Mobility of Workers Across Sectors and the Transition to Clean Technologies

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Abstract

The scientific community agrees on the fact that in order to meet the targets set in the Paris Agreement 2015, a transition from the use of "dirty" to "clean" technologies is necessary. Acemoglu et al. (2012) present the first framework that analyzes how the direction of technical change reacts to different environmental policies. Their result is more optimistic than previous work by other authors, as their model predicts that temporary intervention is sufficient to prevent an environmental disaster. We claim that this result is partly driven by the assumption of perfect-mobility of labor across sectors. We show that for the case where workers cannot switch across sectors, a permanent intervention is indeed necessary to avoid threatening levels of climate change. Given that evidence suggests that workers cannot freely move across sectors but that they face switching costs, we develop a model of imperfect labor mobility that characterizes the conditions under which workers currently employed in the dirty sector are willing to switch to the clean one. Our model predicts that offering higher wages in the clean sector is necessary but not sufficient to direct workers. Regardless of the wages, when the technology level in the clean sector is too developed, the switching costs that workers face are too high and they choose to stay in the dirty sector. In this simple setting this result suggests that the social planner needs not only to subsidize scientists in order to direct technical change towards the clean sector, but he also needs to do so with workers. Moreover, given that for low levels of technological sophistication in the clean sector higher wages in this sector are enough to attract workers, intervention should be immediate to avoid additional costs of delay.

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1 Introduction and Literature Review

In June 2017 the 153 countries ratifying the Paris Agreement of 2015 committed themselves to the long-term goal of limiting the global average temperature increase well below 2 degrees Celsius. In order to reach this goal, the European Union, by his side, implemented the target of reducing greenhouse gas emissions by at least 40% by 2030 and achieving emission cuts of 80-90% below 1990 levels by 2050 (UNFCCC). To decarbonise the economy, the European Commission's policy action acknowledges as critical to reinvent EU's carbon intensive infrastructures and sets as primary step to boost the development of renewable energy technologies (European Comission).

The Paris Agreement brought, for the first time, all nations into the common cause of taking measures to combat climate change adopting the first-ever universal legally binding global climate deal. The efforts to put forward an international climate policy to combat climate change started, however, years ago. The text of the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992, was the first important step, as it recognized that there was a serious problem at a time when scientific evidence was still uncertain. However, as the understanding of the causes and consequences of climate change kept increasing, a long string of literature modeling the links between economic growth and environmental policies emerged.

Nordhaus (1994) constructed the first integrated-assessment model of the economics of climate change, pioneering the economic analysis of environmental policy by relating economic growth, resources and environment. He developed the DICE model, a dynamic integrated model of climate and the economy, extending the neoclassical Ramsey model by including equations that represented emissions and climate change. While Nordhaus' (1994) general equilibrium model takes technology as given, Bovenberg and Smulders (1995) explore the link between economic growth and environmental quality in an endogenous growth model that includes pollution-augmenting technological change and the natural environment. They conclude that the government should intervene to ensure optimal levels of natural and knowledge capital, which have a public-good character in the model. Messner (1997) emphasizes the importance of early investment in new technology development using endogenized technological learning in an energy systems model. He concludes that new technologies will not become cheaper if the government does not put forward determined R&D policy strategies to enhance their development. Newell, Jaffe and Stavins (1999) find evidence showing that the rate of overall innovation is independent of energy prices and regulation, while, instead, the *direction* of innovation is indeed responsive to energy prices. For example, they show that following the increase in oil prices air conditioners became more energy efficient, while when the energy prices were stable the innovation focused on making the products cheaper for consumers. Additionally, they show that this responsiveness increased substantially during the period when the law of energy-efficiency product labeling entered into force.

Bovenger and Smulders (1996) and Goulder and Schneider (1999) use growth models with endogenous technological progress in abatement technologies. The latter examine the implications of induced technical change for CO_2 abatement policies. Their model stresses the need of taking into account the cost of inducing technical change. They show that the GDP costs of carbon taxes change considerably depending on whether the costs to get the knowledge-generating resources are taken into account or not. They also make the same point regarding R&D. The carbon tax not only increases R&D in alternative energy industries, but it also discourages it in fossil-fuel based industries, which lowers the GDP. However, they conclude that in the presence of induced technical change, the net benefits from a given carbon tax are also higher .

Popp (2004) modifies the DICE model of climate change with exogenous technology first developed by Nordhaus by including induced innovation in the energy sector (ENTICE model). He shows that the assumption of exogenous technical change overstates the costs of environmental policies that fight against climate change by 9.4%. The results of his model show that in order to induce technological change towards energy efficiency, signaling innovators that energy-efficiency research will be profitable is necessary. R&D subsidies, for example, could improve the potential gains from induced technologies. On the other hand, same as noted by Bovenger and Smulders, he concludes that the increase in research in new technologies comes at a cost that needs to be accounted for, namely crowding out effect of R&D in other industries, which reduces welfare. Finally, he notes that even if the induced technical change can lower the costs of any climate change policy, it has minimal effects on reducing temperature. This means that in his setting, restrictive climate change policies are necessary to reduce global warming. Notwithstanding, one needs to take into account that the new technologies included in the model are innovations aimed at improving energy efficiency, while the goal of policies to effectively combat climate change is more related to developing renewable technologies that are an alternative to fossil-fuel based energies and that do not release any greenhouse gases. Therefore, by inducing non-carbon based technology development instead of energy-saving technology innovations, the effect on temperature is likely to be more significant than the one found in Popp (2004).

Following this line, Acemoglu et al. (2012) construct a two-sector model of directed technical change to study how different environmental policies affect the direction of technical change. There is a unique final good produced using "dirty" technologies that degrade the environment and "clean" technologies that do not release any greenhouse gases, and hence, which do not contribute to global warming. The endogenous directed technical change is modeled by profit maximizing researchers that can choose to direct their research to either improving the quality of the dirty or the clean machines. Based on Acemoglu (2002) the growth model of endogenous technical change and environmental constraints also features the roles played by the price and market size effects on determining the direction of technical change. The market size effect encourages research in the larger input sector, while the price effect directs researchers towards the sector with the highest prices. They show that the decentralized equilibrium leads to an environmental quality level that is below the critical threshold, what they define as an environmental disaster. However, their analysis concludes that when dirty and clean technologies are highly substitutable, *temporary* carbon taxes and research subsidies are enough to redirect technical change and avoid the so called environmental disaster.

In the European Union, the Directorate-General for Climate Action (DG CLIMA) also uses these two means to stimulate R&D of low carbon technologies and provide support for the uptake of new renewable energies. The main tool is the Emissions Trading System (EU ETS), that puts a price on carbon emissions and hence enhances the development of technologies that do not release greenhouse gases. The second driver includes funding programs that give the necessary financial support to get the new technologies from pilot to commercial scale. The NER 300 funding programme, for example, is one of the world's largest funding programs for the large-scale demonstration of innovative renewable energy technologies within the European Union; supporting wind, ocean, bionergy or solar power energy technologies. Hence, in a very broad way, the policy actions implemented by the European Commission are aligned with the policy recommendation of Acemoglu et al. (2012) that we described above.

Nonetheless, in the transition to achieving a low-carbon sustainable economy, the Paris Agreement does not only stress on the urgent adoption of renewable technologies. There are many possible ways to manage the transition to a zero-carbon world, and the convention sets the guidelines on how this transition should be done. In particular, nations that signed the convention committed themselves to *"taking into account the imperatives of a just transition of the workforce and the creation of a decent work and quality of jobs in accordance with nationally defined development priorities"* (UNFCCC, Conference of the Parties, 21^{st} session).

In order to achieve the objectives and avoid climate change, the sectoral and economic transformation needs to be done in a short time frame and on large scale. This, in turn, creates potential of stranded workers whose communities are highly dependent on coal and oil. As a matter of fact, a transparent planning that includes *just transition* measures such as training, education, and securing pension for older workers will prevent opposition, fear and both inter-sectoral and inter-generational conflicts. In an nutshell, as the International Labor Organization (ILO) states, the transition towards clean technologies cannot only focus on phasing out sectors that pollute, but also on creating new jobs and on giving social protection and training to the communities that depend on fossil fuels in order to prepare them to work managing renewable energy technologies.

Acemoglu et al.'s (2012) model does not allow to analyze the transition of workers from the dirty to the clean sector because they assume a single labor market; which implies that wages of both sectors equalize in equilibrium. When the profit subsidy to the researchers in the clean sector is in place, all scientists engage in research in the clean sector. This means that the quality of the technology in the clean sector will evolve over time, while the technology level in the dirty sector will remain constant. If the market for clean technologies is growing, firms will demand more and more workers to operate renewable technologies. In Acemoglu et al.'s setting (2012) demand instantaneously meets supply and the labor market clears. In other words, they assume that there is perfect mobility of workers, meaning that when the clean sector is demanding more workers, the ones currently employed in the dirty sector can automatically start operating green technologies.

However, as already pointed out, the guidelines of the Paris Agreement or the ILO stress on the need for *just transition* policies that retrain workers and provide them with the necessary green skills. Sharply in contrast with Acemoglu et al.'s (2012) setting, this suggests that, beforehand, workers are not ready to automatically switch. This is an important remark that if it is not taken into account could weaken the effects of the policies to fight against climate change. If workers perceive that they will loss their job due to climate policies and there is no government planning to secure their future, coal and oil dependent communities will oppose the policy measures and, with strong unions, they may put a smooth transition at risk. If the ultimate goal of policy makers is to end up in an economy run by green technologies, the question of whether workers are harmed or not (and hence if they will oppose the transition or not) depends on how easily they can switch from the dirty to the clean sector. There is plenty of evidence pointing out that, in general, there are frictions from switching across sectors. For example, Lee and Wolpin (2006) asses whether individuals face or not costs of switching from the goods to the service sector in a two-sector labor market equilibrium model. Their estimates imply that there are large mobility costs, which reduce output in both sectors to half of what it would be under zero switching costs. Analyzing under which conditions workers currently employed in the dirty sector are willing to switch to the clean sector is therefore an interesting question to solve and we address it later in this paper in a very simple way.

To begin with, we assume the case of no labor mobility across sectors. We start with this framework because it is interesting to see how the policy recommendation changes from assuming one extreme to the other, keeping the same framework. Our result suggests that, indeed, the treatment given to the mobility of labor has important consequences in the results. As long as there are workers employed in the dirty sector, the production of the dirty input keeps growing without boundaries in the long-run equilibrium. Hence, in order to avoid an environmental disaster a *permanent* policy intervention is necessary. This result is at odds with the very optimistic conclusion obtained in the free labor mobility setting, where a *a temporary* subsidy to the researchers in the clean sector is enough to avoid an environmental disaster.

