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Global Warming and Endogenous Technological Change: Revisiting the Green Paradox

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Abstract

How to control and limit climate change caused by a growing use of fossil fuels are among the most pressing policy challenges facing the world today. The green paradox argues that carbon taxes can exacerbate global warming problem because firms have the incentive to bring forward the sale of fossil fuels. This paper shows that when technological progress allows the extraction costs of fossil fuels to be reduced over time, and a positive R&D subsidy is paid, a growing carbon tax reveals a welfare maximizing policy.

Keywords: Global warming, Carbon taxes, Technological change.

JEL classification: O13, O30, Q54, H23

1 Introduction

One of the major policy issues economies have to face in the present and in the next years concerns how to limit and control global warming, at the same time preserving or improving people's well-being. This global negative externality is generated by the use of fossil fuels that generate CO₂ emissions, and therefore both timing and costs of fossil fuels extraction represent key issues for environmental policy. Indeed, as underlined by Sinclair (1992) "the key decision of those lucky enough to own oil-wells is not so much how much to produce as when to extract it."¹

In the light of the above, normative and positive aspects exist which center on the question as to what extent market failures such as global warming distort the extraction path relative to the optimum and which policy instruments could possibly remedy them. In answering this problem, Sinn (2007, 2008) argues that an increasing tax rate on CO₂ emissions can exacerbate global warming in the present because profit maximizing resource owners have the incentive to bring

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¹See, among others, Gerlagh (2010), Van der Ploeg and Withagen (2010), Paltsev et al.'s report (2009), Sinn (2008) for a more detailed discussion about global warming and the economic damages such an environmental issue generates.

forward the extraction and sale of fossil fuels compared to the normative optimal extraction path. This result, named the green paradox, is obtained assuming perfectly competitive markets in the resource sector, and adopting the principle of Pareto optimality as a measure of people's well-being.

With a utilitarian approach recent contributions on the green paradox explicitly consider clean energy sources and mixed results have been found. Hoel (2008) shows that CO₂ emissions may increase also as a consequence of an immediate and once and for all downward shift in the cost of producing a substitute (see also Strand, 2007). Gerlagh (2010) shows that with imperfect CO₂ pricing policies, lower costs for non-carbon energy sources imperfectly substitutable with traditional fossil fuels decreases cumulative fossil fuel use in the long run and may also decrease its current demand. Van der Ploeg and Withagen (2010) show that the green paradox does not arise if clean energy in infinite supply (backstop) is sufficiently cheap relative to the cost of extracting fossil fuels plus marginal CO₂ emission damages because it is optimal to leave some stock of fossil fuels in the ground. Gerlagh et al. (2009) find that government should subsidize private R&D efforts aimed at developing CO₂ emission reducing technologies when climate specific R&D targeting instruments are available, and if government cannot directly determine the development of carbon dioxide emissions, numerical analysis suggests a higher tax on CO₂ than in the former case.²

Differently from the existing literature, and in the same spirit of Sinn's (2007, 2008) contributions, this paper adopts the principle of Pareto optimality, and it explicitly considers endogenous technological progress jointly with global warming externality in evaluating the optimal environmental tax policy. It is found that a positive and increasing subsidy to R&D expenditures, aimed at improving the extraction technology of fossil fuels, allows higher profit flows over time to be expected by the resource owner. In particular, the negative effect of a pro-environmental policy on the expected profit flows raised by the green paradox is more than offset by an increasing subsidy paid for the R&D expenditures aimed at reducing extraction costs over time. This in turn induces the resource owner to postpone extraction over time, and global warming is mitigated in the present. Moreover, it is found that when the demand for traditional fossil fuels is not isoelastic, it is optimal to leave some of the fossil fuel reserves in situ, both from a positive and normative point of view. These results hold with either perfect or imperfect competition in the resource sector. As this paper more closely follows Sinn (2007, 2008) using a pure Pareto optimality principle rather than a utilitarian approach to welfare, it is a complementary analysis to existing literature on the green paradox cited above.

The rest of the paper is organized as follows. Section 2 sets up the basic structure of both arguments and model. Section 3 derives the main policy results. Section 4 draws conclusions.

²The authors adopt an expanding variety R&D-driven growth model, while this paper considers a creative destruction argument. See Gerlagh et al. (2009) for a literature review on a pure R&D approach to climate change and technological progress. See, among others, Hoel (2010), Van der Ploeg and Withagen (2010) for a literature review on the green paradox.

2 The Model Set-up

In describing the economic framework, and differently from Sinn (2007, 2008) who mainly focuses on carbon demand reducing policies, this paper considers endogenous R&D effort aimed at improving fossil fuels extraction technology. Let us consider an unbounded horizon economy, with index time t being a continuous variable, endowed with an exhaustible stock S of fossil fuel resources. Global warming is assumed to be a monotonically increasing function of the stock of CO2 in the air, and such a stock is assumed to be a monotonically increasing function of stock emitted, which is proportional to the stock of carbon extracted. In this framework, global warming is seen as a technological problem that creates a waste of output for protection and reaction costs, such as the necessary preventing and repairing activities due to the damages it generates. In this way, the quality of the environment, in the sense of more resources in situ and therefore lower cumulated CO2 emissions, is seen as an argument of the aggregate production function, and the damages global warming generates are measured in terms of lost output remaining for consumption.³ To get the basic arguments from a general point of view, let the final output Y at any time t be produced according to a production function with the standard neo-classical properties, i.e. $Y = F(R, S, A)$, where $R = -\dot{S} \equiv \frac{\partial S}{\partial t}$ is the flow of fossil resources extraction, S is the stock of fossil fuels, and A represents the technological level, with constant returns to scale preserved also including technological progress.⁴ The resources in situ S capture the environmental quality in the sense of CO2 being absent from the air. In particular, the higher S is, the lower cumulated CO2 emissions are, and the higher people's well-being represented by higher output remaining consumption is. The production function $F(\cdot)$ is defined net of the cost of saving energy or generating it from non-fossil sources, and the technology level A does not include technologies directed at improving environmental quality, and/or the productivity of non-fossil fuels.

