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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, this paper builds a North-South model that combines insights from directed technological change and quality-ladder endogenous growth models with business-stealing innovations. While North represents the region with climate ambitions, both regions have researchers choosing between clean and dirty applications, and the resulting technologies are traded. Three main results emerge: (i) In the long-run, if North's research and development (R&D) sector is large enough, researchers in South will follow the switch from dirty to clean R&D in North, motivated by the growing value of clean markets. (ii) If the two regions direct research effort toward different sectors and the outputs of the two sectors are gross substitutes, then the long-run growth rates in both regions are lower than if the global research effort were invested in one sector. (iii) If North's government induces its researchers to switch to clean R&D through clean technology subsidies, the welfare-maximizing choice for South is to ensure that all of its researchers switch too, unless the social discount rate is high. The last result is true even if South's R&D sector is large.

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Green Innovation and Economic Growth in a North-South Model

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1 Introduction

The mitigation of the greenhouse effect requires limiting greenhouse gas (GHG) emissions by all regions of the world. Limiting emissions by a single region or a coalition of regions cannot prevent the stock of GHG in the atmosphere from rising in the long run if the emissions of major regions outside the coalition grow. Those regions may be unwilling to introduce mitigation policies, such as carbon pricing, because, for instance, their governments believe that the costs of mitigation are too high or that the impact of climate change in their region will be mild. In this situation, emission reductions in outsider regions must be induced by an ambitious coalition of regions that are determined to mitigate climate change by undertaking policy measures unilaterally.

In this paper, we show that a unilateral green R&D effort by a single region (or sub-global coalition) can trigger emission reductions worldwide. R&D in one region results in spillover effects by driving up the value of the market for green technologies. In the long run, this expansion motivates researchers in all remaining regions to shift their research effort towards the further development of clean technologies. Moreover, the optimal policy of governments outside the coalition involves supporting the shift (with clean R&D subsidies) if the change in private incentives of researchers in their regions is insufficient. 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.

Our argument starts with a presumption of quality-ladder technological progress (Grossman and Helpman, 1992): by investing effort, a technology firm has a chance to improve technology developed by a competitor and capture its market. Suppose that one region with strong R&D potential builds up the market of clean technologies: then researchers in other regions will have incentive to jump on the same technological platform and work on innovations that improve 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 competition in the automobile industry. Although the market was pioneered by manufacturers in the United States, Japanese manufacturers partly captured the market through process innovations in the 1960s and 1970s (Cusumano 1988). Kindleberger (1975) describes the fascinating case of advancement of locomotives by German engineers in the mid-19th century. In 1841, all major suppliers of locomotives to the German market were located in Newcastle, Manchester, and Philadelphia. In the 1840s, German manufacturers took a British model, perfected it, and produced a model that outperformed its British rival. Between 1848 and 1854 German firms supplied 10 times more locomotives than all foreign firms together. A similar race was seen in the synthetic dye industry (Kindleberger, 1975). 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, product improvements, and fast market growth. One may expect that a similar competition for improvements in clean technologies could be induced by appropriately designed policy.

If the switch to clean technologies takes place in one region, private researchers in other regions will evaluate whether their benefits to switching are outweighed by lock-in forces keeping them in dirty markets. In this case, assuming South's government is benevolent, it will be strategically motivated to give an additional push to switching, if its discount rate is sufficiently low. Commitment by one region to keep its R&D in the clean sector implies that other regions cannot benefit from inter-regional spillover effects as long as their own R&D remains locked into the dirty sector. Their economic growth rate in this situation is strictly smaller than in the situation in which all regions work on the same technological platform. Therefore, after one region commits to clean R&D, the optimal response of the other regions' governments is to ensure that the switch also happens in their region.

To formalize 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 must choose between developing technologies for the clean or dirty sectors. By allowing both regions to engage in R&D, we depart from the usual setup of the North-South model, whereby North is a technological leader and South imitates the innovations of 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, and less-environmentally ambitious economies (see Dechezleprêtre 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 first closely related work to ours is the study by Acemoglu et al. (2014), who assume that innovations are generated in North and subsequently could be imitated by Southern researchers for their own industries. They demonstrate that a policy supporting green technologies in North can induce imitation of green technologies in South and thus reduce global emissions, provided that there is no international trade. However, if the regions can trade the outputs of dirty and clean sector, then South tends to specialize in dirty production, and the imitation of clean technologies then ceases to be profitable.

In an important departure from Acemoglu et al. (2014), we allow Southern researchers to develop their own innovations, not just imitate, and to trade in their blueprints. This novel approach allows us to demonstrate that (i) emissions reduction by a foreign region can be induced, even if that region is large and has its own strong R&D potential; and (ii) international protection of patents does not prevent R&D policy in one region from redirecting technological change globally. Legally protected clean innovation in North will contribute to clean technological progress in South, because researchers in South will build on top of ideas developed in North.

Innovation capacity in the Southern region has been incorporated in Hemous (2016) and van den Bijgaart (2017), who make different modeling assumptions about international trade, which influence the rationale for Southern researchers to switch to clean innovation. Specifically, these studies assumed, following Acemoglu et al. (2014), that the two regions trade the *output* of the clean and dirty sectors (i.e., clean and dirty intermediate goods, such as cement produced with clean or dirty technologies). Under these conditions, tax on dirty goods imported by North (in combination with climate and industrial policies in that region) then increases the production of clean (or carbon-neutral) goods in South. The increased demand for clean intermediate goods in North then drives clean innovation in South.

However, these studies did not consider the possibility that North and South could trade clean and dirty *technologies*. In Hemous (2016) and van den Bijgaart (2017), although Southern researchers were allowed to innovate, the resulting technologies would not compete directly, but rather only indirectly through intermediate goods trade. In contrast, we focus on direct competition between researchers in the two regions in our model: we assume that the two regions can trade the technologies used in the two intermediate sectors (machines), rather than trade the intermediate goods themselves. Consider, for example, that technologies are solar panels and coal power plant installations (boilers, turbines and pulverizers), which are traded internationally, while the clean and dirty intermediate goods are electricity from PV and from coal, which seldom cross regional boundaries. The trade of and competition on the markets for electricity generating technologies can play a significant role in the transition to a low-carbon economy.

By focusing on trade in clean and dirty technologies, rather than trade in intermediate goods, we highlight different reasons why Southern researchers could switch to clean innovation. We argue that Southern researchers redirect their R&D effort towards the clean technological platform because they want to capture the markets built by Northern researchers.

Furthermore, we show that unilateral action by North can induce global emission reductions under less restrictive conditions than in Hemous (2016) and van den Bijgaart (2017): North's action can now be effective even if it is not able to introduce trade tariffs and, perhaps more importantly, even if its economy is smaller than South's. When North is small, however, the result requires new conditions: a credible commitment by North to work on clean R&D, and sufficient patience on the part of South's government (i.e., a low enough discount rate). The Southern government will choose to motivate its researchers to follow the switch to clean R&D, because otherwise, if Southern researchers continued to work on dirty technological platforms, Southern consumers would never benefit from technological progress made in North. The presence of a patient Southern government is a condition because the private incentives of researchers in South do not include the long-term benefits of coordination with researchers in North.

