

Resource Conservation and Directed R&D: Multiple trajectories ?

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Abstract

I present a simple model of a decentralized economy with endogenous supply of a non-renewable resource and endogenous R&D targeted to the non-renewable resource. I establish the necessary conditions for the emergence of two equilibrium paths, i.e. one with no R&D, no technological improvement and fast depletion, the other with R&D investment, technological progress and resource conservation. The latter equilibrium implies the largest possible expansion of the production possibilities set, because targeted R&D and resource conservation are complements. In fact if both take place, the technological improvement is applied to a larger resource base than otherwise. Coordination among decentralized agents is based on expectations and can therefore fail to exploit this complementarity. The necessary conditions for this type of failure to emerge are identified using a game theoretic model.

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Introduction

The classic debate on the limits to economic growth made some substantial progress in economics during the early 1970's. Theoretical analyses established that the dependency of modern economic systems on the exploitation of non-renewable resources does not necessarily limit the potential for indefinite growth in per-capita consumption if either of the two following conditions are satisfied: (i) there is a sufficiently high potential for substituting capital for non-renewable resources, or/and (ii) the pace of total factors

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productivity growth is fast enough to compensate for the depletion of the non-renewable resource stock (see Stiglitz 1974, Dasgupta and Heal 1974).

The scientific community has rapidly reached a consensus over the empirical implausibility for the first condition to be satisfied, at least if by non-renewable resources one means energy inputs to production. Typically authors working on applied models choose parameter values below unity for the elasticity of substitution of non-energy inputs for energy inputs in the aggregate production function (e.g. van der Zwaan et al. 2003, Popp 2004).

Subsequent attention has focused on the possibility to meet with the second condition. As long as technological change was treated as independent of economic incentives, not much could be added to results obtained in first contributions. The debate on the limits to growth gained new momentum from the development of the new theoretical toolkit for studying the determinants of technological progress in a macroeconomic perspective, i.e. endogenous growth theory (Romer 1986 and 1990, Grossman and Helpman 1991, Aghion and Howitt 1992). In the mid-1990's, a series of papers employed endogenous growth models to explore the topical question of the optimal design and consequences of environmental policies limiting the flow of polluting emissions. Inasmuch as polluting emissions represent an implicit input to the production process, they are equivalent to a renewable resource input available in a limited amount (under effective environmental policy).¹ Only few authors dealt directly with non renewable resources (e.g. Sholz and Ziemes 1999, Groth and Schou 2002, van Zon and Yetkiner 2003, Grimaud and Rouge 2003). These first approaches considered a form of technical progress affecting the economy in a unique and the same way (either labor augmenting or resource augmenting).

Recent research has focused on directed technical change, where technological progress can affect at varying degrees different sectors of the economy. With this approach it is possible to formalize the trade-off between improving the technology in the resource intensive sector rather than in other sectors. Two types of approaches can be distinguished. Some papers study the centrally planned problem, and model properly the limited availability of non renewable resources (e.g. Tahvonen and Salo 2001, Tsur and Zemel 2005). Other papers study the decentralized economy, following the seminal paper of Acemoglu (2002), but resort to simplifying assumptions on the supply of the natural resource, which make it analogous to a renewable resource (Smulders and de Nooij 2003, Bretschger and Smulders

¹See Brock and Taylor (2005), Xepapadeas (2005) or Ricci (2007) for a survey of this literature.

2006, André and Smulders 2004, Di Maria and Valente 2006, Grimaud and Rougé 2006).²

I show in this paper that the analysis of decentralized decisions by, on the one hand, R&D firms targeting improvements in non-renewable-resource specific technology, and, on the one hand, non-renewable-resource owners setting the intertemporal profile of resource supply schedule, raises some peculiar difficulties. In fact these decisions interact in determining the payoff to each type of firms. The choice of R&D labs affects the value of the resource stock, while the decision of resource owners affect the profitability of targeted innovations. I explain how this interaction can give rise to strategic complementarities, i.e. situations where the payoff to R&D increases with the future availability of the resource (resource conservation) and, symmetrically, the payoff to resource conservation for resource owners increases in the expected rate of technological progress (itself positively related to current R&D investment).

