposition 4 *Assume that $\rho > \frac{\alpha_1}{1-\alpha}\gamma\lambda(\mu+\omega)$. If the planner is sufficiently patient (i.e. ρ is sufficiently close to $\frac{\alpha_1}{1-\alpha}\gamma\lambda(\mu+\omega)$), then the social optimum will always involve a switching to clean research.*

Proof. In the text. ■

6.3 Sub-game perfect Nash equilibrium when the South and North are patient

In order to endogenise the behaviour of the North and South governments we consider the following game: first the North region chooses the subsidy rate for clean and dirty research. This choice is observed by the government in the South, which now has to make its own decision. To simplify this game as much as possible, we assume that the payoffs of the North government are strictly increasing in the long run growth of output and strictly decreasing in the growth of the use of dirty resources. We assume that the sole objective of the South government is to maximise the long run growth of output.

The Southern government will always set a subsidy which ensures that Southern researchers work in the same sector as the North researchers. According to the argument in the previous section 4, this will bring the long run growth rate equal to $\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$. Otherwise, i.e. if the government lets its researchers choose a different sector, the long run growth of the economy will be $\frac{\alpha_1}{1-\alpha}\gamma\lambda\max\left(\mu,\omega\right)$.

This strategy of the Southern government implies that, no matter which sector the North will subsidize, the long run growth in the North will always be equal to $g=\frac{\alpha_1}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$.

As a result, if the government in the North was rational, according to this model it shall always choose to give a subsidy to the clean sector. This ensures that all research resources are focused on the development of this sector.

The proposition below summarises this result:

Proposition 5 *If the South and North play a Stackelberg game (with the North as the leader and the South as the follower) where the pay-offs for the South is long run economic growth and the payoff for the North depends positively on long run economic growth and the quality of the environment, then the unique sub-game perfect Nash equilibrium is defined as follows:*

- *The South will always choose research subsidies that ensures that Southern researchers work in the same sector as Northern researchers.*
- *The North will choose research subsidies that ensure that all Northern researchers work for the clean sector.*

Proof. In the text. ■

An important assumption in this game is that the North is the first mover. Effectively this means that the North must be fully committed to its initial decision: no matter what the decision of the South government may be, North must continue subsidizing the clean R&D.

6.4 Optimal path for an impatient South

In this sub-section we illustrate why the result established in section 6.2 will not hold if the South's planner is impatient, that is, if ρ is high.

There are two reasons why the impatient central planner might choose to keep research resources in the dirty sector: (i) the large distance between clean and dirty technology and (ii) the difficulty of entering the clean market. We will discuss them in turn:

Large technological distance

To ease the exposition of argument we return to the assumption on the symmetry between regions.

The relative productivity of the clean and dirty sectors at the initial stage may play a crucial role because when distance is significant, the growing sector is very small while the large sector is stagnant. Thus the growth rate is small (see equation 17). The benefit, as demonstrated in section 6.2, will materialise later, but the impatient central planner will not care about them.

Let's see how this argument could be derived from the model. First, note that the two paths have the same starting point: at time $\tau = 0$, $C_0\,(s=1) = C_0\,(s=0)$. Consequently, the paths of consumption must be detmined by consumption growth rates after the initial point.

Due to high discounting, the central planner will assign small weights to observations in the distant future and thus will not be affected by growth rates in the distant horizon. Instead, planner's decision will be determined by the growth rates immediately after $\tau = 0$.

Since under symmetry

$$C_\tau = (1-\alpha)\,p_{c\tau}Y_{c\tau} + \left(1-\alpha+\frac{2\gamma}{1+\gamma}\alpha_1\right)p_{d\tau}Y_{d\tau} + 2\phi_\tau\,(s,1)\,\frac{\gamma}{1+\gamma}\alpha_1 p_{c\tau}Y_{c\tau}$$

the growth rate at time τ can be determined as a weighted sum of the growth rates of the three terms on the right hand side. The weights depend on the contribution of each term to total consumption. For instance, if the contribution of labor compensation in the clean sector relative to total consumption is initially close to zero, then initially the contribution of the first term to the growth of the total consumption is also close to zero, even if the clean sector grows at a fast rate. Note that the contribution of each term depends on the relative size of the clean and dirty sectors.[4] Thus if the size of the clean sector relative to the dirty sector is small, the weight on the first term and the third term is going to be small also.

