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GREEN TRANSITIONS AND THE PREVENTION OF ENVIRONMENTAL DISASTERS: MARKET-BASED VS. COMMAND-AND-CONTROL POLICIES

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The paper compares the effects of market-based (M-B) and command-and-control (C&C) climate policies on the direction of technical change and the prevention of environmental disasters. Drawing on a model of endogenous growth and directed technical change, we show that M-B policies (carbon taxes and subsidies toward clean sectors) suffer from path dependence and exhibit bounded window of opportunities: delays in their implementation make them ineffective both in redirecting technical change, (i.e. triggering a transition toward clean energy) and in avoiding environmental catastrophes. On the contrary, we find that C&C interventions are favored by path dependence and guarantee policy effectiveness irrespectively of the timing of their introduction. As the hypothesis of path dependence in technological change has received vast empirical support and it is a key feature of many models of growth, we argue that C&C policies should be seen as a valuable and non-equivalent alternative to M-B interventions.

Keywords: Green Transition, Environmental Policy, Command and Control, Carbon Taxes

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1. INTRODUCTION

In this work we study the effectiveness of market-based (M-B) and command-and-control (C&C) policies in triggering a transition toward sustainable growth, thus preventing environmental catastrophes related to climate change.

One of the major contemporary challenges is to cope with environmental degradation—and rising temperature caused by the increasing consumption of fossil fuels above all—together with the search for appropriate policy responses. The debate is still unsettled as some researchers call for major and immediate actions [Stern (2007)], whereas others suggest limited and gradual policy interventions [see, e.g., Nordhaus (2007)]. Acemoglu et al. (2012) and Acemoglu et al. (2016) have recently contributed to the such debate proposing a two-sector model of directed technical change, which allows studying how M-B environmental policies can affect the development of "dirty" and "green" technologies, thus impacting on climate change. When the clean and dirty inputs are "strong" substitutes [more on that in Acemoglu et al. (2012), and in Section 4.3 of this paper], an optimal M-B environmental policy grounded on a "carbon" tax and a green research subsidy can redirect technical change toward the green sector, preventing environmental catastrophes. However, given path dependence in the direction of technical change [Aghion et al. (2016)], we find that the window of opportunity of such policy actions is limited: if the technology gap between the dirty and green inputs becomes sufficiently large, M-B interventions are ineffective and environmental disasters will occur with certainty. The policy window is shorter when the two inputs are "weak" substitutes. Moreover, in the latter case (as well as when inputs are complementary) M-B interventions cannot avoid an environmental catastrophe unless they prevent the economy from growing.

In line with the model from Acemoglu et al., the majority of the literature focuses its policy analysis on environmental directed technical change on M-B monetary incentives (see also Section 2). Nevertheless, the adoption of regulations not grounded on market incentives is quite common in environmental policy and, in many cases, it proved effective. For instance, some international agreements (e.g., the Montreal Protocol on Substances that Deplete the Ozone Layer) fix an exogenous ceiling on specific polluting concentrations. Shapiro and Walker (2015) found that the increasing stringency of US environmental regulation accounted for three quarters of the 60% decrease in pollution emissions (e.g., nitrogen oxides, particulate matter, sulfur dioxide, and volatile organic compounds) from US manufacturing in the period from 1990 to 2008. In general, both price and quantity forms of control can solve allocation problems and there is no a priori criterion to favor one instrument over the other [Weitzman (1974)].

On these grounds, we explore how static M-B and C&C policies impact the long-run trajectory of an economy characterized by path dependence in the history of innovations. More precisely, we account for C&C policies in a model of endogenous growth and directed technical change, and we study their effects on the long-run dynamics of both growth and environmental quality.[1]

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We find that a C&C policy that fixes the maximum amount of dirty inputs for each unit of clean ones *always* redirects technical change toward green technologies avoids environmental catastrophes, independently of the timing of its implementation. In particular, our main result shows that the strength of the C&C policy needed to redirect technical shrinks decreases over time, while that of M-B policies increases. In that, C&C policies are a valuable alternative to M-B ones to reach a green transition whenever the window of opportunity for environmental interventions is bounded. Moreover, even if the dirty and clean inputs are weak substitutes or complementary, C&C interventions imposing a ceiling to the use of polluting inputs avoid disasters without halting economic growth.

The rest of the paper is organized as follows. We present a literature review in Section 2 and the model in Section 3. Alternative policies interventions are compared in Section 4. Finally, we discuss the results in Section 5.

2. LITERATURE REVIEW

The optimal policy to induce a large-scale transition from dirty to clean production system is—in the absence of any other market failure—a Pigouvian price on the polluting substances, typically taking the form of a carbon tax on emissions [Nordhaus (1991)]. Moreover, in a world with perfect knowledge and no uncertainty, the standard duality argument implies the equivalence between the use of prices and quantities as mitigation policy instruments. However, Weitzman (1974) shows that in an imperfect world, the relative advantage of policies on prices vis-à-vis quantities can vary according to the amount and type of inadequate information. As a consequence, quantity-based mitigation policies can be preferred to price-based ones under certain conditions. In this paper, we show that similar conclusions are implied by the interaction of policy choice and path dependence in technical change, while assuming no uncertainty about the different technologies.

Many studies have compared the effects of M-B and C&C policies [see (Hepburn, 2006), for an extensive comparison of environmental and climate policies]. Buchanan (1969); Li and Shi (2010), and Li and Sun (2015) emphasize the drawbacks of marked-based instruments and support the use of regulation.[2] The same conclusion is suggested by recent empirical evidences [see, e.g., Lee et al. (2011) and Shapiro and Walker (2015)]. On the contrary, Rozenberg et al. (2014) show that when underinvestment in polluting capital is possible, carbon pricing is superior to C&C interventions. Recently, van der Meijden and Smulders (2018) find that the two sides of M-B policies might conflict: while R&D subsidies speed up the transition, fossil fuel taxes postpone the switch to renewable energies. More generally, there is no crystal-clear agreement about the identification of the "best" climate policy and the way to compare different instruments. For example, Goulder and Parry (2008) consider a wide range of possible interventions, and they analyze the extent to which they meet a variety of major evaluation criteria, including cost-effectiveness, distributional equity, the ability

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to address uncertainties, and political feasibility. They find that no single instrument is clearly superior and that ensembles of different climate policies can be more effective.