The presence of strategic complementarities can give rise to multiple equilibria, if complementarities are strong enough (see Cooper and John 1988 and references therein). I identify the conditions for the emergence of multiple equilibria, which I dub trajectories because of the dynamic nature of the problem under analysis. In particular I show that there can be a vicious trajectory with no investment in targeted R&D, no improvement in the technology for the exploitation of the resource, and fast depletion of the resource stock. Agents in this same economy can instead coordinate on a virtuous trajectory with targeted R&D investment taking place, resulting in technological progress and resource conservation. The virtuous trajectory is Pareto superior³ to the vicious one, since R&D and resource conservation together expand the production possibilities frontier the most (i.e. technological improvements are applied to a larger resource base under conservation than under fast depletion).

Let me describe more in detail these trajectories. Consider two different sources of energy: a renewable one (R) and a non renewable one (F), to which I refer as the “fossil” resource. The latter is available in a finite quantity S . At the perfect foresight equilibrium, the supply of F and the supply of technology (a) for the conversion of F into effective energy inputs are compatible and no agent regrets its decision. If investment in R&D and investment in the S (resource conservation) are strategic complements, appropriate coordination in expectations between, on the one hand, R&D labs and, on the other hand,

²Eriksson (2004) is an exception but the analysis is, to the best of my knowledge, incomplete.

³This statement should be qualified. The virtuous trajectory implies more investment than the vicious one. Hence if it is impossible to transfer consumption possibilities from future generations to present ones (via public debt for instance), the trajectory with more investment could result in lower utility for non altruistic agents of the present generation.

mine owners can give rise to multiple equilibria. The intuitive coordination scheme is as follows:

- high R&D investment in the fossil sector today,
- \Rightarrow faster expected improvement in a ,
- \Rightarrow stronger bias in the technological gap with respect to the alternative resource R ,
- \Rightarrow greater expected growth in demand for F resource,
- \Rightarrow the mine-owners' optimal supply strategy consists in delaying extraction of F , i.e. conservation of S ,
- \Rightarrow conservation of S implies a larger resource base on which innovations are implemented,
- \Rightarrow larger expected return on R&D in fossil technology,
- \Rightarrow high R&D investment in the fossil sector today;

and symmetrically:

- low R&D investment in the fossil sector today,
- \Rightarrow slower expected improvement in a ,
- \Rightarrow weaker bias in the technological gap with respect to the alternative resource R ,
- \Rightarrow smaller expected growth in demand for F resource,
- \Rightarrow the mine-owners' optimal supply strategy consists in accelerating extraction of F , i.e. faster depletion of S ,
- \Rightarrow faster depletion of S implies a smaller resource base on which innovations are implemented,
- \Rightarrow smaller expected return on R&D in fossil technology,
- \Rightarrow low R&D investment in the fossil sector today.

In view of establishing strategic complementarity, the most critical of the steps above is the consequence of directed technical change on the demand for the row resource. An improvement in the energy efficiency of the fossil resource can in fact foster the demand for

the resource only if the fossil sector takes over some of the demand for other production inputs. If one accepts the consensus according to which there is not much scope for substituting non-energy inputs for energy inputs to production, then this can happen only if there is a sufficiently high degree of substitutability between fossil and non fossil energy inputs. Only in this case, in fact, technological progress in the fossil sector would shift demand from other resources to fossil resources within the energy industry.

The other conditions that I find to be necessary for the emergence of multiple trajectories are: (i) a positive real rate of interest, (ii) a potential rate of technical improvement in the fossil sector above the real rate of interest, and (iii) the fact that the fossil sector's output depends more on resource supply than on technological developments.

The present version of the paper provides an example of the emergence of multiple trajectories with a simple game over two periods, between two agents that take binary actions.

1 A simple (2x2x2) game

The interplay between owners of a non renewable resource and developers of technologies for its exploitation can give rise to multiple -Pareto rankable- equilibria. This is illustrated with a simple two-periods game, where two players choose simultaneously one of two possible actions. This model allows me to identify the necessary conditions for the emergence of multiple equilibria.

1.1 Game structure

Time:

- Period 0: present,
- Period 1: future (10-20 years later).