Finally, we characterize the equilibrium choice of workers regarding sectors under the imperfect labor-mobility assumption. We model the imperfect mobility as a cost that arises from updating one's human capital in order to enter the clean sector. The essence of switching the sector is to incur in a cost today in order to gain an advantage in future earnings. Switching is seen as an investment by workers. We show that in this setting, higher wages in the clean sector are necessary but not sufficient for the workers to be willing to switch. When training costs are too high, workers will decide to stay in the dirty sector. This suggests that an income subsidy to the workers in the clean sector may be necessary, on top of the profit subsidy to the researchers in the clean sector.

The remainder or this article is organized as follows. Section II describes the model. Section III characterizes the decentralized equilibrium under no labor-mobility assumption. Section IV presents a simple policy to avoid an environmental disaster in equilibrium. Section V characterizes workers' decision of moving from the dirty to the clean sector under switching costs. Section VI concludes and suggests directions for further research.

2 Model Setup

We characterize a two-sector model that includes a clean and a dirty sector. The clean, producing intermediate goods Y_c, is defined as the one that does not release any greenhouse gases to the atmosphere. For example, it could use geothermal, nuclear, hydroelectric, solar or wind energy technologies (machines), x_c. In contrast, the dirty sector is the one that in the production of the intermediate inputs Y_d, uses technologies that create pollution and decrease the environmental quality. For instance, machines, x_d, connected to the use, extraction or refinement of fossil fuel based technologies, such as coal, oil or natural gas.

Following Acemoglu et al. (2012), we consider an infinite-horizon discrete time economy comprised by a continuum of households, including workers, researchers and entrepreneurs. The representative household's utility is increasing not only on the amount of consumption, but also in the level of the environmental quality

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} U(C_t, S_t) \tag{1}$$

where C_t is the consumption of the final good produced in the economy, S_t is the level of environmental quality and $\rho > 0$ is the discount rate. The environmental quality evolves according to the following law of motion

$$S_{t+1} = -\xi Y_{dt} + (1+\delta) S_t \tag{2}$$

Note that the dirty intermediate good ,Y_{dt}, produced at time t in the dirty sector using dirty machines x_{dt} decreases the level of the environmental quality by a factor ξ the next period; whereas the production of the clean intermediate good Y_{ct} does not affect the quality of the environment. This means that if the aim is to preserve the environment by decreasing greenhouse gas emissions, the economy should reduce (optimally stop) the production of the dirty input. Finally, δ is the rate of "environmental regeneration". The unique final good of the economy is produced competitively using CES technology with clean and dirty inputs, Y_c and Y_d

$$Y_t = [Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}} \tag{3}$$

where $\epsilon \in (0, \infty)$ is the elasticity of substitution between the two sectors. The intermediate goods Y_c and Y_d are supplied by competitive firms, who use sector-specific workers L_c and L_d and a continuum of sector-specific machines x_{ci} and x_{di} as inputs

$$Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di \tag{4}$$

where $\alpha \in (0, 1)$, A_{ijt} is the quality and x_{jit} is the quantity of the type $i \in (0, 1)$ machines used at time t in sector $j \in (c, d)$. Machines for both the clean and the dirty sector are produced by monopolistically competitive firms. Producing one unit of any machine, regardless of the sector and the quality, costs ψ units of the final good. We normalize $\psi \equiv \alpha^2$. Then, the market clearing condition for the final good implies that

$$C_t + \psi\Big(\int_0^1 x_{cit} di + \int_0^1 x_{dit} di\Big) = Y_t \tag{5}$$

As for the supply of innovations, first note that we want to construct an endogenous directed technical change model. This implies that the scientists, who are the ones that work improving the productivity A_{jit} of machine i in sector j at time t, need to *choose* in which of the two sectors they want to undertake research. If they were randomly allocated to any of the two sectors, the supply of technology would be exogenous in the model.

Then, we characterize the innovation possibility frontier of the economy as follows. At the beginning of each period each scientist chooses whether she wants to direct her research to improving the clean or the dirty technology. Then, she is randomly allocated to one machine such that there is one to one matching between machines and scientists. Each researcher succeeds in innovation with a probability $\eta_j \in (0,1)$ in sector $j \in (c,d)$. If successful, the quality of each type of machine increases by a factor $1+\gamma$ (where $\gamma > 0$)

$$A_{jit} = (1+\gamma)A_{jit-1} \tag{6}$$

If the innovation is successful, the researcher gets a one period patent over the machine that she has improved and becomes the entrepreneur of the current period. If, on the contrary, the scientist was not successful in innovating, the monopoly rights are allocated randomly to any potential entrepreneur, who then produces using the old technology. Finally, we normalize the amount of total scientists in the economy s, to 1. Then, the market clearing condition for scientists implies that

$$s_{ct} + s_{dt} = 1 \tag{7}$$

where s_c and s_d are scientists that direct their research to the improvement of the quality of clean and dirty technologies respectively. Next, we define the average productivity of each sector $j \in (c,d)$ by

$$A_{jt} \equiv \int_0^1 A_{jit} di \tag{8}$$

Therefore, given that $s_{jt} \in (0,1)$ and using equations (6) and (8), we can get the law of motion of the technology in each sector $j \in (0,1)$

$$A_{jt} = (1+\gamma\eta_j s_{jt})A_{jt-1} \tag{9}$$

This equation captures the cumulative character of research. As first used by Isaac Newton in the quote *"If I have seen far, it is by standing on the shoulders of the giants"*, it means that technical progress builds on the foundations provided by earlier innovators.

3 Decentralized Equilibrium Under No Labor Mobility Assumption

In this section we characterize the equilibrium under no-mobility of workers assumption. As described earlier, the technological progress is endogenous and researchers have free-mobility across sectors. However, we did not mention any assumption regarding the mobility of the workers yet. In one extreme one could think of free-mobility. In the other one, of no-mobility of workers. The former implies that if both sectors are producing in equilibrium, both need to offer the same wages. Otherwise, given that workers are free to switch, all of them would move towards the sector offering higher wages ultimately pushing the wages down until they equalize. Under the no-mobility of workers framework, there is not a single labor market, but two, where the clean sector pays wages equal to w_{ct} and the dirty sector equal to w_{dt} at time t. On the other hand, the amount of workers employed in each sector is fixed overt time. Next, we define the decentralized equilibrium outcome under the no-mobility of workers assumption. In Appendix part B.1 we also develop the equilibrium results for the free-mobility of workers case (the model developed by Acemoglu et al. (2012)).

3.1 Definition

An equilibrium is given by a sequence of demands for machines x_{cit} and x_{dit}, demands for workers L_{ct} and L_{dt} and demands for inputs Y_{ct} and Y_{dt}, scientists allocations s_{ct} and s_{dt} , sequences of wages for workers w_{ct} and w_{dt}, prices for inputs p_{ct} and p_{dt}, prices for machines p_{cit} and p_{dit} and the quality of the environment

S_t such that at period t:

(i) p_{cit} and p_{dit} maximize the profits of the monopolistic type i machine producers in the clean and dirty sectors,
(ii) (x_{cit}, L_{ct}) and (x_{dit}, L_{dt}) maximize the profits of the competitive clean and dirty input producers,
(iii) Y_{ct} and Y_{dt} maximize the profits of the competitive final good producers in the clean and dirty sectors,
(iv) s_{ct} and s_{dt} maximize the expected profits of researchers at time t,
(v) the wages w_{ct} and w_{dt} clear the clean and the dirty sector's labor markets,
(vi) the prices p_{ct} and p_{dt} clear the input markets, and
(vii) the law of motion of the environmental quality is given by $S_{t+1} = -\xi Y_{dt} + (1+\delta)S_t$

3.2 The Direction of Technical Change

We first analyze the equilibrium production and labor decisions that result from the profit maximization decisions of the different producers (for a detailed description see Appendix A). From the final good competitive producer's profit maximization problem we obtain the condition

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{Y_{ct}}{Y_{dt}}\right)^{-\frac{1}{\epsilon}} \tag{10}$$

The higher the price of the clean input the lower the demand for this good from the final good sector. Additionally, the extent to which this demand decreases depends on the substitutability of the clean and dirty goods, given by ϵ. We normalize the price of the final good to be the numeraire

$$\left[p_{ct}^{1-\epsilon} + p_{dt}^{1-\epsilon}\right]^{\frac{1}{1-\epsilon}} = 1 \tag{11}$$

In order to determine the direction of the technical change in the economy, we need to know the profitability of the research in each of the sectors. In the end, one can expect that the development and the use of the technology is, at least in part, a response to the profit incentives given by the market. In our setting, this means that scientists, before making the decision regarding the sector in which they want to undertake the research will analyze the expected profits that the one-period monopoly right (patent) will give them. Given the marginal cost per unit of machine in terms of final good, ψ, the monopolistic entrepreneurs choose the price of their machines in order to maximize their profits, taking the demand for machines by the intermediate good sector

$$x_{jit} = \left(\frac{\alpha p_{jt}}{p_{jit}}\right)^{\frac{1}{1-\alpha}} L_{jt} A_{jit} \tag{12}$$

as given. They choose a price p_{jit} for type i machines in sector $j \in (c,d)$ equal to

$$p_{jit} = \alpha \tag{13}$$

Then, the profit of the machine producer in sector $j \in (c,d)$ using technology A_{jit} is given by

$$\pi_{jit} = (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt} A_{jit} \tag{14}$$

Given the law of motion of technology for each type of machine specified in equation (6), using the definition of average productivity in each sector (8) and taking into account the probability η_j of having a successful innovation in each sector $j \in (c,d)$, the expected profit for each scientist working in sector j at time t is

$$\Pi_{jt} = \eta_j (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt}(1+\gamma)A_{jt-1} \tag{15}$$

At this point, scientists will decide to direct their research to either the clean or the dirty sector based on their expected relative profitability

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \underbrace{\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}}_{\substack{price \\ effect}} \underbrace{\frac{L_{ct}}{L_{dt}}}_{\substack{market \\ size \\ effect}} \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{\substack{direct \\ productivity \\ effect}} \tag{16}$$

Whenever the ratio in equation (16) is greater than one researchers will choose the clean sector, as they expect higher profits there. The three forces that determine the equilibrium relative profits are the price effect, the market size effect and the direct productivity effect. The price effect makes innovation more appealing in the sector with higher prices. The market size effect encourages research in the sector with the biggest employment, which means with the biggest market for machines. The direct productivity effect drives scientists towards the sector with higher productivity. This force stems from the cumulative character of research that we defined in equation (9). Using the equilibrium production and labor decisions we can go one step further in order to make the underlying drivers more explicit. Under the assumption of no-mobility of workers the equilibrium allocation of scientists is given by (check equation 46 in Appendix part B.2 to see how it is derived)

$$\frac{\pi_{ct}}{\pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\phi}{\phi-1}} \left[\frac{(1+\gamma\eta_c s_{ct})}{(1+\gamma\eta_d s_{dt})}\right]^{\frac{1}{\phi-1}} \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{\phi}{\phi-1}} \tag{17}$$

where $\phi \equiv (1-\alpha)(1-\epsilon)$. Before analyzing whether the profit ratio of researchers in the clean relative to the dirty sector is likely to be bigger, smaller or equal to one in equilibrium, we need to discuss the plausible assumptions that will pin down the result. First, recalling that $s_{ct} + s_{dt} = 1$, note that we have three possible equilibriums:

(i) In equilibrium all the innovation takes place in the clean sector: $s_{ct} = 1$ and $s_{dt} = 0$, when:

$$\frac{\pi_{ct}}{\pi_{dt}} > 1 \quad \rightarrow \frac{A_{ct-1}}{A_{dt-1}} > \left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}} \left(\frac{L_{ct}}{L_{dt}}\right)^{-1} (1+\gamma\eta_c)^{-\frac{1}{\phi}}$$

(ii) In equilibrium all the innovation takes place in the dirty sector: $s_{ct} = 0$ and $s_{dt} = 1$, when:

$$\frac{\pi_{ct}}{\pi_{dt}} < 1 \quad \rightarrow \frac{A_{ct-1}}{A_{dt-1}} < \left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}} \left(\frac{L_{ct}}{L_{dt}}\right)^{-1} (1+\gamma\eta_d)^{\frac{1}{\phi}}$$

(iii) In equilibrium innovation occurs in both sectors: $s^*_{ct} \in (0,1)$ and $s^*_{dt} = 1 - s^*_{ct}$, when:

$$\frac{\pi_{ct}}{\pi_{dt}} = 1 \quad \rightarrow \quad \eta_c \left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\phi}{\phi-1}} (1+\gamma\eta_c s_{ct})^{\frac{1}{\phi-1}} A_{ct-1}^{\frac{\phi}{\phi-1}} = \eta_d (1+\gamma\eta_d s_{dt})^{\frac{1}{\phi-1}} A_{dt-1}^{\frac{\phi}{\phi-1}}$$

Assumption I:

$$\frac{A_{c0}}{A_{d0}} < min\left\{\left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}} \left(\frac{L_c}{L_d}\right)^{-1} (1+\gamma\eta_c)^{-\frac{1}{\phi}}, \left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}} \left(\frac{L_c}{L_d}\right)^{-1} (1+\gamma\eta_d)^{\frac{1}{\phi}}\right\}$$

By imposing *Assumption I* we ensure that the equilibrium at time period 1 is such that all the innovation takes place in the dirty sector - see Appendix C. At time period 0, the economy starts with a given productivity level in the clean and in the dirty sectors, A_{c0} and A_{d0} respectively. *Assumption I* directs all the researchers to the dirty sector at time period 1. Note that this assumption is nothing more than the reasonable condition stating that, initially, the dirty sector is relatively more advanced than the clean sector. As a consequence, in the beginning researchers innovate in the dirty sector. That currently the renewable energies are relatively backward compared to fossil fuel technologies is a well documented fact. Timmons et al. (2014), for example, report that for the case of hydropower energy, which is the world's largest source of renewable energy, Switzerland, which is the country that has developed its potential the most, developed 88%, while the United Stated has developed only around 16% of its potential. As for wind energy, its capacity factor is around 30% for a wind power plant in a good site, while the coal or nuclear plants' capacity typically exceeds 90% [1]. The analysis of the state of biomass energy or solar energy leads to similar results. One of the reasons of why gasoline and the use of other fossil fuels is so widespread is that they have large amounts of conveniently concentrated energy, readily available to use. Instead, for the case of renewable energies, it takes energy to transform the water, wind, or sun into energy.

Assumption II:

$$\epsilon > 1 \iff \phi < 0$$

Given that the final good sector is characterized by a CES production function where $\epsilon \in (0, \infty)$, we first distinguish three cases: (i) when $\epsilon \to \infty$ the two inputs are perfect substitutes (ii) when $\epsilon \to 0$ they are perfect complements and (iii) when $\epsilon \to 1$ we are in a Cobb-Douglas production function case. As it is clear from equation (17) above, we are interested in knowing whether $\phi > 0$ or $\phi < 0$ in order to determine the impacts of the relative productivity and amount of workers on the expected profits of the researchers. It is important to note that $\phi \equiv (1-\alpha)(1-\epsilon) < 0$ if and only if $\epsilon > 1$ (given that $\alpha \in (0,1)$, as specified above). We refer to the goods that satisfy this last condition as *gross substitutes.*

Papageorgiou, Saam and Schulte (2017) find that the estimates of the elasticity of substitution within the energy aggregate are bigger than one. In particular, they find a value of $\epsilon = 2$ for the electricity generating sector and $\epsilon = 3$ for the case of non-energy industries. Acemoglu et al. (2012) also consider $\epsilon > 1$ as the empirically most relevant benchmark, since renewable energies can offer the same production services (specially once they can be stored and transported efficiently). It is clear that clean technologies are costlier today, but they provide very similar services than the dirty technologies; which warranties a high elasticity of substitution. For example, the Tesla Model S electric car, can carry 7 people, run at more than 300 miles in one charge and accelerates from 0 to 60 mph in 5 seconds. Hence, I restrict the analysis of the paper to the case where $\epsilon > 1$, or equivalently, $\phi < 0$. When $\phi < 0$, the profit ratio is directly proportional to the technology ratio i.e. $\frac{\phi}{\phi-1} > 1$. Hence, ceteris paribus, a more developed technology in the dirty sector would imply higher profits in the dirty sector relative to the clean one (see equation 17).

Assumption III:

$$\frac{L_{c1}}{L_{d1}} < 1$$

We assume that, in the beginning, the dirty sector employs more people than the clean sector. Again, this assumption has a clear empirical counterpart. The United States Energy and Employment Report of January 2017 identifies 1.9 million workers employed in the electric power generation and fuel technologies,

[1] The capacity factor of an energy plant is defined as the ratio of actual energy produced relative to the maximim energy production potential.

of whom 1.1 million worked in traditional coal, oil and gas. On the contrary, less than 800,000 workers were employed in low carbon emission technologies, including renewable energies, nuclear and advanced/low emission natural gas.

For the remainder of the paper we consider that these three assumptions are satisfied unless specifically stated. Then, the relative profit ratio of researchers in the decentralized equilibrium for the no labor mobility case is pinned down. To see how, consider first Assumption I. As already explained, it involves that in time period 1 all researchers start innovating in the dirty sector given that the dirty sector employs more people and the clean sector is relatively backward. However, given this initial condition for technology, the cumulative character of the innovation"standing on the shoulders of the giants" implies that the technology level in the dirty sector evolves according to equation (9). This makes the technology level in the dirty sector grow at a rate equal to $\gamma\eta_d$ and the technology level in the clean sector to remain constant at the time 0 level forever. This pattern, together with the fact that the dirty sector employs more people in the beginning and workers cannot switch sectors, directly implies that there exists a unique decentralized equilibrium under no-labor mobility, where all profit-driven scientists choose to work improving the quality of the dirty machines.

The forces that drive this outcome work as follow: First, the *direct technology effect* induces scientists to undertake research in the dirty sector. This is because of our knowledge-based specification of R&D. As already mentioned, equation (6) embodies the idea that, through spillovers, current scientists "stand on the shoulders of the giants", ensuring that the marginal productivity of research does not decline over time. Another interesting feature in the specification of equation (6) is that we assume extreme state dependence. This implies that the productivity in each sector only depends on the state of knowledge of that sector (an alternative specification in a two-sector model is to assume that the productivity in one sector depends on the state of knowledge of both sectors). Hence, in our specification, an increase in the technology level in the dirty sector today makes machines complementary to workers employed in the dirty sector cheaper to develop, but has no effect on the cost of the "green" skill-complementary machines. As a matter of fact, this implies that the effect that a greater A_d/A_c ratio has on the relative costs of future $R\&D$ is very strong. Second, the *market size effect* directs researchers to the dirty sector. This stems directly from the assumption that the dirty sector employs more workers than the clean one in the beginning. Given that the market for a technology consists of workers who use it, if the dirty sector employs more people than the clean sector, researchers will be more willing to work to improve the technology level of the machines that are complementary to the workers in the dirty sector. This is in line, for example, with the theory explained in Acemoglu (2002) that maintains that the large increase in the supply of skilled workers in the past decades made skill-biased technologies more profitable and firms had greater incentives to adopt and develop such techniques. Finally, the *price effect* is given by

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1-\alpha}{\phi-1}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\phi-1}} \tag{18}$$

The *price effect* favors the innovation in the clean sector. A higher employment in the dirty sector, as just explained, induces more development in the dirty machines, which decreases the production cost of the dirty inputs and increases the one of the clean one, increasing the price of the clean input. Similarly, a higher productivity in the dirty sector directly gives a comparative advantage to this sector's producers, allowing them to lower dirty inputs' prices relative to the price of the clean ones. Given that scientists have an incentive to develop technologies producing more expensive goods, as shown in equation (17) the *price effect* directs researchers towards the clean sector. However, compared to the high state-dependence of technological evolution, embodied in the *direct technology effect* the *price effect* is not strong enough, and the expected profits of the researchers in the dirty sector are higher than in the clean one, which, as mentioned, implies that all scientists will undertake research in the dirty sector.

Given that the technology level in the dirty sector grows over time as specified above, while the one in the clean sector stays constant, by equation (57) in Appendix part D, the production of the dirty input Y_{dt}

increases at the same long-run growth as A_{dt}, $\gamma\eta_d$. In turn, by equation (2) the quality of the environment decreases to its lowest possible level in the long-run, provoking an environmental disaster.

Now, given that we have two different labor markets for workers, we can also analyze the forces that determine the equilibrium relative wages.

$$\frac{w_{ct}}{w_{dt}} = \left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1}{\phi-1}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{\phi}{\phi-1}} \tag{19}$$

In this case there are two forces opposing each other. On the one hand, higher employment in the dirty sector increases wages in the clean sector. This is the usual substitution effect. Excess supply of labor in the dirty sector increases wages in the clean sector, where supply of workers is relatively scarce. On the other hand, a higher productivity in the dirty sector makes wages in the dirty sector higher. This is because when the two factors of production are substitutes, the effect of an increase in the productivity of the machine that is complementary to the employer in the "dirty" sector is as if the worker in the dirty sector is more productive. This is turn increases the demand for workers that are complementary to "dirty" machines. As a result, the marginal product of the workers in the dirty sector increases more than the marginal product of workers in the clean sector. This is the same reasoning described in Acemoglu (2002) that explains why even if the supply of skilled workers increased rapidly in the last thirty years, there was no corresponding decrease in the skill premium, meaning that the demand for skilled workers increased even more than its supply.

Of course, one can argue that if the perfect-mobility of workers setting is not realistic for being a too optimistic scenario in which all workers are ready to start operating renewable energies at any time, the assumption of no labor-mobility is too pessimistic for assuming that workers in the dirty sector could never get into the clean sector. However, characterizing the equilibrium under no labor mobility is valuable, because it helps us understand the extent to which the assumption of perfect labor mobility shapes the policy outcome results. We show this in the following section.

