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ENERGY, TRADE, AND INNOVATION: THE TRAGEDY OF THE LOCALS

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Abstract

This paper analyses the use of different energy sources in a dynamic trade model with endogenous innovation. We consider two countries, North and South, the first with high environmental concerns and the second endowed with abundant fossil fuel resources. In this asymmetric setting, the South specializes in energy production using fossil fuels, causing local and global environmental damages. The North, instead, specializes in other manufacturing and imports energy inputs from the South. Endogenous innovation reinforces this pattern of specialization over time. We show that the North can unilaterally stop the use of fossil fuels and avoid a global climate disaster with two different strategies: either redirecting the comparative advantage of the South towards manufacturing, relocating the production of energy to the North, or buying fossil fuel deposits in the South. These two policies have different implications in terms of monetary costs and environmental outcomes for the North. The choice between the two depends on the valuation of the environment, the energy requirements of final goods' production, the starting time of the policy and the time preferences of the North. Overall, however, there is no costless way for the North to stop unilaterally the use of fossil fuels.

Keywords: Energy, technical change, international trade, comparative advantage, fossil fuels

JEL Classification: F18, O32, O38

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1. Introduction

Sustainable development is one of the key challenges for the future of the world economy. Currently, however, most productive activities rely upon energy from fossil fuels, with unsustainable damages to the global environment. Climate scientists estimate that a large fraction of fossil fuel reserves - as much as 80% of coal deposits - should remain unexploited in order to meet the 2C° climate target (Jakob and Hilaire, 2015). How can the world forego the use of fossil fuels, especially the most abundant ones, such as coal? This paper provides a theoretical framework to analyse different policy strategies to stop burning fossil fuels and to avoid a global environmental disaster. We highlight two major challenges involved in this issue: first of all, fossil fuel ownership is concentrated in the hands of few nations, with no interest in phasing out their use. Secondly, energy generation causes local environmental impacts, so the location of energy production and energy-intensive industries is a sensitive matter.

The first problem is that fossil fuel resources are distributed unevenly across the globe, with only few countries owning the vast majority of reserves (British Petroleum, 2015). The easiest solution for climate change would be for these countries to take action, but this is unlikely to occur. Resource-rich countries built their competitive edge on fossil fuels, and even if the wealthiest ones were to abandon extraction for the sake of the global climate, realistically most developing nations - including major coal producers such as China, India, South Africa or Indonesia - would prioritize consumption growth over environmental protection. So what can the rest of the world do to restrict the emissions of CO_2 from fossil fuels, if these resources are controlled by uncooperative nations?

The second issue is the location of energy production across the world. Generating and processing energy is an environmentally intensive business, and even alternative energy sources are not free from local externalities. Nuclear energy production imposes rare but sizeable risks on the countries producing it, and the cost of managing radioactive waste; hydroelectric energy requires the flooding of entire valleys to build dams; biomass burning releases local air pollutants like SO_X

and NO_X; wind turbines produce noise and landscape impacts. Even if these energy sources do not have significant global spillovers, their local impacts are far from neutral (Markandya, 2012). Moreover, energy-intensive industries, which have long been associated with high water and air pollution intensity (Mani and Wheeler, 1998), may relocate towards cheap energy locations, as it happened with chemicals, petrochemicals and steel industries following the shale gas boom in the USA. In an open economy, this can lead to the creation of "pollution havens" (Copeland and Taylor, 1994; Antweiler et al., 2001; Taylor, 2005). Thus, even if the world abandons fossil fuels, there would still be the issue of who should produce energy and bear the local environmental damages from it.

In this paper, we develop a model that captures the misaligned incentives of resource-rich and resource-less countries, together with the pollution damages from energy generation. We build a North-South dynamic trade model with two sectors, manufacturing and energy production, each characterized by its specific endogenous innovation. The energy sector causes environmental damages, which can be both local and global, depending on whether fossil fuels are used. However, only the South is endowed with fossil fuel resources, which it does not intend to phase out. In this context, trade is fundamental to link economic activity between the two regions, but can also amplify environmental damages by fostering specialization. Similarly, endogenous technical change is a double-edged sword, because policy-makers can use it to redirect production, but otherwise it can lock economies in "dirty" paths of development.

In this setting, the North can either intervene directly on the supply of fossil fuels, or remove the incentives for the South to use them in production. This reflects two opposite policy strategies, one in the spirit of purchasing resource deposits (Harstad, 2012), and the other more akin to directed technical change policies to redirect development paths, as suggested by Hémous (2014). The first policy option requires a compensation to the South for keeping its reserves unexploited. The cost of this strategy might be significant, as it also includes monitoring and enforcing that the deposits are indeed preserved. However, from the point of view of the North, this policy has the advantage that the South remains specialized in energy production, and thus most local environmental damages stay in the Southern pollution haven. Alternatively, to eliminate the incentives to use fossil fuels, the North can re-direct comparative advantage through trade and innovation policies, so that the production of energy and energy-intensive goods shifts to the North. This is perfectly incentive compatible for the South, but the burden of local pollution would move to the North, the region with a stronger interest in a clean environment.

The key result of our model is that the policy choice in the North depends on the valuation of its own environment relative to monetary costs of buying carbon reserves over time. With trade and innovation policies, the North causes a switch in comparative advantage and specializes in energy production, but incurring in some local damages to its own environment. Viceversa, with the purchase of fossil fuel deposits, it ensures a clean domestic environment, with a long term commitment to pay the South to remain the world's power-house and pollution haven. The decision ultimately depends on the relative cost of the two policies, on the discount rate, on the weight that the environment has for the North, on the share of energy required for production, and on the starting time of the policy. To illustrate these different effects, we conduct a simple numerical exercise, showing the value of the two policy strategies with different characterizations of the Northern welfare.

Our results bridge different strands of the literature on international environmental policies. Previous studies proposed a variety of instruments to tackle global environmental externalities, from trade, to innovation, to supply side policies. In an open economy, in fact, standard instruments, such as carbon taxes or regulations to reduce demand, may be insufficient when implemented only by few countries, as they lead to carbon leakages and pollution havens (Markusen, 1975; Babiker, 2005; Levinson and Taylor, 2008; Elliott et al., 2010; Burniaux and Martins, 2012). The trade literature was the first to highlight that environmental policies cannot ignore the role of competitiveness effects and the reallocation of production (Barrett, 1994; Copeland and Taylor, 2004). Moreover, trade specialization can induce persistent dynamics, so that initial discrepancies cumulate over time generating divergent development paths (Krugman, 1981). This is similar to the effect of learning-by-doing in innovation, so that when productivity exhibits path-dependence, specialization in one activity is self-reinforcing (Arrow, 1962; Acemoglu, 2002). In an environmental context, the directed technical change literature has exploited this principle to show that temporary innovation policies can help switching to green growth paths (Newell et al., 1999; Acemoglu et al., 2012; Gans, 2012; Acemoglu et al., 2014; Aghion et al., 2014; Gupta, 2015).

In an open economy context, the green directed technical change optimism must confront with the risk of competitiveness effects identified by the trade literature, but a combination of innovation and trade policies can still effectively shift production to protect the environment (Di Maria and Smulders, 2005; Di Maria and Werf, 2008; Hémous, 2014). These models of trade and directed technical change give ample insights in the problem of pollution havens and the location of dirty production, however they tend to leave just a marginal role for fossil fuel ownership. Fossil fuels reserves are treated as exhaustible resources, whose scarcity could even induce a switch to clean production, as their prices rise with their depletion (Acemoglu et al., 2012).

On the contrary, the literature on supply side policies, suggesting to buy or lease fuel deposits, focuses more on how to deal with abundant carbon reserves (Bohm, 1993; Harstad, 2012, 2013). However, these models do not give much consideration to the trade effects that such resources have on the export profile of a country, and on the creation and location of pollution havens. Few recent papers consider the interplay between natural resource endowments and trade. Peretto and Valente (2011), for example, consider the role of natural resources in driving trade specialization, and its effect on income. Bretschger and Valente (2012) also use a trade and innovation framework to analyse the relative income shares of oil-rich versus oil-poor countries experiencing different productivity growth. Here, however, we go beyond the pattern of specialization and focus on the environmental consequences and policy implications of asymmetric resources. The contribution of our paper is to develop a model that clearly captures the trade-off between these different policies.

The paper proceeds as follows. Section 2 develops the theoretical model. Section 3 characterizes the laissez-faire equilibrium in autarky and free trade. Section 4 analyses different policy instruments and their choice, with a simple calibration of the model. Finally Section 5 concludes.

2. Model

We consider a dynamic model with two regions of the world, North, N, and South, S, linked by international trade and transboundary pollution emissions. Following Copeland and Taylor (1994), we define North as the region with higher income per capita and thus stricter regulation on CO_2 emissions, while South is a poorer region which does not regulate fossil fuel usage. The key distinction between the two regions is that the South can use cheap and abundant fossil fuels for the production of energy and energy-intensive goods, while the North cannot.[1] Each economy $k \in \{N, S\}$ produces a final consumption good, Y, using two types of inputs, indexed as c and d: non-energy inputs, such as raw materials, manufacturing inputs or services like design, and energy inputs, like electricity or energy-intensive goods. Countries can trade internationally all inputs, so that each economy specializes according to relative factor abundance and technological productivity, following an Heckscher-Ohlin/Ricardian mechanism. We now discuss in detail the building blocks of these economies.

2.1 Welfare

Aggregate welfare corresponds to the discounted sum of utility derived from consumption, C, and environmental quality, E. [2] The stream of welfare is given by

$$W_t = \sum_{t=0}^{\infty} \beta^t \; W(C_t \,, E_t) \tag{1}$$

where $0 < \beta < 1$ is the social discount factor, and $W(\cdot)$ is a discontinuous function, which takes the value of zero if environmental quality falls below a level that can sustain human livelihood

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[1] Potentially, the North could have some fossil fuel resources in its territory, but it is not willing to exploit them, given its high demand for a clean environment. This follows the empirical evidence of a strong correlation between a country's income per capita and the stringency of environmental regulation (Gupta, 2015). Alternatively, one could think of the North having signed some binding agreement that forbids the use of any fossil fuels, while the South is not bound by the agreement, such as in the case of non-Annex I countries in climate change negotiations.

[2] These variables are country-specific, but in order to simplify notation, we omit k whenever the analysis is symmetric for both countries. Also we indicate the time subscript t only when equations are dynamic.

$$W(\cdot) = \begin{cases} W(C_t, E_t) & \text{if } E_t > 0 \\ 0 & \text{if } E_t \leq 0 \end{cases} \tag{2}$$

This functional form captures the problem identified by the climate change literature of tipping points, thresholds beyond which ecosystems abruptly switch to a critical state for human activities (Lenton et al., 2008).[3] In this model, we define an environmental disaster as follows:

Definition D.1 – *An environmental disaster occurs when environmental quality falls below a critical threshold,* $E_t = 0$*, for some* $t < \infty$*, such that welfare* $W(E_t = 0) = 0$*, independently of the level of consumption* C*.*

Whenever the environment has not reached the tipping point for a disaster, welfare takes the following additive functional form:

$$W(C_t, E_t > 0) = \frac{(\mu E_t + (1-\mu)\, C_t\,)^{1-\eta}}{1-\eta} \tag{3}$$

where $1/\eta$ represents the elasticity of intertemporal substitution, and μ is the weight that determines the relative amenity value of the environment E and consumption C. The difference between the two regions is that the South assigns a smaller weight to the environment than the North.

Assumption A.1 – *The South values the environment substantially less than the North, and in the welfare function* $\mu^N > \mu^S > 0$*.*

Hereafter, we focus on the policy actions of the North to avoid environmental deterioration to the point of a disaster. The Southern welfare would also collapse in the event of a disaster, but for any

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[3] The greatest threats seem the melting of the Arctic sea-ice and Greenland's ice sheet. Nonetheless, many other potential tipping points are being studied, such as a collapse of the Atlantic thermohaline circulation or a die-back of the Amazon rainforest (Lenton et al., 2008).

positive value of E the North would suffer more from environmental damages, thus it would be the first to take action.

2.2 Environment

The evolution of environmental quality in this model depends on how energy is generated. If energy is produced burning fossil fuels, global emissions accumulate in the atmosphere, causing damages to the environment of both regions of the world. Instead, energy from renewable resources cause only local externalities, with no transnational spillovers. The environment has a fixed regenerative capacity. In each period, environmental quality falls within the interval $E_t \in [0, \overline{E}]$, where $\overline{E}$ denotes the initial, pristine level of the environment before industrialization, and $E_t = 0$ is an irreversible level of environmental degradation, such that no regeneration is possible. This corresponds to the environmental disaster of definition D.1. Environmental quality evolves according to the following law of motion:

$$E^k_{t+1} = (1+\Delta)\,E^k_t - \zeta\ (Y^k_{dLt} + Y^k_{dGt}) - \xi\ Y_{dGt} \tag{4}$$

Thus, environmental quality in country k depends on the previous environmental state E_{t-1}, given some regeneration capacity Δ, and the production of energy inputs Y_d. The production of energy always creates some local externalities, independently of whether energy is generated from renewable or from fossil fuels. The local damage from a unit of energy production into the environment is captured by ζ. These damages are confined to the country k that produces energy. However, if energy is produced by burning fossil fuels (Y_{dG}), there are also global damages of a factor ξ. These damages are independent of the location of energy production and affect symmetrically the whole world, therefore we omit the superscript k. These damages surpass the regenerative capacity of the environment, and thus can lead to an environmental disaster.

Assumption A.2 - *Environmental damages derived from burning the fossil fuel resource are higher than the damages caused by local pollution* $\xi > \zeta > 0$. *Moreover, the damages of global* *pollution from fossil fuels over time lead to an environmental catastrophe, while those of local pollution do not. The global polluting factor* ξ *is high relative to the regeneration capacity of the environment,* Δ*, while the local one,* ζ *is low (see Appendix A for a formal condition for this to hold).*

This stylized formulation for environmental dynamics captures some key difficulties in international environmental negotiations, namely the transnational and intergenerational externality caused by burning fossil fuels. First of all, even if fossil fuels are physically present only in the South, they pollute equally both hemispheres, even if the South does not bear the external cost of damages abroad. Secondly, production and consumption decisions taken at one point in time have repercussions on future generations. The laissez-faire market equilibrium is therefore likely to generate an environmental disaster.