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 monopoly rents, which are proportional to the size of the market (expected demand). Since the size of the market is built by successive innovations, Northern innovations in the clean sector encourage firms in South to direct R&D towards the markets in the same sector.

We elaborate this model next in Section 2. Section 3 explores the pull of research allocation in North on choices and technical change in South. Section 4 investigates the consequences for long-run growth in South, depending on their research allocation. Section 5 discusses the implications for emissions. Section 6 discusses welfare and presents the optimal research policies for the Southern government. Section 7 discusses implications, and Section 8 concludes.

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 produced with clean technologies and the other with dirty. Production of intermediate goods involves labor, which is in fixed supply, sector-specific resources, which are 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 decides whether to allocate research effort in the 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 materialized 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

[1] Greaker et al. (2018) propose a similar combination of DTC framework and the quality ladder set-up. However, they do not consider any interaction between technology firms in North and South.

separated.

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 Southern government, with its economy being the "domestic" economy and the Northern economy viewed as the "foreign" economy. The macroeconomic variables for the foreign economy will be marked with index f, while those for the home economy will have no index, for simplicity of notation. We will focus the analysis on the case in which all Southern researchers are conducting dirty R&D at the outset.

We will first derive the demand for intermediate goods and for technologies. Then we will show how the profit of technology firms 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 they matter for the central planner's optimization, they are not relevant 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 the production of clean and dirty intermediate goods at time t, $\epsilon > 1$ is the elasticity of substitution between the two goods, and Φ is the productivity parameter with symmetric impact on productivity of clean and dirty technologies.

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 optimization 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:

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

for $j = c, d$. We will use the symbol "$\hat{}$" to denote the value of prices or quantities associated with the production in the clean sector relative to their value in the dirty sector; i.e., for any variable x, $\hat{x} \equiv x_c / x_d$. 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 labor (L_j), natural resources (R_j) and a composite of machines (X_j):

$$Y_j = R_j^{\alpha_R} L_j^{1-\alpha} X_j^{\alpha_X},$$

with $\alpha = \alpha_X + \alpha_R$.

We consider the clean and dirty goods as using different natural resources (e.g., R_c might be land required for wind turbines while R_d is coal), which each have constant unit costs p_{Rc} and p_{Rd}, respectively (expressed in terms of the final good), and no scarcity rents.

The technology composite is formed of a continuum 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 characterized by its own productivity parameter A_{ij}.

We use the subscript h to denote goods produced for domestic market using domestic blueprints and m to denote goods produced for domestic market using foreign blueprints.[2] The machine of variety ij can be either produced using the most recent domestic blueprint (delivering Z_{hij}) or the most recent foreign blueprint (at quantity Z_{mij}), provided it could be adapted to domestic market. The two types of 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 domestic market ij. The best technology could be either domestic or foreign. The production and characteristics of the machines are described in the subsequent subsection.

We assume that the intermediate goods producers take all prices as given. Let w_t denote wages (which must be equal in both sectors as we assume free flow of labor within a country). The price of machine ij designed by a domestic inventor is p_{hij} and the price of machine ij designed by foreign inventor is p_{mij}.[3]

The optimization problem for the representative firm in an intermediate good sector is

$$\max_{Z_j,R_j,L_j} \quad P_j R_j^{\alpha_R} L_j^{1-\alpha} X_j^{\alpha_X} - p_{Rj} R_j - w L_j - \int_0^1 p_{hij} Z_{hij} di - \int_0^1 p_{mij} Z_{mij} di$$

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

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

$$\alpha_R P_j Y_j = R_j p_{Rj} \tag{3}$$

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

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

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

[2] Note that subscript h together with superscript f would denote goods produced for foreign (i.e. North) markets using foreign blueprints and subscript m together with superscript f would denote goods produced for foreign markets using domestic (i.e. South) blueprints.

[3] Note that p_{hij} and p_{mij} refer to prices paid by domestic producers of intermediate goods. In contrast, foreign intermediate goods producers would need to pay p^f_{hij} for machines designed by foreign inventors and p^f_{mij} for machines designed by domestic inventors.

its foreign competitor, then $Z_{ij} = Z_{hij}$, $Z_{mij} = 0$, and $p_{ij} = p_{hij}$. Otherwise, $Z_{ij} = Z_{mij}$, $Z_{hij} = 0$, and $p_{ij} = p_{mij}$.

Trade

We assume that factors of production are immobile and there is no international borrowing or lending, which means that net exports must be balanced in every period. There are two types of tradable goods: 1) the final good, which is excludable and rival, and 2) blueprints, which are partly excludable (the innovator can sell the blueprints giving a right to manufacture a machine) but not rival. Due to the non-rivalry of blueprints, the model is different from a typical Ricardian trade model. Trade takes place because each region generates blueprints that are potentially valuable in the other region. If a firm in one region wants to purchase a blueprint invented in the other region, it can always compensate the inventor by purchasing and exporting some final good. At the level of a region, if the region is a net importer of blueprints, it must be a net exporter of the final good.

Final goods produced in either country are identical, so their price is identical as long as there is trade. Because we normalized price of South's final good to unity, the price of North's final good is also equal to unity. This means that all values for the foreign economy (such as profit from using a blueprint in the foreign region) are expressed in the units of final good.

We assume that an innovator can sell blueprints to domestic and foreign monopolists (manufacturers of machines) at different prices, which means that we can consider two separate and independent monopolists' optimization problems and use their outcome to determine the price of blueprints for domestic and foreign markets.

Labor and wages

Domestic supply of labor engaged in clean or dirty production 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 final good output:

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

We assume no population growth, so L and L^f (labor supply in the foreign regions) are constants.

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 characterized 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. In the context of directed technological change, a similar set-up was considered by Greaker et al. 2018. This formulation allows to explicitly take into account that when technological firms decide where to allocate their effort, they consider the value of the market of a particular machine.

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, $p_{hij} = (1 + \gamma) \psi$. The monopolist does not have an incentive to set a lower price because the demand curve is unit elastic. 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

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

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

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

If the innovation is applicable abroad, which happens with probability ω (exogenous in our model), the newcomer also receives the instantaneous profit from the foreign market. The expected value of that profit is given by

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

where superscript f is used to denote the variable for the foreign economy and ω is the probability that the domestic innovation could be successfully applied on foreign market.

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 variety will therefore be equally likely.[4]

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

[4]The symmetry between profits for varieties 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.

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 ($\epsilon > 1$).