Players:

- Mine-owner,
- R&D lab.

Actions:

- the Mine-owner can exhaust rapidly the resource by selling a lot \bar{S} in 0 and little $\underline{S} < \bar{S}$ in 1 (action denoted by $x = 0$), or ‘conserve’ the resource by selling \underline{S} in 0 and \bar{S} in 1 (i.e. $x = 1$);
- the R&D lab can invest (action denoted by. $y = 1$) or not (i.e. $y = 0$).

Assumptions:

A set of simplifying assumptions that presumably are not crucial

- A1. players act as price-takers⁴;
- A2. players are risk-neutral;
- A3. the real rate of interest, r , is exogenous;

The argument I develop is based essentially on the interaction between actors of the fossil sector. It is not essential to model the rest of the economy. I assume the existence of some demand function linking the unit price of fossil energy, p_Y , to the quantity used in the economy, Y . In the next section I consider a macroeconomic setting where the inverse demand function equates the unit price to the marginal product of fossil energy in terms of the final consumption good. The moment being there is no need to specify the demand function.

The fossil sector’s production function $Y = f(a, F)$ gives the quantity of fossil energy obtained from a given quantity of fossil primary input, F , using a given technology, a .

I assume that

- A4. $f(\cdot)$ is characterized by constant returns to scale with respect to primary inputs F , and therefore increasing returns to scale with respect to F and a together. I adopt the following specification:

$$Y = f(a, F) \equiv aF$$

As mentioned already the supply of primary resource can either be \underline{S} or $\bar{S} = \theta \underline{S} > \underline{S}$, where I define:

$$\theta \equiv \bar{S}/\underline{S} > 1$$

⁴With this assumption I can consider only two players to analyze the case of perfect competition both in the supply of the resource (i.e. many competing mine-owners) and in R&D activity (i.e. a competitive market for researchers and specialized consultants). This is a crucial feature of the problem under analysis. Coordination failures are most plausible when players interact on decentralized markets, without acting strategically.

The primary input is therefore available in finite quantity, as a non renewable resource:

$$F_1 = \{\underline{S}, \bar{S}\} , F_2 = \{\underline{S}, \bar{S}\} \text{ and } F_1 + F_2 = \underline{S} + \bar{S} = S$$

The technical index measuring the efficiency of primary fossil resource in providing energy services is denoted by a . It equals \underline{a} at date 0. It can jump to

$$\bar{a} = \gamma \underline{a} \text{ with } \gamma > 1$$

in period 1 if and only if the R&D lab invests $K > 0$ units of final good in period 0. I make the following simplifying assumption

A5. there is no uncertainty in the innovation process.

It follows that the fossil sector's output can take four possible values :

$$Y^L = \underline{a}\underline{S} \quad ; \quad Y^N = \bar{a}\underline{S} = \gamma Y^L \quad ; \quad Y^M = \underline{a}\bar{S} = \theta Y^L \quad ; \quad Y^H = \bar{a}\bar{S} = \gamma \theta Y^L$$

Let me introduce the notation $VA \equiv p_Y Y$ to measure the revenue (or value added) of the fossil fuel sector as a whole. Revenue can also take four possible values, given that the actions considered in this game only concern the fossil sector. I use the notation VA^i with $i \in \{L, N, M, H\}$. I make one restrictive assumption:

A6. the fossil sector's revenue function is assumed to be an increasing and quasi-concave function of Y .

Finally, given assumption A.4 actors of the sector cannot be rewarded at their marginal product. The following assumption is made:

A7. the Mine-owner and the R&D lab share the fossil sector's revenue (value added) in exogenous shares $\beta \in (0, 1)$ for the former, $1 - \beta$ for the patent owner (either the incumbent or the successful R&D lab):

$$VA^i = \underbrace{\beta p_{Y^i} Y^i}_{\text{mine-owner}} + \underbrace{(1 - \beta) p_{Y^i} Y^i}_{\text{patent-holder}}$$

1.2 Behavior

The **Mine-owner** chooses $x \in \{0, 1\}$ to maximize

$$E \left[p_{F0} \underline{S} + \frac{p_{F1}}{1+r} \underline{S} + p_{F0} (\bar{S} - \underline{S}) (1-x) + \frac{p_{F1}}{1+r} (\bar{S} - \underline{S}) x \right]$$

the expectation operator is used here because the Mine-owner chooses before observing prices p_{F0} and p_{F1} .