4 Policy to Redirect Technical Change Under No Labor Mobility Assumption

As already mentioned, Assumptions I, II and III imply that there is a unique decentralized equilibrium where innovation always occurs in the dirty sector and where the long-run growth rate of the input production of this sector, Y_{dt}, is $\gamma\eta_d$. Of course this is a result that the social planner would like to avoid, given that if the production of the dirty input grows forever the quality of the environment will surpass a critical threshold where the climate change can put the future of humanity at risk. This implies that some kind of public intervention is necessary if one wants to avoid a disaster.

Following Acemoglu et al. (2012), in the setting that we have characterized the policy objective of the government involves directing all the scientists to undertake research in the clean sector. This ensures that the productivity of the clean sector's technologies will improve, while the technology level in the dirty sector will remain constant. In the framework that we considered all scientists are the same and their only driver to choose one sector or the other is the profits that they expect to have in each of them. Additionally, the decision about in which sector to undertake research is taken in the beginning of each period, where the researcher is still out of the labor market. This means that in our simple setting, same as in Acemoglu et al. (2012), offering higher expected profits in the clean sector is enough in order to end up in an economy where all the research is undertaken in this sector, or equivalently, the only possibility of having researchers working in both sectors is the case where both of the sectors offer the same profits to scientists.

However, one could argue that considering a transition where the only goal is to develop renewable technologies that do not release any greenhouse gases is not only unrealistic, but also harmful for the economy in the short-run transition (even if we keep it as the long-term goal). This is because the representative household derives utility not only from the quality of the environment, but also from consumption. Given that the technology in the clean sector is backward compared to the dirty one, suddenly switching to the production of clean inputs alone necessarily means reducing the growth rate of the final output during the transition adjustment process, which ultimately means forcing a reduction in the overall consumption of the economy. Hence, another possibility in order to analyze the welfare maximizing short-term transition process could be to include three different sectors for research. Apart from the clean and dirty sector for innovation, that would work the same way as described until now, we could introduce a third sector, defined as the "grey" sector. Researchers in this sector would work improving the energy efficiency of the dirty technologies. From an environmental perspective, "grey" inputs are preferred to the dirty ones in that they require less fossil fuel for its production. Additionally, innovations directed to increasing the energy efficiency of dirty inputs make the overall cost of these inputs cheaper, as they reduce the use of fossil fuel per unit of input. This, in turn, ceteris paribus, makes these innovations also beneficial from the utility maximization perspective of the representative consumer, as cheaper inputs help them maintain a given level of consumption. Hence, in the short-term, having researchers allocated in both the clean and the grey sectors could be welfare maximizing, and analyzing this setting would be worth it. In any case, this framework would only be interesting to analyze the short-term transition costs. In the long-run, the fact that these innovations make dirty inputs cheaper would increase the total consumption of them in society, which in the end would have counterproductive long-run environmental effects. Hence, even if diversifying researchers between the development of clean and energy efficient innovations may be helpful in the short-run, it should not be a long term objective. Related to this, the distinction of short-run and long-run effects of the development of different types of innovations raises the issue of intergenerational conflicts. In principle, current generations would support putting forward policies aimed at energy efficiency, as they contribute to a better quality of the environment without sacrificing much (or any) consumption. On the contrary, future generations would only support the development of clean technologies, as energy saving technologies keep degrading the environment and can have counterproductive effects if overall consumption of these technologies increases as they get cheaper. Aghion et al. (2012) carry out an empirical study related to the auto industry innovations that supports this hypothesis. They distinguish three types of innovations, dirty, clean and grey (energy saving), using patents as a proxy. Their result shows that R&D subsidies are not statistically significant in promoting clean innovations, while they are significant in promoting grey innovations. This suggests that the type of policies that have been implemented so far (they construct a panel data of patents across 80 countries over several decades) have been for energy efficiency, rather than the promotion of more radical, renewable technologies that would require more sacrifice of current generations in favor of future ones. Given that in this section we focus on the long-term effects, we leave the analysis of the potential three-sector model to analyze the short-term transition for further research.

Hence, back to our two-sector model framework, given that all researchers are identical i.e. it is as if we had a representative researcher, the most straightforward way of redirecting researchers to the clean sector is by giving a profit subsidy q_t to the ones that decide to undertake research in the clean sector (financed by a lump-sum tax on the representative household). Hence, the expected profits of the researchers in the clean sector are given by

$$\Pi_{ct} = (1+q_t)\eta_c(1-\alpha)\alpha p_{ct}^{\frac{1}{1-\alpha}} L_{ct}(1+\gamma)A_{dt-1} \tag{20}$$

while the expected profits of researchers in the dirty sector are still given by equation (15). Any subsidy that is above the threshold value q_t^* is sufficient to redirect all the scientists towards the clean sector (see equation (63) in Appendix part F).

$$q_t \geq q_t^* \equiv \frac{\eta_d}{\eta_c}(1+\gamma\eta_d)^{\frac{1}{\phi-1}}\Big(\frac{A_{dt-1}}{A_{ct-1}}\Big)^{\frac{\phi}{\phi-1}}\big(\frac{L_{dt}}{L_{ct}}\big)^{\frac{\phi}{\phi-1}} - 1 \tag{21}$$

On the contrary, if the subsidy is below the threshold value, all the researchers will choose the dirty sector, because the subsidy is not high enough to overcome both the market size effect and the productivity gap between the two sectors. From now on we assume that the subsidy to direct researchers towards the clean sector is in place. Then, while this subsidy is in place, the ratio A_{ct}/A_{dt} will grow at a rate equal to $\gamma\eta_c$ in the long-run. However, from equation (57) in Appendix part D, we have that the production of the dirty input in the long-run is not zero, but it grows at a rate equal to $A_{ct}^{-\frac{\alpha}{\phi-1}}$ (recall that throughout all the paper $\phi < 0$, by Assumption II, making the exponent always positive). This result is key: even if all the researchers work in developing clean innovations, the production of the dirty input still grows at a constant rate in the long-run, degrading the environment and eventually causing an environmental disaster unavoidably. This result contrasts with the benchmark model's outcome. Under perfect-mobility of workers assumption, the equilibrium level of output in the dirty sector is given by equation (60) in Appendix part E. It shows that when the research subsidy to the scientists in the clean sector is high enough, the production of the dirty input grows at a rate $A_{ct}^{\alpha+\phi}$ in the long-run. Now, in contrast to the no labor-mobility case, Assumption II does not pin down the sign of the exponent $\alpha + \phi$. Under the additional assumption of $\alpha < \phi$, or equivalently $\epsilon > \frac{1}{1-\alpha}$ what we call *strong substitutability* of clean and dirty inputs, the long-run growth rate of the dirty input Y_{dt} will be zero, because $\alpha + \phi < 0$ (by Assumption II and $\alpha < \phi$). As explained, having a zero long-run equilibrium growth rate of the dirty input production is never attainable in the no labor mobility case, even when all the researchers are working in the dirty sector and the degree of substitutability between the clean and the dirty input is high. The result is intuitive. In the perfect labor mobility setting, under the strong substitutability assumption, the market size effect dominates the price effect, as we can infer from equation (60): when the workers are free to switch across sectors, as the average quality of the machines in the clean sector increases, wages of the workers in the clean sector also increase and workers are automatically allocated to the clean sector. In contrast, under no-mobility of workers, allocating more workers to the clean sector is impossible. In this case the price effect is necessarily stronger than the market size effect. This is, as the technology in the clean sector develops, and the production costs of the clean inputs decrease, the price of the dirty input becomes relatively higher. As already explained, higher prices of the dirty input encourage production of this input (price effect).

In summary, under free-mobility of workers, the market size effect, which is stronger than the price effect under strong substitutability assumption [2], encourages production in the clean sector. Hence, while researchers in the clean sector are receiving the subsidy, the ratio A_{ct}/A_{dt} will increase, and once the ratio is sufficiently high, it will become automatically more profitable for both workers and scientists to be employed in the clean sector without the need of any subsidy. As a matter of fact, Acemoglu et al. (2012) get the optimistic result that a *temporary* subsidy to the researchers in the clean sector is enough to avoid an environmental disaster, as in this case the growth rate of Y_{dt} is zero. This contrasts with the no-mobility of workers setting. In this case, even when inputs in the clean and dirty sectors are strong substitutes, the outcome will necessarily be much more pessimistic. Here, the *temporary* subsidy to researchers will never avoid an environmental disaster, as the production of the dirty input keeps growing driven by the price effect. In this case, a *permanent* government regulation is necessary to avoid an environmental disaster.

First, note that this result implies that the cost of the policy intervention is much higher in the case of no labor mobility, because the government intervention needs to be *permanent*. However, in this framework, the policy intervention is costly for another reason too. Similar to the labor mobility case, the reason lies on the fact that while the clean technology catches up with the technology level in the dirty sector, the growth rate of the final output is slower than in the case where the technology keeps developing in the dirty sector. Clearly, this result directly stems from the fact that innovation follows the "standing on the shoulder of the giants" process. Hence, this characterization also implies costs of delay. The longer we wait to put forward the policy to direct researchers, the greater will be the technology gap between the technology level in the dirty sector relative to the clean one, and hence, the longer the period of slow growth in the final output (which means a longer period of low total consumption, lowering the utility of the representative household).

[2] Acemoglu et al. (2012) argue that the strong substitutability assumption between the clean and the dirty input i.e. $\epsilon > \frac{1}{1-\alpha}$ is the empirically plausible case.

At this point it is interesting to calculate the growth rate of final output under the no-mobility of labor hypothesis, and to compare it with the perfect labor mobility case.

From equations (56) and (57) we observe that under no labor mobility and strong substitutability assumption, the long-run growth rate of the clean input production is equal to A_c and the long-run growth rate of the dirty input production is $A_c^{-\frac{\alpha}{\phi-1}}$. From equations (59) and (60), on the other hand, we infer that under perfect mobility of labor and strong substitutability assumption, the long-run growth rate of the clean input production is equal to A_c, while the dirty input production does not grow in the long-run. Because the final good is a combination of the dirty and the clean input, given by the CES production function specified in equation (3), it is straightforward to conclude that the long-run growth rate of the final good is higher under the no-mobility of workers assumption. This leads to two main conclusions: when workers cannot move across sectors, the transition cost towards an economy where innovation only happens in the clean technology is smaller in terms of foregone output growth, or equivalently, in terms of consumption decrease along the long-run transition. However, having end up in an economy where R&D only happens in the clean sector is not enough in order to avoid an environmental disaster, given that the production of the dirty input grows at constant rate in equilibrium. To avoid the environmental disaster, relocating all (or part of) the workers that are currently employed in the dirty sector into the clean sector is necessary, which will bring additional costs.