Furthermore, Acemoglu et al. (2012) study how directed technical change can support the transition to a "green" economy and prevent environmental disasters.[3] They find that the joint adoption of carbon taxes and research subsidies can direct innovation toward clean technologies [on the complementarity of tax and subsidies see also Grimaud et al. (2011)]. These works have inspired a good deal of recent contributions on environmental policy impact in presence of directed technical change. For instance, Mattauch et al. (2015) add learning by doing effects and explore the role of substitution effects between clean and dirty inputs, showing that the policy proposed in Acemoglu et al. (2012) might be excessively limited in scope; Durmaz and Schroyen (2016) include the effects of an abatement (carbon capture and storage) technology; Greaker et al. (2018) introduce decreasing returns to R&D and allow future carbon taxes influencing current R&D decisions. Even more recently, Kruse-Andersen (2017) develops a variant of the model accounting for population growth effects, while Bezin (2017) enriches it to study the effects of cultural transmission mechanisms. Finally, van den Bijgaart (2017) extends the framework to a two-country setting [see also Hemous (2012) for an alternative North–South model extension]. Such stream of studies showed the usufulness of models of directed technical change in the analysis of environmental policy.

However, the fundamental role of innovation for the effectiveness of climate and environmental policy has a long history and it has extensively been explored both at theoretical [Goulder and Schneider (1999); Gillingham et al. (2008), and Otto and Reilly (2008)] and empirical levels [(Popp, 2002) and Jaffe et al. (2003)].[4] These contributions pointed out that the rewards from the development of new technologies do come not from current or future pollution reductions, but from the expected profits associated with technological improvements. Expected profitability has been shown depending, in turn, on the size of the economy [Sue Wing (2003)], on the scarcity of fossil fuels (Gans, 2012), and on the past history of innovations [Acemoglu et al. (2012) and Aghion et al. (2016)].

In particular, Acemoglu et al. (2016) show that if the initial technological gap between dirty and clean technologies is too wide, the potential transition to clean technology cannot occur as clean research must climb several steps to catch up with dirty technology and the gap discourages research efforts in "green" technology. As a consequence, the effects of path dependence (i.e., the history of innovations) should be considered in assessing the effectiveness of different climate policy instruments to induce "green" transitions, as well as to prevent environmental disasters related to excessive greenhouse gas emissions.

The above literature on and environmental policy directed technical change often concentrates on the determination of the optimal mix of carbon taxes and R&D subsidies. However, it does not offer a systematic comparison of price-based and quantity-based policies. This is exactly the starting point of the present paper.

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Finally, our work also relates to the one of Gerlagh et al. (2009). While they show that the introduction of optimal emission reduction policies strongly depends on the set of instruments available, we take the opposite perspective and study how policies can lose their effects as time goes by. In that, we are close to Bretschger and Schaefer (2017), where energy policies affect the interplay between the history of innovations and the expectations on future technologies in determining the transition. While they just focus on taxes and subsidies, we contrast the latter with regulation policies.

3. THE MODEL

The baseline structure of our model is akin to the one in Acemoglu et al. (2012). There is a continuum of households (composed of workers, entrepreneurs, and scientists) with utility function:

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

where ρ is the discount rate, C is final consumption good, and $S \in [0, \bar{S}]$ captures the quality of the environment. Naturally, the instantaneous utility function is increasing in consumption and environmental quality.[5]

On the supply side, a homogeneous final good is produced under perfect competition employing *clean* and *dirty* inputs Y_c and Y_d:

$$Y_t = \left(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}, \tag{2}$$

where $\epsilon \in (0, +\infty)$ is the elasticity of substitution between the two inputs. Note that the two inputs are complements when $\epsilon < 1$ and substitutes if $\epsilon > 1$.

Both Y_c and Y_d, which can be read as energy units from different technologies, are produced using labor and a continuum of sector-specific machines according to the production functions:

$$Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di, \tag{3}$$

with $j \in \{c, d\}$ and $\alpha \in (0, 1)$; A_{jit} is the productivity of machine i in sector j and x_{jit} is the quantity of such machine. The aggregate productivity of the two sectors is defined as

$$A_{jt} \equiv \int_0^1 A_{jit} di. \tag{4}$$

Total labor supply is normalized to 1 and the market-clearing condition for labor requires $L_{ct} + L_{dt} \leq 1$. Machines in both clean and dirty sectors are produced by monopolistic competitive firms. The cost of producing a single machine is constant across time and sectors and corresponds to $\psi = \alpha^2$.

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In both industries, an innovation occurs if a scientist successfully discovers a new design. At the beginning of each period scientists try to develop a new clean or dirty technology. If a scientist is successful, which happens with probability $\eta_j \in (0, 1)$, she obtains a 1-year patent for its machine i and becomes a monopolistic supplier.[6] Innovations increase the productivity of a machine by a factor $1 + \gamma$, with $\gamma > 0$. Normalizing the number of scientists to 1 the market-clearing condition for scientists becomes $s_{ct} + s_{dt} \leq 1$, where s_{jt} indicates the share of scientists conducting research in sector $j = \{c, d\}$ at time t. As scientists are randomly allocated to machines in the sector they choose, the average productivity of sector j evolves according to

$$A_{jt} = (1 + \gamma \eta_j s_{jt}) A_{jt-1}. \tag{5}$$

The variation of environmental quality S_t depends on environmental degradation linked to the production of dirty inputs, as well as on environmental regeneration due to the intrinsic dynamics of the Earth's physical and biological system:

$$S_{t+1} = -\xi Y_{dt} + (1 + \delta) S_t, \tag{6}$$

with S_{t+1} bounded between 0 and $\bar{S}$. The environmental degradation term catches the negative effects of CO_2 emissions,[7] while the environmental regeneration term captures the absorption of CO_2 by the oceans and the biosphere [Oeschger et al. (1975); Goudriaan and Ketner (1984), and Nordhaus (1992)]. Note that if $S_t = 0$, an environmental disaster occurs.