Solution

$$x = \begin{cases} 0 & \text{if } E \left(\frac{p_{F1}}{p_{F0}} \right) < 1+r \\ 1 & \text{if } E \left(\frac{p_{F1}}{p_{F0}} \right) > 1+r \end{cases}$$

This is the Hotelling rule for a discontinuous extraction process. Expectations about prices depend on the expected pace of technical progress, since under assumption A.7 the unit value of the primary fossil input is given by:

$$p_F = \frac{\beta V A}{F} = \beta a p_Y$$

Notice that an improvement in technology a has two effects on the (inverse) demand curve for primary inputs, F . First an improvement in a exerts a direct effect on demand, resulting in an homothetic upward shift in the demand curve. Second it exerts an indirect effect by affecting the value of fossil energy, p_Y , for a given volume of primary input. In principle this ‘value effect’ can either be negative or positive, and quite crucially so. I introduce the following

Definition : *Technology is complementary to primary resource supply if $\frac{\partial p_F}{\partial a} > 0$ once the adjustment in p_Y is accounted for. Since p_F is proportional to revenue the condition can be stated in the following terms: $\frac{\partial V A}{\partial a} > 0$.*

Let V denote the value of a patent. The **R&D lab** chooses $y \in \{0, 1\}$ to maximize

$$E \left[0(1-y) + \left(-K + \frac{1}{1+r} V \right) y \right]$$

Solution

$$y = \begin{cases} 0 & \text{if } E(V) < (1+r)K \\ 1 & \text{if } E(V) > (1+r)K \end{cases} \quad \text{where } E(V) = (1-\beta) E(VA_1)$$

The expectation operator considers possible realizations at date 1 for the fossil sector’s

revenue. The latter depends on the mine-owner choice of F_1 and for the innovator (i.e. given \bar{a} at date 1) it can take two possible values:

$$V = \begin{cases} \underline{V} = (1 - \beta)VA^N = (1 - \beta)p_{Y1}\bar{a}\underline{S} & \text{if } F_1 = \underline{S} \\ \bar{V} = (1 - \beta)VA^H = (1 - \beta)p_{Y1}\bar{a}\bar{S} & \text{if } F_1 = \bar{S} \end{cases}$$

with p_{Y1} to be determined endogenously.

1.3 Reduced form game

In each cell of figure 1 the first payoff accrues to the R&D lab, the second to the Mine-owner. In this section I compute the expected payoffs for each possible combination of actions.

		Mine-owner	
		$x = 0$	$x = 1$
R&D lab	$y = 0$	$0, v$	$0, u$
	$y = 1$	q, t	s, w

Figure 1: The reduced form game.

1.3.1 Low (L) case $(y, x) = (0, 0)$

No R&D: $a = \underline{a}$ is constant. No conservation.

- fossil sector's output: $Y_0 = Y^M$ and $Y_1 = Y^L$
- fossil sector's revenue: $p_{Y0}Y_0 = VA^M$ and $p_{Y1}Y_1 = VA^L$
- resource price: $p_{F0} = \beta VA^M / \bar{S}$ and $p_{F1} = \beta VA^L / \underline{S}$
- for the Mine-owner to behave coherently it is necessary that $p_{F1}/p_{F0} < 1 + r$, i.e.

$$VA^M > \frac{\theta}{1 + r} VA^L$$

- payoffs
 - Mine-owner's payoff $v = \beta [VA^M + VA^L / (1 + r)]$
 - for the R&D lab the payoff is zero.

1.3.2 North-East (NE) case $(y, x) = (0, 1)$

No R& D: $a = \underline{a}$ is constant. Conservation: $F_0 = \underline{S} < \bar{S} = F_1$.