2.3 Production

In this economy, the production of any final good Y for consumption requires two inputs: energy and non-energy manufactured components, assembled in a Cobb-Douglas aggregate by perfectly competitive firms[4]

$$Y = (Y_c)^{\upsilon} \ (Y_d)^{1-\upsilon} \tag{5}$$

Non-energy inputs Y_c represent broadly all those parts, components, raw materials and even services or design that do not require much energy, while Y_d are energy intensive goods, that rely either on burning fossil fuels (Y_{dG}) or on renewable energy sources (Y_{dL}).[5] We assume that the

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[4] The Cobb-Douglas functional form for this technology captures well the fact that both inputs are necessary. They could also be represented as a CES function with elasticity of substitution smaller than 1, up to the extreme case of Leontief production with fixed input proportions. However a CES with elasticity of substitution greater than 1 would yield different results, and it would not be plausible as currently we cannot substitute any other input for energy.

[5] We talk both about energy and energy intensive inputs because often energy needs to be embedded in other products to be used for production and to be traded. So, this category can include crude oil that is used directly in the production of final goods, but also intermediate goods that embed high amounts of energy inputs, such as refined oil or steel.

two energy inputs are perfect substitutes:

$$Y_d = Y_{dL} + Y_{dG} \tag{6}$$

From the point of view of final goods assemblers, it does not matter whether the energy source for energy inputs was fossil fuels or renewable energy. The cheapest one will always be used.[6] For instance, in order to make textiles, final goods producers combine cotton with weaving machines powered by electricity, but it does not make a difference if the energy of the second component is produced using coal or hydroelectric power plants. Thus, the demand for energy-intensive inputs of final goods assemblers is

$$Y_{dL} = 0 \text{ if } p_{dL} > p_{dG}$$
$$Y_{dG} = 0 \text{ if } p_{dG} > p_{dL}$$

Energy and non-energy inputs are traded worldwide. Their production takes place under perfect competition, using four non-traded factors of production: labour, machines, scientists and natural inputs (like water, clean air, soil). Moreover, a fifth input is available for the production of energy only in the South: a fossil fuel resource such as coal. Each country has a fixed amount of these endowments in each period, except for machines (capital), whose quantity is determined by the market equilibrium demand, and whose stock can build up over time.

Non-energy inputs (Y_c) - The production of non-energy inputs does not require natural resources, but only labour plus sector-specific machines. The production function for these inputs is

$$Y_c = (L_c)^{1-\gamma} \int_0^1 A_{ci}(x_{ci})^{\gamma} di \tag{7}$$

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[6] The perfect substitutability of fossil fuel and renewable energy may be a valid assumption in the long run, but possibly less so over short time horizons. However for the purpose of this model we do not want substitution to be a constraint for the adoption of renewable resources, as we focus instead on the role of trade specialization and endogenous innovation. The results of our models would still be valid with a lower elasticity of substitution, but transitions would be slower.

where L_c is the amount of labour employed in this sector, x_{ci} is the quantity of machines used, and A_{ci} is the technological productivity level associated to machine i in the c sector. The parameter $0 < \gamma < 1$ captures the share of machines used in the production function. The interplay between machines x_i and productivity A is the core of innovation activities, as discussed in the next section.

Energy inputs (Y_d) - In order to produce energy and energy-intensive products, a country must use some natural capital, K, like water. Then, the production technique changes depending whether fossil fuels are being used or not. The two possible products of the energy sector are

$$Y_{dL} = \left(L_{dL}^{\psi} K_{dL}^{1-\psi} \right)^{1-\gamma} \int_0^1 A_{dLi}(x_{dLi})^{\gamma} di \tag{8}$$

where ψ is the share of labour used to produce Y_{dL}.[7] Alternatively, if energy production also uses fossil fuels R:

$$Y_{dG} = \left(L_{dG}^{\beta} K_{dG}^{1-\alpha-\beta} R^{\alpha} \right)^{1-\gamma} \int_0^1 A_{dGi}(x_{dGi})^{\gamma} di \tag{9}$$

where α represents the share of fossil fuel resource used in production.

Fossil fuels - The fossil fuel resource R has two important characteristics: it is only used in the South, as mentioned before, so the North can only produce energy in the form of Y_{dL}, and it is abundant, in the sense that the South is not constrained by scarcity considerations in the use of this input. Other models of green directed technical change have treated fossil fuel resource as fully exhaustible: as they are depleted, scarcity increases its price and reduces its use, encouraging R&D in clean technologies (Acemoglu et al., 2012). We depart from this approach and consider the case where fossil fuels are in excess supply relative to the time scale of critical climate degradation.[8] In our model, R is constantly available in every period, and the problem is rather the opposite, its excess availability.

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[7] For now we simplify the model assuming the same ψ across different countries. An extension of this work could study the implication of asymmetric factor shares between the North and the South.

[8] Oil is the only fossil fuel resource expected to become significantly more expensive to extract in the near future. On the contrary, forecast about coal reserves are in the range of several hundred years, so fossil fuels as a whole can hardly be considered exhaustible before climate change damages reach dangerous tipping points (Van der Ploeg and Withagen, 2012; McGlade and Ekins, 2015).

Machines - There is an infinite number of varieties of machines x_i, with $i \in [0,1]$. They are produced under monopolistic competition, so that their owners can charge a mark-up above their marginal costs and make profits, which creates the incentives to innovate. This market structure and the presence of a mark-up over marginal cost determines the production of too few machines. Since this is not a new insight for our model, we assume that both regions correct for this monopoly distortion with a simple production subsidy, as in Hémous (2014). Following the structure of (Acemoglu et al., 2012), entrepreneurs face a fixed cost of producing a machine, given by $\varsigma = \gamma^2$ units of final output. Each entrepreneur sells a variety i of the machine within its country; machines are not traded, but patents can be exchanged internationally, transferring part of the productivity A.[9] Therefore, if entrepreneurs can increase the productivity of their machine, they can retain the profits of this innovation, justifying an investment in R&D. In the next section we discuss how innovation takes place at the machine production level.

2.4 Innovation

Innovation occurs in each input sector $z \in \{c, dL, dG\}$ due to a cumulative learning-by-doing process, with knowledge growing in the manufacturing and energy sectors independently and pushing the frontier of technological productivity (Arrow, 1962; Romer, 1986). We assume no technology spillovers across countries or sectors, but we will discuss technology transfers as a possible policy in section 4. Technology improvements on every machine are modelled similarly to classic models of directed technical change (Acemoglu et al., 2012):

$$A_{zit} = [1 + \varphi_z (\vartheta_z s_{zit})] A_{zit-1} \tag{10}$$

where s_{zit} is the number of scientists hired by an entrepreneur to work on machine x_{ci} in a given sector at time t, φ_z is the size and significance of a discovery, and $\vartheta_z \in (0,1)$ the probability of

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[9] Bond and Yomogida (2014) examine the effects that innovation in the home country's energy sector has on environmental quality when trade in machinery is allowed. However, in their model, innovation cannot occur in the foreign country due to its lower level of economic development.

a successful innovation. These two parameters, φ and ϑ, capture two opposite dynamics in the innovation process: on the one hand, research in those technologies that "stand on the shoulders of giants" have a wider knowledge basis and therefore are more likely to successfully increase the productivity of the sector. On the other hand, innovation in one technology might incur in decreasing returns to research, so the chances of a break-through fall as more research is performed. The size and probability of a discovery could be modelled with even further detail, for instance including decreasing returns to the scientists hired due to a crowding out effect, or knowledge spillovers across machines in the same sector and country, but for the purposes of our model it is sufficient to have this simple setting for path dependent innovation over time.

The crucial choice for innovative activities is the allocation of a fixed mass of scientists s, normalized to one

$$\int_0^1 s^k_{cit} + s^k_{dLit} + s^k_{dGit}\, di = s = 1 \tag{11}$$

In every period entrepreneurs hire scientists depending on the profitability of their industry. If innovation is successful, leading to an improvement of $(1+\varphi)$ in the quality of the machine, the entrepreneur has a one period patent that allows for extra monopoly profits. This short-term patent system makes entrepreneurs myopic and unaware of their role in shaping the path of specialization and future innovation of a country (a classic problem of knowledge externality). Overall, the average productivity of a sector is:

$$A_{zt} = \int_0^1 A_{zit}\, di \tag{12}$$

with $z \in \{c, dL, dG\}$.

This model unifies in a simple framework the key features of the problem at hand: two different energy sources, with different pollution intensity, and one of them - fossil fuels - only present in one region; global climate damages from fossil fuel use; path dependent sectoral innovation; and asymmetric concerns for the environment. We now proceed to solve the model, to show that under laissez-faire this setting leads to unsustainable outcomes. Afterwards we discuss different policy options available to the North to avoid the environmental disaster.

3. Laissez Faire

Having described the main building blocks of the model, we now turn to the equilibrium. We start our analysis from the case of laissez-faire, without any policy in place, except for the simple subsidy in both countries correcting for the monopoly inefficiency in machines production. We consider in turn the autarky and free trade equilibrium.

3.1 Autarky

In a closed economy scenario, each country has to be self-sufficient and produce the quantity of both energy and manufactures that it needs for final goods consumption. The amounts produced depend completely on the endowments and technology of the region, since no exchanges or technology spillovers are allowed. The autarky equilibrium without any policy intervention is characterized as follows. Goods and inputs markets clear thanks to the profit maximization of final and intermediate goods producers. In each period, entrepreneurs hire scientists in the different sectors, proportionally to the relative profitability of the energy and non-energy activities, which in turn depend on factors allocations, final goods prices and the relative levels of technology. This allocation of R&D efforts shapes the future evolution of the corresponding sector's technology. The environment evolves depending on how much and what type of energy goods are produced in equilibrium.

Definition D.2 – *In autarky, an equilibrium is defined as a sequence of domestic demands for factors of production (L_z, K_d, R_{dG}) and factor prices (wages w, price of environmental goods r, and price for fossil fuel resources q), demand and price for machines (x_{jit}), scientists' allocations (s_z), and quality of environment (E_t) such that, for every period t: (i) the price of machines and their quantity, x_{jit}, and the demand for scientists s_{zt}, maximizes profits of the owner of machine i in sector z; (ii) L_{zt}, K_{zt} and R_{zt} maximize profits by producers of intermediate input j; (iii) Y_{zt} maximizes the profits of input goods' producers (energy and non-energy), subject to the production function of final goods Y, which in turn depends on the demand from consumers in country k; (iv)* *factor prices clear the factor markets, and intermediate and final goods prices clear the market for Y, Y_c and Y_d; and (v) the evolution of the environment E_t is given by (4).*

We analyse the equilibrium in the two regions separately. For a full derivation of the equilibrium conditions, see Appendix B.

North - Given the absence of fossil fuel resources, there is no choice in the North on how to generate energy: the only possibility is to use renewable energy sources, *dL*.

The equilibrium demands for each factor of production and the consequent factors prices are:

$$L_c^{N*} = \frac{\bar{L}^N}{\left(1 + \frac{(1-\upsilon)}{\upsilon}\psi\right)} \tag{13}$$

$$L_{dL}^{N*} = \frac{1-\upsilon}{\upsilon}\frac{\bar{L}^N}{\left(1 + \frac{(1-\upsilon)}{\upsilon}\psi\right)}\psi \tag{14}$$

$$K_{dL}^{N*} = \bar{K}^N \tag{15}$$

$$w^{N*} = A_c^{\frac{1}{1-\gamma}}(1-\gamma) \tag{16}$$

$$r^{N*} = \left(A_c^N\right)^{\frac{1}{1-\gamma}}\frac{\bar{L}^N}{\bar{K}^N}(1-\gamma)(1-\psi)\frac{(1-\upsilon)}{\upsilon+(1-\upsilon)\psi}. \tag{17}$$

where variables with an upper bar indicate the fixed factor endowments and r and w the price of natural inputs and labour. Since the only good produced in North making use of environmental resources K is dL, all the endowment available in each period will be allocated to the production of Y_{dL}^N.

At each time t, scientists in the North are hired in sector of production c or dL, based on the relative ratio of profits between the two sectors:

$$\frac{\pi_{ci,t}^N}{\pi_{dLi,t}^N} = \frac{\vartheta_c^N}{\vartheta_{dL}^N}\frac{L_c^{N*}}{\left(L_{dL}^{N*}\right)^{\psi}}\frac{1}{\left(K_{dL}^{N*}\right)^{1-\psi}}\left(\frac{p_c^N}{p_{dL}^N}\right)^{\frac{1}{1-\gamma}}\left(\frac{A_{ci,t-1}^N}{A_{di,t-1}^N}\right)^{\frac{1}{1-\gamma}} \tag{18}$$

Everything else equal, more scientists are present in (i) the largest sector, as captured by the ratio of labour and natural resource inputs, (ii) the most valuable sector, where the price ratio is higher, and (iii) the more advanced sector - where the productivity levels are higher, as indicated by the ratio of A_z. Such a structure mimics the three innovation driving forces found in Acemoglu et al. (2012): size effect, price effect and technological effect.

Prices in autarky depend uniquely on domestic technology and on the relative abundance of resources. We set the price of non-energy goods as the numeraire, $p_c = 1$, and consequently express the price of energy inputs relative to other inputs as

$$p_{dL}^{A} = \frac{1}{A_{dL}^{N}} \left(\frac{1}{1-\gamma} \right)^{(1-\gamma)} \left(\frac{r}{1-\psi} \right)^{(1-\gamma)(1-\psi)} \left(\frac{A_c^{N\,\frac{1}{1-\gamma}} (1-\gamma)}{\psi} \right)^{\psi(1-\gamma)} \tag{19}$$

Clearly, the higher the technological productivity A_{dL}, the lower the price. Since this price is relative to that of c inputs, the technology of the other sector A_C has the opposite effect. Moreover, it also matters if environmental resources like water are expensive, as captured by r.