Now consider the case of no subsidies in South and so no movement from the dirty to the clean sector. Since $s = 0$, the productivities in the two sectors grow at the same rate, the shares of each sector are constant and all three terms on the right hand side grow at the same constant rate given by $\frac{\alpha_1}{1-\alpha}\gamma\lambda$.

Next, consider the choice of subsidies that ensure the movement from the dirty to the clean sector. In this case $s = 1$, the productivity of the clean sector grows at the rate $2\frac{\alpha_1}{1-\alpha}\gamma\lambda$ while productivity in the dirty sector is stagnant.

Consequently, the first term, which captures labor compensation in the clean sector, grows at a high rate; however its contribution to the growth is small. The reason for this is that if the technological distance $\frac{A_c}{A_d}$ is initially large the relative size of the sector $\frac{p_{c\tau}Y_{c\tau}}{p_{d\tau}Y_{d\tau}}$ is close to zero at $\tau = 0$. Similarly, the third term may have potentially high growth rates; however, as in the case of the first term, its weight will be close to zero. Meanwhile, the second term, which is proportional to the output of the dirty sector, receives a large weight, but its growth rate will be zero.

Altogether, if the initial distance between technologies is sufficiently large, the growth rate of the economy at time $\tau = 0$ can be arbitrarily small (to show this formally, we also need to demonstrate that the growth is bounded, which we demonstrate in Appendix A2). In combination with the high discount rate, this implies that the South government will favour the status-quo with the growth of the dirty sector than the choice of subsidies that could incentivise the switch from dirty to clean R&D.

Laborious entry

In this section we investigate how the speed of capturing the Northern markets by Southern technology firms affects the decisions of a central planner in South. In section 6.2 we demon-

[4]For instance, the weight on the first term is given by $\frac{(1-\frac{\gamma}{1+\gamma}\alpha_1)p_{c\tau}Y_{c\tau}}{C_\tau} = \frac{(1-\frac{\gamma}{1+\gamma}\alpha_1)p_{c\tau}Y_{c\tau}/p_{d\tau}Y_{d\tau}}{(1-\frac{\gamma}{1+\gamma}\alpha_1)p_{c\tau}Y_{c\tau}/p_{d\tau}Y_{d\tau}+(1+\frac{\gamma}{1+\gamma}\alpha_1)+2\phi_\tau(s,1)\frac{\gamma}{1+\gamma}\alpha_1 p_{c\tau}Y_{c\tau}/p_{d\tau}Y_{d\tau}}$.

strated that this speed is irrelevant for a patient central planner in South with a very low discount rate because consumer welfare depends primarily on technological progress. However, speed may be a pivotal factor for the decision of the central planner who is impatient.

If a region i at the beginning has $\phi = 1$ and no innovation whatsoever, then the path of ϕ will be given by

$$\phi(\tau) = e^{-\lambda(n_{-i})\tau}$$

where n_{-i} is the number of researchers in the region other than i

Taking the derivative we get

$$\frac{d\phi}{d\tau} = -\lambda e^{-\lambda(n_{-i})\tau} = -\lambda\phi$$

We could consider two alternative setups. In the first setup neither the South nor North could coordinate their researchers. Thus a researcher in South might steal a business of another researcher in South. In the second setup the researchers within each region could coordinate their effort.