Let $A_j(t)$ stand for the geometric average of technologies in sector j at time t raised to the power $\frac{\alpha_X}{1-\alpha_X}$ (we introduce this exponent to simplify algebra):

$$\ln(A_j(t)) = \frac{\alpha_X}{1-\alpha_X} \int_0^1 \ln(A_{ij}(t))\, di.$$

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

$$P_j = \Omega A_j^{-(1-\alpha_X)} p_{Rj}^{\alpha_R} w^{1-\alpha}, \tag{10}$$

where $\Omega = \alpha_R^{-\alpha_R} \left(\frac{\alpha_X}{(1+\gamma)\psi}\right)^{-\alpha_X} (1-\alpha)^{-(1-\alpha)}$ 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 labor market equilibrium (6), wages are $w = (1-\alpha) Y/L$. Combining this with equation (10), we can then express the revenue in sector j as a function of final good output, the cost of resources, and the technology used in sector j. The revenue in sector j is proportional to:

$$P_j Y_j \propto A_j^{\varphi_X} p_{Rj}^{-(\epsilon-1)\alpha_R} Y^{(1-\varphi)}, \tag{11}$$

where $\varphi_X = (1-\alpha_X)(\epsilon-1)$ and $\varphi = (1-\alpha)(\epsilon-1)$.[5]

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

[5]With total labor supply (L) assumed to be constant, it is not included on the right-hand side.

all research effort is channeled to the clean sector, i.e., $\varphi > 1$. This condition mirrors the condition on the elasticity of substitution in the Acemoglu et al. (2012) paper. If the condition is not satisfied, then long-run growth of emissions cannot be prevented, even if global R&D effort is directed towards clean innovation.

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

$$Y \propto \left(A_c^{\varphi_X} p_{Rc}^{-(\epsilon-1)\alpha_R} + A_d^{\varphi_X} p_{Rd}^{-(\epsilon-1)\alpha_R} \right)^{\frac{1}{\varphi}} \tag{12}$$

Using (11) we can also express revenues as

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

where

$$\sigma_j \equiv \frac{p_j Y_j}{Y} = \frac{\left(A_j^{1-\alpha_X} p_{Rj}^{-\alpha_R}\right)^{\epsilon-1}}{\left(A_d^{1-\alpha_X} p_{Rd}^{-\alpha_R}\right)^{\epsilon-1} + \left(A_c^{1-\alpha_X} p_{Rc}^{-\alpha_R}\right)^{\epsilon-1}} \tag{14}$$

is the share of sector j in the total output.

To summarize the analysis to this point, we have demonstrated that the profit of a successful innovator is proportional to the total revenue of that sector (equation 8) and that the revenue is determined by the level of final good output 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 A_c/A_d 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 share of researchers devoted to clean technologies.

Technology paths

Differentiating the average of productivity of technologies in sector j with respect to time,

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

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 assumed 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, the expected number of improvements per unit of time delivered by domestic researchers is $\lambda\mu s$ and the expected number of domestically applicable improvements delivered by the foreign research sector is $\lambda\omega s^f$.[6] Due to the law of large numbers, the expected number of improvements is equal to the fraction of varieties improved. Thus there are $\lambda(\mu s + \omega s^f)$ 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

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

The value of a blueprint

As noted in the previous section, innovation is associated with the loss of monopoly profit on the part of the owner of the previous blueprint. On the one hand, the innovator captures the entire value of the market and thus benefits from all previous innovations. This effect is known in the endogenous growth literature as the *intertemporal spillover effect*. On the

[6] Recall that the number of researchers in North is normalized to unity.

other hand, the innovator only receives the dividend until the next incremental innovation arrives and captures the full value again. This effect is known as the *business-stealing effect*.

The presence of the two effects was the central feature in the models of Grossman and Helpman (1991) and of Aghion and Howitt (1992). Their relative sizes determined whether decentralized 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 two effects is central: as we will see, the possibility of winning the market and benefiting from intertemporal spillovers encourages innovators in South to operate in the same sector as innovators in North. On the other hand, the crowd of researchers concentrated in one sector leads to frequent business stealing and discourages innovating there in the short-run.

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 an asymptotic steady-state (SS) where s, s^f and the growth rates of productivity in the two sectors are constant. Throughout the analysis we assume that the economy converges toward such an asymptotic SS, i.e we rule out the possibility of cycles.

Note that since the innovators are indifferent between working on any variety within 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 $\lambda\left(\mu s+\omega s^f\right)$. 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 variety i in the clean sector is then given by

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

where ρ denotes the discount rate used by a firm.

This can be also expressed as

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

where

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

and

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

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

$$\Gamma_c\left(s, s^f\right) = \int_{\tau=t}^{\infty} e^{-\chi\left(s,s^f,g\right)(\tau-t)} \tag{17}$$

where

$$\chi\left(s, s^f, g\right) = \rho + \left(1 - \gamma\alpha_X(\epsilon - 1)\right)\lambda\left(\mu s + \omega s^f\right) + (\varphi - 1)\,g \tag{18}$$

.

In order to ensure that the value of technology firm is finite, we assume that $\gamma\alpha_X(\epsilon - 1) < 1$. If the condition is satisfied, $\chi > 0$ and the integral in Γ_c is finite.

Incentives for researchers in the long run: The intuition

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

$$g = \frac{1-\alpha_X}{1-\alpha}\left(\sigma_c g_c + \sigma_d g_d\right), \tag{19}$$

Since in the asymptotic SS 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 (determined in equation (19)) converges to a positive constant; $\chi\left(s, s^f, g\right)$ (determined in equation (18)) converges to a strictly positive constant;

and Γ_c (determined in equation (17)) approaches its finite and strictly positive limit given by $1/\chi\left(s, s^f, g\right)$. The same argument applies to $\Gamma_c^f\left(s, s^f\right)$, $\Gamma_d\left(s, s^f\right)$ and $\Gamma_d^f\left(s, s^f\right)$.

Since Γ's are constant in the long run, equation (16) implies that v_c grows (or vanishes) together with π_c and π_{cf}. The growth of profit as a function of growth of technologies can be determined using equations (8), (9) and (11). The growth of technologies as a function of allocation of researchers is determined by equation (15). Combining all these equations, enables us to relate the growth of v_c with 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 the value of the innovation (v_c) grows together with the value of the market ($Y_c p_c$). 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 value of innovation is fully captured by only one researcher: the one who came up with the most recent innovation. This *intertemporal spillover effect* will result in a gravitational force that pulls researchers into one sector. Every researcher will wish to work for the sector that has accommodated a large number of researchers in the past. We formalize this argument in the next section.

3 Research allocation and technical change

We have established how the opportunity for 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 Northern researchers to the clean sector will build up the value of this sector in the long run and thus generate an incentive for Southern researchers to follow the switch. We will formally present this argument in the next two subsections.