South - For the South, two possible situations can arise:

$$1)\ p_{dL} \leq p_{dG}$$

$$2)\ p_{dL} > p_{dG}$$

Case 1) represents a situation where the availability of fossil fuels does not really provide cheaper energy to the Southern region, making it preferable to produce with alternative power sources, as if no fossil fuels existed. In such a scenario, the productivity path of the South parallels exactly the one of the North, with no compelling implications even when opening to trade: the globally polluting resource is never exploited and both regions produce the cheapest possible energy goods, without damaging the global environment.

Case 2) is more interesting for the analysis of climate change, as we observe that fossil fuels are greatly used by the countries that have them. This case indicates that the presence of fossil fuels actually provides a cheap energy source, and we adopt it as the baseline for our model. To ensure that this is the case in our model, the following condition is required (proof in Appendix D):

$$\frac{Ad_L}{A_{dG}}\left[\frac{\psi^{\psi}}{\beta^{\beta}}\left(\left(\frac{1-\upsilon}{\upsilon}\right)\bar{L}^S\right)^{\psi-\beta}\frac{\left(1+\left(\frac{1-\upsilon}{\upsilon}\right)\beta\right)^{\beta-1}}{\left(1+\left(\frac{1-\upsilon}{\upsilon}\right)\psi\right)^{\psi-1}}\frac{\left(\bar{K}^S\right)^{\alpha+\beta-\psi}}{\left(\bar{R}\right)^{\alpha}}\right]^{1-\gamma} = \frac{p_{dG}}{p_{dL}} < 1 \tag{20}$$

The larger the endowment of the fossil fuels available in every period, $\bar{R}$, and the higher the productivity of the fossil fuel sector A_{dG}, relative to the one of renewable energy A_{dL}, the more likely for this condition to hold.

Assumption A.3 – *We assume that the regularity condition (20) holds, so that $p_{dG} < p_{dL}$. For the South it is always cheaper to produce energy and energy-intensive goods using fossil fuels.*

Whenever A.3 does not hold, we are back in the situation of two countries not endowed with any significant fossil fuels resources, a case similar to Hémous (2014).

In the South, factors demands and prices in equilibrium are:

$$L_c^{S*} = \frac{\bar{L}^S}{\left(1+\frac{(1-\upsilon)}{\upsilon}\beta\right)} \tag{21}$$

$$L_{dG}^{S*} = \frac{1-\upsilon}{\upsilon}\frac{\bar{L}^S}{\left(1+\frac{(1-\upsilon)}{\upsilon}\beta\right)}\beta \tag{22}$$

$$K_{dG}^{S*} = \bar{K}^S \tag{23}$$

$$R_{dG}^{*} = \bar{R} \tag{24}$$

$$r^{S*} = \left(A_c^S\right)^{\frac{1}{1-\gamma}} \frac{\bar{L}^S}{\bar{K}^S} (1-\gamma)(1-\alpha-\beta)\frac{(1-\upsilon)}{\upsilon+(1-\upsilon)\beta} \tag{25}$$

$$q^{*} = \left(A_c^S\right)^{\frac{1}{1-\gamma}} \frac{\bar{L}^S}{\bar{R}} (1-\gamma)\,\alpha\frac{(1-\upsilon)}{\upsilon+(1-\upsilon)\beta}^{10} \tag{26}$$

where q indicates the exploitation price of fossil fuel resources R.

Given that $p_{dG} < p_{dL}$, Southern scientists are either in the manufacturing sector or in the energy sector that depletes R, depending on which one is more profitable. Each period entrepreneurs face a relative profits ratio of:

$$\frac{\pi^S_{ci,t}}{\pi^S_{dGi,t}} = \frac{\vartheta^S_c}{\vartheta^S_{dG}} \frac{L^{S*}_c}{\left(L^{S*}_{dG}\right)^{\beta}} \frac{1}{\left(K^{S*}_{dG}\right)^{1-\alpha-\beta}(R^*)^{\alpha}} \left(\frac{p^S_c}{p^S_{dG}}\right)^{\frac{1}{1-\gamma}} \left(\frac{A^S_{ci,t-1}}{A^S_{di,t-1}}\right)^{\frac{1}{1-\gamma}} \tag{27}$$

This condition captures again the aforementioned effects - size, price and technology, but here we can add a fourth one: a fossil fuel-abundance effect, which pushes scientists towards the dirty energy sector for a larger endowment of R.

Proposition 1 – *Fossil fuel resources drive innovation through their effect on the relative profits of the dirty energy sector. Cheap fossil fuels create a* resource-abundance *effect on innovation.*

Proof. By inspection of equation (27), given assumption A.3.

As for the North, we can examine the price of energy inputs relative to $p_c = 1$ also in the South

$$p^A_{dG} = \frac{1}{A_{dG}}\left(\frac{1}{1-\gamma}\right)^{(1-\gamma)} \left(\frac{r}{1-\alpha-\beta}\right)^{(1-\gamma)(1-\alpha-\beta)} \left(\frac{A_c^{\frac{1}{1-\gamma}}(1-\gamma)}{\beta}\right)^{\beta(1-\gamma)} \left(\frac{q}{\alpha}\right)^{\alpha(1-\gamma)} \tag{28}$$

Again, the higher the technology A_{dG} the lower the price of energy. Since fossil fuels enhance the incentives to do R&D in their sector, the value of A_{dG} is higher than that in the North in terms of A_{dL}, especially as time passes and competitiveness builds up through path-dependent innovation.

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[10] Since the resource R is only present in South we will always omit the superscript S from q.

Further, in the South, the price of energy intensive goods depends also on the cost of fossil fuels q; however, if the deposits of carbon resources are abundant, the cost of fossil fuels in competitive markets will be low.

How do the autarky prices compare across the two countries? If there was some smuggling between the two regions, in which direction would it go? The cheapest goods would be sold in the region where they are more expensive, so for instance if energy in the North was more costly, some coal could be smuggled from the South even if there was not free trade. The South would have relatively cheaper energy goods if

$$\frac{p^N_{dL}}{p^N_c} > \frac{p^S_{dG}}{p^S_c} \tag{29}$$

Rearranging the expressions for the price of energy inputs relative to other inputs in eq. (19) and (28), we get that

$$\frac{A^S_{dG}}{A^N_{dL}} \left(\varpi \, \frac{(r^N)^{1-\psi}}{(r^S)^{1-\alpha-\beta}} \right)^{1-\gamma} \left(\frac{\alpha}{q} \right)^{\alpha(1-\gamma)} > \tau \, \frac{(A^S_c)^{\beta}}{(A^N_c)^{\psi}} \tag{30}$$

where $\varpi \equiv \frac{(1-\alpha-\beta)^{1-\alpha-\beta}}{(1-\psi)^{1-\psi}}$ and $\tau \equiv \left(\frac{\psi}{1-\gamma}\right)^{\psi} \left(\frac{1-\gamma}{\beta}\right)^{\beta}$. Equation (30) captures both the effect of A technologies in the d and c sector, and that of endowments, particularly in the ratio of cost of natural inputs r, the price of fossil fuels q, plus the various parameters that capture the relative contribution of these factors of production to energy and non-energy goods. This comparison of autarky prices already illustrates which direction specialization will take, depending on the technologies and the cost of endowments. If the South has sufficiently abundant fossil fuel resources, their cost q will be extremely low and their energy goods cheaper than Northern ones.

In terms of innovation, it is important to note that while renewable energy technology grows in the North, which has no alternative energy sources, in the South there would be no reason to invest in A^S_{dL}. We can therefore safely assume that A^S_{dL} is relatively quite small:

Assumption A.4 – *Southern renewable energy technology is less advanced than the Northern one,* $A_{dL}^{S} < A_{dL}^{N}$ *. Further, we assume that* A_{dL}^{S} *is sufficiently small that South would not have a relative advantage in renewable technologies, that is* $A_{dL}^{S}/A_{c}^{S} < A_{dL}^{N}/A_{c}^{N} \Rightarrow A_{dL}^{S} < A_{dL}^{N}A_{c}^{S}/A_{c}^{N}$.

In this autarky scenario, it is clear why an environmental disaster soon occurs: all energy production in the South uses the dG technique, with the consequent massive exploitation of fossil fuels and increasing damages to the global environment. The North would not be able to prevent an environmental disaster, since the two regions are not connected by trade. Therefore we now move to an open economy setting, which captures the economic interaction between the two countries and allows for more policy interventions.

3.2 Free Trade

We now analyse the equilibrium when allowing for international trade (see Appendix C for derivations). We show that the world economy reaches a natural disaster even sooner than in autarky, due to the specialization of the South in energy production with the use of fossil fuels. This is then the benchmark over which the North can implement various policies to avoid the environmental disaster. The two regions are free to exchange inputs and final goods, but production factors - labour, machines, fossil fuels and natural resources - are immobile. Due to perfect competition, no price discrimination is possible and the law of one price holds for all traded goods (we abstract from trade costs). The goods that effectively drive trade specialization are the energy and non-energy inputs: the d and c sectors. Since markets do not differentiate between energy coming from dirty or renewable sources, within the d sector only the cheapest one is used.

Definition D.3 – *In free trade, an equilibrium is defined as a sequence of demands for factors of production* (L_z, K_d, R_{dG}) *and factor prices (wages* w*, price of environmental goods* r*, and price for fossil fuel resources* q*), demand and price for machines* (x_{jit})*, scientists' allocations* (s_z)*, and quality of environment* (E_t) *such that, for every period* t*: (i) the price of machines and their quantity,* x_{jit}*, and the demand for scientists* s_{zt}*, maximizes profits of the owner of machine* i *in sector* *z; (ii) L_{zt}, K_{zt} and R_{zt} maximize profits by producers of intermediate input j; (iii) Y_{zt} maximizes the profits of input goods' producers (energy and non-energy), subject to the production function of final goods Y worldwide, which in turn depends on the global demand from consumers in both countries; (iv) factor prices clear the factor markets, and intermediate and final goods prices clear the market for Y, Y_c and Y_d; and (v) the evolution of the environment E_t is given by (4).*

Given the equilibrium defined in D.3, we can examine how the world's production and environment evolves under free trade.

Trade specialization - There are two driving forces in the model: technology, as in the classic Ricardian trade models, and factor endowments, à la Heckscher-Ohlin. The key element is the presence of an abundant factor of production, R, located only in one region. Since we imposed with equation (20) that the South in autarky always chooses to produce energy with fossil fuels, given the lower marginal costs, this must also be valid under free trade. The North, instead, can only produce Y_{dL} due to the lack of fossil fuels. As only the cheapest energy source is used in the production of final goods, as per eq. (6), it follows that under free trade there will be full specialization in the production of energy goods. The pattern of specialization depends on which energy production technique is cheaper under free trade, relative to the production of other non-energy inputs. Prices under free trade are

$$p_{dG}^{FT} = \left(\left(\frac{1-\upsilon}{\upsilon} \right) \frac{{A_c^N}^{\frac{1}{1-\gamma}} \overline{L}^N + {A_c^S}^{\frac{1}{1-\gamma}} \left(\overline{L}^S - L_{dG} \right)}{{A_{dG}^S}^{\frac{1}{1-\gamma}} {L_{dG}}^{\beta} {K_{dG}}^{1-\alpha-\beta} R^{\alpha}} \right)^{1-\gamma} \tag{31}$$

$$p_{dL}^{FT} = \left(\left(\frac{1-\upsilon}{\upsilon} \right) \frac{{A_c^N}^{\frac{1}{1-\gamma}} \left(\overline{L}^N - L_{dL}^N \right) + {A_c^S}^{\frac{1}{1-\gamma}} \left(\overline{L}^S - L_{dL}^S \right)}{{A_{dL}^N}^{\frac{1}{1-\gamma}} {L_{dL}}^{N\psi} {K_{dL}}^{N(1-\psi)} + {A_{dL}^S}^{\frac{1}{1-\gamma}} {L_{dL}}^{S\psi} {K_{dL}}^{S(1-\psi)}} \right)^{1-\gamma} \tag{32}$$

Combining the two equations above, we see that the South produces all energy inputs only if it can produce them more cheaply than the North

$$\left(\frac{A_{dL}^{N}}{A_{dG}^{S}}\right)^{\frac{1}{1-\gamma}} \; \frac{L_{dL}^{N\,\psi}}{L_{DG}^{S\,\beta}} \; \frac{K_{dL}^{N\,(1-\psi)}}{K_{dG}^{S\,(1-\alpha-\beta)}} \; \frac{1}{R^{\alpha}} \quad < \quad \frac{\left(A_c^N/A_c^S\right)^{\frac{1}{1-\gamma}}\left(\overline{L}^N - L_{dL}^N\right) + \overline{L}^S}{\left(A_c^N/A_c^S\right)^{\frac{1}{1-\gamma}}\overline{L}^N + \left(\overline{L}^S - L_{dG}^S\right)} \tag{33}$$

The left-hand side of the condition above gets smaller the higher the endowments of R in the South. From the right hand side, we see that the fraction is larger the more labour is allocated to dG in the South, and the less labour is allocated to dL in the North. We thus make the following assumption to ensure a unique direction of specialization:

Assumption A.5 – *South has a comparative advantage in energy production given by the fossil fuel resource R, which ensures that condition (33) is met. Further, we assume that the endowments of natural resources K are not too different across the two regions.*[11]

We refrain from making any specific assumption about the relative technologies of the two countries, namely whether $A_{dL}^N/A_c^N \lesseqgtr A_{dG}^S/A_c^S$, or about the endowments of labour L.

Proposition 2 – *When opening to free trade, the energy goods are produced exclusively by the South using fossil fuels, that is* $Y_d = Y_{dG}^S$*, if fossil fuel resources in the South are sufficiently abundant.*

Proof. It follows straightforwardly from equation (6), the regularity condition (20) and assumption A.5.