In the following section we characterize the problem faced by workers regarding the decision of switching sectors under an imperfect labor mobility setting. Hence, we analyze what are the incentives that the workers require in order to choose to move from the dirty to the clean sector, in a scenario where switching requires some kind of investment from them i.e. there is no free mobility. This allows us to analyze qualitatively if there could be any other possible policy intervention (apart from the subsidy to the researchers), to avoid an environmental disaster and, if there is, how it would look like.

5 Imperfect Labor Mobility: Workers' Sectoral Choice Under Switching Costs

As already argued, in the benchmark model of free mobility of workers higher wages in the clean sector are enough to direct all the labor to work in the clean sector. However, as we show in this section, under the imperfect-mobility of workers assumption this does not need to be true. In what follows we consider the case of imperfect mobility of workers across sectors modeled by switching costs. This means that the relative ratio of workers in the clean over the dirty sector is not fixed any more but we keep having two different labor markets, and hence different wages in each sector in equilibrium.

As Magee, Davidson and Matusz (2009) recognize, in the real world factors are quasi-convex and move between sectors in response to changes in factor rewards. Usually, workers face significant adjustment costs when switching sectors due to costs of retraining. This suggests that ignoring these adjustments that workers need to undertake can lead to misleading policy conclusions. In particular, it may underestimate the transition costs, given that it neglects the potential need for policies aimed at compensating workers in the dirty sector. Simple labor market policies would include retraining subsidies or unemployment benefits for workers, for example.

In this section we characterize the optimal choice of workers under switching costs. In a similar way that scientists sorted themselves by choosing to undertake research in one sector or the other based on expected profits, in this model workers will sort themselves by choosing an occupation in the dirty or the clean sector based on the net expected wages offered in each of them. Our starting point is a worker that is currently working in the dirty sector. We assume that in period t he can decide whether he wants to either remain in the dirty sector or switch to the clean one. Therefore, the decision is characterized by

$$V_t = \max\left\{V_t^d(w_d), V_t^c(A_c, w_c)\right\} \tag{22}$$

We assume that while the worker is employed by the dirty sector he can always choose to switch to the clean sector in the next period. However, moving to the clean sector is an irreversible decision. This assumption is not restrictive and it easies computation. Even if workers that are already in the clean sector could choose to move back, they would always decide to stay in the clean sector. This is so because, assuming that the subsidy to the researchers in the clean sector is in place, the productivity in the clean sector grows over time and so do wages in the clean sector. Even if more workers start being employed in the clean sector, wages in the clean sector will keep increasing[3]. If the sequence of expected wages over time is higher in the clean sector, once the switching cost is undertaken it is not in the benefit of the workers to go back to the dirty sector. Then, the value functions of a worker employed by the dirty and clean sector respectively are as follows. In the dirty sector

$$V_t^d = w_t^d + \beta \max\left\{V_{t+1}^d, V_{t+1}^c\right\} \tag{23}$$

The worker that decided to stay in the dirty sector at time t will receive a wage equal to w_t^d. In the next period, t+1, he will still have the chance to decide again whether he wants to stay in the dirty sector or on the contrary, wants to switch to the clean one. The value function in the clean sector is given by

$$V_t^c = (w_t^c - \gamma A_t^c) + \beta W_{t+1}^c \qquad \text{where} \tag{24}$$

$$W_t^c = w_t^c + \beta W_{t+1}^c \tag{25}$$

The worker that decides to switch to the clean sector at time t will face a switching cost γA_t^c that depends on the technology level of the clean sector at time t, and where $\gamma \in (0,1)$, is a parameter measuring how difficult it is to get the green skills. The higher the value of γ the greater the switching costs that need to be incurred. On the other hand, the higher the technology sophistication in the clean sector, the costlier it is for a worker coming from the dirty sector to get the necessary skills, and hence the greater the switching costs too. For example, Louie and Pearce (2016) quantified the costs of retraining coal workers for employment in the solar photovoltaic industry, and concluded that while a structural engineer in the coal industry would not need any additional retraining to work in the solar industry, some solar-related engineering positions, for which the technological sophistication is high, call for a university degree whose cost ranges between 18,000$ and 136,000$ in the United States. Moreover, note that in our specification the switching cost is incurred only once, at time t, the date that the worker switches. Once in the clean sector, $\forall t' > t$, the worker will receive a wage equal to w_t^c every period and will stay in the clean sector forever. To finish with, recall that when $\gamma = 0$ there are no switching costs i.e. the difficulty of getting green skills is zero. In this case the worker switching to the clean sector will earn a wage equal to w_t^c, including period t and forever. Hence, in this case $V_t^c = W_t^c$, $w_c = w_d$ in equilibrium and we are back to Acemoglu et. al's (2012) perfect mobility of workers case (see Appendix part G for a proof).

Given this framework, we want to characterize the equilibrium condition that determines the willingness of workers in the dirty sector to switch to the clean one. Hence, we analyze the value functions in the steady state, and proceed as follows. From equation (25) in the steady sate, $W_t^c = W_{t+1}^c$,

$$W^c = \frac{w_c}{1-\beta} \tag{26}$$

Then, plugging equation (26) in equation (24) in the steady state we have that

[3] This argument is based on previous work of Acemoglu (2002a) and Acemoglu (2002b) that explained the phenomenon that we have been observing for the past sixty yeas, of an increase in the supply of skilled workers that was not accompanied by a decrease in skill premium. He argues, in a very similar setting to the one that we construct, that an increase in the supply of skilled labor made it profitable for firms to develop machines complementary to skilled labor, which increased the demand for skilled labor even more. This, translated to our setting, means that wages in the clean sector would increase as the technology in the clean sector develops.

$$V^c = w^c - \gamma A^c + \beta \frac{w_c}{1-\beta}$$

In equilibrium, in equation (23), the marginal worker currently in the dirty sector needs to be indifferent between remaining in the dirty sector or switching to the clean one in the next period t+1. Hence, $V^d_{t+1} = V^c_{t+1} = V \quad \forall t$. Now we can rewrite equation (23) as $V = w^d + \beta V$, and hence,

$$V = \frac{w^d}{1-\beta} \tag{27}$$

Substituting equations (27) and (26) in equation (24)

$$\frac{w^d}{1-\beta} = w^c - \gamma A^c + \beta \frac{w^c}{1-\beta}$$

Finally, rearranging the terms we get the threshold technology level A^{c*}

$$A^{c*} = \frac{1}{\gamma}\Big(\frac{w^c - w^d}{1-\beta}\Big)$$

To make the analysis as general as possible, we include the case where wages in the dirty sector can be higher than the wages in the clean sector in equilibrium. However, because the threshold level of technology can not be negative, we set the lower bound equal to zero.

$$A^{c*} = \max\left\{\frac{1}{\gamma}\Big(\frac{w^c - w^d}{1-\beta}\Big), 0\right\} \tag{28}$$

For any technology level in the clean sector below the threshold value i.e. $\forall A^c \leq A^{c*}$, workers will choose to switch to the clean one. On the contrary, for any value above the threshold i.e. $\forall A^c > A^{c*}$ workers will decide to remain in the dirty sector. Given that for a worker currently employed in the dirty sector the cost of switching is directly proportional to the technological sophistication in the clean sector, when the technological level in the clean sector is very advanced it is too costly for the worker to acquire the necessary skills or education to be able to work in the clean sector, and hence, he will choose to remain in the dirty sector even if the wages are higher in the clean one. In other words, having higher wages is a necessary but not sufficient condition in order to incentivize workers for switching -see Figure 1.

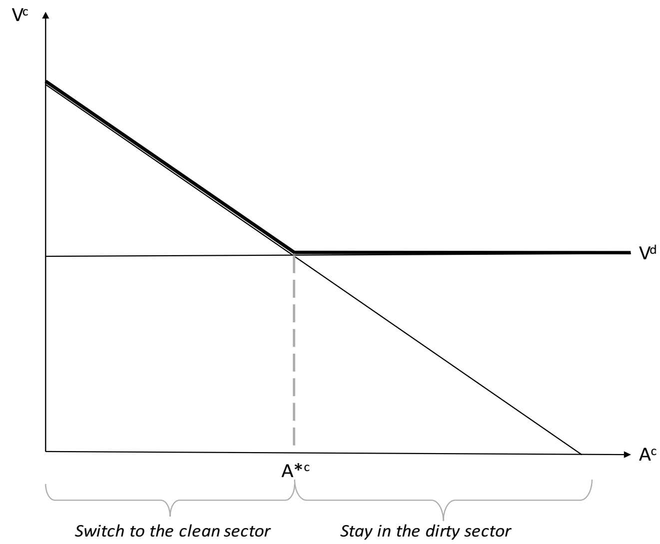

Figure 1: Threshold level of technology in the clean sector.

Whenever the wages in the dirty sector are higher than the wages in the clean sector the threshold level of technology in the clean sector is equal to zero i.e. $A^{c*} = 0$. Given that at any point in time the technology level in the clean sector is strictly positive, this means that $A^c > A^{c*}$ necessarily, and all the workers currently employed in the dirty sector will choose to stay there. Hence, offering higher wages in the clean sector is a necessary condition in order the workers to be willing to switch. Additionally, the higher the wages in the clean sector relative to the wages in the dirty one, the *likelier* it is for workers to choose to move, as the threshold level of technology increases. This result contrasts with the perfect mobility of workers setting, where higher wages in the clean sector are sufficient to ensure the switch. Recall that when γ approaches 0 the threshold level of technology becomes infinity, and hence, all workers will decide to switch to the clean sector. As explained, we are back to the benchmark model where switching costs are zero and higher wages are enough to attract workers. Finally, when γ is high, the switching cost is high, and the threshold value of technology is low. This makes it likelier that $A^{c*} < A^c$ making it unworthy for workers to switch to the clean sector (when γ is infinity no one will be willing to move). To finish with, β is the discount factor. When β is low, the worker derives a much lower utility from working and getting paid a given amount of wage in future periods relative to the present. The lower the value attributed to future periods, the lower is the threshold level of technology and the likelier it is that workers stay in the dirty sector. This makes sense, because incurring in switching costs at time t is an investment done today in order to benefit from higher payments in the future (recall that individuals will never switch if $w_d > w_c$). Hence, if workers do not value the future, it is not worth for them to incur in a high cost today to have a better payment in the future.