3.1 Symmetric regions

We will first analyze the simplest case when the two regions are symmetric – at least in the sense that they have the same labor force, the same prices of resources, p_{Rj}'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 characterized 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

$$\hat{v}_t = \frac{v_{ct}}{v_{dt}} = \hat{\Gamma}\hat{\pi}; \tag{20}$$

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

Profit, $\hat{\pi}$, can be expressed (using (8), (11) and (15)) as

$$\hat{\pi}\left(s, s^f\right) = \hat{A}(t)^{\varphi_X}\hat{p}_R^{-(\epsilon-1)\alpha_R} = \hat{A}_0^{\varphi_X}\hat{p}_R^{-(\epsilon-1)\alpha_R}\left(\frac{e^{\gamma\lambda\left(s+s^f\right)t}}{e^{\gamma\lambda\left(2-s-s^f\right)t}}\right)^{\alpha_X(\epsilon-1)} \tag{21}$$

In the asymptotic SS, $\hat{\Gamma}$ is constant and can be expressed as:

$$\hat{\Gamma}\left(s, s^f\right) = \frac{\rho + \left\{\lambda\left(2-s-s^f\right)\right\} - \left[\alpha_X\left(\epsilon-1\right)\gamma\lambda\left(2-s-s^f\right)\right] + \left(\varphi-1\right)g\left(s, s^f\right)}{\rho + \left\{\lambda\left(s+s^f\right)\right\} - \left[\alpha_X\left(\epsilon-1\right)\gamma\lambda\left(s+s^f\right)\right] + \left(\varphi-1\right)g\left(s, s^f\right)} \tag{22}$$

Thus, in the long-run the relative value, $\hat{v}$ will change over time along with $\hat{\pi}$: depending on the allocation of researchers, it 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 compensation for research effort in the two sectors and allocates its entire research effort to the dirty sector if $v_{ict} + \frac{\xi_c}{\lambda} \leq v_{idt} + \frac{\xi_d}{\lambda}$. Note that in this specification, for any parameter values, the government always has the possibility to incentivize 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 decrease the equilibrium number of researchers working for the dirty sector. We are interested in the consequence of this shift for the allocation of researchers in 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 (22) 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 imply that once the innovator captures the market, the revenue is not constant, but rather increases over time. This effect is marked with square brackets in (22).

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 $g\left(s, s^f\right)$ in equation (22).

Finally, the more researchers are working in the clean sector, the faster is the productivity growth of the machines in the clean sector relative to that in the dirty sector. Consequently, the demand for the clean intermediate good grows and so does the size of the market (quantity demanded) for clean machines. The benefit from capturing one of such markets in the event of a successful innovation thus also grows. Conversely, fewer researchers in the dirty sector implies slower growth of that sector and fewer benefits from capturing a market in the dirty industry in the long run. This effect is framed in the exponential terms in equation (21).

Note that, contrary to the first three effects, which change the *level* of the blueprint's value (through the changes in the asymptotic SS 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. We will label this effect the long-run pulling effect.

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.[7]

The second possibility is the limit on the growth of productivity. In our model, the exponential growth of productivity under a 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 North to the clean sector will 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 South.

Suppose at time $t = 0$ all Southern researchers work in the dirty sector and all Northern researchers work on clean technologies (with productivity factor). Let A_{d0} and A_{c0} denote

[7]Theoretically, in our model $\hat{\Gamma}$ could decline due to an increase in the business-stealing rate, $\lambda\left(s + s^f\right)$, 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 productivity of machines in the dirty and clean sector, respectively, at time $t = 0$. The following proposition clarifies under what conditions the Southern researchers switch to the clean sector.

Proposition 1 *Allocation of Southern researchers when there is no government intervention in South and the two regions are otherwise symmetric: If at time $t = 0$, $s = 0$ and $s^f = 1$, then the Southern researchers will stay in the dirty sector if*

$$A_{c0}^{\varphi_X} p_{Rc}^{-\alpha_R(\epsilon-1)} \leq A_{d0}^{\varphi_X} p_{Rd}^{-\alpha_R(\epsilon-1)}$$

Proof. Allocation of Southern researchers when the two regions are asymmetric: when all Southern researchers are working in the dirty sector ($s = 0$) and all Northern researchers are working in the clean sector ($s^f = 1$), then the condition above together with (21) implies that at $t = 0$

$$\hat{\pi} = \hat{A}_0^{-\varphi_X} \hat{p}_R^{-(\epsilon-1)\alpha_R} \leq 1$$

In addition, since the two profits grow at the same rate, $\Gamma_c = \Gamma_d$. Hence, by equation (20), 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 ($s^f = 1 - s = 1$), the two sectors grow at exactly the same rate and the condition stated in the proposition holds in all subsequent periods. ■

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 an asymptotic SS with the two sectors growing at the same pace. The reason why the switch in North is not propagated in South is that the long-run pulling effect driven by the progress in clean technologies is offset by the lock-in effect driven by the progress of dirty technologies: from the perspective of an individual researcher, all other researchers in South continue fueling progress of dirty technologies, which drives growth of value of dirty varieties. As a result, the researcher has an incentive to stay in the dirty sector.

In the symmetric model with an equal number of researchers in South and in North, the long-run pulling effect and the lock-in effect will be exactly equal to each other. To change the asymptotic SS, we would need the long-run pulling effect to be at least marginally larger than the lock-in effect. This case will be discussed in the case of asymmetric regions in the subsequent section.

3.2 Asymmetric regions

Let us now drop the assumption of 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 $\omega \leq 1$; 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

$$g_c^f = \frac{\alpha_X}{1-\alpha_X}\gamma\lambda\left(\omega\mu s + s^f\right) \tag{23}$$

$$g_d^f = \frac{\alpha_X}{1-\alpha_X}\gamma\lambda\left(\omega\mu\left(1-s\right) + 1 - s^f\right) \tag{24}$$

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

$$v_j = \pi_j\Gamma_j + \pi_j^f\Gamma_j^f \tag{25}$$

The evolution of π_j and π_j^f will be determined by the paths of technologies and the growth rate of final good output:

$$\pi_j \propto (A_j)^{\varphi_X} p_{Rj}^{-(\epsilon-1)\alpha_R} Y^{(1-\varphi)}$$

$$\pi_j^f \propto (A_j^f)^{\varphi_X} p_{Rj}^{-(\epsilon-1)\alpha_R} \left(Y^f\right)^{(1-\varphi)}$$

where Y^f is the foreign final good output per capita.

Meanwhile, in the asymptotic SS, $\Gamma_j\left(s, s^f\right)$ 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 North work on clean technologies. The asymptotic SS with some Southern researchers in the dirty sector is only possible when the number of researchers in South is larger than the number of researchers in 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 asymptotic SS with constant $s < 1$ is not feasible.

First, we will consider the asymptotic SS with $s = 0$ (all Southern researchers working in the dirty sector). Afterwards, we will consider the asymptotic SS with $s \in (0, 1)$.

The value of the clean blueprint is determined by equation (25). Since Γ's are constant in the asymptotic SS, the first term in this expression grows at the growth rate of $A_c^{\varphi_X} Y^{(1-\varphi)}$ given by

$$\alpha_X (\epsilon - 1) \gamma \lambda \omega - (\varphi - 1) g \tag{26}$$

The second term grows at the growth rate of $\left(A_c^f\right)^{\varphi_X} \left(Y^f\right)^{(1-\varphi)}$ given by

$$\alpha_X (\epsilon - 1) \gamma \lambda - (\varphi - 1) g^f \tag{27}$$

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 foreign economy, if $\mu < 1$ and North has more researchers than South, the clean sector is always the fastest-growing sector and thus $g^f = \frac{\alpha_X}{1-\alpha} \gamma \lambda$. Then (27) reduces to $\frac{\alpha_X}{1-\alpha} \gamma \lambda$. In the case of the domestic economy, we have to distinguish between the two cases. If $\mu \leq \omega$, then $g_c \geq g_d$ and $g = \frac{\alpha_X}{1-\alpha} g_c = \frac{\alpha_X}{1-\alpha} \gamma \lambda \omega$, so (26) reduces to $\frac{\alpha_X}{1-\alpha} \gamma \lambda \omega$. If $\mu > \omega$, then $g_c < g_d$ and $g = \frac{\alpha_X}{1-\alpha} g_d = \frac{\alpha_X}{1-\alpha} \gamma \lambda \mu > \frac{\alpha_X}{1-\alpha} \gamma \lambda \omega$. In this case the expression in (26) must be smaller than $\frac{\alpha_X}{1-\alpha} \gamma \lambda \omega$.