Therefore, in the absence of policy interventions, all final goods are produced using energy inputs derived from fossil fuels Y_{dG} rather than renewable sources Y_{dL}, and world production of the latter stops. The open economy equilibrium requires:

$$\frac{1}{p_{dG}} = \frac{\upsilon}{(1-\upsilon)} \, \frac{Y_{dG}}{Y_c^N + Y_c^S} \tag{34}$$

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[11] This second part of the assumption ensures that the endowment of environmental resources K does not drive the specialization of the two countries, given that this input is not used in the non-energy sector. In this way, we can isolate only one endowment of interest, R, and the technologies A_z.

and, consequently, the equilibrium factors demands and prices are:

$$L_{dL}^{S*} = L_{dL}^{N*} = 0 \tag{35}$$

$$L_c^{N*} = \bar{L}^N \tag{36}$$

$$L_c^{S*} = \bar{L}^S - \frac{\beta\left(1-\upsilon\right)}{\upsilon+\beta\left(1-\upsilon\right)} \frac{\left(A_c^{N\frac{1}{1-\gamma}}\bar{L}^N + A_c^{S\frac{1}{1-\gamma}}\bar{L}^S\right)}{A_c^{S\frac{1}{1-\gamma}}} \tag{37}$$

$$L_{dG}^{*} = \frac{\beta\left(1-\upsilon\right)}{\upsilon+\beta\left(1-\upsilon\right)} \frac{\left(A_c^{N\frac{1}{1-\gamma}}\bar{L}^N + A_c^{S\frac{1}{1-\gamma}}\bar{L}^S\right)}{A_c^{S\frac{1}{1-\gamma}}} \tag{38}$$

$$K_{dG}^{*} = \bar{K}^S \tag{39}$$

$$K_{dL}^{S*} = K_{dL}^{N*} = 0 \tag{40}$$

$$R_{dG}^{*} = \bar{R} \tag{41}$$

$$r^{S*} = \frac{\left(1-\upsilon\right)\left(1-\gamma\right)\left(1-\alpha-\beta\right)}{\upsilon+\beta\left(1-\upsilon\right)} \frac{\left(A_c^{N\frac{1}{1-\gamma}}\bar{L}^N + A_c^{S\frac{1}{1-\gamma}}\bar{L}^S\right)}{\bar{K}^S} \tag{42}$$

$$q^{*} = \frac{\alpha\left(1-\gamma\right)\left(1-\upsilon\right)}{\upsilon+\beta\left(1-\upsilon\right)} \frac{\left(A_c^{N\frac{1}{1-\gamma}}\bar{L}^N + A_c^{S\frac{1}{1-\gamma}}\bar{L}^S\right)}{\bar{R}} \tag{43}$$

In such a scenario, scientists in the North do not have a choice on which sector to enter, since the only remaining active sector is the clean one. As a result, the Northern clean technology grows unambiguously under free trade with no active policies. In the South, on the other hand, both sectors c and dG are active and the choice of Southern inventors is based on the profit ratio between the two sectors, as per equation (27).[12]

Again, this trade equilibrium leads inevitably to an environmental disaster, because of the produc-

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[12] While our model determines a full specialization with respect to energy production, we do not expect that the same should happen for other non-energy inputs. Y_c can be produced by both countries, depending on the difference in labour endowments between the two countries.

tion of Y_{dG}, as in the case of autarky. However the decline is even more rapid under free trade, because Y_{dG} is produced not only for Southern use, but also for the Northern energy needs. We simulate the evolution of the environment in free trade under laissez faire for the North and the South. Figure 1 shows how opening to free trade brings both countries to an environmental disaster more rapidly than under autarky, using some stylized parameters (see Appendix F). This occurs since all production of the dirty good is stirred by trade openness towards the cheapest, globally polluting energy source. Production specializes immediately: the South produces in the first years of free trade a bit of non-energy input goods as well (Y_c), but shortly after it fully specializes in Y_{dG}, as its productivity builds up with the evolution of A_{dG}. In a world of free trade, policy interventions to avoid environmental disasters are then more urgent than with closed economies. International trade expands markets and induces the countries to specialize in their most competitive sectors, thus the ownership of endowments like fossil fuels becomes extremely significant. The larger exploitation of polluting resources under free trade makes this regime more prone to global disasters.

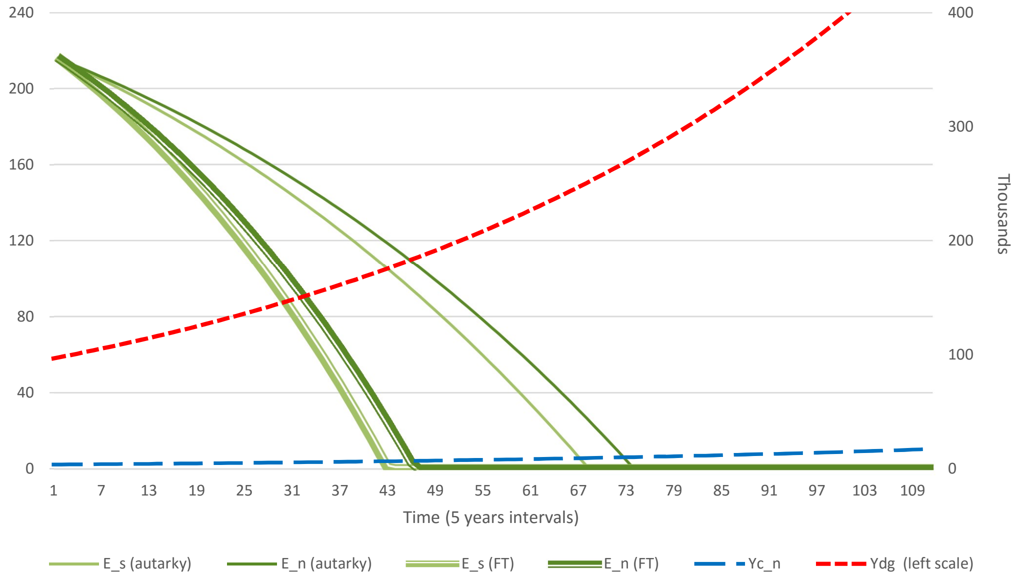

Figure 1: Evolution of the environment and production

In the next sections, we will analyse the possible policy options available to avoid the rapid approach of a global disaster described in this open economy, laissez-faire scenario. The focus is set on the role of fossil fuel resources owned by the South and how to stop their exploitation.

4. Policy instruments

The Northern government can use a number of different policy tools, but in this context their effectiveness in avoiding an environmental disaster varies. We consider the following policies: i) carbon taxes; ii) import tariffs, to correct for the other country's pollution externality and to encourage the development of a competitive market for renewable energy; iii) research subsidies or taxes, to redirect the path of the innovation process, since myopic investors with short term patents do not account for the long term impacts of their R&D decisions; iv) price subsidies for green technologies; v) international transfers to purchase the deposits of fossil fuels, to stop their use at the source; and vi) international transfers of green technology. The model developed here allows for a clear comparison of these policies. Ultimately, we show that the North can take two opposite approaches to curb the use of fossil fuels: either eliminating the incentives for the South to use fossil fuels, by switching its comparative advantage away from energy production, or compensating the South for giving up fossil fuels, with a systematic transfer scheme. The next two sections deal in turn with each of these strategies, but first we examine each policy instrument individually.

i. Carbon taxes and import tariffs. Unilateral carbon taxes, the classic instrument to correct environmental externalities in a closed economy, are generally less effective in an open economy because of carbon leakage. In our model, with the North producing no significant amount of fossil fuel emissions, carbon taxes become useless when applied in isolation. Taxing energy-intensive goods imported from the South is equivalent to an import tariff. It makes these energy inputs more expensive in the North, and reduces their demand, however the South would still produce Y_{dG} for its own domestic market, and this would not prevent the environmental disaster. Even the most prohibitive tax, one that makes fossil fuel energy goods completely unaffordable in the North, or a full trade ban, would not solve the problem, because the South would keep consuming them at home.

ii. Research subsidies or taxes. The North can encourage R&D in renewable energy either by subsidizing research in this field, or taxing research in other sectors so to redirect investments and scientists to green technology. This policy strategy is similar in spirit to green directed technical change policies, namely the use of innovation subsidies to redirect paths of industrial development away from "dirty" production (Acemoglu et al., 2012). In an open economy, however, unilateral innovation policies cannot fully redirect paths of specialization if factors of production are fixed. In our model, we assume that the mass of scientists in each economy cannot change: therefore the North can never catch up with the relative productivity of the energy sector in the South. At best, if the North allocates all its scientists to the energy sector, it could match the productivity *growth* of the South in that sector, but not its absolute value, which ensures its comparative advantage. It is not possible, with research subsidies alone, to make green energy technologies from the North more competitive than Southern fossil fuel-based energy production, because the South started innovating in this sector sooner.

iii. Price subsidies for green technologies. Another alternative to sponsor the use of renewable technologies is to offer a price subsidy on renewable energy inputs, both for domestic use and for exports to the South. This policy is different from R&D subsidies, because it is not constrained by fixed resources like the number of scientists in a country, and can automatically bring the price of renewable energy inputs below the one of fossil fuels, inducing an immediate switch in the type of energy used. [13] This policy is very effective, but entails a transfer of income to the South, which would benefits from the cheap subsidized energy inputs sold by the North.

iv. Purchase of fossil fuel deposits. Acting directly on the supply side, the North can pay the South to stop fossil fuels use at the source, by purchasing the deposits of coal. This idea has been proposed by Harstad (2012), who suggests to the most environmentally–concerned countries to

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[13] Of course, if renewables and fossil fuels were not perfect substitutes, as indicated in eq. (6), there would be some attrition in the process. However qualitatively the result would be the same, just taking more time.

get in a coalition to buy foreign deposits of coal and preserve them. This policy can achieve an immediate halt in the use of fossil fuels, but its costs can be sizeable. Not only the North must compensate the South for the foregone income from fossil fuels exploitation, but it would also incur into indirect costs, such as monitoring and enforcement that foreign deposits are actually not being used. This policy is not incentive compatible from the Southern point of view: even if the North buys the deposits, the South would always find it profitable to extract some of the resource on the side, as long as no other cheaper energy source is present on the market.

v. International transfers of green technology. Another rapid policy instrument is technology transfer. This works particularly if the North is more advanced technologically than the South, so transferring patents can boost the productivity of the South in renewable energy industries, making the transition away from fossil fuels more rapid. Note that the technology required to ensure that South commits to renewable energy production should not only match the productivity of the fossil fuels sector (A_d), but also surpass the competitive advantage given by the cheap and abundant fossil fuel reserves R present in the South. Naturally, this policy is limited by the amount of green energy technologies available in the North. Furthermore, there can be costs and foregone revenues attached to the transfers of green technology.

Overall, in an open economy, not all policy instruments are effective in avoiding an environmental disaster, and none is free. First of all, a policy combination must ensure that fossil fuels are no longer burnt and that the climate does not reach the threshold of a disaster. Secondly, a policy strategy must determine which region would produce energy and bear the local environmental costs associated with it. Thus, we now analyse two opposite policy strategies, both capable of achieving the first goal, but with opposite outcomes in terms of the location of energy production. The first policy combination examined in the next paragraphs, called for simplicity Policy A, redirects the specialization path of the South away from energy production into other non-energy inputs. It also relocates the production of energy to the North. Viceversa, in section (4.2), we analyse a different policy strategy, Policy B, that leaves the production of energy in the South, but eliminates the use of fossil fuels for energy generation.

4.1 Policy A - redirecting specialization paths

The first policy strategy that the North can implement is to eliminate all incentives for the South to use fossil fuels. In an open economy setting, this occurs only if the South specializes fully in non-energy production, which by definition does not require fossil fuels. If the North encourages an expansion of the Southern market for non-energy inputs, the comparative advantage of the South would shift away from energy production, stopping the use of fossil fuels and global pollution. However, energy inputs are always required for final goods' production, so in general equilibrium energy must be produced somewhere. Thus, the North also needs to redirect its own industrial specialization, and start producing energy goods through renewable resources.

A similar policy package is proposed by Hémous (2014) in a model of polluting and non-polluting goods without any fossil fuels. He suggests that the North should combine innovation policies with trade restrictions, in order to swap comparative advantage. Also in his model innovation subsidies alone are not sufficient to redirect production in an open economy, because the number of scientists is fixed. However a combination of innovation and trade policies can avoid a climate disaster. Trade restrictions temporarily bring the two countries to a state similar to autarky, where both need to produce all goods, without full specialization. In this situation, not all scientists in the South are working in the dirty industry, and so the North can catch up. With a research subsidy for the Northern clean sector, and a trade tax on dirty imports coming from the South, the growth rate of the A_d technology of the North can surpass that of the South. These two policy instruments only redistribute income across sectors, but do not reduce the income of the North. After some time, the innovation subsidies coupled with trade protectionism would cause a switch in the comparative advantage of the two countries, so that the South acquires a competitive edge in the clean sector. Once the switch of comparative advantage has been achieved, innovation and trade policy can be discontinued.

We find that a similar policy combination can avoid the environmental disaster also in our model. However, our framework has two fundamental differences from the one of Hémous (2014): first of all, the fossil fuel endowments in our model allow for the switch in comparative advantage only once the A technologies overcome the competitiveness effect given *both* by fossil fuels and by the productivity in that sector, A_{dG}. As shown in free trade, fossil fuel resources provides the South with a unique source of comparative advantage in energy industries (see eq. (33)). Over time, this is coupled with increasing levels of productivity in the fossil fuel industry, A_{dG}, since all investments in innovation are in that sector. Therefore, in a model with fossil fuels, the switch occurs later than in a model where the South does not benefit from any comparative advantage from natural resources.

Remark 1 – *Trade and innovation policies á la Hémous (2014) to reverse comparative advantage must overcome two sources of competitiveness in the Southern energy sector: i) the (fixed) endowment of cheap fossil fuels, and ii) the growing productivity of the fossil fuel sector, since all R&D is allocated to that activity in the South. Point i) implies that, ceteris paribus, a model without cheap fossil fuel endowments should predict a faster switch in comparative advantage than one that includes them. Point ii) implies that a policy introduced later will take longer to achieve the switch in comparative advantage than one introduced sooner. See equation (33).*

A second important difference between our model and the one of Hémous (2014) is that in our set-up the South uses energy also for its own domestic consumption. Thus, before the switch in comparative advantage, global pollution is still accumulating in the atmosphere because of Southern production and use of fossil fuel-intensive energy. Even the most aggressive trade policy from the North, a trade ban on fossil fuel energy inputs, does not halt the decline of the global environment. This has important implications for the effectiveness of this policy: it cannot guarantee that under all circumstances it can avoid an environmental disaster. The time necessary to bridge the gap in competitiveness between green energy in the North and fossil fuels in the South might be longer that the time-scale for an environmental disaster.