As simple as it is, this model serves as the first approach to get interesting insights. We showed that even for the case where the only switching costs that workers face are represented by retraining costs, higher wages in the clean sector are not enough to attract workers to this sector. If the technological level is too sophisticated in the clean sector, requiring workers to make a significant investment to acquire the necessary skills, workers will not be willing to switch. This leads us to conclude that, similar to the case of the subsidy to the researchers, where we explained that there are costs of delay, the same can be applied here. First note that we assume the subsidy to the researchers is in place. Then, the ratio A_{ct}/A_{dt} grows at a rate equal to $\gamma\eta_c$. However, given that today, still, the technology level in the clean sector is relatively backward and the dirty sector employs more people, the wages for workers in the dirty sector will be higher than the wages for workers in the clean sector. As we proved in this setting, offering higher wages in the clean sector is a necessary condition in order to make them choose to switch. Additionally, this condition is also sufficient as long as the technology level in the clean sector is still low. Hence, provided that the policy intervention is immediate, a simple income subsidy to the workers in the clean sector would be enough to attract them. However, we can also observe that there are costs of delay. As the technology in the clean sector evolves and the switching costs for the workers increase, offering a higher wage in the clean sector is no longer enough and the policy will also need to be aimed at providing some financial support for the retraining of the workers.

In this section we developed the simplest possible model of imperfect labor mobility, where the only switching cost that workers face are retraining costs. As the model developed by Davidson and Matusz (2009; Chapter 9), together with retraining costs we could also include unemployment. Put it in another way, not only training costs but also job searching costs on top of them. All the three models that we have referred to so far assume that factors of production are employed at all times. However, workers usually cycle between periods of employment and unemployment. Finding jobs quickly is difficult and the amount of time that workers can remain unemployed might be long and costly. This suggests that an important characteristic that should be taken into account is the turnover rates in each of the sectors. When policies to combat climate change are in place, one expects the job separation rate for workers in the dirty sector to be higher relative to the clean one, and, at the same time, the job creation rate of workers in the clean sector to be higher compared to the dirty one. In this setting, workers would cycle between periods of employment, unemployment and training, where the length of each labor market state would be determined by the turnover rates of each sector.

Additionally, in order to make the model more stylized, one could remove our implicit assumption that each sector accepts a representative worker. In other words, we assumed that there is a representative wage for each sector. Instead, one could assume heterogeneity of wages within each of them. We could consider that each worker z has a different ability level a_z where a_z is uniformly distributed between [0,1]. Using the notation employed throughout our model, then, if Y_j denotes the units of output produced in sector $j \in (c, d)$, a type-z sector-j worker would produce a flow of $Y_j a_z$ units of output and receive a wage equal to $p_j Y_j a_z$. Workers with a higher skill in each sector would produce more, and hence would receive higher wages than their low-skilled counterparts within each sector.

In most of the models, see Davidson and Matusz (2009) or Mitra and Ranjan (2009), for example, the cost of retraining is modeled as an exogenous sunk cost (different in each sector) that does not change over time. In contrast, in our model, retraining costs are endogenous i.e. depend on the technological sophistication level of the clean sector at the time that the worker switches, which is endogenously determined. Linked to the previous point, we could refine this assumption further. We could consider that apart from being endogenous, the switching costs are also idiosyncratic, related to the job position that one is going to fill in the clean sector. Hence, someone earning a higher wage (someone with higher skills) would also need to incur in higher switching costs, given that one can expect that higher positions require a better knowledge of the latest technological developments, as argued by Louie and Pearce (2016).

6 Concluding Remarks and Future Research

With a growing concern over climate change, there is a lot of interest among policy makers in knowing how the development of clean technologies may help to reduce the release of greenhouse gases to the atmosphere. Acemoglu et al. (2012) are the first ones addressing the question of how clean and dirty technologies respond to different environmental policies using a two-sector model of directed technical change and environmental constraints. Their results are much more optimistic than what it is stated in the very much influential Stern Review (2006) or in his later book, A Blueprint for a Safer Planet (2009), which is a follow-up of the review. While Stern (2009) argues that the intervention needs to be immediate, extensive and *permanent* even if this may entail considerable economic cost, Acemoglu et al. (2012) argue that for the empirically plausible case where the clean and dirty inputs are *strong substitutes*, even if intervention needs to be immediate, policies need to be in place only for a *temporary* period. In this case the market size effect is stronger than the price effect and the long-run growth of the production of the dirty input is zero, avoiding an environmental disaster. Our paper argues that, in part, this optimistic result is driven by the assumption of perfect labor-mobility across sectors. This assumption implies that as the technology level in the clean sector improves over time (which happens when the subsidy to researchers in the clean sector is in place), the demand for workers in the clean sector rises and workers are automatically reallocated towards this sector. However, we prove that when the assumption of free-mobility is removed the result becomes much more pessimistic, in line with Stern (2009). In particular, assuming that workers cannot switch sectors at all, the same model developed by Acemoglu et al. (2012) predicts that even for the case of high substitutability, some kind of *permanent* intervention is, indeed, necessary in order to prevent an environmental disaster given that, driven by the price effect, the production of the dirty input grows at a positive rate in the long-run equilibrium. This result implies considerably higher economic costs relative to the perfect mobility setting, and suggests that in reality, under imperfect mobility of workers (the empirically most plausible case) transition costs may be higher than the optimistic results presented by Acemoglu et al. (2012).

The *Just Transition* criteria put forward in the Paris Agreement and the ILO stress on the need for an adequate management of the transition to clean technologies. This means that it needs to be inclusive to all parties and that supports, particularly, workers that are currently employed in the dirty sector and that, potentially, could be negatively affected by the policies intended to boost the clean sector. Given that the extent to which these workers may suffer is directly proportional to how easily they can switch from the dirty to the clean sector, we develop a very simple model of imperfect labor mobility in order to analyze under which conditions these workers would switch to the clean sector. In line with Mitra and Ranjan (2009) and Davidson and Matusz (2009) the imperfect-mobility of workers is modeled by including switching costs in terms of retraining. In our model, all the workers currently employed in the dirty sector need to retrain if they want to start working in the clean sector. Additionally, we assume that the cost of retraining is proportional to the level of technological sophistication in the clean sector. This assumption seems logical. When the technology level in the clean sector is very advanced and sophisticated, a worker coming from the dirty sector needs to acquire many new skills and learn a long string of new techniques, which increases the retraining costs. We show that in this setting, offering a higher wage for workers in the clean sector is necessary but not sufficient to attract workers. When the technology level in the clean sector is too advanced no worker will be willing to move from the dirty sector, as the switching cost would be too high. In our setting, this calls for a quick policy intervention not only for scientists but also for workers in the clean sector. This is so because in the beginning, given that the technology level in the dirty sector is more advanced and the dirty sector employs more workers, wages in the dirty sector will be higher, what makes income subsidies to the workers in the clean sector necessary in order to attract them. If this intervention is immediate, because the technology in the clean sector is still relatively backward, higher wages in the clean sector are sufficient to direct all workers to the clean sector. If, on the contrary, the government does not take quick action and waits until the technologies in the clean sector are too advanced, there would be additional costs of delay.

This paper is a first attempt in order to analyze how, taking into account the empirically proven fact that workers face switching costs across sectors, might bring important implications for policy making in models that use directed technical change as a means to combat climate change. As further research, in section III we argued that in order to analyze a welfare maximizing short-run transition, building a three sector model where scientists can make clean, dirty or energy saving innovations may be interesting. In this framework the optimal policy could be to diversify researchers between the clean and the energy efficient sectors, which would lower the transition costs in terms of foregone final good while still contributing to the improvement of the environment. However, we argued that even if this option would be preferred by current generations, it would not benefit future ones, and could not be a long-term policy objective. On the other hand, as mentioned in section IV, there are two main directions in which the model of switching costs should be improved in order to have a more realistic framework that delivers more insightful results. First, the model should take account of the steady state job destruction and job creation rates in each sector. As stated by ILO, if managed well, the transition to cleaner economies can become a strong driver for job creation, and it would be interesting if the model could embody these features. In this case workers would not only face retraining, but also job searching costs and they would cycle between periods of training, employment and unemployment. Additionally, one could improve the setting by assuming heterogeneous wages that depend on the idiosyncratic level of skills of each worker within each sector and where they face idiosyncratic levels of switching costs. Even if there will be an average productivity level in each sector, one can imagine that workers with different skills will occupy different kind of positions, that require greater or a lower knowledge of the latest technology advancements.

To finish with, incorporating in the general equilibrium model that we described in the beginning of the paper the workers' decision regarding sectors, that we characterized by switching costs, is the most demanding part and ultimate goal as further research, that could bring very interesting outcomes. Building the general equilibrium model would allow to do welfare analysis and quantify the total transition costs, including the searching and switching costs of workers that we only mentioned qualitatively. Governments demand measures of the expected switching costs towards the transition to clean technologies. High switching costs in terms of foregone economic growth can be painful for the society, but, as argued by Acemoglu et al. (2012) or Stern (2009), the more we wait for an effective policy intervention, the higher the costs to be born by future generations.

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APPENDIX:

A General Model Setup

The competitive firms in the final good sector choose how much of the dirty input and how much of the clean input they want to use in order to produce the final good in a profit maximizing way:

$$\max_{Y_{ct},Y_{dt}} p_t Y_t - p_{ct} Y_{ct} - p_{dt} Y_{dt}$$

$$s.t: Y_t = [Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}} \tag{29}$$

The competitive firms in the clean (dirty) intermediate good sector choose how much clean (dirty) labor to hire and how many clean (dirty) machines to use in order to produce the clean (dirty) input in a profit maximizing way:

$$\max_{L_{jt},x_{jt}} p_{jt} Y_{ct} - w_{jt} L_{jt} - \int_0^1 p_{jit} x_{jit} di$$

$$s.t: Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di \tag{30}$$

where $j \in (c, d)$.