Sinn (2008) shows that whenever the environmentalist concerns become more and more popular, the resource owner expects an increasing tax rate on CO2 emissions, and hence she also expects lower and lower profit flows over time. In this way, a steeper fossil fuels extraction path rather than a flatter one reveals to be the optimal path, and global warming is exacerbated rather than mitigated in the present.⁵

This paper shows that when technological change is the result of purposeful

³See the Stern report (2006), and Kamien and Schwartz (1982). A similar approach is also adopted by Brock and Taylor (2010).

⁴The usual neoclassical properties of the production function are assumed, i.e. $F_R \equiv \frac{\partial F(\cdot)}{\partial R} > 0$, $F_{RR} < 0$, $F_S > 0$, $F_{SS} < 0$. As in Sinn (2007, 2008) man-made capital could be considered in the production function and in the analysis without altering any qualitative result and policy implication, and it is excluded for the sake of notational simplicity. I drop the time index as long as this causes no confusion.

⁵Such results refer to a cash-flow tax on the resource owner's profit flow. Sinn (2008) shows that the same results also hold for an ad-valorem tax rate whenever the extraction costs are absent, and for a high enough ad-valorem tax growth rate whenever extraction cost are not negligible.

investments in R&D rather than being represented as a simple exogenous time trend, the conclusions and the policy implications raised by the green paradox are reversed. In order to render the arguments of the paper comparable with the existing literature, let us use a simplified version of the neoclassical production function as the following:

$$F(S, R, A) = \varphi(R, t) + \psi(S) + \gamma(A), \quad (1)$$

with $\varphi_R > 0$, $\varphi_{RR} < 0$, $\psi_S > 0$, $\psi_{SS} < 0$. Here $\varphi(R, t)$ is the partial production function of carbon inputs, $\psi(S)$ denotes that part of the output that is not needed to compensate for the damages of global warming, $\gamma(A)$ is the technology level that positively affects the production function, with $\gamma_A > 0$.⁶ The partial derivatives of the production function with respect to resources in situ S imply positive and increasing marginal damage from cumulative resources extraction, in particular $\psi_S > 0$ denotes the flow of marginal damages from the extracted stock of carbon. Both perfect stock market and bonds with constant instantaneous certain net flows reward i are assumed to exist in this economy.

Let $P(R, t) = \varphi_R(R, t)$ denote the inverse demand function for carbon implied by this specification, with $P_R < 0$, and let $-\varepsilon = -(\partial R / \partial P)(P/R)$ be the price elasticity of demand, with ε being its absolute value. Due to the definition of the production function as given above, the shape of this demand function reflects the technological substitution possibilities for fossil fuels that would endogenously be activated by higher carbon prices.⁷

Finally, as output Y is defined net of the cost of saving energy or generating it from non-fossil (read non polluting) energy sources, final output can be used for consumption C , fossil fuels resource extraction $g(S, A_R)R$, where A_R represents the level of the extraction technology of fossil fuels, and R&D expenditures for the extraction technology $h(S)R$, i.e. $Y = C + g(S, A_R)R + Nh(S)R$, where N is the constant mass of firms investing in R&D to obtain a new extraction technology of fossil fuels.⁸ As in Sinn (2008), let us assume the unit extraction costs $g(S, A_R)$, the unit R&D expenditures $h(S)$, and the flow of marginal damages from the extracted stock of carbon $\psi(S)$ to be bounded from above as R and/or S go to zero. Let all functions of the model be differentiable and well

⁶Once technological progress is introduced in the analysis, productivity-adjusted consumption is considered and the same analysis and results as in Sinn (2007) are easily obtained. The term $\gamma(A)$ can be written as $\gamma(A)\chi_B(R)$, where χ is the indicator function, and $B = [\varkappa, S_0] \subseteq [0, S_0]$, with $\varkappa > 0$ and S_0 is the stock of fossil fuels at time zero. Therefore $\chi_B(R) = \begin{cases} 1 & \text{if } R > 0 \text{ (} R \in B \text{)} \\ 0 & \text{if } R = 0 \text{ (} R \notin B \text{)} \end{cases}$. This simply means that technological level alone, i.e. for $R = 0$, does not allow a positive output to be obtained in the economy. As this formulation is too cumbersome it is not indicated in the main text for the sake of notational simplicity.

⁷The fossil fuels demand reduction can come from more use of solar and wind energies, bio-fuels, better insulation of homes, more sophisticated energy efficient engines, etc. All these technical possibilities of reducing the demand for fossil fuels are costly, in the sense that they absorb parts of the economy's production capacity that otherwise would have been available for the production of consumption goods. See van der Ploeg and Withagen (2010) about the implications of this argument.

⁸The R&D expenditures for the general technology level A in the final output equation are not included to simplify exposition. The inclusion of such expenditures does not alter any qualitative result of the model.

defined for nonzero values of their arguments. Notice that $g(S, A_R)$ is both the average and marginal extraction cost function for a given level of the extraction technology A_R , which is assumed to be bounded above by $\bar{A} < \infty$. Moreover, $g_S(S, A_R) < 0$ is assumed because a higher stock of fossil fuels allows lower unit extraction costs, and $g_{A_R}(S, A_R) < 0$ holds because a better extraction technology allows lower unit extraction costs for any given level of R and S .

Under these specifications, Appendix A derives the essential properties of the extraction path in the R, S space that will be discussed below.

2.1 The Market Optimal Extraction Dynamic Path

Let us consider a resource owner who possesses a stock of the resources in situ S with different degrees of accessibility. In this framework the extraction technology of fossil fuels A_R evolves as a result of purposeful R&D expenditures. A firm j investing in R&D can produce a constant and instantaneous Poisson arrival rate of innovation $\alpha_j > 0$ by spending $V_j = h_j(S) R_j$ units of final output.⁹ The Poisson arrival rate of innovation of any firm j is a function of its research effort, i.e. $\alpha_j = \frac{R_j}{X}$, where X is a variable (function) that renders constant the Poisson arrival rate of innovation. In the case at hand X is assumed to be tied to total R&D effort, and in particular it is proportional to fossil fuel resources, i.e. $X = \eta R$ ($\eta > 0$) so that $\alpha_j = \frac{R_j}{\eta R}$.¹⁰ The firms investing in R&D are assumed to be symmetric, so that $h_j(S) = h(S)$ for any j .