4. CLIMATE POLICIES AND THE DIRECTION OF TECHNICAL CHANGE

In this section, we first recall the *laissez-faire equilibrium* (Section 4.1), where no environmental policies are in place. We then study the impact of different policy initiatives aimed at redirecting technical change toward the green sector in order to reduce the total amount of dirty inputs used in the economy and, in turn, avoid environmental disasters. More specifically, we compare the success of M-B policies (cf. Section 4.2), composed of carbon taxes and subsidies to the clean sector, with C&C interventions (cf. Section 4.3), which fix ceilings for the production of dirty inputs.

4.1. The Laissez-Faire Equilibrium

Following Acemoglu et al. (2012), an equilibrium is represented by a sequence of wages (w_t), prices for inputs (p_{jt}) and machines (p_{jit}), demands for inputs (Y_{jt}) and machines (x_{jit}), labor (L_{jt}), quality of environment (S_t), and research allocations of scientists (s_{jt}) such that: firms maximize their profits, scientists maximize their expected profits, labor and input markets clear, and environmental quality evolves according to equation (6). We recall that the laissez-faire equilibrium occurs when no environmental policies are in place.

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Now, let us assume that the productivity of the green sector is sufficiently lower than the one of the dirty industry:

ASSUMPTION 1. $\frac{A_{c0}}{A_{d0}} < \min\left((1+\gamma\eta_c)^{-\frac{\varphi+1}{\varphi}}\left(\frac{\eta_c}{\eta_d}\right)^{\frac{1}{\varphi}},\ (1+\gamma\eta_d)^{\frac{\varphi+1}{\varphi}}\left(\frac{\eta_c}{\eta_d}\right)^{\frac{1}{\varphi}}\right)$,

with $\varphi \equiv (1-\alpha)(1-\epsilon)$. Assumption 1 will hold throughout the rest of the paper. If $\epsilon > 1$, innovation occurs only in the dirty sector and the long-run growth rate of dirty inputs is $\gamma\eta_d$. If $\epsilon < 1$, innovation happens first in the clean sector, then it will occur also in the fossil fuel one, and the long-run growth rate of dirty inputs will be $(\eta_d\eta_c)/(\eta_d+\eta_c) < \eta_d$. If Assumption 1 holds and $\epsilon > 1$, the laissez-faire allocation will always produce an environmental disaster, that is, $S_t = 0$ for some t [Acemoglu et al. (2012)].

Note that the direction of technical change is determined by the incentives scientists face when they decide to conduct their research in the clean or dirty sector. More specifically, the relative benefit from undertaking research in sector c rather than in sector d is expressed by the ratio:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}\frac{L_{ct}}{L_{dt}}\frac{A_{ct-1}}{A_{dt-1}}. \tag{7}$$

Equation (7) reveals that the relative profitability of research in the two sectors can be decomposed in three components which capture productivity differentials (A_{ct-1}/A_{dt-1}), relative prices $((p_{ct}/p_{dt})^{\frac{1}{1-\alpha}})$, and market size (L_{ct}/L_{dt}). Finally, the equilibrium demand of the two inputs is determined by

$$Y_c = \left(A_c^{\varphi} + A_d^{\varphi}\right)^{-\frac{\alpha+\varphi}{\varphi}} A_c^{\alpha+\varphi} A_d, \tag{8}$$

$$Y_d = \left(A_c^{\varphi} + A_d^{\varphi}\right)^{-\frac{\alpha+\varphi}{\varphi}} A_d^{\alpha+\varphi} A_c, \tag{9}$$

whose evolution over time depends on the sectoral allocation of scientists [cf. equation (7)] and on the stochastic process characterizing the dynamics of machines' productivity.

4.2. M-B Environmental Policies

In the model, an M-B environmental policy is composed of a carbon tax and a subsidy toward clean research proportional to firms' profits. When the two inputs Y_c and Y_d are substitutes ($\epsilon > 1$) and the economy is initially stuck in the *bad* laissez-faire equilibrium, the social planner can redirect technical change toward the green technology introducing a carbon tax t_d on the production of dirty inputs and a public subsidy q_c supporting the research in the clean sector.[8] Both the carbon tax and the R&D subsidy can be introduced at any time $t = T$, with the obvious consequence that a delayed introduction might imply a stronger intervention. Throughout the paper we assume that (i) after introduction, the strength of the policy is constant (i.e., tax and subsidy levels do not vary over time)[9] and

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(ii) subsidies have to be finite and the carbon tax, expressed as a percentage of the price of dirty inputs, must be lower than one. In particular $t_{dt} < p_{dt}$ and $q_{ct} < +\infty$. Notice that if such assumptions do not hold, the model collapses to a degenerate case of a one-sector economy where the issue of directed technical change loose its rationale. For the sake of consistency, a similar assumption will be introduced for the case of C&C policies.

REMARK 1. We stress that M-B policies considered in this section directly affect the expected profitability of conducting research in either of the two sectors. In particular, t_{dt} reduces the proceedings from sales of dirty inputs that scientists conducting research in the dirty sector might expect. Solving the profit maximization problem for firms in the dirty sector at the time of policy intervention $t = T$ yields

$$\Pi_{dT} = \eta_d(1+\gamma)(1-\alpha)\big(p_{dT} - t_{dT}\big)^{\frac{1}{1-\alpha}} L_{dT} A_{dT-1}. \tag{10}$$

It follows that increasing t_{dT} implies—ceteris paribus—lower expected profitability from the dirty sector and that $t_{dT} = p_{dT}$ would make such sector completely unprofitable.

However, the direction of technical change is not only dependent on policy variables (t_{dt} and q_{ct}). In fact, the past history of innovations, which in turns determines the relative productivity of the clean and dirty sectors and the profitability of performing research therein, plays a fundamental role. As a consequence, given the importance of path dependence [Aghion et al. (2016)], even if carbon taxes and subsidies might affect the direction of technical change, they have a bounded time interval to push the economy away from a bad, carbon-intensive equilibrium.