- fossil sector's output: $Y_0 = Y^L$ and $Y_1 = Y^M$
- fossil sector's revenue: $p_{Y0}Y_0 = VA^L$ and $p_{Y1}Y_1 = VA^M$
- resource price: $p_{F0} = \beta VA^L / \underline{S}$ and $p_{F1} = \beta VA^M / \bar{S}$
- for the Mine-owner to behave coherently it is necessary that $p_{F1}/p_{F0} > 1 + r$, i.e.

$$VA^M > \theta(1 + r)VA^L$$

- payoffs
 - Mine-owner's payoff $u = \beta [VA^L + VA^M / (1 + r)]$
 - for the R&D lab the payoff is zero;

1.3.3 South-West (SW) case $(y, x) = (1, 0)$

Active R&D: $a_0 = \underline{a} < \bar{a} = a_1$. No conservation.

- fossil sector's output: $Y_0 = Y^M$ and $Y_1 = Y^N$
- fossil sector's revenue: $p_{Y0}Y_0 = VA^M$ and $p_{Y1}Y_1 = VA^N$
- resource price: $p_{F0} = \beta VA^M / \bar{S}$ and $p_{F1} = \beta VA^N / \underline{S}$
- for the Mine-owner to behave coherently it is necessary that $p_{F1}/p_{F0} < 1 + r$, i.e.

$$VA^M > \frac{\theta}{1 + r}VA^N$$

- payoffs
 - Mine-owner's payoff $t = \beta [VA^M + VA^N / (1 + r)]$
 - for the R&D lab $q = (1 - \beta)VA^N / (1 + r) - K$

1.3.4 High (H) case $(y, x) = (1, 1)$

Active R& D: $a_0 = \underline{a} < \bar{a} = a_1$. Conservation: $F_0 = \underline{S} < \bar{S} = F_1$.

- fossil sector's output: $Y_0 = Y^L$ and $Y_1 = Y^H$
- fossil sector's revenue: $p_{Y0}Y_0 = VA^L$ and $p_{Y1}Y_1 = VA^H$
- resource price: $p_{F0} = \beta h_1(E^L, L)g_1(Y^L, R)\underline{a}$ and $p_{F1} = \beta h_1(E^H, L)g_1(Y^H, R)\bar{a}$
- resource price: $p_{F0} = \beta VA^L/\underline{S}$ and $p_{F1} = \beta VA^H/\bar{S}$
- for the Mine-owner to behave coherently it is necessary that $p_{F1}/p_{F0} > 1 + r$, i.e.

$$VA^H > \theta(1 + r)VA^L$$

- payoffs
 - Mine-owner's payoff

$$w = \beta [VA^L + VA^H / (1 + r)]$$

- For the R&D lab

$$s = (1 - \beta) VA^H / (1 + r) - K$$

1.4 Equilibria

Proposition 1 *Two Nash equilibria in pure strategies, one on the Low outcome, the other on the High outcome, can emerge if the following conditions hold:*

- (i) *there is an opportunity cost to resource conservation;*
- (ii) *the potential rate of technological progress in the fossil sector is greater than the real rate of interest;*
- (iii) *resource conservation by itself increases more the energy sector's output than R&D investment alone.*

These three conditions are:

$$\theta > \gamma > 1 + r > 1$$

These conditions are sufficient if value added of the fossil sector is almost linear in its output level, Y .

This result is obtained from the following analysis.

For the Mine-owner

$$\begin{aligned} \text{if } y = 0 & \quad \left\{ \begin{array}{l} x = 0 \Rightarrow \text{payoff } v \\ x = 1 \Rightarrow \text{payoff } u \end{array} \right. \Rightarrow x = 0 \quad \text{only if } v > u \\ \text{if } y = 1 & \quad \left\{ \begin{array}{l} x = 0 \Rightarrow \text{payoff } t \\ x = 1 \Rightarrow \text{payoff } w \end{array} \right. \Rightarrow x = 1 \quad \text{only if } w > t \end{aligned}$$

For the R&D lab

$$\begin{aligned} x = 0 & \quad \left\{ \begin{array}{l} y = 0 \Rightarrow \text{payoff } 0 \\ y = 1 \Rightarrow \text{payoff } q \end{array} \right. \Rightarrow y = 0 \quad \text{only if } q < 0 \\ x = 1 & \quad \left\{ \begin{array}{l} y = 0 \Rightarrow \text{payoff } 0 \\ y = 1 \Rightarrow \text{payoff } s \end{array} \right. \Rightarrow y = 1 \quad \text{only if } s > 0 \end{aligned}$$