In the light of the above, a resource owner investing in R&D with the aim to improve the extraction technology expects to gain at any time t the instantaneous rent flows $\alpha_j \Pi - h(S) R_j = \alpha_j [\Pi - h(S) \eta R]$, where $\Pi = PR - g(S, A_R) R$ are the instantaneous profit flows in the resource sector gained with an instantaneous probability α_j , and where $\alpha_j = \frac{R_j}{\eta R}$ has been used for the R&D costs specification on the right hand side of the equality, that are incurred with certainty (see Appendix B1).

This framework is compatible with both perfectly and imperfectly competitive markets. In particular, this set-up allows endogenous technological progress to be carried out in perfectly competitive economies as in Boldrin and Levine (2002). In this case the R&D expenditures V are interpreted as a flow sunk cost, which is assumed non-binding. The same set-up is compatible with Schumpeterian growth models, which admit some degree of market power in the economy (see e.g. Aghion and Howitt, 1992; Grossman and Helpman, 1991). In this strand of literature perfect competition is assumed in the R&D sector, and imperfect competition in the resource sector generated by a perfectly enforceable patent law allows strictly positive profit flows Π to be gained that serve either to

⁹It is assumed $h_{jS} \geq 0$ capturing the idea that the higher fossil fuels stock S is, the higher R&D average costs are because of lower technology level and spillovers.

¹⁰This specification for the variable (function) X is very close to Segerstrom (1998), and it is referred to as increasing complexity in R&D. The parameter $\eta > 0$ only represents a proportionality factor. This allows the strong scale effect on growth empirically rejected by Jones (1995) to be eliminated. The same result is obtained interpreting X as the final output. See Madsen (2008) for the empirical evidence.

incur R&D expenditures or to pay for the use of innovations. Such expenditures are here represented by the flow cost V . As long as perfect competition in R&D is assumed, both incumbent and outsider firms find it profitable to positively invest in R&D, and therefore the aggregate Poisson arrival rate of innovation α includes the R&D efforts of both incumbent and outsider firms (see e.g. Cozzi, 2007). In this framework, the interarrival time between two successful innovations is distributed according to an exponential distribution with parameter α , and the resource owner's instantaneous probability to keep its rent flows until the next innovation at any time t is $e^{-\alpha t}$.¹¹ It seems worth underlying that both the R&D costs V and the innovation rate α_j can be referred either to a pure R&D investment by a technological leader, such as a firm in a developed country, or to an imitation and adaptation investment of a technological laggard, such as a firm in a developing or less developed country.

As in Sinn (2008) we also consider insecure property rights within a setting that is as simple as possible. Let us suppose that a resource owner, like an oil sheik, has a constant and instantaneous probability $\pi > 0$ to be expropriated of his ownership. In this case, the probability of surviving as a fossil fuels resource owner at any time t is $e^{-\pi t}$. As the risk of being expropriated is a private, and not a social concern, it is only considered in the positive maximization problem.

Let us introduce government intervention due to the existence of environmental and knowledge externalities in the economy. Let τ^* be the cash flow tax rate on CO2 emissions, with $\theta^* \equiv 1 - \tau^*$ being the corresponding tax factor. Let us suppose that a cash flow tax factor θ^* changes at a constant rate $\hat{\theta}^* \equiv \frac{\dot{\theta}^*}{\theta^*}$ over time. An increasing cash flow tax rate implies a decreasing tax factor $\theta^*(t)$, i.e. $\hat{\theta}^* < 0$ whenever a more and more environmental policy is adopted economy-wide, and the cash flow tax factor at time t is $\theta^*(t) = \theta^*(0) e^{\hat{\theta}^* t}$, with $\theta^*(0) > 0$. In the light of all such elements, the effective discount factor of a resource owner who maximizes the expected cash flows from resources extraction at any time t is $e^{-(i+\pi+\alpha-\hat{\theta}^*)t}$.

Finally, let us suppose that government intervention in the economy also takes into account the firms' R&D effort aimed at improving the extraction technology. In particular, let government pay a R&D subsidy $\sigma \tau^* h(S) \eta R$, with $\sigma \in [0, \frac{1}{\tau^*}]$. When $\sigma = 0$ no R&D subsidy is paid, and when $\sigma = \frac{1}{\tau^*}$ the R&D expenditures are completely refunded back to the resource owner by the government (see Appendix B2).¹²

¹¹See Appendix B1. When R&D is only conducted by the incumbent firm as in Peretto (1998), the same qualitative results hold with the only modification of the effective discount factor for the resource owner profit flow which becomes $e^{\alpha t}$. A standard simplifying assumption in R&D-driven growth models is assuming the returns to R&D expenditures to be independently distributed across firms, across industries, and over time. In this way, the aggregate Poisson arrival rate of innovation is simply the summation of the firms' arrival rates. In this framework the aggregate Poisson arrival rate α could not be the summation of the firms' innovation rate, and it can represent more general aspects of the R&D activity in the economy.

¹²As usual the R&D subsidy can be represented with a parameter $\nu \in (0, 1)$. In this framework, the subsidy is rewritten as $\tau^* \sigma \equiv \nu$, with $\sigma \in [0, \frac{1}{\tau^*}]$ because $\nu \in (0, 1)$. In this way both the normative and positive optimal extraction dynamic paths can be easily

Considering the intertemporal cash flows maximization problem of the resource owner, the following market optimal dynamic extraction path in R, S space is obtained (see Appendix A1):

$$\frac{dR}{dS} = -\frac{\dot{R}}{R} = \varepsilon \left\{ \left(i + \pi - \hat{\theta}^* + \alpha \right) \left[1 - \frac{g(S, A_R)}{P} - \frac{(1 - \sigma \tau^*) h(S) \eta}{P} \right] + \frac{g_{A_R}(S, A_R) \dot{A}_R}{P} - \frac{\sigma \dot{\tau}^* h(S)}{P} \right\}. \quad (2)$$

Equation (2) shows that technological progress in the extraction of fossil fuels allows the optimal dynamic path chosen by the resource owner to be flatter, as evident from the term $g_{A_R}(S, A_R) \dot{A}_R$ (recall $g_{A_R}(S, A_R) < 0$). Moreover, from a policy point of view, equation (2) shows that a positive R&D subsidy ($\sigma > 0$) allows the optimal extraction path to be flatter than in the case of no R&D subsidy ($\sigma = 0$), and this effect becomes stronger when an increasing tax rate on CO2 emissions is adopted, i.e. for $\dot{\tau}^* > 0$. Indeed, an increasing subsidy allows the resource owner to expect higher and higher profit flows over time, and this allows the optimal dynamic extraction path to become flatter. Notice that when in-house innovation exists, and technological advances only come from the incumbent firm, the effective discount factor is higher, $(i + \pi - \hat{\theta}^* + \alpha) > (i + \pi - \hat{\theta}^* - \alpha)$, and the positive extraction path becomes flatter than an economy where innovations can be introduced by both incumbent and outsider firms. Yet, the same policy implications arise in any case, as will be proved in the next sections.