PROPOSITION 1. *Assume $\epsilon > 1$ and that Assumption 1 holds. Assume that a government is considering the implementation of an M-B policy scheme, (q_{ct}, t_{dt}), composed of a finite subsidy q_{ct} for the clean sector and a carbon tax t_{dt} on the production of dirty inputs lower than their unitary price, $t_{dt} < p_{dt}$, both to be introduced at time $t = T$. Then, there exists a finite $\bar{A}_d > 0$ s.t. $\forall A_{dt} > \bar{A}_d$*

(i) (q_{cT}, t_{dT}) is ineffective in re-directing technical change toward the clean sector,
(ii) the unique equilibrium allocation of scientists is $s_{dt} = 1$ and $s_{ct} = 0$ for any $t > 0$.

Proof. See Appendix A.1. in Supplementary Material. ■

Proposition 1 shows that given M-B environmental policies fail whenever the productivity differentials between the dirty and clean sectors are sufficiently large. The intuition behind such a result is that once the relative productivity advantage of dirty technology is large enough, it will always compensate the cost of the carbon tax and the benefit of the subsidy. This happens because the policy scheme affects the relative profitability of clean technologies only via the market size

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effect. Accordingly, potential entrepreneurs will maximize expected profits by investing in the carbon-intensive sector, thereby undermining the effectiveness of the carbon tax.

REMARK 2. Formally, the M-B policy shifts the economy toward a good equilibrium ($s_{ct} = 1$ and $s_{dt} = 0$) whenever the following condition is satisfied:

$$(1 + q_{cT})\frac{\eta_c}{\eta_d}\left(\frac{p_{dT} - t_{dT}}{p_{dT}}\right)^{-\epsilon}(1 + \gamma\eta_d)^{\varphi+1}\left(\frac{A_{cT-1}}{A_{dT-1}}\right)^{-\varphi} > 1,$$

where T is the time step the policy is introduced in (details in Appendix A.1. in Supplementary Material). Crucially, such condition depends on A_{dT-1}, which embodies the past history of innovations, that is, the dynamics of A_{dt} for $t = 1, \ldots, T-1$. Further, Assumption 1 implies that A_{dt} increases (on average) over time, while A_{ct} remains constant. We will see in the next section that, conversely, a C&C policy is immune from such a path-dependent effect.

The next proposition states that process of technical change will push, sooner or later, the productivity of dirty machine beyond any threshold $\bar{A}_d$ with certainty.

PROPOSITION 2. *Assume that $\epsilon > 1$ and that Assumption 1 holds. Then, it exits a time step $t = T^*$ such that $A_{dT^*} > \bar{A}_d$ for any $\bar{A}_d \geq A_{d0}$.*

Proof. See Appendix A.2. in Supplementary Material. ■

The main consequence of Proposition 2 is that the timing of the introduction of M-B environmental policies is crucial. If the economy is stuck in the bad equilibrium ($s_d = 1$), then there exists a bounded window opportunity for policy scheme (q_{ct}, t_{dt}) to be effective. More precisely, the window opportunity for an M-B policy introduced at time T lasts $\left[\log\left(\frac{\bar{A}_d}{A_{dT}}\right)\right]/[\log(1 + \eta_d\gamma)]$ periods.

REMARK 3. Given the evolution of the quality of the environment [equation (6)], a too much delayed policy intervention inevitably leads to an environmental disaster. Indeed, as the economy is stuck in a bad equilibrium ($s_d = 1$), Y_{dt} increases at a rate of $\gamma\eta_d$, static M-B policies become ineffective, and S_t reaches zero in finite time, thereby producing a disaster.

REMARK 4. The higher the elasticity of substitution between the two inputs (ϵ), the shorter the time window in which M-B policies are effective.

The intuition underlying the last remark is straightforward. If the elasticity of substitution of clean and dirty inputs increases, producers will have higher incentives to switch toward the cheaper dirty ones, creating additional demand for these inputs. Accordingly, the relative profitability of dirty inputs increases, reducing the threshold $\bar{A}_d$ above which policy interventions are ineffective.

Carbon taxes are a meaningful tool for emission control policy. At the same time, Propositions 1 and 2 show that, when markets are competitive and dirty and clean inputs are substitutes, their effectiveness cannot be guaranteed a priori.

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TABLE 1. Minimum carbon taxes to redirect technical change and corresponding window of opportunities (in parenthesis) under different policy schemes

Backwardness of clean technologies	Expected productivity growth	Subsidy (proportion of clean sector' profits)		
		20%	10%	5%
Low (70% of dirty)	Low	19.0% (118)	20.4% (117)	20.0% (117)
Medium (50% of dirty)		33.8% (106)	34.4% (105)	34.7% (105)
High (20% of dirty)		61.8% (76)	62.1% (75)	62.3% (75)
Low (70% of dirty)	High	21.6% (36)	22.3% (36)	22.6% (36)
Medium (50% of dirty)		35.9% (33)	36.5% (32)	36.8% (32)
High (20% of dirty)		63.0% (23)	63.3% (22)	63.5% (22)
Low (70% of dirty)	Asymmetric	30.5% (33)	31.1% (33)	31.4% (33)
Medium (50% of dirty)		43.2% (30)	43.7% (30)	43.9% (30)
High (20% of dirty)		67.2% (20)	67.5% (20)	67.6% (20)

Notes: Low, medium, and high expected productivity growth correspond to an average growth rate of machines' productivity of 1%, 3%, and 8%, respectively. With asymmetric expected productivity growth, they correspond to 8% for dirty technologies and 3% for clean ones. The minimum carbon tax is computed until it reaches 99%.

The productivity gap between carbon-intensive and green technologies becomes crucial for the success of M-B environmental policies. In addition, such a gap widens over time due to the sub-martingale nature of machines' productivity (cf. proof of Proposition 2), implying that—for given policy schemes (q_c, t_d)—delayed interventions are likely to be ineffective. However, when the government is allowed to fix the tax rate as close to 100% as it wants, a sufficiently high tax can redirect technical change as well.