In both cases ($\mu \leq \omega$ and $\mu > \omega$), in the long run the first term in (25) 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 $\frac{\alpha_X}{1-\alpha}\gamma\lambda$.

Let's now consider the dirty sector. The first term in expression (25) evaluated for the dirty sector will grow at the rate

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

The second term in expression (25) evaluated for the dirty sector will grow at the rate

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

Thus, the value of a blueprint in dirty sector will grow more slowly 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 $\frac{\alpha_X}{1-\alpha}\gamma\lambda (1 + \omega\mu s)$ while the growth of the value of the dirty blueprint cannot be larger than $\frac{\alpha_X}{1-\alpha}\gamma\lambda (1 - s) \mu$. 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 condition that s stays constant in the asymptotic SS. ■

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

Note also that the asymptotic SS 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 $\frac{\alpha_X}{1-\alpha}\gamma\lambda (\mu + \omega)$, as well as the growth of π_c^f, which is equal to $\frac{\alpha_X}{1-\alpha}\gamma\lambda (\omega\mu + 1)$, is positive. Meanwhile the growth of π_d, which is equal to $-(\varphi - 1) g$ and π_c^f, which is equal to $-(\varphi - 1) g^f$, 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 asymptotic SS with $s = 1$.

As a result, the government in South is always able to incentivize 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 favor of the clean sector.

4 The consequences for long-run growth

In this section we will explore the long-run growth rate of the Southern economy when all researchers in both regions work in the clean sector ($s = s^f = 1$) as compared to when the research effort is split, with researchers in North working in the clean sector and researchers in South working in the dirty sector ($s = 0$, $s^f = 1$). In the next section we will use these growth rates to evaluate the welfare of Southern consumers and discuss the optimal choice of policy by the government in South.

When all researchers focus on the clean sector, the growth of productivity in the clean and dirty sectors can be derived using (15) as $g_c = \frac{\alpha_X}{1-\alpha_X}\gamma\lambda\left(\mu+\omega\right)$ and $g_d = 0$, respectively. Inserting it into the expression for final good output growth in (19), we obtain

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

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

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

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

In this asymptotic SS, since productivity in the dirty sector grows faster than in the clean sector,[8] in the long run the dirty sector will dominate the economy, implying that the long-run growth of the Southern economy is given by $g = \frac{\alpha_X}{1-\alpha}\gamma\lambda\mu$. This growth rate 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 can differ from final-good output due to trade in technologies. It can be 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 the domestic economy given by $\frac{\alpha_X}{1-\alpha}\gamma\lambda(\mu+\omega)$. If the research effort is split ($s = 0$, $s^f = 1$), consumption cannot grow faster than $g = \frac{\alpha_X}{1-\alpha}\gamma\lambda\mu$ (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

$$R_d = constant * \left[\frac{\left(A_d^{\varphi_X} p_{Rd}^{\alpha_R(1-\epsilon)}\right)}{\left(A_d^{\varphi_X} p_{Rd}^{\alpha_R(1-\epsilon)}\right) + \left(A_c^{\varphi_X} p_{Rc}^{\alpha_R(1-\epsilon)}\right)}\right]^{\frac{\varphi-1}{\varphi}} \left(A_d p_{Rd}^{-1}\right)^{\frac{1-\alpha_X}{1-\alpha}}$$

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 $\varphi_X > 0$). 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.

[8] Recall from proposition 2 that for the asymptotic SS with $s = 0$, it must be that $\mu > 1 > \omega$ and hence $g_c = \frac{\alpha_X}{1-\alpha_X}\gamma\lambda\omega < \frac{\alpha_X}{1-\alpha_X}\gamma\lambda\mu = g_d$

By contrast, in the asymptotic SS 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 $\frac{1-\alpha\chi}{1-\alpha} g_d = \frac{\alpha\chi}{1-\alpha}\gamma\lambda\mu > 0$. This last result does not depend on the elasticity of substitution between the two goods.

6 Optimal strategies for South

In the analysis until now we have assumed the absence of governmental subsidies in 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 asymptotic SS with South researchers working in the same sector as researchers in North. If the government is impatient, however, the optimal decision of the government in 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 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 the clean sector. In this paper, we consider the extreme case in which the planner in South does not have these additional incentives.

In each instance of time, consumption is determined by

$$C = (1 - \alpha) Y + \Pi + \Pi^f \tag{28}$$

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. Domestic consumption differs from domestic final-good output due to exports (necessary to purchase the foreign technologies) and imports (financed by the sale of domestic technologies abroad).

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

$$Y \propto \left(A_c^{\varphi_X} p_{Rc}^{-(\epsilon-1)\alpha_R} + A_d^{\varphi_X} p_{Rd}^{-(\epsilon-1)\alpha_R} \right)^{\frac{1}{\varphi}}$$

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 South switch from dirty to clean R&D ($s = s^f = 1$) then at time τ,

$$\Pi(\tau) = \phi_c(\tau) \frac{\gamma}{1+\gamma} \alpha_X P_c(\tau) Y_c(\tau) + \frac{\gamma}{1+\gamma} \alpha_X P_d(\tau) Y_d(\tau) \tag{29}$$

$$\Pi^f(\tau) = \phi_c^f(\tau) \frac{\gamma}{1+\gamma} \alpha_X P_c^f(\tau) Y_c^f(\tau) + \frac{\gamma}{1+\gamma} \alpha_X P_d^f(\tau) Y_d^f(\tau) \tag{30}$$

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 in the asymptotic SS and given by $\mu/(\mu + \omega)$. Similarly, $\phi_c^f = \omega\mu/(1 + \mu\omega)$.

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

$$\Pi(\tau) = \frac{\gamma}{1+\gamma} \alpha_X P_d(\tau) Y_d(\tau) \tag{31}$$

$$\Pi^f(\tau) = \frac{\gamma}{1+\gamma} \alpha_X P_d^f(\tau) Y_d^f(\tau) \tag{32}$$

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 faster long-run growth in consumption. Here, we sketch the argument (we provide more formal derivations in Appendix A3).

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 a constant rate which cannot be smaller than the growth of the domestic economy given by $g = \frac{\alpha \chi}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$. Thus, in the long-run, South's welfare approaches

$$W_0\left(1\right) \to \int_0^{\tau^*} e^{-\rho\tau} C\left(\tau;1,1\right) d\tau + \int_{\tau^*}^{\infty} e^{-\left(\rho-g(1,1)\right)\tau} C\left(\tau^*;1,1\right) d\tau \tag{33}$$

$$= \int_0^{\tau^*} e^{-\rho\tau} C\left(\tau;1,1\right) d\tau + \frac{C\left(\tau^*;1,1\right)}{\rho - g\left(1,1\right)} \tag{34}$$

where $C\left(\tau;1,1\right)$ denotes consumption at time τ when $s=1$ and $s^f=1$, $g\left(1,1\right)$ denotes the growth of the domestic economy when $s=1$ and $s^f=1$ and $W_0\left(1\right)$ denotes welfare when $s=1$.