Finally, the monopolistic firms producing machines in the clean (dirty) sector, choose the price at which they want to sell the machine to maximize profits taking into account the demand for machines of the clean (dirty) intermediate sector:

$$\max_{p_{jit}} p_{jit} x_{cit} - \psi x_{jit}$$

$$s.t: x_{jit} = \left(\frac{\alpha p_{jt}}{p_{jit}}\right)^{\frac{1}{1-\alpha}} A_{jit} L_{jt} \tag{31}$$

where j $\in (c, d)$

A.1 Optimal Input Decisions by Sector

A.1.1 Intermediate Good Sector

From the intermediate good sector profit maximization problem defined in the general setup we construct the Lagrangian:

$$\mathcal{L} = p_{jt} L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di - w_{jt} L_{jt} - \int_0^1 p_{jit} x_{jit} di$$

$$\frac{\partial \mathcal{L}}{\partial x_{jit}} = \alpha p_{jt} L_{jt}^{1-\alpha} A_{jit}^{1-\alpha} x_{jit}^{1-\alpha} - p_{jit} = 0$$

$$x_{jit} = \Big(\frac{\alpha p_{jt}}{p_{jit}}\Big)^{\frac{1}{1-\alpha}} L_{jt} A_{jit} \tag{32}$$

where x_{jit} is the demand for type i machine of sector j at time t.

$$\frac{\partial \mathcal{L}}{\partial L_{jt}} = (1-\alpha) p_{jt} L_{jt}^{-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di - w_{jt} = 0$$

$$w_{jt} = (1-\alpha) p_{jt} L_{jt}^{-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di \tag{33}$$

A.1.2 Monopolistic Producer

From the monopolist's profit maximization problem defined in the general setup we construct the Lagrangian:

$$\mathcal{L} = (p_{jit} - \psi) x_{jit} = (p_{jit} - \psi)\Big[\Big(\frac{\alpha p_{jt}}{p_{jit}}\Big)^{\frac{1}{1-\alpha}} A_{jit} L_{jt}\Big]$$

$$\frac{\partial \mathcal{L}}{\partial p_{jit}} = x_{jit} + p_{jit} \frac{1}{1-\alpha}\Big(\frac{\alpha p_{jt}}{p_{jit}}\Big)^{\frac{1}{1-\alpha}-1} A_{jit} L_{jt}\Big(-\frac{\alpha p_{jt}}{(p_{jit})^2}\Big) - \psi \frac{1}{1-\alpha}\Big(\frac{\alpha p_{jt}}{p_{jit}}\Big)^{\frac{1}{1-\alpha}-1} A_{jit} L_{jt}\Big(-\frac{\alpha p_{jt}}{(p_{jit})^2}\Big) = 0$$

;

$$x_{jit}\Big[1 - \frac{\alpha p_{jt}}{(p_{jit})^2} \frac{1}{1-\alpha} p_{jit} \frac{p_{jit}}{\alpha p_{jt}} + \frac{\alpha p_{jt}}{(p_{jit})^2} \psi \frac{1}{1-\alpha} \frac{p_{jit}}{\alpha p_{jt}}\Big] = 0$$

;

$$(1-\alpha) p_{jit} - p_{jit} + \psi = 0$$

;

and taking into account that $\psi \equiv \alpha^2$ we get that

$$p_{ijt} = \alpha \tag{34}$$

Hence, the profit maximizing price that the monopolistic producer sets is a constant markup over the marginal cost i.e. $p_{jit} = \frac{1}{\alpha}\psi = \alpha$.

A.1.3 The Final Good Sector

From the final good sector's profit maximization problem defined in the general setup we construct the Lagrangian:

$$\mathcal{L} = p_t\Big(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}}\Big)^{\frac{\epsilon}{\epsilon-1}} - p_{ct} Y_{ct} - p_{dt} Y_{dt}$$

$$\frac{\partial \mathcal{L}}{\partial Y_{jt}} = p_t \frac{\epsilon}{\epsilon-1}\Big(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}}\Big)^{\frac{1}{\epsilon-1}} \frac{\epsilon-1}{\epsilon} Y_{ct}^{-\frac{1}{\epsilon}} - p_{jt} = 0$$

$$p_{jt} = p_t Y_t^{\frac{1}{\epsilon}} Y_{jt}^{-\frac{1}{\epsilon}} \tag{35}$$

B The Equilibrium Expected Profit Ratio of Researchers

First, in order to get the equilibrium profits for the monopolits producing machine i in sector j, we plug equation (34) in equation (32) and we get that:

$$x_{jit} = p_{jt}^{\frac{1}{1-\alpha}} L_{jt} A_{jit} \tag{36}$$

Now, taking into account that $\psi \equiv \alpha^2$ and plugging equation (34) and (36) in the profit function of the monopolist producing machine i in sector j ; $\pi = (p_{jit} - \psi)x_{jit}$ we get the monompolist's equilibrium profits:

$$\pi_{jit} = (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt} A_{jit}$$

Given that the productivity of each machine i in sector j increases accoring to $A_{jit} = (1+\gamma)A_{jit-1}$ from one period to the other:

$$\pi_{jit} = (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt}(1+\gamma)A_{jit-1}$$

In order to get the expected profits for a scientist engaged in research in sector j at time t, we take the integral over the continuum of all types of machines $i \in (0,1)$, and by definition, we get that:

$$\pi_{jt} = (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt}(1+\gamma)A_{jt-1}$$

Finally, given that each researcher has a successful innovation with probability η_j for $j \in (c,d)$, the expected profit for each scientist working in sector j at time is :

$$\pi_{jt} = \eta_j(1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt}(1+\gamma)A_{jt-1} \tag{37}$$

B.1 The equilibrium Expected Profit Ratio of Researchers, Relative Wages and Relative Input Prices under Perfect-Mobility of Workers Assumption

In this case there is only one labor market and the market clearing condition implies

$$L_{ct} + L_{dt} = 1$$

assuming that labor is inelastically supplied and normalized to to one. Given that at any point in time workers are able freely move across sectors, in equilibrium, the labor wages in the clean sector must equalize labor wages in the dirty sector.

Plugging equation (36) in equation (33) and assuming $w_{jt} = w_t$, we get

$$(1-\alpha)p_{jt}L_{jt}^{-\alpha}\int_0^1 A_{jit}^{1-\alpha}\Big[p_{jt}^{\frac{\alpha}{1-\alpha}} L_{jt}^{\alpha} A_{jit}^{\alpha}\Big]di = w_t$$

$$(1-\alpha)p_{jt}^{\frac{1}{1-\alpha}}\int_0^1 A_{jit}di = w_t$$

Summing over all the types of machines i

$$p_{jt} = \Big(\frac{w_t}{(1-\alpha)A_{jt}}\Big)^{1-\alpha}$$

Now, we can get the price of the intermediate goods in the clean sector relative to the price in the dirty sector

$$\frac{p_{ct}}{p_{dt}} = \Big(\frac{A_{ct}}{A_{dt}}\Big)^{-(1-\alpha)} \tag{38}$$

On the other hand, from equation (35) and using equation (34) we can also derive the price of the intermediate good in the clean sector relative to the one in the dirty sector

$$\frac{p_{ct}}{p_{dt}} = \Big(\frac{Y_{ct}}{Y_{dt}}\Big)^{-\frac{1}{\epsilon}} \tag{39}$$

Substituting equation (36) in equation (30) and summing over all the type of machines,i, we get

$$Y_{jt} = L_{jt}p_{jt}^{\frac{\alpha}{1-\alpha}}A_{jt} \tag{40}$$

Plugging equation (40) in equation (39)

$$\Big(\frac{p_{ct}}{p_{dt}}\Big)^{-\epsilon} = \Big(\frac{p_{ct}}{p_{dt}}\Big)^{\frac{\alpha}{1-\alpha}}\frac{A_{ct}}{A_{dt}}\frac{L_{ct}}{L_{dt}}$$

$$\frac{L_{ct}}{L_{dt}} = \Big(\frac{p_{ct}}{p_{dt}}\Big)^{-\epsilon-\frac{\alpha}{1-\alpha}}\Big(\frac{A_{ct}}{A_{dt}}\Big)^{-1} \tag{41}$$

Substituting equation (38) in equation (41) and defining $\phi = (1-\alpha)(1-\epsilon)$, we have that

$$\frac{L_{ct}}{L_{dt}} = \Big(\frac{A_{ct}}{A_{dt}}\Big)^{-\phi} \tag{42}$$

Directly plugging equations (38) and (42) into equation (16)

$$\frac{\pi_{ct}}{\pi_{dt}} = \frac{\eta_c}{\eta_d}\Big(\frac{A_{ct}}{A_{dt}}\Big)^{-(1+\phi)}\frac{A_{ct-1}}{A_{dt-1}} \tag{43}$$

Substituting equation (9) into equation (43) we have that

$$\frac{\pi_{ct}}{\pi_{dt}} = \frac{\eta_c}{\eta_d}\Big[\frac{(1+\gamma\eta_c s_{ct})A_{ct-1}}{(1+\gamma\eta_{dt}s_{dt})A_{dt-1}}\Big]^{-(1+\phi)}\frac{A_{ct-1}}{A_{dt-1}}$$

Hence, the expected profit ratio for each researcher in the clean sector relative to the dirty sector when there is perfect mobility of workers across both sectors is given by

$$\frac{\pi_{ct}}{\pi_{dt}} = \frac{\eta_c}{\eta_d}\Big[\frac{(1+\gamma\eta_c s_{ct})}{(1+\gamma\eta_{dt}s_{dt})}\Big]^{-(1+\phi)}\frac{A_{ct-1}}{A_{dt-1}}^{-\phi} \tag{44}$$

B.2 The Equilibrium Expected Profit Ratio of Researchers, Relative Wages and Relative Input Prices under No-Mobility of Workers Assumption

Plugging equation (40) in equation (39)

$$\frac{p_{ct}}{p_{dt}} = \Big[\frac{L_{ct}p_{ct}^{\frac{1}{1-\alpha}}A_{ct}}{L_{dt}p_{dt}^{\frac{1}{1-\alpha}}A_{dt}}\Big]^{-\frac{1}{\epsilon}}$$

$$\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{(1-\alpha)\epsilon+\alpha}{(1-\alpha)\epsilon}} = \left(\frac{L_{ct}A_{ct}}{L_{dt}A_{dt}}\right)^{-\frac{1}{\epsilon}}$$

$$\left(\frac{p_{ct}}{p_{dt}}\right) = \left(\frac{L_{ct}A_{ct}}{L_{dt}A_{dt}}\right)^{-\frac{(1-\alpha)}{(1-\alpha)\epsilon+\alpha}}$$

Recalling that $\phi = (1-\alpha)(1-\epsilon)$

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1-\alpha}{\phi-1}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\phi-1}} \tag{45}$$

Now, we can plug equations (45) in (16) and get the ratio of profits of the researchers in each of the sectors:

$$\frac{\pi_{ct}}{\pi_{dt}} = \frac{\eta_c}{\eta_d}\left[\frac{L_{ct}}{L_{dt}}^{\frac{1-\alpha}{\phi-1}} \frac{A_{ct}}{A_{dt}}^{\frac{1-\alpha}{\phi-1}}\right]^{\frac{1}{1-\alpha}} \left(\frac{L_{ct}}{L_{dt}}\right)\frac{A_{ct-1}}{A_{dt-1}}$$

Plugging equation (9) in the relative productivity of the sectors and rearranging the terms we gat that:

$$\frac{\pi_{ct}}{\pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\phi}{\phi-1}} \left[\frac{(1+\gamma\eta_c s_{ct})}{(1+\gamma\eta_d s_{dt})}\right]^{\frac{1}{\phi-1}} \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{\phi}{\phi-1}} \tag{46}$$

Now, given that the wages for the workers in each sector are different, we can compute the relative ratio of them. Plugging equation (36) in equation (33) and summing over all the type of machines we get that:

$$w_{jt} = (1-\alpha)p_{jt}^{\frac{1}{1-\alpha}}A_{jt}$$

Hence, relative wages are defined by:

$$\frac{w_{ct}}{w_{dt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}\frac{A_{ct}}{A_{dt}} \tag{47}$$

Finally, plugging equation (45) into equation (47) we get that

$$\frac{w_{ct}}{w_{dt}} = \left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1}{\phi-1}}\left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{\phi}{\phi-1}} \tag{48}$$

C Proof of Assumption 1

Assumption I states that :

$$\frac{A_{c0}}{A_{d0}} < min\left\{\underbrace{\left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}}\left(\frac{L_c}{L_d}\right)^{-1}(1+\gamma\eta_c)^{-\frac{1}{\phi}}}_{1(c)}, \underbrace{\left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}}\left(\frac{L_c}{L_d}\right)^{-1}(1+\gamma\eta_d)^{\frac{1}{\phi}}}_{2(d)}\right\}$$

In what follows we prove diagrammatically that Assumption I implies that at $t = 1$ all the researchers engage in research in the dirty sector.