Table 1 collects results from numerical experiments that support these claims. It considers different scenarios defined by the expected productivity growth, initial relative backwardness of clean technologies, and the size of the subsidy. In many cases, the window of opportunity for M-B policy lasts very few periods, and the carbon tax needed to redirect technical change is extremely high. For example, when the productivity of clean technologies is initially half of the dirty ones and the expected productivity growth is high, the carbon tax required to move the economy toward the "green" equilibrium is above 35% and it has to be introduced within 30 periods. With even stronger backwardness of clean technologies, the minimum tax would correspond to 61% of dirty sector's revenues and the window of opportunity reduces to about 20 periods.

A further insight on the potential shortness of M-B's effectiveness period is provided by Figure 1. Numerical simulations of the model under different technological regimes (corresponding to the technological opportunities in the two sectors) allow illustrating the dynamics of productivities that, in turn, determine the magnitude of the minimum carbon tax necessary to put the economy on a "green" development path. Simulation results show that, in many circumstances, the minimum tax rate rapidly approaches the unit, becoming ineffective as a

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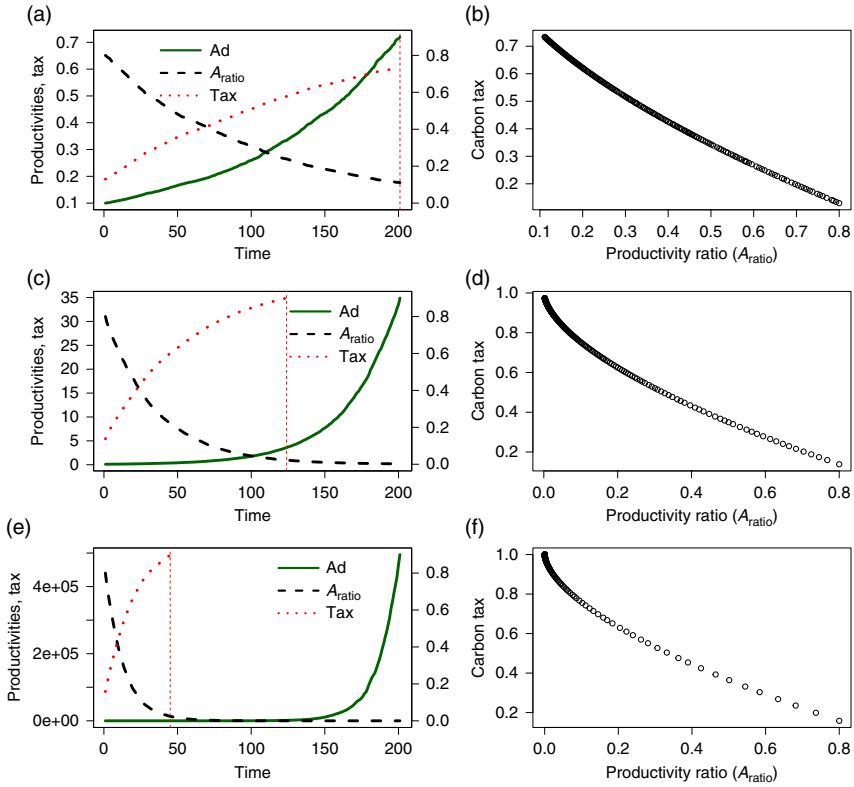

Notes: Figures on the left column (a),(c),(e) show the Monte Carlo average dynamics of productivities (left vertical axis) and minimum carbon tax (left vertical axis) to redirect technical change obtained across 100 independent runs; figures on the right column (b),(d),(f) show the relationship between average carbon taxes and the ratio between clean and dirty sector productivity, each point represents a period. The minimum tax rate is reported until it reaches 99%. Each row of figures is characterized by different technological regimes: low (a),(b) corresponds to an average productivity growth of 1%, medium (c),(d) corresponds to an average productivity growth of 3%, high (e),(f) corresponds to an average productivity growth of 8%. All simulations are obtained setting $\epsilon = 10$, $\alpha = 1/3$, and initial the initial productivity ratio $A_{c0}/A_{d0} = 0.8$.

FIGURE 1. Window opportunities, minimum carbon tax, and productivities under different technological regimes. (a) $\eta_d = 0.1$, $\gamma = 0.1$. (b) $\eta_d = 0.1$, $\gamma = 0.1$. (c) $\eta_d = 0.3$, $\gamma = 0.1$. (d) $\eta_d = 0.3$, $\gamma = 0.1$. (e) $\eta_d = 0.4$, $\gamma = 0.2$. (f) $\eta_d = 0.4$, $\gamma = 0.2$.

policy instrument. Such evidences are partially confirmed when a gradual carbon tax is considered, which is a quite diffused practice in the literature [see, e.g., Stern (2007)].[10] Numerical simulations summarized in Figure 2 show that when technological change is relatively slow and the productivity ratio of clean to dirty technologies declines gradually, a sharply increasing carbon tax might be sufficient to redirect technical change [see panel (b)]. However, under either too gradual carbon taxation [panel (a)] or sustained technological change [panels (c)

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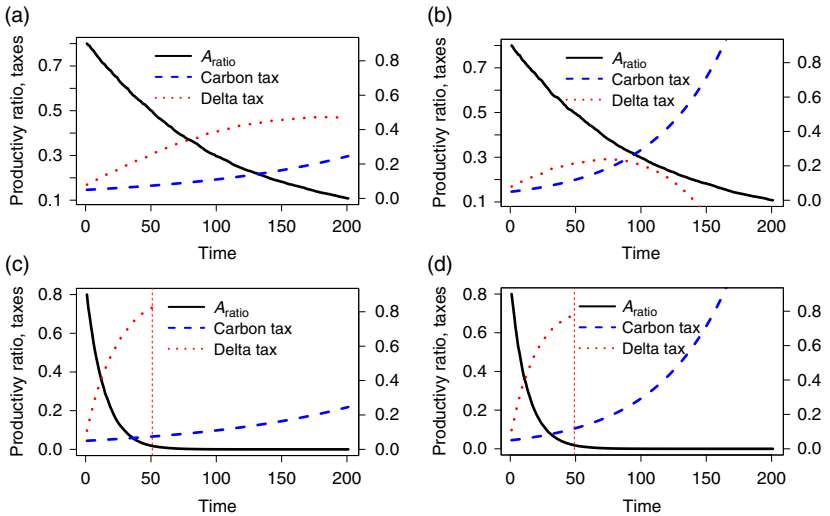