By analogous argument, we can express welfare when Southern researchers stay in the dirty sector ($s=0$) as:

$$W_0\left(0\right) = \int_0^{\tau^*} e^{-\rho\tau} C\left(\tau;0,1\right) d\tau + \frac{C\left(\tau^*;0,1\right)}{\rho - g\left(0,1\right)} \tag{35}$$

where $C\left(\tau;0,1\right)$ denotes consumption at time τ when $s=0$ and $s^f=1$, $g\left(0,1\right)$ denotes the growth of the domestic economy when $s=0$ and $s^f=1$ and $W_0\left(0\right)$ denotes welfare when $s=0$.

To ensure that all integrals converge, we assume that $\rho > g\left(1,1\right) = \frac{\alpha\chi}{1-\alpha}\gamma\lambda\left(\mu+\omega\right)$. For this reason, the terms in $W_0\left(1\right)$ and $W_0\left(0\right)$ are finite. However, we can make the term $\frac{C\left(\tau^*;1,1\right)}{\rho-g\left(1,1\right)}$ in (34) arbitrarily large by choosing a ρ that is sufficiently low (i.e., sufficiently close to $\frac{\alpha_X}{1-\alpha}\gamma\lambda(\mu+\omega)$). In turn, the term $\frac{C(\tau^*;0,1)}{\rho-g(0,1)}$ in (35) is bounded from above by $\frac{C(\tau^*;0,1)}{g(1,1)-g(0,1)} = \frac{C(\tau^*;0,1)}{\frac{\alpha_X}{1-\alpha}\gamma\lambda\omega}$. This implies that there exists a threshold level, $\rho^*(0)$, such that for every $\rho < \rho^*(0)$, $W_0(1) > W_0(0)$.

More generally, let $W_0(s)$ be South's welfare when the share of Southern researchers working in the clean sector in the long run is s. We can follow exactly the same logic as above to show that $W_0(1) > W_0(s)$ for $s < 1$. In this case, the term $\frac{C(\tau^*;s,1)}{\rho-g(s,1)}$ (corresponding to the second term in (35)) is bounded from above by $\frac{C(\tau^*;s,1)}{g(1,1)-g(s,1)}$, which is finite unless $s \to 1$. Meanwhile, as noted in the paragraph above, we can make the term $\frac{C(\tau^*;1,1)}{\rho-g(1,1)}$ in (34) arbitrarily large by choosing a ρ that is sufficiently low (i.e., sufficiently close to $g(1,1) \equiv \frac{\alpha_X}{1-\alpha}\gamma\lambda(\mu+\omega)$). Thus, for every s, there exists a threshold level, $\rho^*(s)$, such that for every $\rho < \rho^*(s)$, $W_0(1) > W_0(s)$.

We summarize the result of this subsection in the following proposition.

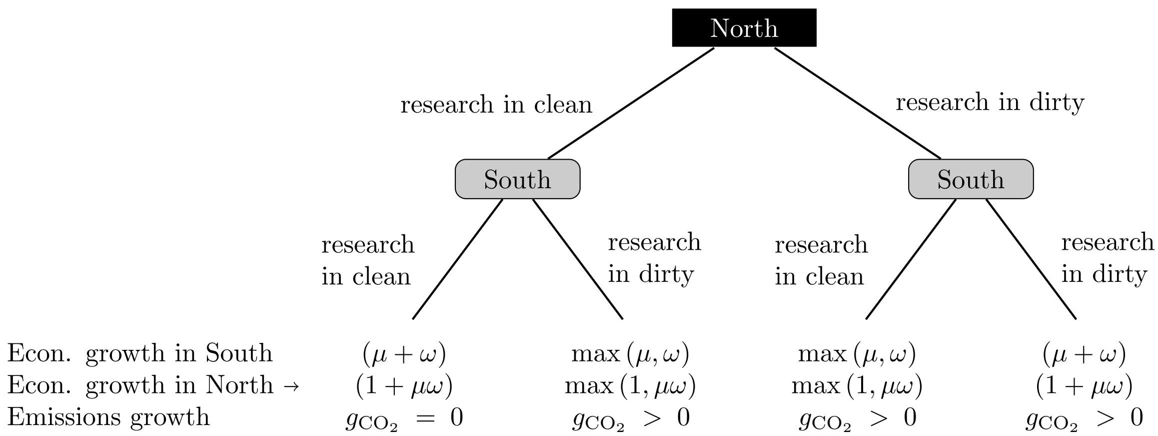
Proposition 4 *Assume that $\rho > g(1,1) = \frac{\alpha_X}{1-\alpha}\gamma\lambda(\mu+\omega)$, so that welfare, W, is always finite. If the planner is sufficiently patient (i.e., ρ is below the threshold level $\min_s\{\rho^*(s)\}$), then the social optimum will always involve a switching to clean research in the long run.*

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

Finally, in order to endogenize the behavior of both the North and South governments, we consider the following game: First, North chooses the subsidy rate for clean and dirty research. This choice is observed by the government in South, which then has to make its own decision. To simplify this game as much as possible, we assume that the payoffs of North's 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 South's government is to maximize the long-run growth of output. South's government will always set a subsidy that ensures that Southern researchers work in the same sector as the researchers in North. According to the argument in section 4, this will bring the long run growth rate equal to $\frac{\alpha_X}{1-\alpha}\gamma\lambda(\mu+\omega)$. Otherwise, i.e., if the government lets its researchers choose a different sector, the long-run growth of the economy will be $\frac{\alpha \chi}{1-\alpha}\gamma\lambda \max(\mu, \omega)$.[9]

This strategy of the Southern government implies that, no matter which sector North subsidizes, the long-run growth in North will always be equal to $g = \frac{\alpha \chi}{1-\alpha}\gamma\lambda (1 + \mu\omega)$. These payoffs are summarized in Figure 1.[10]

Figure 1: Long-run outcomes in a Stackelberg game



As a result, if North's government is rational and concerned about the environment, 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 summarizes this result:

Proposition 5 *Suppose that South and North choose the allocation of their researchers between clean and dirty sector (by choosing appropriate research subsidies) and they play a sequential game with North as the leader and South as the follower. Suppose that the payoff for South is long-run economic growth, and the payoff for North is an increasing function of both long-run economic growth and environmental quality. Then the unique subgame perfect Nash equilibrium of that game is defined as follows:*

- *The government in South will always choose research subsidies that ensure that Southern researchers work in the same sector as Northern researchers.*

[9] Suppose that South invests all effort in sector j and North invests in the other sector, $-j$. Using (15) and derivations in section 4, if $\mu > \omega$, $g_j > g_{-j}$, $\sigma_j \to 1$ and $g = \frac{\alpha \chi}{1-\alpha}\gamma\lambda\mu$. If $\mu \leq \omega$, then $g = \frac{\alpha \chi}{1-\alpha}\gamma\lambda\omega$.