So if $v > u$, $w > t$, $q < 0$ and $s > 0$

- the Low case is a Nash-equilibrium since the Mine-owner plays $x = 0$ if it expects the R&D lab to play $y = 0$, and vice versa the R&D lab plays $y = 0$ if it expects the Mine-owner to play $x = 0$;
- the High case is a Nash-equilibrium since the Mine-owner plays $x = 1$ if it expects the R&D lab to play $y = 1$, and vice versa the R&D lab plays $y = 1$ if it expects the Mine-owner to play $x = 1$.

Condition $v > u$ is trivial if

$$r > 0 \tag{1}$$

since for the Mine-owner it is better to sell as soon as possible in the absence of technological progress. This is condition (i) in the proposition.

The following conditions are less obvious to be satisfied simultaneously

- R&D is worth under resource conservation

$$s > 0 \quad \Leftrightarrow \quad VA^H > \frac{1+r}{1-\beta} K \tag{2}$$

- R&D is not worth without resource conservation

$$q < 0 \quad \Leftrightarrow \quad VA^N < \frac{1+r}{1-\beta}K \quad (3)$$

- Conservation is profitable with technical progress

$$w > t \quad \Leftrightarrow \quad VA^H - VA^N > (1+r)(VA^M - VA^L) \quad (4)$$

On the top of that, for the Low and High outcomes to be equilibria it is necessary that the Mine-owner behavior be coherent with the Hotelling rule:

- resource exhaustion is rational in the Low case

$$\frac{p_{F1}}{p_{F0}} < 1+r \quad \Leftrightarrow \quad VA^M > \frac{\theta}{1+r}VA^L \quad (5)$$

- resource conservation is rational in the High case

$$\frac{p_{F1}}{p_{F0}} > 1+r \quad \Leftrightarrow \quad VA^H > \theta(1+r)VA^L \quad (6)$$

Conditions (2) and (3) can be satisfied for appropriate values of the R& D cost parameter K , and of the share accruing to the innovator, $1-\beta$.

I have to identify the pattern of parameters for which the three conditions (4), (5) and (6) are simultaneously satisfied.

Under assumption A.6 condition (4) requires

$$\theta > \gamma \quad (7)$$

In fact (4) implies $VA^H - VA^N > VA^M - VA^L$. If VA is a concave function of Y , inequality (7) requires that $Y^H - Y^N > Y^M - Y^L$, which is satisfied if and only if $Y^M > Y^N$ since $Y^N, Y^M \in (Y^L, Y^H)$. This is condition (iii) in the proposition.

Condition (4) also requires that

$$\gamma > 1+r \quad (8)$$

This is condition (ii) in the proposition. Restriction (8) can be shown to be a necessary condition in the case of a revenue function VA proportional to output Y . If $VA = kY$,

the conditions above imply

$$\begin{aligned}\frac{VA^H - VA^N}{VA^M - VA^L} &> (1+r) &\Rightarrow \frac{(\theta-1)\gamma Y^L}{(\theta-1)Y^L} &> (1+r) \\ VA^M &> \frac{\theta}{1+r} VA^L &\Rightarrow \theta Y^L &> \frac{\theta}{1+r} Y^L \\ VA^H &> \theta(1+r) VA^L &\Rightarrow \gamma\theta Y^L &> \theta(1+r) Y^L\end{aligned}$$

All three conditions hold under the parametric restriction in proposition 1, i.e. if (1), (7) and (8) are satisfied. Since these three inequalities hold strictly under the parametric restriction of proposition 1 in the linear case, they must also hold, by continuity, for a concave revenue function that is sufficiently close to linearity. I have proved the proposition.