Notes: Figures show the Monte Carlo average dynamics of productivity ratio (left vertical axis), gradually increasing carbon tax, and minimum additional policy strength (delta tax; right vertical axis) to redirect technical change obtained across 100 independent runs. The additional tax is reported until the overall tax rate reaches 99%. Each row of figures is characterized by different technological regimes: low (a),(b) corresponds to an average productivity growth of 1%, high (e),(f) corresponds to an average productivity growth of 8%. All simulations are obtained setting $\epsilon = 10$, $\alpha = 1/3$, and the initial productivity ratio $A_{c0}/A_{d0} = 0.8$. Moderately increasing carbon tax grows at a rate of 0.8% per period; rapidly increasing carbon tax grows at a rate of 1.8% per period. The initial level of the carbon tax is 5%.

FIGURE 2. Window opportunities, minimum carbon tax, and productivities under different technological regimes. (a) $\eta_d = 0.1$, $\gamma = 0.1$ and moderately increasing carbon tax. (b) $\eta_d = 0.1$, $\gamma = 0.1$ and rapidly increasing carbon tax. (c) $\eta_d = 0.4$, $\gamma = 0.2$ and moderately increasing carbon tax. (d) $\eta_d = 0.4$, $\gamma = 0.2$ and rapidly increasing carbon tax.

and (d)], the behavior of the windows of opportunity (indicated by the red dashed vertical line) is almost identical to the case of abrupt, one-shot policy intervention (Figure 1).

Given such dismal results, are there alternative policy interventions that redirect technical change toward the green sector, thus preventing climate catastrophes, without suffering from path dependence? In the next section, we will show that such objectives can be achieved by appropriate C&C policies.

4.3. C&C Policies

A C&C policy refers to an environmental intervention that relies on regulation (permission, prohibition, standard setting, and enforcement) as opposed to monetary incentives, i.e., economic instruments of cost internalization [UN (1997)]. In particular, we consider a policy that establishes the maximum amount

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κ of dirty inputs that can be used for each unit of clean ones. Further, we assume that, after its introduction, such a policy does vary over time[11]:

$$\frac{Y_{ct}}{Y_{dt}} \geq \kappa, \quad \forall t > T, \tag{11}$$

where $\kappa \in (0; +\infty)$ represents the C&C policy chosen by the government and introduced at any time $t = T$. We underline that our assumption requiring κ to be finite and strictly positive is, in comparative terms, equivalent to the requirement we made on t_d in Section 4.2; both assumptions are introduced to prevent the trivial case where the market for dirty inputs is not profitable and, thus, economically viable. Given Assumption 1, as in the laissez-faire equilibrium, innovations start in the more productive dirty sector. Moreover, if $\epsilon > 1$ and given equations (8) and (9), C&C policies [cf. equation (11)] will be binding in equilibrium. In the laissez-fair case, dirty (Y_{dt}) and clean (Y_{ct}) inputs are employed competitively by final good producers, which maximize their profits according to:

$$\max_{Y_{ct}, Y_{dt}} \{p_t Y_t - p_{ct} Y_{ct} - p_{dt} Y_{dt}\} \quad s.t. \quad Y_t = \left(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}. \tag{12}$$

Assuming that the C&C policy is introduced as a constraint on final good producers, first-order conditions imply

$$\frac{Y_{ct}}{Y_{dt}} \neq \left(\frac{p_{ct}}{p_{dt}} \right)^{-\epsilon}, \tag{13}$$

due to the presence of the policy. However, as in the laissez-faire equilibrium, relative prices are determined by relative productivity of dirty and clean technologies:

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{A_{ct}}{A_{dt}} \right)^{-\frac{1}{1-\alpha}}. \tag{14}$$

Furthermore, as dirty inputs are relatively cheaper, equation (11) binds and it is possible to express the relative employment in the clean sector as

$$\frac{L_{ct}}{L_{dt}} = \frac{Y_{ct}}{Y_{dt}} \left(\frac{p_{ct}}{p_{dt}} \right)^{-\frac{\alpha}{1-\alpha}} \left(\frac{A_{ct}}{A_{dt}} \right)^{-1} = \kappa \left(\frac{A_{ct}}{A_{dt}} \right)^{-(1-\alpha)}. \tag{15}$$

Equation (15) shows that whenever the relative demand of dirty inputs is constrained by the C&C policy, any productivity gain in the carbon intensive sector is labor destroying. Indeed, since firms cannot expand production, any increases in machine productivity will increase profits by reducing the number of employees needed for production. The profitability ratio of conducting research in the two sectors then becomes

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$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}} \frac{L_{ct}}{L_{dt}}\frac{A_{ct-1}}{A_{dt-1}} \tag{16}$$

$$= \frac{\eta_c}{\eta_d}\kappa\left(\frac{A_{ct}}{A_{dt}}\right)^{-(1-\alpha)}\frac{A_{ct-1}}{A_{dt-1}} = \frac{\eta_c}{\eta_d}\kappa\left(\frac{1+\eta_c s_{ct}}{1+\eta_d s_{dt}}\right)^{-(2-\alpha)}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{-(1-\alpha)},$$

where the second equality follows combining equations (7), (13) and (15), and the third one is obtained via equation (5). It follows that under a C&C policy the equilibrium expected profitability of the two sectors depends upon the productivity of currently available machines, but with an opposite effect of the policy with respect to the laissez-faire and M-B cases. In particular, the relative profitability of the green sector increases with the productivity of dirty technologies thanks to the market size effect incorporated in equation (15). We can now state the following proposition.