As proved in the body of the paper, when

$$\frac{A_{ct-1}}{A_{dt-1}} > \underbrace{\left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}} \left(\frac{L_{ct}}{L_{dt}}\right)^{-1} (1+\gamma\eta_c)^{-\frac{1}{\phi}}}_{1(c)} \qquad \text{Condition 1}$$

in equilibrium all the innovation takes place in the clean sector and when

$$\frac{A_{ct-1}}{A_{dt-1}} < \underbrace{\left(\frac{\eta_c}{\eta_d}\right)^{-\frac{\phi-1}{\phi}} \left(\frac{L_{ct}}{L_{dt}}\right)^{-1} (1+\gamma\eta_d)^{\frac{1}{\phi}}}_{2(d)} \qquad \text{Condition 2}$$

all the innovation takes place in the dirty sector. Then, if $\frac{A_{ct-1}}{A_{dt-1}}$ is placed to the right of 1(c) Condition 1 is satisfied and hence all the research takes place in the clean sector. When $\frac{A_{ct-1}}{A_{dt-1}}$ is placed to the left of 2(d) Condition 2 is satisfied and all the innovation takes place in the dirty sector. Both for the case where $1(c) > 2(d)$ or $1(c) < 2(d)$, when $\frac{A_{c0}}{A_{d0}}$ is smaller than the minimum of the two we ensure that at time $t = 1$ in equilibrium all the researchers engage in research in the dirty sector i.e. $s_{d1} = 1$ and $s_{c1} = 0$

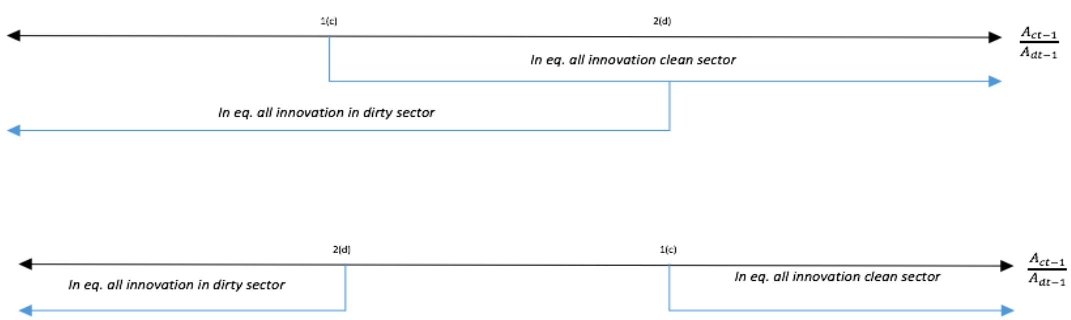

Figure 2: Proof of Assumption I.

D Equilibrium Productions Under No-Mobility of Workers

First, recall that equation (40) for the case of the clean sector is given by

$$Y_{ct} = p_{ct}^{\frac{\alpha}{1-\alpha}} L_{ct} A_{ct} \tag{49}$$

Defining equation (45) as "a" we have that

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1-\alpha}{\phi-1}} \left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\phi-1}} \equiv a \quad \rightarrow \quad p_{ct} = a p_{dt} \tag{50}$$

Substituting equation (50) in equation (11) we get that

$$[p_{dt}^{1-\epsilon}(a^{1-\epsilon}+1)]^{-\frac{1}{1-\epsilon}} = 1 \tag{51}$$

$$p_{dt} = \frac{1}{[a^{1-\epsilon}+1]^{\frac{1}{1-\epsilon}}} \tag{52}$$

Plugging equation (52) in equation (50)

$$p_{ct} = \frac{a}{[a^{1-\epsilon}+1]^{\frac{1}{1-\epsilon}}} \tag{53}$$

Substituting the above defined "a" in equation (53) we get that

$$p_{ct} = \frac{\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1-\alpha}{\phi-1}}\left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\phi-1}}}{\left[\left[\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{1-\alpha}{\phi-1}}\left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{1-\alpha}{\phi-1}}\right]^{1-\epsilon}+1\right]^{\frac{1}{1-\epsilon}}} \tag{54}$$

Plugging equation (54) in equation (49)

$$Y_{ct} = \frac{\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\alpha}{\phi-1}}\left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{\alpha}{\phi-1}}}{\left[\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\phi}{\phi-1}}\left(\frac{A_{ct}}{A_{dt}}\right)^{\frac{\phi}{\phi-1}}+1\right]^{\frac{\alpha}{\phi}}} L_{ct}A_{ct} \tag{55}$$

$$Y_{ct} = \left[1+\left(\frac{L_{ct}}{L_{dt}}\right)^{-\frac{\phi}{\phi-1}}\left(\frac{A_{ct}}{A_{dt}}\right)^{-\frac{\phi}{\phi-1}}\right]^{-\frac{\alpha}{\phi}} L_{ct}A_{ct}$$

Therefore, after some algebra we get that the production of the clean input in equilibrium is

$$Y_{ct} = \left[(L_{dt}A_{dt})^{-\frac{\phi}{\phi-1}}+(L_{ct}A_{ct})^{-\frac{\phi}{\phi-1}}\right]^{-\frac{\alpha}{\phi}}(L_{dt}A_{dt})^{-\frac{\alpha}{\phi-1}}L_{ct}A_{ct} \tag{56}$$

And by symmetry, the production of the dirty input in equilibrium is given by

$$Y_{dt} = \left[(L_{dt}A_{dt})^{-\frac{\phi}{\phi-1}}+(L_{ct}A_{ct})^{-\frac{\phi}{\phi-1}}\right]^{-\frac{\alpha}{\phi}}(L_{ct}A_{ct})^{-\frac{\alpha}{\phi-1}}L_{dt}A_{dt} \tag{57}$$

To compute the total output in the economy we plug the two last equations in (56) and (57) in (3) and we get that

$$Y_t = \left[(L_{dt}A_{dt})^{-\frac{\phi}{\phi-1}}+(L_{ct}A_{ct})^{-\frac{\phi}{\phi-1}}\right]^{-\frac{\alpha}{\phi}}\Big(L_{dt}A_{dt}L_{ct}A_{ct}\Big)\left[(L_{dt}A_{dt})^{\frac{\epsilon-1}{\epsilon}(-\frac{\alpha}{\phi-1}-1)}+(L_{ct}A_{ct})^{\frac{\epsilon-1}{\epsilon}(-\frac{\alpha}{\phi-1}-1)}\right]^{\frac{\epsilon}{\epsilon-1}}$$

$$Y_t = \left[(L_{dt}A_{dt})^{-\frac{\phi}{\phi-1}}+(L_{ct}A_{ct})^{-\frac{\phi}{\phi-1}}\right]^{\frac{\phi-1}{\phi}}L_{dt}A_{dt}L_{ct}A_{ct} \tag{58}$$

E Equilibrium Productions Under Perfect Mobility of Workers

Following the same steps as the ones explained in the Appendix part D, we get the following results under the perfect labor mobility assumption

$$Y_{ct} = (A_{dt}^{\phi}+A_{ct}^{\phi})^{-\frac{\alpha+\phi}{\phi}}A_{ct}A_{dt}^{\alpha+\phi} \tag{59}$$

$$Y_{dt} = (A_{dt}^{\phi}+A_{ct}^{\phi})^{-\frac{\alpha+\phi}{\phi}}A_{dt}A_{ct}^{\alpha+\phi} \tag{60}$$

$$Y_t = (A_{dt}^{\phi}+A_{ct}^{\phi})^{-\frac{1}{\phi}}A_{ct}A_{dt} \tag{61}$$

F Equilibrium Research Subsidies in the Clean Sector

Diving equation (20) by equation (15) we get that

$$\frac{\pi_{ct}}{\pi_{dt}} = (1+q_t)\frac{\eta_c}{\eta_d}\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\phi}{\phi-1}}\left[\frac{(1+\gamma\eta_c s_{ct})}{(1+\gamma\eta_d s_{dt})}\right]^{\frac{1}{\phi-1}}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{\phi}{\phi-1}} \tag{62}$$

We first calculate the threshold level of subsidy q^*. At the threshold, the expected profits of scientists are the same in the clean and in the dirty sector. Therefore, until this threshold is reached, all the scientists will decide to undertake research in the dirty sector i.e. the subsidy is not high enough to direct them towards the clean sector.

$$(1+q_t^*)\frac{\eta_c}{\eta_d}\left(\frac{L_{ct}}{L_{dt}}\right)^{\frac{\phi}{\phi-1}}\left(\frac{1}{1+\gamma\eta_d}\right)^{\frac{1}{\phi-1}}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\frac{\phi}{\phi-1}} = 1$$

Then, any subsidy $q \geq q^*$ will be sufficient to engage all researchers in the clean sector.

$$q_t \geq q^* \equiv \frac{\eta_d}{\eta_c}(1+\gamma\eta_d)^{\frac{1}{\phi-1}}\left(\frac{A_{dt-1}}{A_{ct-1}}\right)^{\frac{\phi}{\phi-1}}\left(\frac{L_{dt}}{L_{ct}}\right)^{\frac{\phi}{\phi-1}} - 1 \tag{63}$$

G Workers' Sector Choice Under No Switching Costs

From equation (22) in the text

$$V_t = \max\left\{V_t^d(w_d), V_t^c(w_c)\right\} \tag{64}$$

The value function of the workers in the dirty sector is the same as in equation (23) In the dirty sector,

$$V_t^d = w_t^d + \beta\max\left\{V_{t+1}^d, V_{t+1}^c\right\}$$

Taking the value function in the clean sector, equation (24) and setting $\gamma = 0$ we get that

$$V_t^c = w_t^c + \beta V_{t+1}^c \tag{65}$$

In the steady state

$$V^c = \frac{w_c}{1-\beta} \tag{66}$$

Given that in equation (65) in equilibrium the marginal worker is indifferent between staying the dirty sector or moving to the clean one $V^d = V^c = V$ we can rewrite it as

$$V^d = w_t^d + \beta V^d$$

$$V^d = \frac{w^d}{1-\beta} \tag{67}$$

Setting $V_d = V_c$

$$\frac{w^d}{1-\beta} = \frac{w^d}{1-\beta} \tag{68}$$

and hence we are back to Acemoglu et al.'s (2012) setting of free mobility of workers where $w^d = w^c$.