Finally, the optimal dynamic path described in equation (2) implies that the resource owner leaves some amount of fossil fuels strictly larger than zero in the ground whenever the demand function of fossil fuels is not isoelastic. On the contrary, if the demand is isoelastic the optimal extraction dynamic path implies the complete exhaustion of the resources stock.

2.2 The Normative Extraction Dynamic Path

Let us consider the normative problem. In maximizing the consumption flow over time the social planner takes into account both the dynamic law of resources extraction and the dynamic evolution of the technology. The normative optimal dynamic path in R, S space is (see Appendix A2):

$$\frac{dR}{dS} = -\frac{\dot{R}}{R} = \varepsilon \left\{ [i - (\alpha + \beta)] \left[1 - \frac{g(S, A_R)}{P} - \frac{N h(S)}{P} \right] + \frac{\psi_S(S)}{P} + \frac{g_{A_R}(S, A_R) \dot{A}_R}{P} \right\}, \quad (3)$$

The optimal dynamic path described in equation (3) implies that a strictly positive amount of fossil fuels is left in the ground whenever the demand function of fossil fuels is not isoelastic. On the contrary, the optimal extraction dynamic

compared without any loss of generality in the analysis.

path of fossil fuels when the demand is isoelastic determines the complete exhaustion of the resources stock.¹³

The inspection of both equations (2) and (3) shows that a positive and constant research subsidy ($\sigma > 0$, and $\dot{\tau}^* = 0$) renders the market optimal extraction path flatter than the same extraction path with no subsidy, yet the path remains steeper than the normative one. When an increasing tax rate on CO2 emissions is implemented, the relative position of both normative and positive extraction paths changes, as will be discussed in the next section. Notice that the market extraction path is steeper than the normative one also because the resource owner has a positive probability α to be replaced in each instant of time due to technological progress, while the centralized solution for the extraction path incorporates all the positive knowledge spillovers due to technological advances. This result also holds when innovations are only introduced by the incumbent.

From the considerations above, when the demand of fossil fuels is not isoelastic the amount of fossil fuels left in the ground by a decentralized market economy is always lower than the optimal stock of fossil fuels left in the ground by a benevolent social planner, if a more and more severe pro-environmental tax policy is not adopted.

3 The Optimal Environmental Tax Policy

In this section the optimal environmental tax policy for the economic framework described above is obtained. To this aim, let us consider a pro-environmental policy over time ($\dot{\tau}^* > 0$). In the light of both equations (2) and (3), the normative and the positive optimal dynamic paths coincide whenever the following condition is satisfied:

$$\begin{aligned} & \left\{ [i - (\alpha + \beta)] \left[1 - \frac{g(S, A_R)}{P} - \frac{Nh(S)}{P} \right] + \right. \\ & \quad \left. - \frac{\psi_S(S)}{P} + \frac{g_{A_R}(S, A_R)\dot{A}_R}{P} \right\} = \\ & = \left\{ (i + \pi - \hat{\theta}^* + \alpha) \left[1 - \frac{g(S, A_R)}{P} - \frac{(1 - \sigma\tau^*)\eta h(S)}{P} \right] + \right. \\ & \quad \left. + \frac{g_{A_R}(S, A_R)\dot{A}_R}{P} - \frac{\sigma\dot{\tau}^*h(S)}{P} \right\}. \end{aligned} \quad (4)$$

Solving equation (4) for the cash flow tax growth $\dot{\tau}^*$ the following is obtained:

$$\begin{aligned} \dot{\tau}^* = & \left\{ \begin{aligned} & (i + \pi + \alpha) [P - g(S, A_R) - (1 - \sigma\tau^*)\eta h(S)] + \\ & - [i - (\alpha + \beta)] [P - g(S, A_R) - Nh(S)] + \psi_S(S) \end{aligned} \right\}^* \\ & * \left\{ \eta h(S) \sigma - \frac{P - g(S, A_R) - (1 - \sigma\tau^*)\eta h(S)}{1 - \tau^*} \right\}^{-1} \end{aligned} \quad (5)$$

¹³As in Sinn (2008), we assume parameter restrictions such that the dynamic path always increases from the origin, i.e. $[i - (\alpha + \beta)] \left[1 - \frac{g(S, A_R)}{P} - \frac{Nh(S)}{P} \right] - \frac{\psi_S(S)}{P} + \frac{g_{A_R}(S, A_R)\dot{A}_R}{P} > 0$.

As shown above, the normative path is flatter than the positive one whenever a constant cash flow tax rate and a constant R&D subsidy are assumed, i.e. $\sigma > 0$ and $\dot{\tau}^* = 0$. From the continuity of functions in equation (5), the numerator of the right hand side of the same equation remains positive for $\dot{\tau}^* > 0$, and therefore the optimal cash flow tax should grow at a positive rate whenever the following condition holds:

$$\left[\eta h(S) \sigma - \frac{P - g(S, A_R) - (1 - \sigma \tau^*) \eta h(S)}{1 - \tau^*} \right] > 0. \quad (6)$$

In perfectly competitive markets in both resource and R&D sectors the price of the resources is as close as possible to marginal costs, i.e. $P = g(S, A_R) + (1 - \sigma \tau^*) \eta h(S) + \delta$, with $\delta \rightarrow 0$ being strictly positive and instantaneous rent flows once a new extraction technology is introduced into the market. This condition also holds when imperfect market competition in the resource sector and perfect competition in the R&D sector exist, as assumed in Schumpeterian growth models. In this case the resource owner's strictly positive profit flows Π are spent to incur R&D costs. Finally, the same condition holds with imperfect market competition and free entry into the R&D sector.¹⁴ This last assumption does not seem too demanding because, in this framework, the R&D effort refers to an economy-wide activity, and the endogenous research can be interpreted either as pure investment by a technological leader or as the imitation and adaptation activity by a technology laggard.