Therefore, we consider a variation of the policy package proposed by Hémous (2014), introducing instead of a trade tariff a *price subsidy* for green energy. This is more costly than trade barriers, because part of the price subsidy is transferred to the energy users in the South, but it ensures an immediate switch away from fossil fuels, and guarantees that the environmental disaster never occurs.

Definition D.4 – *Policy A - we define a first policy package that the North can implement to avoid the environmental disaster as: i) research subsidies to green energy R&D, and ii) a price subsidy to green energy such that* $p_{dL} \leq p_{dG}$. *This policy transfers energy production to the North.*

There is one last important implication of this policy strategy: all production of energy and energy-intensive goods shifts to the North. This inevitably has environmental costs associated with local pollution. Thus, depending on how much the North values its own environment, this policy can have significant drawbacks. Next, we turn to an alternative policy package of international transfers and supply side policies, which keeps the production of energy in the South.

4.2 Policy B - Purchase of deposits

An alternative solution to avoid a global environmental disaster is for the North to block the supply of fossil fuels in the South, buying its deposits at a price that makes the South indifferent between producing energy with fossil fuels or without. This idea has been proposed by the literature in other contexts; for instance, to avoid carbon leakages, Harstad (2012) suggests to the most environmentally–concerned countries to get in a coalition to buy foreign deposits of coal and preserve them. In our model, this policy is fast in terms of stopping fossil fuels' usage, but it can have sizeable costs, not only for the purchase of the deposits, but also to monitor and enforce that they are not used. Buying fossil fuel deposits does not change the incentives for the South to use fossil fuels, since the country remains in the business of energy production. The temptation to use irregularly the fossil fuels purchased by the North is always present, as long as they are cheaper. The North should thus encourage the development of a green energy sector in the South with other policy instruments: in particular, if Northern technologies are more advanced than Southern ones, it can operate an international transfer of technology, so that the sector catches up more quickly with fossil fuels productivity, and the incentives to cheat on the deposits diminish over time.

The transfer of green technology to the South has also a second, important purpose: to avoid a switch in comparative advantage like in Policy A. The South in our model does not invest in any renewable energy technology under *laissez-faire*, because it always produces energy using cheap fossil fuels (even in autarky); therefore, once the key source of its competitiveness, fossil fuels, is removed, its most competitive sector in relative terms would be the non-energy one (following Assumption A.4 and A.5). Thus the two countries would swap paths of specialization, like in the previous case of policy A, but possibly at a greater cost. If instead the North wants to avoid the switch of specialization paths (something it cannot achieve with Policy A), it must transfer some of its more advanced green energy technology to the South, so to give sufficient competitiveness to its renewable resources. As the production of energy causes local environmental damages, the North has a preference for a policy that, for a given monetary cost, keeps energy production in the South. So the advantage of Policy B can be exactly the fact that energy production does not need to relocate to the North.

Remark 2 – *A purchase of fossil fuel deposits causes a swap in the comparative advantage of the two regions, if the South never produced any clean energy. Instead, with transfers of green energy technology from the North, the South would continue producing energy inputs and bear the local environmental costs of this activity.*

Over time, the South can build up a competitive edge in green energy through sectoral innovation, and then this policy can be suspended, once the green technology of the South has achieved a price that is equivalent or cheaper than fossil fuels.

Definition D.5 – *Policy B - we define a second policy package for the North to avoid the environmental disaster as: i) international payment to the South to purchase its fossil fuel deposits, and ii) a technology transfer if the North has more advanced green energy technologies than the South. This policy leaves energy production in the Southern region.*

Next, we compare the welfare implications of these two opposite strategies, highlighting under what circumstances one is preferred to the other.

4.3 Policy choice

The primary goal of the North is to avoid an environmental disaster. To do so, it must encourage a global substitution away from the emission intensive Y_{dG} and into renewable energy production that does not harm the global climate, Y_{dL}. The two strategies described in the previous paragraphs can both achieve this goal. Which one should the North choose? There are important differences in the economic and environmental implications of the two policy strategies. As described above, green innovation policies and price subsidies for clean energy (Policy A) can modify comparative advantages, but create an environmental cost for the North as it starts producing energy goods. Viceversa, with an international purchase of deposits and transfers of green technology to the South (Policy B), energy production remains confined into the Southern pollution haven, with no damages to the Northern local environment.

The monetary costs of the two policies are also different in nature: Policy A imposes a cost on the North to the extent that the clean energy exported to the South is subsidized. Instead Policy B requires a purchase of fossil fuel deposits, plus monitoring costs, and potentially even some costs for technology transfers. We do not make assumptions about which policy costs more in monetary terms. In the numerical exercise we solve endogenously for the prices of energy inputs and for the value of the fossil fuel resources, while leaving out monitoring costs and frictions in technology transfers.

This section discusses the choice between these two alternative policy options with the support of a simple calibration (see Appendix F for details). We cannot exclude that other more complex policy solutions exist, but we opted for these two parsimonious strategies, which have immediate effectiveness in avoiding the environmental disaster. Fig. 2 shows a comparison of the two policies, displaying the evolution of the environment and production. In both cases the policy is introduced at time t=5.

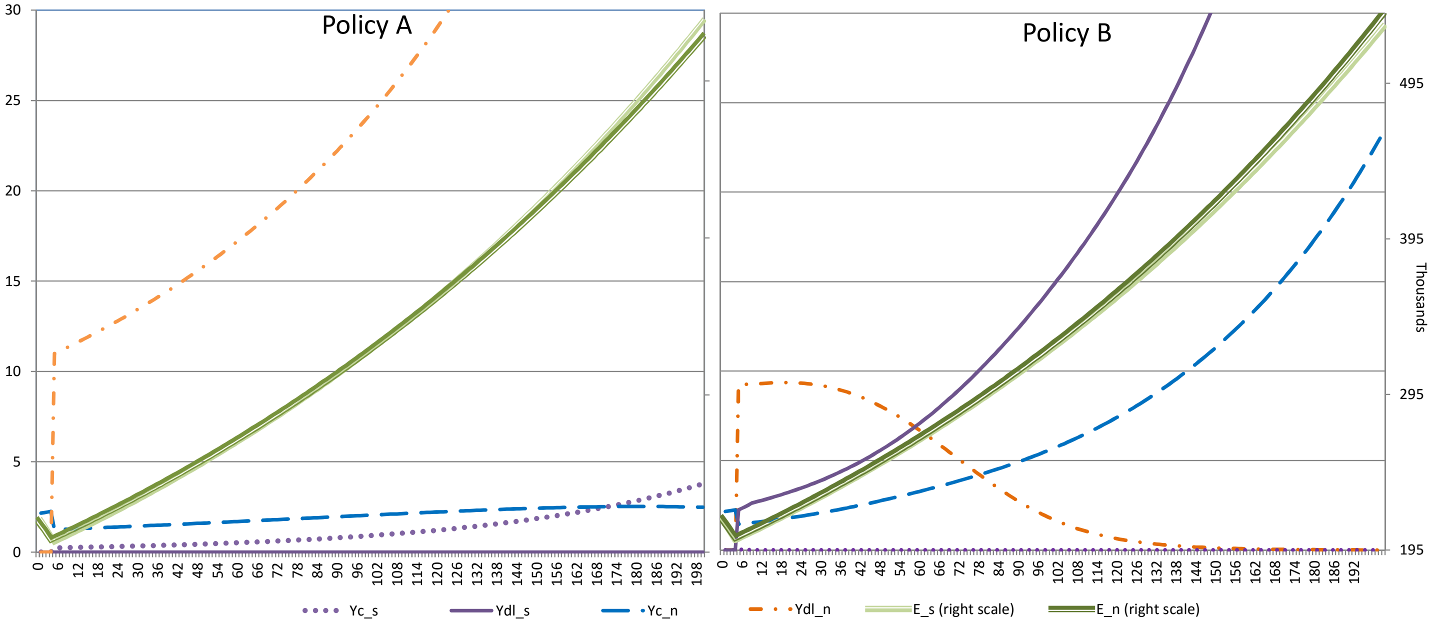

Figure 2: Evolution of production and environment with policies

Production of Y_{dG} comes to a halt as soon as any of the two policies start (thus, it is not displayed in the graph). In both cases, the environment stops collapsing and steadily recovers. However, in the case of Policy A (left panel), the production of Y_{dL} takes place exclusively in the North (dotted-dashed orange line, Ydl_n). The South instead produces non-energy goods (Yc_s dotted violet line). As a consequence, the environment of the South improves slightly more than the Northern one. Under Policy B (right panel), when fossil fuel deposits are sealed, initially both countries produce Y_{dL}, but then over time only the South specializes in it, while the North specializes in non-energy products. In this case the environment of the North is slightly better off than the one of the South.

The changes in production and environmental quality translate in different welfare outcomes, depending on on the value that environment and consumption have. The overall welfare if a policy strategy $P \in [A, B]$ is implemented at time t^* is given by the welfare function in equilibrium:

$$W_t^P = \frac{1}{1-\eta}\left[\ \sum_{t=t^*}^{T} \beta^t \ \left(\mu E_t + (1-\mu)\,\widehat{C}_t\right)^{1-\eta} \ + \ \sum_{t=T}^{\infty} \beta^t \ (\mu E_t + (1-\mu)\,C_t\,)^{1-\eta}\right] \tag{44}$$

First of all, we can now exclude the event of an environmental disaster, so welfare is positive if either policy A or B is implemented. We have two periods, one for the duration of the policy, up to T, and one afterwards, once the policy is discontinued, from T up to infinity. Both policies can be removed once the comparative advantage of the two countries is the same in laissez faire as with the policies. In the first period, consumption is characterized by $\widehat{C}$, as the policy is costly from the point of view of the North (or beneficial from the point of view of the South), and generates lower (or higher) income. The choice between the two policies depends on a number of factors. Four salient ones are illustrated in Fig. 3.

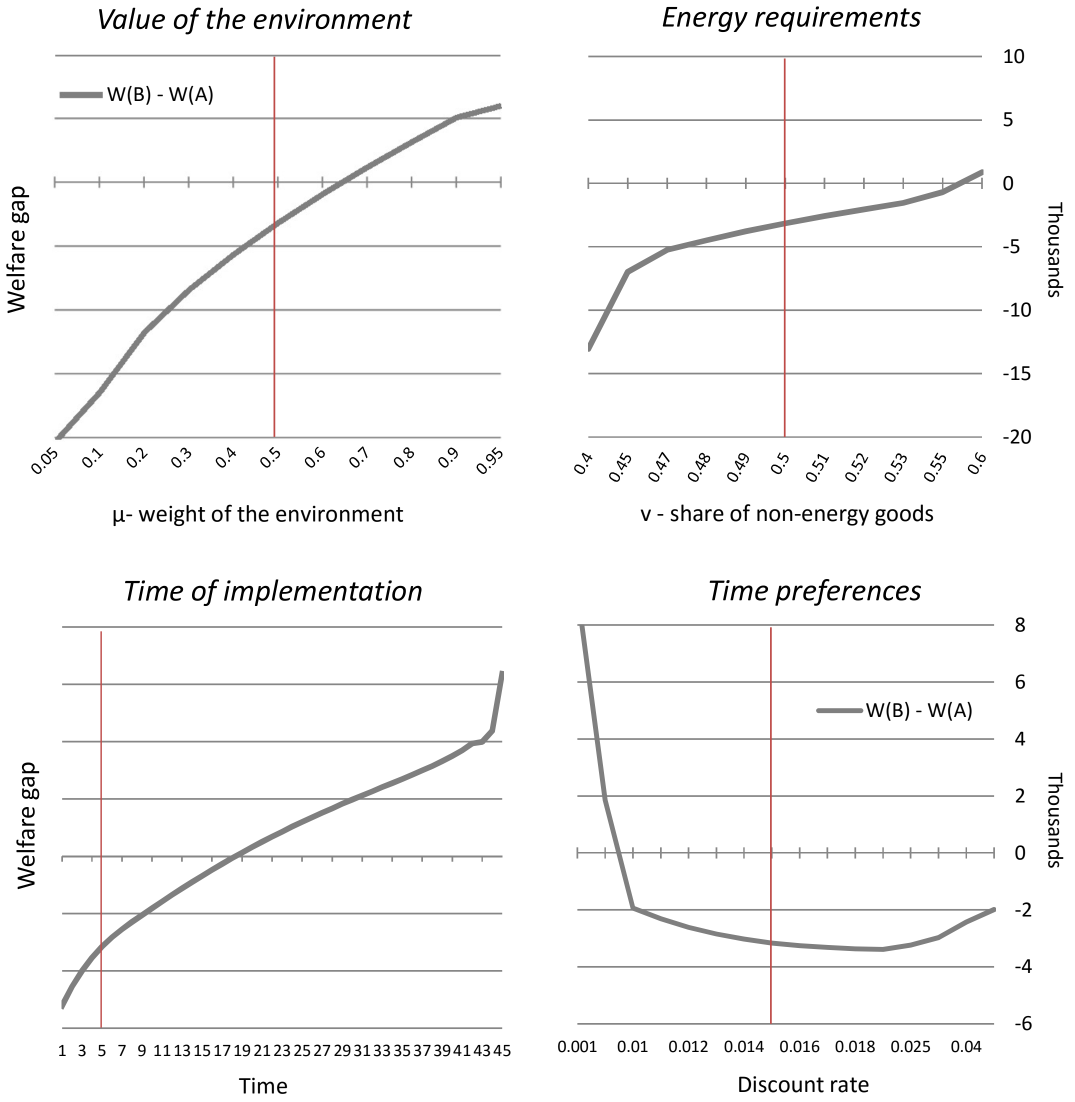

Figure 3: Policy choice with different parameters

Value of the environment. First and foremost, a key difference between the two policies is the location of energy production: so the choice depends on the welfare valuation of the environment for the North. This is captured by the parameter μ in the welfare function. If there was no environmental difference between the two policies, clearly any policy maker would just prefer the cheapest one. However, since Policy A causes local environmental costs because it relocates energy production to the North, it is preferred, *ceteris paribus*, when the value of the environment of the welfare function is not particularly high. The top-left panel of Fig. 3 shows the difference in welfare between Policy A and B, against an increasing value of the environment, captured by μ. The thin red line is the reference value used to produce the previous figures. The higher the value of the environment, the higher welfare benefits from policy B relative to A, because the Northern local environment is not compromised.