1.5 Discussion

An interpretation for condition (7) is that fossil sector's output must be more sensitive to primary resource supply (θ) than to technology (γ). In this case a miss-match between R&D and conservation proves to be particularly costly, i.e. Y^N is relatively low, meaning that R&D alone has a moderate impact on the sector's output. Greater resource supply allows the sector's output to increase more than can be obtained with R&D alone. Nevertheless conditions (iii) and (7) really hinge on the fossil sector's revenue and it is even stronger. They are obtained from condition (4) which requires that the sector's revenue be more sensitive to changes in the supply of the primary resource under improved technology than without technical progress. If actions were continuous variables, condition (4) could be written as

$$\frac{d^2VA}{dFda} > r. \quad (9)$$

Technical progress shifts upward the marginal revenue schedule, and substantially so. More precisely this effect should be larger than the real rate of interest. In such a situation the return on joint investment, by both the mine-owner (in the form of conservation) and the R&D lab, is higher than the return on riskless reference assets, i.e. r . Condition (9) provides support for an empirical enquiry. A related empirical literature in energy economics explores the plausibility of a 'rebound' effect by which technical improvements in the use of one resource can increase demand for the resource (Khazzoom, 1980). The strong version of the 'rebound' effect predicts an increase in resource consumption (a 'backfire' effect, i.e., a rebound exceeding 100%), whereas its weak version predicts a reduction in resource use that is less than proportional to resource efficiency improvement. Empirical results based on sectorial data find rebound between 10% and 60%, increasing

with the time horizon (Dimitropoulos, 2007).

Let me now turn to the parametric restriction (8). As suggested in its version (ii) it has a clear interpretation: technical progress in the fossil sector is stronger than average. In fact, although here the rate of return on savings is taken to be exogenous, in general equilibrium models r is positively related to the rate of technological progress (i.e. to the economic growth rate in the usual Keynes-Ramsey condition). So if $1 + r$ reflects the average rate of technological progress, (8) can be satisfied only if technological progress is (potentially) faster than average. In a dynamic setting à la Ramsey, the no-Ponzi game condition requires r to be greater than the economic growth rate, g . This restriction is not in contradiction with (8) to the extent that the (potential) technological progress in the fossil sector is substantially above the average across sectors. In other words (8) is compatible with the no-Ponzi game condition since $\gamma > 1 + r > 1 + g$ is possible.

The strong form of complementarity that makes the emergence of multiple equilibria possible in this paper is very much related to the concept of equilibrium bias in technology developed in Acemoglu (2007). Consider how the supply of primary fossil inputs affects the expected reward from R&D investment targeted to fossil fuels. On the one hand, a larger supply of primary inputs tends *ceteris paribus* to depress the marginal product (and the price) of fossil energy. This price effect reduces incentives to undertake R&D activities in the sector. The price effect is however weaker the greater is the elasticity of demand for fossil energy. It is therefore potentially much weaker in the long run than in the short run under technology-primary input complementarity if technology improves. On the other hand, a larger supply of primary fossil inputs has a positive market-size effect on the reward to innovation. Acemoglu (2007) proves that overall an increase in the supply of the primary input may induce more targeted R&D under fairly general conditions (global increasing returns to scale, as assumed in A.4). Moreover, the complementarity can be so strong that the long run adjustment implies an increase in the relative marginal product of the resource along with the increase in its relative supply (strong bias).

Let me consider the typical CGE model based on a structure of nested CES production functions, such as the following:

$$\begin{aligned} E = g(Y, R) &\equiv \left(Y^{\frac{\sigma-1}{\sigma}} + R^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} & \sigma > 1 \\ Q = h(E, L) &\equiv \left(E^{\frac{\psi-1}{\psi}} + L^{\frac{\psi-1}{\psi}} \right)^{\frac{\psi}{\psi-1}} & \psi < 1 \end{aligned}$$

where Q is final output, L is all other factors of production other than E , which is energy.