In the light of the above, a positive and increasing cash flow tax rate on CO2 emissions is a welfare maximizing policy when a positive ($\sigma > 0$) and increasing R&D subsidy is paid, independently of the fiscal burden on the resource owner is (i.e. for any $\tau^* < 1$). Therefore, the following can be stated:

Proposition 1 *A positive and increasing subsidy of firms' R&D expenditures aimed at improving the extraction technology of fossil fuels allows an increasing cash flow tax rate on CO2 emissions to be a welfare maximizing policy.*

When endogenous technological progress is explicitly accounted for, the policy implications against global warming contrast with those raised by the green paradox as in Sinn (2008).¹⁵ In that framework the Pareto efficient extraction path is the flattest one when the greenhouse effect is accounted for, and the market equilibrium path is always steeper than the normative one. It is argued that a decreasing carbon tax, starting with a high enough tax value today, may induce a supply reaction in the appropriate direction, in the sense of flattening the positive dynamic extraction path towards the normative one and thus

¹⁴This result holds as long as constant returns to scale prevail in the research activity. In the case of imperfectly competitive market structure the price of resources P is taken as given because each resource owner can not affect the price at the world-wide level, even if she can be a monopolist in her own country. In either case all the qualitative results of the model hold.

¹⁵Here I do refer to other useful policies against global warming that are closely related to the mechanisms of the paper.

mitigating global warming in the present. This paper shows that efficiency improvements in extraction technology allows lower extraction costs to be obtained over time whereby a flatter extraction path becomes profitable for the resource owner. When an increasing extraction technology R&D subsidy is paid, saving on R&D expenditures further flatten the positive dynamic extraction path and an increasing tax rate on CO₂ emissions reveals a welfare maximizing policy.¹⁶ These economic mechanisms mainly concern expected profit flows. When a pro-environmental policy is expected to prevail, the positive effect on expected profit flows due to both lower extraction costs and lower R&D expenditures over time outweighs the negative effect on expected profit flows due to an increasing fiscal burden on CO₂ emissions. As a consequence the resource owner has the incentive to postpone fossil fuels extraction over time.

Moreover, these policy measures against global warming contrast with those raised by the green paradox in their practicability. A decreasing carbon tax does not seem practicable because government should levy a high tax today, and it should announce a tax cut over time. This generates a second major difficulty consisting in the credibility of the government on a tax cut commitment, given the actual environmental concerns. This problem is magnified because the tax rate would become negative in finite time, and the government would have to subsidize resource consumption. The policy measures indicated in the paper overcome these difficulties and allow some economic benefits, other than lower cumulated CO₂ emissions, to be gained. Indeed, an increasing tax rate on CO₂ emissions jointly with an increasing R&D subsidy allow the resource owner's goals to match the environmental concerns, and government can get high credibility for its policy commitments. Moreover, the R&D subsidy is a general policy measure regarding all industries and sectors in the economy, including fossil fuels extraction, allowing positive effects to be obtained such as knowledge spillovers and efficiency gains.

The generality of the R&D subsidy also renders its practicability easier than subsidizing only the stock in situ to induce the resource owner to keep fossil fuels in the ground, which is another useful policy raised by the green paradox.¹⁷ It is worth remarking that the payment of an increasing R&D subsidy, as well as the payment of direct subsidy, to the resource owner may raise a major drawback because countries in the Kyoto agreements could be required to send money to Middle East regimes. Yet, these countries usually are technology laggard, and the extraction technology is very specific. In this way, Middle East regimes could obtain a technology transfer, constrained to application and supervision agreements, from more advanced countries that are at the technological frontier at a lower cost, which is equivalent to reducing the R&D expenditures through

¹⁶These results are in line with Gerlagh et al.'s (2009) findings because, in a variety proliferation framework, the authors suggest a decreasing R&D subsidy for carbon abatement technologies under the assumption that the productivity of abatement equipment does not diminish over time. On the contrary, in this paper technological progress reduces the extraction costs. This sheds light on the role of the creative destruction mechanism which allows improvements in extraction technology, and then lower extraction costs over time.

¹⁷Notice that even a direct subsidy to the resource owner raises problems tied to government credibility about policy commitment, given the actual environmental concerns.

a direct subsidy. In this case the mechanisms described in the paper and the results hold. Certainly, when talking about money and technology transfers to dictatorial regimes other considerations, such as political opportunity, are involved which go beyond the scope of the paper.

3.1 A simple numerical analysis

Even if a full empirical analysis is beyond the scope of the paper, a simple numerical simulation of condition (6) brings the theoretical results to the data. A threshold value τ_{\max}^* for the cash flow tax rate τ^* is obtained through a simple algebra manipulation of condition (6), i.e.:

$$\tau^* < \tau_{\max}^* \equiv \frac{\nu \eta h(S)}{\nu \eta h(S) + [P - mc]} = \frac{\nu \eta h(S)}{\nu \eta h(S) + mc[\mu - 1]}, \quad (7)$$

where $\nu \equiv \sigma \tau^*$ has been used without any loss of generality in the analysis. In equation (7) the term $[P - g(S, A_R) - (1 - \nu) \eta h(S)]$ is rewritten as $[P - mc]$, where $mc = g(S, A_R) + (1 - \nu) \eta h(S)$ is the marginal cost, and where the standard specification for price $P = \mu mc$ is used, with $\mu > 1$ being the gross mark-up. Equation (7) indicates that, when the tax rate is lower than the threshold τ_{\max}^* , a strictly positive tax growth rate $\frac{\dot{\tau}^*}{\tau^*} > 0$ reveals a welfare maximizing policy. The U.S. are chosen for the numerical analysis because all needed data are available for this country. Table 1 summarizes the numerical simulation results. The first row indicates the R&D subsidy values. The second row shows the minimum and maximum values of the gross mark-up. The last row indicates the predicted values for the tax rate threshold τ_{\max}^* calculated using the fossil fuels production share of 60%. The use of this share and of per capita R&D expenditures (as percentage of GDP) give the lowest value of the threshold τ_{\max}^* , for any given value of both gross mark-up and R&D subsidy, so that the less favorable scenario for the results of the paper is considered.¹⁸