Energy requirements. If the production of final goods does not require much energy, as captured by the Cobb-Douglas share ν, relocating the production of energy inputs to the North would not create high welfare damages. The top-right panel of Fig. 3 shows how this changes as energy requirements increase. If energy takes a share greater than half in the production of final goods, policy B is more likely to be chosen, since it leaves the energy production to the South.

Starting time of the policy. Policy A provides a higher welfare than Policy B particularly if it is implemented relatively soon. The longer the North waits, the higher the level of specialization that the South achieves in energy production, and the harder to modify its comparative advantage. So, initially the subsidy for green energy prices that the North must pay is not too large, but as time passes this becomes larger and larger, making Policy B preferred.

Discount rate and time preferences. A key parameter for comparing the two strategies is how the North perceives time. The discount rate is a fundamental factor in weighting costs over time. The more impatient the North is (higher discount rate), the more it will prefer Policy A, because it would weight less the future cumulative damages on the environment, while it would notice more the immediate fall in income due to the transfer to the South in Policy B. The bottom-right panel of

Fig 3 illustrates how different discount rates can produce extremely different welfare evaluations of the two policies. This is because environmental quality is a cumulative function that evolves over time, and thus imposes dynamic costs and benefits on a country.

5. Conclusions

Countries endowed with abundant carbon resources are unlikely to give them up gratuitously. Fossil fuels provide a cheap source of energy and can increase the competitiveness of a country in the production of energy-intensive goods. This "dirty" comparative advantage builds up over time, reinforced by endogenous innovation. Therefore, the countries that care the most about global environmental outcomes must take the initiative to reduce carbon emissions by dealing with the issue of energy production worldwide.

Our model shows that halting the consumption of fossil fuels unilaterally is not a free lunch. A policy strategy that combines price and innovation subsidies for green energy can redirect specialization paths, giving resource-rich countries a new area of competitiveness other than the energy sector. While this policy is incentive compatible for the South not to use fossil fuels, it creates local environmental damages for the North, as it transforms it into an energy supplier and to some extent a pollution haven. Alternatively, the resource-rich South must receive a compensation for abandoning fossil fuels and a technology transfer to move into renewable energy sources, so that it keeps producing energy-intensive inputs for the rest of the world. This policy leaves some scope for cheating by the South, and thus might require extra monitoring and enforcement costs.

The contribution of this model is two-fold: first of all, by looking simultaneously at fossil fuel resources and local damages from energy production, it shows that the debate about green directed technical change cannot be too optimistic. Indeed, innovation policies combined with trade instruments can direct development paths, but it is not costless and in equilibrium someone must bear the environmental externalities of producing energy. Secondly, the model shows that supply side policies, such as purchasing coal deposits, work well for the Northern environment, but may imply a sizeable income transfer to the countries owning the reserves, and their environmental degradation. The costs of these supply side policies can be mitigated by technology transfers, if the North is more advanced in R&D on renewable energy.

Overall, we conclude that there is no costless way for the North to get rid of fossil fuel use in the South. This is what we define the "tragedy of the locals": a combination of the local ownership of fossil fuels and the local damages of energy production. On the one hand fossil fuels, even if they produce a global externality, are concentrated in the hands of few countries, and this makes international coordination more difficult. Since the incentives to use fossil fuels are asymmetric, a simple solution like a global agreement to ban coal cannot be sustained. On the other hand, the world requires large amounts of energy, which can be produced anywhere globally, but that cause local environmental externalities only in the countries that specialize in it. Our model captures this tension between the need for energy, the urge to stop generating it with fossil fuels, and the problem of where to locate this production.

The countries that are more concerned about climate change must be prepared to pay some of the price of moving away from fossil fuels, even if they do not directly own them. Either they can pay the resource-rich regions not to extract their local reserves, or they can subsidize renewable energy production and sell it cheaply around the world. Either way, though, policy-makers must be aware of the competitiveness effects that these policies have and of the environmental costs of energy production, at least for the types of energy that humanity knows so far.

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Appendices

A. Environment damages dynamics

Assumption A.3 in the model states that environmental catastrophes are caused only by the global pollution deriving from burning fossil fuels, and not from local environmental damages of energy production. In order to ensure that this condition is met, and thus if a country switches to renewable energy production Y_{dL} it would not experience an environmental disaster, we need the following condition to hold.

Looking exclusively at local damages, the environment at a final time T reads:

$$E_T = (1+\Delta)^T E_0 - \zeta Y_{d,1} \left[\sum_{t=0}^{T-1} (1+\Delta)^t (1+\overline{g})^{T-1-t} \right] \tag{A.1}$$

where E_0 refers to the pristine value of environment, $Y_{d,1}$ is the the initial value of energy production (from renewable sources, fossil fuels or both) under free trade, and $\overline{g}$ is the constant growth rate of Y_d. We need to ensure that $E_T > 0$, so that

$$(1+\Delta)^T E_0 > \zeta Y_{d,1} \left[\sum_{t=0}^{T-1} (1+\Delta)^t (1+\overline{g})^{T-1-t} \right] \tag{A.2}$$

which re-arranging coefficients reads

$$(1+\Delta)^T E_0 > \zeta Y_{d,1} \left[\sum_{k=0}^{T-1} (1+\Delta)^{T-1-k} (1+\overline{g})^{k} \right] \tag{A.3}$$

or, readjusting

$$(1+\Delta) E_0 > \zeta Y_{d,1} \left[\sum_{k=0}^{T-1} \left(\frac{1+\overline{g}}{1+\Delta} \right)^{k} \right] \tag{A.4}$$

In an infinite setting we can rewrite this condition as

$$(1+\Delta)E_0 > \zeta Y_{d,1}\left[\sum_{k=1}^{\infty}\left(\frac{1+\overline{g}}{1+\Delta}\right)^k\right] \tag{A.5}$$

which requires as regularity condition to be convergent

$$\Delta > \overline{g}$$

then knowing that a geometric series with argument smaller than one converges to

$$\sum_{k=1}^{\infty} z^k = \frac{1}{1-z} - 1$$

we can easily find our solutions

$$\frac{(1+\Delta)}{(1+\overline{g})}(\Delta - \overline{g}) > \zeta \frac{Y_{d,1}}{E_0} \tag{A.6}$$

This condition ensures that local damages are not too large relative to the environment's regenerative capacity. Since Y_{dG} and Y_dL are perfect substitutes a country never produces both simultaneously, so for the above condition is sufficient to have it applied to any of them separately. The opposite condition applies to global damages from fossil fuel energy production, and their pollution parameter ξ. The derivation in that case would be analogous. So overall the condition required by assumption A.3 is

$$\xi \frac{Y_{dG,1}}{E_0} > \frac{(1+\Delta)}{(1+\overline{g})}(\Delta - \overline{g}) > \zeta \frac{Y_{dz,1}}{E_0} \tag{A.7}$$

where $\overline{g_z}$ is the constant growth rate of the energy source in question, either Y_{dG} or Y_{dL}.

B. Autarky

In this appendix we derive the laissez – faire autarky equilibrium for the North and the South. To simplify notation we omit the superscript k when the analysis is symmetric for the two countries.

In equilibrium, the income of a country is spend by consumers on the final good, and on the production of machines (capital)

$$pY = pC + \gamma^2 \int_i x_i \, di \tag{B.8}$$

where p is the price of final goods. Final goods assemblers of Y generate the demand for energy and manufactured inputs. They maximize their profits as

$$\Pi = pY - [p_c Y_c + p_{dL} Y_{dL} + p_{dG} Y_{dG}] \tag{B.9}$$

where

$$Y = (Y_c)^{\upsilon} \;\; (Y_{dL} + YdG)^{1-\upsilon}$$

which yields the following first order conditions with respect to the various inputs

$$Y_c \quad : \quad pv \left(\frac{Y_{dG} + Y_{dL}}{Y_c} \right)^{1-v} = p_c \tag{B.10}$$

$$Y_{dL} \quad : \quad p(1-v) \left(\frac{Y_c}{Y_{dL} + Y_{dG}} \right)^{v} = p_{dL} \tag{B.11}$$

$$Y_{dG} \quad : \quad p(1-v) \left(\frac{Y_c}{C_{dG} + Y_{dL}} \right)^{v} = p_{dG} \tag{B.12}$$

Combining (B.11) and (B.10) we get

$$\frac{1-v}{v} \frac{Y_c}{(Y_{dL} + Y_{dG})} = p_{dL}$$

and analogously with (B.12) and (B.10)

$$\frac{1-v}{v} \frac{Y_c}{(Y_{dL} + Y_{dG})} = p_{dG}$$

Next, we can look at the profit maximization problem of input producers in each sector,

$$\underset{K_c, x_{ci}}{Max} \left\{ p_c Y_c - rK_c - \int_0^1 p_i x_{ci} di \right\}$$

$$\underset{K_{dL},L_{dL},x_{dLi}}{Max}\left\{p_{dL}Y_{dL}-rK_{dL}-wL_{dL}-\int_0^1 p_i x_{dLi}di\right\}$$

$$\underset{K_{dG},L_{dG},R,x_{dGi}}{Max}\left\{p_{dG}Y_{dG}-rK_{dG}-wL_{dG}-qR-\int_0^1 p_i x_{dGi}di\right\}$$

leading to the following inverse demand for machines:

$$x_{ci}=\left(\frac{\gamma p_c A_c}{p_i}\right)^{\frac{1}{1-\gamma}}L_c \tag{B.13}$$

$$x_{dLi}=\left(\frac{\gamma p_{dL} A_{dL}}{p_i}\right)^{\frac{1}{1-\gamma}}L_{dL}^{\psi}K_{dL}^{1-\psi} \tag{B.14}$$

$$x_{dGi}=\left(\frac{\gamma p_{dg} A_{dG}}{p_i}\right)^{\frac{1}{1-\gamma}}L_{dG}^{\beta}K_{dG}^{1-\alpha-\beta}R^{\alpha} \tag{B.15}$$

Monopolistic machine producers set their prices to maximize their profit $\pi_i=(p_i-\varsigma)x_{zi}$, with $z\in\{c,dL,dG\}$. Given inverse demands for machines from input producers and a fixed cost of $\varsigma=\gamma^2$, the profit maximizing price for machine producers is $p_i=\gamma$. Thus, the equilibrium demands for machines are in each sector:

$$x_{ci}=(p_c A_c)^{\frac{1}{1-\gamma}}L_c \tag{B.16}$$

$$x_{dLi}=(p_{dL}A_{dL})^{\frac{1}{1-\gamma}}L_{dL}^{\psi}K_{dL}^{1-\psi} \tag{B.17}$$

$$x_{dGi}=(p_{dG}A_{dG})^{\frac{1}{1-\gamma}}L_{dG}^{\beta}K_{dG}^{1-\alpha-\beta}R^{\alpha} \tag{B.18}$$

which yields to the following equilibrium profits for machine producers:

$$\pi_{xci}=\gamma(1-\gamma)L_c\,(p_c A_c)^{\frac{1}{1-\gamma}} \tag{B.19}$$

$$\pi_{xdLi}=\gamma(1-\gamma)L_{dLi}^{\psi}K_{dLi}^{1-\psi}\,(p_{dL}A_{dL})^{\frac{1}{1-\gamma}} \tag{B.20}$$

$$\pi_{xdGi}=\gamma(1-\gamma)L_{dGi}^{\beta}K_{dGi}^{1-\alpha-\beta}R^{\alpha}\,(p_{dG}A_{dG})^{\frac{1}{1-\gamma}} \tag{B.21}$$

Plugging the equilibrium input demands on equations (7), (8) and (9), we obtain the following equilibrium production of inputs:

$$Y_c = A_c{}^{\frac{1}{1-\gamma}} L_c p_c{}^{\frac{\gamma}{1-\gamma}} \tag{B.22}$$

$$Y_{dL} = A_{dL}{}^{\frac{1}{1-\gamma}} L_{dL}{}^{\psi} K_{dL}{}^{1-\psi} p_{dL}{}^{\frac{\gamma}{1-\gamma}} \tag{B.23}$$

$$Y_{dG} = A_{dG}{}^{\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha} p_{dG}{}^{\frac{\gamma}{1-\gamma}} \tag{B.24}$$

The relative prices of inputs are derived by combining the equilibrium quantity of machines with the first order derivative with respect to labour for each input sector. [14]

$$\frac{p_c}{p_{dL}} = \frac{A_{dL}}{A_c} \left(L_{dL}^{\psi-1} K_{dL}^{1-\psi} \psi \right)^{1-\gamma} \tag{B.25}$$

$$\frac{p_c}{p_{dG}} = \frac{A_{dG}}{A_c} \left(L_{dG}^{\beta-1} K_{dG}^{1-\alpha-\beta} R^{\alpha} \beta \right)^{1-\gamma} \tag{B.26}$$

$$\frac{p_{dG}}{p_{dL}} = \frac{A_{dL}}{A_{dG}} \left(\frac{\psi}{\beta} \frac{L_{dL}^{\psi-1}}{L_{dG}^{\beta-1}} \frac{K_{dL}^{1-\psi}}{K_{dG}^{1-\alpha-\beta}} \frac{1}{R^{\alpha}} \right)^{1-\gamma} \tag{B.27}$$

Energy and manufactured input producers choose their factors demand by minimizing their costs. In the North, the active sectors of production are c and dL, while in the South, given $p_{dG} < p_{dL}$ from the assumption of eq. (20), the sectors are c and dG. Thus, the factors demand are

$$L_c = \frac{Y_c}{A_c{}^{\frac{1}{1-\gamma}}} \tag{B.28}$$

$$L_{dL} = \frac{Y_{dL}}{A_{dL}} (1-\gamma)^{\gamma} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\psi} \right)^{\psi(1-\gamma)-1} \left(\frac{r}{1-\psi} \right)^{(1-\gamma)(1-\psi)} \tag{B.29}$$

$$L_{dG} = \frac{Y_{dG}}{A_{dG}} (1-\gamma)^{\gamma} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\beta} \right)^{\gamma+(1-\gamma)(\beta-1)} \left(\frac{r}{1-\alpha-\beta} \right)^{(1-\gamma)(1-\alpha-\beta)} \left(\frac{q}{\alpha} \right)^{\alpha(1-\gamma)} \tag{B.30}$$