[10] We suppress the term $\frac{\alpha \chi}{1-\alpha}\gamma\lambda$ in expressions of economic growth rates to ease the exposition.

- *The government in 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 North is the first mover. Effectively this means that the government in North must be fully committed to its initial decision: no matter what the decision of the Southern government may be, North must continue subsidizing the clean R&D.

6.4 Optimal path for an impatient South

In this subsection, we illustrate why the result established in section 6.2 will not hold if 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 each in turn. For ease of exposition, we return to the assumption of symmetric regions.

Large technological distance

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 19). The benefits of switching to clean R&D for consumers in South, as demonstrated in section 6.2, will materialize 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, whether $s = 1$ or $s = 0$. Consequently, the paths of consumption must be determined 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, the planner's decision will be determined by the growth rates immediately after $\tau = 0$.

With symmetric regions, consumption in South could be expressed (by evaluating the right hand side of (28)) as

$$C(\tau) = (1-\alpha)\, p_c(\tau)\, Y_c(\tau) + \left(1 - \alpha + \frac{2\gamma}{1+\gamma}\alpha_X\right) p_d(\tau)\, Y_d(\tau) + \phi_\tau(s,1)\, \frac{2\gamma}{1+\gamma}\alpha_X p_c(\tau)\, Y_c(\tau),$$

so 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 are determined by the contribution of each term to total consumption. For instance, if the contribution of labor compensation $((1-\alpha)\, p_c(\tau)\, Y_c(\tau))$ 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.[11] 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 $\frac{\alpha_X}{1-\alpha}\gamma\lambda$.

Next, consider the choice of subsidies that ensure the movement from the dirty to the clean sector. In this case $s = 1$, and the productivity of the clean sector grows at the rate $2\frac{\alpha_X}{1-\alpha}\gamma\lambda$ 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 growth is small. The reason is that if the technological distance is initially large ($\frac{A_c}{A_d}$ small), 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,

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

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 favor the status-quo with the growth of the dirty sector than the choice of subsidies that could incentivize 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 demonstrated that this speed is irrelevant for a patient central planner in South with a very low discount rate, because consumer welfare depends primarily on long-run growth. However, speed may be a pivotal factor for the decision of the central planner who is impatient.

If a region r at the beginning has full market share in the sector of clean technologies ($\phi_r = 1$) and no innovation whatsoever, then the path of ϕ_r will be given by

$$\phi_r(\tau) = e^{-\lambda(n_{-r})\tau}$$

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

Taking the derivative we get

$$\frac{d\phi_r}{d\tau} = -\lambda e^{-\lambda(n_{-r})\tau} = -\lambda\phi_r$$

Notice that South's government would like to prevent the situation in which a researcher in South captures the market of another researcher in South. The same preference applies to the government in North. We could consider two alternative setups. In the first setup, neither 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 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 productivity distance between the two technologies is small. If initially Southern technology 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.[12]

7 Discussion

The optimal policy in North encourages competition between researchers in North and South over the clean technology markets. Preventing Southern researchers from standing on the shoulders of technological giants in North would push them back to the dirty sector. At best, if the Southern R&D sector is smaller than the sector in North, the distance between dirty and clean technologies would decrease more slowly compared to the situation where everyone works on the clean technology platform. At worst, if South's R&D sector is larger than the one in North, preventing Southern researchers from using Northern knowledge would slow the increase in clean technologies relative to dirty technologies. Note that in this case, the

[12]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.

Southern government has no incentive to subsidize clean research no matter how patient it is.

Indeed, North could increase the chance that Southern researchers will join the clean technology platform by adopting measures that improve the capacity of researchers in South to adapt and improve clean technologies developed in North. Concrete examples include training for engineers in South, financing common clean R&D projects, and perhaps technology transfer and licensing. This policy decreases the profits of technology firms in the short run (see the static market capturing effect described in section 3.1), but increases consumer welfare in the long run.

However, increasing capacity of South to improve clean blueprints must not eliminate the legal protection of blueprints developed in North. Legal protection ensures that successful innovators in North receive a stream of monopoly rents. If there is no such stream, the market returns to innovations in North are zero.[13] Indeed, the presence of temporary monopoly rents is essential for long-run technological progress (see the discussion on monopolistic competition among innovators in Romer 1989, and more recently Acemoglu 2008).

Turning now to the optimal policy of South, the patient government should ensure that its consumers benefit from the ideas developed in North. If in the steady state researchers in South and North work on two different and substitutable technological platforms, in the long run ideas developed in North have no value for consumers in South, because production there is based on the dirty technology platform. If instead South and North researchers work on the same platform, they build on each other's ideas. Given the commitment of North to clean R&D, South's government should not allow technology firms to stay focused on dirty technologies, if its objective is to maximize the long-run growth of consumption.

If the Southern government is impatient, the optimal policy depends on the relative size of R&D sector in North. If North's R&D sector is much smaller than the one in South, then its potential contribution to long-run growth is small, and thus the benefits of working on one technology platform are small. At the same time, redirecting Southern R&D involves high opportunity costs in the short run: redirecting R&D effort away from the dirty technology

[13] In theory, in our setup the firms might still develop clean blueprints incentivized by the clean R&D subsidy. However the costs of such policy in North would be large.

platform implies that in the first years the largest economic sector is stagnant. In this case, the government does not encourage the shift of R&D to the clean sector, if its objective is to maximize its discounted consumption path. On the other hand, if the size of the R&D sector in North is comparable to the one in South, the benefit of faster long-run growth could be substantial. Whether or not future growth outweighs the short-run cost depends on factors such as the discount rate, the speed at which Southern firms could capture clean markets, and the distance between clean and dirty technologies.

The argument above shows that the long-run decarbonization of the global economy depends on the R&D potential of the coalition of countries committed to support clean R&D. If the coalition has a majority or near-majority in the global R&D potential, other countries will switch to clean R&D too and emissions will drop in the long run. If the coalition is too small, however, the other countries will continue working on dirty technologies if they are impatient.

8 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 technology goods (i.e., machines that embody the innovations). A successful innovation in 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 as well. 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 and the intertemporal spillover effects brings two important forces into the model when Northern researchers switch their attention 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, having 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. By 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.

The pulling force will not be sufficient to ensure the switch of all Southern researchers if it is offset by an opposing force deriving from the lock-in effect. When the initial stock of accumulated knowledge in the dirty sector is large, it encourages some of the researchers in 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 South. If the research sector in South is smaller than in 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 South over the long run.

We examined the macroeconomic effects of the two possible asymptotic steady states: 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. In the alternative asymptotic SS, the global research effort is split between two sectors producing substitutable goods. Due to this substitutability, the size of the clean sector in South shrinks to zero in the long run and the aggregate economy in South will not benefit from any innovations developed in North.

Finally, we endogenized 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 subgame perfect equilibrium in this setup 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 place less emphasis on 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.