If researchers cannot coordinate then the number of blueprints lost by the South at each instance of time will be $\lambda(\mu + \omega)$. The number of blueprints developed by researchers in South will be $\lambda\mu$. Then the path of ϕ_c is determined by

$$\frac{d\phi_c}{d\tau} = -\lambda\phi_c(\omega + \mu) + \lambda\mu$$

The share of Southern technological firms will converge to the steady state ($\frac{d\phi_c}{d\tau}$=0) at $\phi_c = \frac{\mu}{\omega+\mu}$. By analogous derivations, we can show that $\phi_c^f = \frac{\omega\mu}{1+\omega\mu}$

Suppose now that initially, the technological distance between the two technologies is small. If initially Southern technological firms are absent from the clean market, then at time t the speed of gaining blueprints will be given by $\frac{d\phi_c}{d\tau} = \lambda\mu$. If that speed is very high the central planner will take into account the additional benefit from investing in clean R&D in terms of capturing the foreign market and will decide to switch to clean technologies. Conversely, if the speed is very low, an impatient central planner will find that the benefit from investing in clean R&D is small.[5]

7 Conclusions

Building on the framework of Acemoglu et al. (2012) and Grossman and Helpman (1991), we have presented a North-South model in which both regions can innovate in clean or in dirty technologies and which allows the regions to trade in the technology goods (i.e. machines that embody the innovations). A successful innovation in the South allows the innovator to capture the domestic market and, if the innovation is applicable externally (which happens with exogenous probability), the market in the North region. A successful innovator will then receive a stream of profits until this market is 'stolen' by a subsequent innovation, which may come either from the South or North.

The presence of the business-stealing effect brings two important forces into the model when Northern researchers switch from the dirty to the clean sector. On the one hand, this switch implies more intensive innovation and business stealing in the clean sector and shorter expected periods in which a successful firm can enjoy its profits. It also implies less research and thus less competition in the dirty sector. On the other hand, more researchers working in the clean sector increases the value of the market that a potential innovator in the clean sector can capture.

The importance of the latter effect grows over time. A positive number of researchers in the clean sector allows the average value of the market in this sector to grow exponentially. This growth provides stronger and stronger incentives for Southern researchers to switch to the clean sector. In contrast, the former effect (of an increased competition in the clean sector) leads only to a level decrease in the value of the blueprint in the clean sector. Consequently, it will be always dominated in the long run. The total effect of an increase in the number of Northern researchers in the clean sector will always exert a force pulling Southern researchers to the same sector.

[5] If both central planners are strategic (i.e. coordinate the effort of own researcher), then the North will exert an effort of $\frac{1}{\phi_c}$ per blueprint concentrated on stealing Southern blueprints. Thus the stealing rate will be $-\lambda\phi_c\frac{1}{\phi_c}$. The South will concentrate its effort on Northern blueprints with an effort of $\frac{\mu}{1-\phi_c}$ per blueprint. Thus $\frac{d\phi_c}{d\tau} = -\lambda\phi_c\frac{1}{\phi_c} + \lambda\frac{\mu}{1-\phi_c}(1-\phi_c)$. So the entire market is eventually won by whoever has more researchers.

The pulling force will not be sufficient to ensure the switch of all researchers in the South if it is offset by an opposing force deriving from the the lock-in effect. When the initial stock of accumulated knowledge in the dirty sector is large, it encourages some of the researchers in the South to stay in the dirty sector. These researchers will continue to produce growth in the dirty blueprint market, which in turn increases the incentive for other Southern researchers to stay in the dirty sector in the future.

The size of the lock-in effect in the long run depends on the size of the population of researchers in the South. If the research sector in the South is smaller than in the North, then in the long run the lock-in effect will be always dominated by the foreign pull effect described before. Otherwise, we can observe a dirty sector lock-in in the South over the long run.

Subsequently, we examined the macroeconomic effects of the two possible balanced growth paths: one in which all researchers are working in the clean sector and one in which researchers are split, with all Southern researchers working in the dirty sector and all Northern researchers working in the clean sector. Ironically, while at the micro level the concentration of all researchers in the clean sector produces the strongest possible business stealing, at the macro level, such concentration produces the fastest possible economic growth. The entire global research effort is focused on building growth in the clean sector, which in the long run determines the final output growth in both regions. Along the alternative balanced growth path, the global research effort is split between two sectors producing substitutable goods. Due to this substitutability, the size of the clean sector in the South shrinks to zero in the long run and the aggregate economy in the South will not benefit from any innovations developed in the North.