PROPOSITION 3. *Consider a C&C policy κ. If $\epsilon > 1$, then there exists a finite $\bar{\kappa} > 0$ such that any $\kappa \geq \bar{\kappa}$ always redirects technical change toward the green sector.*

Proof. See Appendix A.3. in Supplementary Material. ■

The main intuition behind Proposition 3 is that any C&C policy sufficiently limiting the relative share of dirty inputs creates an additional demand for clean ones, thus increasing the profitability of the green sector. Further, in presence of C&C policies, and in contrast to M-B interventions, innovations in the dirty sector are increasingly labor destroying and reduce the relative profitability of the industry. As a consequence, the minimum C&C policy needed to redirect technical change shrinks over time, as indicated by equation (16). The foregoing results are also robust to the case where the C&C constraint hits producers of dirty inputs rather than final good ones.[12]

If a suitable policy is implemented, technical change moves toward a development path where innovations occur only in the clean sector. Moreover, once the new equilibrium is achieved, the economy behaves as in the "good" laissez faire scenario, where output Y_t and use of clean inputs Y_{ct} grow at the long-run rate $\gamma\eta_c$ [see equations (8), (9), and (4) and recall that A_{ct} grows at a rate of $\gamma\eta_c$ while A_{dt} remains constant].

REMARK 5. A *temporary* C&C policy intervention κ is sufficient to redirect technical change permanently.

Sooner or later, any strength of the C&C policy becomes effective. When the economy moves toward a "good" equilibrium, Y_{ct} grows faster than Y_d, as the clean sector is more profitable than the dirty one, thus increasing the ratio Y_{ct}/Y_{dt}. The C&C policy sustains the improvement of machines' productivity in the clean sector, thereby increasing the ratio A_{ct}/A_{dt}. When such ratio becomes sufficiently high, the C&C policy is not needed anymore as research is spontaneously performed only in the clean sector.

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Given the results in Acemoglu et al. (2012) and using equations (8) and (9), one can conclude that when all scientists are allocated to the clean sector ($s_{ct} = 1$), the production of dirty inputs (Y_{dt}) grows at a rate $(1 + \gamma\eta_c)^{\alpha+\gamma} - 1 > 0$ if the two inputs are weak substitutes [i.e., $1 < \epsilon < 1/(1-\alpha)$]. In contrast, when inputs are strong substitutes [$\epsilon > 1/(1-\alpha)$], Y_{dt} behaves in the long run as $A_{ct}^{\alpha+\varphi}$, which in turns decreases over time.

These considerations, coupled with findings of Section 4.2, lead to the central results of the paper, which are collected in the following theorem.

THEOREM. *Assume that a government is planning the introduction of an environmental policy aimed at inducing a green transition. If $\epsilon > 1$, path dependence in technological change*

1. *favors the effectiveness of a C&C policy κ,*
2. *hinders the effectiveness of a M-B policy (q_c, t_d).*

The history of innovations makes it dynamically easier to induce an equilibrium where all scientist conduct research on clean technologies via a C&C policy fixing the maximum usable amount of dirty inputs for each unit of clean ones; to the contrary, an M-B intervention (made up of combinations of taxes and subsidies) must be increasingly stronger as technological change gradually takes place. As a consequence, any given M-B policy can be ineffective in promoting the transition if sufficiently delayed, while the likelihood of success of a C&C intervention increases with the speed of technological change. Obviously, when the government is allowed to fix the tax rate as close to 100% as it wants, a sufficiently high tax can redirect technical change as well.

The above results imply that appropriate climate policies are able to prevent environmental catastrophes under the assumption that dirty and clean inputs are strong substitutes. More precisely, C&C policies are always successful in avoiding S_t to reach zero, whereas M-B solutions are effective only if they are implemented at the right time. If inputs are weak substitutes instead, final good production requires increasing amount of dirty inputs which cannot be replaced by clean ones, even though the productivity of dirty machines keeps constant. As a result, an environmental disaster looks inevitable.

Given such a gloomy perspective, is there an environmental policy that works even if clean and dirty inputs are weak substitutes? The next proposition provides a positive answer.

PROPOSITION 4. *Let $\hat{\kappa}$ be a C&C policy imposing a fixed ceiling on the use of dirty inputs Y_{dt} such that $Y_{dt} \leq \hat{\kappa}$ and assume $\epsilon > 1$. Then, there exists a finite $\hat{\kappa}' > 0$ such that $\forall\, \hat{\kappa} \in (0, \hat{\kappa}')$ the policy always redirects technical change toward the green sector and prevents an environmental disaster.*

Proof. See Appendix A.4. in Supplementary Material. ■

The claim follows straightforwardly from Proposition 3 and equation (6).[13] A fixed-ceiling C&C policy is always effective, even when inputs weak

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TABLE 2. Policy intervention and guaranteed results

	Redirection of technical change		Prevention of environmental disaster	
	Weak substitutes	Strong substitutes	Weak substitutes	Strong substitutes
M-B				
Taxes	Window only	Window only	No	Window only
Subsidies	Window only	Window only	No	Window only
Taxes and subsidies	Window only	Window only	No	Window only
Optimal policy	Window only	Window only	No	Window only
C&C				
Relative share	Yes	Yes	No	Yes
Absolute limit	Yes	Yes	Yes	Yes

Notes: By optimal policy we mean the combination of taxes and subsidies derived in Acemoglu et al. (2012).

substitutes, whereas in Acemoglu et al. (2012) disasters can be avoided only by switching off economic growth.

The results obtained from our policy exercises are summarized in Table 2. Only a C&C policy fixing the maximal amount of dirty inputs in the economy is always able to guarantee both technical change redirection and avoidance of environmental disasters. Marked-based solutions are effective only within their limited window of opportunity but, in general, they fail to guarantee disasters' prevention.

The lack of symmetry between the effects produced by the two types of policy instruments is attributable to the role of path dependence in technical change. In the laissez-faire and M-B cases, innovation has a self-perpetuating nature grounded on its own past success. This makes the transition to a clean equilibrium more and more difficult over time. On the contrary, in the C&C scenario, the labor-destroying effect of innovation [see equation (15)] either compensates (when the constraint is imposed on input producers) or overcomes (in case the constraint is imposed on final good producers) the direct productivity effect.[14] An interesting future development of the current framework will be the introduction of aggregate uncertainties on disasters and technological progress á la Weitzman (1974) to study the joint effects of path-dependent innovation processes and the presence of uncertainty in a growth model characterized by directed technical change.