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[14] The analysis is conducted under the normalization $p_c = 1$. It follows that $w = A_c^{\frac{1}{1-\gamma}} (1-\gamma)$.

$$K_{dL} = \frac{Y_{dL}}{A_{dL}} (1-\gamma)^{\gamma} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\psi} \right)^{\psi(1-\gamma)} \left(\frac{r}{1-\psi} \right)^{\psi(\gamma-1)-\gamma} \tag{B.31}$$

$$K_{dG} = \frac{Y_{dG}}{A_{dG}} (1-\gamma)^{\gamma} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\beta} \right)^{\beta(1-\gamma)} \left(\frac{r}{1-\alpha-\beta} \right)^{(1-\gamma)(1-\alpha-\beta)-1} \left(\frac{q}{\alpha} \right)^{\alpha(1-\gamma)} \tag{B.32}$$

$$R_{dG} = \frac{Y_{dG}}{A_{dG}} (1-\gamma)^{\gamma} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\beta} \right)^{\beta(1-\gamma)} \left(\frac{r}{1-\alpha-\beta} \right)^{(1-\gamma)(1-\alpha-\beta)} \left(\frac{q}{\alpha} \right)^{\alpha(1-\gamma)-1} \tag{B.33}$$

Also from the input producers' minimization problem we obtain p_{dL} and p_{dG} as

$$p_{dL} = \frac{1}{A_{dL}} \left(\frac{1}{1-\gamma} \right)^{(1-\gamma)} \left(\frac{r}{1-\psi} \right)^{(1-\gamma)(1-\psi)} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\psi} \right)^{\psi(1-\gamma)} \tag{B.34}$$

$$p_{dG} = \frac{1}{A_{dG}} \left(\frac{1}{1-\gamma} \right)^{(1-\gamma)} \left(\frac{r}{1-\alpha-\beta} \right)^{(1-\gamma)(1-\alpha-\beta)} \left(\frac{A_c^{\frac{1}{1-\gamma}} (1-\gamma)}{\beta} \right)^{\beta(1-\gamma)} \left(\frac{q}{\alpha} \right)^{\alpha(1-\gamma)} \tag{B.35}$$

It follows that, in the North where there are no fossil fuels

$$Y_{dL} = \frac{1-\upsilon}{\upsilon} \frac{Y_c}{p_{dL}} \tag{B.36}$$

while in the South

$$Y_{dG} = \frac{1-\upsilon}{\upsilon} \frac{Y_c}{p_{dG}} \tag{B.37}$$

Pugging the expressions for p_{dL} and p_{dG} into equations (B.36) and (B.37) respectively, and solving for L_{dL} and L_{dG} we obtain

$$L_{dL} = \frac{1-\upsilon}{\upsilon} L_c \psi \tag{B.38}$$

$$L_{dG} = \frac{1-\upsilon}{\upsilon} L_c \beta \tag{B.39}$$

The labour market clearing condition are given by $L_c + L_{dL} = \overline{L}$ and $L_c + L_{dG} = \overline{L}$ for North and South, respectively. Combining equations (B.38) and (B.37) with the labour market clearing conditions, we derive for each region the labour equilibrium demands presented in the paper. Following the same logic for K_{dL}, K_{dG} and R we calculate the consequent equilibrium factors prices for both regions. Combining the equilibrium factors demand and the price ratio between goods dG and dL yields the regularity condition implied in equation (20).

Finally, the evolution of the clean and dirty technology is determined by the scientists allocations among the two sectors. In the North, scientists can only be hired in the intermediate sectors of production c or dL, while in the South the choice is between the sectors c and d_G or c and dG, depending on the price scenario. Given $\vartheta_z \in (0,1)$, with $z \in \{c, dL, dG\}$, and $(1+\varphi)$, we can calculate the relative profit ratios simply by combining the equilibrium factors demand with equilibrium profits for input producers.

C. Free Trade

C.1 Solution

In this section we alter the autarky equilibrium allowing trade interactions among the regions under the two price scenarios. We continue the analysis under the normalization $p_c = 1$ but with country specific labour rent. Consumers still maximize their utility subject to their budget constraint with the choice between domestically or internationally produced goods.

Starting with the $p_{dG} < p_{dL}$ case, the new maximization problem imposes

$$\frac{1}{p_{dG}} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dG}}{Y_c^N + Y_c^S} \tag{C.1}$$

where

$$Y_c{}^N = A_c{}^{N\frac{1}{1-\gamma}} L_c{}^N \tag{C.2}$$

$$Y_c{}^S = A_c{}^{S\frac{1}{1-\gamma}} L_c{}^S \tag{C.3}$$

and likewise in autarky,

$$Y_{dG} = A_{dG}{}^{S\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha} p_{dG}{}^{\frac{\gamma}{1-\gamma}} \tag{C.4}$$

Plugging the equations for $Y_c{}^N$, $Y_c{}^S$ and Y_{dG} into the consumer's maximization problem and knowing that $L_c{}^S = \overline{L^S} - L_{dG}$ from the market clearing, we derive an expression for p_{dG} as

$$p_{dG} = \left(\left(\frac{1-\upsilon}{\upsilon}\right) \frac{A_c^{N\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\frac{1}{1-\gamma}} \left(\overline{L}^S - L_{dG}\right)}{A_{dG}{}^{S\frac{1}{1-\gamma}} L_{dG}{}^{\beta} K_{dG}{}^{1-\alpha-\beta} R^{\alpha}} \right)^{1-\gamma} \tag{C.5}$$

Despite free trade, d_G goods are produced exclusively in the South where the natural resource is available. As a result, final producers in the dirty sector face the same cost minimization problem as in autarky, leaving the factors demands and the expression for p_{dG} unchanged. Taking ratios of the factors demand and imposing the market clearing conditions $K_{dG} = \overline{K^S}$ and $R_{dG} = \overline{R}$, we derive the following relations

$$q^* = \frac{\overline{K}^S}{\overline{R}} \frac{r^{S*}}{(1-\alpha-\beta)} \alpha \tag{C.6}$$

$$L^*_{dG} = \overline{K}^S \frac{\beta}{(A^S_c)^{\frac{1}{1-\gamma}}(1-\gamma)} \frac{r^{S*}}{(1-\alpha-\beta)} \tag{C.7}$$

Finally, combining the two expressions for p_{dG} and solving for r^S gives

$$r^{S*} = \frac{(1-\upsilon)(1-\gamma)}{\beta(1-\upsilon)+\upsilon}\frac{(1-\alpha-\beta)}{\overline{K}^S}\left(A_c^{N\frac{1}{1-\gamma}}\overline{L}^N + A_c^{S\frac{1}{1-\gamma}}\overline{L}^S\right) \tag{C.8}$$

Under the $p_{dG} > p_{dL}$ scenario, the active final sectors are c and dL and the production of dirty goods is no longer restricted to the South. Allowing international trade, both goods can be produced and consumed in the North and the South without globally damaging the environment. Given the cheaper price of dL, the consumer's maximization problem leads to

$$\frac{1}{p_{dL}} = \frac{\upsilon}{1-\upsilon}\frac{Y^N_{dL}+Y^S_{dL}}{Y^N_c+Y^S_c} \tag{C.9}$$

Following the same steps as before, but now with $L_c{}^N = \overline{L}^N - L_{dL}{}^N$ and $L_c{}^S = \overline{L}^S - L_{dL}{}^S$, we derive p_{dL} as

$$p_{dL} = \left(\left(\frac{1-\upsilon}{\upsilon}\right)\frac{A_c^{N\frac{1}{1-\gamma}}\left(\overline{L}^N - L^N_{dL}\right) + A_c^{S\frac{1}{1-\gamma}}\left(\overline{L}^S - L^S_{dL}\right)}{A_{dL}{}^{N\frac{1}{1-\gamma}} L_{dL}{}^{N\psi} K_{dL}{}^{N(1-\psi)} + A_{dL}{}^{S\frac{1}{1-\gamma}} L_{dL}{}^{S\psi} K_{dL}{}^{S(1-\psi)}}\right)^{1-\gamma} \tag{C.10}$$

Final producers continue to minimize their costs in both regions, so by taking ratios again, we obtain two symmetrical expression for L_{dL}

$$L^{N*}_{dL} = \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{1-\psi}\overline{K}^S \tag{C.11}$$

and

$$L^{S*}_{dL} = \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{C.12}$$

Abstracting from trade costs and assuming that the law of one price holds, we express r^S as a function of r^N by taking ratios of the expressions for p_{dL} obtained through the cost minimization problem in both regions. Thus,

$$r^{S*} = \frac{r^{N*}}{\left[\left(\frac{A_c^S}{A_c^N}\right)^{\frac{\psi}{1-\gamma}}\left(\frac{A_{dL}^N}{A_{dL}^S}\right)^{\frac{1}{1-\gamma}}\right]^{\frac{1}{1-\psi}}} \tag{C.13}$$

Finally, combining (*********) with the p_{dL} expression derived from the southern cost minimization, and solving for r^N we obtain

$$r^{N*} = \frac{A_c^{N\frac{1}{1-\gamma}}\overline{L}^N + A_c^{S\frac{1}{1-\gamma}}\overline{L}^S}{H} \tag{C.14}$$

where

$$H = \frac{\upsilon}{(1-\upsilon)(1-\gamma)}\frac{1}{A_{dL}^{S\ \frac{1}{1-\gamma}}}\frac{A_c^{S\frac{\psi}{1-\gamma}}(1-\gamma)^{\psi}}{1-\psi}\frac{1}{G}\left[A_{dL}^{N\ \frac{1}{1-\gamma}}\frac{\overline{K}^N}{A_c^{N\frac{\psi}{1-\gamma}}(1-\gamma)^{\psi}} + A_{dL}^{S\ \frac{1}{1-\gamma}}\frac{\overline{K}^S}{A_c^{S\frac{\psi}{1-\gamma}}(1-\gamma)^{\psi}}\frac{1}{G^{\frac{\psi}{1-\psi}}}\right]$$

$$+\left[A_c^{N\frac{1}{1-\gamma}}\frac{\psi}{A_c^{N\frac{\psi}{1-\gamma}}(1-\gamma)^{\psi}}\frac{\overline{K}^N}{1-\psi} + A_c^{\frac{1}{1-\gamma}}\frac{\psi}{A_c^{S\frac{\psi}{1-\gamma}}(1-\gamma)^{\psi}}\frac{\overline{K}^S}{1-\psi}\frac{1}{G^{\frac{1}{1-\gamma}}}\right] \tag{C.15}$$

and

$$G = \left[\left(\frac{A_c^S}{A_c^N}\right)^{\frac{\psi}{1-\gamma}}\left(\frac{A_{dL}^N}{A_{dL}^S}\right)^{\frac{1}{1-\gamma}}\right] \tag{C.16}$$

D. Regularity Condition

We assume that $p_{dL} > p_{dG}$ for the South, so that fossil fuels are preferred to renewable energy in those countries that own them. For this condition to hold, we compare the equilibrium prices of these two inputs. We start from the ratio derived in eq. (B.27) and substitute in it the factor demands for the South analogue to equations (13) to (15).

$$\frac{Ad_L}{A_{dG}}\left[\frac{\psi}{\beta}\frac{\left(\left(\frac{1-\upsilon}{\upsilon}\right)\psi\frac{1}{1+\left(\frac{1-\upsilon}{\upsilon}\right)\psi}\bar{L}\right)^{\psi-1}}{\left(\left(\frac{1-\upsilon}{\upsilon}\right)\beta\frac{1}{1+\left(\frac{1-\upsilon}{\upsilon}\right)\beta}\bar{L}\right)^{\beta-1}}\ \frac{\bar{K}^{1-\psi}}{\bar{K}^{1-\alpha-\beta}\bar{R}^{\alpha}}\right]^{1-\gamma} = \frac{p_{dG}}{p_{dL}} < 1 \tag{D.17}$$

Rearranging the above equation we get the result in the regularity condition of eq. (20).

Otherwise, using the autarky prices of eq. (28) and eq. (19) and substituting the r with eq. (25) for p_{dG}, (17) for p_{dL} and (26) for q we get that

$$\frac{A_{dL}}{A_{dG}}\left(\frac{\overline{R}}{\overline{L}^S}\frac{\nu+\beta\left(1-\nu\right)}{1-\nu}\right)^{\alpha(1-\gamma)}>1 \tag{D.18}$$

When opening to free trade, prices adjust to meet the new conditions of the market, and due to more cumbersome calculation we are unable to find an explicit solution, as before, for $p_{dL}^{FT}>p_{pG}^{FT}$, but with the help of a dedicated software we could still verify that this condition is met whenever Equation (20) is satisfied.

Figures 4, 5, 6 explore the relation between the regularity condition under autarky and free trade while the main endowment factors (namely natural capital, $\overline{K}$, labour, $\overline{L}$, and the fossil fuel resource, $\overline{R}$) are varied.[15] Whenever $p_{dL}^{A}>p_{pG}^{A}$ is satisfied we can also confirm $p_{dL}^{FT}>p_{pG}^{FT}$, as the ratio of prices is, in both cases, above the unity.