Finally, we endogenised the behavior of the governments in the two regions. When the Southern government cares only about long run growth, its optimal strategy will always be to set research subsidies that ensure the Southern researchers will be working in the same sector as the Northern researchers. If the Northern government values both long run growth and the quality of the environment, the only possible sub-game perfect equilibrium in this set-up is the one with subsidies ensuring that both regions work only on the growth of the clean sector. Importantly, this result rests on the assumption that both governments will ignore the economic costs of the policy during the transition period. It also rests on the assumption that the North region can commit to its strategy of supporting clean technologies and it will not alter it under any circumstances.

Appendices

Appendix A1

Consumption is defined by equation 25 (restated below for convenience):

$$C = (1-\alpha)\,Y + \Pi + \Pi^f$$

We assume that at time $t = 0$, all clean technologies are owned by Northern firms while all dirty technologies are owned by Southern firms.

When all researchers in both regions work in the clean sector ($s = s_f = 1$) the growth of the aggregate economy along the BGP at home is the same as the growth of the clean sector. Thus the growth rate of consumption cannot be smaller than $\frac{\alpha_1}{1-\alpha}\gamma\lambda\,(\mu+\omega)$.

When researchers in South work in the dirty sector ($s = 0$, $s_f = 1$) the long run growth of the Southern economy as well as the growth of $\Pi = \frac{\gamma}{1+\gamma}\alpha_1 p_d Y_d$ are given by $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu$. The long run growth of $\Pi^f = \frac{\gamma}{1+\gamma}\alpha_1 p_d^f Y_d^f$ cannot be larger than the growth of foreign economy. If A_d^f grows faster than A_c^f then the dirty sector will dominate foreign economy and the growth of Π^f is given by $\frac{\alpha_1}{1-\alpha}\gamma\lambda\mu\omega$ (which is smaller than the growth rate of domestic economy). If A_c^f grows faster, clean sector dominates foreign economy which will grow at the rate $\frac{\alpha_1}{1-\alpha}\gamma\lambda < \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu$ (since this BGP requires $\mu>1$). This means that the consumption cannot grow faster than $g = \frac{\alpha_1}{1-\alpha}\gamma\lambda\mu$.

Appendix A2

The first term has growth bounded by $\left((\epsilon-1)\,\alpha_1\,(\gamma\lambda 2) + (1-\varphi)\,\frac{1-\alpha_1}{1-\alpha}\,(\sigma_{ct}g_c + \sigma_{dt}g_d)\right)$ with $(\sigma_{ct}g_c + \sigma_{dt}g_d) = \left(\sigma_{ct}\frac{\alpha_1}{1-\alpha_1}\gamma\lambda 2\right) < \gamma\lambda\frac{\alpha_1}{1-\alpha_1}2$

The second term has growth bounded by

$$\left(0+(1-\varphi)\,\frac{1-\alpha_1}{1-\alpha}\,(\sigma_{ct}g_c+\sigma_{dt}g_d)\right)$$

The third terms has two components: (i) the growth of ϕ weighted by $\frac{2\phi(s,1)\frac{\gamma}{1+\gamma}\alpha_1 p_c Y_c}{(1-\alpha)p_c Y_c+\left(1-\alpha+\frac{2\gamma}{1+\gamma}\alpha_1\right)p_d Y_d+2\phi(s,1)\frac{\gamma}{1+\gamma}\alpha_1 p_c Y_c}$. Growth of ϕ is $-\lambda\,(1+1)+\frac{\lambda}{\phi}$ (see the section on laborious entry). This multiplied by the weight gives $\frac{\frac{2\gamma}{1+\gamma}\alpha_1 p_c Y_c(-\lambda\phi(1+1)+\lambda)}{(1-\alpha)p_c Y_c+\left(1-\alpha+\frac{2\gamma}{1+\gamma}\alpha_1\right)p_d Y_d+2\phi(s,1)\frac{\gamma}{1+\gamma}\alpha_1 p_c Y_c}$ which is bounded. If the clean sector is initially small, this terms is initially very small. (ii) the second term is a growth of the clean sector. For this growth - see the bound on the first term

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