Energy is a composite produced using fossil sector's output, Y , or output of alternative energy sources, R . If all sectors are assumed to be competitive, the inverse demand functions will give the fossil sector's price and revenue as

$$p_Y = h'_1(E, L) g'_1(Y, R) \quad ; \quad VA = h'_1(g(Y, R), L) g'_1(Y, R) Y$$

The consequence of a technological improvement (an increase in a) on the demand for primary fossil resource inputs F depends on the elasticity of demand for the fossil sector as a whole. Suppose for instance that demand is perfectly inelastic. In this case any increase in a translates into a proportional downward shift of the demand for F . It should therefore be clear the importance of the asymmetry in the elasticities: one compounds the other. If the output of the fossil sector is a good substitute for the alternative resource R , then an improvement in a can drive up the demand for F as their joint output Y takes over some of R 's share in the energy market $p_E E$ (where $p_E = \partial Q / \partial E$). Thus assumption $\sigma > 1$ is crucial for complementarity between resource conservation and directed R&D to emerge, and even more so given assumption $\psi < 1$. It should be noticed that these assumptions reflect the most commonly used configuration in applied models of the energy sector. There is some consensus over the fact that there is little scope to substitute other factors for energy inputs, but that there is some margin in combining different sources of energy within the energy sector (e.g. Popp 2004, Otto et al. 2005, Jacoby et al. 2006, Wing 2006).

As a numerical example proving the possibility of multiple equilibria, the following pattern of parameters ensures that conditions (2)-(6) hold simultaneously: $\sigma = 2$, $\psi = .75$, $L = 1000$, $R = 100$, $K = 7$, $\beta = .1$, $\underline{S} = 10$, $\theta = 2$, $\underline{a} = 1$, $\gamma = 1.8$, $r = .25$.

2 Conclusion

This paper identifies the conditions for the emergence of multiple trajectories in technological development and resource exhaustion rate in a non-renewable resource sector (dubbed the fossil fuel sector). Multiplicity requires that sectorial R&D and the supply of the resource be strategic complements. This is the case only if sectorial technology improvement is beneficial to the demand for the resource. Hence a first necessary condition constraints the elasticity of substitution of the production function with respect to the output of the fossil sector. Sectorial technical progress increases the demand for the resource only if fossil energy is a good substitute for alternative energy sources (at least if one retains

the common assumption of poor substitutability between energy and non-energy inputs to the aggregate production function). If the alternative resource has a relevant share of the energy sector, then sectorial technical progress is beneficial to the demand for the resource, because the fossil sector takes over some part of the energy-market share of the alternative resource. The revenue (and value added) of the fossil sector is increasing in the fossil sector output, in this case.

If furthermore sectorial revenue is quasi-concave in sectorial output, three other conditions must be satisfied to have multiple equilibrium trajectories. There must be an opportunity cost to resource conservation (i.e. a positive real interest rate). There must be scope for substantial technical progress in the fossil sector. More precisely, the technically-feasible rate of improvement of fossil resource efficiency in energy production should be greater than the real rate of interest. Note that this condition concerns only the potential rate of sectorial technical progress, that is the one prevailing along the virtuous trajectory. If the economy follows the vicious trajectory, the observed rate of technical progress in the fossil sector can be below the rate of interest and may provide no information on the validity of the condition. This is a problem for testing the empirical plausibility of this condition.

Finally, a fourth condition must be satisfied for multiple equilibrium trajectories to emerge: the fossil-sector's output should depend more on the supply of the resource than on sectorial technical progress. One possible interpretation of this condition is that technical progress alone is unable to compensate for the reduction in supply of the resource (in terms of the volume of sectorial output). This (pessimistic) condition links the paper to the strand of literature presented in the introduction. Testing its empirical validity is quite a challenging task on the research agenda.

It seems worthwhile to check how robust the results are with respect to some generalizations. First, it should be established if allowing the players to choose their actions out of a continuum set is sufficient to ensure uniqueness of the equilibrium. Second, a version of the model with infinite horizon should be analyzed, with an endogenous date of full exhaustion of the stock of resource.

Moreover a number of extensions seem feasible within the framework of the model. It can be used to analyze the interaction between R&D and technological developments in the competing sub-sectors of the energy industry. I plan to allow for the possibility to perform R&D targeted to the alternative -renewable- resource. In this context it will be possible to study how some exogenous intensification of R&D opportunities in the alternative resource

(e.g. public subsidies to renewable sources of energy) may affect the incentives to perform R&D and modify the intertemporal profile of sales in the fossil sector. In the case of multiple equilibria, exogenous changes can have drastic consequences. But the extension should be of interest even in the case of a unique equilibrium.

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