Table 1				
	$\nu = 0.06$		$\nu = 0.18$	
Gross mark-up	$\mu = 1.03$	$\mu = 1.05$	$\mu = 1.03$	$\mu = 1.05$
τ_{\max}^*	0.57	0.45	0.82	0.73

Table 1 shows that the lowest threshold value for the cash flow tax rate τ_{\max}^* is 0.45 meaning that an increasing tax rate on CO2 emissions allows people's well-being to increase whenever $\tau^* < 0.45$. The numerical analysis shows that a higher value of the R&D subsidy allows higher predicted threshold values of the tax rate τ_{\max}^* to be obtained, for any value of the gross mark-up. In line with the theoretical results of the model, considering a given period of time and starting with a cash flow tax rate below threshold $\tau_{\max}^* = 0.45$, an increase in the R&D subsidy allows a higher cash flow tax growth to be obtained because

¹⁸The use of average research and development expenditures (as percentage of GDP) for total population always generates a threshold cash flow tax rate slightly higher than 1, i.e. $\tau_{\max}^* > 1$.

of a higher threshold value τ_{\max}^* . Moreover, the closer the fossil fuel sector to a perfectly competitive market is, i.e. the lower the gross mark-up is, the higher the threshold cash flow tax rate is, for any given value of the R&D subsidy. Indeed, a lower mark-up generates a lower price and a higher demand for fossil fuels, which in turn generates higher CO2 emissions. Accordingly with the theoretical results of the paper, the cash flow tax growth rate on carbon emissions, and therefore the threshold τ_{\max}^* , is higher for any given value of the R&D subsidy.

4 Conclusions

One of the major issues economies and policy makers have to face in the present and in the next years concerns mitigation of the global warming negative externality generated by the use of fossil fuels, while preserving or improving people's well-being. One of the policy implications of the green paradox states that an increasing tax rate on CO2 emissions can exacerbate global warming in the present. This paper shows that this policy implication arises when only the negative environmental externality is accounted for. Purposeful technological progress, and the knowledge spillovers it generates, allows the combination of a pro-environmental policy and a fiscal support of research efforts consisting respectively in an increasing tax on CO2 emissions and an increasing R&D subsidy to be a welfare maximizing policy. These results hold with either perfect or imperfect competition in the resource sector, and when the new extraction technology of fossil fuels is introduced either by incumbent or outsider firms.

Appendix A

In this Appendix the firm's resource owner and the normative optimal dynamic extraction paths are obtained.

A1. Positive solution

Let us consider the simplified model in Section 2, with a tax factor at time t given by $\theta^* = \theta^*(0) e^{\hat{\theta}^* t}$, with $\hat{\theta}^*$ constant, and $\theta^*(0) > 0$. Let $i + \pi + \alpha > \hat{\theta}^* > c$, where $c < 0$ is constant.

The resource owner's problem can be written as:

$$\begin{aligned} \underset{\{R\}}{Max} \int_0^\infty \theta^*(0) \alpha_j e^{-[i+\pi-\hat{\theta}^*+\alpha]t} \left\{ \begin{aligned} & [P(t) R(t) - g(S(t), A_R(t)) R(t)] + \\ & - (1 - \sigma\tau^*) \eta h(S(t)) R(t) \end{aligned} \right\} dt \\ \text{s.t.} \quad -\dot{S} = R, \\ S(0) = S_0. \end{aligned} \quad (\text{A1})$$

Each firm takes as given the technology level A_R , so that it does not represent a state variable in problem (A1) (see among others Acemoglu, 2009). It is assumed that the representative resource owner takes the price path as given, notwithstanding the fact that in the aggregate the price level depends on the extraction volume: $P = P(R, t)$.

The current value Hamiltonian for this problem is:

$$H = \theta^*(0) \alpha_j [(PR - g(S, A_R)R) - (1 - \sigma\tau^*) \eta h(S) R] - \lambda R, \quad (\text{A2})$$

The necessary conditions for an optimum are the stationary optimality condition

$$\theta^*(0) \alpha_j [(P - g(S, A_R)) - (1 - \sigma\tau^*) \eta h(S)] = \lambda, \quad (\text{A3})$$

the canonical equation for the state variable

$$\frac{\dot{\lambda}}{\lambda} - \theta^*(0) \alpha_j \frac{g_S(S, A_R)R + (1 - \sigma\tau^*) h_S(S) R}{\lambda} = i + \pi - \hat{\theta}^* + \alpha, \quad (\text{A4})$$

and the transversality condition

$$\lim_{t \rightarrow \infty} \theta^*(0) \alpha_j \lambda(t) S(t) e^{-[i+\pi-\hat{\theta}^*+\alpha]t} = 0. \quad (\text{A5})$$

The slope of the possible paths in R, S space can be derived from equations (A3) and (A4), if (A3) is differentiated with respect to time, and the assumptions that $P = P(R, t)$ with $\partial P / \partial t \leq 0$ for $t \leq T$, $P > 0$ for $R > 0$ and $\partial P / \partial t = 0$ for $t > T$ are respected. The paths on which R is bounded away from zero as time goes to infinity are not feasible, as the stock of the resources becomes zero in finite time, so that the necessary marginal conditions can no longer be satisfied. Let us consider the paths on which S is bounded away from zero as time goes to infinity while R converges to zero. The dynamics change drastically depending on the boundness of the price elasticity of demand ε . When the

demand elasticity ε , the marginal extraction cost $g(S, A_R)$, the marginal R&D expenditures $h(S)$, and the growth rates $\hat{\theta}^*$ are bounded, equation (A3) implies that $\lambda \rightarrow \infty$ as $R \rightarrow 0$. As both $g(S, A_R)$ and $h(S)$ are differentiable, the second term in (A4) vanishes as $R \rightarrow 0$, and hence $\frac{\dot{\lambda}}{\lambda}$ converges to $(i + \pi - \hat{\theta}^* + \alpha)$ as $R \rightarrow 0$. This means that $\lambda(t) e^{-[i + \pi - \hat{\theta}^* + \alpha]t}$ does not converge to zero as time goes to infinity so that the transversality condition can only be satisfied if S goes to zero. On the contrary, when the demand elasticity ε is not bounded, because both $g(S, A_R)$ and $h(S)$ are differentiable, the second term in (A4) vanishes as $R \rightarrow 0$, and hence $\frac{\dot{\lambda}}{\lambda}$ converges to $(i + \pi - \hat{\theta}^* + \alpha)$ as $R \rightarrow 0$. Yet, in this case (A3) implies that $\lambda \rightarrow \Omega < \infty$ as $R \rightarrow 0$, where Ω is the least upper bound of the left hand side of (A3) corresponding to $\varepsilon \rightarrow \infty$ as $R \rightarrow 0$, i.e. Ω is the least upper bound of the term $\theta^*(0) \alpha_j [(P - g(S, A_R)) - (1 - \sigma \tau^*) \eta h(S)]$ as $R \rightarrow 0$ and $\varepsilon \rightarrow \infty$. This in turn implies that $\lambda(t)$ does converge to its least upper bound Ω in finite time, and then the transversality condition is satisfied with $S(t) > 0$ as $t \rightarrow \infty$. Q.E.D.