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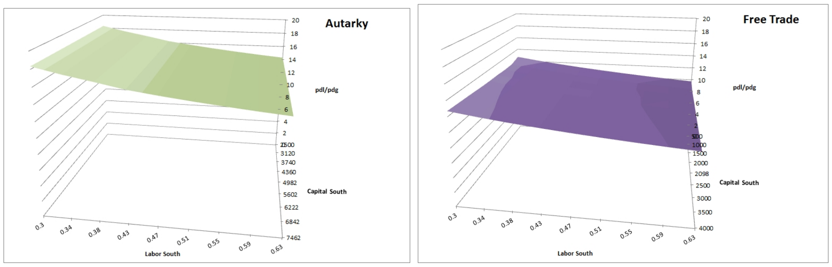
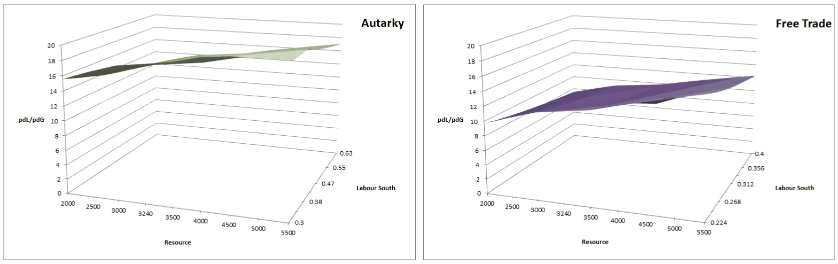
[15] In the figures endowments of South are represented, but equivalent results can be found when the parameters of North are taken as controls



(a) Autarky

(b) Free Trade

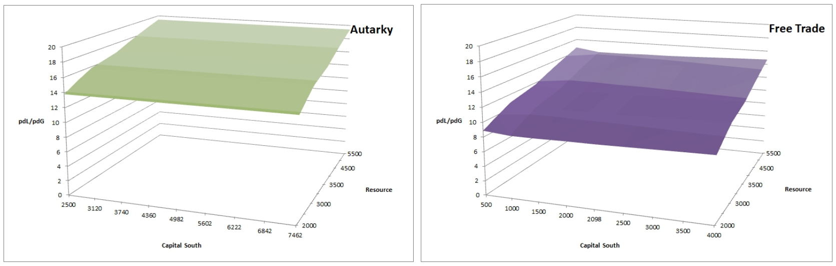
Figure 4: Regularity Condition under Autarky and Free Trade - $\overline{R}$ fixed



(a) Autarky

(b) Free Trade

Figure 5: Regularity Condition under Autarky and Free Trade - $\overline{K}$ fixed



(a) Autarky

(b) Free Trade

Figure 6: Regularity Condition under Autarky and Free Trade - $\overline{L}$ fixed

E. Policy implementation

E.1 North bans the purchase of Y_{dG}

Under this policy, consumers in the North can only demand Y_{dL} goods produced either in the North or the South,

$$\frac{1}{p_{dL}} = \frac{\upsilon}{1-\upsilon}\frac{Y_{dL}^N + Y_{dL}^S}{Y_c^N + Y_c^S} \tag{E.1}$$

while in the South, the decision is still based on the price of the two goods. If $p_{dG} > p_{dL}$, the result from the consumer maximization problem mimics the North and we fall into the laissez-faire free trade equilibrium with Y_{dL} being the cheaper good. If $p_{dG} < p_{dL}$, consumers in the South demand Y_{dG} from the dirty sector given by

$$\frac{1}{p_{dG}} = \frac{\upsilon}{1-\upsilon}\frac{Y_{dG}}{Y_c^N + Y_c^S} \tag{E.2}$$

Applying the market clearing conditions and following the same logic applied in the laissez-faire scenario, we derive the equilibrium factors demand and prices:

$$L_{dL}^{N*} = \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{E.3}$$

$$L_c^{N*} = \overline{L}^N - \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{E.4}$$

$$L_{dL}^{S*} = \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{1-\psi}K_{dL}^{S*} \tag{E.5}$$

$$L_{dG}^{S*} = \frac{\beta}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{(1-\alpha-\beta)}\left(\overline{K}^S - K_{dL}^{S*}\right) \tag{E.6}$$

$$L_c^{S*} = \overline{L}^S - \frac{r^{S*}}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\left[\frac{\beta}{(1-\alpha-\beta)}\left(\overline{K}^S - K_{dL}^{S*}\right) - \frac{\psi}{(1-\psi)K_{dL}^{S*}}\right] \tag{E.7}$$

$$K_{dL}^{N*} = \overline{K}^N \tag{E.8}$$

$$K_{dL}^{S*} = \frac{{A_{dL}^{S}}^{\frac{1}{1-\gamma}} \frac{\overline{K}^{S}}{(1-\alpha-\beta)H} - {A_{dL}^{N}}^{\frac{1}{1-\gamma}} \frac{\overline{K}^{N}}{(1-\psi)}}{\left(\frac{A_c^N}{A_c^S}\right)^{\frac{\psi}{1-\gamma}} \frac{A_d L^{S\frac{1}{1-\gamma}}}{(1-\psi)H^{\psi}} + \frac{{A_{dL}^{S}}^{\frac{1}{1-\gamma}}}{(1-\alpha-\beta)H}} \tag{E.9}$$

$$K_{dG}^{S*} = \overline{K}^{S} - \frac{{A_{dG}^{S}}^{\frac{1}{1-\gamma}} \frac{\overline{K}^{S}}{(1-\alpha-\beta)H} - {A_{dG}^{N}}^{\frac{1}{1-\gamma}} \frac{\overline{K}^{N}}{(1-\psi)}}{\left(\frac{A_c^N}{A_c^S}\right)^{\frac{\psi}{1-\gamma}} \frac{{A_{dG}^{S}}^{\frac{1}{1-\gamma}}}{(1-\psi)H^{\psi}} + \frac{{A_{dG}^{S}}^{\frac{1}{1-\gamma}}}{(1-\alpha-\beta)H}} \tag{E.10}$$

where

$$H = \left(\frac{A_c^S}{A_c^N}\right)^{\frac{\psi}{(1-\gamma)(1-\psi)}} \left(\frac{A_{dL}^N}{A_{dL}^S}\right)^{\frac{1}{(1-\gamma)(1-\psi)}} \tag{E.11}$$

$$R_{dG} = \overline{R} \tag{E.12}$$

$$r^{N*} = \frac{(1-\upsilon)(1-\gamma){A_{dL}^{N}}^{\frac{1}{1-\gamma}}}{\upsilon} \left[\frac{{A_c^N}^{\frac{1}{1-\gamma}} \overline{L}^{N} + {A_c^S}^{\frac{1}{1-\gamma}} \overline{L}^{S}}{O}\right] \tag{E.13}$$

where

$$O = J\left[\frac{K_{dL}^{S}}{H}\left(\frac{\psi}{(1-\gamma)(1-\psi)} - \frac{\beta}{(1-\gamma)(1-\alpha\beta)}\right) + \frac{\psi\overline{K^{N}}}{(1-\gamma)(1-\psi)} + \frac{\beta\overline{K^{S}}}{(1-\gamma)(1-\alpha-\beta)}\right]$$
$$+ \frac{A_{dL}^{S}}{H(1-\alpha-\beta)\left(\overline{K^{S}} - K_{dl}^{S}\right)} \tag{E.14}$$

and

$$J = \frac{A_{dL}^{N}(1-\gamma)(1-\upsilon)}{\upsilon} \tag{E.15}$$

$$r^{S*} = \frac{r^{N*}}{\left[\left(\frac{A_c^S}{A_c^N}\right)^{\psi}\left(\frac{A_{dL}^N}{A_{dL}^S}\right)^{\frac{1}{1-\gamma}}\right]^{\frac{1}{1-\psi}}} \tag{E.16}$$

$$q^{*} = \frac{K_{dG}^{S*}}{\overline{R}} \frac{r^{S*}}{(1-\alpha-\beta)}\alpha \tag{E.17}$$

E.2 North buys the natural resource at q^*

By removing the endownment of R, the South redirects its production towards Y_{dL} and consumers will no longer be able to choose between Y_{dG} and Y_{dL}^S. Thus, the consumer maximization problem is symmetrical in both regions and we fall into the free trade laissez-faire equilibrium with $p_{dG} > p_{dL}$.

E.3 North buys the natural resource at q^* and bans all dirty goods from the South. Trade war

In this subsection we assume an active South that reacts against the northern banning of all dirty goods produced in the South by banning imports of Y_{dL}^N goods. Given that dirty goods will not be traded, we allow the two prices, p_{dL}^N and P_{dL}^S, to differ.

Once again, from the consumer's maximization problems in the North and South, the following relations are derived:

$$\frac{1}{p_{dL}^N} = \frac{\upsilon}{1-\upsilon}\frac{Y_{dL}^N}{Y_c^N + Y_c^S} \tag{E.18}$$

and

$$\frac{1}{p_{dL}^S} = \frac{\upsilon}{1-\upsilon}\frac{Y_{dL}^S}{Y_c^N + Y_c^S} \tag{E.19}$$

respectively.

Under this scenario, the equilibrium factors demand and prices are as follows

$$L_{dG} = K_{dG} = R_{dG} = 0 \tag{E.20}$$

$$L_{dL}^{N*} = \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{E.21}$$

$$L_c^{N*} = \overline{L}^N - \frac{\psi}{A_c^{N\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{N*}}{1-\psi}\overline{K}^N \tag{E.22}$$

$$L_{dL}^{S*} = \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{1-\psi}\overline{K}^S \tag{E.23}$$

$$L_c^{S*} = \overline{L}^S - \frac{\psi}{A_c^{S\frac{1}{1-\gamma}}(1-\gamma)}\frac{r^{S*}}{1-\psi}\overline{K}^S \tag{E.24}$$

$$K_{dL}^{N*} = \overline{K}^N \tag{E.25}$$

$$K_{dL}^{N*} = \overline{K}^N \tag{E.26}$$

$$r^{S*} = r^{N*} \frac{\overline{K}^N}{\overline{K}^S} \tag{E.27}$$

$$r^{N*} = \frac{\frac{(1-\gamma)(1-\psi)}{\psi \overline{K}^N} \left(A_c^{S\,\frac{1}{1-\gamma}} \overline{L}^S + A_c^{N\,\frac{1}{1-\gamma}} \right)}{2 + \frac{\upsilon}{\psi(1-\upsilon)}} \tag{E.28}$$

E.4 North buys the natural resource at q^* and bans all dirty goods from the South. No trade war

In this case, we assume a passive South that chooses consumption based on the p_{dL}^S / p_{dL}^N ratio. Thus, for $p_{dL}^S < P_{dL}^N$, it is true that

$$\frac{1}{p_{dL}^S} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dL}^S}{Y_c^N + Y_c^S} \tag{E.29}$$

and we fall into the previous case.

If instead $p_{dL}^S > P_{dL}^N$, the utility maximization of the consumers lead to

$$\frac{1}{p_{dL}^N} = \frac{\upsilon}{1-\upsilon} \frac{Y_{dL}^N}{Y_c^N + Y_c^S} \tag{E.30}$$

and the South produces only the clean good.

Following the usual steps, we derive the equilibrium factors demands and prices.

$$L_c^{S*} = \overline{L}^S \tag{E.31}$$

$$L_{dL}^{N*} = \frac{\psi r^{N*} \overline{K}^N}{A_c^{N\,\frac{1}{1-\gamma}} (1-\gamma)(1-\psi)} \tag{E.32}$$

$$L_c^{N*} = \overline{L}^N - \frac{\psi r^{N*} \overline{K}^N}{A_c^{N\,\frac{1}{1-\gamma}} (1-\gamma)(1-\psi)} \tag{E.33}$$

$$r^{N*} = \frac{(1-\upsilon)(1-\psi)}{\upsilon \overline{K}^N} \frac{\left[A_c^{N\,\frac{1}{1-\gamma}} \overline{L}^N + A_c^{S\,\frac{1}{1-\gamma}} \overline{L}^S \right]}{\frac{1}{1-\gamma} + \frac{(1-\upsilon)\psi}{\upsilon} (1-\gamma)} \tag{E.34}$$

F. Calibration

For the calibration exercise we select values as close as possible to the existing literature, to capture the key differences arising from our model. In particular we relate our calibration parameters to Hémous (2014). Initial values for our simulations are based on the 2003-2007 world economy (from the UNIDO database). A standard approach is to identify with the North Annex I countries[16] and with the South non-Annex I countries,[17]. The energy sector d that causes high local and global environmental damages is identified with chemical, petrochemical, non-ferrous metals, non-metallic minerals and iron and steel, while all other manufacturing inputs (sector c) is identified with all other sectors. Labour L is the total employment in both sectors c and d of each country, and the natural resources used only for energy production, K, is the total natural capital in both sectors for the country. We recover data for fossil fuel resources from the Statistical Review of World Energy 2013; we picked the coal production for non-Annex I countries (in million tonnes oil equivalent) across all years under consideration.

The discount rate is, as in Nordhaus (2008), 0.0015. For our baseline we set the share of energy inputs c at 0.257 as did Hémous (2014) for polluting goods, and the share of machines used in the production at 0.33. We rely on Hémous calibration also for the initial values of environment and productivity in both sectors in North and South. The polluting factor associated with the burning of fossil fuel in Y_{dG} is equalized to the polluting factor of the South in Hémous analysis, which is the most polluting country among the two, while the pollution of Y_{dL} is scaled down by a factor of 20, in order to reflect the smaller and non-catastrophic effects hypothesized in the model.The full list of parameters is shown in Table 1 below.

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[16] Australia, Austria, Belgium, Bulgaria, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

[17] Albania, Azerbaijan, Brazil, China, Colombia, Cyprus, Georgia, India, Indonesia, Macedonia, Mexico, Moldova, Pakistan, Philippines, Qatar, South Africa, South Korea and Thailand.

TABLE 1: CALIBRATION PARAMETERS

Parameter	Description	Value
υ	share of input c required for final goods' production	0.5
γ	share of machines used in inputs' production	0.33*
$\bar{R}$	endowment of fossil fuels in South only	3240
K^S	endowment of natural resources in South	4982*
K^N	endowment of natural resources in North	2098*
L^S	endowment of labour in South	0.43*
L^N	endowment of labour in North	0.29*
ψ	share of labour in production of Y_{dL}	0.7
α	share of R used in production of Y_{dG}	0.5
β	share of L in production of Y_{dG}	0.2
A_c^S	initial level of technology in sector c in South	82.75*
A_c^N	initial level of technology in sector c in North	512.58*
A_d^S	initial level of technology in sector d in South [18]	107.53*
A_{dL}^N	initial level of technology in sector dL in North	666.02*
ξ	pollution factor from Y_{dG}	0.008*
ζ	pollution factor from Y_{dL}	0.0004
Δ	regeneration rate of the environment	0.001
E_0^S	initial state of the environment is South	20289.01
E_0^N	initial state of the environment is North	20289.01
η	elasticity of intertemporal substitution	0.2
$\phi\vartheta$	probability of success and size of innovation	0.01
μ	amenity value of environment in welfare of the North	0.5
ρ	discount factor	0.015

Values with an asterisk indicate that the parameter is the same as (Hémous, 2014)