The results obtained in this paper raise additional questions. In the model we assumed that there are only two regions and that one of them always invests in clean technologies. However, the strategic interaction between regions could be more complex. In reality the number of regions is large and their exposure to the effects of climate change is heterogeneous. One could explore under what conditions some of these regions could join a coalition that commits to R&D in clean technologies.

For the case when the R&D sector was larger in South than North, our analysis was focused on the asymptotic steady states with corner solutions regarding the allocation of scientists ($s = 1$ or $s^f = 0$). Contrasting these two steady states allowed us to picture and discuss the main forces shaping the incentives of researchers and governments to choose clean R&D. Further research would be necessary to explore whether there are multiple steady states, perhaps some with the interior solutions for $s = 1$ or $s^f = 0$. The presence of the business-stealing effect (that disincentivizes research in crowded sectors) suggests that an interior solution could exist for some initial conditions, at least in the short run. Exploring such cases would shed more light on the role of lock-in in South and the transition dynamics of the system after North introduces a subsidy for clean R&D. Consideration of interior solutions is also necessary to confront the predictions of the model with the pattern observed in data on research expenditure in clean and dirty industries (Fried 2018).

Future research could also explore optimal policy mixes. The only instrument of climate policy we considered in the paper was a clean R&D subsidy. In the future one could consider whether introduction of carbon tax and other climate policy instruments could be beneficial for South.

Another potential avenue of research is further exploration of strategic interactions between the two regions in the short run. If Southern researchers delay their switch to clean R&D, the size of clean markets will remain small for a longer period of time and clean R&D will bring low returns for firms in North. Moreover, the government in North will be aware that a large share of the long-term returns from R&D investment will be eventually captured by firms in South. Therefore, an important question arises of whether the gains from climate change mitigation justify high cost of clean R&D from the perspective of the North. We leave these questions for future research.

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Appendices

Appendix A1

Consumption is defined by equation 28 (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 in the asymptotic SS at home is the same as the growth of the clean sector. Thus the growth rate of consumption cannot be smaller than $\frac{\alpha_X}{1-\alpha}\gamma\lambda\,(\mu+\omega)$.

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 $\Pi = \frac{\gamma}{1+\gamma}\alpha_X p_d Y_d$ are given by $g = \frac{\alpha_X}{1-\alpha}\gamma\lambda\mu$. The long-run growth of $\Pi^f = \frac{\gamma}{1+\gamma}\alpha_X p_d^f Y_d^f$ 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 $\frac{\alpha_X}{1-\alpha}\gamma\lambda\mu\omega$ (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 $\frac{\alpha_X}{1-\alpha}\gamma\lambda < \frac{\alpha_X}{1-\alpha}\gamma\lambda\mu$ (since this asymptotic SS requires μ>1). This means that the consumption cannot grow faster than $g = \frac{\alpha_X}{1-\alpha}\gamma\lambda\mu$.

Appendix A2

In this appendix, we demonstrate that the long-run growth is bounded. With symmetric regions, consumption is given by

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

(see section 6.4). The first term has growth bounded from above by $\left((\epsilon-1)\,\alpha_X\,(\gamma\lambda 2) + (1-\varphi)\,\frac{1-\alpha_X}{1-\alpha}\,(\sigma_{ct}g_c+\sigma_{dt}g_d)\right)$ with $(\sigma_{ct}g_c+\sigma_{dt}g_d) = \left(\sigma_{ct}\frac{\alpha_X}{1-\alpha_X}\gamma\lambda 2\right) < \gamma\lambda\frac{\alpha_X}{1-\alpha_X}2$.

The second term has growth bounded from above by

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

The third term has two components: (i) the growth of ϕ weighted by

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

Appendix A3

In this appendix we provide formal derivations for proof in proposition 4.

Let $g_{1,1}\left(\sigma_c\left(\tau\right),\sigma_c^f\left(\tau\right)\right)$ be the growth of economy at time τ when both, South and North researchers work in the clean sector. Let $g_{0,1}\left(\sigma_c\left(\tau\right),\sigma_c^f\left(\tau\right)\right)$ be the growth of the economy at time τ when North researchers work in the clean sector and South researchers work in dirty sector. Let $\epsilon\left(\tau^*,1,1\right)=\max_{\tau>\tau*}\left\{\left|g\left(1,1\right)-g_{1,1}\left(\sigma_c\left(\tau\right),\sigma_c^f\left(\tau\right)\right)\right|\right\}$ and $\epsilon\left(\tau^*,0,1\right)=\max_{\tau>\tau*}\left\{\left|g\left(0,1\right)-g_{0,1}\left(\sigma_c\left(\tau\right),\sigma_c^f\left(\tau\right)\right)\right|\right\}$.

To ensure that welfare is always finite, we assume that

$$\rho>g\left(1,1\right) \tag{36}$$

When South researchers switch to clean sector, we have

$$\begin{aligned}W_0\left(1,1\right) &> \int_0^{\tau^*}e^{-\rho\tau}c_\tau\left(1,1\right)d\tau+\int_{\tau^*}^{\infty}e^{-(\rho-(g(1,1)-\epsilon(\tau^*,1,1)))\tau}c_{\tau^*}\left(1,1\right)d\tau\\ &= \int_0^{\tau^*}e^{-\rho\tau}c_\tau\left(1,1\right)d\tau+\frac{c_{\tau^*}\left(1,1\right)}{\rho-\left(g\left(1,1\right)-\epsilon\left(\tau^*,1,1\right)\right)},\end{aligned}$$

noting that for $\tau^*\to\infty$, $\epsilon\left(\tau^*,1,1\right)\to 0$.

When South researchers stay in the dirty sector, we have

$$W_0\left(0,1\right)<\int_0^{\tau^*}e^{-\rho\tau}c_\tau\left(0,1\right)d\tau+\frac{c_{\tau^*}\left(0,1\right)}{\rho-\left(g\left(0,1\right)+\epsilon\left(\tau^*,0,1\right)\right)},$$

noting that for $\tau^*\to\infty$, $\epsilon\left(\tau^*,0,1\right)\to 0$.

Observe that $g\left(1,1\right)-g\left(0,1\right)$ is strictly positive. This means that there exists a value $\overline{\tau}$

such that

$$g(1,1) - g(0,1) > \epsilon(\overline{\tau}, 0, 1) \tag{37}$$

Notice that we can make the term $\frac{c_{\overline{\tau}}(1,1)}{\rho - (g(1,1) - \epsilon(\overline{\tau},1,1))}$ arbitrarily large by choosing ρ that is sufficiently low, i.e. sufficiently close to $(g(1,1) - \epsilon(\overline{\tau},1,1)) = \frac{\alpha_1}{1-\alpha}\gamma\lambda(\mu+\omega) - \epsilon(\overline{\tau},1,1))$.

Meanwhile, given (36), the term $\frac{c_{\overline{\tau}}(0,1)}{\rho - (g(0,1) + \epsilon(\overline{\tau},0,1))}$ is bounded from above by $\frac{c_{\tau^*}(0,1)}{g(1,1) - (g(0,1) + \epsilon(\overline{\tau},0,1))}$ (which is finite as established by (37)). This implies that we can find ρ^* such that for every $\rho < \rho^*$, $W_0(1,1) > W_0(0,1)$.

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