A2. Normative solution

The social planner maximizes the consumption flow over time. To compare the positive and the normative intertemporal maximization problems, and because the R&D investments are independently distributed across firms, across industries, and over time, the constant and aggregate instantaneous Poisson arrival rate of innovation ϑ of the general technology A can be written as $\vartheta \equiv \alpha + \beta$, where $\alpha > 0$ is the instantaneous Poisson arrival rate of innovation for the extraction technology A_R , and β is the instantaneous Poisson arrival rate of innovation for the general technology, but the extraction technology one. The benevolent social planner takes into account the future gains from higher technological levels, so that the effective discount rate is $[i - (\alpha + \beta)] > 0$, with $i > (\alpha + \beta)$ assumed to hold.

The social planner problem can be written as:

$$\begin{aligned} \text{Max}_{\{R\}} \int_0^\infty e^{-[i - (\alpha + \beta)]t} & \left\{ \begin{array}{l} \varphi(R(t), t) + \psi(S(t)) + \gamma(A(t)) + \\ -g(S(t), A_R(t)) R(t) - Nh(S(t)) R(t) \end{array} \right\} dt \\ \text{s.t.} \quad & -\dot{S} = R, \quad S(0) = S_0, \\ & \dot{A} = \varphi(A), \quad A(0) = A_0. \end{aligned} \quad (\text{A6})$$

where $Nh(S(t)) R(t)$ are aggregate R&D expenditures at any time t . The current value Hamiltonian of this problem is:

$$H = \varphi(R, s) + \psi(S) + \gamma(A) - g(S, A_R) R - Nh(S) R - \lambda R + \mu A \quad (\text{A7})$$

The necessary conditions for an optimum are the stationary optimality condition

$$P - g(S, A_R) - Nh(S) = \lambda \quad (\text{A8})$$

and the necessary conditions for the state variables

$$\frac{\dot{\lambda}}{\lambda} - \frac{g_S(S, A_R)R + Nh_S(S)R}{\lambda} + \frac{\psi_S(S)}{\lambda} = i - (\alpha + \beta) \quad (\text{A9})$$

$$\frac{\dot{\mu}}{\mu} + \frac{\gamma_A(A)}{\mu} - \frac{g_{A_R}(S, A_R)R}{\mu} = i - (\alpha + \beta) \quad (\text{A10})$$

with $\gamma_A(A) = \frac{\partial \gamma(A)}{\partial A}$. The transversality conditions are

$$\lim_{t \rightarrow \infty} \lambda(t) S(t) e^{-(i-\alpha-\beta)t} = 0 \quad (\text{A11})$$

$$\lim_{t \rightarrow \infty} \mu(t) A(t) e^{-(i-\alpha-\beta)t} = 0 \quad (\text{A12})$$

The possible paths in R, S space follow from equations (A8) and (A9). Paths that reach the ordinate above the origin once again are not feasible since they end in finite time, and make it impossible to satisfy the marginal conditions thereafter. Moreover, equation (A8) and the boundness assumptions for $\varepsilon, g(S, A_R)$, and $h(S)$, imply that λ goes to infinity as R approaches zero. The differentiability of $g(S, A_R)$ and $h(S)$, and the assumption that $\psi(S)$ is bounded from above imply that $\frac{\dot{\lambda}}{\lambda}$ approaches $(i - \alpha - \beta)$ as time goes to infinity, which in turn implies that the transversality condition (A11) can only be met as S goes to zero when time goes to infinity. The same reasoning as above implies that whenever the demand elasticity ε is not bounded, then some amount of fossil fuels strictly larger than zero is left in the ground even from a normative point of view, i.e. $S(t) > 0$ as $t \rightarrow \infty$.

Moreover, by assuming that A , and therefore A_R , is bounded, as time elapses condition (A10) implies that $\frac{\dot{\mu}}{\mu}$ tends to $(i - \alpha - \beta) - \frac{\gamma_A(A)}{\mu} + \frac{g_{A_R}(S, A_R)R}{\mu}$, which is assumed to be negative, i.e. $(i - \alpha - \beta) - \frac{\gamma_A(A)}{\mu} + \frac{g_{A_R}(S, A_R)R}{\mu} < 0$. This in turn implies that the shadow price for technology tends to decrease in the very long run, and it will be zero in the long run. In this way, the condition (A12) will be satisfied for t that goes to infinity with $A(t) > 0$ and $\mu(t) = 0$. Such a dynamic evolution has a natural economic interpretation. Indeed, as time elapses and tends to infinity, the benefits from higher and higher technology levels tend to an upper bound, and the shadow price for newer technologies tends to zero as the economy is closer and closer to such an upper bound. Q.E.D.

Appendix B

B1. This Appendix derives a sufficient condition which leads to profitable R&D effort by the resource owner. To this aim, the following inequality must hold:

$$\alpha_j [PR - g(S, A_{R1})R - h(S)\eta R] > PR - g(S, A_{R0})R, \quad (\text{B1})$$

where $A_{R1} = \gamma A_{R0}$ is the technological level after the first innovation, with $\gamma > 1$ being the size of the technology level jump, and $A_{R0} > 0$ is the technological level at the very beginning of the economy. Solving inequality (B1) in the innovation size γ , it is possible to write the innovation size as a function of the

resource stock S , i.e. the inequality (B1) can be rewritten as $\gamma > f(S, A_{R0})$, where $f(\cdot)$ is increasing in S , and it does not depend on R because the price P is taken as given and α_j is constant. In this way, a sufficient condition for inequality (B1) to hold is a high enough innovation size at the very beginning of the economy, i.e. $\gamma > f(S_0, A_{R0})$. When such a condition holds for the first innovation, it will always hold for subsequent innovations because S will be lower and lower over time. Q.E.D.