5. CONCLUSIONS

In this work we have compared the impact of environmental M-B policies with C&C ones in a model with endogenous growth and directed technical change. M-B policies are grounded on a carbon tax and a subsidy to the green sector,

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whereas C&C interventions fix limits to the production of dirty inputs and related greenhouse gas emissions.

We find that M-B policies are not always successful to redirect technical change from the dirty to the green sector. Given the cumulativeness of technical change [Aghion et al. (2016)], time is fundamental and a green transition can be triggered only in a limited window of opportunity. In particular, if the productivity gap between the dirty and green sectors becomes too high, M-B policies become ineffective. The time for an effective intervention gets shorter if the two inputs are "weak" substitutes. In the latter case, M-B policies are never able to prevent environmental catastrophes. On the contrary, if the dirty and green inputs are "strong" substitutes, *timely* M-B interventions can successfully avoid the occurrence of disasters.

C&C policies are more effective than M-B interventions. This result arises because M-B policies work only via a market size channel (larger input sector stimulates innovation), whereas C&C interventions also affect relative prices and are favored (or unaffected) by the productivity gap between dirty and green technologies [cf. equation (7)]. This explains why the evolution of the technologies contributes to the success of C&C policies, which are also *always* effective in preventing environmental disasters when inputs are strong substitutes. If the dirty and green inputs are weak substitutes, the only environmental policy that guarantees avoiding a climate catastrophe is a C&C intervention fixing an absolute limit on the use of polluting inputs.

Despite its simplicity, our work delivers clear-cut insights on the effectiveness and flexibility of policy intervention. In particular, our findings support the current behavior of governments, which are timid in introducing carbon pricing, and rely instead on regulations that redirect investment toward clean capital, such as stricter energy efficiency standards on new capital and buildings [IEA (2016)]. Beyond sustaining the transition toward clean technologies, such regulatory measures are effective in preventing the occurrence of environmental disasters by directly imposing physical limits on polluting substances. In addition, recent empirical evidence shows that environmental regulation has a pivotal role from an international perspective, as it helps prevent "pollution havens" [Jobert et al. (2018)]. For these reasons, we also believe quantity-based environmental policy should receive much larger attention in the economic literature that, to the contrary, tends focusing on the analysis of price-based mechanisms. As a future work, the model could be extended to account for the political-economy processes involved in the design of climate-change policies and to incorporate an international dimension and aggregate uncertainty in the process of technical change.

SUPPLEMENTARY MATERIAL

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NOTES

1. This paper is not the only contribution recently investigating the effectiveness of environmental policy in relation to economic factors beyond uncertainty [Weitzman (1974)]; for example, Constant and Davin (2018) evaluate the relationship between policy, education, and growth when green preferences are endogenous; while Palivos and Varvarigos (2017) focus on abatement policy and growth when environmental degradation comes with health-depressing effects. The present paper concentrates on the role of path-dependent technological change in shaping policy effectiveness.

2. Lamperti et al. (2018) use an agent-based integrated assessment model to show that, in general, M-B policies need to be remarkably strong to have an appreciable effect on the chances of a transition and, further, that climate shocks interact with the policy itself.

3. The works of Smulders and De Nooij (2003) and Popp (2004) are examples of earlier studies on directed technical change and environmental issues.

4. For an excellent review on technological change and the environment see also Popp et al. (2010).

5. The utility function is twice differentiable and jointly concave in C and S. Standard Inada-type conditions hold for C and S approaching zero and infinity. Therefore, households' utility considerably falls when environmental quality approaches zero. Further, if $S = \bar{S}$, additional increases of environmental quality do not lead to utility improvements.

6. In sectors where the innovation process is unsuccessful, a 1-year patent is randomly assigned to one of the producers using the old technology.

7. One could reasonably define CO_2 emissions as directly proportional to the use of dirty inputs: $Em_t \propto Y_{dt}$.

8. As in Acemoglu et al. (2012) we assume that the social planner has access to lump-sum taxes and transfers to complement and/or finance such policy measures.

9. We present a numerical exercise to show how the model behaves when removing such assumption. Results are robust. It is sufficient to consider the static (constant) policy equal to the maximum level of the dynamic one to obtain the same results as those described in the text.

10. The graduality of the carbon tax often stems from the combination of concave utility and convex damage functions.

11. The effects of such policy on the direction of technical change are equivalent to the ones of an absolute upper bound for the use of dirty inputs. We refer to the relative threshold per unit of clean inputs to simplify computations.

12. In such scenario, relative prices are determined by the relative demands of inputs, which resemble those of the laissez-faire equilibrium. Under a binding constraint, one gets $\Pi_{ct}/\Pi_{dt} = (\eta_c/\eta_d)\kappa^{\frac{\epsilon-1}{\epsilon}}\,[(1+\eta_c s_{ct})(1+\eta_d s_{dt})]^{-1}$, that is, the relative profitability does not depend on the past history of innovations. Hence, a sufficiently high (but finite) κ is enough to redirect technical change avoiding path dependence. Formally, the C&C policy shifts the economy toward a good equilibrium ($s_{ct} = 1$ and $s_{dt} = 0$) whenever the following condition is satisfied: $(\eta_c/\eta_d)\kappa_T^{\frac{\epsilon-1}{\epsilon}}\,(1+\eta_c\gamma)^{-1} > 1$, where T is the time step the policy is introduced. Such condition does not depend on past relative productivities.

13. The maximum Y_{dt} allowed by the regulation policy at time t must be below S_{t-1}/ξ in order to prevent the realization of an environmental disaster.

14. Also the use of a carbon tax equal to the price of dirty inputs would completely remove expected profits in that sector, triggering a complete shift toward the clean technology. However, we rule out such a trivial scenario, where the tax would completely erode the profitability of the dirty sector thereby leaving alive just the green one, by assumption. Further, we claim that such a choice can be justified through political economy arguments [see also Goulder and Parry (2008), on the generally low political workability of carbon taxes].

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