B2. In this Appendix both the cash flow tax and the R&D subsidy regimes are considered. The cash flow tax system implies that a fraction of the extraction cost is refunded back to the resource owner. When no R&D expenditures exist, the firm gets $\theta^* [PR - g(S)R] = PR - \tau^* PR - g(S)R + \tau^* g(S)R$, where $\theta^* \equiv (1 - \tau^*)$ has been used. In this way, the resource owner gets back a fraction τ^* of the extraction cost $g(S)R$. Let us consider now the R&D expenditures and the subsidy to such expenditures. In this case the firm gets: $\theta^* [PR - g(S, A_R)R - (1 - \sigma\tau^*) h(S)R] = PR - \tau^* PR - [g(S)R + h(S)R] + \tau^* [g(S)R + h(S)R] + \sigma\tau^* (1 - \tau^*) h(S)R$, where a fraction τ^* of the total cost is refunded back to the resource owner, and where the extra term $\sigma\tau^* (1 - \tau^*) h(S)R$ represents the R&D subsidy. As $\sigma \in [0, \frac{1}{\tau^*}]$, the firm gets $PR - \tau^* PR - [g(S)R + h(S)R] + \tau^* [g(S)R + h(S)R]$ when no R&D subsidy is paid ($\sigma = 0$), and it gets $PR - \tau^* PR - g(S)R + \tau^* g(S)R$ when the R&D subsidy completely refunds the R&D costs ($\sigma = \frac{1}{\tau^*}$). In this way, it is shown that the cash flow tax regime with R&D expenditures is consistent with the cash flow tax regime with no R&D expenditures. Q.E.D.

Appendix C

This appendix explains how the parameter values are calibrated. Martins et al. (1996) estimate the gross mark-up for the petroleum refineries to be in the range of 1.03 and 1.05. The data on marginal costs for the extraction of fossil fuels are taken by the Energy Administration Agency (EIA, website: <http://www.eia.gov/>) and refer to real costs per crude oil, natural gas, and dry well drilled for the period 1996-2004. Only data on average costs per well are provided by the EIA, yet the use of average costs per unit of extracted resources would give a higher value of τ_{\max}^* . The data for R&D expenditures, taken from the World Development Indicators (WDI, 2006), refer to average per capita research and development expenditures (as percentage of GDP) for the period 1996-2004, and are used to measure the term $\eta h(S)$. In consistence with the available data on extraction costs, the R&D expenditures have been weighted with the production share of oil and natural gas (liquid and dry) on the total energy production, which consists of all traditional fossil fuels that generate CO2 emissions (oil, natural gas, coal). The share varies between 60% and 68% for the period 1980-2035 (as forecast). These data come from the EIA. The U.S. R&D subsidy increased from 6% in 1979 to 18% in 1991, remaining constant in the following years (see Bloom et al., 2002).

References

- [1] Acemoglu D, (2009) Introduction to Modern Economic Growth. Princeton University Press, Princeton.
- [2] Aghion P, and Howitt P (1992) A Model of Growth Through Creative Destruction. *Econometrica* 60, 323-351.
- [3] Boldrin M, and Levine D (2002) The Case Against Intellectual Property. *American Economic Review* P&P: 209-212.
- [4] Bloom N, Griffith R, and Van Reenen J (2002) Do R&D Tax Credits Work? Evidence from a Panel of Countries 1979-97. *Journal of Public Economics*, 85: 1-31.
- [5] Brock W A, Taylor M S (2010) The Green Solow Model. *Journal of Economic Growth*, 15: 127-153.
- [6] Gerlagh R (2010) Too Much Oil. Working Papers 2010.14, Fondazione Eni Enrico Mattei.
- [7] Gerlagh R, Kverndokk S, Rosendahl K E (2009) Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities. *Environmental and Resource Economics*, 43:369-390.
- [8] Grossman G M, and Helpman E (1991) Innovation and Growth in the Global Economy. Cambridge: MIT Press.
- [9] Hoel M (2010) Is there a Green Paradox? Cesifo Working paper no. 3168.
- [10] Jones C (1995) Time Series Tests of Endogenous Growth Models. *Quarterly Journal of Economics* 110, 495-525.
- [11] Kamien M I, and Schwartz N L (1982) The Role of Common Property Resources in Optimal Planning Models with Exhaustible Resources. in V. K. Smith and J. V. Krutilla, *Explorations in Natural Resource Economics*, RFF Press, Baltimore.
- [12] Madsen J B (2008) Semi-endogenous versus Schumpeterian growth models: testing the knowledge production function using international data. *Journal of Economic Growth*, 13: 1-26.
- [13] Martins J O, Pilat D, Scarpetta S (1996) Mark-Up Ratios in Manufacturing Industries. OECD Economics Department Working Papers No. 162.
- [14] Paltsev S, J M Reilly H D, Jacoby, and Morris J F (2009). The cost of climate policy in the United States, Report No. 173, MIT Joint Program on the Science and Policy of Global Change, MIT, Cambridge, Mass.
- [15] Peretto P (1998) Technological Change and Population Growth. *Journal of Economic Growth*, 3: 283-311.

- [16] Segerstrom P (1998) Endogenous Growth Without Scale Effects. *American Economic Review* 88: 1290-1310.
- [17] Sinclair PJN (1992) High does nothing and rising is worse: carbon taxes should keep declining to cut harmful emissions. *The Manchester School*, 60: 41-52.
- [18] Sinn W H (2008) Public policies against global warming: a supply side approach. *International Tax Public Finance*, 15: 360-394.
- [19] Sinn W H (2007). Pareto optimality in the extraction of fossil fuels and the greenhouse effect. *Cesifo working paper* n. 2083.
- [20] Stern N, Peters S, Bakhshi V, Bowen A, et al. (2006) *Stern Review: The Economics of Climate Change*, HM Treasury, London.
- [21] Van der Ploeg F, and Withagen C (2010) *Is There Really a Green Paradox?* *OxCarre Research Paper* n. 35.
- [22] *World Development Indicators* (2006). The World Bank Group, Washington, DC.